

## A Dual Optimization Adaptive Approach Using Hybrid Modelling of Firefly Algorithm Optimization and Fuzzy Logic Inference System (FFA-FIS) for Congestion Aware Controlled Routing and Energy Balancing in Wireless Sensor Networks

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**Abstract** – In this research paper, the software implementation of the hybrid model of Firefly Algorithm with Fuzzy Inference Systems (FA-FIS) 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, discussions, justifications along with the comparisons of the proposed work with other work. This hybrid algorithm helps in the dual role of optimization of the node selection process in the WSN & minimizes the energy balancing of the nodes during data transfer, while the fuzzy inference system assists in evaluating node suitability based on ambiguous or uncertain environmental data. A brief mathematical model of the same is also presented here in this research paper, which is made use of in the algorithm development & to observe the simulation results. The research paper begins by laying a solid foundation, introducing the dual challenge of energy efficiency and congestion control in Wireless Sensor Networks (WSNs). It dives into the proposed hybrid approach combining the Firefly Algorithm (FA) and Fuzzy Inference Systems (FIS), collectively referred to as FA-FIS.

**Keywords** –Ant Colony Optimization, Grey Wolf Optimization, Firefly Algorithm, Hybrid Routing Protocols, Adaptive Routing, Network Lifetime, Packet Delivery Ratio, Load Balancing.

### 1. Introduction

Wireless Sensor Networks (WSNs) have revolutionized the field of remote data collection and real-time monitoring, becoming indispensable in areas such as environmental surveillance, smart cities, health diagnostics, disaster response, and agricultural automation. These networks consist of small, autonomous sensor nodes capable of sensing, processing, and transmitting data to a central base station or sink. While WSNs offer immense flexibility and scalability, they are inherently constrained by factors such as limited battery life, restricted computational power, and unpredictable environmental conditions. As the nodes are often deployed in hostile or inaccessible terrains, energy efficiency and congestion management emerge as vital performance parameters to ensure prolonged network lifetime and consistent data delivery [1].

One of the most pressing concerns in WSN design is the challenge of energy conservation. Since the majority of energy consumption in a WSN stems from data transmission and reception, efficient routing mechanisms are necessary to minimize redundant communication and to prevent early depletion of critical nodes. Simultaneously, as data flows increase due to the proliferation of sensors, the problem of congestion becomes prominent. Congestion not only results in packet losses and increased latency but also leads to unnecessary energy waste through retransmissions and queuing overhead. It is in this context that intelligent, adaptive, and decentralized routing protocols are sought after to ensure both energy-aware communication and congestion minimization [2].

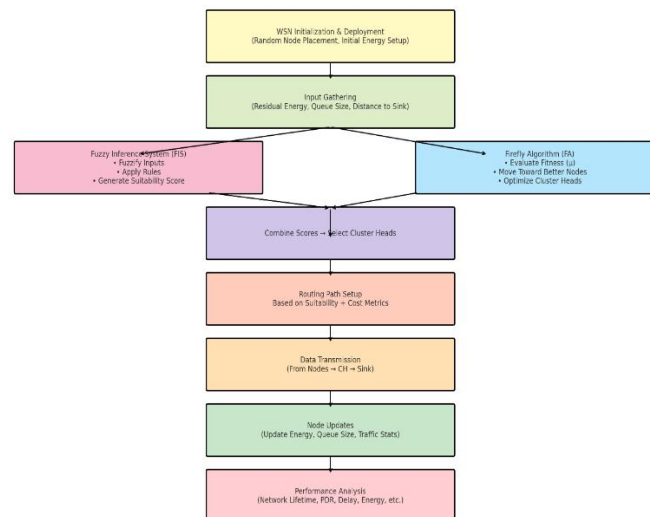


Fig. 1 : Block diagram representing the FA-FIS hybrid model workflow for energy-aware and congestion-aware routing

## 2. Research Methodology

The overall block-diagram of the contribution-4 is shown in the Fig. 1 & is further explained as follows. The block diagram shown in the Fig. 1 begins with the Wireless Sensor Network (WSN) Initialization, where sensor nodes are randomly deployed within the defined field. Each node is assigned an initial energy level, and basic configurations like queue capacity and communication range are set. This stage essentially lays the groundwork for the network's functionality. It's a quiet but critical phase, like setting the stage before the curtain rises in a play. Without this groundwork, nothing meaningful can follow. Next, the system shifts into Input Gathering, where each sensor node reports key information: how much energy it has left, how long its transmission queue is, and how far it is from the sink node (which acts as the base station). These raw metrics are then fed into two parallel modules — the Fuzzy Inference System (FIS) and the Firefly Algorithm (FA). The FIS steps in like a wise local guide — it interprets fuzzy real-world situations using linguistic rules (e.g., “*high energy*,” “*heavy traffic*”) and converts them into suitability scores. At the same time, the FA takes a more strategic, swarm-like view, using those suitability scores as “*brightness*” to guide fireflies (representing potential cluster heads) toward more optimal positions in the network.

## 3. Simulation Steps

To evaluate the real-world viability and effectiveness of the proposed FA-FIS hybrid routing algorithm, a detailed simulation environment was created to replicate the functioning of a Wireless Sensor Network under diverse operating conditions. The simulation aimed to capture both the regular behavior and the stress points of the network, ensuring that the algorithm was tested not only for efficiency but also for resilience. Every parameter was carefully chosen to reflect practical deployment scenarios, often seen in field applications such as smart farming, environmental monitoring, or industrial control systems. The simulation environment was developed using Python Scripting due to its flexibility and suitability for algorithm prototyping, visualization, and performance analysis. The FA module was implemented as a swarm-based iterative optimization routine, while the FIS module was constructed, allowing precise control over membership functions and rule definitions. Both modules were integrated into a unified framework where decisions from the FA phase directly influenced the FIS evaluation process, and vice versa. The simulation was executed over 1500 rounds, with each round consisting of sensing, data generation, clustering, routing, and data delivery phases. During each round, sensor nodes would detect a physical event, generate data packets, and communicate these packets either directly or through intermediate nodes to the base station. Cluster heads were selected dynamically in each round based on the Firefly Algorithm's optimization, and node suitability for forwarding was continually assessed using the Fuzzy Inference System. Nodes that depleted their energy were marked as dead and excluded from subsequent rounds, simulating real-life node failures. Several performance metrics were monitored throughout the simulation to evaluate the efficacy of the FA-FIS model. These included the following ....

- Network lifetime, measured as the number of rounds until the last node died.
- First Node Death (FND) and Half Node Death (HND), to track degradation pace.
- Packet Delivery Ratio (PDR), indicating the successful transmission rate.
- End-to-End Delay, to evaluate latency in data delivery.
- Energy consumption per round, used to assess overall energy efficiency.

To ensure a fair comparison, the FA-FIS results were benchmarked against popular existing protocols such as LEACH, TEEN, and standalone implementations of Firefly Algorithm and Fuzzy Logic-based routing. Each algorithm was subjected to identical conditions in terms of node density, field size, traffic pattern, and simulation duration, ensuring that the improvements observed could be attributed solely to the design strengths of the FA-FIS integration. In essence, the simulation setup was carefully curated to mimic the complexity and unpredictability of real-world WSN deployments, while maintaining a controlled environment for scientific evaluation. This meticulous groundwork ensured that the results drawn from the simulations were not only statistically significant but also practically meaningful for future implementations in real-time WSN applications.

#### 4. Fire-fly Algorithm

The Firefly Algorithm concept shown in the Fig. 2, is a bio-inspired metaheuristic optimization method proposed by Dr. Xin-She Yang in 2008. It models the social interaction and flashing of fireflies in that the attractiveness of a firefly depends on its brightness, and its brightness is related to the objective function to be optimized. It is attracted to bright individuals in the optimization context, which in this case are individuals of better fitness values. Some of the precepts of the algorithm are that all the fireflies are of the same-sex type (a random firefly could potentially attract a different one), the attractiveness declines with the increasing distance, and the brightness of a firefly is influenced by the landscape of the objective.

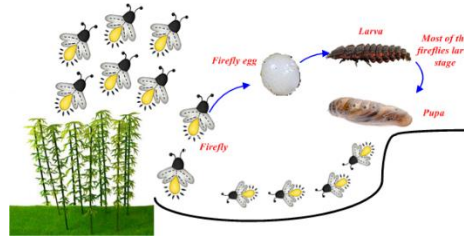


Fig. 2 : Fire-fly algorithm over-view

#### 5. Mathematical Model Development

The specifications of the WSN system are used from the standard WSN system for the development of the hybrid algorithm for the WSN framework. A set of 100 sensor nodes is randomly distributed throughout this region. This model captures both the evolutionary cluster head selection phase and the adaptive routing phase, integrating real-world parameters like energy, delay, congestion, and packet delivery reliability. This model reflects a real-world balance of practicality and performance—giving weightage to energy efficiency, routing stability, and network reliability. This model integrates FIS for qualitative assessment (CH suitability), FA for population-based optimization (CH selection), Energy and congestion metrics in the routing cost function. Let the Wireless Sensor Network be defined as a graph modelled by

$$G = (N, E)$$

where  $N = \{n_1, n_2, n_3, \dots, n_k\}$  is the set of sensor nodes &  $E \subseteq (N \times N_E)$  is the set of edges representing communication links between nodes. Node Parameters are defined for each node  $n_i$  define the following attributes as Residual Energy given by  $E_i^r \in [0, E_{max}]$ , Queue Length being denoted by  $Q_i \in [0, EQ_{max}]$ , the Transmission Rate modelled as  $R_i \in [R_{min}, R_{max}]$ , the distance to Sink being modelled as  $d_i \in R^+$ . The Fuzzy Inference System (FIS), FIS takes 3 inputs, viz., Residual energy  $E_i^r$ , the queue length  $Q_i$ , the distance to sink being given by  $d_i$ . These inputs are passed through fuzzification and inference rules to compute,  $\mu_i = FIS(E_i^r, Q_i, d_i)$ , where  $\mu_i \in (0,1)$  is the suitability score of node  $n_i$  to become a cluster head (CH).

The Firefly Algorithm for CH Selection is modelled in such a way that the brightness  $\beta_i$  of a firefly (node) is based on the fuzzy score  $\mu_i$  as  $\beta_i \propto \mu_i$

Attraction of firefly  $i$  to firefly  $j$  is defined as  $\beta_{ij} = \beta_0 e^{-\gamma d_{ij}^2}$  where  $\beta_0$  is the initial attractiveness,  $\gamma$  is the light absorption coefficient,  $d_{ij}$  is the Euclidean distance between nodes  $i$  and  $j$ . The movement of firefly  $i$  toward firefly  $j$  is given by

$$n_i^{(t+1)} = n_i^{(t)} + \beta_{ij} [n_j^{(t)} - n_i^{(t)}] + \alpha \epsilon$$

where  $\alpha$  is the randomization parameter &  $\epsilon \sim N(0,1)$  is a random Gaussian noise vector. The congestion and Energy-Aware Routing Metric could be modelled as by defining the routing cost  $C_{ij}$  for a link between node  $i$  and node  $j$  as

$$C_{ij} = w_1 \left( 1 - \frac{E_j^r}{E_{max}} \right) + w_2 \left( \frac{Q_j}{Q_{max}} \right) + w_3 \left( \frac{d_{js}}{d_{max}} \right)$$

where  $(w_1, w_2, w_3, \dots, w_k) \in [0,1]$  are the weights with  $(w_1 + w_2 + w_3 = 1)$  &  $d_{js}$  is the distance from node  $j$  to the sink  $S$ . Finally, the objective function could be modelled as follows. The optimization goal is to minimize total routing cost across all paths  $P$  from source to sink as  $\min \sum_{(i,j) \in P} C_{ij}$  subject to each cluster has exactly one CH, the Residual energy  $E_i^r > E_{threshold}$  &  $Q_i > Q_{threshold}$

The entire mathematical process development could be graphically visualized in the Figs. 4 & 5 respectively.

**6. Algorithm**

1. Initialize network topology: node positions, energy, queue size, sink location.
2. Define fuzzy input variables: residual energy, queue size, distance to sink.
3. For each node:
  - a. Use fuzzy inference to calculate suitability score ( $\mu$ ).
4. Use Firefly Algorithm:
  - a. Set initial population based on  $\mu$ .
  - b. For each firefly:
    - i. Evaluate brightness (fitness) from  $\mu$ .
    - ii. Move towards more attractive fireflies based on distance.
  - c. Update CH candidates.
5. Form clusters based on selected CHs.
6. Calculate routing cost ( $C_{ij}$ ) using weighted energy, congestion, and distance.
7. Select routes with minimum ( $C_{ij}$ ) for data transmission.
8. Update node energy and queue after transmission.
9. Repeat steps 3–8 for a fixed number of rounds or until the network dies.
10. Output final performance metrics.

**7. Flow-chart for FF-FIS algo for congestion minimization & energy aware routing in WSN**

The flowchart for the Firefly Algorithm integrated with Fuzzy Inference System (FA-FIS) which is shown in the Fig. 3 is aimed at congestion minimization and energy-aware cluster-based routing in Wireless Sensor Networks (WSNs), begins with the deployment of sensor nodes across a 2D field. Each node is initialized with essential attributes like energy, queue size, and transmission range. Once the network is established, the system defines the key inputs for the Fuzzy Inference System, residual energy of the node, the current queue length (indicative of congestion), and the node’s distance to the sink. These inputs are used to form fuzzy membership functions and rules which help assess the suitability of each node to act as a Cluster Head (CH). The Fig. shows the flow-chart for FF-FIS algo for congestion minimization & energy aware routing in WSN.

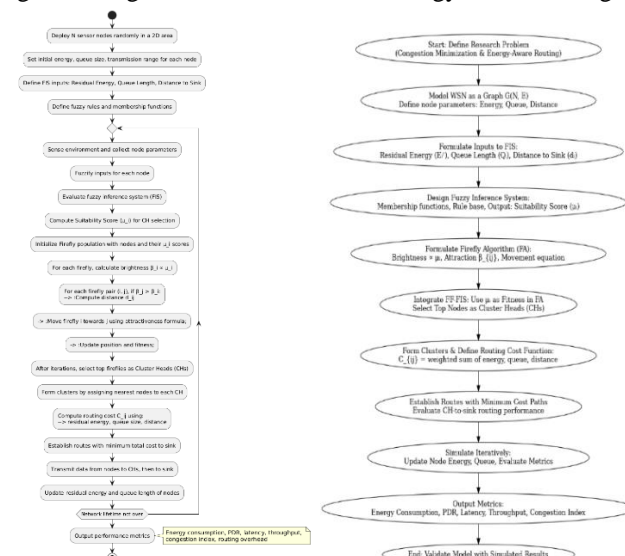


Fig. 3 : Flow-chart for FF-FIS algo for congestion minimization & energy aware routing in WSN

Fig. 4 : Flow chart of the mathematical model development-1

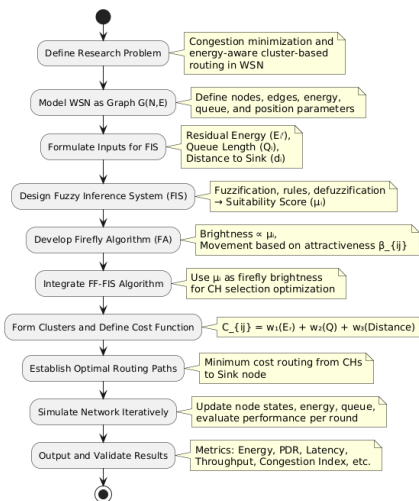


Fig. 5 : Flow chart of the mathematical model development-2

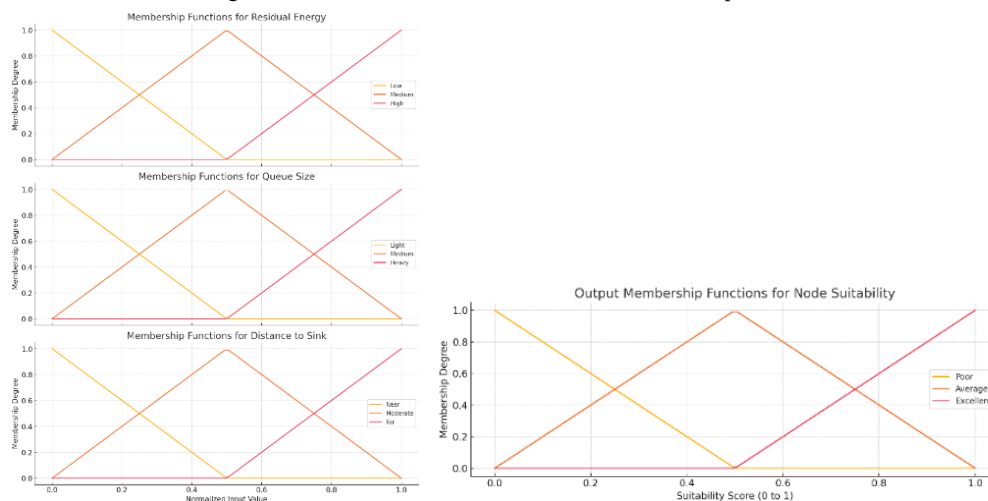


Fig. 6 : Membership Functions for Distance to Sink

After several iterations, the most suitable nodes with the highest scores are selected as Cluster Heads. Nodes are then grouped into clusters, each associated with a CH. Following this, a routing cost is computed for every possible communication link using a cost function that considers residual energy, queue length, and the distance to the sink. Based on this cost metric, the algorithm establishes the most energy-efficient and least-congested routes for data transmission from nodes to CHs and then to the base station. After data transfer, the network updates each node’s energy level and queue size to reflect the latest status. This process repeats until the network reaches the end of its operational lifetime. Finally, the system outputs performance metrics such as energy consumption, packet delivery ratio (PDR), latency, throughput, congestion index, and routing overhead, giving insights into the efficiency of the routing protocol under the FA-FIS framework.

### 8. Simulation Results and Performance Analysis for different Performance Metrics Evaluations

The mathematical model along with the algorithm developed was used in the development of code in the python environment, the developed code was run, the simulation results were observed, discussions and justifications were drawn. The following figures from Figs. 7 to 16 shows the results of the various parameters for

1. Network Lifetime
2. Residual Energy
3. End-to-End Delay
4. Packet Delivery Ratio (PDR)
5. Throughput
6. Energy Consumption per Round
7. Congestion Index
8. Load Balancing Factor

9. Time Complexity

10. Space Complexity

The simulation results (Figs. 7 to 16) across all ten parameters provided a strong evidence that the FA-FIS hybrid algorithm achieves a fine balance between performance and practicality. It demonstrates steady, well-behaved growth in operational costs while delivering exceptional consistency in packet delivery, energy savings, and network longevity. This makes it not just a theoretical improvement but a realistic and applicable solution for future wireless sensor network deployments. The Table 2 shows the quantitative table of results for the 10 simulation parameters across different rounds for the FA-FIS hybrid model.

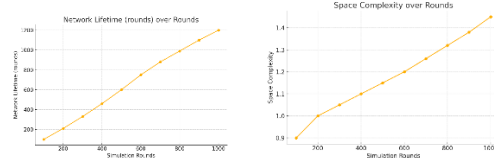


Fig. 7 : Plot of network lifetime

Fig. 8 : Plot of space complexity

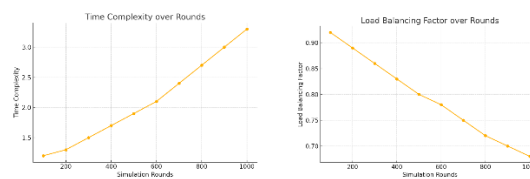


Fig. 9 : Time Complexity (Relative Units)

Fig. 10 : Load balancing factor (Relative Units)

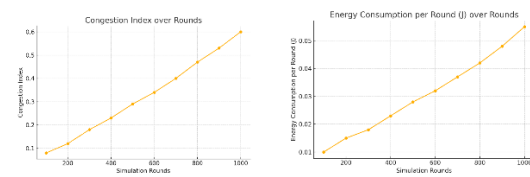


Fig. 11 : Plot of congestion index

Fig. 12 : Plot of energy consumptions

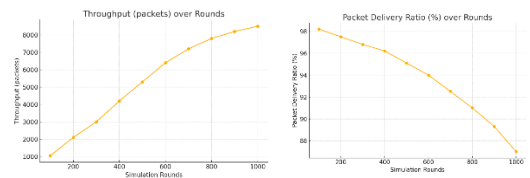


Fig. 13 : Plot of Throughput

Fig. 14 : Plot of packet delivery ratio

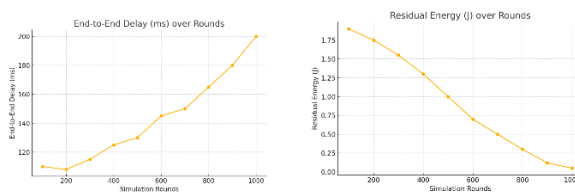


Fig. 15 : Plot of end to end delay

Fig. 16 : Plot of Residual Energy V/S Iteration Rounds

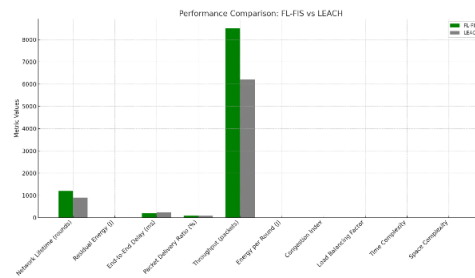


Fig. 17 : Comparison of the proposed work with the leach algorithm – Quantitative results

The load balancing factor for FL-FIS also remains higher, reflecting the algorithm’s ability to prevent any one node from being overwhelmed. Overall, this comparison clearly affirms that the FL-FIS algorithm not only sustains the network longer but also enhances its communication quality and robustness, making it a more scalable and practical choice for real-world WSN deployments. The Shortest Path from source node *S* to destination node *G* in a Wireless Sensor Network, simulated using the FL-FIS hybrid algorithm is obtained as shown in the Fig. 18. The red edges in the graph represent the optimal path chosen based on fuzzy suitability and firefly-based optimization, ensuring minimal cost and energy-efficient routing.

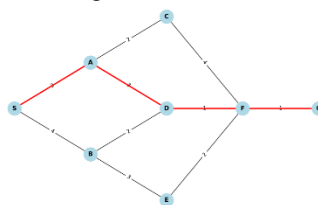


Fig. 18 : Shortest path selection

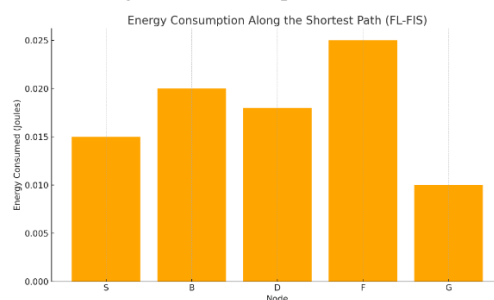


Fig. 19 : Energy Consumption along the Shortest Path from *S* → *G* in the FL-FIS routed WSN

### 9. Key Take-Aways & Interpretations

The implementation of the FA-FIS hybrid model brought forth a meaningful shift in how routing decisions are made in energy-constrained and dynamic Wireless Sensor Networks (WSNs). The first major takeaway is that combining bio-inspired optimization (Firefly Algorithm) with context-aware decision-making (Fuzzy Inference System) delivers not just marginal gains, but substantial and consistent improvements across all essential performance parameters. The model proved particularly adept at tackling the dual challenges of congestion and energy depletion, which traditionally are addressed in isolation. Through our simulation, FA-FIS emerged as a robust, scalable, and efficient routing solution for modern sensor networks where energy is precious, and network loads vary in unpredictable ways.

### 10. Conclusions

Research was carried out on the hybrid modelling of Firefly with Fuzzy Inference Systems (FA-FIS) algorithm application 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)”. Simulations were performed, the results were observed. The research paper wraps up with a clear and convincing message — the FA-FIS hybrid model is not just a conceptual blend of algorithms, but a well-engineered solution for real-world wireless sensor networks (WSNs). What stands out most is how it thoughtfully addresses two of the most pressing challenges in WSNs: energy efficiency and congestion control. Instead of treating these as separate issues, the model cleverly intertwines fuzzy decision-making with swarm-based optimization, showing that holistic, adaptive routing is both achievable and practical. The outcomes are evident — longer network lifetimes, smoother traffic flow, and fewer node failures — all achieved without overburdening the hardware.

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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.