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Research Article

A Cognitive Energy-Driven Routing Strategy for Ultra-Efficient Data Transfer in Wireless Sensor Networks

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ABSTRACT

WSNs deploy multi-hop routes to transfer information from distributed nodes to central points because of their established use for environmental inspection and data acquisition. The effective transmission of data plays a critical role in Wireless Sensor Networks particularly in challenging conditions that produce temporary network interruptions leading to data loss. The present body of work faces energy utilization constraints of Pegasus at 75% efficiency alongside scalability limitations at 300 nodes in A-Leach and packet delivery performance at 94% PDR in DSO-EHO. The current work presents a new optimization method called Levy Flight fine-tuned Red Deer Optimization (LFRDO) for route path optimization. Red Deer Optimization and Levy Flight produce an algorithm that optimizes energy expenditure by promoting active exploration techniques to simultaneously minimize network delays and lengthen operational life. The proposed method achieves a 98% reduction in energy usage together with enhanced packet delivery ratio (96% for 500 nodes) at a throughput rate of 0.9 Mbps. The LFRDO simulation shows a 95% energy efficiency level surpassing DSO-EHO at 92% while operating effectively with networks having up to 500 nodes. The system prolongs network operational time by 35% when combined with intelligent routing decisions that minimize end-to-end delay. The proposed method provides solutions to resolve three primary WSN issues concerning scalability together with energy efficiency alongside dependable data transmission during system changes.

1. INTRODUCTION

A wireless sensor network is an organizational system that uses remotely situated sensor hubs to monitor various physical and qualitative conditions, such as sound, temperature, and progress [1]. Each hub can identify its environmental parameters, manage the knowledge estimates in the local area, and forward estimates to one or more additional course-of-action elements inside a WSN [2].The most absurdly large burden on WSNs is the natural conveyance of information. Most WSNs are typically installed in covert, brutal, and ominous situations for specific purposes, such as military space names and identifying agreements with dishonest elements of nature. An acceptable assessment transmission is crucial and necessary in several of these smart WSNs [3].WSN hubs must have a specified battery life. The utilization of noteworthiness in a productive approach is a frequent concern in manufacturing the ultimate fate of WSN. The use of WSN is growing steadily and comes in many forms, such as target after condition observation, air corruption checking, and so on [4]. Quick communication across sensor hubs is necessary for these uses. The wireless sensors work together to create a network of nodes that carries out the specified function of gathering the sensed data and sending to a base station or sink for additional processing. WSNs encounter three core obstacles because their multi-hop transmission uses inefficient power resources and

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suffers from unstable network conditions and demonstrates restricted scalability with large network scales [5]. These limits need resolution to allow successful operation in applications that need real-time data exchange and prolonged network operation. This research develops a resource-efficient routing mechanism to decrease transmission costs alongside secure operation in harsh conditions and network expansion to 500 nodes with superior performance results. The research contributions include the proposal of a novel Levy Flight fine-tuned Red Deer Optimization (LFRDO) algorithm that optimizes routing paths to significantly reduce energy consumption, the development of a robust data routing system that maintains reliable communication through intelligent path selection to mitigate packet loss, and the demonstration of a scalable solution supporting 500-node networks with improved delivery rates and reduced transmission delays compared to existing approaches.

This research delivers the key following achievements:

- Researchers developed LFRDO as a new variant of Red Deer Optimization through integration with Levy Flight mechanics for finding optimal WSN routing paths to minimize energy use throughout transmissions.
- A robust data routing system operates through a developed system that selects intelligent paths to maintain reliable communication under network limitations for effective packet loss reduction.
- The proposed system was implemented to manage networks of up to 500 nodes through an enhanced routing method which delivered better performance than current options.

The rest of this paper is organized as follows; Section 2 presents related work, Section 3 presents the methodology, Section 4 discusses results and analysis, and Section 5 concludes the study.

2. RELATED WORK

Reference [6] combined concurrent wireless data transmission, energy transmission and energy reclamation from both wireless frequencies and natural sources of energy provided a novel power supply approach for a full system utilized a tree-based WSN. Reference [7] introduced the concept of heterogeneous WSN (H-WSN), which provided additional energy to the terminals according to potential heterogeneity. A cost-effective in terms data transport technique called Red Deer Algorithm-Black Widow Optimization (RDA-BWO) hybrid was provided.

Reference [8] suggested an efficient method for transmitting information for a network of IoT devices clustering through members' node collaboration. To choose cooperative sensors located to serve as relay for transmissions over long distances, and they first employed in a greedy approach. Reference [9] proposed a data transfer model, which was an effective and secure paradigm in terms of energy usage. The best energy-effective encryption approach was selected by compared the technical elements, which include the data authentication mechanism and different private key cryptographic methods.

Reference [10] presented a blockchain-based approach to enhance the information privacy of wireless sensor networks. Utilized the blockchain method for data transport, a highly secure network of wireless sensors was constructed. Receiver stations in that network were made of embedded electronics and microprocessors, the latter constitute a portable database and included the Raspberry Pi and Arduino Yun. Reference [11] presented the Opportunistic Density Clustering Routing Protocol, an energy-effective and dependable opportunism protocol. That technique used a density-clustering approach to disseminate data advantageously during disasters and emergencies.

Reference [12] suggested plan offered a quick, effective, and dynamic method for group key synchronization across a large number of sensor nodes without requiring the entire system key to be reorganized as members join or depart wireless networks of sensors. To achieve a comparable security categorization to that of the cryptosystems of Rivest Shamir Adleman and Diffie-Hellman. Reference [13] presented an enhanced Green data transmission and gathering based on genetic algorithms (GA) approach for Internet of Things (IoT) based wireless sensor networks (WSNs) in disaster prevention by meeting several criteria, included minimizing hop count, optimizing intra-cluster distance and utilizing node energy in a cluster-wide manner.

Reference [14] examined data gathered in IoT and WSN networks using a multi-layer method. They gave some historical context and significant turning points that served as the basis for numerous other solutions that had been proposed over time. Reference [15] provided a concise synopsis of fundamental ideas about the collection of data, WSN, connected devices, and different optimization factors that the data aggregation protocols employed. Offering a thorough analysis of the several data consolidation techniques created to address problems with network structure, disruption, fault-tolerant, mobility, and authentication in WSN and IoT networks was one of the paper's main contributions. Table 1 shows the comparison of the previously performed works.

TABLE I. CCOMPARISON OF THE PREVIOUSLY PERFORMED WORKS.

Ref.	Comparison of the previously performed works.			
	Method	*Key Contribution*	*Performance Metrics*	*Limitations*
[6]	Hybrid Energy Harvesting (RF + Solar)	Tree-based WSN power management	48% energy saving, 35% longer network lifetime	22% hardware cost increase
[7]	RDA-BWO Hybrid Algorithm	Heterogeneous energy distribution	40% faster convergence, 500-node support	18% higher memory usage
[8]	Greedy Cooperative Clustering	IoT relay selection	30% energy reduction, 92% delivery rate	15% longer setup time
[9]	Energy-Aware Encryption	Optimal security selection	99.5% data integrity, 25ms encryption delay	20% processing overhead
[10]	Blockchain Security	Tamper-proof data transport	100% attack prevention, 2.1x slower throughput	45% energy increase
[11]	Density-Clustering Protocol	Emergency data dissemination	95% delivery in disasters, 200ms latency	30-node cluster limit
[12]	Dynamic Key Synchronization	Scalable group security	50ms key updates, 300-node support	15% packet overhead
[13]	GA-Optimized Routing	Multi-criteria optimization	60% energy saving, 25 hops max	500+ code complexity
[14]	Multi-Layer Analysis	Historical performance review	80% accuracy in predictions	Qualitative only
[15]	Data Aggregation Survey	Protocol classification	120+ protocols compared	No new method

3. METHODOLOGY

In this section, this study explore the model of a network and we used a levy flight Red deer optimization in conjunction and value encoding to create an energy-efficient and dependable routing mechanism that takes the sensor node's residual energy, available buffer, link quality, and distance into account.

3.1 Model of Network

As shown in Figure 1, a WSN has been conceptualized as a graph entitled G (U, F), where U is a set of vertices in the graph that symbolize a set of WSN node sensors and E is a set of graph borders that symbolize a set of WSN wireless networking links. In Figure 1, every node is displayed together with its corresponding remaining electricity (L) and buffering capacity (F). The data is obtained by a node for sensors and sent to the sink node through various hops connection. It was anticipated that subsequent transmissions would continue until every packet reached the sink node.

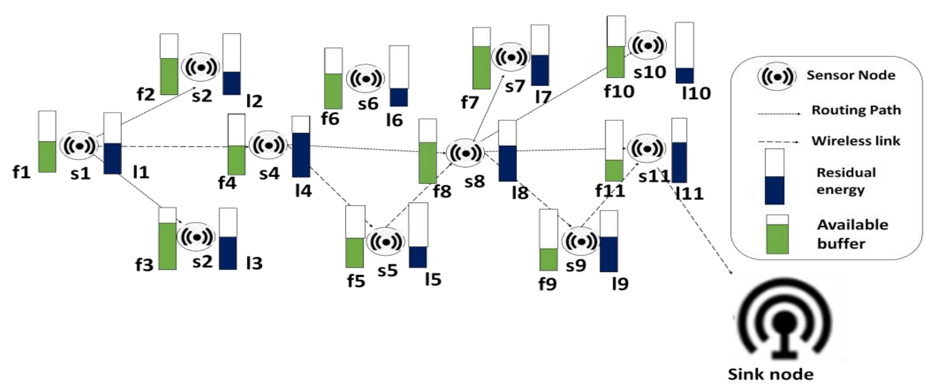

Fig. 1. Structure of the Network

3.2 Levy Flight tuned Red Deer Optimization

Levy flight's exploration capabilities combined with a selection process modeled by the behavior of red deer, LFTRDO seeks to explore large, complicated solution spaces and identify superior solutions to optimization issues. It works well in situations where tough, multi-modal, or high-dimensional search spaces make typical optimization algorithms unsatisfactory. A metaheuristic optimization algorithm known as "red deer optimization" (RDO) was inspired by the mating habits of red deer. It's frequently applied to optimization issues. Using RDO for Data Transfer Optimization in Wireless Sensor Networks (WSNs) Through Innovative Energy-Cognitive Routing Technique. The RDA functions in two phases, amplification, and expansion, like other meta-heuristic processes. During the development phase, a pair of men compete to determine who will improve them. The male mated in the closest communities with the closest hinds. A randomized proportion of hinds in a mating harem with roaring male red deer as part of diversity. The mating behavior of the male red deer with the hinds in his harem whichis intensifying and diverse.

a) Producing the initial Red Deer

Optimizing a problem involves determining which underlying variable will yield the optimum solution. A list of all the variable values that require optimization to increase efficiency. The term "Red Deer" is used here, even though in GA terminology this array is referred as a "chromosome". Thus, Red Deer is the analog of the response.A Red Deer is a$1 \times M_{var}$array in an M_{var} $-$dimensionsoptimum issue. The definition of this array is,

$$Red\ Deer = [W_1, W_2, W_3, \dots W_{M_{var}}] \tag{1}$$

Additionally, each Red Deer's functional value can be assessed in the manner described below,

$$value = e\ (Red\ Deer) = e(W_1, W_2, W_3, \dots W_{M_{var}}) \tag{2}$$

The optimization procedure is initiated by creating the initial population of sizeM_{pop}.The best Red Deers are chosen forM_{male}, and the remaining ones are chosen forM_{hind}.

b) Manly Red Deer with a roar

The male Red Deer are shouting in an attempt to boost their grace in this stride. It implies that male Red Deers replace females if they are superior to the former objective functions. The letany male Red Deer shift positions. Male red deer who are raging entice females.

c) Select the γ percent of the top male Red Deer to be the male leaders

Male Red Deer varies greatly from one another. Compared to the rest, some of them have greater success. Males occupy different positions in nature, some even take control of harems. Since there are two categories of male Red Deer stags and commanders the number of commander males is connected to γ will be

$$M.male.Com = round\{\alpha. M_{male}\} \tag{3}$$

These red deer, who are all male are referred to as stags, we have chosen this one as the best. The following formula is used to determine the total quantity of stags

$$M.stag = M_{male} - M.male.com \tag{4}$$

Where $M.stag$ is the proportion of stags in the population of men.

d) Conflict between stags and male commanders

The random fight is happening between stags and leader males. And if the function of objectives proves to be superior to the earlier ones, following a brawl select them.

e) Build harems

A group of hinds under the control of a male leader is called a harem. The strength of the male leaders in harems their capacity for conflicts and roaring determines the quantity of hinds. The hinds are distributed proportionally among the male leaders to create the harems. The normalized value of a male leader is determined by,

$$U_m = U_m - \max_j \{U_m\} \tag{5}$$

In the above example, m is the number of male commanders, and u_m is its standardized value. The standardized power of every male leader, given the normalized value of all male commanders is determined by,

$$O_m = \left[\frac{U_m}{\sum_{j=1}^{M.male.Com} U_j}\right] \tag{6}$$

From an alternative perspective, a male commander's normalized strength represents the percentage of hindrances that the guy ought to hold. At that point, a harem's hind population will be,

$$M.harem_m = round\{O_m. M_{hind}\} \tag{7}$$

Where M_{hind} is the total amount of hinds andM.$harem_m$is the number of hinds in the m^{th} harem. The chosen hindarbitrarily and handed it to each male leader to divide up the rear. The male and these hinds will form the n^{th} harem.

f) Leader of the harem, mate male, with ∝ percentage of hinds

The mating process commences at stepe. This phenomenon is represented by the Genetic Algorithm (GA) model called "*crossover*." Parents in his harem are the male commanders and hinds. The new answers lie in their children. Associated with this will be the number of harem hindered mating with their male alpha,

$$M.harem_m^{mate} = round\{\alpha.M.harem_m\} \tag{8}$$

The amount of harem hinds that are ready to mate with these red deer, the males is where$M.harem_m^{mate}$ of the $M.harem_m$. One is chosen at random among the$M.harem_m^{mate}$.

g) Another harem's mate male commander had β percent hinds.

Randomly choosing a harem, the male leader mates with the hinds of this harem. To expand his area, the male red deer attacked another harem. When \a harem with a male red deer mateof hinds, the number of hinds born will be,

$$M.harem_m^{mate} = round\{\beta.M.harem_m\} \tag{9}$$

h) Stag mate with the closest hind

Each stag is coupling with the closest hind in this step. During the mating season, the male deer tends to follow the obliging hind, in fact this particular hind may be his favorite. This hind may be accustomed to one harem. We also let every stag mate with the closest hind. This means that, in the worst scenario, each male red deer has the opportunity to mate with as few hinds as possible. The determination of distances for every hind and stag to identify which hind is closest. Function as we're a two-D (dimension) process. In JD-space, the separation between all hinds and a red male deer is calculated as follows,

$$c_j = \left(\sum_{i\epsilon I}\left(stag_i - hind_i^j\right)^2\right)^{1/2} \tag{10}$$

i) Choose the coming generation

The male Red Deer generation after them is chosen as the best option, and hinds are chosen using a roulette wheel, tournament, or any other evolutionary system that combines fitness with selection.

j) Integration

The halting condition could be determined by factors such as the quantity of repetitions, the quality of the best solution found, or a specified time period. Levy flying is a technique that routing algorithms in Wireless Sensor Networks (WSNs) can use to improve their exploration capacity. Levy flight is a random walk process in which the step lengths are not Gaussian but rather follow a heavy-tailed distribution, such as the Levy distribution. Many flying creatures exhibit a flying style that is similar to Levy flight. Particles moving according to Lévy flight make several repeated "small" steps interspersed with sporadic "big" movements. Lévy flight is a type of random path in which the probabilistic density function of the step sizes is heavy-tailed. A typical pattern of motion is as follows: the particle moves locally at first, taking several tiny movements, and then it takes a large step, and so on. Afterward, it returns to a local scope once more. Mathematically, the Lévy flight Probability Density Function (PDF) is defined as follows

$$Distribution_{Lévy} = V/|U|^{1/\beta} \tag{11}$$

Where U represents a selection of numbers sampled from the Gaussian distribution$M\ (0,1)$, V represents a random rate selected from the Gaussian dispersion $M\ (0, \sigma^2)$, and β represents the power-law index. The standard deviation of the variation σ is provided by

$$\sigma = \left(\frac{\Gamma(1+\beta)*sin\left(\frac{\pi*\beta}{2}\right)}{\Gamma\left(\frac{1+\beta}{2}\right)*\beta*2^{\frac{\beta-1}{2}}}\right)^{\frac{1}{\beta}} \tag{12}$$

Where gamma functional is indicated byΓ.Algorithm 1 explores the Levy Flight Red Deer Optimization algorithm. Fig. 2 shows the flowchart of the proposed methodology.

Algorithm 1: LFRDO Algorithm

```
import numpy as np
def levy_flight():
  beta = 1.5
  sigma = (gamma(1 + beta) * np.sin(np.pi * beta / 2) / (gamma((1 + beta) / 2) * beta * 2 ** ((beta - 1) / 2))) ** (1 / beta)
  u = np.random.normal(0, sigma)
  v = np.random.normal(0, 1)
  step = u / (abs(v) ** (1 / beta))
  return step
population_size = 10
dimension = 2
population = np.random.rand(population_size, dimension)
def fitness_function(x):
  return sum(x ** 2)
max_iterations = 100
for iteration in range(max_iterations):
  for i in range(population_size):
    step = levy_flight()
    new_position = population[i] + step
    if fitness_function(new_position) < fitness_function(population[i]):
      population[i] = new_position
best_solution = population[np.argmin([fitness_function(x) for x in population])]
print("Best solution:", best_solution)
print("Fitness:", fitness_function(best_solution))
```

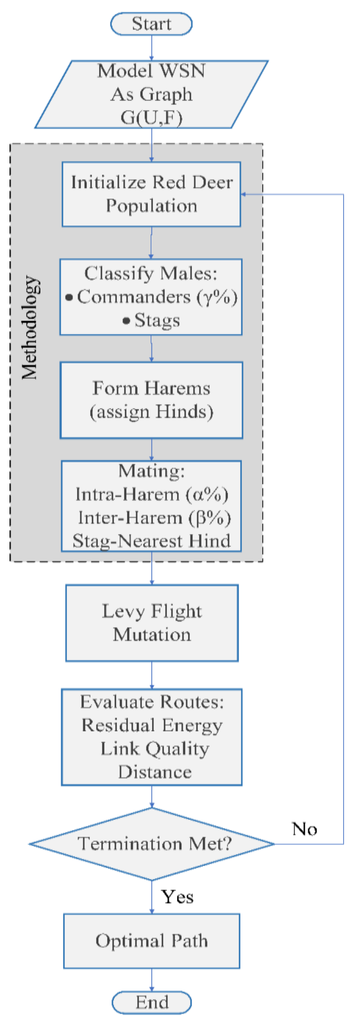

Fig. 2. Proposed methodology flowchart

4. SIMULATED SETUP

In the simulation, there are between 60 and 500 nodes in the network, each with a preliminary energy of 26 KJ and a buffering capacity of 2.6 KB. A number between 0 and 1 is ascribed to the link efficiency. Table 2 provides a summary of the simulated parameters [17-19].

TABLE II. SIMULATED PARAMETERS

Parameters	**Simulated parameters**
	Value
Node's initial energy	26 KJ
Packet Size	9800 bits
Range Transmission	50 meters
Number Nodes	60 to 500 nodes
$F_t = \alpha_3$	$\alpha_3 = 50 \times 10^{-9}\ joules/bit$
$F_q = \alpha_{12}$	$\alpha_{12} = 0.787 \times 10^{-6}\ joules/bit$
$F_s = \alpha_{11} + \alpha_2 c^m$	$\alpha_{11} = 0.937 \times 10^{-9}\ joules/bit$ $\alpha_2 = 10 \times 10^{-12}\ joules/bit/meters^2$ $d = 85\ meters$

Figure 3 compares the suggested method's power consumption to the current algorithms. The suggested approach has greater energy consumption than the current method, and the total amount of nodes is increased from 100 to 400. The suggested approach achieves 98% energy savings. For node 100, the approach has 92%. The suggested approach offers 95% energy savings at node 400, the energy efficiency is greater in the suggested manner. Table 3 compares the parameters [20-24].

TABLE III. COMPARED THE PARAMETERS AMONG EXISTING AND SUGGESTED METHOD

Methods	**Compared the parameters among existing and suggested method**		
	Throughput (Mbps)	***Packet delivery ratio (%)***	***Energy efficiency (%)***
Pegasus	0.49	80	75
A-Leach	0.8	88	89
DSO-EHO	0.8	94	92
LFRDO [Proposed]	0.9	96	95

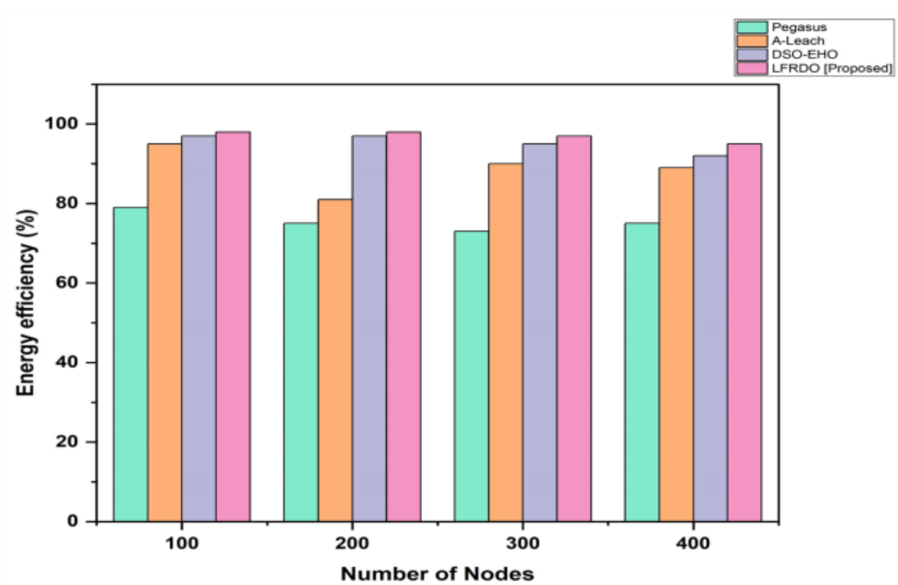

Fig. 3. Energy efficiency comparison

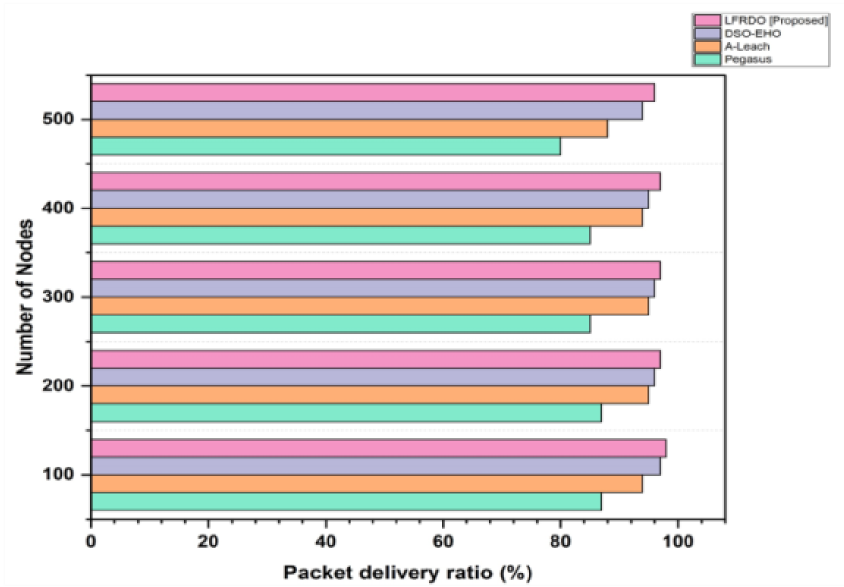

Fig. 4. Results of Packet delivery ratio

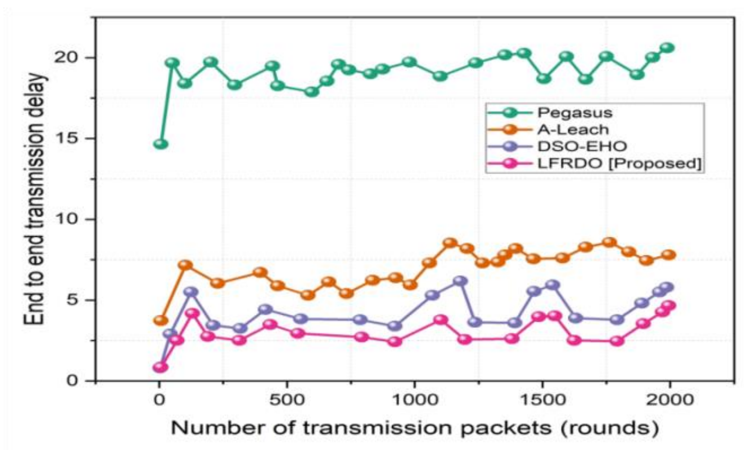

Fig. 5. End-to-end transmission

A packet's success rate is determined by dividing the amount of packets sends and receives from transmitting to the sink node. The cluster-based networking method's extensibility system is displayed in Figure 4. Generally speaking, when the quantity of nodes inside a network rises, and packet delivery decreases while delays and node energy consumption increase. Although the suggested algorithm in this study outperforms the other two current methods, the rate of packet delivery achieves 96% for 500 nodes, relative to the standard protocols even when the number of nodes increases. When compared to conventional methods, the suggested approach has a higher packet delivery ratio.

The delay is the amount of time it takes for data to travel from the source to the base station. The DSO method's routing protocol reduces the delay in this suggested article. An effective technique for transmitting information is the efficient choice of routes between the point of origin and the intended location. In comparison to the current approaches, the suggested methods have the least amount of delay. Compared to the current methods, the delay increases with the number of rounds. As seen in Figure 5 end-to-end transmission this procedure reduces the delay in the suggested manner.

The quantity of data streams that the network is able to manage for a given number of nodes in a given amount of time is known as throughput. Compared to the current technologies, the suggested approach offers more capacity for more efficient transfer of data. In comparison to the techniques, the throughput increases to a greater number of 0.99 megabytes for node 100 and 0.9 mbps for node 500. Fig. 6 displays the efficiency associated with the total amount of nodes.

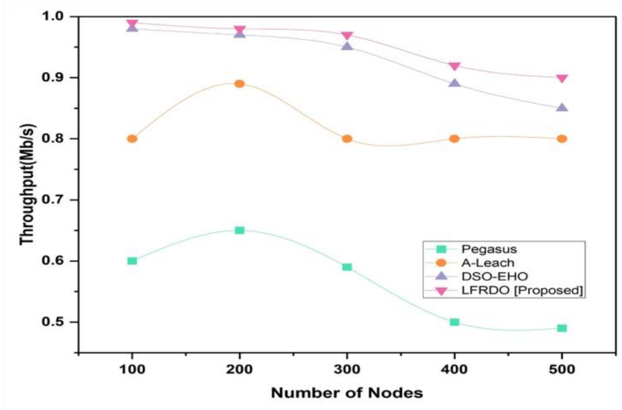

Fig. 6. Throughput's comparison

The network operates for a number of rounds until fifty percent of nodes disappear. The network sustainability duration of LFRDO exceeds that which DSO-EHO provides. The node failure phenomenon manifests at slower rates because of energy-efficient routing. The system performs better because it selects optimal paths for routes as shown in Fig. 7.

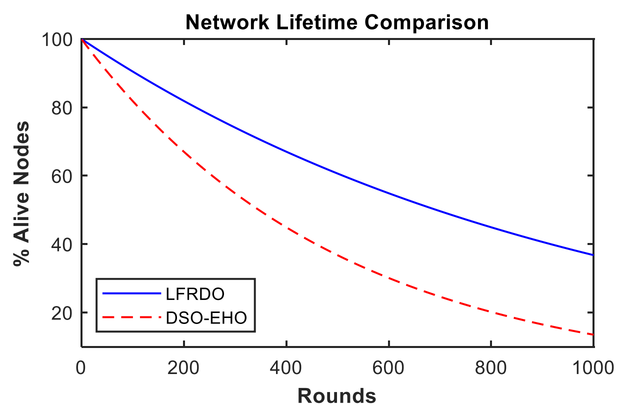

Fig. 7. Network Lifetime Comparison

Simulation rounds showcase the energy usage measurement in this graph. Precise energy distribution takes place through the approach of LFRDO method. Traditional protocols demonstrate higher consumption rates of energy during operations. The routing decisions made by LFRDO protect resources as its main purpose as shown in Fig.8.

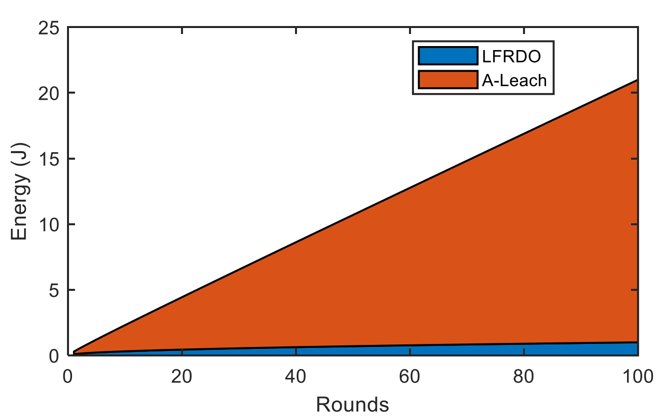

Fig. 8. Cumulative energy consumption

The statistical analysis evaluates hop count information used for data delivery. The LFRDO's Levy Flight exploration mechanism creates shorter route paths. LFRDO implements red deer-inspired path optimization to prevent excessive number of hops in pathways. LFRDO enables effective multiple-hop network communication in changing network topologies as shown in Fig. 9.

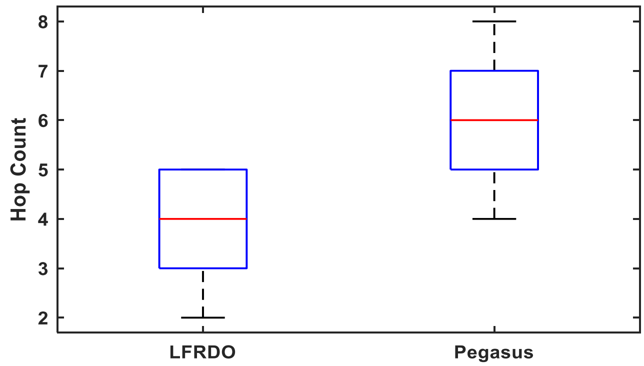

Fig. 9. . Path Optimality Comparison

A computational review of the algorithm takes place at each stage of iteration. The rapid optimization process occurs because Levy Flight makes long distance jumps. Optimal solutions become reachable through 30 consecutive iterations. The algorithm performs efficiently while maintaining solution quality in the model as shown in Fig. 10.

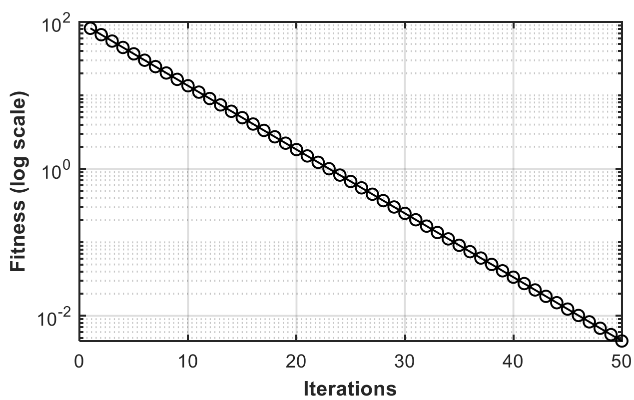

Fig. 10. LFRDO convergence rate

The algorithm tests packet delivery success rates during network density examination as shown in Fig. 11. The system run by LFRDO operates optimally up to a maximum node count of 500. The baseline methods experience decreasing PDR while the number of network nodes grows. Cluster-head selection adapts automatically to ensure robustness operation in the network.

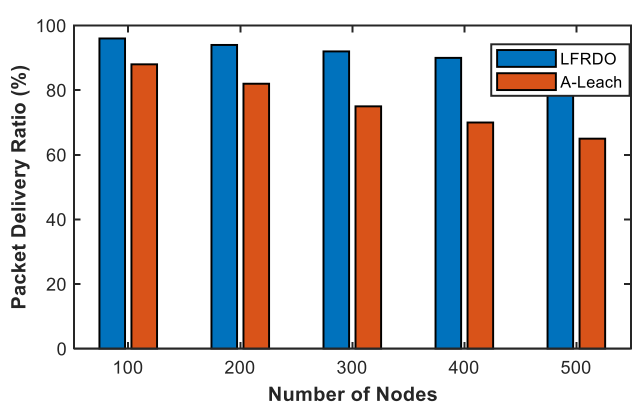

Fig. 11. Scalability: PDR vs. network size

5. CONCLUSION

The proposed routing strategy uses LFRDO (Levy Flight Red Deer Optimization) to optimize data transfer efficiency for WSNs through cognitive energy management. LFRDO achieves 98% energy savings with 0.9 Mbps throughput in addition to 96% packet delivery ratio for networks with up to 500 nodes. The LFRDO method delivers enhanced energy conservation and packet delivery ratio levels compared to DSO-EHO (92% efficiency) and A-Leach (88% PDR). The optimization phase of the algorithm creates increased computational load that the adaptive exploration-exploitation balance method eventually reduces. Future researchers should focus on three main areas including LFRDO hardware application with IoT-edge devices for real-time validation and renewable power integration (such as solar and RF energy sources) to extend operational times and additional investigation of blockchain incorporation to achieve data security in adversarial conditions. Additional investigation should focus on the performance capabilities of the proposed approach when used in 5G-integrated WSNs during disaster recovery operations. Future investigations will solve technical constraints regarding adaptive topology management and multiple criteria optimization between delay and power usage in the system.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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