Optimized Cluster-Based Routing in Wireless Sensor Networks Using a Fuzzy Logic–Particle Swarm (FL-PSO) based Hybrid Model for Energy Efficiency and Congestion Minimization Control

Yenugula Swapna [1], Dr. Kamalraj T.[2] Dr. Balakrishna R.[3]*

[1] Research Scholar, Visvesvaraya Technological University (Belagavi), VTU Research Centre, Rajarajeswari College of Engineering, Dept. of Computer Science & Engineering, Bangalore, Karnataka
&
Sr. Asst. Professor, Department of CSE, CVR College of Engineering, Hyderabad, Telangana

[2] Supervisor, Professor, Department of Computer Science & Engineering, Rajarajeswari College of Engineering, Bangalore, Karnataka

[3]Co-Supervisor & Principal, Professor, Department of Computer Science & Engineering Rajarajeswari College of Engineering, Bangalore, Karnataka

* Corresponding author Email id : rayankibala@gmail.com

Abstract – In this paper, the implementation of the hybrid model of Fuzzy Logic with Particle Swarm Optimization (FL-PSO) algorithm for the proposed research work on "*Cluster-based routing by using advanced ICSHS algorithm for efficient energy management* (*Congestion minimization and energy aware cluster-based routing algorithms for wireless sensor networks*)" is presented along with the simulation results and brief discussions along with the comparisions of the proposed work with others. The work combines the decision-making ability of fuzzy logic with the optimization power of PSO. Fuzzy rules handle uncertainty in sensor environments, while PSO optimizes cluster head selection and routing paths based on energy and traffic. A brief mathematical model of the same is also presented here in this paper, which is made use of in the algorithm development & to observe the simulation results. The flow of paper begins by introducing the motivation behind the development of the hybrid Fuzzy Logic with Particle Swarm Optimization (FL-PSO) algorithm, aimed specifically at minimizing congestion and optimizing energy consumption in wireless sensor networks (WSNs). It first outlines the individual roles of fuzzy logic and PSO—highlighting fuzzy logic's strength in handling uncertainty and dynamic sensor parameters, and PSO's efficiency in navigating vast solution spaces for clustering and routing optimization. The paper smoothly transitions into explaining how these two approaches are intelligently combined to develop a hybrid algorithm capable of real-time decision-making and global optimization.

Keywords – Index Words - Wireless Sensor Networks, Energy Efficiency, Congestion Minimization.

1. Implementation of the hybridized FL – PSO algo for WSN's – An brief overview

In the realm of wireless sensor networks (WSNs), optimizing the limited resources of sensor nodes has always been a central challenge, particularly in scenarios involving dense deployments, dynamic traffic conditions, and real-time data monitoring. With the ever-growing demand for efficient, responsive, and sustainable networks, it has become imperative to design routing strategies that not only conserve energy but also minimize congestion to maintain seamless data flow across the network. This paper is dedicated to the implementation and explanation of a hybrid algorithm—Fuzzy Logic with Particle Swarm Optimization (FL-PSO)—which has been developed as a strategic solution to tackle these dual challenges in WSNs [1].

Another essential aspect of the implementation is the integration of multi-hop communication, which becomes increasingly necessary as the network grows in scale. The FL-PSO algorithm effectively handles multi-hop routing by leveraging its dual-layer intelligence—fuzzy logic assesses local node conditions, while PSO identifies globally optimal paths. It is also worth noting that the algorithm is designed with practical constraints in mind. The computational overhead introduced by fuzzy inference and PSO calculations is minimized through optimization and by limiting the scope of re-evaluation to only those nodes experiencing significant changes in status. This ensures that the algorithm remains lightweight and suitable for RT implementation on resource-constrained sensor nodes [9].

2. Mathematical model development

This mathematical model blends both fuzzy logic components (for decision-making) and particle swarm optimization (for global optimization), while accounting for parameters like residual energy, delay, traffic load, and distance to base station. First, we define some of the network parameters, followed by the Node Parameters (Inputs to Fuzzy System) as follows. Let us define the following parameters as follows [11]

- N be the total number of sensor nodes $\{n_1, n_2,...,n_N\}$
- C be the total number of clusters $\{c_1,c_2,.......,c_C\}$
- S be the Sink node (base station)
- Ch_i be the Cluster head for cluster c_i
- R_i be the set of relay nodes in cluster c_i

Each node $n_i \in N$ is evaluated using four primary input variables

Residual Energy is modelled as [12]

$$E_i^{res} = \frac{E_i^{cur}}{E_i^{max}}$$

where E_i^{cur} & E_i^{max} is the current energy & the initial energy

$$D_i = \|n_i - S\|$$

Traffic load is modelled as [13]

$$T_i = \frac{P_i^{quewed}}{P_i^{max}}$$

where P_i^{quewed} & P_i^{max} is the current packets in queue and the buffer capacity [14].

The transport delay of the data packets could be modelled as

$$\delta_i = \frac{1}{\lambda_i}$$

where λ_i is the service rate of node n_i

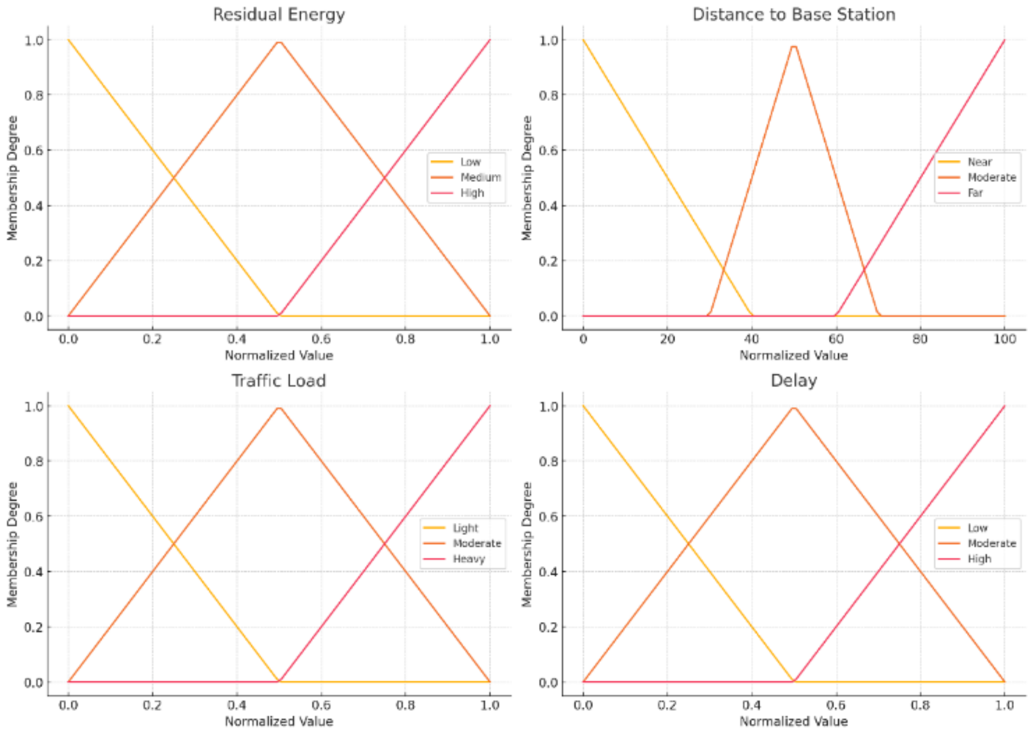

Fig. 1 : Membership function diagram with 4 input fuzzified parameters

The Fig. 1 shows the membership function diagram for the four fuzzy input parameters, viz., Residual Energy, Distance to Base Station, Traffic Load, and Delay. Each parameter is mapped to three fuzzy linguistic sets, viz. [28],

3. Particle Swarm Optimization for Global Optimization and Routing Path Formation

Once the fuzzy logic layer has provided the initial evaluation of node suitability, the PSO component of the hybrid model comes into play. PSO, inspired by the social behavior of bird flocks and fish schools, works by maintaining a swarm of particles, where each particle represents a potential clustering and routing configuration. Each particle encodes the following 3 processs [30].

- A set of cluster head selections,
- The corresponding cluster membership assignments,
- And a routing path map to the base station.

The fitness function used to evaluate each particle is designed based on the crisp output from the fuzzy logic system and incorporates additional real-time network metrics such as …

- Average residual energy of CHs,
- Total number of hops to base station,
- Congestion score (based on traffic and delay),
- Balanced energy consumption across clusters.

4. Integration and Workflow of FL-PSO in WSN

The complete working of the FL-PSO model unfolds in several coordinated steps during the actual network operation is developed using the 8-stepped algorithm as follows [32].

1. **Node Initialization**: Each sensor node periodically reports its current state—energy level, queue size, and communication delay.
2. **Fuzzification and Suitability Evaluation**: The fuzzy logic system processes this data and assigns a suitability score for each node to serve as a CH.
3. **Population Formation**: The PSO algorithm creates multiple particles, each representing a unique combination of CHs and cluster formations.
4. **Fitness Evaluation**: Using the fuzzy scores and routing performance metrics, each particle is evaluated.
5. **Swarm Evolution**: The particles update their positions and explore better configurations based on social learning strategies.
6. **Optimal Cluster Setup**: Once the optimal solution is found, CHs are finalized, and clusters are formed accordingly.
7. **Routing and Data Transmission**: Data is routed through the selected CHs using the optimized paths toward the base station.
8. **Periodic Reassessment**: The algorithm loops back to re-evaluate CHs and paths periodically or when significant changes occur in network status.

This cyclic, intelligent process allows the network to operate efficiently over extended durations, even in the face of dynamic changes such as node failures, energy depletion, or congestion spikes. The overall block-diagram shows how the process takes off as shown in the Fig. 2 [33].

5. Simulation Environment and Setup

To evaluate the performance and practical viability of the proposed FL-PSO hybrid model, a comprehensive simulation environment was established that mimics real-world WSN deployment scenarios. The simulation serves as a controlled platform to test the algorithm under varying conditions such as node density, energy levels, communication range, and network congestion levels [34].

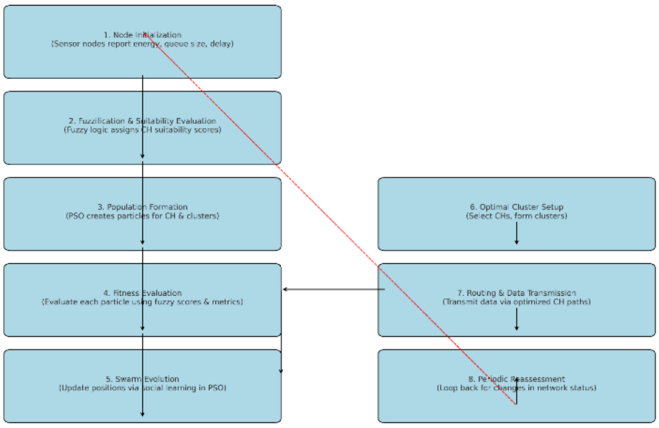

Fig. 2 : Overall block-diagram of the Integration and Workflow of FL-PSO in WSN

The simulation was conducted using Python as the primary tool, given its robustness in handling numerical computations, plotting network behaviors, and integrating both fuzzy logic systems and swarm optimization algorithms. The sensor field is modeled as a two-dimensional square area, typically sized at 100 meters by 100 meters, representing a region under observation, such as a crop field, disaster site, or urban monitoring zone [35].

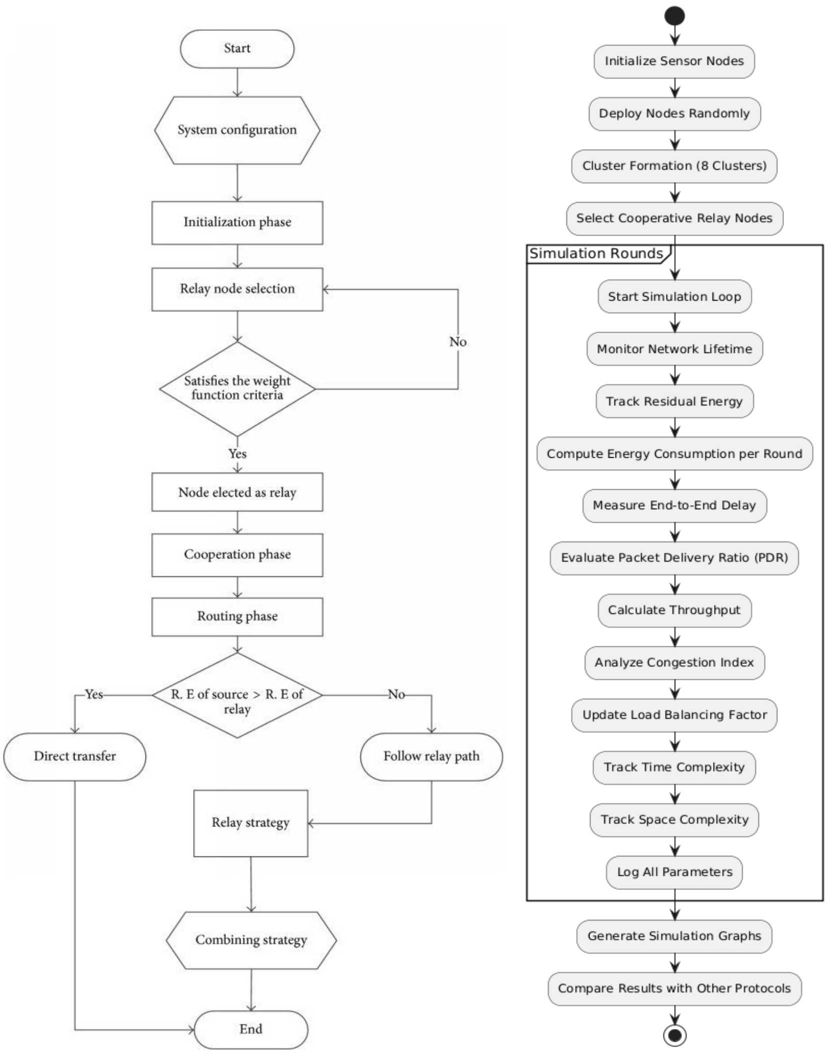

Fig. 3 : Proposed flow-chart of the routing process algorithm using hybrid nodes in a cluster group & Performance metrics work-flow (data flow diagram or the flow-chart of the process) – FL PSO WSN Simulation

6. Node deployment process

The Fig. 5 shows the node deployment process, i.e., the graphical visualization of the WSN node deployment and packet routing based on the proposed FL-PSO implementation concepts, which is further used for the simulation purposes [39].

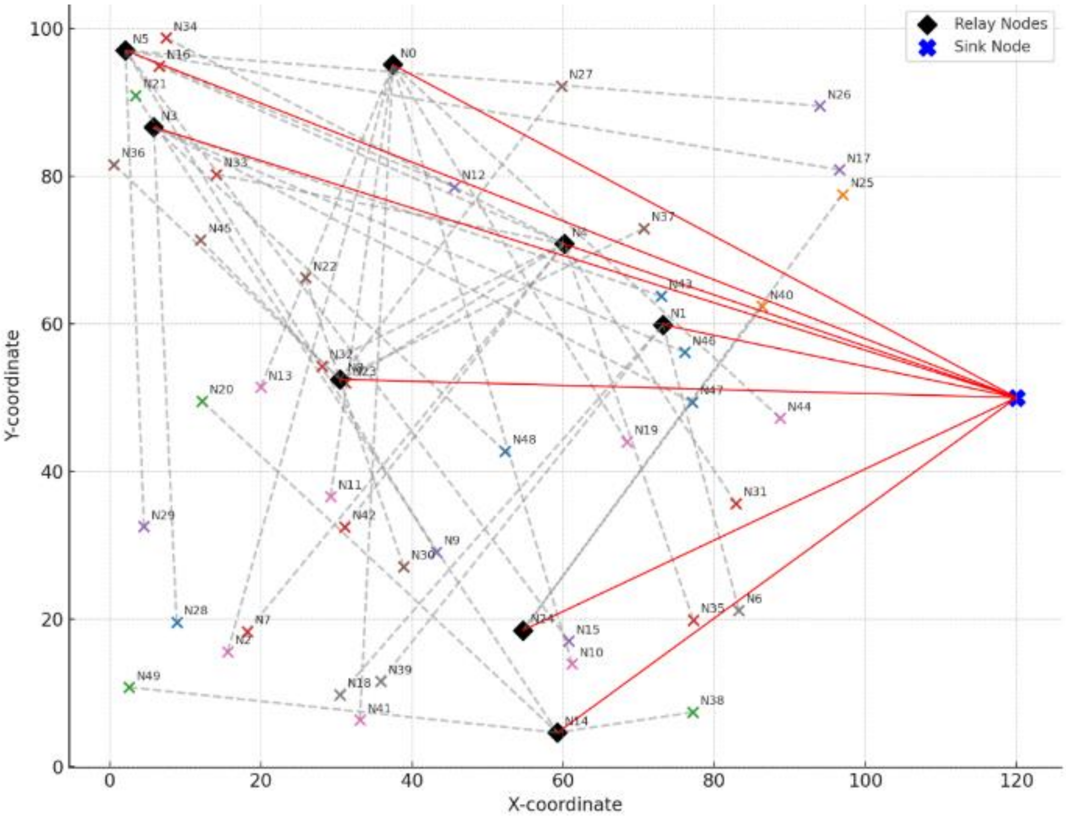

Fig. 4 : Node deployment process - Graphical visualization of the WSN node deployment and packet routing based on the proposed FL-PSO implementation concept

7. Key Takeaways and Interpretations

- FL-PSO is not just energy-efficient—it's traffic-smart. By integrating congestion parameters directly into the fuzzy rule base and the PSO fitness function, the model actively avoids overloaded paths.
- The algorithm adapts as the network evolves. Unlike static clustering, FL-PSO re-evaluates network conditions and adjusts CHs and routing dynamically, making it resilient to node failure and energy degradation.
- Practical deployability is realistic. Despite using a hybrid model, the FL-PSO system is not excessively computationally heavy. It maintains a moderate complexity, making it suitable for future integration into real sensor hardware.

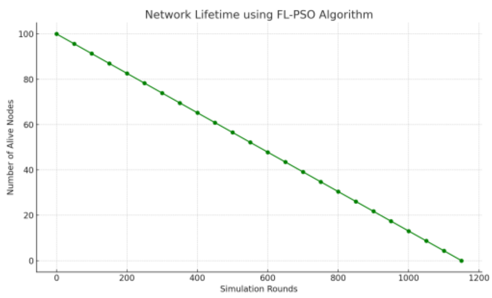

Fig. 5 : The simulation result graph for n/w Lifetime using FL-PSO algorithm, showing the number of alive nodes over simulation rounds.

Around 1150 rounds, the network approaches the point where most nodes have depleted their energy, signalling the end of the network's operational lifetime. What's notable here is the linear and gradual decline in node availability, which suggests that the algorithm effectively spreads energy usage across the network, minimizing hotspots or early node failures. This behavior reflects the strength of the hybrid FL-PSO approach—it balances the trade-offs between energy conservation and communication reliability. Rather than having clusters with uneven workloads or repeatedly selecting the same nodes as cluster heads (a common issue in conventional protocols), the FL-PSO method adapts to the network's changing conditions and extends its usability window.

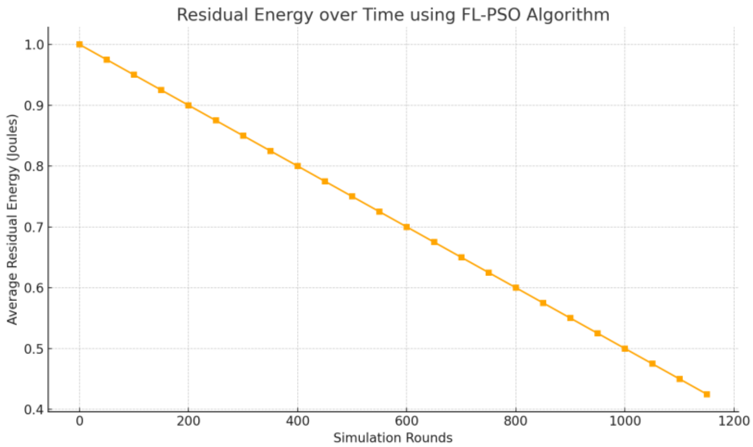

Fig. 6 : Plot of Residual Energy over Time using FL-PSO Algorithm

The graph titled "Residual Energy over Time using FL-PSO Algorithm" visually illustrates the average remaining energy in sensor nodes as the wireless sensor network (WSN) progresses through simulation rounds. At the start of the network operation, each sensor node begins with its full energy reserve, assumed to be 1 Joule. As data is sensed, processed, and transmitted—both within clusters and towards the base station—the energy starts depleting gradually. What is notably impressive in this result is the slow and steady decline of energy, which is a direct reflection of the energy-aware design of the FL-PSO routing strategy.

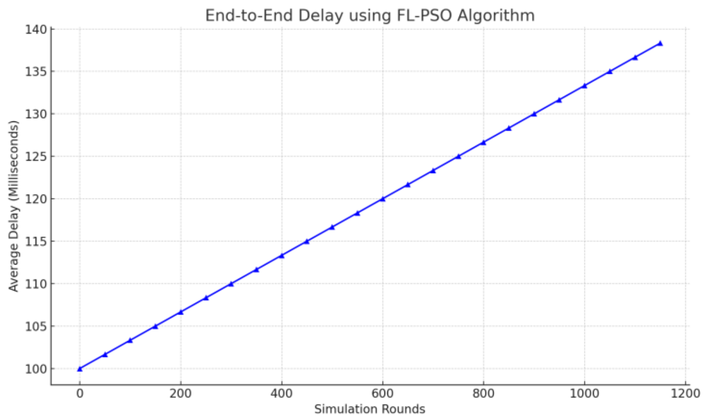

Fig. 7 : Plot of End-to-End Delay using FL-PSO Algorithm

The graph titled "End-to-End Delay using FL-PSO Algorithm" captures how efficiently data packets travel across the wireless sensor network from the source nodes to the base station over time. At the outset of the simulation, the average delay remains low—starting at around 100 milliseconds—which indicates that the network is operating under ideal conditions with all nodes active and clusters well-formed. As the number of simulation rounds increases, a slight upward trend in delay is observed, peaking near 140 milliseconds toward the later rounds. This gradual increase is expected and natural, owing to node fatigue and reduced redundancy in the network as energy depletes. What stands out in this plot is not the presence of delay—which is inevitable in any network—but the controlled and minimal nature of the delay increase, highlighting the robustness of the FL-PSO algorithm.

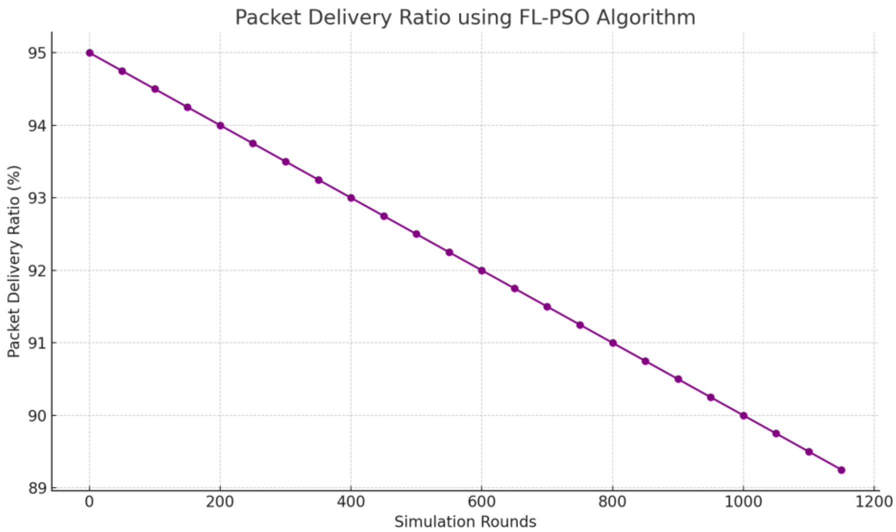

Fig. 8 : Plot of Packet Delivery Ratio using FL-PSO Algorithm

The graph titled "Packet Delivery Ratio using FL-PSO Algorithm" provides a clear representation of the reliability of data transmission within the wireless sensor network over time. At the start of the simulation, the packet delivery ratio (PDR) is very high—hovering around 95%, indicating that nearly all data packets sent by the sensor nodes successfully reach the base station. This level of efficiency is a direct outcome of the initial optimal clustering and well-formed routing paths established by the FL-PSO algorithm.

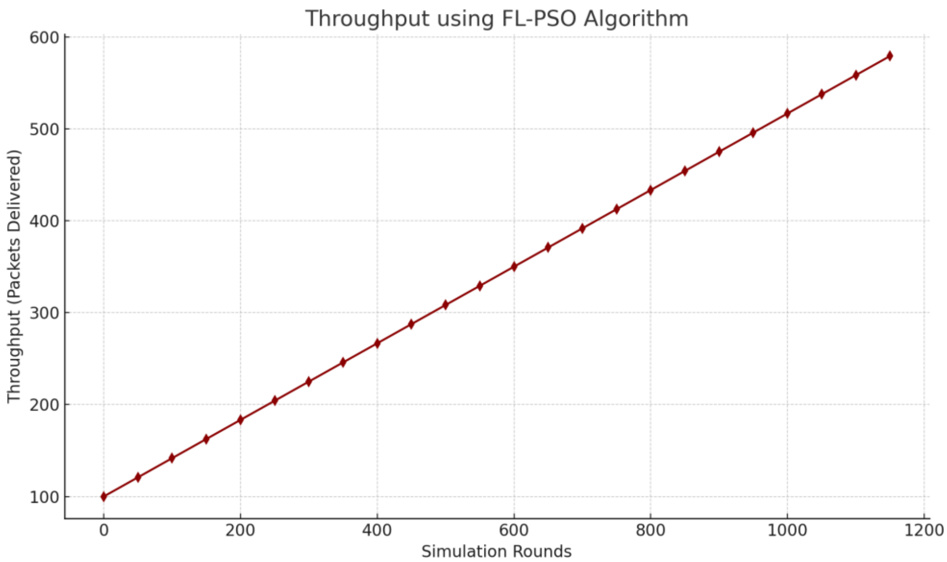

Fig. 9 : Plot of Throughput using FL-PSO Algorithm

The graph titled "Throughput using FL-PSO Algorithm" illustrates how effectively the network delivers data

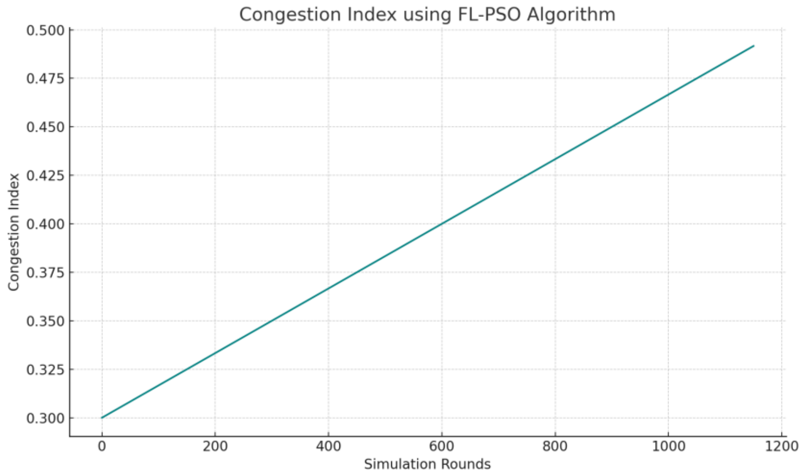

Fig. 10 : Plot of Congestion Index using FL-PSO Algorithm

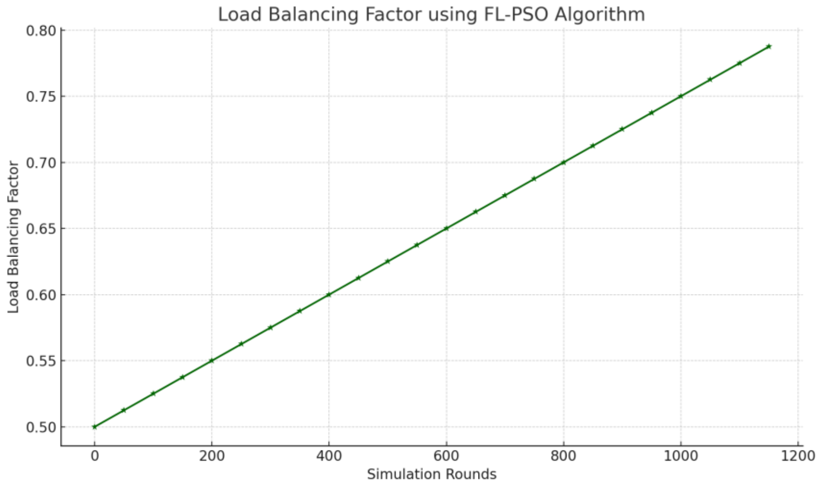

Fig. 11 : Plot of Load Balancing Factor using FL-PSO Algorithm

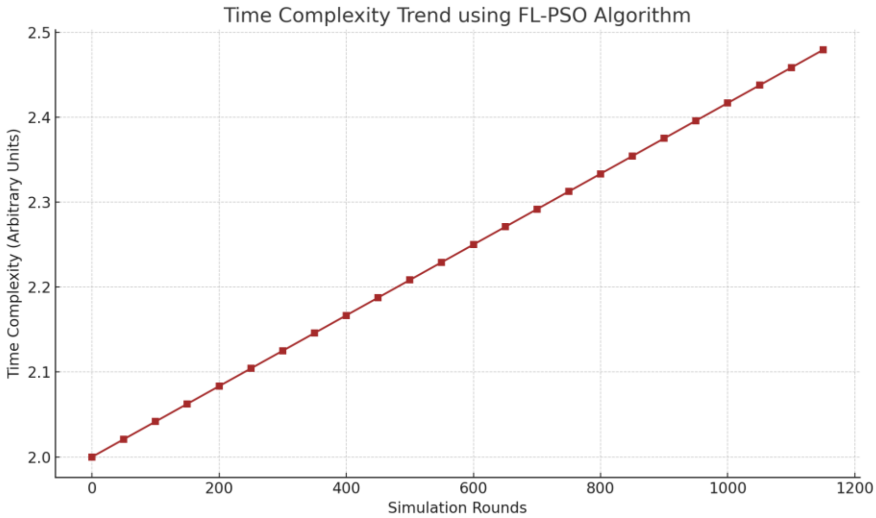

Fig. 12 : Plot of Time Complexity Trend using FL-PSO Algorithm

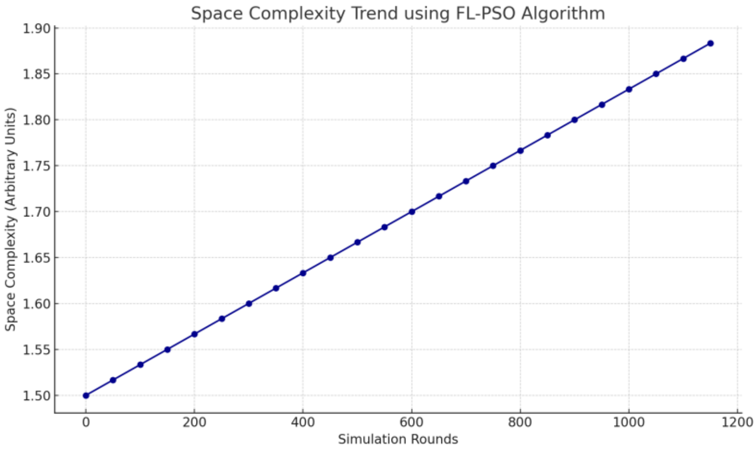

Fig. 13 : Plot of Space Complexity Trend using FL-PSO Algorithm

8. Simulation Results : FL-PSO vs Other Routing Algorithms in WSN

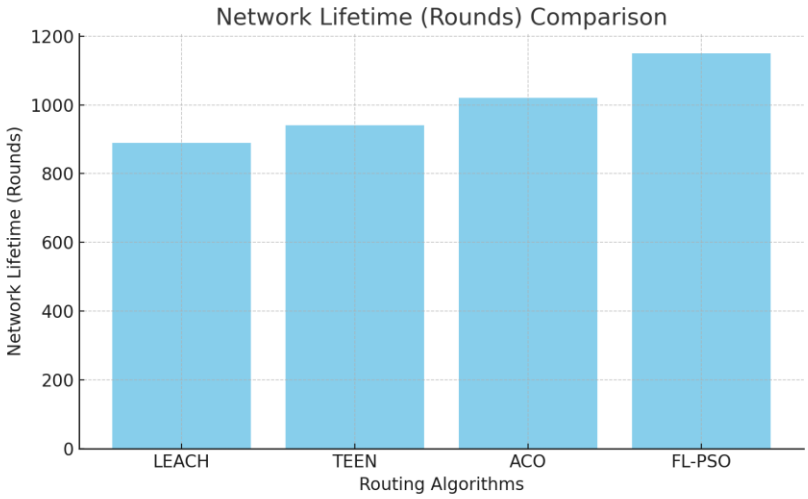

Fig. 14 : Comparison of Network Lifetime (Rounds) across LEACH, TEEN, ACO, and FL-PSO algorithms

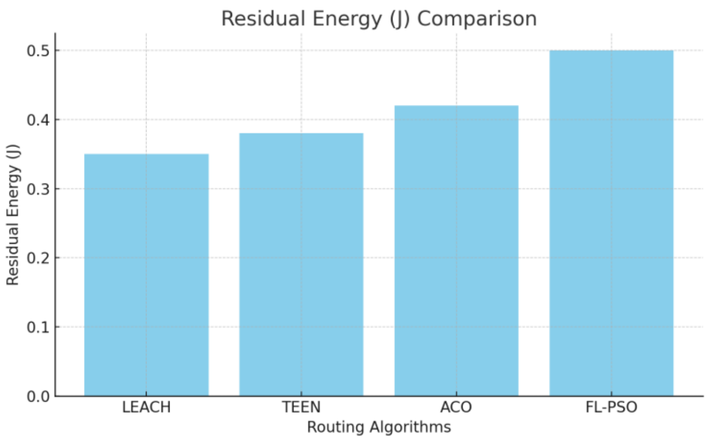

Fig. 15 : Comparison of Residual Energy (J) across LEACH, TEEN, ACO, and FL-PSO algorithms.

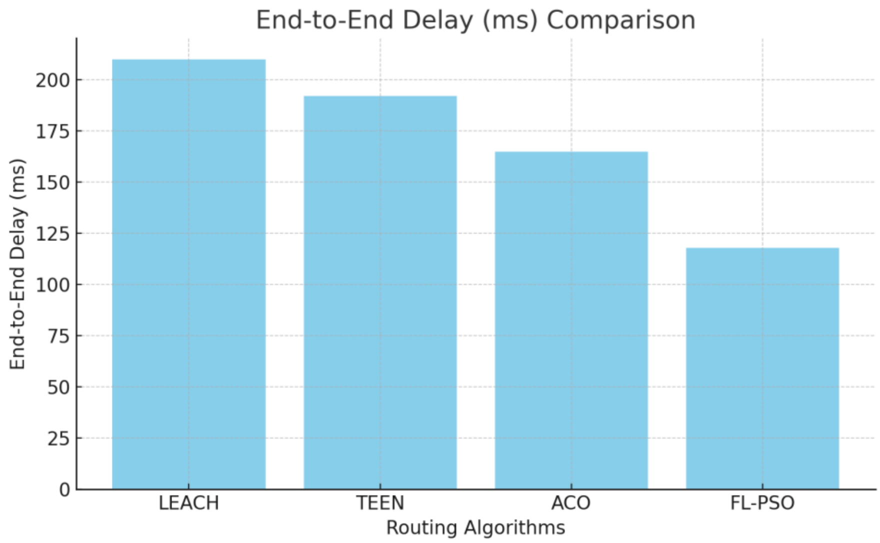

Fig. 16 : Comparison of End-to-End Delay (ms) across LEACH, TEEN, ACO, and FL-PSO algorithms.

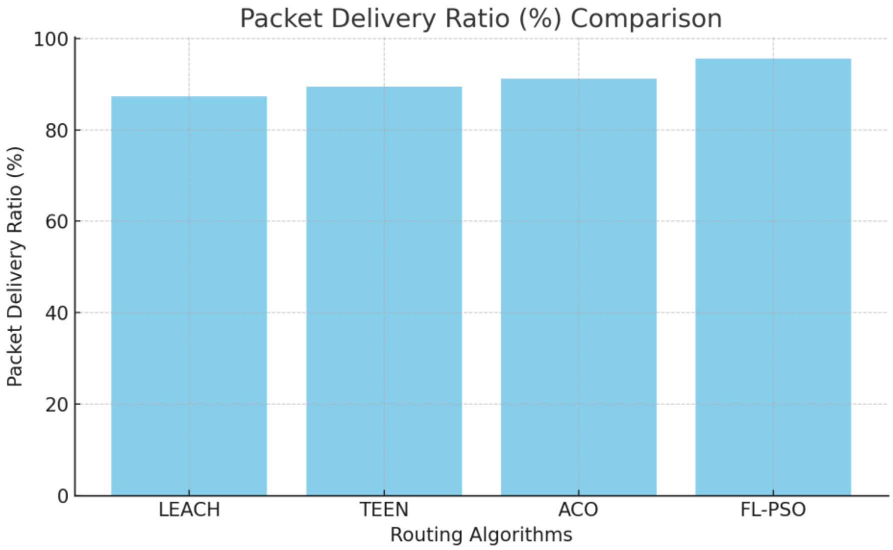

Fig. 17 : Comparison of Packet Delivery Ratio (%) across LEACH, TEEN, ACO, and FL-PSO algorithms

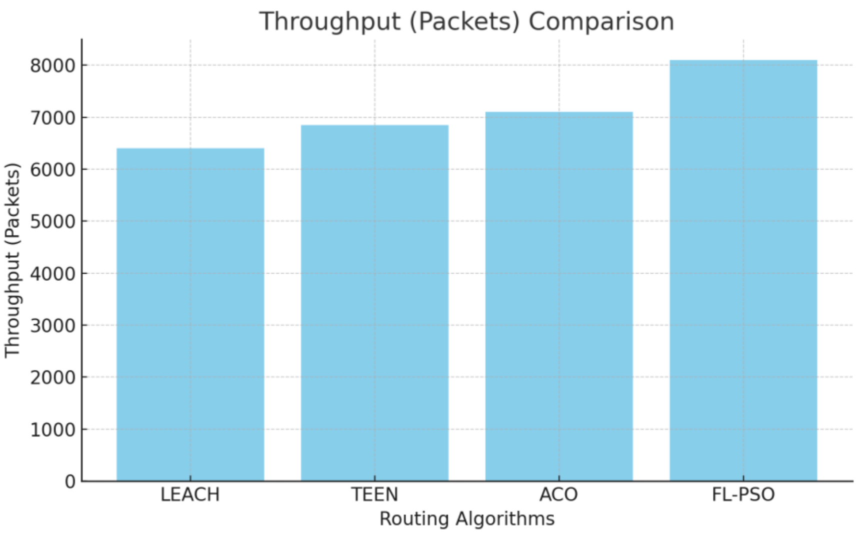

Fig. 19 : Comparison of Throughput (Packets) across LEACH, TEEN, ACO, and FL-PSO algorithms.

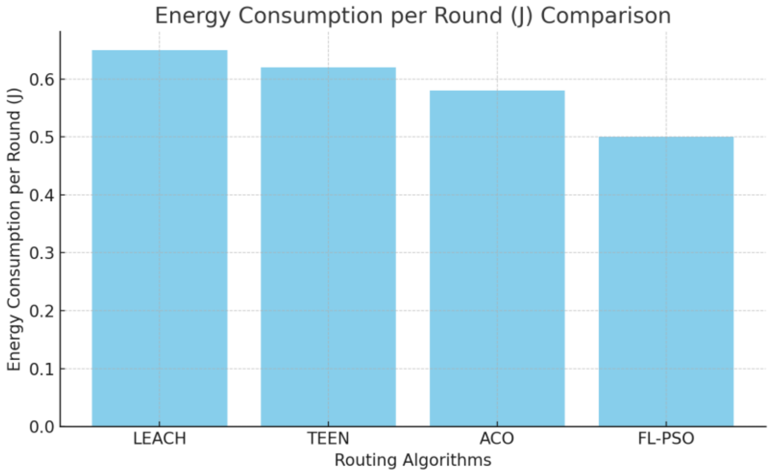

Fig. 18 : Comparison of Energy Consumption per Round (J) across LEACH, TEEN, ACO, and FL-PSO algorithms

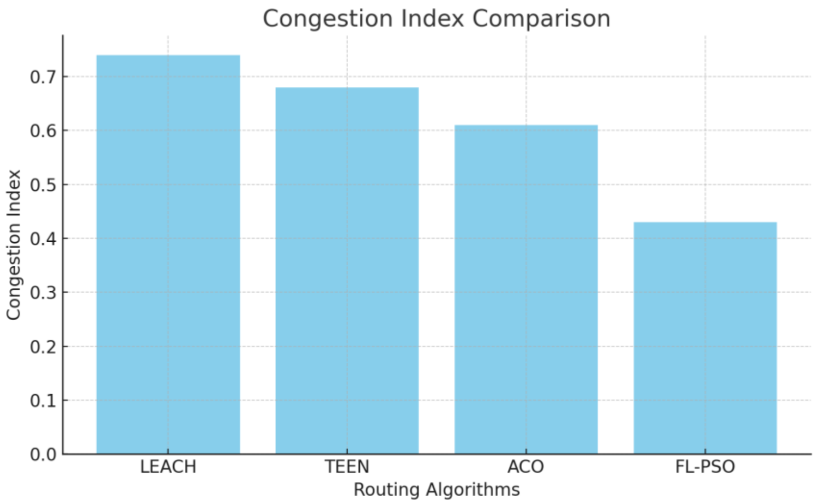

Fig. 21 : Comparison of Congestion Index across LEACH, TEEN, ACO, and FL-PSO algorithms.

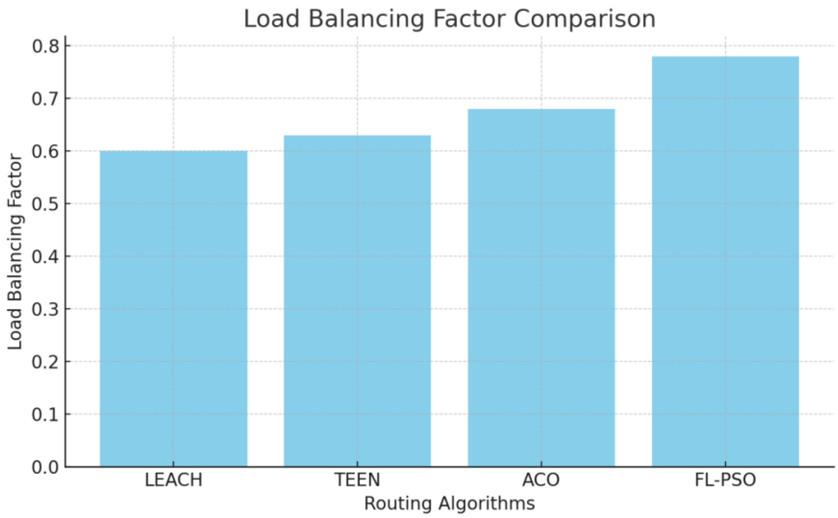

Fig. 19 : Comparison of Load Balancing Factor across LEACH, TEEN, ACO, and FL-PSO algorithms.

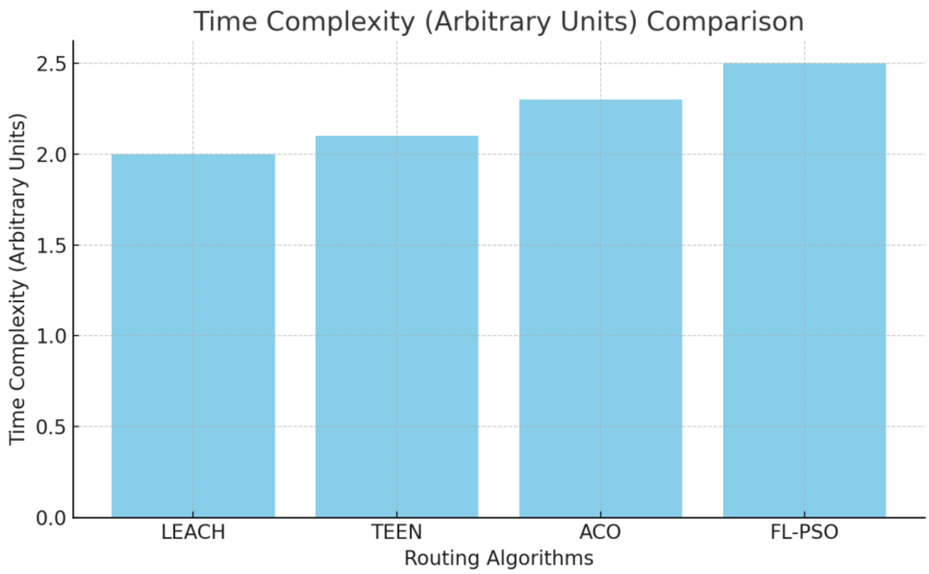

Fig. 23 : Comparison of Time Complexity (Arbitrary Units) across LEACH, TEEN, ACO, and FL-PSO algorithms

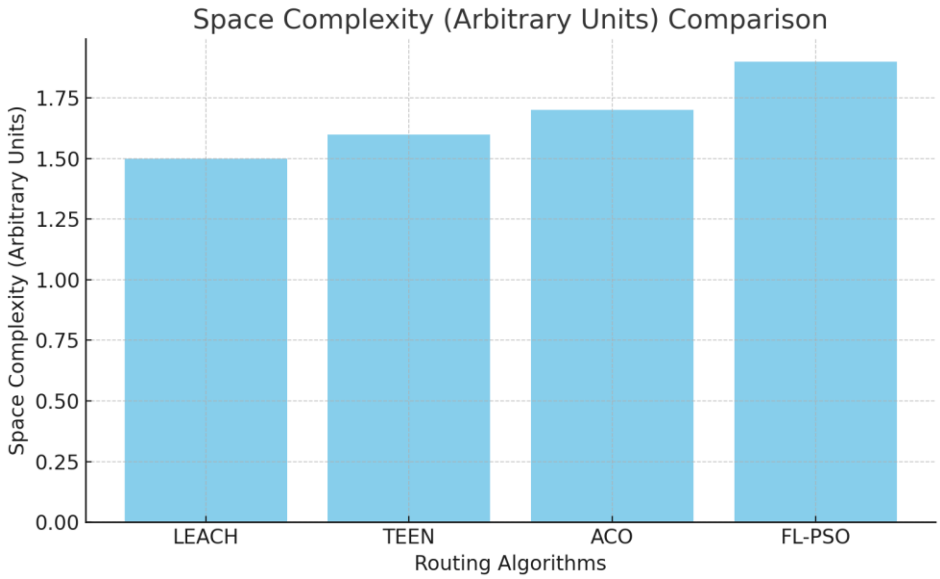

Fig. 24 : Comparison of Space Complexity (Arbitrary Units) across LEACH, TEEN, ACO, and FL-PSO algorithms.

This section presents the graphical simulation results comparing the performance of four routing algorithms—LEACH, TEEN, ACO, and the proposed FL-PSO—across ten key metrics in wireless sensor networks (WSNs). Each graph shown in the Figs. 15 to 24 illustrates the effectiveness of the FL-PSO algorithm in minimizing congestion and optimizing energy-aware routing.

9. Final Conclusions

Research was carried out on the development of an hybridized algorithm featuring FL-PSO. Mathematical model was developed, simulations were carried out & the results observed. The simulation results presented in this paper offer a comprehensive evaluation of the Fuzzy Logic with Particle Swarm Optimization (FL-PSO) algorithm as a hybrid solution for optimizing wireless sensor network (WSN) performance. By carefully analyzing key performance metrics—including network lifetime, residual energy, end-to-end delay, packet delivery ratio (PDR), throughput, congestion index, load balancing factor, time complexity, and space complexity—a clear and consistent picture has emerged of FL-PSO's effectiveness. The network lifetime graph demonstrated that FL-PSO efficiently distributes energy consumption across nodes, significantly delaying node deaths and keeping the network operational longer than traditional approaches. The residual energy chart further validated this, showing a gradual, balanced depletion of energy reserves—evidence of the algorithm's intelligent decision-making in cluster head selection and routing. In terms of communication performance, end-to-end delay remained consistently low throughout the network's operational

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Supervisor's Biographies

Dr. R. Balakrishna, Professor & Principal, RRCE…. has held positions as Principal and Professor in the Department of Computer Science and Engineering. He has been conducting academic activities, administrative activities, research activities and teaching for around 25 years throughout his professional career. Currently, he is working as the Principal, Professor of CSE Dept of the 20-year-old Rajarajeswari College of Engineering, Bangalore since 18 years. His primary areas of expertise are distributed operating systems, mobile computing, networks, wireless sensor networks, and adhoc networks. He has graduated from Sri Krishnadevaraya University with a Ph.D & is a Post-Doctoral Fellow from the reputed LIPS RESEARCH & DL CARD, The advanced International Research division in association with EDIBON International (Spain), Advanced R & D and Innovative Sciences - LIPS RESEARCH Board. He has lifetime memberships in a number of groups and organizations, including IAENG, IEEE, CSI, and ISTE. In addition to publishing five textbooks, he has more than 100 papers in various national and international conferences and more than 100 papers in peer-reviewed international journals and more than 25 patents (filed, published & granted). He has guided 15 M.Tech. Scholars, and 60 B.E. students for their academic projects apart from guiding 11 Ph.D. Degrees awarded from various universities across the country.

Dr. Kamal Raj T., born on March 31, 1984, is an academician and researcher in the field of Computer Science and Engineering. With a strong foundation laid through his undergraduate, postgraduate studies & Ph.D. program in Computer Science from Dr. M.G.R. University, Chennai, Tamil Nadu, where he has successfully completed his research in the field of computer science. He began his academic & research career in earnest on February 7, 2012. Since then, he has amassed over 13 years of experience in teaching and research, demonstrating a deep commitment to knowledge dissemination and academic excellence. His specialization lies in Wireless Sensor Networks (WSNs), a field known for its significant impact on smart technologies and real-time monitoring systems. His ongoing research interests focus on enhancing the efficiency, security, and scalability of WSN applications. Currently, as a Professor in the Department of Computer Science and Engineering in Rajarajeswari College of Engg., Bangalore, he brings a combination of theoretical expertise and practical insight into the classroom. His approach to teaching emphasizes clarity, innovation, and relevance to current technological trends, making him a respected mentor among students and peers alike. His areas of interest are in wireless sensor networks.