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Optimizing Routing Efficiency in Wireless Sensor Networks with Link Score and Delay Awareness Routing

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Abstract
This work introduces a **Delay-Aware Routing Protocol based on Link Score (LSDAR)** for Wireless Sensor Networks (WSNs), aimed at enhancing routing efficiency by incorporating both link quality and hop count in decision-making. The protocol evaluates each forwarding candidate using a link score derived from its residual energy, estimated delay, and packet delivery success rate. By prioritizing nodes with higher link scores, LSDAR ensures data is transmitted through paths with lower delay and higher reliability. Simulation analysis confirms that LSDAR significantly extends network lifetime, improves delivery ratios, and minimizes end-to-end delays compared to conventional routing schemes. Additionally, it reduces packet collisions and optimizes energy consumption. Results show that LSDAR achieves nearly 75% improvement in throughput and conserves up to 60% of total energy relative to baseline protocols, making it well-suited for real-time, energy-sensitive WSN applications.
Keywords: Delay-Aware Routing, Energy Efficiency, Link Quality Assessment, Network Lifetime, Packet Delivery Ratio, Wireless Sensor Networks

1. INTRODUCTION

Wireless Sensor Networks (WSNs) have become essential in diverse domains such as environmental monitoring, healthcare, and industrial automation [1–3]. The efficiency of a WSN largely depends on the routing protocol, particularly in applications where minimizing delay is critical [4–5]. Conventional routing strategies like shortest path routing typically rely on hop count alone when choosing the next forwarding node, often neglecting the quality of the communication link [6]. However, in practical deployments, factors such as noise, interference, and physical distance can significantly degrade link quality [7].

To overcome this limitation, this paper introduces a new delay-aware routing strategy termed **Link Score-based Delay Aware Routing (LSDAR)**. Unlike traditional methods, LSDAR incorporates link quality metrics alongside hop count to determine the optimal next hop. It evaluates each candidate node by computing a link score that reflects its residual energy, estimated delay, and packet delivery ratio. The node with the most favourable score—indicating reliable and timely communication—is selected for data forwarding.

Extensive simulations demonstrate that LSDAR consistently delivers superior performance over existing routing protocols with improvements in network lifespan, reduced end-to-end delay, and enhanced packet delivery ratio [8–11]. Furthermore, the protocol significantly minimizes packet collisions and boosts energy efficiency [12–15]. These outcomes highlight LSDAR's suitability for real-time and energy-sensitive WSN deployments.

Key Contributions of this Paper: A novel routing metric, Receiver Data Rate (RDR), is introduced to evaluate a sensor node's capacity to deliver packets within a defined time unit. This metric significantly improves the selection of efficient forwarder nodes, contributing to timely and reliable data delivery. The proposed routing protocol ensures a stable, lightweight, and loop-free routing path by leveraging the newly introduced metrics. This reduces route discovery overhead and

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enhances the energy efficiency of the network. By adopting a delay-aware route selection approach, the protocol minimizes average energy consumption across sensor nodes. This leads to a substantial improvement in the overall network lifespan. The LSDAR protocol is shown to deliver notable improvements in energy efficiency and end-to-end delay, all while maintaining a high packet delivery ratio, making it suitable for time-sensitive WSN applications. The structure of the paper is as follows: Section 2 reviews recent advancements in energy-efficient MAC protocols for WSNs. Section 3 outlines the proposed LSDAR approach. Section 4 details the simulation setup and discusses the obtained results. Section 5 concludes the paper with final remarks and future research directions.

II. RELATED WORK

Several significant research efforts have been carried out in the field of routing optimization for Wireless Sensor Networks (WSNs), focusing on enhancing energy efficiency, reducing delay, and improving overall network performance. Singh et al. [16] introduced a link score-based energy-efficient routing protocol that selects optimal routes by considering residual energy and link quality. Similarly, Chen et al. [17] proposed a delay-aware routing protocol that integrates energy consumption and delay into a weighted cost function, with added congestion control. Other works like Sharma and Verma [18] extended this idea by including security parameters in the link score for secure routing. Jiang et al. [19] used a clustering-based greedy approach to reduce delay and energy usage, while Li et al. [20] employed Pareto optimization to balance energy and delay in multi-objective routing. Chen et al. [21] and Liu et al. [22] further refined link score-based algorithms to include hop count and node mobility respectively, enhancing adaptability and robustness. Oshin et al. [23] and Shahriar et al. [24] emphasized energy-aware and delay-sensitive dynamic routing methods, demonstrating better network lifetime and packet delivery through innovative metrics like EALS and dynamic time slot allocation. Liu et al. [25] incorporated hybrid energy sources to create a routing mechanism sensitive to energy harvesting. Hierarchical approaches were explored by Sabet and Naji [26], while Swain et al. [27] improved MAC protocol efficiency using channel hopping techniques. Selvi et al. [28] proposed a fuzzy rule-based approach for delay-constrained routing, and Liu et al. [29] presented QTSAC for dynamic slot allocation to reduce delay. Zhang et al. [30] and Nisha et al. [31] focused on balancing load among sinks and link delay optimization. Sami Ullah et al. [32] addressed unique UWSN challenges with a delay and reliability-aware scheme, and Li et al. [33] proposed a mobile sink-based strategy to prevent energy imbalance. Collectively, these studies highlight the importance of adaptive routing strategies that account for diverse parameters such as energy, delay, security, node mobility, and traffic load to enhance the efficiency and lifespan of WSNs.

III.PROBLEM DEFINITION

The end-to-end delay experienced by a data packet in a Wireless Sensor Network (WSN) can be broken down into four key components:

1. **Processing Delay** – the time required by a sensor node to examine and process the packet header,
2. **Queuing Delay** – the waiting time of a packet in the routing queue before it can be transmitted,
3. **Transmission Delay** – the time it takes to push the packet onto the communication link, and
4. **Propagation Delay** – the time taken for the signal to travel from the sender to the receiver.

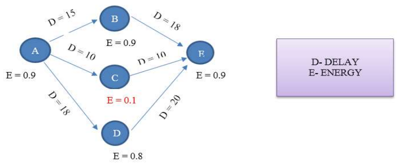

Figure 1: A small WSN with 5 nodes

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Table1: Routing metric calculation results

ROUTES	DELAY (Sec)	TOTAL RESIDUAL ENERGY (Joules)
ABE	33	2.7
ACE	20	1.9
ADE	38	2.6

Although the ACE path offers the lowest delay, it also exhibits the lowest residual energy. Prioritizing this path might result in the rapid depletion of node C's energy, which can degrade overall network performance and longevity.

This scenario underscores the importance of using a composite routing metric that balances both delay and residual energy. To tackle this problem, we propose LSDAR (Link Score-based Delay Aware Routing)—a routing protocol that combines multiple metrics to intelligently select the most efficient forwarder. LSDAR is designed to optimize energy consumption, extend network lifetime, and ensure reliable data delivery in energy-constrained and delay-sensitive WSN environments.

IV.PROPOSED SYSTEM

This section details the working of the proposed **Link Score-based Delay Aware Routing (LSDAR)** protocol and its improvements over established methods such as **DEEH-CB [26]**, **Adv-MMAC [27]**, **DCEMRA [28]**, and **QTSAC [29]**. The LSDAR protocol employs an enhanced forwarder selection mechanism that evaluates several key parameters: **residual energy, distance, delay, Received Signal Strength Indicator (RSSI), Receiver Data Rate (RDR),** and **Expected Transmission Count (ETX)**. Each sensor node is given a score reflecting its performance in data transmission. Higher scores indicate greater reliability and suitability for packet forwarding. **Figure 1** depicts the block diagram representing the overall structure of the proposed protocol.

LSDAR Routing Workflow

The operation of the LSDAR protocol follows a structured four-phase process:

1. **One-Hop Neighbour Discovery**
2. **Metric Computation**
3. **Link Score Assessment**
4. **Best Forwarder Selection**

1. One-Hop Neighbour Discovery

In this initial phase, every sensor node broadcasts a **HELLO message** containing its unique identifier (ID) multiple times to its surrounding nodes. Upon reception, neighbouring nodes extract the information and update their **neighbor list** accordingly. These lightweight HELLO messages are also used to compute the **ETX** between pairs of nodes, providing an estimate of link quality.

2. Metric Computation

Following neighbor discovery, each node sends out metric packets to its 1-hop neighbors. These packets include information such as **ETX, RDR, RSSI, delay, distance**, and **residual energy**. On receiving these packets, a node processes and stores the data in its **neighbor table**. For every neighbor, the routing metric is evaluated and continuously updated as new information becomes available.

3. Link Score Evaluation

Each link is then assigned a **link score** using the stored parameters. This score acts as an indicator of the overall quality, stability, and energy efficiency of that link. It enables the protocol to determine the most appropriate forwarding node for reliable and timely data transmission.

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4. Source Node Forwarder Selection

Once link scores are calculated, the node with the **highest link score** among the available candidates is selected as the **next-hop forwarder**. This selection ensures that both energy efficiency and transmission reliability are maintained throughout the routing process.

5. Expected Transmission Count (ETX)

To estimate **link quality**, the **Expected Transmission Count (ETX)** is employed. ETX considers both forward and reverse delivery ratios and the probability of successful packet acknowledgment. It quantifies the expected number of transmissions (including retransmissions) required for a packet to be successfully delivered across a link. ETX also captures the impact of bidirectional losses and interference between successive links. The ETX for a given link can be computed using the following formulation:

$$ETX = \frac{1}{p_f \, x \, p_r} \qquad (1)$$

With the use of advertising link probe packets, the delivery ratios p_r and p_f are obtained. During a small period, a fixed number of probes are broadcasted by each sensor node. The delivery ratio is a / b when packets $a\,(a \le b)$ are received by the receiver and b link probe packets are sent. The ETX will remain at a maximum value and is determined by the application if 'a' is equal to zero.

RDR: -Owing to the effect of an environment, the condition of a channel between two sensor nodes is varied with the time specified in the intertidal environment in which tides rise and ebb intermittently. The delivery of a packet tends to be failed, which results in the improvement of packet retransmissions if associated with an unreliable link. As a parent node, it's preferred to be choosing the neighbor node with a stable link. For evaluating the link quality's level, ETX is implemented and performs well for representing the quality of a link. The definition of RDR can be described as mentioned below equation (2):

$$RDR = \frac{E_{res}}{ETX_{ij} \, x \, E_{tx}(l,d_{ij}) \, x \, D_{ij}} \qquad (2)$$

Where D_{ij} is the end-to-end delay of link, $E_{tx}(l,d_{ij})$ is the conservation of energy to transmit an l-bit packet over a distance d_{ij}, d_{ij} is the distance between nodes n_i and n_j, ETX_{ij} is the ETX value between two neighbour nodes $n_i$and n_j, E_{res} is the sensor node's remaining energy and RDR is the RDR value of link.

Link score calculation: In the link score calculation, two parts are included such as the link score and the route score. The individual link's score between two neighbor nodes is referred to as the link score. The sum of the link scores in a routing path is defined as the route score. However, the values of RDR and the reverse of RDR can be utilized as the link score. These scores link score Clk and route score Crt is demonstrated as follows in equations (3) and equation (4):

$$S_{link}(i,j) = \frac{1}{RDR_{ij}}, \qquad (3)$$

$$S_{route}(i) = min\{S_{route}(j) + S_{link}(i,j)\} \qquad (4)$$

Where $S_{route}(i)$ the node's route score and $S_{link}(i,j)$ is the link score in its routing path. The minimum value of the route score has included in the sink node that can be set as zero. A few numbers of iterations are needed in the estimation of route score. The route score for its neighbour nodes is computed by each sensor node that can be acted as next-hop candidates and the best score is calculated after the calculation of metric values. The best route score is advertised by each sensor node for the update of the scores.

Source selection: For each of the neighbor nodes, the route score is updated by each node and the best score is determined. The scores are updated completely after making various iterations. To make the forwarding of sensed data, the neighbor with the best route score is chosen as a parent node. If the entire sensor nodes are updated their scores of the route, the routing paths are estimated.

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Medium Access Control Mechanisms and Proposed LSDAR Framework:

Carrier Sense Multiple Access with Collision Avoidance (**CSMA/CA**) is a fundamental medium access protocol defined in the IEEE 802.11 standard, which operates using a **Distributed Coordination Function (DCF)**. Since nodes cannot detect ongoing transmissions while simultaneously transmitting, **collision detection is not feasible** in this context. Instead, prior to initiating a transmission, a node listens to the communication channel to verify if it is idle. Upon successful packet delivery, the receiving node sends an **Acknowledgment (ACK)** within a short timeframe. If the sender does not receive an ACK, it assumes the transmission failed and attempts a **retransmission**.

Channel sensing in CSMA/CA occurs via two methods:

- **Physical Carrier Sensing**, which involves detecting energy levels or activity on the radio channel.
- **Virtual Carrier Sensing**, implemented using **Request to Send (RTS)** and **Clear to Send (CTS)** packets. These packets include timing information in their headers, allowing nodes to reserve the channel virtually and avoid collisions.

In contrast, **Time Division Multiple Access (TDMA)** assigns discrete time slots to each node, permitting data transmission only during the allocated slot. This method necessitates **synchronization** among nodes, typically managed using preamble bits at the beginning of each time slot. Though **Time Division Multiplexing (TDM)** and TDMA are conceptually similar, they differ in application: TDM is a physical-layer technique for aggregating low-bandwidth channels into a high-bandwidth stream, whereas TDMA serves as a **data link layer protocol** for controlling channel access. TDMA coordinates slot allocation without involving a physical multiplexer.

Frequency Division Multiple Access (FDMA) splits the available spectrum into multiple non-overlapping frequency bands, with each node permanently assigned a unique frequency. Unused portions of the spectrum act as **guard bands** to minimize inter-channel interference. Like TDM, **Frequency Division Multiplexing (FDM)** is a physical-layer mechanism that merges several narrowband signals for transmission over a higher-bandwidth channel using modulation and filtering techniques. In FDMA, the **data link layer instructs the physical layer** to modulate signals into the assigned frequency band, and no explicit hardware multiplexer is used.

LSDAR Model Overview

The architecture of the proposed Link Score-based Delay Aware Routing (LSDAR) protocol is shown in Figure 2. This model outlines the entire process, from network initialization to the dynamic selection of the transmission mode based on real-time network conditions.

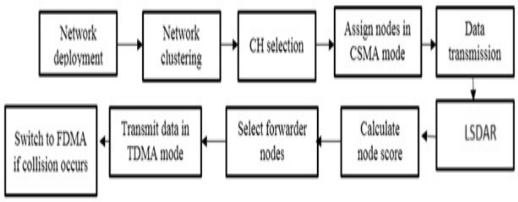

Figure 2: Block diagram of proposed protocol

Once **Cluster Heads (CHs)** are elected and **member nodes** are associated, all sensor nodes default to **CSMA mode** for initial communication. When transmitting data, nodes evaluate potential forwarders using a **scoring mechanism** that takes into account factors such as:

- **Residual Energy**
- **Distance to the destination**
- **Transmission Delay**
- **RSSI (Received Signal Strength Indicator)**
- **RDR (Remaining Delivery Ratio)**
- **ETX (Expected Transmission Count)**

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Based on these scores, the optimal **forwarder node** is chosen. For data delivery, **TDMA** is employed where each sensor node is given a specific time slot, minimizing contention. In cases where **packet collisions** are detected, the system dynamically switches to **FDMA**, allocating frequency bands to ensure reliable delivery.The processes of **network clustering**, **score computation**, and **routing path selection** are further elaborated through detailed algorithms accompanying this model.

Algorithm for Clustering

d_{ij}= distance; E_{res} = residual energy; CH[i] = cluster head list
##

For all the nodes n
Calculate d_{ij}
Calculate E_{res}
If (d_{ij}= low || E_{res} = high)
   CH[i] = n
End for
For all the nodes n
If n ε CH[i]
Informs about its CH election to other nodes
   Else
Joins with the nearest CH as cluster member
End for

Algorithm for Score calculation & Route selection

d_{ij}= distance; E_{res} = residual energy
ETX = expected transmission count; D_{ij} = delay of the link
$S_{link}(i,j)$ = link score of the link(i,j); $S_{route}(i)$ = route score of route (i)
FSR = final selected route

###
For all the nodes 'n'
   1-hop discovery phase
      Broadcast HELLO packets
      Update neighbour node table
   End
      For each 1-hop neighbour node n
         Calculate distance d_{ij}

$$d_{ij}= \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}$$

      Estimate E_{res}
      $E_{res}=(E_{initial} - E_{consumed})$
      Estimate ETX
      Estimate D_{ij}
Estimate $RD = \frac{E_{res}}{ETX_{ij}\ x\ E_{tx}(l,d_{ij})\ x\ D_{ij}}$
End for

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For each node n and link l
Estimate link score $S_{link}(i,j)=\frac{1}{RD_{ij}}$,
Estimate $S_{route}(i,j)$
If ($S_{route}(i)>S_{route}(j)$)
FSR = (i)
Else
FSR = (j)
End If
End for

For each FSR
Assign nodes in CSMA mode
If (data = true)
Member nodes transmit the data using TDMA
End If
If (collision = true)
Switch to FDMA
End IF

V. RESULTS & DISCUSSION

The performance evaluation of the proposed **LSDAR protocol** is conducted using the **NS-2 network simulator**, incorporating key performance metrics such as **Link Score**, **Expected Transmission Count (ETX)**, **Remaining Delivery Ratio (RDR)**, and **Received Signal Strength Indicator (RSSI)**. **Table 2** outlines the simulation parameters. The simulation utilizes **Constant Bit Rate (CBR)** traffic to regulate data flow, while **AOMDV** serves as the underlying routing protocol. For comparison, existing methods including **DEEH-CB**, **Adv-MMAC**, **DCEMRA**, **QTSAC**, and the proposed **LSDAR** are evaluated.The simulation is configured with a **packet size of 1024 bytes**, a **transmission interval of 0.1 ms**, and a **maximum node speed of 35 m/s**. The total simulation time is set to **20 seconds**, and the network topology comprises **21 sensor nodes** deployed within a **500 × 500 m² area**. The **clustering mechanism**, along with the **score calculation** and **route selection algorithms**, are implemented as part of the simulation model.

Table 2: Simulation parameters

Parameters	Values
Number of Nodes	50 to 250
Communication range	100m
Area of simulation	1000m*1000m
Priority distribution	Uniform distribution with 20% distribution for each priority
Node Deployment Topology	Random
Simulation time	30 minutes
Interface Queue	50

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Length	
MAC	802.11
Number of Base station	1
Location of Base station	Upper right
Initial energy of nodes	100 joules
Weights w1, w2, w3	w1=w2=w3=0.33

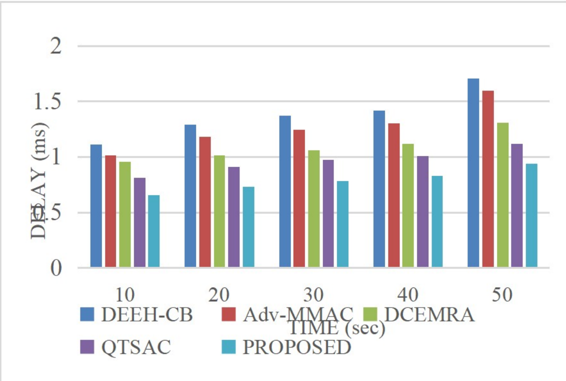

Figure 3: Evaluation of End-to-End Delay

Figure 3 presents the trend of **end-to-end delay over time**. Compared to the baseline protocols—DEEH-CB [26], Adv-MMAC [27], DCEMRA [28], and QTSAC [29]—the LSDAR protocol demonstrates a noticeable improvement in reducing communication delay between nodes. This improvement is attributed to its score-based route selection strategy, where each path is evaluated using performance indicators such as ETX, RDR, and RSSI. Routes with higher scores, indicating lower delays and better reliability, are prioritized for data forwarding. As a result, LSDAR achieves faster data delivery and lower average delay, outperforming previously proposed methods in simulation experiments.

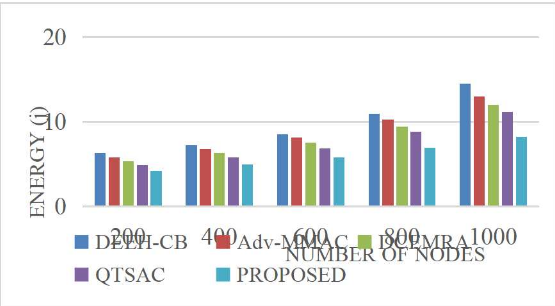

Figure 4: Analysis of Energy Consumption

Figure 4 illustrates the energy efficiency achieved by the proposed LSDAR protocol. Compared to existing routing methods such as **DEEH-CB [26]**, **Adv-MMAC [27]**, **DCEMRA [28]**, and **QTSAC [29]**, LSDAR demonstrates superior performance in conserving energy. This improvement is attributed to its **score-based route selection mechanism**, which evaluates potential paths during each communication cycle. By choosing **low-delay, interference-free paths**, the protocol minimizes transmission interruptions and reduces the likelihood of route failures. As a result, **fewer retransmissions occur**, and the **overall energy consumption** of the network is significantly lowered.

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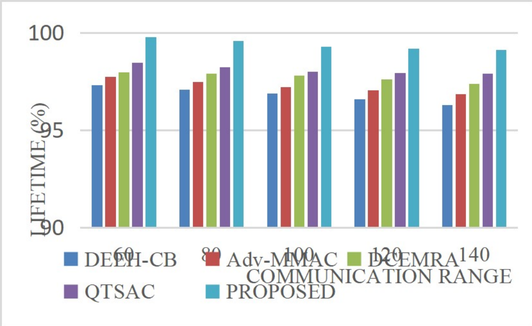

Figure 5: Network Lifetime versus Communication range

Figure 5 presents the relationship between **network lifetime and communication range.** The **LSDAR protocol** achieves **enhanced network longevity**, particularly at lower communication ranges, outperforming other existing schemes such as **DEEH-CB [26]**, **Adv-MMAC [27]**, **DCEMRA [28]**, and **QTSAC [29]**. A key limitation of these earlier methods is their **lack of consideration for parameters like RSSI** during route formation, which leads to performance degradation in networks with varying communication ranges. In contrast, the proposed LSDAR protocol incorporates **RSSI as a crucial metric** in route scoring. By assessing the signal strength between nodes during neighbor discovery, LSDAR effectively selects nodes that are better suited for stable communication within the desired range. This **prevents unnecessary energy expenditure** and ensures **consistent performance across different communication ranges**, thereby extending the overall network lifetime.

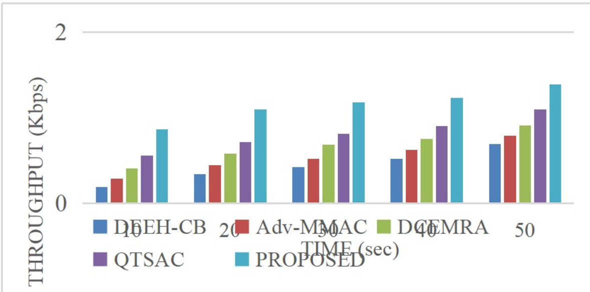

Figure 6: Estimation of Throughput ratio

Figure 6 illustrates the network's performance by plotting simulation time against throughput. The graph clearly shows that the **LSDAR protocol** achieves **superior throughput** compared to existing routing methods such as **DEEH-CB [26]**, **Adv-MMAC [27]**, **DCEMRA [28]**, and **QTSAC [29]**. This performance gain is attributed to SDAR's intelligent path selection, which prioritizes routes with minimal interference, lower delay, and a high likelihood of successful data delivery. By reducing the latency between successive transmissions, the algorithm enables **faster and more efficient packet forwarding**, resulting in a **significantly improved data rate** within the same simulation duration. Consequently, LSDAR consistently demonstrates **higher throughput efficiency** than the other protocols evaluated.

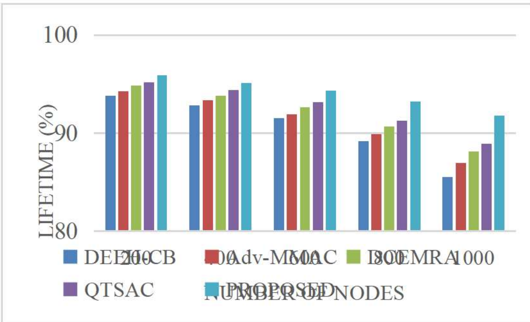

Figure 7: Network lifetime versus Number of Nodes

Figure 7 illustrates how network lifetime varies with the number of deployed nodes, with the corresponding values summarized in Table 7. The results indicate that the proposed LSDAR protocol delivers a notable improvement in network longevity compared to existing methods such as DEEH-CB [26], Adv-MMAC [27], DCEMRA [28], and QTSAC [29]. This enhancement is primarily due to LSDAR's ability to efficiently manage energy usage by selecting communication paths that minimize the need for retransmissions. Since retransmissions and excessive link delays are key contributors to energy drain in wireless sensor networks, the score-based route selection strategy in LSDAR plays a vital role in avoiding such inefficiencies. As a result, LSDAR significantly extends the overall operational lifespan of the network.

VI. CONCLUSION

The proposed LSDAR protocol addresses routing challenges in harsh WSN environments by using a novel metric called Remaining Delivery Ratio (RDR) to select reliable forwarder nodes. LSDAR calculates a composite score per node and selects routes with the highest accumulated scores. It integrates Hybrid MAC protocols for efficient intra- and inter-cluster communication. NS2 simulation results show LSDAR reduces energy consumption by 60%, improves throughput by 75%, and lowers transmission delay by up to 85% compared to existing protocols. However, performance in heterogeneous networks and fairness in route selection remain areas for future work.

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