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OEE-WCRD: Optimizing Energy Efficiency in Wireless Sensor Networks through Cluster Head Selection Using Residual Energy and Distance Metrics

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Abstract

Wireless Sensor Networks (WSNs) play a pivotal role in various applications, including environmental monitoring, industrial automation, and healthcare. However, the limited energy resources of sensor nodes pose a significant challenge to the longevity and performance of WSNs. To address this challenge, this paper presents an Optimized Energy Efficient Protocol in Wireless Sensor Networks through Cluster Head Selection Using Residual Energy and Distance Metrics (OEE-WCRD). This research paper presents a novel approach to cluster head selection in WSNs by harnessing a combination of residual energy and distance metrics. The proposed method aims to significantly enhance the energy efficiency of WSNs by prioritizing nodes with ample residual energy and proximity to their neighbors as cluster heads. Through extensive simulations and evaluations, we demonstrate the effectiveness of this approach in prolonging network lifetime, optimizing data aggregation, and ultimately advancing the energy efficiency of WSNs, making it a valuable contribution to the field of WSNs protocols.

Keywords : Base Station, Cluster, Residual Energy, Sensor Node, Wireless Sensor Network

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1. Introduction

A Wireless Sensor Network (WSN) is a network of small, self-contained sensor nodes equipped with sensors, communication capabilities, and often limited processing power. These nodes collaborate to collect and transmit data from their surroundings to a central base station, sink, or gateway as shown in Figure 1. The data collected by the sensors can be related to various environmental parameters, such as temperature, humidity, light, or motion, and they are used for applications like environmental monitoring, surveillance, or industrial automation. The nodes in a WSN communicate wirelessly, forming a distributed network that enables real-time data collection and analysis for various applications [1][2][3].

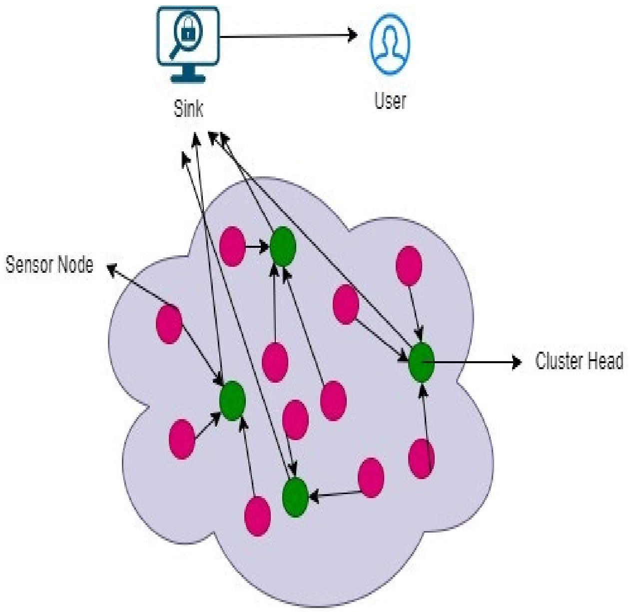


Figure 1: Structure of Wireless Sensor Network

The ubiquitous deployment of WSNs in various fields, including environmental monitoring, healthcare, and industrial automation, has brought about significant challenges related to energy efficiency and network longevity. The resource-constrained nature of sensor nodes, often powered by limited-capacity batteries, necessitates innovative solutions to prolong network lifetime while maintaining efficient data communication. One promising approach to address this issue is the implementation of cluster-based algorithms within WSNs [4][5][6].

Cluster-based algorithms have gained substantial attention due to their ability to mitigate energy consumption and improve network scalability. These algorithms organize sensor nodes into clusters, electing a cluster head responsible for aggregating and forwarding data from member nodes to a central sink or gateway. By limiting the number of nodes actively transmitting data, these algorithms reduce energy overhead and extend the network's operational lifespan [7][8][9].

This research paper introduces a novel cluster-based algorithm tailored to enhance energy efficiency in WSNs. Our algorithm seeks to optimize the allocation of energy resources within the network, ultimately prolonging its lifespan while maintaining data integrity and network coverage. We present a comprehensive analysis of our algorithm's design, highlighting its adaptability to dynamic network conditions and its potential to address the energy efficiency challenges encountered in WSNs [10][11].

Through extensive simulations and experimental evaluations, we provide empirical evidence of the algorithm's effectiveness in enhancing the energy efficiency of WSNs across a range of practical scenarios. The results of our research contribute to the ongoing efforts to harness the full potential of WSNs in various applications while minimizing their energy footprint [12][13].

1.1. Motivation and Contribution

The motivation behind this research stems from the critical need to enhance the energy efficiency and network performance of WSNs, which play a pivotal role in various applications, including environmental monitoring, healthcare, and industrial automation. Existing cluster-based approaches have shown promise in mitigating energy consumption, but there is a growing demand for innovative solutions that can further optimize these networks [14][15].

Our research contributes to this domain by introducing a novel cluster-based algorithm designed to significantly improve energy efficiency in WSNs. By intelligently organizing sensor nodes into clusters and employing dynamic cluster reconfiguration mechanisms, our algorithm not only extends the network's operational lifespan but also ensures data integrity and coverage quality, making it a valuable advancement in the field of cluster-based WSNs [16][17].

The manuscript is organized as follows: In the introduction, we provide an overview of the significance of cluster-based WSNs and outline the research objectives. The next section presents a comprehensive review of existing cluster-based techniques and their limitations. Subsequently, we detail our proposed novel cluster-based algorithm, discussing its design, operation, and adaptability to dynamic network conditions. The experimental methodology section describes the setup and metrics used for evaluating the algorithm's performance. Results and discussions follow, presenting empirical findings and their implications. Finally, we conclude with a summary of contributions, highlighting the practical significance of our novel cluster-based approach in enhancing energy efficiency and network longevity in WSNs, and discussing avenues for future research [18][19].

1.2. Organization structure

This paper is organized in a very fancy manner. Section 2 is related to related works. The proposed model is defined under section 3. Section 4 discusses experimental results and discussion. Finally, the paper is closed with the conclusion and future direction under section 5.

2. Related works

Gulati et al. [18], provide an overview of various techniques and technologies used in IoT applications, highlighting the role of WSNs in collecting and transmitting data from IoT devices. Majid et al. [19], explore how WSNs and IoT technologies are leveraged in industrial settings, emphasizing their role in enabling the fourth industrial revolution. Arumugum et al. [20], focus on optimizing energy efficiency for data gathering in WSNs, a crucial aspect of sensor network performance. They also published their "EE-LEACH" protocol in the EURASIP Journal on Wireless Communications and Networking, emphasizing the importance of energy-efficient data-gathering protocols for WSNs. Hassan et al. [21], evaluate the performance of different routing protocols, providing insights into their suitability for various network scenarios. They also presented their comparative study of routing protocols at an IEEE conference, further highlighting the significance of protocol selection in WSNs.

Arumugam et al. [22], authors address the challenge of optimizing coverage while considering energy efficiency in sensor networks. Jia et al. [23], authors applied queueing theory to analyze path delay in wireless sensor networks. This study contributes to understanding the delay characteristics of data transmission in WSNs, which is crucial for real-time applications. Qiu et al. [24] focus on optimizing routing in WSNs using bio-inspired optimization techniques. Zhao et al. [25], address the selection of cluster heads to optimize energy consumption and reduce data transmission delays in the network. Sarkar et al. [26], explore the use of a novel optimization algorithm in improving data compression techniques at the network edge, which is crucial for efficient data handling in resource-constrained environments. Qiu et al. [27], address the security challenges in cognitive radio networks, enhancing the reliability of communication in such dynamic environments.

Vivekanand et al. [28], contribute to the advancement of antenna design, which is essential for optimizing wireless communication systems. Kannadhasan et al. [29], address the challenge of efficient data collection in sensor networks with energy constraints, making it relevant for various IoT applications. Yongmin et al. [30], algorithm has potential applications in various optimization problems, including those in wireless sensor networks. Xue et al. [31], demonstrate the algorithm's adaptability to solving complex engineering problems, such as fault detection. Gai et al. [32], contribute to energy-efficient routing in WSNs, a critical factor for prolonged network operation. Chu et al. [33], address the crucial issue of cluster head selection, impacting network efficiency and longevity. Rao et al. [34], contribute to the understanding of security challenges and solutions in WSNs. Dhivya et al. [35], provide a comprehensive overview of existing security protocols, aiding researchers and practitioners in selecting appropriate security measures for WSN applications.

Narayan et al. [37] employs fuzzy logic to optimize routing decisions, considering energy efficiency. This protocol aims to extend the network's lifespan by intelligently routing data while minimizing energy consumption, improving the overall performance of wireless sensor networks. E-FEERP is a valuable contribution to enhancing the efficiency and longevity of sensor networks. D. V. S. Babu et al. [38] present novel metaheuristic algorithms for improving cluster head selection and energy efficiency in wireless sensor networks, offering insights into wireless communication optimization.

Bahadur, L. et al. [39] presents a novel method for optimizing energy consumption in wireless sensor networks using genetic algorithms, providing insights into efficient energy management. Bharany Salil et al. [40] introduces an energy-efficient clustering protocol for underwater wireless sensor networks using optimized glowworm swarm optimization, contributing to improved underwater sensor network performance. Reddy et al. [41] focuses on energy-efficient cluster head selection in wireless sensor networks, utilizing an improved Grey Wolf Optimization Algorithm to enhance network efficiency. Imourane A. et al. [42] explores energy conservation in wireless sensor networks using embedded artificial neural networks, potentially contributing to energy-efficient sensor network designs.

Table 1: Features and Challenges of Existing Work

Reference	Technique Used	Key Features	Cluster-Based
Qiu and Li [27]	Chaos Mutation Adaptive Sparrow Search Algorithm	Edge data compression, adaptive algorithm	No
Vivekanand and Bagan [28]	Distance-Based Improved LEACH Routing	Enhanced security in cognitive radio networks	Yes (LEACH Routing)
Kannadhasan and Nagarajan [29]	Not specified (Antenna and Band	Performance improvement of slot antenna	No

	Pass Filter Study)		
Zhang, He, and Chen [30]	Near-Optimal Data Gathering	Rechargeable sensor networks, mobile sink	No
Xue and Shen [31]	Sparrow Search Algorithm	Swarm intelligence optimization approach	No
Gai et al. [32]	Parameter-Optimized Deep Belief Network	Gear fault severity detection	No
Chu, Horng, and Chang [33]	Improved Ant Colony Algorithm	Numerical optimization of energy consumption	No
Rao, Jana, and Banka [34]	Particle Swarm Optimization	Energy-efficient cluster head selection	Yes
Dhivya Devi and Santhi [35]	Study on Security Protocols	Security protocols in WSN	No
Revathi and Amutha [36]	Survey on Security Protocols	Survey of security protocols in WSN	No
Narayan, V. et al. [37]	Fuzzy Logic-Based Routing Protocol	Enhanced energy-efficient routing for wireless sensor networks. - Utilizes fuzzy logic for intelligent routing decisions.	Yes
D. V. S. Babu et al. [38]	Metaheuristic Algorithms	Optimizes cluster head selection and energy efficiency. - Novel metaheuristic algorithms used for routing.	Yes
DilipKumar Jang Bahadur et al. [39]	Genetic Algorithm	Focuses on energy consumption optimization in wireless sensor networks.	Not specified
Bharany Salil et al. [40]	Glowworm Swarm Optimization	Specifically designed for underwater wireless sensor networks. - Uses optimized glowworm swarm optimization for energy-efficient clustering.	Yes

Addressing these hurdles necessitates the development of innovative energy harvesting techniques, scalable communication protocols, robust fault tolerance mechanisms, and privacy-preserving data analytics. Standardization efforts are crucial for managing heterogeneity and ensuring interoperability among diverse IoT devices and platforms. Additionally, overcoming resource constraints on WSN nodes requires the development of lightweight, resource-efficient algorithms and protocols.

3. Proposed Methodology

The proposed OEE-WCRD protocol uses two parameters viz: the residual energy and average distance of node base station for the selection of CH.

3.1 Residual Energy Evaluation:

Calculate the residual energy of each sensor node in the network using the available energy estimation techniques, such as monitoring battery voltage or current consumption[43][44].

Assign a weight to each node based on its residual energy, considering nodes with higher energy levels as more favorable candidates for cluster head selection.

3.2 Distance Metric:

Define a distance metric that quantifies the proximity of each sensor node to its neighboring nodes. Common metrics include Euclidean distance or signal strength-based distance [45].

Nodes that are closer to their neighbors are preferred for cluster head roles, as they can efficiently collect data from nearby nodes [46] [47].

3.3 Combining Residual Energy and Distance:

Develop a selection criterion that combines residual energy and distance metrics to prioritize potential cluster head nodes.

For instance, a weighted scoring system could be used to rank nodes based on their residual energy and proximity to other nodes.

Determine a threshold or ranking threshold to identify cluster head candidates.

3.4 Cluster Head Election:

Based on the selection criterion and ranking, elect cluster heads among the eligible nodes.

Cluster heads should ideally have both sufficient residual energy and proximity to cluster members for efficient data aggregation.

3.5 Clustering:

3.5.1. Cluster Formation:

Once cluster heads are elected, form clusters by associating nearby sensor nodes with their respective cluster head.

The distance metric can be used to determine which sensor nodes should join each cluster.

3.5.2. Cluster Size Control:

Implement a mechanism for controlling the size of each cluster to ensure balanced energy consumption.

Dynamic resizing or merging of clusters can be employed to optimize network performance.

3.5.3. Data Aggregation:

Establish communication links between cluster members and their respective cluster heads.

Utilize the cluster head nodes for data aggregation and transmission to the base station or sink.

3.5.4. Cluster Head Rotation:

Periodically rotate cluster heads to distribute energy consumption evenly across the network and prevent early depletion of specific nodes.

3.5.5. Adaptation to Network Dynamics:

Develop algorithms or rules for adapting the clustering structure in response to changing network conditions, such as node failures or mobility.

Algorithm: OEE-WCRD

Initialization:

1. Initialize network parameters such as the number of nodes, cluster formation threshold (T), and the maximum number of rounds (R).

Randomly assign each sensor node a value between 0 and 1 (a probability).

2. Probability Calculation:

Calculate the probability of each node becoming a cluster head using the formula:

$$P_{ch} = \begin{cases} T/1 - T(r \bmod 1/T), & \text{if } r<1/T \\ 0, & Otherwise \end{cases}$$

where P_{ch} is the probability of becoming a cluster head,

T is the threshold

r is a random value between 0 and 1 assigned to each node.

3. Cluster Head Selection:

Each sensor node compares its calculated probability (P_{ch}) with a random number (p) generated between 0 and 1.

If $P_{ch}>p$, the node becomes a cluster head; otherwise, it remains a regular node.

Cluster Formation:

4. Cluster Formation by Cluster Heads:

Cluster heads broadcast their identity to neighboring nodes, inviting them to join their clusters.

5. Node Association:

Sensor nodes decide which cluster head to join based on signal strength or proximity.

6. Data Collection and Aggregation:

Sensor nodes periodically collect data from their environment.

Cluster heads aggregate data from member nodes and compress it if necessary.

7. Data Transmission to Sink:

Cluster heads transmit the aggregated data to the base station or sink node.

8. Termination:

After data transmission, nodes may become dormant or switch roles in subsequent rounds.

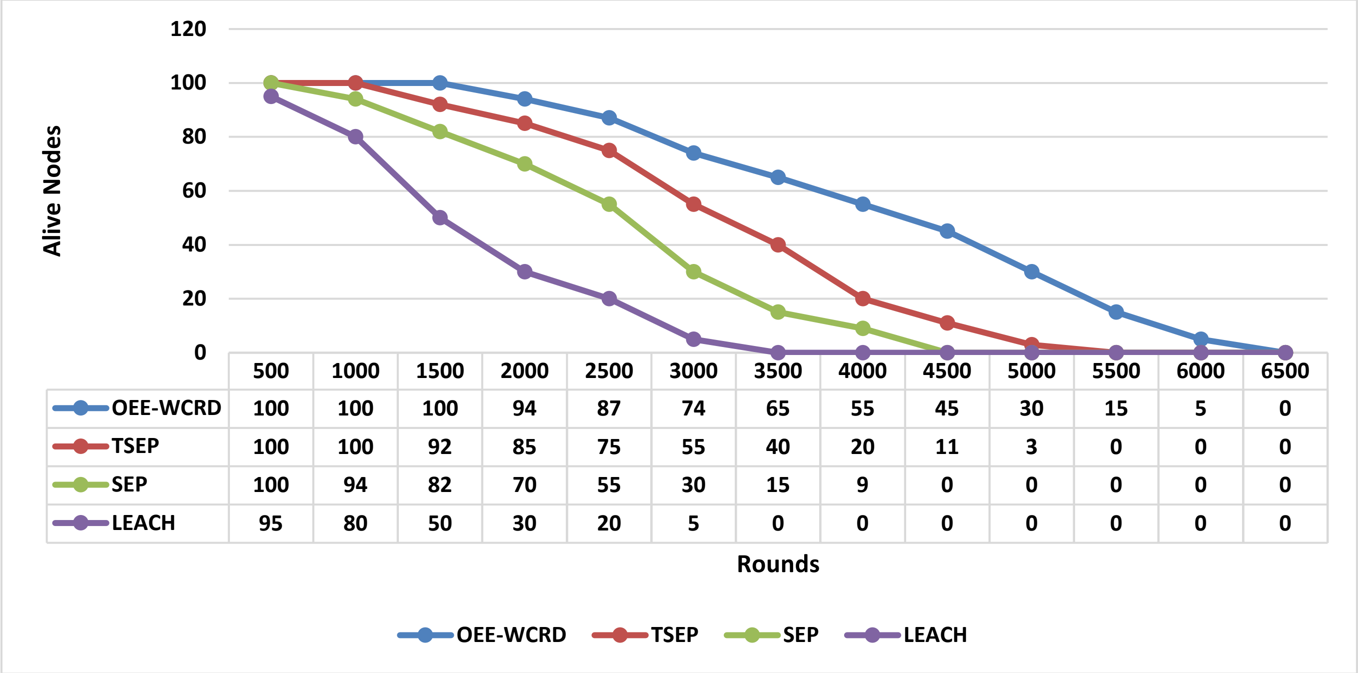
9. Repeat:

Steps 2-8 are repeated for multiple rounds (up to R rounds).

4 Experimental Results and Discussion

Experiment 1:

An "alive node" refers to a sensor node that is currently operational, actively functioning, and able to communicate with other nodes within the network. An alive node has not experienced critical failures, such as hardware malfunctions, depletion of energy resources, or communication breakdowns. The presence of alive nodes is vital for the network's proper functioning, as they contribute to data collection, forwarding, and routing tasks, ensuring the network's overall reliability and performance. Monitoring the status of live nodes is crucial for network management, fault detection, and energy conservation strategies in WSNs. Figure 2 shows the alive nodes per round.



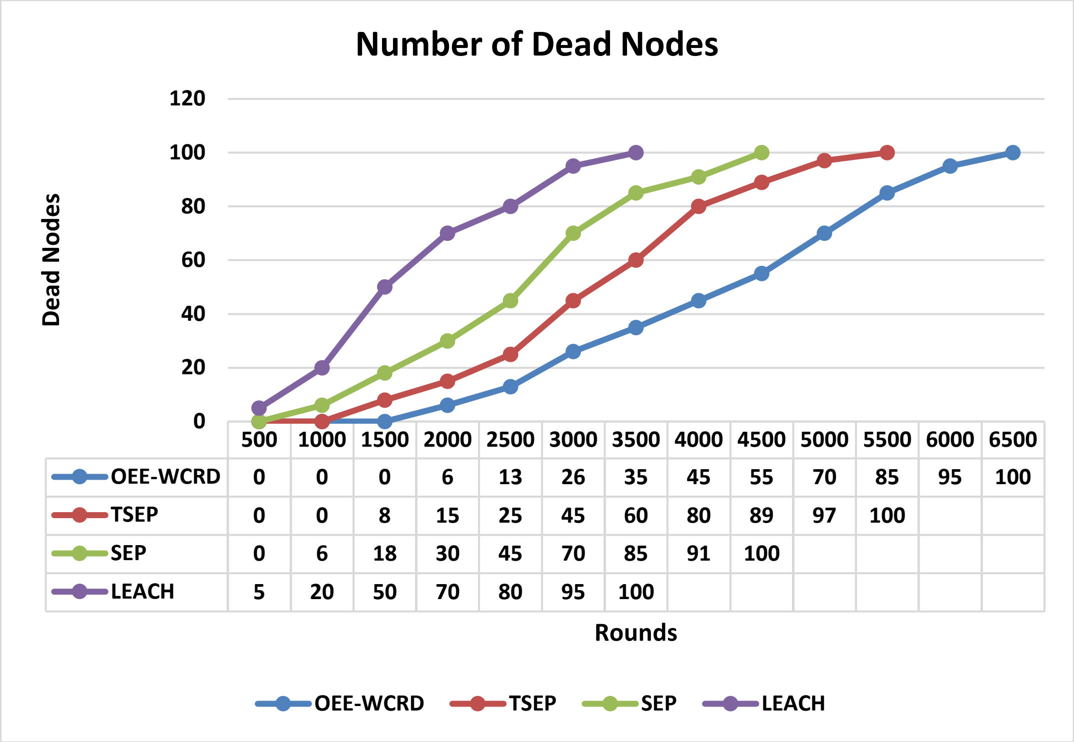
	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500
OEE-WCRD	100	100	100	94	87	74	65	55	45	30	15	5	0
TSEP	100	100	92	85	75	55	40	20	11	3	0	0	0
SEP	100	94	82	70	55	30	15	9	0	0	0	0	0
LEACH	95	80	50	30	20	5	0	0	0	0	0	0	0

Figure 2: Alive Nodes Number

The alive nodes of the proposed OEE-WCRD Protocol are significantly high which is 5 as compared to TSEP, SEP, and LEACH Protocol where no alive node present at 6000 rounds hence it enhance the network lifetime.

Experiment 2:

A dead node in a WSN(WSN) refers to a sensor node that has exhausted its available energy resources and can no longer actively participate in network operations. This typically occurs due to continuous data transmission, sensing, or routing tasks, leading to rapid energy depletion within the node's limited power source, such as a battery. Dead nodes can disrupt network connectivity, compromise data collection, and potentially impact the overall performance of the WSN. Effective strategies for mitigating dead nodes, such as energy-efficient routing algorithms, dynamic clustering, or proactive energy management techniques, are crucial for maintaining the network's functionality and longevity. Figure 3 shows the dead nodes per round.



	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500
OEE-WCRD	0	0	0	6	13	26	35	45	55	70	85	95	100
TSEP	0	0	8	15	25	45	60	80	89	97	100		
SEP	0	6	18	30	45	70	85	91	100				
LEACH	5	20	50	70	80	95	100						

Figure 3: Dead Nodes Number

The dead nodes per round of the proposed OEE-WCRD Protocol are significantly less as it survived for 6500 rounds compared to TSEP, SEP, and LEACH Protocol where all nodes in LEACH,SEP,TSEP dead at 3500 rounds, 4500 rounds, and 5000 rounds respectively, which shows performance improvement in the proposed OEE-WCRD protocol.

Experiment 3:

Packet delivery in Wireless Sensor Networks (WSNs) refers to the process by which data packets are successfully transmitted from a source sensor node to a destination, typically a sink node or a central data repository. This critical operation depends on several factors, including the efficiency of routing protocols, the network topology, the quality of wireless links, and the energy levels of the involved sensor nodes. Achieving reliable packet delivery is vital for the accurate and timely gathering of data in WSNs, as these networks are often deployed in remote or harsh environments where manual intervention is impractical. Effective packet delivery mechanisms ensure that sensor nodes can efficiently collect, aggregate, and transmit data to their intended destinations, facilitating various applications such as environmental monitoring, healthcare, and industrial automation. Figure 4 shows the packets sent per round.

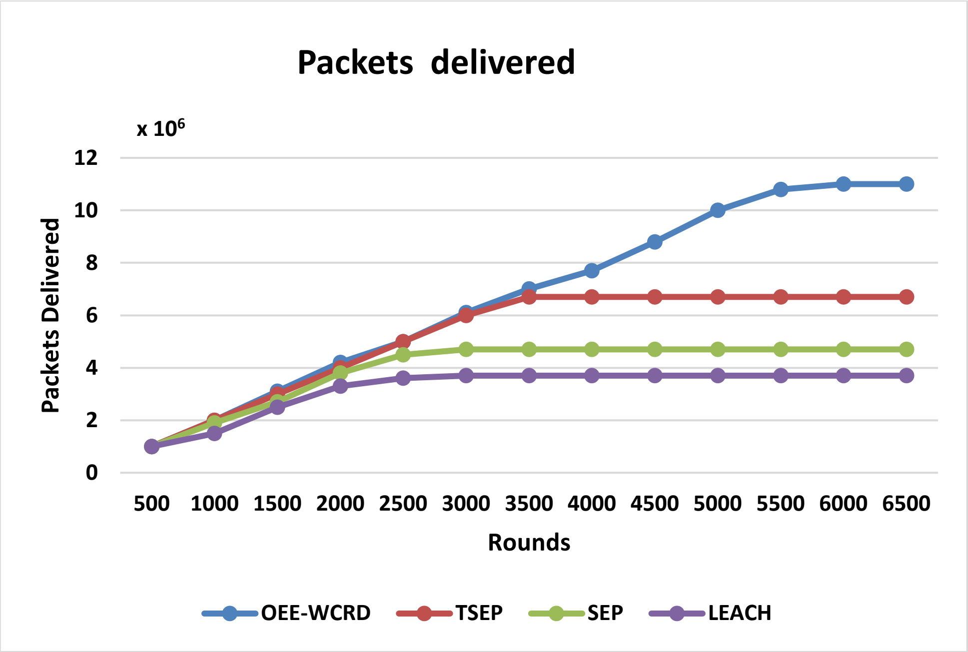


Figure 4: Packet Transmitted to the BS

The performance of the proposed model is evaluated based on the various security analysis, performance analyses, processing time, and accuracy of authentication.

Table 2: Number of Alive Nodes

Rounds	**The packet delivered in lacs**			
	OEE-WCRD	**TSEP**	**SEP**	**LEACH**
500	1 x 10^6	1 x 10^6	1 x 10^6	1 x 10^6
1000	2.2 x 10^6	2 x 10^6	2 x 10^6	1.7 x 10^6
1500	3.4 x 10^6	3 x 10^6	2.9 x 10^6	2.5 x 10^6
2000	4.4 x 10^6	4.3 x 10^6	3.7 x 10^6	3.1 x 10^6
2500	5.2 x 10^6	5 x 10^6	4.7 x 10^6	3.6 x 10^6
3000	6 x 10^6	5.7 x 10^6	5 x 10^6	3.7 x 10^6
3500	7 x 10^6	7 x 10^6	5 x 10^6	3.7 x 10^6
4000	8 x 10^6	7.6 x 10^6	5 x 10^6	3.7 x 10^6
4500	9 x 10^6	7.6 x 10^6	5 x 10^6	3.7 x 10^6
5000	10 x 10^6	7.6 x 10^6	5 x 10^6	3.7 x 10^6
5500	10.8 x 10^6	7.6 x 10^6	5 x 10^6	3.7 x 10^6
6000	11.4 x 10^6	7.6 x 10^6	5 x 10^6	3.7 x 10^6
6500	11.8 x 10^6	7.6 x 10^6	5 x 10^6	3.7 x 10^6

The proposed OEE-WCRD protocol transmitted 11.8 x 10^6 packests to the BS while TSEP, SEP, and LEACH transmitted 7.6 x 10^6, 5 x 10^6 , and3.7 x 10^6 packets to the BS.

5 Conclusion and Future Work

This research has presented a novel cluster-based energy-efficient algorithm for WSNs, which has demonstrated substantial improvements in energy conservation and network longevity. Our algorithm's intelligent clustering approach, coupled with dynamic cluster reconfiguration mechanisms, has effectively reduced energy consumption while maintaining data integrity and coverage quality. The proposed OEE-WCRD Protocol demonstrates notable advantages over existing protocols such as TSEP, SEP, and LEACH in terms of network lifetime and performance. With a significantly higher number of alive nodes and a longer survival time of 6500 rounds, compared to the limited lifespan of other protocols, OEE-WCRD stands out for its enhanced network longevity. Moreover, the protocol exhibits improved efficiency by transmitting a greater number of packets 11.8 x 10^6 to the base station, surpassing the packet transmission rates of TSEP, SEP, and LEACH. These findings underscore the effectiveness and potential of the OEE-WCRD Protocol for optimizing wireless sensor networks and advancing communication reliability and longevity. In future directions, we plan to explore advanced machine learning and artificial intelligence techniques to enhance cluster head selection and routing decisions, further optimizing the network's energy efficiency and adaptability to changing environmental conditions. Additionally, we aim to implement and test our algorithm in real-world scenarios to validate its practical applicability across a range of WSN applications, thereby advancing the state of the art in energy-efficient cluster-based WSNs.

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