# Pathways to Sustainability: Routing-Based Energy Optimization Techniques for Performance Enhancement and Lifetime Extension in Wireless Sensor Networks

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## Abstract:

WSNs (Wireless Sensor Networks) play a pivotal role in various applications. However, the inherent constraints of sensor nodes, particularly limited energy resources, pose significant challenges to the overall performance and longevity of WSNs. This research explores innovative pathways towards sustainability in WSNs by introducing advanced routing-based energy optimization techniques. This research begins with a comprehensive analysis of the existing challenges in WSNs, emphasizing the critical importance of energy efficiency for prolonged network lifetime. Novel routing strategies are proposed to enhance performance and extend the operational lifetime of sensor networks, leveraging this considerate. These strategies incorporate intelligent energy-aware algorithms and protocols that dynamically adapt to the network conditions. The exploration explores the design and execution of the proposed routing-based energy optimization techniques, providing a detailed examination of their impact on network performance metrics such as latency, throughput, and reliability. Simulation results validate the efficiency of the introduced strategies. Furthermore, the study explores the implications of these advancements in diverse application scenarios, including environmental monitoring, healthcare, and smart cities. The potential for sustainable and resilient WSNs is discussed, highlighting the broader significance of the proposed routing-based energy optimization techniques in addressing the evolving demands of contemporary sensor network applications. Finally, this research presents a significant step forward in the pursuit of sustainable WSNs. The proposed routing-based energy optimization techniques offer a promising way for enhancing the performance and extending the lifetime of WSNs, thereby contributing to the realization of efficient and permanent solutions for a wide range of applications.

***Keywords:*** *Advanced Routing-Based Energy Optimization Techniques, Energy Efficiency, Prolonged Network Lifetime, Energy-Aware Algorithms, Latency, Limited Energy Resources, Network Performance Metrics, Operational Lifetime of Sensor Nodes, Reliability, Sustainability, Throughput, Wireless Sensor Networks (WSNs).*

## 1. Introduction:

In recent years, the proliferation of Wireless Sensor Networks (WSNs) has significantly contributed to advancements in numerous fields, comprising environmental observing, healthcare, agriculture, and industrial computerization. Nevertheless, the limited energy resources of sensor nodes remain a critical challenge, impacting the overall performance and longevity of WSNs. Efficient energy management is imperative to address this challenge and unlock the full potential of WSNs for sustainable and long-term deployment [1].

This paper explores the promising avenues of routing-based energy optimization techniques to enhance the performance and extend the lifetime of WSNs. By strategically optimizing the energy consumption of sensor nodes through intelligent routing protocols, we aim to mitigate the adverse effects of energy depletion, ensuring the reliability and sustainability of WSNs in diverse applications [2].

**Background:**

- Briefly discuss the rapid growth and widespread applications of WSNs [3].
- Highlight the significance of energy constraints in sensor nodes and its impact on network performance and longevity [4].
- Introduce the need for sustainable solutions to address energy challenges in WSNs [5].

**Motivation:**

- ✓ Emphasize the importance of sustainable WSNs for continued advancements in data collection, monitoring, and automation [6].
- ✓ Discuss the potential economic and societal benefits of prolonging the lifetime of WSNs through energy optimization techniques [7].
- ✓ Present the ecological motivation for reducing the environmental footprint of WSNs [8].

**Challenges:**

- ✓ Identify key challenges associated with energy consumption in WSNs, such as limited battery capacity, irregular node deployment, and dynamic network conditions [3].
- ✓ Discuss the implications of these challenges on network reliability, data accuracy, and overall system performance [9].

**Objectives of the Study:**

- ❖ Clearly outline the goals and objectives of the paper, focusing on the development and evaluation of routing-based energy optimization techniques.
- ❖ Emphasize the intention to enhance WSN performance, extend network lifetime, and contribute to sustainable deployment practices.

**Scope and Significance:**

- ❖ Define the scope of the study, specifying the targeted routing-based energy optimization techniques.
- ❖ Discuss the broader significance of the research, including potential applications and the impact on various industries.

**Organization of the Paper:**

Provide a brief overview of the structure of the paper, outlining the main sections and their respective contributions.

Mention the key methodologies, techniques, and case studies that will be discussed in subsequent sections.

By exploring and implementing routing-based energy optimization techniques, this study aims to pave the way for sustainable and resilient WSNs, ensuring their continued effectiveness in diverse environments. Through the systematic evaluation of these techniques, we anticipate uncovering practical solutions that not only enhance performance but also extend the operational lifetime of wireless sensor networks.

## 2. **Literature Review**:

### 2.1 Overview of Wireless Sensor Networks (WSNs):

This literature survey serves as a foundation for the subsequent sections, providing a comprehensive understanding of the current landscape of routing-based energy optimization techniques in WSNs. The synthesis of existing knowledge sets the stage for the presentation of novel contributions, ultimately contributing to the development of more sustainable and efficient Wireless Sensor Networks.

2.2 Brief Literature Review:

The most important factor for the development of WSN routing protocol is energy efficiency, which has a straight impact on the network's lifetime. Lot of work has done to achieve it in WSNs. Several surveys are around to develop routing protocols with energy efficiency. Some of those routing protocols are presented below [10]. A survey done on routing protocols for WSNs is discussed in which classifies the routing protocols into three categories according to the structure of the network: Flat, location-based and hierarchical infrastructure. These protocols are further classified into query-based, multipath- based, QoS (Quality of service) based and negotiation-based routing techniques according to protocol operations. Thus, the survey describes the limited supply of energy, computing power and bandwidth of the wireless sensor nodes along with the advantages and disadvantages of each routing protocol. In this work, we compare energy-efficient routing protocols comprehensively focusing on energy efficiency issues to help the researchers on their work [11].

A few routing protocols were discussed in a survey for WSNs and classified into hierarchical, data-centric and location-based protocols. The two considered primary energy metrics are: Minimizing the total power consumption of all the nodes during transmission in the multicast session. Maximizing the time of operation until the battery of the first node is depleted. Though, a good number of surveys for WSNs and their routing algorithms are provided in the reference. Our work gives an analytic survey over the energy-efficient WSN routing protocols. It focuses on an energy-efficient WSN routing protocol to aid the readers in choosing the most appropriate energy-efficient routing protocol for wireless sensor networks. We also discussed the strength and weaknesses of each protocol and compared each of them with some metrics such as Mobility, Scalability, Power usage, Route metric, robustness, QoS Support, and periodic message type. Many researchers raise the issue of energy efficiency in WSN by designing different routing protocols to elaborate the lifetime [12].

In some previous protocols like Flooding, each node broadcast its control packet and data packets that it has received from other nearest nodes, and until and unless the destination reaches repeating of this process is done several times. Network protocol design should be scalable to different sized networks. Because of which the general problems like, Overlap and Implosion occurs. Due to the small or tiny size of the node, it can easily minimize the required power for getting energy efficiency and it automatically reduces the value of sensor nodes. In-network protocol designing when density and topology changes, the sensor node should be adaptive to such changes immediately. Furthermore, WSN consists of several nodes; by reducing each node cost it can easily reduce the whole network's cost. In literature, several energy- efficient protocols based on the cluster with different metrics considered in route selection were designed based on the present energy status of the particular node [13].

Routing is nothing but selecting an efficient (Energy) path to process and transport the information in the network, or over several networks. In the case of WSN, routing should be handled carefully because it is a very important task. This routing mechanism is necessary for transmitting the data information link between the sensor nodes and the destination, to organize proper communication between them. This mechanism will decrease the network lifetime with increased power utilization of the sensor nodes. So, to reduce power consumption and to elaborate the network lifetime various routing protocols have been developed till now. The categorization of various routing protocols can be done depends on the mode of functioning, the participation of nodes, the structure of the network and the clustering of protocols. Furthermore, the various problems in these techniques are efficient energy, deployment of nodes, coverage area, scalability, connectivity, and the security [14].

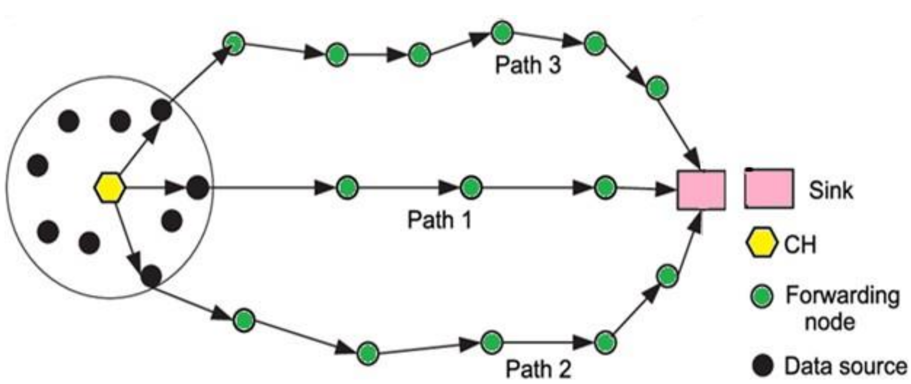


Figure 1: Different routing paths in WSN

In this organization of nodes, the intermediate nodes are routers that are also called gateways, network hardware devices, firewalls, or switches. This action normally maintains data information of the path to several network base and forwarding based on the routing tables. The routing schemes used in WSN messages are classified into four categories i.e. Network structure scheme, Communication model scheme, Reliable routing schemes, and topology-based routing schemes. Simultaneously, in many routing protocols, non-uniform energy consumption and the unbalancing of load are the major issues that result in the partitioning of a network [15].

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Furthermore, the consumption of energy and the lifetime of the network will be affected by the reduced packet delivery ratio. Especially in the case of WSN, the routing mechanism should be handled carefully because it is a very important task. It is necessary for transmitting the data information link between the sensor nodes and the destination, to organize proper communication between them. This mechanism will decrease the network lifetime with increased power utilization of the wireless nodes. So, to reduce the consumption of energy and to elaborate the lifetime of the network various routing protocols have been developed. The categorization of various routing protocols can be done based on the mode of functioning, the participation of nodes, the structure of the network and the clustering of protocols. The figure below shows different routing protocols with efficient-energy related to WSN [16].

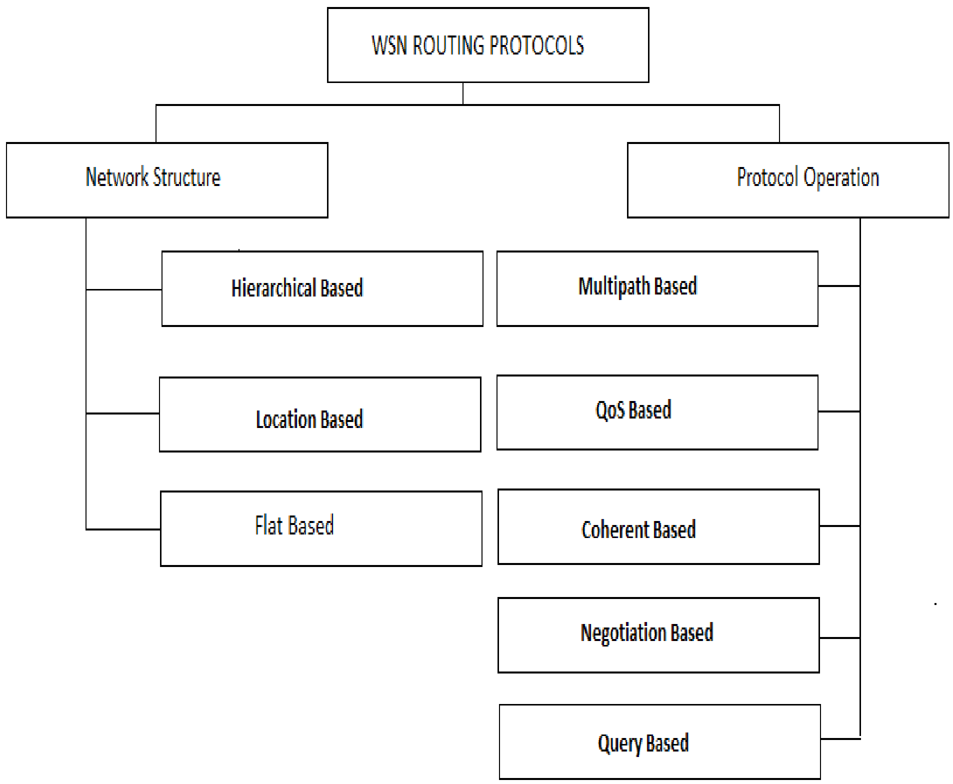


Figure 2: Routing Protocols with Efficient Energy in WSN

### 2.4 Extended Network Lifespan:

Energy optimization techniques can prolong the operational lifespan of network equipment and reduce maintenance costs, ensuring the long-term sustainability of WSN infrastructure [17].

### 2.5 Scalability:

These strategies can also make Wireless networks more scalable, allowing them to accommodate the increasing number of connected devices and emerging applications [18].

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### 2.6 Improved Quality of Service (QoS):

Effective routing and clustering can lead to better QoS for end-users, ensuring that they have a seamless experience when using WSNs services [19].

### 2.7 Enhanced Performance:

Optimized routing and clustering strategies can ensure that data reaches its destination quickly and reliably, meeting the stringent performance requirements of WSNs applications [20].

The below figure will give the basic structure for WSN based-IoT networks.

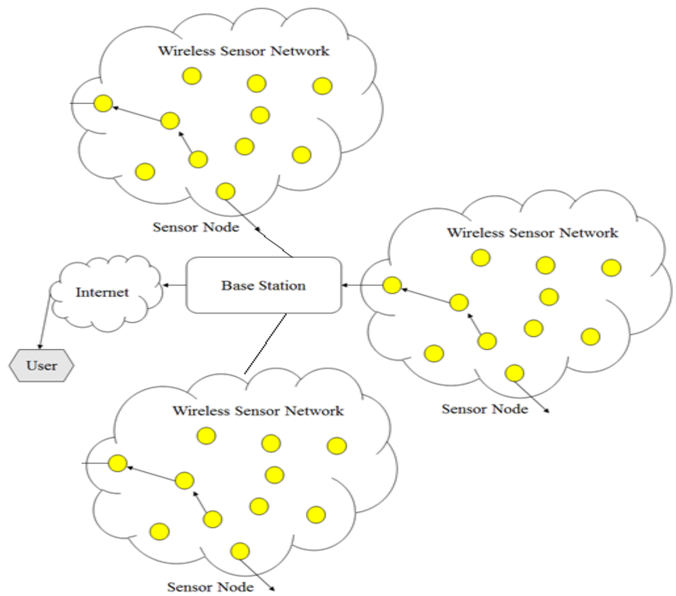


Figure 3: Basic Structure of WSNs Based-IoT Network

## 3 PROPOSED WORK:

The proposed protocol is designed to select the neighbor nodes, which were supposed not to drop the data packets due to any constraint it may either be energy or buffer. To elaborate on the network lifetime and performance, multiple matters were combined in a distinct procedure for calculating the routing pathway among the transmission bodies. At all intervals of time, every node desires to estimate its position concerning energy, in the wireless network. Furthermore, this work computes proactively as, the utmost amount of data information packet it can operate (accept, process, and broadcast) within the existing amount of power [21]. Additionally, within the wireless net, every node must need to analyze its stack management condition. Furthermore, in this exertion, it is also reactively computed depending on a predefined threshold value, as the available queue at the node buffer is less than or larger than the threshold value. To eliminate a node to turns out to be a bottleneck intermediate node two factors are used thereby mitigating the loss of the packet [22].



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The drop in the information packet due to node constraint 'energy' can be mitigated by an intermediary node and can be overwhelmed through multi-objective optimization progression. To facilitate the capability of the node to optimize the utmost packets and can be handled using an intermediary node within its limits of existing residual energy. Let's assume that, an intermediary node outfitted through a battery capability of (E) joules, also it can process the utmost number ′n′ of data packets within its present power limits [23].

### 3.1 Multi-objective development:

1. Node power: Necessary power to course the data packet

Let us think, for processing an individual data packet; the power consumed by an intermediary node is $'P_1'$ and it is measured through equation 1.

$$(P_1) = E_r(P_1) + E_p(P_1) + E_t(P_1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where,

$E\,(P_1) = energyrequiretoreceivethepacket'P_1'$

$E\,(P_1) = energyrequiretoprocessthepacket'P_1'$

$E\,(P_1) = energyrequiretotransmitthepacket'P_1'$

Now, after dealing out $'P_1'$ data packet the residual power of the node is specified by equation 2.

$$(\text{R}esidual\ \text{Energy}) = E - E\,(P_1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

After processing the data packets, the residual power of the node is given by a multi-dimensional (two) array, as given below.

$$[P_i, E\,(residual)\,] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

In the above equation, $i = number of packets$

$(\text{R}esidual\ \text{Energy}) = \text{Remaining E}nergy\ \text{of}\ the\ \text{Node}$

Calculating the capacity to optimize the utmost packet that can be processed through an intermediary node within its existing power is specified in equation 4.

$$K[P_i\,, (Residual)\,E] = \text{Max}\,(K[P_{i-1}\,, (Residual)E]\,,\ K_i + K\,[P_{i-1}\,, (Residual)E]) \ldots (4)$$

$$\forall\ 1 \leq P_i n$$
$$and$$
$$0 \leq (residual) \leq E$$

Here, ‘K’ is two dimensional constant, $[P_i, (Residual)]$, provides the ability to optimize the utmost packets which can be processed by the intermediary node within its residual energy.

 

## 4 Proposed Methodology:

### 4.1 Proposed Routing Protocol:

The proposed protocol is an extension of the existing energy-efficient routing protocol designed for a wireless network, i.e., LEACH. The brief discussion about the LEACH protocol is explained as follows, and further, the proposed model is explained [24].

The routing protocols used in wireless networks are cluster-based. The main intention behind it is, to select the top-quality wireless nodes randomly as a cluster head. Further, these selected nodes are used as the router to the destination node. The cluster head node's choice is done based on the node's residual energy in that particular period [25]. The formula for finding the threshold value of energy for selecting the cluster head is given by $T(n)$, it can be determined by the following formula,

$$T(n) = \begin{cases} \dfrac{p}{1-p\times[r \bmod (1/p)]}, n\in G \\ 0, others \end{cases} \quad \text{............} \quad 8$$

Where, $p = needed\ percentage\ of\ power\ to\ become\ a\ cluster\ head$, $r = existing\ rout$, $G$ = Number of wireless nodules.

Once cluster formations are done, then, the head nodes create a TDMA schedule. This will issue a notice to every node when it can pass on the data packet to the head of the particular cluster. Finally, the heads of the particular cluster gather data packets and transmit them to the destination node [26].

For communicating with the intermediate wireless nodes in the network, the model used is RWMM. Thus, the mobile nodes stay at a particular place near the existing intermediate node for some time interval to communicate and, afterward change their location by using the RWMM model. After that time interval, the node changes the position to other intermediate nodes based on the status of the node. Initially, the sink selects the intermediate node randomly moves closer toward it, and communicates through it. Then, the sink node selects the new intermediate node for communication and moves toward it according to the RWMM model theory [27].

### 4.2 Energy-Load Aware Routing Protocol for 5G Networks:

#### 4.2.1 Network Model:

We are assuming that the wireless nodes were dispersed with one movable destination node in the sensor field. Every sensor node has constrained recourses such as energy and buffer and they are static and cannot move after the deployment. While the movable sink node has unconstrained energy and an adequate buffer for communication. The wireless nodes identify their position through GPS. In this scenario, the initial location of the movable destination node is not considered [28].

### 4.3 **Energy and Load Awareness:**

The proposed protocol aims to decide the neighbor nodule to a mobile destination based on its buffer and energy status. So, the intermediate node should not drop the data packets and should not exhaust. At this stage, we are considering two parameters in the single process for calculating the routing path between the communication nodes. Primarily, the Cluster head must compute the status regarding energy and buffer (load). In this proactive computation is done to get the utmost number of data packets the head can process within its accessible power. Secondarily, each wireless node has to calculate its load position in the network. In this, reactive computation is done to find out the accessible queue at the node buffer, in fewer or greater, as per the predefined threshold rate. These factors were used to reduce the data packet loss and keep a wireless node from becoming a bottleneck intermediate node.

Let's us assume that, the power consumed for processing one data packet by an intermediate node is $'P_1'$. The total energy used by an intermediate wireless node is computed by, equation 9.

$$(P_1) = E_r(P_1) + E_p(P_1) + E_t(P_1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Where,
$E_r(P_1)$ = $Energy\ Required\ to\ Receive\ the\ Packet\ 'P_1'$
$E_p(P_1)$ = $Energy\ Require\ to\ Process\ the\ Packet\ 'P_1'$
$E_t(P_1)$ = $energy\ Require\ to\ Transmit\ the\ Packet\ 'P_1'$

Furthermore, the residual energy of the wireless node after dealing with the packet $'P_1'$ is shown in the equation 10.

$$(residual) = E - (P_1)\,E \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Finally, the capability of the intermediate node, to optimize maximum data packets can be processed in its existing energy and it can be achieved by entries of the arrays (two-dimensional), which are shown under.

$$[P_i, (residual)\ ] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Where, $i = 1, 2, \ldots .\ Number\ of\ Packets$
$E\ (residual) = Residual\ Enrgy\ Required\ by\ the\ Node\ to\ Process\ the\ Packet$
Also, the calculation of the capability to optimize the utmost data packets can be processed by the intermediary wireless node within its present power status, which is shown under the below consideration.

$$\forall \; 1 \le P_i n$$
$$and$$
$$0 \; \le E(residual) \le E$$

Where, $[P_i, E\ (residual)]$, provides the capability of the intermediary wireless node to optimize maximum packets and process them within its available power.

### 4.4 Performance in Dynamic Environment:

The following performance metrics were considered to calculate the performance,

I. **Throughput**: A performance metric of the network to analyze how many data packets are transmitted in a particular amount of time from source to destination [29].

II. **Delay**: Delay is a very important metric in the wireless network to measure how much is taken by the data packets to receive at the sink node transmitted from the base node [30].

III. **Overhead**: The overhead can be defined as, the relation between the number of control (path finding & route maintaining) packets to authentic information data packets transmitted within the wireless network [31].

The network simulation parameters were made known in the table below

Table 1: Simulation parameters

| Sr. No. | Network Parameters | Values |
|---|---|---|
| 1 | Time for Simulation | 1000 seconds |
| 2 | Nodes used (Number) | 10-100 units |
| 3 | Nature of Link Layer | Logical Link (LL) |
| 4 | IEEE Standard for MAC Protocol | 802.11 |
| 5 | Type of Communication (Radio) | Two-Ray Ground |
| 6 | Queue Style | Drop-Tail Priority Style |
| 7 | The protocol used for Routing | Proposed |
| 8 | Traffic Methodology | CBR |
| 9 | Specified Area of the Network | 1500m x 1500m |
| 10 | Type of Mobility | Random Way Point Mobility |

For calculating the performance of the proposed routing protocol, Network Simulator (version NS2.34) is used. The outcomes were compared with the present routing protocols. This simulator evaluates the performances of different metrics like routing overhead, time delay, as well as the throughput of the wireless network. In the simulation part, the time for simulation is assumed as 1000s with different three scenarios with different performances. Furthermore, for verification of the results, the assumptions are made that there is an uneven quantity of nodes with the mobility model of Random waypoint mobility. The source power for every node is assumed as of 10j and the period of 20 m/s is assumed as pause time. The radio range for communication is fixed at 250m and the MAC IEEE 802.11 is considered with a data rate card of 2 Mbps. While talking about the transmitting and receiving power, these are kept as 300mW (receiving power) and transmission power is 600mW. Finally, the packet size is considered in bytes of 512 values, and the traffic in the network is considered as CBR.

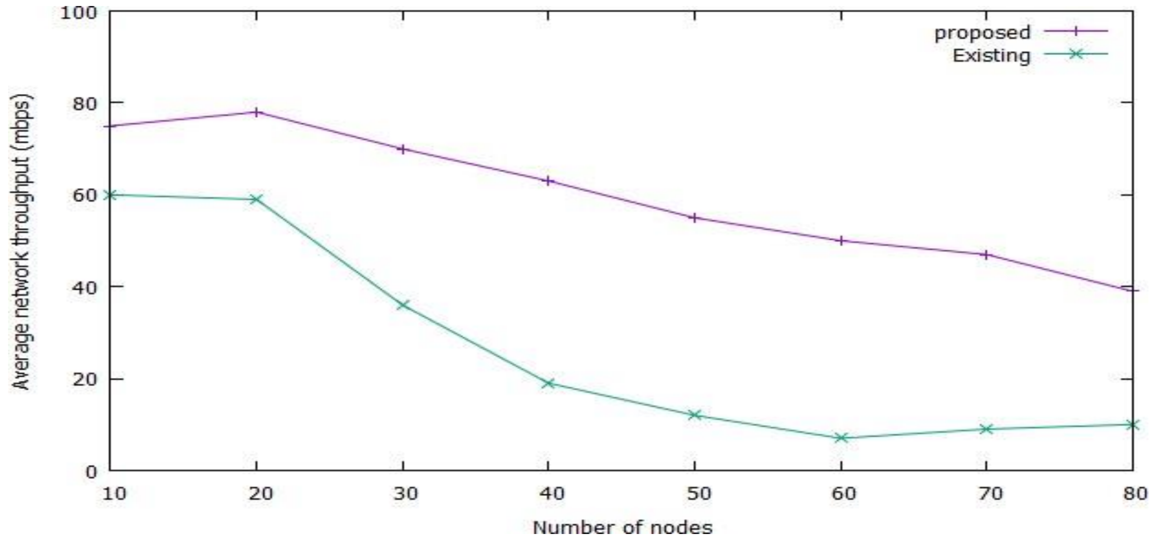


Figure 5: Delay Comparison

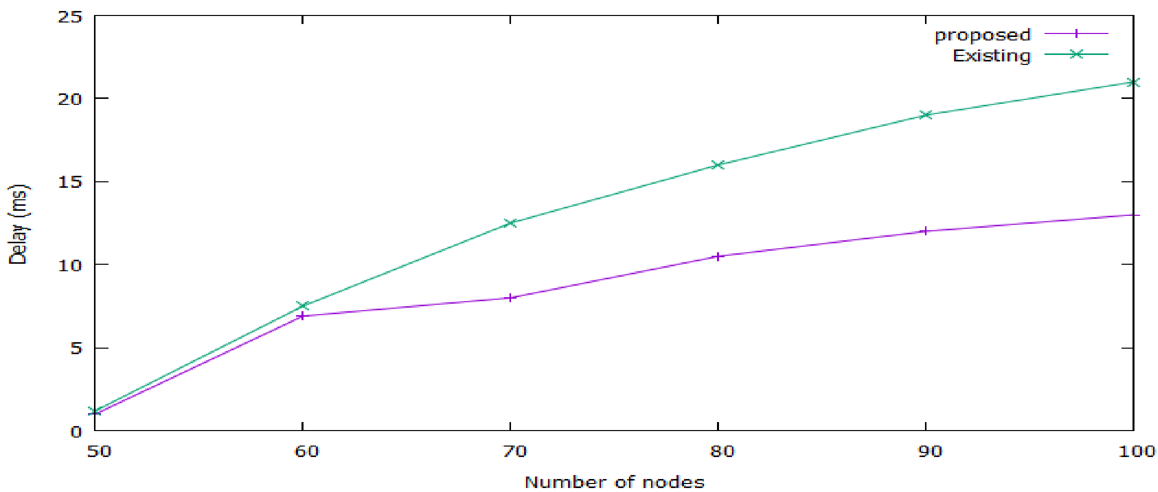


Figure 6: Throughput Comparison

All the above results show that the projected work outperforms in terms of network lifetime enhancement, network delay minimization, and throughput. Additionally, it mitigates the loss of data information packets by extending the energy efficiency of the wireless network.

## 4.5 5. Conclusions & Future Scope of the Work:

### 5.1 Conclusion:

The proposed work has explored and analyzed various routing-based energy optimization techniques aimed at enhancing the performance and extending the lifetime of WSNs. The ever-growing demand for efficient and sustainable solutions in the field of sensor networks has prompted researchers to investigate innovative approaches to mitigate the energy constraints inherent in these networks. Through a comprehensive review of the literature, it is evident that routing strategies play a pivotal role in determining the overall energy consumption and, consequently, the operational lifespan of WSNs. Techniques such as Energy-Efficient Routing Protocols, Cluster-based Routing, and Machine Learning-based Routing have been scrutinized in terms of their efficacy in optimizing energy usage, improving network performance, and prolonging sensor node lifetimes.

The findings indicate that a holistic approach to energy optimization, considering both proactive and reactive strategies, is essential for achieving sustainable WSNs. Furthermore, the integration of emerging technologies, such as the Internet of Things (IoT) and machine learning algorithms, demonstrates promising avenues for future research and development in the realm of WSNs.

### 5.2 Future Scope:

As we navigate towards a future where WSNs are integral to various applications, including environmental monitoring, smart cities, and healthcare, the significance of sustainable and energy-efficient designs cannot be overstated. The insights presented in this paper contribute to the ongoing discourse on the development of WSNs that not only meet the demands of today but also pave the way for a greener and more sustainable tomorrow. The exploration of routing-based energy optimization techniques provides valuable insights for researchers, practitioners, and policymakers alike, as they collaborate to address the challenges associated with energy consumption in WSNs. By adopting and further refining these strategies, we can work towards achieving a harmonious balance between performance enhancement and the extension of the operational lifetime of wireless sensor networks, thereby fostering a more sustainable and resilient technological landscape.

## Author contributions:

Conceptualization, SA, AKL, and GSSR; methodology, SA; software, SA, AKL; validation, SA, SA and GSSR; formal analysis, SA; investigation, GSSR; resources, SA; data curation, SA; writing—original draft preparation, GSSR, AKL and SA; writing—review and editing, SA; visualization, GSSR; supervision, SA; project administration, SA; funding acquisition, GSSR. All authors have read and agreed to the published version of the manuscript.

 

## Conflict of interest:

The authors declare no conflict of interest.

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