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Energy Enhancement and Hotspot Mitigation for Wireless Sensor Network by Data Aggregation

N. Karthik[1], Dr. V. Kathiresan [2]

[1]Research Scholar, Department of Computer Science, Park's College, Tirupur.
Email ID: shreekarthy@gmail.com
[2]Principal, A.V.P. College of Arts and Science, Tirupur.
Email ID: vkathirmca@gmail.com

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ABSTRACT
A Wireless Sensor Network (WSN) is a network of distributed sensors, which are used to sense the physical environment and transmit information through wireless media. Data aggregation is very important in WSNs because it helps in minimizing on the number of transmitted data, hence saving power, and increasing the lifetime of the network. Due to the concentration of information at the intermediate nodes, it reduces the amount of traffic that has to be passed across the network, the amount of energy consumed, and increases the network utilization. The Poly disperses Steiner Minimum Tree-based Routing Protocol (PSMT-RP) protocol improves energy consumption and eliminates hotspots in WSNs by optimizing data aggregation with the help of the PSMT. Based on the concept of SMT, the proposed protocol reduces the length of the communication paths by choosing the proper intermediate nodes and thus, conserves energy and reduces latency. It adapts the node communication range to provide optimal data routing, thereby increasing the network duration and power consumption. Due to data aggregation at the intermediate nodes, it minimizes the transmission distances and prevents congestion which in turn fosters load balancing. Due to its efficiency in meeting Quality of Service (QoS) demands and in the management of energy resources, it is ideal to be implemented in large networks with limited energy supply. The simulation outcome is compared with existing state-of-art techniques whereas PSMT-RP outperforms and achieves high throughput with minimal energy consumption.

Keywords: *Communication paths, Data aggregation, Energy consumption, Quality of Service, Wireless Sensor Network*

1. INTRODUCTION

In the last few decades, WSNs have become more popular. More and more civilian and military uses can benefit from WSNs, which can boost efficiency, particularly in inhospitable and out-of-the-way places [1-2]. Despite the fact that WSN research has remained a high priority and that many efforts have been made to improve their efficiency, there are still several problems that need innovative solutions [3–4]. Many problems, including energy waste, needless delay, network congestion, and failure, arise for WSN as a result of the large number of applications and the network's self-management. A number of issues arise within the network as a result of these several causes, one of which is the hotspot problem [5-6]. Essentially, when the nodes are set up on a massive

Nowadays, WSNs are considered a promising technology [12–13]. WSNs collect data from their surrounding surroundings and can detect changes in parameters such as pressure, humidity, sound, temperature, vibration, and motion intensity [14–15]. There are a wide variety of typical uses for WSNs, including but not limited to: smart home monitoring systems, environments, habitats, traffic, inventory management, biomedical, health, industrial robots, and military applications [16-17]. Any combination of static and dynamic sensor nodes (SNs) is possible in a WSN. Since SNs rely on batteries for power, it is safe to say that they have energy limitations [18-19].

The remaining sections of this work are structured as follows. In Section 2, many authors discuss potential countermeasures. Part 3 contains the PSMT-RP model. In Section 4, we outline the results of the enquiry. Section 5 concludes with a discussion of the results and future research objectives.

1.1 Motivation of the paper

The limited energy resources of sensor nodes inspire our work as efficient communication in WSNs is becoming important. Energy economy and network lifetime are very critical in these networks. Particularly when these networks develop more complex and vast in size, traditional routing methods often lead to energy hotspots and too high latency, which reduces the general performance of WSNs. Reducing communication distances and improving data aggregation helps the Polydisperse Steer Minimum Tree-based Routing Protocol (PSMT-RP) increase energy efficiency and load balancing, hence addressing these issues. The work aims to provide a powerful solution extending WSN operational lifespan and guaranteeing consistent data transfer. Applications in environmental sensing and remote monitoring notably benefit from it as it emphasizes resource management and Quality of Service (QoS).

2. BACKGROUND STUDY

Abubakar, Z. M. et al. [2] Routing systems cannot effectively address the hotspot problem even if they were supposed to make networks more energy efficient and longer lasting unless a way was developed or included into them. to successfully reduce the impact of the hotspot issue, the routing algorithm can make use of any of the aforementioned techniques or mechanisms.

Ali, T. et al. [4] The Subnet Based Hotspot Algorithm (SBHA) for WSN hotspot issue was introduced in this research. By precisely outlining all the pertinent properties, conditions, traits, and integrity of the method, the originality of this algorithm was essentially confirmed and confirmed explicitly. These authors used a subnet-based approach however the concept was mostly based on an existing method that divides the network into clusters. The head of each subnet was in charge of the communication between the sink and the source. Hotspots were less likely to form since the node next to the sink does not experience any traffic load.

Alsolai, H. et al. [6] to eliminate hotspots in energy-aware WSNs, this research presents a new Improved Tuna-Swarm-Algorithm-Based Unequal Clustering for Hotspot Elimination (ITSA-UCHSE) approach. To fix the hotspot issue and the unequal dissipation of energy in the WSN, the ITSA-UCHSE method was developed. Furthermore, the ITSA was a variant of the classic TSA that uses a tent chaotic map. Also, using measures for energy and distance, the ITSA-UCHSE method determines a fitness value. The ITSA-UCHSE method for determining cluster sizes also helps in solving the hotspot problem.

Diédié, G. H. F. et al. [9] these authors Time Division Multiple Access (TDMA)-based solution to the hot spot problem—the rapid energy drains in the one-hop vicinity of the sink—was LMDP (Last Mile Delivery Protocol), which the authors introduced in this study. The two famous optimization problems—the precedence-constrained knapsack issue and the one involving aeroplanes landing on a single runway—were combined to generate this question.

Khalaf, O. I. et al. [11] these authors can infer that routing methods have the potential to increase the energy efficiency of sensor networks or to prolong the life of these networks. Nonetheless, the authors were still thinking about the hotspot problems. These authors research solved the issue of hotspots in WSN. In a hotspot situation, the sensor nodes nearest to the base station (BS) use more power and drain it more quickly than the nodes further away. Hotspots form in the vicinity of the BS as a result of the high volume of data sent there from CMs and other CHs. Hotspot problems in WSNs were not yet solved.

Lata, S. et al. [13] A novel clustering technique based on centralized fuzzy logic was presented in this research. The authors selected a cluster head using fuzzy logic by considering three parameters: energy level, concentration, and centrality. The LEACH algorithm uses the obtained signal strength to form clusters. Once again, the authors used fuzzy logic to choose a vice cluster leader after taking all three criteria into consideration.

Mishra, M. et al. [15] With the goal of extending the useful life of WSNs in Internet of Things (IoT) settings, this research created a trust-based particle swarm optimization and Genetic

Algorithm (PSOGA) model. Following grid creation, this approach's optimum CH selection based on a trust model among stationary nodes allows sensor nodes to reliably transmit data to the cluster head.

Prasad, V. K., & Periyasamy, S. [17] the optimal energy optimization solution in wireless sensor networks remains elusive, despite the abundance of methods for implementing protocols in wireless sensors. This was due to the fact that protocols were designed to enhance performance. Despite the fact that the sensor's battery was often non-rechargeable, designers of the protocols have focused on ways to cut down on power use. Because this was now the researchers' exclusive option, the algorithms were built with this in mind.

2.1 Problem definition

WSNs face significant challenges in energy management, data transmission efficiency, and network longevity due to the limited power supply of sensor nodes. Existing routing protocols often lead to energy hotspots, where certain nodes deplete their energy faster than others, resulting in network failure and decreased performance. While some techniques seek to solve hotspot problems via uneven clustering approaches, others like DACOR [19] concentrate on reducing hotspot difficulties using distributed ACO-based routing. These methods can not, however, completely maximize data aggregation or modify routing pathways, therefore causing higher latency and worse QoS.

3. MATERIALS AND METHODS

In this section, we present the proposed Polydisperse Steiner Minimum Tree-based Routing Protocol (PSMT-RP), designed to enhance the performance of Wireless Sensor Networks (WSNs) by optimizing data aggregation and routing efficiency. PSMT-RP utilizes the concept of the Steiner Minimum Tree to determine optimal intermediate nodes, thereby minimizing communication path lengths and conserving energy.

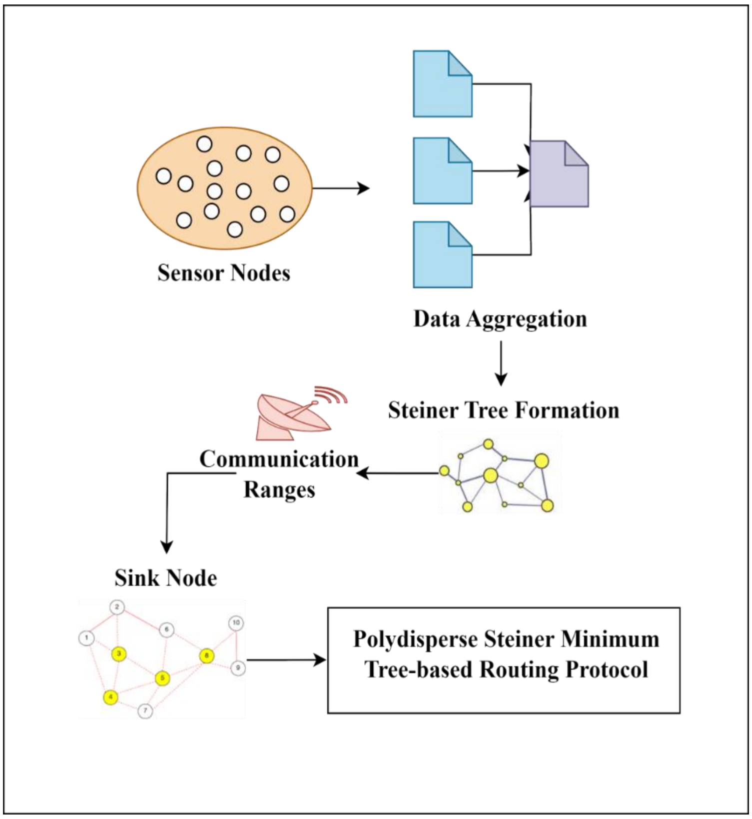

Figure 1: PSMTRP workflow architecture

3.1 Network model

The goal of the Polydisperse Steiner Minimum Tree-based Routing Protocol (PSMT-RP) is to optimize energy usage and minimize latency in Wireless Sensor Networks (WSNs) by efficiently aggregating data. We can characterize the behavior of the PSMT-RP protocol by outlining a network model containing crucial equations.

Nodes and Network Setup: Let $N = \{n_1, n_2, \ldots, n_k\}$ be the set of sensor nodes in the WSN, where each node n_i has limited battery power E_i and communicates wirelessly within a specific communication range. Nodes are distributed randomly across the sensing area.

Concept of the Steiner Minimum Tree (SMT): The SMT finds the shortest route between any two nodes by minimizing the total length of their edges by picking intermediate nodes. By reducing link lengths and aggregating data at intermediate nodes, the PSMT-RP protocol applies this idea to WSNs.

$$C_{SMT} = \sum_{(i,j)\in E} d(i,j)$$

where $d(i,j)$ is the distance between nodes n_i and n_j, and E is the set of edges in the network. PSMT-RP seeks to minimize C_{SMT} by selecting proper intermediate nodes.

Energy Consumption Model: The energy consumption E_{ij} for transmitting data from node n_i to node n_j is modeled as:

$$E_{ij} = p_t . d(i,j)^a$$

where:

- p_t is the transmission power,
- $d(i,j)$is the distance between nodes n_i and n_j,
- α is the path loss exponent (typically $2 \leq \alpha \leq 4$).

3.2 Data aggregation

When talking about WSNs, "data aggregation" means gathering information from several sensor nodes and sending it to one main hub. This method's decrease of data transmission across the network produces lower energy use and network traffic. WSNs have a major characteristic in their capacity to compile data at intermediary nodes. More precise data, lower transmission costs, and better network efficiency are therefore made possible. To achieve significant energy savings, longer network lifetimes, and better resource use, PSMT-RP and other energy-efficient routing techniques depend on data aggregation methods.

During the steady-state phase, data is sent to the sink after being aggregated at the cluster heads. During the setup phase, a certain proportion of nodes (f) choose to be the cluster head. There is a threshold n_i that a sensor node i uses to compare a random integer n (between 0 and 1) against. Becoming a cluster head is the state of the sensor node when n is greater thann_i. The value of ηi gives the threshold.

$$n_i = \frac{f}{1 - f\left(n\, mod\left(\frac{1}{f}\right)\right)}$$

Modulus is an operation that returns the residual after division; mod stands for modulus. Once elected, each cluster head notifies every sensor in the network by broadcast message that they have been elected. In response to this ad, all nodes other than cluster heads determine their cluster membership according to the received signal intensity.

3.3 Polydisperse Steiner Minimum Tree-based Routing Protocol

One routing protocol that aims to optimize power usage and data aggregation in WSNs is the Polydisperse Steiner Minimum Tree-based Routing Protocol, more commonly known as PSMT-RP. By modifying the idea of the Steiner Minimum Tree (SMT), it is able to reduce transmission distances, save energy, and decrease latency by choosing ideal intermediary nodes to minimize communication route lengths. PSMT-RP distributes data aggregation duties among nodes to evenly distribute the load, which increases the lifespan of the network, prevents hotspots from forming, and ensures equal energy usage. The protocol also dynamically adjusts the communication range of nodes, which further improves energy economy and preserves QoS in large-scale networks. According to the simulation findings, PSMT-RP achieves better outcomes than the state-of-the-art methods with regard to network durability, throughput, and energy efficiency.

At intermediate nodes, PSMT-RP uses data aggregation algorithms. Instead of sending data straight to the sink, sensor nodes will instead communicate with intermediary nodes in the area. Before sending out a message, these intermediary nodes compile all of the data from all of the readings. As a result, less data has to be sent over the network, which helps to save energy.

The protocol takes use of the idea of the Polydisperse Steiner Minimum Tree (PSMT) to choose intermediate nodes smartly according to their positions and energy levels. The PSMT-RP algorithm optimizes the pathways for data transmission by selecting nodes that are geographically close to both the source and the sink. This helps to distribute the network's energy load more evenly by reducing transmission distance and energy usage.

Create a subtree, T1, in the network G, where each node s represents a source node.

$$Let\ i = 1\ and\ M_i = \{S\} \text{ ------------- (1)}$$

$$d_i \in M \backslash M_i, to\ T_i \text{ ------------ (2)}$$

PSMT-RP adjusts the sensor nodes' communication range according to the demands of the network and the present state of the network. The protocol prevents hotspot development, in which certain nodes use their energy quicker than others, by constantly altering the maximum distance that nodes can communicate.

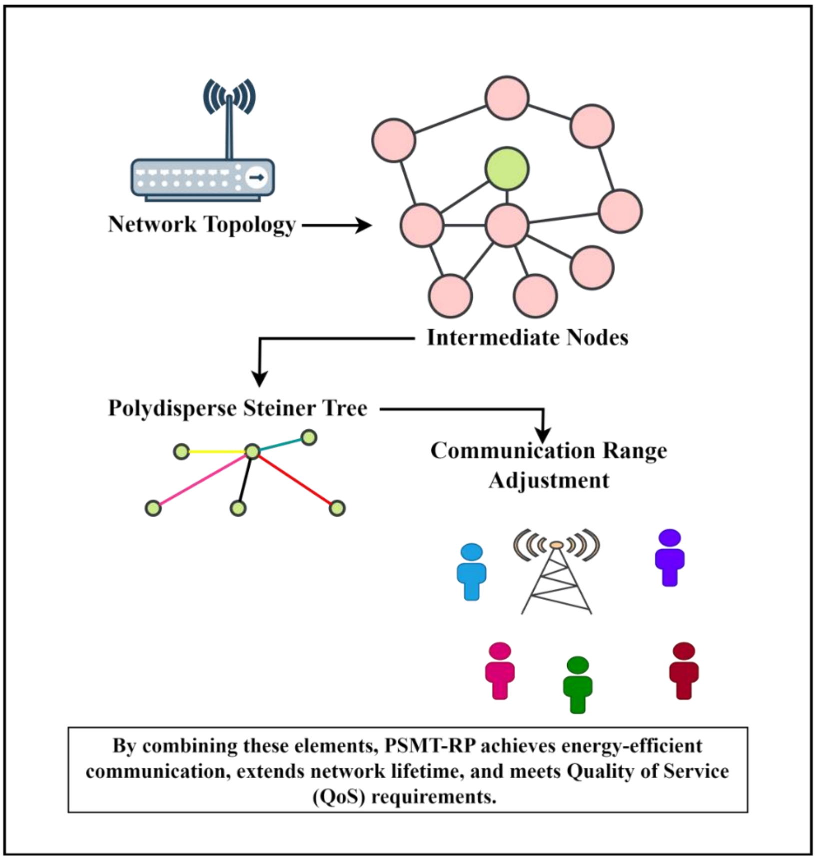

Figure 2: PSMT-RP architecture

The suggested wireless sensor network is in the form of a graph$G(V, E)$, where G is the collection of nodes that make up the network (such as the source node S and other sensor nodes) and E is the collection of paths that allow data to be sent between nodes.

$$N(a) = \{b \in G | b \neq a^{a,b} \in E\} \text{ ---------- (3)}$$

In addition, the sensor node's position data is stored as a dynamic identifier (DID_i) in addition to the global identifier (PID_i) that each node in the network has. A node-state information table is kept by both the source node S and every other node in a WSN. The ClusterHead Flag option can be set to either 0 or 1 in this table. If this node is 0 then it is a Member Node (MN), and if it is 1 then it is a cluster head (CH). To meet the needs of quality of service, PSMT-RP checks that energy management plans are in sync. The protocol satisfies the needs of many WSN applications by keeping the delivery ratio high and the latency to a minimum.

Algorithm 1: PSMT-RP

Input:

Set of sensor nodes V representing the network, including the source node S and other sensor nodes.

Steps:

- Define the network topology $G(V, E)$ where V is the set of nodes (sensor nodes and the source node S) and E is the set of communication links between nodes.
- Assign each node a global identification PID_i and a dynamic identification DID_i (location information).
- Each node collects information on:
  - Its energy level.
  - Its current state (active/inactive).
  - Neighbors defined as $N(a) = \{b \in G | b \neq a \text{ and } (a, b) \in E\}$

- Define the Quality of Service (QoS) requirements such as acceptable delay, required throughput, and reliability.
- Initialize the subtree T_1 consisting of the source node S only.
- Set i=1i and $M_i = S$.
- For each node d_i in M\M_i:
    - Evaluate potential intermediate nodes based on:
        - Proximity to S.
        - Remaining energy levels.
        - Contribution to overall network load balancing.

Output:

A subtree T_1 is constructed starting with the source node S. The selected intermediate nodes based on their positions and energy levels are included to form an optimal Steiner Tree T.

The PSMT-RP optimizes energy consumption and data aggregation in WSNs. It constructs an optimal communication tree by selecting intermediate nodes based on their proximity to the source, remaining energy, and contribution to network load balancing. By reducing transmission distances and dynamically adjusting node communication ranges, PSMT-RP conserves energy, mitigates hotspot formation, and ensures even energy usage across the network.

4. RESULTS AND DISCUSSION

In this section, we present the results obtained from the simulation of the Polydisperse Steiner Minimum Tree-based Routing Protocol (PSMT-RP) and discuss the performance metrics compared to existing state-of-the-art protocols.

Table 1: Throughput value comparison table

Packet Size (bytes)	DACOR	POBUCT	PSMTRP
100	2.4	2.6	3.0
200	4.7	4.9	5.6
300	7.0	7.3	8.4
400	9.3	9.6	11.2
500	11.5	11.9	13.7

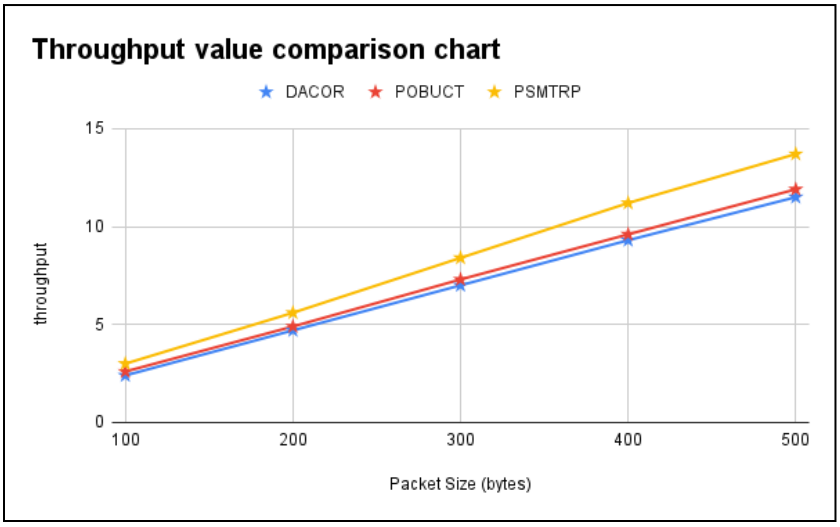

Figure 3: Throughput value comparison chart

Over all packet sizes, PSMT-RP routinely beats DACOR, POBUCT, according to table 1 and figure 3, which illustrates throughput comparison between the two protocols. For instance, DACOR obtains a throughput of 2.4 Mbps, POBuct 2.6 Mbps, and PSMT-RP reaches 3.0 Mbps, therefore suggesting greater efficiency in data transmission from a packet size of 100 bits. The performance difference closes further as the packet size rises; PSMT-RP reaches 13.7 Mbps for 500 bytes while POBUCT reaches 11.9 Mbps and DACOR reaches 11.5 Mbps. This implies that PSMT-RP is more suited for managing bigger packets, hence enhancing network speed and data throughput.

Table 2: Energy level Consumption table

Number of Nodes	DACOR	POBUCT	PSMTRP
10	50	48	42
20	92	88	78
30	135	128	110
40	178	167	145
50	220	208	180

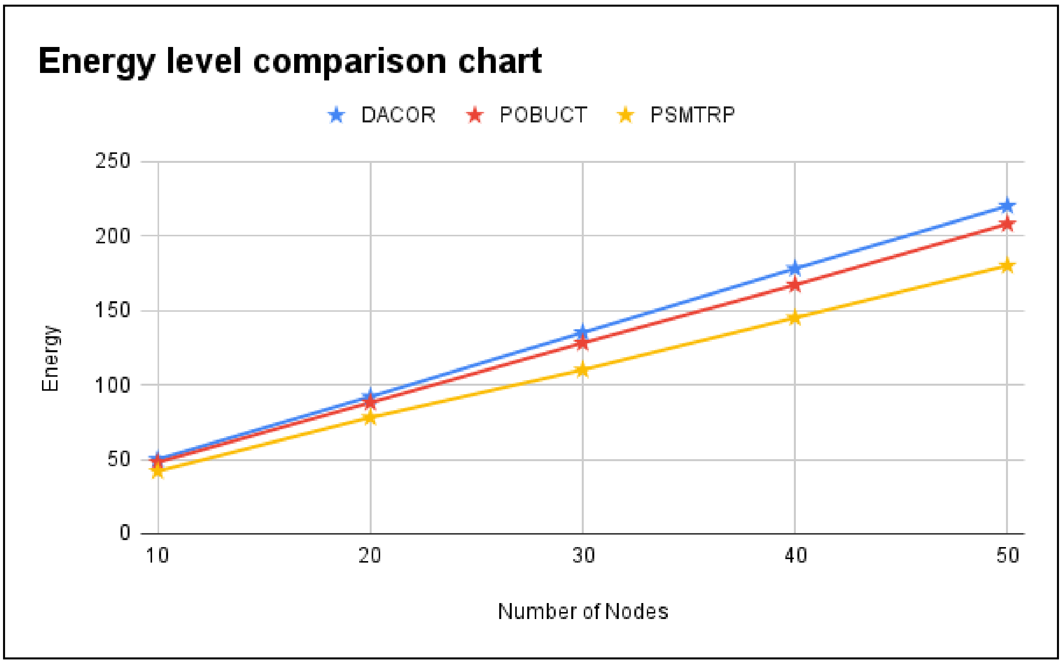

Figure 4: Energy level comparison chart

Energy consumption comparison among DACOR, POBUCT, and PSMT-RP for different numbers of nodes indicates in table 2 and figure 4 that PSMT-RP displays best energy efficiency across all conditions. With 10 nodes, DACOR consumes 50 Joules; POBuct uses 48 Joules; PSMT-RP drastically lowers consumption to 42 Joules. Whereas PSMT-RP still maintains a lower consumption level at 180 Joules, DACOR's energy usage climbs to 220 Joules as the number of nodes grows to 50 and POBUCT's to 208 Joules. This graph indicates that PSMT-RP regularly uses less energy than both DACOR and POBUCT, thereby stressing its efficiency in maximising energy consumption in Wireless Sensor Networks as the network size increases.

Table 3: Time delay value comparison table

Number of Nodes	DACOR	POBUCT	PSMTRP
10	15	13	10
20	28	25	20
30	40	37	32
40	55	50	42
50	70	63	55

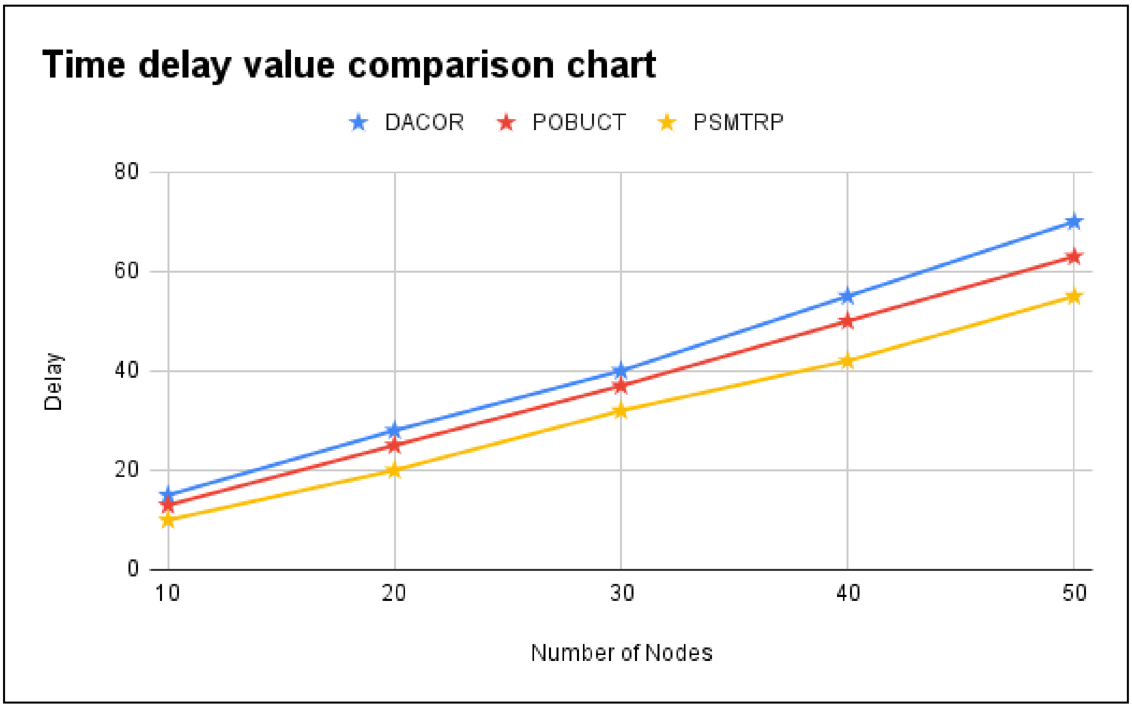

Figure 5: Time delay value comparison chart

Time delay comparison among DACOR, POBUCT, and PSMT-RP for changing numbers of nodes demonstrates in table 3 and figures 5 that PSMT-RP achieves lowest latency across all investigated cases. With 10 nodes, DACOR has a time delay of 15 ms; POBUCT has 13 ms; PSMT-RP has the highest performance with a delay of only 10 ms. Whereas PSMT-RP maintains a very low latency of 55 ms, DACOR's time delay climbs to 70 ms as the number of nodes rises to 50 and POBUCT's to 63 ms. This figure shows that as the network grows, PSMT-RP lowers communication latency hence improving responsiveness in Wireless Sensor Networks.

Table 4: Overhead value comparison table

Number of packets (bytes)	DACOR	POBUCT	PSMTRP

100	12	10	7
200	18	16	12
300	25	22	17
400	30	27	21
500	35	32	25

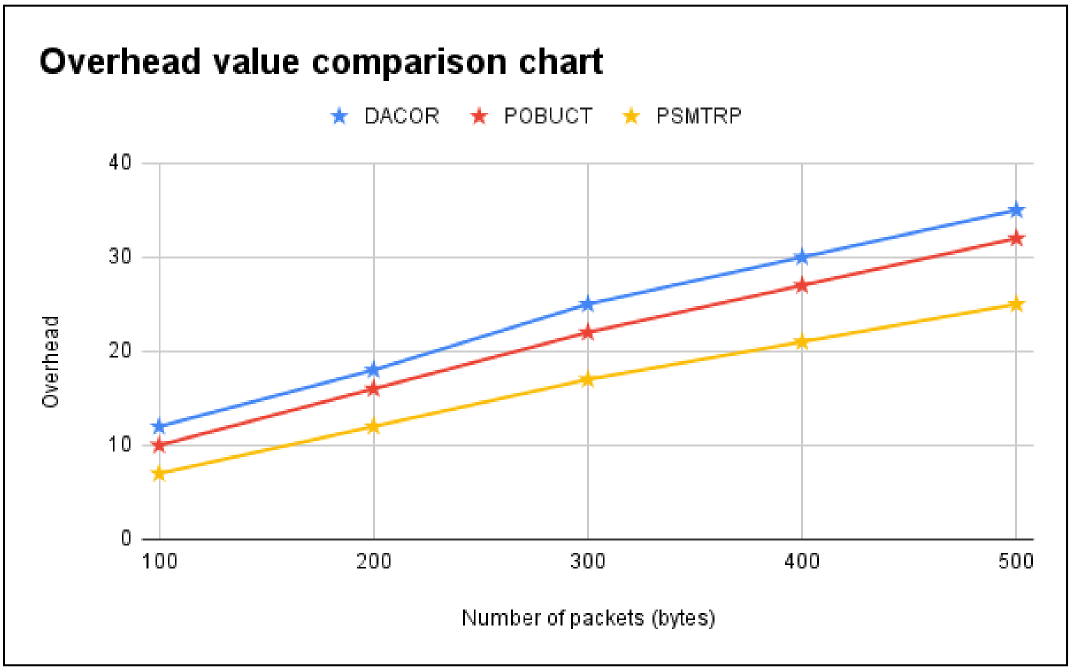

Figure 6: Overhead value comparison chart

For various packet counts (in bytes), table 4 and figure 6 exhibit overhead comparison among DACOR, POBUCT, and PSMT-RP showing that PSMT-RP incurs the least overhead across all situations. For example, DACOR has an overhead of 12% with 100 packets; POBuct has 10%; PSMT-RP has a somewhat less overhead of 7%. DACOR's overhead climbs to 35%, POBUCT's to 32%, and PSMT-RP's lowers overhead of 25% as the packet count grows to 500. This trend shows that, as the packet size rises, PSMT-RP is increasingly effective in controlling protocol overhead, hence it is a good option for best use of resources in Wireless Sensor Networks.

Table 5: Network Lifetime value comparison table

Number of packets (bytes)	DACOR	POBUCT	PSMTRP
100	120	130	150
200	110	120	140
300	100	110	130

400	90	100	120
500	80	90	110

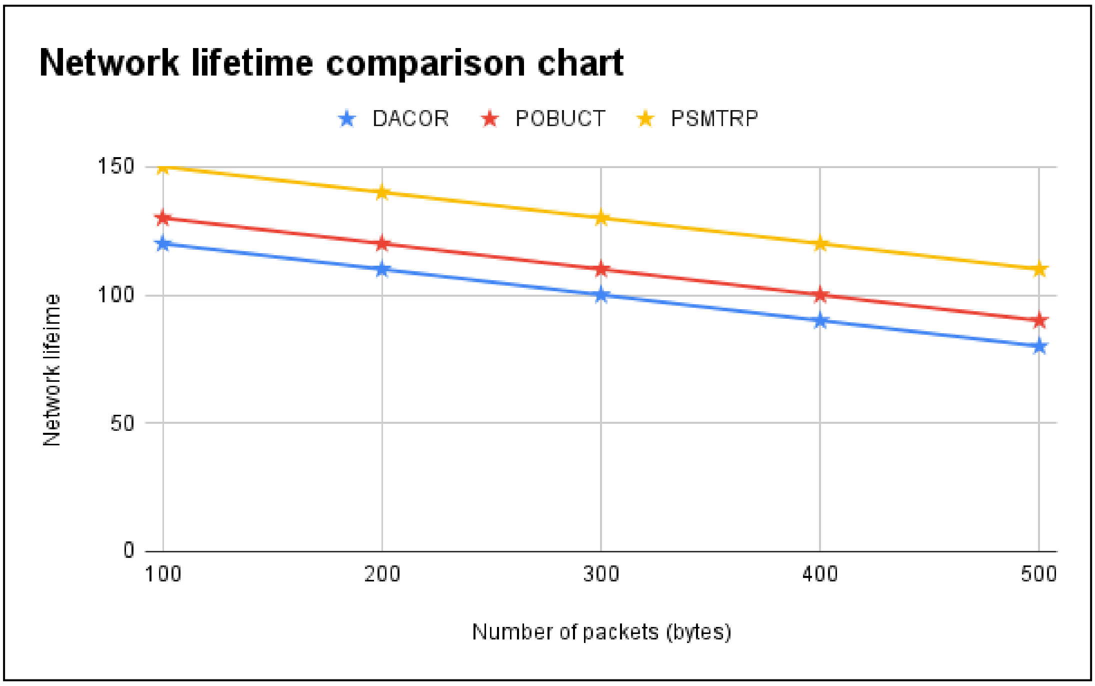

Figure 7: Network lifetime comparison chart

For various packet counts (in bytes), table 5 and figure 7 illustrate network lifespan comparison among DACOR, POBUCT, and PSMT-RP indicating that PSMT-RP greatly increases network lifetime across all situations. For example, DACOR provides a network lifespan of 120 hours with 100 packets; POBUCT delivers 130 hours; PSMT-RP excels with a lifetime of 150 hours. DACOR's network lifespan drops to 80 hours when the packet count rises to 500; POBUCT's to 90 hours; PSMT-RP still has a longer lifetime at 110 hours. This steady trend implies that PSMT-RP is very efficient in extending the operational lifetime of Wireless Sensor Networks, so it is a great option for uses demanding maximum network availability.

Table 6: Packet delivery ratio value comparison table

Number of packets (bytes)	DACOR	POBUCT	PSMTRP
100	97.6	98.2	98.6
200	98.8	99.1	99.3
300	99.2	99.4	99.53
400	99.4	99.55	99.65
500	99.52	99.64	99.72

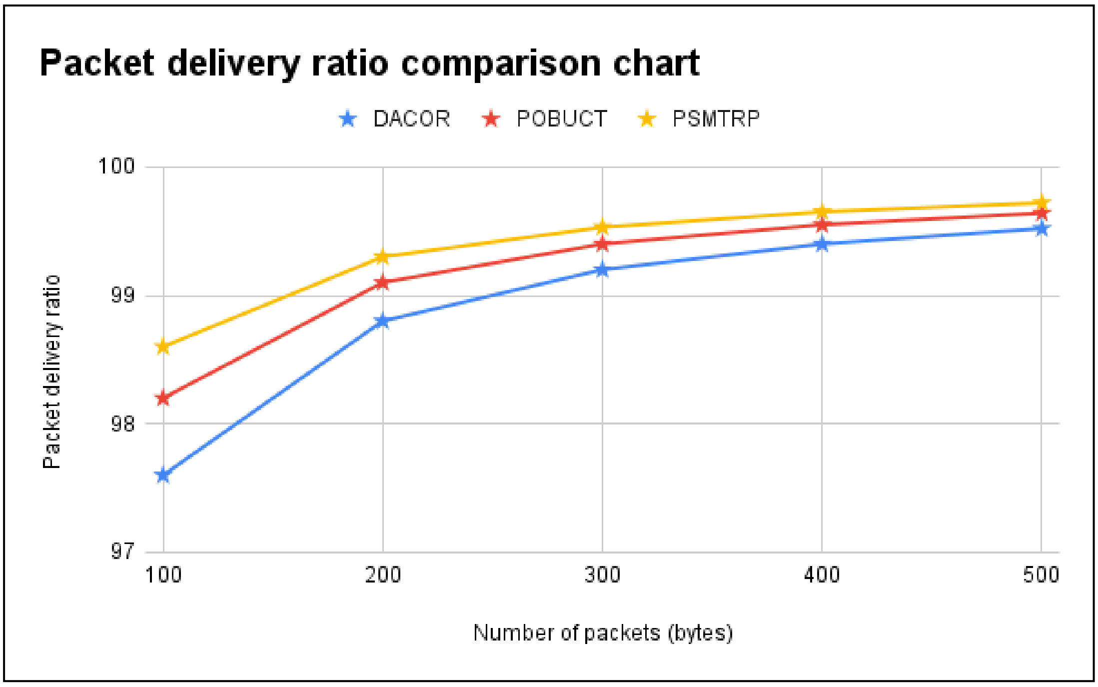

Figure 8: Packet deliver ratio comparison chart

For various packet counts (in bytes), the table 6 and figure 8 exhibit packet delivery ratio (PDR) comparison among DACOR, POBUCT, and PSMT-RP consistently indicates PSMT-RP consistently obtains the greatest delivery ratios. For example, DACOR notes a PDR of 97.6% with 100 packets; POBUCT reports 98.2%; PSMT-RP leads with a PDR of 98.6%). DACOR's PDR somewhat improves to 99.52%, POBuct climbs to 99.64%, and PSMT-RP performs even better with a PDR of 99.72% when the packet count grows to 500. This trend indicates that PSMT-RP not only maintains a high packet delivery ratio but also displays the most notable improvement with growing packet sizes, thereby confirming its efficiency in guaranteeing dependability in Wireless Sensor Networks.

5. CONCLUSION

By means of data aggregation and communication channels, the Poly Disperses Steer Minimum Tree-based Routing Protocol shows outstanding benefits in Wireless Sensor Networks (WSNs), thereby optimizing energy efficiency, load balancing, and low latency. The network's lifespan is extended and energy is efficiently saved by carefully choosing intermediary nodes and changing the communication range. For large-scale WSNs, particularly those with strict Quality of Service (QoS) criteria and limited energy resources, its capacity to reduce transmission lengths and eliminate congestion makes it rather appropriate. The simulation findings show that PSMT-RP beats current state-of-the-art technologies by high throughput with low energy consumption, which is essential for the sustainable operation of WSNs in many applications.

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