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# PETAR: A Predictive Energy and Trust-Aware Secure Routing Protocol for Energy-Efficient Wireless Sensor Networks in Smart Healthcare and Urban Monitoring

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**Abstract**

Wireless Sensor Networks (WSNs) are commonly applied in smart health care and smart urban sensing systems for collecting and transmitting real-time data from different devices. However, low energy capacity, unstable communication, and security concerns are major challenges facing WSNs. Therefore, this paper proposes a Predictive Energy and Trust-Aware Routing (PETAR) algorithm for enhancing energy efficiency, secure communication, and network stability in WSNs. The proposed PETAR algorithm utilizes predictive energy and trust-aware node evaluation for efficient cluster head selection and routing. The PETAR algorithm forecasts the future energy level of nodes and evaluates the trustworthiness of neighboring nodes for selecting efficient nodes for data transmission. Additionally, an adaptive clustering scheme and secure data transmission are integrated into the PETAR algorithm for minimizing energy consumption and enhancing communication reliability. The simulation outcomes reveal that the suggested approach surpasses traditional routing protocols such as LEACH, PEGASIS, Energy-Aware Routing, and AI-based routing protocols. The proposed PETAR algorithm exhibits better network lifetime, residual energy level, packet delivery ratio, network throughput, and end-to-end delay relative to traditional routing protocols. The PETAR algorithm also supports a greater number of active nodes for a longer simulation period compared to traditional routing protocols The PETAR algorithm offers a robust solution for achieving energy efficiency and security in WSNs. As a result, it is well-suited for deployment in smart healthcare systems and sustainable urban sensing environments.

**Keywords:**
Good Health and Well-being, Secure Data Transmission, Smart Healthcare, Smart Cities, Sustainable Cities and Communities.

## 1.Introduction

With the explosion of the Internet of Things (IoT) concept, smart environments have been enabled through the use of WSNs. It consists of sensor nodes used for information collecting from the environment. Several smart environments including smart cities, industrial control, smart home, healthcare monitoring and ecosystem monitoring have utilized WSNs. Due to the use of WSNs in collecting data from the environment in real-time, it has become a pivotal framework in the development of smart cities and sustainable environments [11], [18].

WSNs have gained significant importance in smart healthcare environments in recent years. Wearable healthcare devices and wireless body area networks can help in monitoring the health conditions of the patient, such as heart rate, body temperature, physical activities, etc. However, one of the major challenges in healthcare monitoring environments is the prolonged operation of the network, considering that the sensor nodes are equipped with limited battery power resources. Thus, efficient communication protocols are essential for the functioning of network [5], [8]. In order to achieve this, several researchers have contributed different techniques for clustering and routing in WSNs [9], [14].

In addition to the healthcare sector, WSNs can also be applied to environmental monitoring and smart city management. Sensors can be installed in the city to collect data on temperature, humidity, pollution level, water quality, and infrastructure. This data can contribute to more accurate decisions by the city authorities. For instance, sensors can be employed to measure environmental conditions in the city, which is helpful in enhancing the city's sustainability [6]. Moreover, it is possible to maintain environmental safety by using WSNs to monitor the water quality [12].

Although WSNs enjoy many advantages, several challenges remain. Among the challenges facing WSNs is the issue of energy consumption. WSNs operate on batteries, and it is not possible to change the batteries frequently. Therefore, the limited energy resources available to sensor nodes remain one of the most significant challenges in WSNs, directly influencing network lifetime, reliability, and overall performance. It is important to note that several techniques, including clustering, data aggregation, duty cycle, and numerous routing protocols have been developed to reduce energy consumption and extend the operational lifetime of WSNs [30], [13]. Traditional clustering protocols, including LEACH-based routing protocols, involve the creation of clusters to reduce communication overhead and energy consumption [31]. However, with the increase in the complexity of IoT applications, intelligent techniques are needed.

Another significant factor in WSNs is data security. Since these networks are deployed in open environments, there is a possibility of data interception, node capture, and malicious attacks. Therefore, data security is very significant, especially in health care applications. Various security solutions have been presented by different researchers using artificial intelligence and blockchain technology. Artificial intelligence-based security models can identify unusual activity in the network and protect the sensor networks from possible attacks [1]. Similarly, blockchain-based security solutions can provide security for IoT-based networks by maintaining data integrity and preventing unauthorized access [4], [2].

In recent years, Advanced machine learning and intelligent optimization approaches have also been considered to strengthen the performance of WSNs. The AI - driven routing protocols can be used to dynamically select efficient routing paths to transmit information based on current network conditions, thus reducing delays and improving reliability in data transmission [3]. Deep learning approaches have also been considered to optimize the performance of wireless sensor networks in terms of energy consumption and traffic in large-scale sensor systems [25]. In addition, optimization methods such as

metaheuristic methods and bio-inspired methods have also been considered to ensure fair energy consumption among the sensor nodes [19], [23], [27].

Modern WSN systems are increasingly using adaptive clustering and intelligent routing techniques for better network stability. The use of learning-based routing protocols and reinforcement learning is also seen to improve network efficiency and fault tolerance [20], [29]. Self-healing clustering techniques are also being considered for better network connectivity in case of node failures or network conditions [28]. Hybrid optimization and fuzzy logic are also being used for better cluster formation and data transmission efficiency in IoT-based health care networks [9].

Recent studies have emphasized the significance of implementing energy-efficient communication and intelligent network management techniques for better WSN systems in smart cities. Machine learning-based WSN systems are being considered for better network performance and reduced energy consumption and costs [24]. Advanced techniques such as adaptive virtualization and intelligent data fusion are also being considered for better network scalability and efficiency in IoT-based systems [7], [16].

However, despite the availability of a number of solutions for addressing these challenges of energy efficiency and security in WSNs, these two problems are generally addressed individually. In most practical scenarios such as health care monitoring and smart city surveillance, both energy efficiency and security are of equal significance. The existing solutions have shown some limitations in handling scalability, uneven energy consumption, and security risks [21], [22], [32].

In order to overcome these challenges of energy efficiency and security in WSNs, a new framework is required that integrates energy-efficient communication and security mechanisms. Such a framework should have the capability to handle health care monitoring and environmental surveillance efficiently and securely. In view of these challenges of energy efficiency and security in WSNs, this research aims to develop a new framework for WSNs called the Predictive Energy and Trust-Aware Secure Routing Protocol (PETAR) which is particularly useful for smart health care and sustainable urban surveillance systems. The proposed framework will improve the network lifetime and overall security of WSNs by optimizing the routing and clustering mechanisms for efficient and secure data transmission.

### 1.1. Research Goals

This research aims to create a secure and energy-saving wireless sensor network design for smart healthcare and urban sensing systems. The proposed framework enhances the efficiency of data collection, communication and security within sensor networks, which helps to build innovative and reliable digital infrastructure and promotes SDG 9. Furthermore, it also aids in the healthcare services sector and urban monitoring to make cities smarter, safer and more sustainable, carrying SDG 11. The specific objectives of the research are:

1.Analyze the conventional power-efficient routing and clustering protocols for WSNs.

2.Develop an optimized routing and clustering mechanism for WSNs to minimize energy consumption.

3.Integrate security features for WSNs to ensure data security for smart healthcare monitoring.

4.Improve the reliability of WSNs by applying intelligent optimization techniques.

5.Evaluate the performance of the developed wireless sensor network model considering energy efficiency, network lifetime, data delivery ratio, and security.

## 2.Related Works

WSNs have become a key technology in supporting intelligent communication in Internet of Things (IoT) environments. The applications of WSNs are broad, ranging from smart healthcare, environmental monitoring, smart agriculture, and smart infrastructure management, among many others. However, energy constraints, scalability, and security are still key challenges in developing efficient WSNs architectures. Several studies have focused on solving these problems through efficient routing protocols, intelligent clustering techniques, and secure communication protocols, among many other techniques.

### 2.1. Energy-Aware Data Communication for Prolonged Operation of WSNs

Energy efficiency is considered a major design criterion for WSNs due to the limited power of the nodes' batteries. Previous studies have primarily focused on optimizing routing protocols and clustering mechanisms for energy-conserving communication in WSNs. The optimization of routing protocols and clustering mechanisms helps to support long-term network operation by efficiently utilizing the limited power of the nodes' batteries. An optimization of routing protocols based on LEACH helps to efficiently utilize the limited power of the nodes' batteries by dividing the energy consumption among the nodes of the network [31].

However, recent studies have also proposed more efficient optimization mechanisms for WSNs. The optimization mechanisms for IoT-based WSNs in smart cities have emphasized the need for adaptive routing protocols for efficient communication and reduced communication overhead [10]. The optimization mechanisms for sustainable IoT-based WSNs have also emphasized the need for energy-efficient communication protocols for minimizing data transmission overhead [13].

The optimization mechanisms for WSNs have also proposed clustering-based communication protocols for efficient communication. The surveys have emphasized the significance of data aggregation and clustering mechanisms for minimizing data transmission overhead in WSNs [30]. The optimization mechanisms for WSNs have also proposed hierarchical clustering and data fusion mechanisms for efficient communication [16]. The optimization mechanisms for WSNs have also proposed agent-based clustering mechanisms such as Energy Conservation Clustering Through Agent Nodes and Clusters (EECANC) for efficient communication in WSNs [14].

Metaheuristic optimization mechanisms have also been proposed for optimizing WSNs. The optimization mechanisms for WSNs have proposed a metaheuristic-based routing protocol for minimizing energy consumption and communication delay in smart parking systems [19]. The optimization mechanisms for WSNs have also proposed an adaptive hybrid optimization algorithm for selecting cluster heads and optimizing energy consumption in WSNs [27].

### 2.2. Intelligent Learning-Based Approaches for Energy Conservation in WSNs

Recently, the application of Artificial Intelligence (AI) and Machine Learning (ML) techniques in WSNs has brought new opportunities to enhance the performance and adaptability of the networks. For instance, the application of AI-based routing techniques can adapt to the communication paths in the networks. Studies have shown that the application of AI-based routing techniques can efficiently improve the performance in terms of energy efficiency while maintaining the reliability of data transmission in WSNs [3].

In recent times, deep learning techniques have been applied to optimize the performance in relation to energy efficiency in WSNs. For instance, deep learning techniques can efficiently predict the traffic

pattern in the networks and optimize the performance in relation to energy efficiency in WSNs [25]. Moreover, the application of AI-based clustering and routing techniques can efficiently improve the performance in relation to energy efficiency in WSNs.

In recent times, advanced learning techniques such as reinforcement learning and evolutionary learning techniques have been employed to improve the performance in terms of stability in WSNs. For instance, evolutionary reinforcement learning techniques can efficiently improve the performance with regard to fault tolerance and topological stability in WSNs [29].

In recent times, extensive survey studies have been carried out to show the importance of machine learning-based green WSNs. For instance, machine learning techniques can significantly improve energy efficiency in IoT-based sensor networks. [24].

### 2.3. Security Concerns in Wireless Sensor Networks

In addition to energy efficiency, security is another important issue in WSNs, which is considered to be significant in applications such as healthcare and infrastructure management. WSNs are vulnerable to various security attacks such as data interception, node capture, denial of service, and unauthorized access.

Recently, the main focus of research is to design intelligent security frameworks to address the security challenges in WSNs. For example, intelligent security models using AI approaches have been introduced to protect WSNs from security threats in smart city applications. These security models can effectively prevent security attacks in WSNs using machine learning techniques [1].

In recent times, blockchain technology is also being used to ensure the security of WSNs. Blockchain technology provides greater security to WSNs compared to other security techniques. Blockchain technology can be used to ensure the integrity and trust management of IoT-based WSNs. Moreover, unauthorized data modification can be prevented using blockchain technology in WSNs [4]. Furthermore, intelligent security models using blockchain technology and AI techniques can be developed to ensure the security and predictive monitoring of WSNs [2].

Intelligent optimization techniques can be used to improve the security and efficiency of WSNs. For example, QoS-aware fuzzy deep reinforcement learning frameworks can be developed to ensure the security and efficiency of WSNs [32].

### 2.4. Applications of WSNs in Smart Healthcare and Urban Monitoring

WSNs contribute to smart healthcare applications by supporting ongoing patient assessment and remote healthcare management. Wireless Body Area Networks (WBANs) allow sensors to collect physiological data from patients and send it to medical professionals. Energy-efficient communication protocols play an essential role in the functioning of healthcare monitoring networks [5].

In the context of IoT-based health monitoring networks, secure and energy-efficient architectures have been proposed. These highlight the importance of developing integrated solutions to address the constraints of energy consumption and data security. Adaptive fuzzy logic-based clustering mechanisms have also been developed to strengthen the efficiency of IoT-based WSNs in the context of healthcare networks [9].

In addition to healthcare, WSNs can be applied to the context of environmental monitoring and sustainable urban management. Sensors can be installed in the urban environment to collect data related

to environmental parameters. IoT-based sensor networks can effectively monitor environmental parameters in densely populated areas [6].

Another application is water quality monitoring. WSNs can be applied to track environmental parameters to support public health initiatives. Energy-efficient sensor network frameworks can be developed to monitor water quality while considering public health factors [12]. Another application is related to the development of smart agricultural networks. Energy-efficient routing and data aggregation techniques can be applied to monitor soil and environmental factors.

### 2.5. Emerging Technologies for Sustainable WSNs

The development of new advancements in networking technology has introduced new techniques for improving the sustainability of wireless sensor networks. For example, adaptive virtualization techniques have been introduced for improving resource management in large-scale IoT networks [7]. Moreover, self-healing cluster-based routing techniques have been introduced for improving the sustainability of WSNs [28].

Bio-inspired optimization techniques have also gained significant popularity in managing wireless sensor networks. For example, particle swarm optimization techniques have shown promising results in improving the sustainability of wireless sensor networks [23]. Moreover, adaptive techniques have been introduced for improving the sustainability of WSNs [21].

It has been concluded in several reviews that machine learning techniques, clustering algorithms, and duty cycling techniques need to be employed for improving the sustainability of wireless sensor WSNs [20]

### 2.6. Research Gap

WSNs have been used in many applications, including smart healthcare, environmental monitoring, and smart city. Many researchers have contributed to the improvement of WSN performance by using different techniques to enhance the efficiency of the networks. For example, the LEACH-based protocols and hierarchical clustering techniques can improve the lifetime of the networks by reducing the energy consumption during data transmission [31], [16]. Moreover, optimization techniques and metaheuristics can be applied to improve the efficiency of the cluster head selection and the energy consumption among the sensor nodes [19], [27]. However, these techniques have been focusing on the efficiency of the networks and security requirements, which is important in many applications, including healthcare monitoring.

In contrast, many researchers have contributed to the improvement of security requirements in WSNs using different techniques, including AI-based security models and blockchain techniques [1], [4], [2]. Although the security requirements can be improved using these techniques, the efficiency of the networks can be compromised, which can shorten the operational lifespan of the sensor nodes.

Therefore, there is a need to propose an integrated framework to enhance the efficiency, security requirements, and data transmission reliability in WSN-based smart healthcare and smart city applications [3], [25], [29].

On a general note, existing research has achieved significant progress in advancing the performance of WSNs in relation to energy-efficient communication protocols, intelligent clustering techniques, and robust security mechanisms. In this regard, artificial intelligence, machine learning, and blockchain technologies have significantly improved the capabilities of WSNs in smart healthcare and urban monitoring systems.

It is worth noting, however, that most existing techniques handle energy efficiency and security as two separate issues in WSNs. In a real-world smart city system, these two issues are interrelated and must be integrated to provide efficient, secure, and sustainable WSNs in healthcare and urban monitoring systems.

Thus, there is a clear need to propose a unified approach to optimize energy consumption, communication, and security in WSN-based healthcare and urban monitoring systems.

## 3. Proposed Methodology

To overcome these challenges associated with energy consumption and security in WSNs, this research proposes a novel framework called Predictive Energy and Trust-Aware Routing (PETAR) for smart healthcare and sustainable urban monitoring environments. The objective of this framework is to improve the overall performance of WSNs while ensuring secure communication among these nodes in a network. This research develops a new model that aims to strengthen the efficiency, reliability, and security of WSNs in smart healthcare and sustainable city monitoring applications. The PETAR algorithm combines predictive energy, trust, clustering, secure data aggregation, and routing to prolong the operational lifetime of the network and secure data transmission.

The working principle of the proposed system includes various phases such as node initialization, predictive energy estimation, trust-based cluster head selection, adaptive clustering, secure data aggregation, and dual routing to the base station. Figure 1 describes the structural view of the proposed approach.

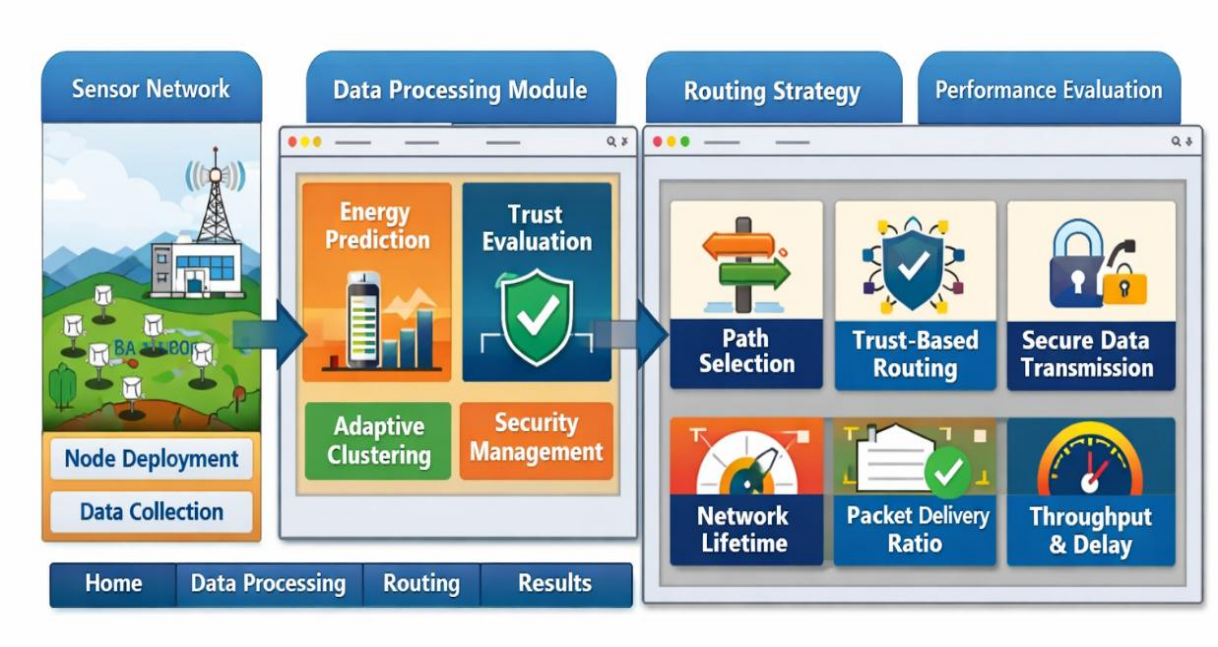



**Figure 1. System Architecture of Proposed System**

### 3.1. Sensor Node Deployment Strategy

Sensor nodes are randomly positioned within the monitoring field to enable the collection of healthcare and environmental data. These nodes continuously monitor different parameters related to the patient's health, such as the heart rate and body temperature. These parameters are extremely important for the development of real-time health monitoring systems. At the same time, these nodes also collect important pieces of environmental data, including temperature, humidity, and pollution level. Moreover,

the nodes can also collect data related to the infrastructure of the city, which is extremely important for the city authorities. Despite the fact that the nodes perform different functions, each node is limited in its own way. It is limited in terms of battery power, processing power, and communication distance.

### 3.2. Predictive Energy Estimation and Trust Evaluation Mechanism

Energy consumption is a major limiting factor in WSNs. To overcome this problem, the PETAR algorithm proposes a new energy prediction method, which predicts the energy available in the nodes for the next round instead of using their current residual energy level. Each sensor node will keep track of its power usage across sensing, processing, and communication stages. On the basis of this information, the PETAR algorithm predicts the future energy level of the nodes, and those nodes with higher energy levels are given priority in the CH election process.

Security and reliability are key issues to be considered in a WSN, especially when sensitive information such as health information is being transmitted. To overcome this problem, a trust evaluation mechanism has been included in the PETAR framework to identify reliable nodes within a particular network. Unlike conventional methods, where all nodes within a network are considered to be equal, the PETAR framework evaluates the behavior of neighboring nodes and assigns a specific value to each node.

The value is determined based on factors such as packet forwarding rates, communication consistency, cooperation level, and packet loss. Nodes that forward packets and participate actively in communication tend to have higher values, whereas nodes that frequently lose packets and fail to cooperate tend to have lower values. This is a unique feature of the PETAR framework, where reliable nodes can be identified compared to unreliable or malicious nodes.

### 3.3. Hybrid Cluster Head Selection and Adaptive Cluster Rotation

In the PETAR model, the CH election is done using the hybrid approach based on the predicted level of energy and trust value. Unlike the other CH selection techniques, the PETAR model is different in the sense that it takes into account the predicted residual energy, trust value, distance to the BS, and the communication capability of the nodes. Based on these parameters, the nodes with high reliability and efficiency are elected as the CHs. Then the remaining nodes join the CH considering the distance to the communication.

PETAR proposes the adaptive cluster rotation mechanism to avoid rapid depletion of the energy of the CHs. If the level of energy of a cluster head falls below a certain level, then a new cluster head is selected dynamically from the cluster. This periodic rotation of the cluster heads ensures that the nodes are distributed equally in terms of workload.

### 3.4. Secure Data Aggregation and Dual-Path Secure Routing

After the formation of these clusters, sensor nodes will start sensing various health and environmental parameters from the monitoring area. The sensor node will send the collected information to their respective cluster heads. The cluster heads will process the information by aggregating the data, which will remove redundant information from the data set. It will also integrate information from various sensor nodes and compress the data to reduce transmission overhead. Before forwarding the information to the next level or base station, data is secured by applying a lightweight encryption technique to maintain data confidentiality and integrity during transmission.

Finally, once the data aggregation process is complete, the CH sends the encrypted information to the BS leveraging a dual path secure routing mechanism. As part of the PETAR scheme, there is a creation

of two different communication paths between the CH and the BS. The two paths are designed in a way that one path is used as a primary path in the event of data transmission, while the other path is used as a secondary path in case there is a node failure in the main path of communication. The path used in routing is determined by a cost function based on factors such as the forecasted residual energy of nodes, trust values, and transmission distance between nodes. These parameters make the routing mechanism more reliable in ensuring the secure transmission of health data.

After every communication round, the nodes update the level of energy and trust. Nodes with low energy levels compared to the minimum level are removed from the routing process. The clustering and routing process is repeated to obtain the next communication round. This process is repeated until the level of energy in the network is minimal, which shows the end of the network lifetime

### 3.5. Proposed PETAR (Predictive Energy and Trust-Aware Routing) Algorithm

The PETAR algorithm is designed to strengthen the efficiency, reliability, and security of wireless communication systems. The proposed approach divides the sensor nodes into clusters and selects the cluster head based on characteristics such as projected residual energy, trust value, distance to the base station, and communication capacity. Cluster head election considers nodes with higher expected energy and trust scores. After clusters are formed, sensor nodes communicate their collected information to the cluster head. Data aggregation is done at the cluster head to remove redundant information. PETAR also includes a trust evaluation system to monitor nodes and build up trust for communication purposes.

The proposed algorithm employs dual-path routing to transmit the information to the BS. This includes the regular route plus a backup plan in case of an emergency. PETAR is a combination of the advantages of the energy prediction and trust-based routing algorithms with the dual-path routing method. The flowcharts of the suggested system are shown in Figure 2.

### 3.6. Mathematical Model

The proposed framework utilizes the radio energy dissipation model for estimating the energy consumed by the sensor nodes for communication. In this model, the nodes having greater residual energy are considered for a greater priority for selecting the cluster head. The energy required for transmission of data is calculated by the following equation (1).

Energy required to transmit $k$bits over distance $d$: [33]

$$E_{tx}(k,d) = \begin{cases} kE_{elec} + k\epsilon_{fs}d^2, & d < d_0 \\ kE_{elec} + k\epsilon_{mp}d^4, & d \geq d_0 \end{cases} \quad (1)$$

where

- $E_{elec}$= energy consumed by electronic circuit
- $\epsilon_{fs}$= free space amplification energy
- $\epsilon_{mp}$= multipath fading amplification energy
- $d_0$ =threshold distance.

The energy consumption for receiving data by a sensor node is calculated as in equation (2).

$$E_{rx}(k) = kE_{elec} \quad (2)$$

$$E_{residual} = E_{initial} - E_{consumed} \quad (3)$$

The residual energy of a sensor node indicates the remaining energy after communication operations. It is calculated using equation (3).$E_{initial}$is the initial energy assigned to the node and $E_{consumed}$ represents the total energy used for sensing, processing, and communication. This residual energy value helps in selecting suitable nodes as cluster heads in the network.

**Algorithm: PETAR — Predictive Energy and Trust-Aware Routing**

Input: N sensor nodes; $E_0$ initial energy; BS base station; TR transmission range

Output: Secure data delivery; optimised routing; balanced energy; extended lifetime

**Step 1 — Initialisation**

Deploy N nodes randomly in the monitoring region

For each node i: set $E_i = E_0$; $T_i = 1.0$; compute neighbour list within TR

**Step 2 — Predictive Energy Estimation**

For each node i:

$EP_i \leftarrow E_i - (E_{tx} + E_{rx} + E_{pro}^c)$

**Step 3 — Trust Evaluation**

For each node i:

$T_i \leftarrow Successful_Packets_i / Total_Packets_i$

Nodes with $T_i < T_threshold$ are excluded from CH candidacy and routing

**Step 4 — Hybrid Cluster Head Selection**

For each node i: compute $CH_i \leftarrow \alpha \cdot EP_i + \beta \cdot T_i + \gamma \cdot (1/D_s^l)$

Select node with highest $CH_i$ in each cluster as Cluster Head

Non-CH nodes join nearest CH

**Step 5 — Adaptive Cluster Rotation**

IF CH energy < rotation threshold THEN

Re-run CH selection among remaining cluster members

**Step 6 — Secure Data Aggregation**

Member nodes transmit sensed data to CH

CH performs: redundancy removal, data compression, encryption

**Step 7 — Dual-Path Secure Routing**

Compute routing cost $C_r$ for all candidate paths

Select primary path (min $C_r$); maintain backup path (next-best $C_r$)

Transmit encrypted data via primary path

IF primary path fails THEN switch to backup path automatically

**Step 8 — Energy & Trust Update**

For each node: update $E_i$ [Eq. 8]; update $T_i$

Remove nodes with $E_i < E_min$ from active routing

**Step 9 — Termination**

IF all node energies ≤ threshold THEN stop

ELSE proceed to next sensing round

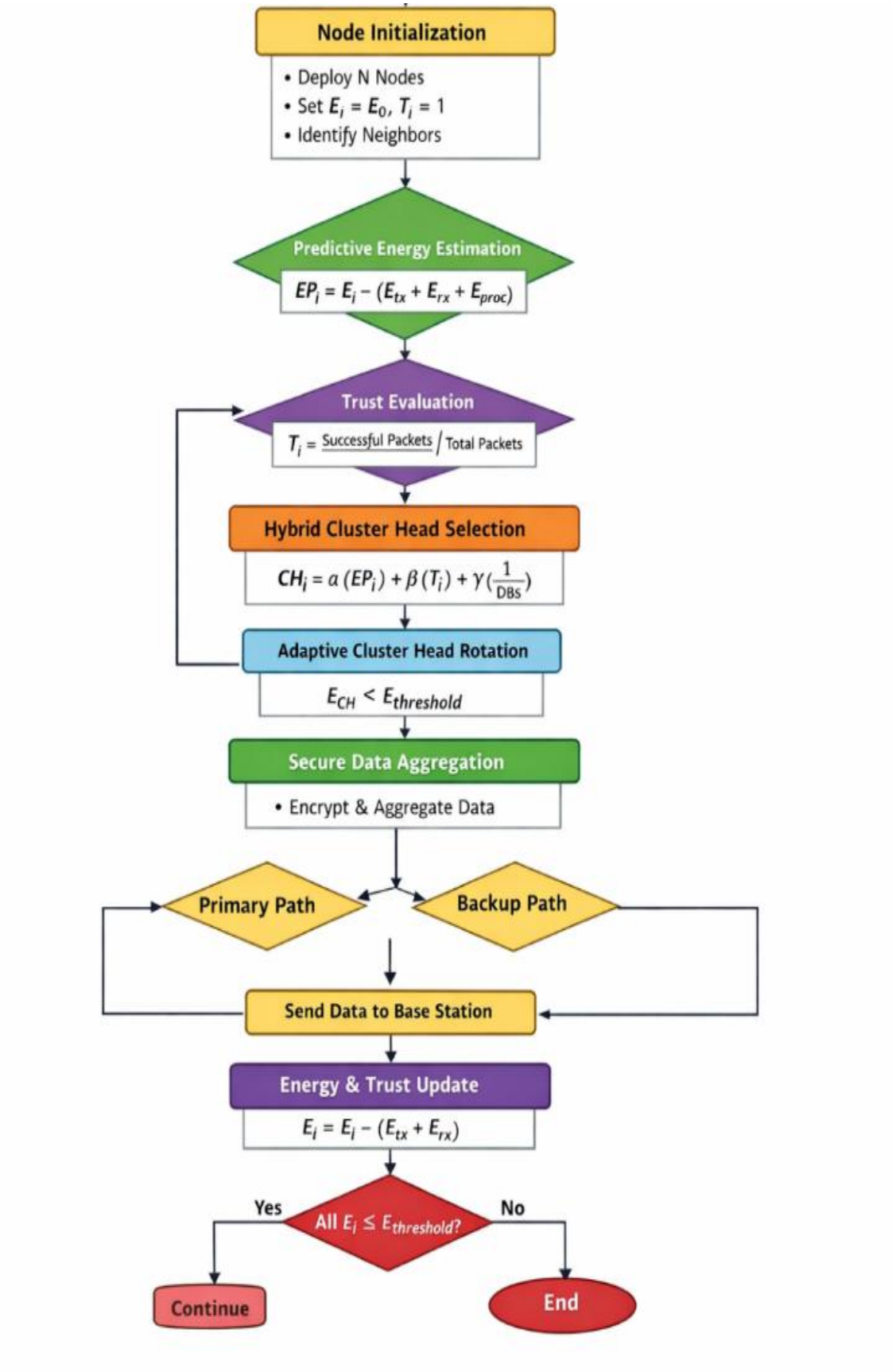



**Figure 2. The flowcharts of Proposed System**

## 4.Results and Discussion

The efficiency of developed PETAR framework was tested through simulation experiments. This was achieved by use of the MATLAB tool. The simulation environment is intended to mimic a wireless sensor network in order to build smart healthcare systems and monitor the environment in urban areas. The environment will help the system to simulate the working of the sensor node.

The algorithm called PETAR is simulated using the software MATLAB in order to analyze its performance for the application in the WSN. For depicting the environment of monitoring, the nodes are distributed randomly within the two-dimensional space. Each of the nodes is allocated an initial amount of energy along with certain communication parameters such as transmission range and packet sizes. A Base Station (BS) is deployed for receiving data from the sensor nodes. The network performs repeated communication cycles for data collection, relaying, and transmission to the base station to ensure reliable data delivery.

The parameters for this simulation have been given in Table 1 below. Parameters define the structure of the network by indicating how nodes are arranged and how they operate in terms of energy usage and communication capabilities.

**Table 1: Simulation Setup**

| S.No. | Parameter | Value |
|---|---|---|
| 1 | Simulation Area | 100 m × 100 m |
| 2 | Number of Sensor Nodes | 100 |
| 3 | BS Location | (50,150) |
| 4 | Initial Node Energy | 0.5 Joules |
| 5 | Data Packet Size | 4000 bits |
| 6 | Communication Model | First Order Radio Model |
| 7 | The rate of transmission | 512 kbps |
| 8 | Transmission Energy | 50 nJ/bit |
| 9 | Receiver Energy | 50 nJ/bit |
| 10 | Free Space Amplifier | 10 pJ/bit/$m^2$ |
| 11 | Multipath Amplifier | 0.0013 pJ/bit/$m^4$ |
| 12 | Maximum Rounds | 5000 |

### 4.1. Simulation Procedure

The performance of the PETAR algorithm is tested using simulation. At first, the implementation process begins by deploying sensor nodes throughout the designated observation area, ensuring adequate coverage for sensing and communication activities. All sensors are assigned an initial energy level and communication qualities. A centralized BS is employed to acquire data transmitted by the sensor nodes and serve as the primary point for data processing and network management

The nodes are deployed and the PETAR algorithm groups them in such a way that it prioritizes nodes with greater trustworthiness and higher remaining energy for cluster head roles. The other nodes are added to the CH that is closest to them to reduce the distance. All the sensor nodes gather data about health and environmental conditions and send it to their cluster chiefs. Cluster heads are responsible for gathering data from sensor nodes and aggregating the collected information to reduce redundancy. Subsequently, the aggregated data is transmitted to the base station using a dual-path routing strategy, which improves transmission efficiency and fault tolerance. Light-weight encryption methods are used to protect the data.

The simulation is executed for many communication rounds considering node energy and trust values. The proposed algorithm's performance is evaluated based on network lifetime, residual energy, packet delivery ratio, throughput, and end-to-end latency. It is benchmarked against the performance.

### 4.2. Performance Metrics

The proposed framework's performance may be evaluated using various key indicators that show the wireless sensor network's efficiency and dependability.

**Network Lifetime:**

This is a measure to estimate the lifespan of the sensor network before the sensor nodes' batteries run out. Clearly, the longer the battery life the higher the performance.

**Energy Consumption:**

This parameter measures the average amount of energy consumed by the sensor nodes for communication and transmission of data.

**Package Delivery Ratio (PDR):**

It is a metric for the wireless sensor network's reliability, defined as the ratio of the number of data packets delivered successfully to the total number of data packets sent.

**Throughput:**

Throughput is a key network performance indicator that describes the amount of data successfully communicated through the network over a given time interval, providing insight into the efficiency of data transmission.

**End-to-end delays:**

End-to-end delay measures the total time required for sensed information to be conveyed from a source node to the base station, reflecting the responsiveness and communication efficiency of the network

### 4.3. Compared Protocols

To investigate the capabilities of the PETAR Framework, the suggested technique is benchmarked against different routing protocols. The comparison also covers the currently available routing protocols like LEACH, PEGASIS, energy-aware clustering and AI-based routing protocols. The proposed method can be evaluated against widely adopted routing protocols using standard performance metrics to determine its efficiency and overall network performance.

Table 2 presents a comparative evaluation of the suggested PETAR framework with some conventional routing approaches like LEACH, PEGASIS, Energy-Aware Clustering and AI-based Routing. The performance is assessed based on the following parameters: network lifetime, remaining energy, packet

delivery ratio, throughput, delay, alive nodes. The experimental findings reveal that the that the suggested PETAR approach delivers better outcomes than the other routing protocols. In the suggested strategy, the number of nodes that stay alive for a longer period in the simulation was better, showing better energy management and network stability. The proposed method achieved the maximum network lifetime as 2100 rounds and maximum residual energy as 13.8 J.

Furthermore, the proposed technique obtained a maximum packet delivery ratio of 96% and a maximum throughput of 3500 kbps, ensuring dependable and reliable data communication The end-to-end delay has been reduced to 420 ms, allowing for speedier communication throughout the network. The findings indicate that the suggested PETAR approach strengthen the efficiency, reliability, and performance of smart healthcare and urban monitoring systems.

**Table 2 Performance Assessment of the Proposed Approach**

| Approaches | Network Lifetime (Rounds) | Residual Energy (J) | PDR (%) | Throughput (kbps) | End to End Delay (ms) |
|---|---|---|---|---|---|
| LEACH | 1,200 | 8.2 | 82 | 2,200 | 820 |
| PEGASIS | 1,400 | 9.5 | 85 | 2,500 | 720 |
| Energy-Aware Routing | 1,600 | 10.4 | 88 | 2,800 | 650 |
| AI-Based Routing | 1,750 | 11.6 | 91 | 3,100 | 580 |
| Proposed PETAR | 2,100 | 13.8 | 96 | 3,500 | 420 |

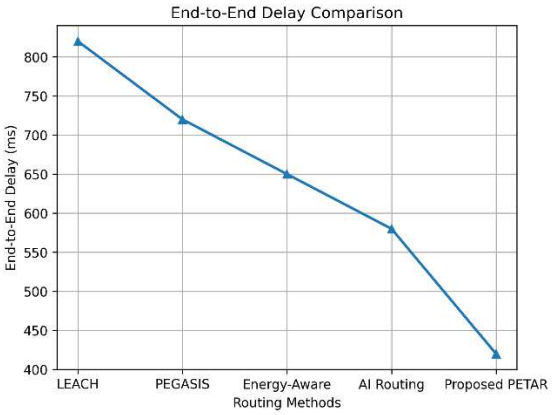



**Figure 3. Comparison of Delay**

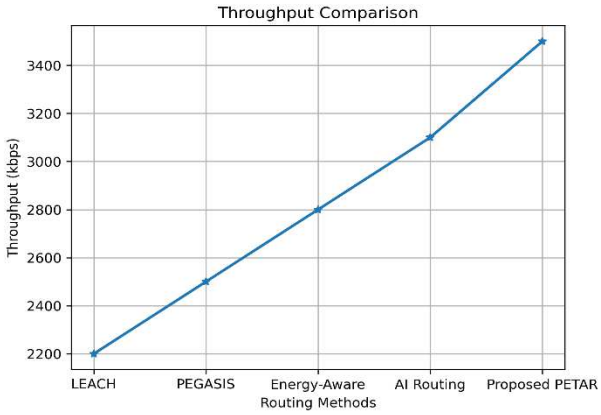
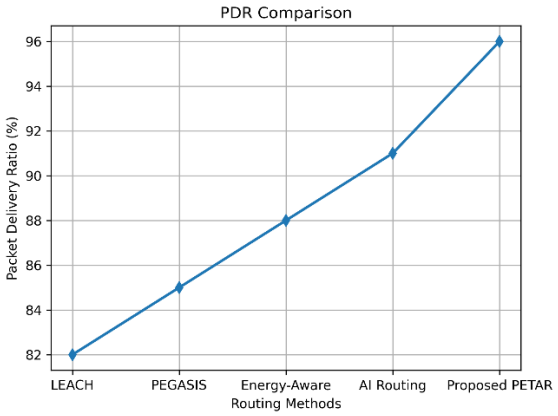



**Figure 4. Comparison of Throughput**

A number of comparison graphs are provided to illustrate the performance of the introduced methodology. Figure 3 shows the latency effectiveness of the developed technique relative to established routing protocols, demonstrating its ability to support timely data transmission across the network. As shown in figure 4, the throughput capability of developed technique is evaluated against conventional routing protocols. The findings demonstrate that the suggested method attains the highest throughput, thereby supporting efficient and reliable data transmission across the network.



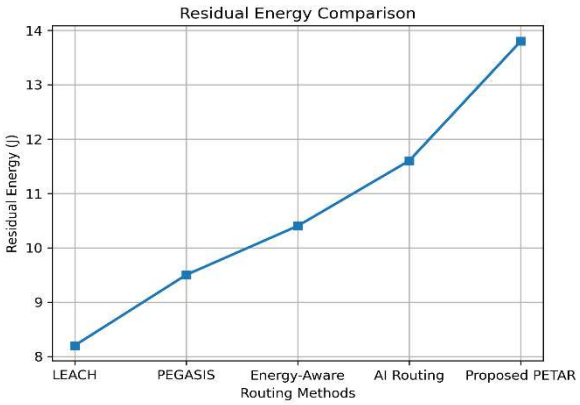
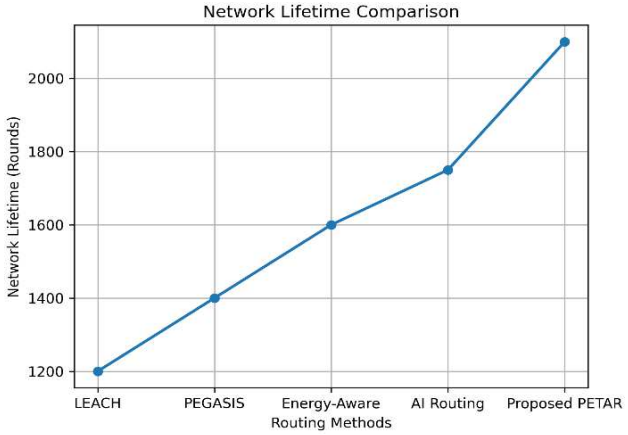




**Figure 5. Assessment of PDR** **Figure 6. Assessment of Energy Consumption**

As illustrated in Figure 5, the packet delivery performance of the suggested framework is evaluated against widely used routing protocols. The findings show that the suggested method achieves the highest packet delivery ratio, thereby ensuring dependable data delivery and improving network communication effectiveness. As shown in Figure 6, the energy efficiency of the suggested technique is evaluated against conventional routing protocols. The findings demonstrate that the suggested method delivers the highest energy efficiency, highlighting its effectiveness in optimizing energy utilization within the network.



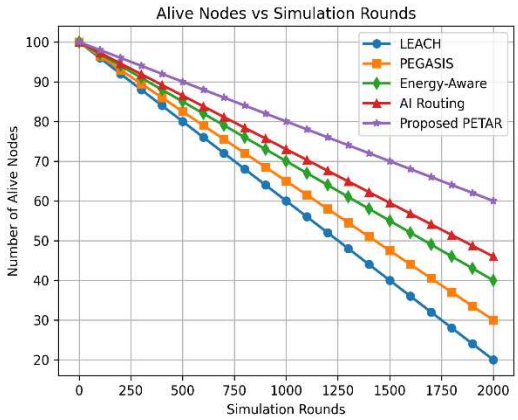




**Figure 7. Assessment of Network Lifetime** **Figure 8. Assessment of Alive Nodes**

Figure 7 shows that the suggested technique increases the network lifetime to nearly 2100 rounds. In addition, Figure 8 compares the number of alive nodes achieved by the suggested method with those of existing routing protocols. The findings reveal that the suggested approach sustains node activity for a longer duration, contributing to improved network stability and longevity.

## Conclusion

WSNs are considered to be one of the most significant technologies for acquiring real time environmental and health data for smart healthcare and smart city applications. Nevertheless, the limited battery power and data security challenges remain the main challenges facing WSNs. Therefore, this research proposed the PETAR, which can effectively address the challenges facing WSNs. The simulation results demonstrate that the PETAR protocol works better than other protocols like LEACH, PEGASIS, Energy-optimized and AI-driven routing protocols. The proposed protocol offers many advantages such as increased network lifetime, residual energy, PDR, throughput and reduced EED. In

addition, the proposed method retains more alive nodes during a longer time of simulation. The PETAR protocol is a new solution for smart healthcare and smart city applications, where reliable and efficient communication is critical. The simulation results show that PETAR protocol is efficient in WSNs, where energy consumption is a critical factor in network longevity.

**Declarations:**

**Ethical Statement and Consent to Participate:** Not Applicable.

**Animal and Human Rights:** No animals/humans are used/harmed for the proposed research work.

**Consent for Publication:** Not Applicable

**Data Availability:** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Funding:** Not applicable

**Conflicts of Interest:** There are no conflicts of interest among the authors

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**Author Contributions:**

M. Muthukumar contributed to the conceptualization of the study. M.Ashok Kumar developed the methodology, and prepared the original draft of the manuscript. K. Kalaivanan managed data curation, contributed to methodology, and provided necessary resources for the study. R. Santhana Krishnan handled the software implementation, validation, and visualization of the results. K.Saravanan was responsible for formal analysis, assisted in methodology, and contributed to reviewing and editing the manuscript. All authors reviewed and approved the final manuscript.

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