A Non-hierarchical Multipath Routing Protocol Using Fuzzy Logic for Optimal Network Lifetime in Wireless Sensor Network

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***Abstract*—The prospective integration of Wireless Sensor Networks (WSNs) with the Internet of Things (IoT) in pivotal domains underscores the paramount significance of preserving the network lifespan. Notwithstanding, traditional algorithms evince insufficient energy conservation, necessitating an innovative approach to enhance the energy efficiency of WSN. The research presents a novel sink-initiated decentralized routing framework that enhances network lifespan and mitigates energy consumption by utilizing routing-centric parameters and fuzzy logic. The approach is based on an energy-conscious model that selects initiator nodes from 1-hop neighbors for multiple path formation, thereby damping redundancy in the network. To boost the quality-of-service, forward relay node is chosen amalgamating significant parameters including the total residual energy, radio link quality between the consecutive nodes, and distance to the sink. A fuzzy inference mechanism has been devised to discern the preeminent trajectory from a plethora of possible routes. The mechanism employs discerning descriptors such as End to End latency, link caliber, and progressive advancement towards the sink, to ascertain the path most appropriate for the task at hand. The proposed model called Energy Aware Data Centric Query Driven Receiver initiated (EADQR) routing protocol excels over the conventional methods like AOMDV, OLSR, ZRP and EEDR with increased network throughput, substantial energy utilization and improved rate of packet delivery across all iterations. EADQR outperforms OLSR by 94%, AOMDV by 93%, ZRP by 97%, and EEDR by 87% in terms of network lifetime.**

***Keywords*—non-hierarchical routing, internet of things, flat top routing, sink initiated routing**

I. INTRODUCTION

Wireless Sensor Networks have transpired into a cardinal technology in wireless communication, owing due to their extensive deployment and ubiquitous nature. A wireless sensor network is an assemblage of random spatially distributed resource-constrained intelligent sensing devices called nodes to communicate with other devices through wireless media [1]. The defining attributes of sensor nodes include low cost, computational power, small size, and transmission across short distances. The multivariate processing capabilities of SNs include monitoring real-time critical surroundings and processing and routing the information block to the sink either via single path or multiple paths [2]. The transmission of data packets amidst the SNs and the sink node requires energy to be dissipated. Often, the energy expended is more than the actual energy demand as there may be energy wastage due to various factors.

In hierarchical clustering models, sensor nodes are grouped into clusters [3]. Then, an appropriate cluster head is selected to propagate data to the sink and discover an inter-cluster path to communicate with other cluster heads. However, the constrained energy range of cluster heads can deplete during coordination and computation and the difficulty of recharging or replacing these cluster heads with alternate power sources may cause network partitioning and degrade the network's lifetime [4–6]. This issue is adequately discoursed by Non-hierarchical or decentralized routing since it has demonstrated competence to preserve energy and enhance the network's lifetime [7]. Decentralized approach for data forwarding and path selection precludes a single point of failure. Besides, it ensures precise and reliable routing decisions compared to the hierarchical routing approach [8]. Optimizing the network's lifetime is a paramount issue in WSNs. The duration for which the sensor network functions until the first node stops working can be referred to as the network lifetime. The applicability of fuzzy logic in wireless sensor networks arises from its capacity to endure erroneous and imprecise sensor readings. Fuzzy logic's resemblance to human cognitive processes is striking in comparison to crisp logic and this surpasses other probability theory-based classification algorithms by its inherent simplicity and ease of use. While there have been several studies utilizing fuzzy logic to improve cluster head election, the use of fuzzy logic for flat top routing has so far not received enough attention. Additionally, because clustering approach is centralized, it

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is not appropriate for widely dispersed WSNs. A hierarchical network topology may not be deemed fit for IoT-enabled smart environment fueled by growth of 5G on account of the dynamic nature of IoT devices. Consequently, a non-hierarchical peer-to-peer communication network is being advocated which would facilitate the creation of a flexible topology reliant on network information.

Proposed here is a QoS-aware soft computing-based sink-initiated routing protocol that improvises energy usage, increases throughput, and enhances network lifetime. To optimize the transmission of the routing protocol, the minimum node degree is derived by considering the one-hop neighbors of the sink node to establish reliable and efficient multiple communication paths between sink node and the source. The protocol utilizes routing centric parameters to make intelligent and informed decisions about the accurate relay node selection. The optimal path is determined based on collaborative consensus utilizing a fuzzy inference system. The proposed multi-path routing vastly enhances the network function by offering load-balancing capacities. In addition, this routing communicates information concurrently by lowering latency and traffic in the network. Simulations are conducted to authenticate the efficacy of the suggested routing protocol vis-à-vis the routing metrics pertinent to sensing environments.

The paper is structured as follows: The related work is briefly reviewed in Section II. Section III illustrates the proposed routing model. Section IV demonstrates the simulation model. Finally, Section V states the performance analysis followed by conclusion.

II. Literature Review

The network must comprise a wireless communication architecture to establish a WSN in an environment devoid of infrastructure. Nevertheless, most wireless communication protocols with moderate or high data throughputs do not prioritize energy efficiency. IEEE 802.15.4, a standard communication architecture for WSN nodes that defines the MAC and physical layers, was then proposed for low-power, single-hop wireless communication [9]. However, this standard does not sufficiently address essential criteria for IoT applications, including minimal latency, greater trustworthiness, and resilience. ZigBee, on the contrary, is a high-level framework based on IEEE 802.15.4 that includes features and functions like peer-to-peer multi-hop communication, security measures, and an application framework [10, 11]. However, the added Zigbee characteristics cause a substantial rise in routing overhead resulting in higher latency and increased network resource consumption.

Since energy plays a crucial role, forwarding techniques in WSNs use cluster-based algorithms to reduce and balance energy LEACH is a notable clustering protocol proposed for WSN applications [12, 13]. In this protocol, each cluster head transmits its aggregated information to the sink. However, the positioning and degree of CHs during the node clustering phase are not guaranteed by LEACH, as there could be irregular node distribution. In addition, LEACH's one-hop connection between CHs and sink nodes renders it unsuitable for large-scale networks where only a few can communicate directly with the sink node. To address this issue, the author of [14] provided an entropy-based clustering approach that utilizes information, including distance to the sink and sensor node residual energy and density to form clusters and cluster head selection.

The key idea behind clustering protocol using fuzzy logic is to build smaller clusters close to the sink. Unfortunately, a significant distance to the sink node affects the smaller sets. Also, CH in multi-hop communication is characterized by excessive data collection, which might lead to an energy hot spot. Therefore, an unequal energy-aware multi-path hierarchical algorithm [15] was proposed, which provides load balance to the relay nodes in the cluster to avoid energy-hole problems using fuzzy logic inference. The importance of IoT in WSN was demonstrated in [16]. Considering that IoT devices are dynamic, this scenario does not execute well in an environment where IoT is supported.

The energy required to communicate in IoT-based sensing devices presents a significant barrier to minimizing packet loss and rapid energy depletion across the network, reducing node performance and lengthening packet delivery time [17, 18]. WSNs often generate time-sensitive data, it's vital to avoid data collection methods that could potentially result in data loss. Moreover, transmitting data from other nodes to the base station poses significant challenges. The nodes geographically close to the destination node lose their power more quickly, lowering the overall service quality. Controlling node energy consumption is essential for enhancing network performance. Cluster Formation Protocol [19] was presented employing Fuzzy Logic to enhance performance by leveraging deep learning techniques, utilizing a convolution-based neural network to estimate energy for efficient routing.

Although clustering can provide better network scalability, cluster head replacement owing to energy depletion of the cluster heads can impose a substantial signaling load on the network. To overcome these issues, distributed peer-to-peer protocols of routing are developed for homogenous sensor networks having nodes with identical data processing and transmission capabilities and equivalent packet transmission roles.

DSR is a prototypical example of a distributed routing protocol that uses the lesser hop to determine the path without considering other parameters that significantly impact the performance of the routing algorithm, such as energy usage and the energy available with nodes in the network. To boost throughput and packet delivery ratio while concurrently mitigating transmission delay, a potent hybrid routing [19] mechanism is deployed, leveraging the minimum execution time and moth flame optimization technique.

In the Directed Diffusion (DD) routing protocol, sensor nodes have unbalanced energy and transmitted sensing data in plaintext leading to a lack of privacy and security

[20]. Consequently, a Secure Directed Diffusion protocol to route data is proposed to enhance Energy Trust Model networks. The protocol picks highly reliable relay nodes to construct a dedicated link and transmit sensed information in WSN.

The receiver-initiated handshake in parallel reservation requires only one receiver to transmit an ACK packet to apprise the other initiators of successful packet delivery. On the contrary, in sender-initiated protocols, due to the one-to-many technique, each receiver in a parallel reservation is required to respond with an ACK message resulting in increased energy consumption. In [21], an energy-efficient Receiver initiation Access Control (MAC) protocol was proposed based on adaptive Multi-Priority Backoff which considers event priority, residual energy, and the number of data packet.

The duration of network operation until the first node exhausts its energy and becomes inoperative is commonly referred to as network lifetime. Higher the Network Lifetime ratio, the better the algorithm's performance in the network. Different unique definitions for the Network Lifetime ratio exist in the literature. The Network Lifetime ratio also accounts for satisfactory value of SNR for a period T under QOS constraint [22]. At least a single SN can perform the detection operation over a while [23]. The time duration before the SN will lose its energy altogether [24] and the time duration until the packet delivery ratio reduces its value by a certain threshold [25].

It can be deduced from the literature review that energy conservation has always been a critical component of WSN efficiency. Conventional routing methods typically prioritize the selection of forward nodes based on propagation distance and energy consumption along the path. However, this approach tends to favor fewer long hops over multiple short hops over high-bandwidth radio links. Moreover, the algorithms often overlook residual energy, leading to certain nodes running out of energy prematurely, which negatively impacts energy distribution and network reliability. Furthermore, such methods can be computationally intensive and require significant communication overhead, which can prove to be a significant burden in practical applications. As a result, it is irrational to make routing decisions based on a single piece of routing information, and it is also required to consider the network's multiple features holistically.

Consequently, an energy-efficient and reliable routing algorithm was proposed using fuzzy logic to maximize energy efficiency, network longevity and data transmission reliability [26]. The algorithm uses multiple parameters such as radio link quality, hop count etc. relative to the receiver node and end-to-end delay to optimize the route and prolong the network lifetime.

III. Proposed Energy Aware Routing Method

In this work, the Energy aware data centric query driven receiver initiated routing protocol is proposed for WSNs to optimize the load balancing across sensor nodes and energy consumption throughout network. Fig. 1 summarizes the optimal route selection in EADQR.

- First, an energy-conscious model is employed to whittle down the list of potential initiator nodes from the neighbour list N_L of sink node for path formation to avoid a high degree of redundancy.
- The selection of candidate nodes for forward relay to create multiple routes between sink and source relies upon each sensor's residual energy, link quality indicator and forward headway towards the sink to distribute the traffic load and subsequently meliorate network lifetime.
- A fuzzy logic-assisted energy-efficient data dissemination protocol is conceived based on routing-centric parameters to determine the optimal path among the multiple routes for transmission.

A. Network and Energy Model

The network model consists of N Sensors with symmetric radio links placed randomly in the network field with unique dimensional pairs. The node density is sufficient to provide network connectivity and deliver information to one of its surrounding sensors. The network model is described in Algorithm 1.

B. Network Assumptions

- A homogeneous network is considered in which all nodes have identical processing power, sensing area, and other attributes.
- At the time of deployment, all nodes possess the same energy level. Nodes remain static following their deployment in the region of interest.
- Each sensor node consumes distinct amounts of energy, resulting in network energy heterogeneity.

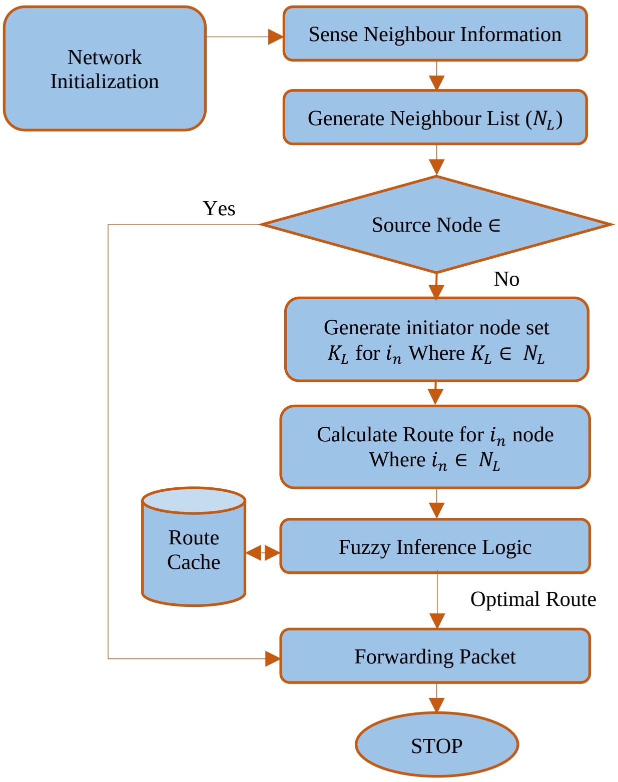

Figure 1. Flow diagram of EADQR routing protocol.

If the sensing node forms a path between two nodes involved in path formation, it will lose its energy level [27, 28] and the energy loss on the link between node A to node B is defined as in Eq. (1).

$$E_{L(A,B)} = 2 \times E_{tr} + E_p \; ld_{(\mathrm{A,B})}{}^{attf} \tag{1}$$

$$E_{tr} = E_{tx} + E_{rx} \tag{2}$$

The energy consumed during transmission and reception of K bits is analyzed using first order radio model defined as in Eqs. (3) –(4).

$$E_{tx} = \begin{cases} k\left(E_{elec} + \varepsilon_{fs}.d^2\right), d < d_0 \\ k\left(E_{elec} + \varepsilon_{mp}.d^4\right), d \geq d_0 \end{cases} \tag{3}$$

$$E_{rx} = n.E_{elec} \tag{4}$$

where, $E_{L(A, B)}$ is the energy loss on the link between SN-A and SN-B, E_{tr} is the energy required between SN-A and SN-B for the transmission and reception of data. E_p is the energy for packet creation at SN-A, $ld_{(\mathrm{A,B})}$ is the link distance between SN-A and SN-B. $attf$ is the attenuation factor from a minimum of 0.1 to a maximum of 1.E_{tx} and E_{rx} denote energy depletion for transmission and reception on k bits respectively, E_{elec} is the energy required to power electronic circuit, ε_{fs} and ε_{mp} represent free space path loss and multipath propagation loss to transmit k bits respectively.

The residual energy of the node involved in transmission can be defined as the difference between the residual energy of the node in the previous period of transmission and the energy consumed during the current transmission as in Eq. (5).

$$UE_{node} = PE_{node} - E_{L(A,B)} \tag{5}$$

where, UE_{node} is the updated energy, PE_{node} is the previous node energy.

Algorithm 1 Wireless sensor network Initialization

Input:N_{nodes} ,Hd_{min} ,Hd_{max} ,Vd_{min} ,Vd_{max}
Output: Sensing Network Trace Matrix (SNTM)
Process:

1. $a = 1$
2. $a = 1 \longrightarrow N_{nodes}$
3. Find the horizontal position Hd_{pos} for the Node randomly between Hd_{min} and Hd_{max}
4. $Hd_{pos} = Hd_i$
5. $if\ Hd_{min} \leq Hd_i \leq Hd_{max}$ & $Hd_i \neq Hd_k$
6. Find the vertical dimensional Vd_{pos} for the Node randomly between Vd_{min} and Vd_{max}
7. $Vd_{pos} = Vd_i$
8. $if\ Vd_{min} \leq Vd_j \leq Vd_{max}$ & $Vd_j \neq Vd_k$
9. Hd_i - horizontal position of Node
10. Vd_i - vertical position of Node
11. Form a triplet in the format (a, Hd_i ,Vd_j) ,
12. Save the a^{th} data of Matrix

Node ID	Positional Value
a	Hd_i ,Vd_j

13. $a = a + 1$
14. Repeat process to place N_{nodes}

C. Initiator Node Selection

The sensor node d_{ni} broadcasts a hello packet within a one-hop transmission radius b_{ri} in an N x N network area to generate a list of neighboring nodes N_L .The routing protocol limits the number of paths discovered with M/2 initiator nodes, where M is the length of the initiator subset and includes all the neighbor nodes within the node d_{ni} one hop transmission radius. The initiator node list IN_l is derived from N_L by eliminating dead nodes based on threshold value such that each node in $IN_l \subseteq N_l$. Each $SN_{sn} \in IN_l$ discovers transmission route and appends the route to d_{ni} node. The summary for initiator SN selection is described in Algorithm 2.

Algorithm 2 Initiator Node Selection

Input: initiator SN, transmission range, battery levels for SNs
Output: Set of SNs
Process:

1. Find the SNs which are within the transmission range
   $SG_1, SG_2, SG_3, \ldots, SG_{tr}$
   SNi – ith SN in the WSN
   tr < N where N is total SNs in the WSN
2. Find the battery level for SNs
   $bl_1, bl_2, \ldots, bl_{tr}$
3. Eliminate Dead SNs
   $SN_2, SN_4, SN_6, \ldots, SN_M$
   Where M is an integer which is less than TR
4. Sort the SNs based on battery level remaining in descending order
   $SN_4, SN_6, SN_M, \ldots, SN_2$
5. Pick the first M/2 SNs as the initiator SNs
   $SN_{s1}, SN_{s2}, SN_{s3}, \ldots, SN_{sn/2}$

D. Relay Node Selection

The path establishment process initiates with sink node. The initiator node selects relay node next in line from the 1-hop neighbor node list. If source node gets included in the neighbor node list, then the path to source node gets directly established. If not, then the initiator node selects next hope node from the neighbor nodes placed the search space of source node with highest value of F_{node}. Based on SN_i's residual energy and distance between forward node and destination node, the forward node FN_i is selected.

The F_{node} value defined in Eq. (7) mirrors the correctness and reliability of the node, where SN_a is any forward neighbor node of node SN_i, d_{ia} is the distance from node SN_i to SN_a, and TR is the transmission radius of node SN_i, where F_{node} is the selection factor for the relay node.

$$F_{Ni} = \{\, SN_a , d_{ia} \leq TR \,\} \tag{6}$$

$$F_{node}\,(SN_a , SN_b) = RE_b + CQI\,(SN_a , SN_b) + (1/d_{SN_a}, Sn\,) \tag{7}$$

$$RE_b = PE_b - E_{L(A,B)} \tag{8}$$

RE_b is the residual energy of the sensor node. $CQI\,(SN_a , SN_b)$ is the channel quality between SN_a and SN_b. The link quality indicator is calculated using the formula [29, 30].

$$LQI = \left|\frac{SNIR}{1.02} + 16.62\right| \tag{9}$$

The measured signal for SNR is given by Eq. (10).

$$SNIR = \frac{\rho}{N_O \; S_B \; N_F} \times P_G \quad (10)$$

where, $-16 < \text{SNIR} < 14$, LQI= Link Quality Indicator, SNIR=Signal to Noise Ratio.

$$\rho = \frac{T_p}{P_l} \quad (11)$$

where T_p is Transmission Power, P_l is Path Loss, S_B is Signal BW, N_F is Noise Figure, N_O = $1.38\times10^{-3} \times 290$.

E. Multiple Path Discoveries

The proposed algorithm works in two phases the selection of initiator nodes for route initiation from one-hop neighbors and determining the multiple routing paths from the set of initiator nodes. Following the neighbor discovery phase, every node knows its neighbor nodes. The sink is assumed to know the source node's location and that the sink initiates route request based on the source's location using initiator nodes. Following the route discovery phase, the routes discovered by initiator nodes are added to the sink. The sink node selects the optimal path from the multiple candidates using fuzzy inference knowledge and requests data transmission from the source node. Multiple path formation is summarized in Algorithm 3.

Algorithm 3 Multiple Path Formation

Input: ISN, Initiator SNs, DSN, Distance Matrix, Transmission range
Output: Multiple Paths between ISN to DSN along with total Criteria
Process

1. Find the count of Initiator SNs i.e., K_L
2. a:1→N
3. Find the ath initiator i.e., a ∈ K_L
4. If DSN ∈ K_L initiate transmission.
5. If DSN ∉ K_L
6. Find the path between ath initiator SN to DSN
   a. Using Path Formation using EADQR
7. Append the ISN to the path
8. Execute the fuzzy logic to choose the optimal path
9. During fuzzy implementation each route is assigned a rating based on fuzzy if-then rules present in knowledge base.
10. Defuzzification is done using centroid function for optimal route selection.

F. Fuzzy Inference System

Fuzzy logic is used in perceptual reasoning to determine the energy-efficient optimal routing path based on the fuzzy input parameters maximizing the network [31, 32]. The fuzzy Inference model is described in Fig. 2.

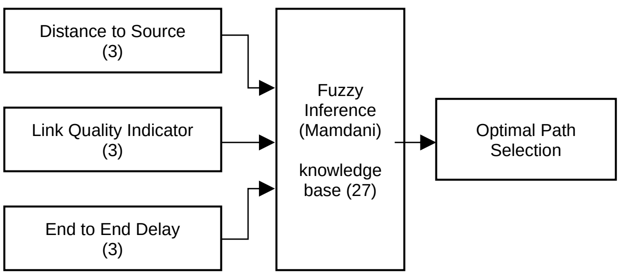

Figure 2. Fuzzy logic model.

The linguistic variable for input is classified into three levels is based on boundary conditions defined from Eq. (8) to Eq. (13). The input fuzzy variables are Distance to sink, Link quality indicator and End-to-End delay. The optimal output is selected based on If-then rules included in fuzzy knowledge base.

$$BC_1 = 1 \quad (12)$$

$$BC_2 = (LN_r/3) \quad (13)$$

$$BC_3 = (LN_r/3) + 1 \quad (14)$$

$$BC_4 = (LN_r/2) \quad (15)$$

$$BC_5 = (LN_r/2) + 1 \quad (16)$$

$$BC_6 = (LN_r) \quad (17)$$

where LN_r is the number of routes discovered between sink and source. For fuzzy input Distance to source and End-to-End delay, the LN_r is sorted is ascending order, for Link Quality Indicator, the LN_r is sorted in descending order, once sorted they are labelled based on boundary condition. To model the normal distributed variables gaussian function is used to generate the membership function using Eq. (18).

$$f(x;\sigma,c) = exp\left[-\left(\frac{x-c_k}{2\sigma_k}\right)^2\right] \quad (18)$$

σ_k and c_k control the shape and slope of the membership function for different k value. The Distance for each route is labelled as Near, Medium, and Far as shown in Fig. 3 based on the boundary conditions. The sorted length is labelled as Near if the distance of the k^{th} route d_k lies between $BC_1 \leq d_k \leq BC_2$. The sorted length is labelled as Medium if the distance of the k^{th} route d_k lies between $BC_3 \leq d_k \leq BC_4$. The sorted length is labelled as Far if the distance of the k^{th} route d_k lies between $BC_5 \leq d_k \leq BC_6$.

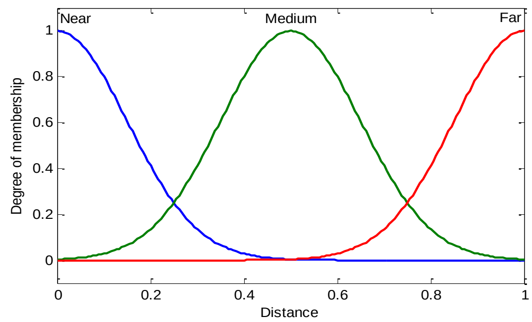

Figure 3. Fuzzy membership function of total distance.

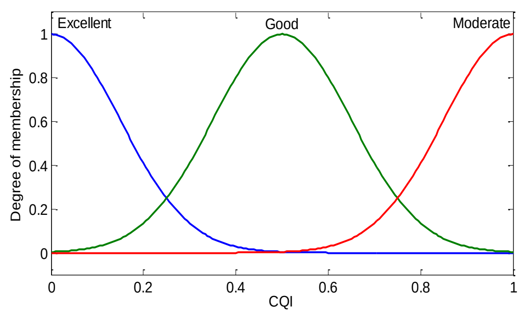

Figure 4. Fuzzy membership function of link quality indicator.

The Link Quality Indicator for each route is labelled as Excellent, Good, and Moderate as shown in Fig. 4 based on the boundary conditions. If the LQI value of the k^{th} route lies between $BC_1 \leq LQI_k \leq BC_2$ then LQI_k is labelled as Excellent.

If the LQI value of the k^{th} route lies between $BC_3 \leq LQI \leq BC_4$ then LQI_k is labelled as Good. If the LQI of the k^{th} route lies between $BC_5 \leq LQI_k \leq BC_6$ then LQI_k is labelled as Moderate.

The End-to-End delay for each route is labelled as Less, Medium, and High as shown in Fig. 5 based on the boundary conditions. If the end-to-end delay of the k^{th} route lies between $BC_1 \leq T_k \leq BC_2$ then T_k is labelled as Less. If the value lies between $BC_3 \leq T_k \leq BC_4$, then T_k is labelled as Medium. If the value lies between $BC_5 \leq T_k \leq BC_6$, then T_k is labelled as High.

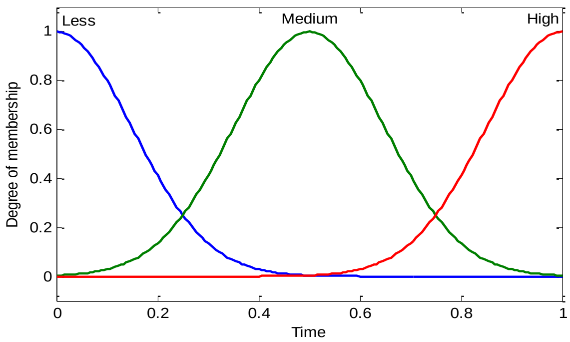

Figure 5. Fuzzy membership function of end-to-end delay.

Fig. 6 shows the fuzzy output variable representing the chance factor for the optimal path classified as optimal, suboptimal, and below optimal.

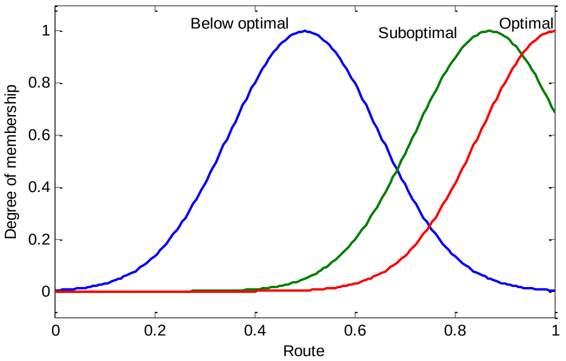

Figure 6. Fuzzy Membership function of output variable.

The fuzzy inference system is based on the Mamdani method [33]. The knowledge base of the fuzzy system consists of 27 rules. Some of these rules are shown in Table I.

TABLE I. FUZZY IF-THEN RULES

Input Parameters			Output
Distance to Source	**End-to-End Delay**	**Link Quality Indicator**	**Chance Factor**
Near	Less	Good	2
Medium	Medium	Moderate	12
Far	Medium	Excellent	16
Near	High	Good	19
Medium	High	Moderate	24
……..	…….	…….	…….

If the distance is near, the delay is Less, and LQI is average, then the chance factor of it being selected as the optimal path is 2. If the distance is Far, the delay is medium, and LQI is excellent, then the chance factor is 16. Finally, if distance is near, the delay is high and the LQI is average the chance that the corresponding route will be selected as the optimal route is 19.

The defuzzification constructs the chance of a route to be an optimal path using the centroid method computed [34] using Eq. (19).

$$\text{x Centroid} = \frac{\sum_i \mu(x_i) x_i}{\sum_i (x_i)} \quad (19)$$

where $(\mu(x)_i$ is the membership value for a point x_i in the universe of discourse.

IV. Result and Discussion

The simulation was carried out in a 100×100 m^2 area with 100 sensor nodes randomly placed with unique dimensional pairs. Other simulation parameters are given in Table II.

TABLE II. INPUT PARAMETERS

Parameter Name	Parameter Value
Transmission Range	45 m
Source Node	32
Sink Node	44
Transmission Energy	20 mJ
Amplification Energy	10 mJ
Attenuation Factor	0.8
Initial Energy	5000J
Area	100×100 m
Data Packet Size	1000Kb

Fig. 7 portrays the node placement in WSN Network. The sensor nodes are placed randomly for maximum coverage in the defined area. Each SN has its dimensional pair and a unique id. The source, as well as the sink, are within the network area.

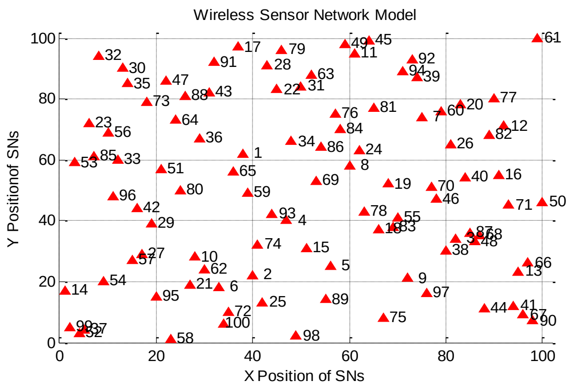

Figure 7. WSN network formation.

Fig. 8 illustrates the path length traversed by multiple routes between sink and source. The total number of routes is proportional to length of initiator node set derived from 1-hop neighbor set.

Fig. 9 shows the total time required(ms) for the sink node to discover route between the sink and the source. It is given by $t_a - t_s$ where t_s is the time the sink generates the route req packet to initiate route discovery, t_a is the time the sink node gets route acknowledge packet from the source node.

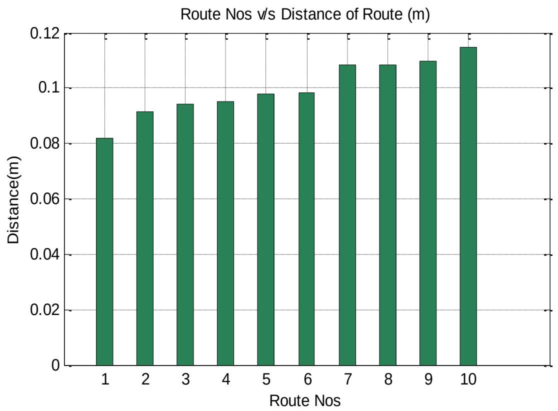

Figure 8. Routes vs total distance.

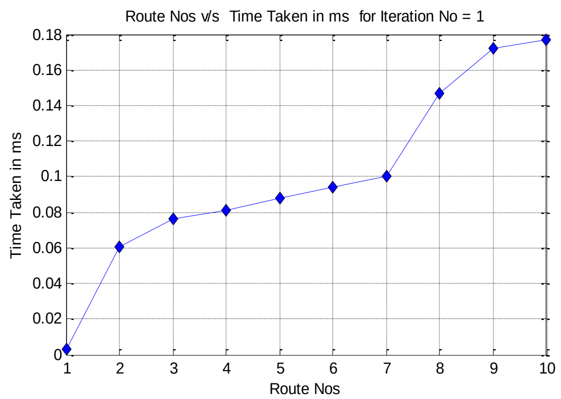

Figure 9. Route vs end-to-end delay.

Fig. 10 shows the link quality indicator of the multiple routes between the sink and the source.

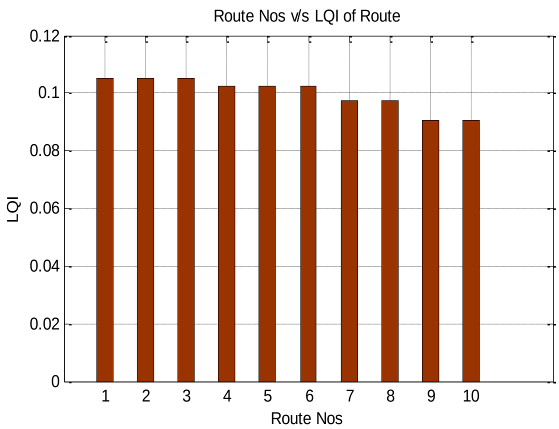

Figure 10. Route v/s link quality indicator.

Fig. 11 shows the nodes involved in route no 3. Route indexed 3 is selected as the best path among the 10 routes discovered between sink node source node. The traversed path to create a transmission link between node 44 and node 32 is 44 → 46 → 74→ 56→ 32.

Table III shows the routes labelled into the optimal, sub-optimal, below optimal route based on fuzzy if-then rules, and the centroid function is used to select the best path among the marked optimal paths.

TABLE III. ROUTE TABLE

Route Index Number	Fuzzy Label	Chance
1	Optimal route	1
2	Optimal route	2
3	Optimal route	3
4	Sub-optimal route	12
5	Sub-optimal route	10
6	Below optimal route	21
7	Below optimal route	24
8	Below optimal route	20
9	Below optimal route	21
10	Below optimal route	26

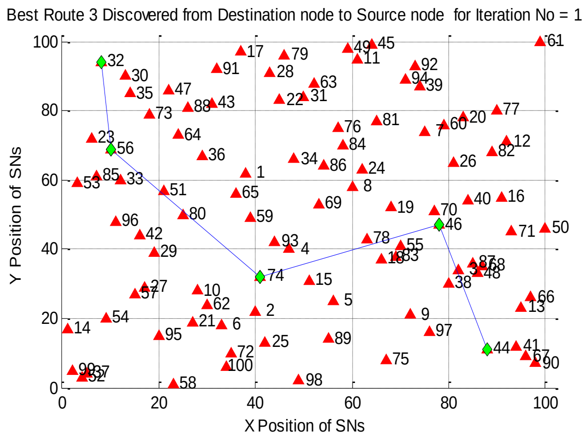

Figure 11. Optimal route.

A. Performance Analysis

This section evaluates the distinction of the proposed EAQDR routing protocol by conducting MATLAB simulation. The proposed algorithm is compared to AOMDV, OLSR, ZRP, and EEDR [35–37] algorithms for various performance metrics to assess routing protocol adaptability and reliability.

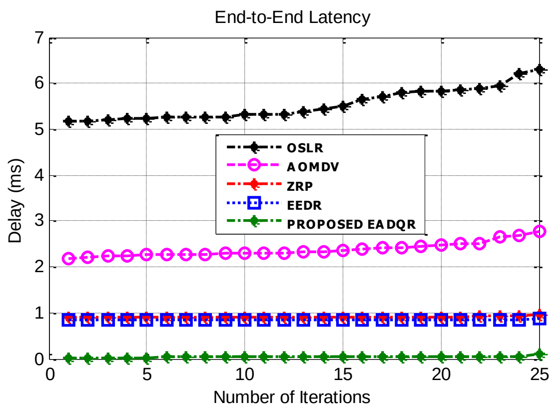

Figure 12. Delay comparison.

Fig. 12 shows the end-to-end delay. It is calculated as the average amount of time between generating the first data packet from the source and the reception of the last packet at the sink. The data is transmitted using a single path by EADQR. When the path fails, fuzzy inference logic discovers an alternate route. EADQR protocol exhibits lower delay than EEDR, AOMDV, ZRP, and OLSR. The end-to-end latency increases as the iterations increases. At the end of iterations, the delay of the EADQR method is below 0.2ms, whereas that of EEDR is around 0.65 ms ZRP is about 0.83 ms, AOMDV is about 1.5 ms, and OLSR is having highest delay, close to 4.9 ms.

Fig. 13 illustrates the total energy consumed by control and data packet transmission and reception. We can notice that the total energy consumption of EADQR is the least, followed by EEDR and ZRP. The proposed approach has less routing overhead, reducing the computational load and improving efficiency. In AOMDV and OLSR, the high routing overhead increases energy consumption. The total energy consumed by the EADQR, EEDR and ZRP never exceeds 1.65 kJ, whereas AOMDV is 1.6 kJ and OLSR has the highest energy consumption of 5 kJ.

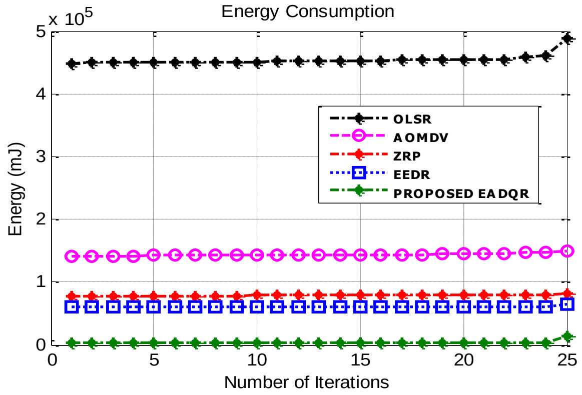

Figure 13. Total energy consumption comparison.

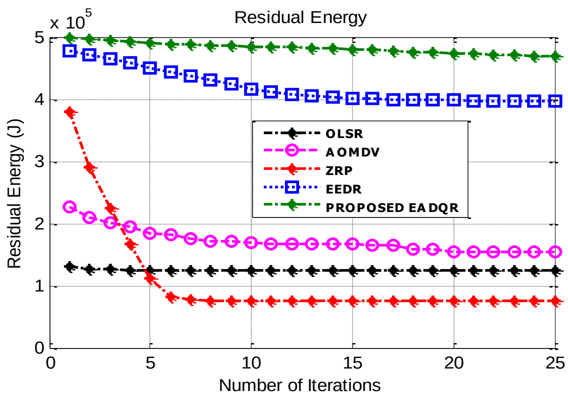

Figure 14. Average residual energy performance.

Fig. 14 shows the residual energy of nodes with uniform data packets. In AOMDV and OLSR, constant flooding to maintain the routing table renders many nodes with less residual energy than EAQDR and EEDR. In comparison to existing routing protocols, EADQR employs fewer intermediate nodes. As the iterations increase, the residual energy of nodes for all analyzed routing approaches decreases. The residual energy for the proposed method is about 485 kJ. EEDR is 397 kJ. Residual energy of ZRP experiences steady decline up to 6 iterations at the end of 25 iterations residual energy is about 80 kJ, AOMDV and OLSR is left with150 kJ and 125 kJ respectively at the end of 25 iterations.

Fig. 15 illustrates the network's lifetime; it is the time from network inception to the failure of the first node. The lifetime is directly impacted by the control packets meant for route discovery. The EADQR routing protocol has a high network lifetime followed by EEDR and ZRP. The network's lifetime of AOMDV and OLSR is similar due to the high routing overhead. As iterations increase, the network lifetime of the proposed EADQR arguably remain higher than that of AOMDV, OLSR, ZRP and EEDR.

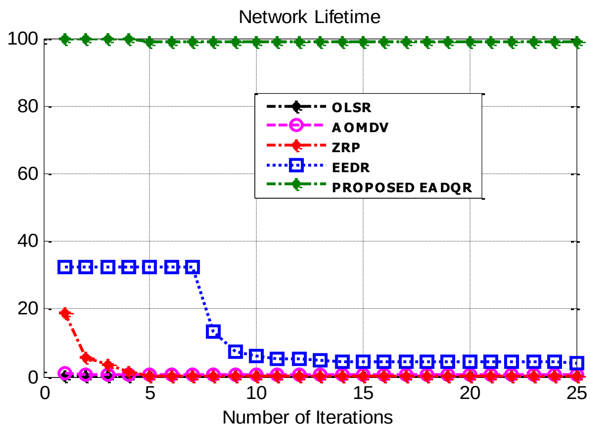

Figure 15. Network lifetime ratio.

Fig. 16 shows throughput performance as a function of the number of iterations. Throughput is a crucial metric in gauging the effectiveness of the protocol. Initial iterations show higher throughput performance. As the iterations increase, throughput decreases. While AOMDV, OLSR, ZRP and EEDR offer steady throughput across the iterations, AOMDV and OLSR experience high traffic rate. And the nodes mostly remain active for the most network operation. Relay node in ZRP is chosen without considering QoS. The proposed EADQR approach has the highest throughput, followed by EEDR, ZRP, AOMDV and OLSR.

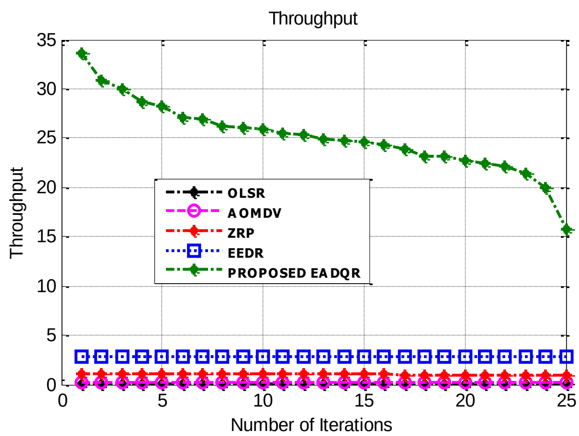

Figure 16. Throughput performance.

Fig. 17 shows that EADQR has the highest packet delivered ratio because the node-link established based on the link quality indicator has a lower probability of link break. However, since link failure and packet congestion become more prevalent as network size increases, the packet loss percentage rises. Therefore, the packet delivery ratio for EADQR routing schemes decrease as the iteration increases. At the end of 25 rounds, the PDR of proposed EADQR is around 98%, EEDR is about 94%, ZRP is about 84%, AOMDV is about 78%, and the least is OLSR which is around 68%.

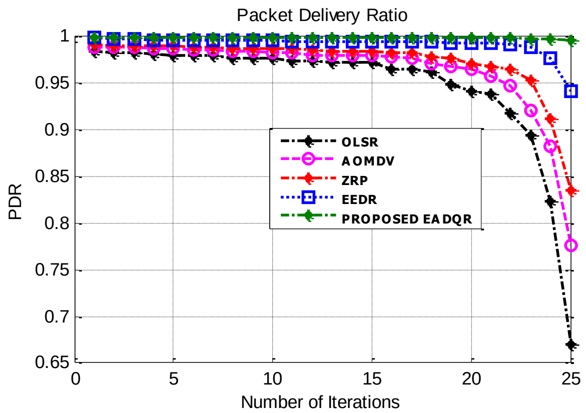

Figure 17. Packet delivery ratio performance.

TABLE IV. NUMERICAL ANALYSIS OF SIMULATED PARAMETERS

Parameters	**Protocols**				
	OLSR	AOMDV	ZRP	EEDR	Proposed EADQR
Time in ms	113.49	35.89	19.66	15.04	0.7978
Energy Consumed (mJ)	9.5×10^7	2.7×10^7	0.26×10^7	0.04×10^7	0.01×10^7
Network Lifetime	0.3044	0.3675	0.1205	0.7629	5.8902
Throughput	0.2203	0.6966	1.2715	3.6619	37.705
Residual Energy (mJ)	1.25×10^5	1.71×10^5	1.07×10^5	4.19×10^5	4.82×10^5
PDR	0.9468	0.9660	0.9749	0.9920	0.9986

The percentage improvement of the proposed EADQR routing protocol compared over the existing routing protocol is tabulated in Table IV.

V. CONCLUSION

The research proposes a fuzzy logic-based energy-efficient receiver-initiated routing protocol for Non-hierarchical wireless sensor networks to maximise the network lifetime. While most of existing research focuses on energy factor for efficient routing, the proposed EADQR selects the forward relay node from 1-hop neighbours based on routing metrics such as residual energy, distance to the sink and link quality indicator for improved QoS. EADQR utilises multiple hops for efficient routing. The optimal path is selected based on fuzzy logic.

The simulation results show that the proposed EADQR routing protocol exhibits better performance for QoS-required implementations with higher network lifetime expectancy, increased throughput and improved packet delivery ratio while minimizing latency. When compared to proactive and reactive routing protocols, EADQR performs noticeably better, improving by 54% against OLSR and 48% against AOMDV respectively. EADQR exhibits a 32% improvement over the receiver initiated EEDR routing protocol. When compared with Zone routing protocol EADQR exhibits 39% improvement in routing performance.

EADQR's energy efficiency outperforms OLSR by 78%, AOMDV by 72%, ZRP by 43%, and EEDR by 35%, positioning it as a promising protocol for extending the network lifetime while minimizing energy consumption.

Compared to OLSR, AOMDV, ZRP, and EEDR, EADQR exhibits a reduction in latency by 98%, 97%, 95%, and 94%, respectively, highlighting its potential for facilitating real-time communication and supporting latency-critical applications.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

This research work was carried out by Mohamed Najmus Saqhib under the guidance of Dr. Lakshmikanth S, and all authors have approved the final version.

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