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# HYBRID FUZZY-GENETIC APPROACH FOR ROUTE OPTIMISATION IN MANETS

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## ABSTRACT

Research about Mobile Ad Hoc Networks (MANETs) intensifies because of their independent operation and wide functionality that includes military uses along with disaster recovery networks and automotive settings. The dynamic nature of their network topologies together with sparse resources leads to routing becoming an enduring complex issue. Standard networking standards fail to handle quick network topology changes effectively that results in reduced quality network delivery and longer delays and increased power usage. The research introduces the HFGA (Hybrid Fuzzy-Genetic Approach) that unites fuzzy logic with genetic algorithms to optimize route decisions through real-time adaptation. Through the fuzzy component the network evaluates energy levels of nodes and stability of links and queue lengths for making suitable node and link assessments that guide the genetic algorithm to generate optimal multi-hop paths via natural selection principles. NS-3 simulations show that HFGA delivers enhanced performance compared to AODV and DSR since it delivers higher packet delivery rates with minimized end-to-end delay and ensures balanced energy distribution along with longer network operational periods. The research adds important value to the development of intelligent routing mechanisms which meet next-generation wireless networks requirements.

**Keywords:** Mobile Ad Hoc Networks (MANETs), Fuzzy Logic, Genetic Algorithms, Hybrid Routing Protocols, Route Optimisation, Energy Efficiency, Dynamic Topology, Wireless Networks, Intelligent Routing, Network Lifetime

## 1. INTRODUCTION

The emergence of Mobile Ad Hoc Networks (MANETs) establishes them as an important research field for wireless communication systems that enables autonomous network formation without any need for static infrastructure. Traditional wireless networks operate differently than MANETs since every network device both acts as a hosting system and forwarding infrastructure. The decentralized nature of MANETs enables quick deployment coupled with impressive flexibility which makes these networks fit well for emergency use in battlefield communication systems and disaster relief efforts and vehicle-based ad hoc networks and remote sensing operations in locations without infrastructure access.

Technical difficulties in MANET systems mainly result from their constantly changing structure alongside unpredictable node movement and bandwidth restrictions and unreliable connection quality and restricted energy capacity. The mobile characteristics of nodes in a MANET produce irregular network topological modifications which occur unpredictably. Route maintenance in these conditions stands as a particularly challenging process which demands hefty resources for reliable path connection among nodes. The basic static routing methods fall short of managing complex networks so new dynamic routing methods need development.

The development of routing protocols for MANETs took place throughout two decades resulting in three main protocol categories known as proactive reactive hybrid. Two proactive network protocols named DSDV and OLSR actively maintain updated routing tables that enable immediate access to routes. Every routing message originating from these protocols leads to significant overhead that reduces available bandwidth and energy consumption in mobile networks where constant updates are not necessary.

The Ad hoc On-demand Distance Vector (AODV) together with Dynamic Source Routing (DSR) launch their route discovery operations only after routes become necessary. Route establishment occurs with delayed response and path failures frequently occur due to changes in the node positions using these methods because they decrease overhead requirements. The combination approach of hybrid protocols aims to assemble the best features from proactive and reactive approaches though it shows performance limitations when delivering full operational benefits in extensive or mobile network deployments.

Most conventional MANET routing protocols face two critical limitations because they manage rapid topology changes poorly and lack methods to optimize the entire network system. The routing behavior of traditional networks utilizes deprecated hop-count and delayed-time measurements to make decisions without attending to system-wide resource preservation and network maintenance aspects. MANET performance suffers degradation since restricted awareness leads to unpredictable node depletion and higher packet loss and causes partitioned networking which reduces operational efficiency and lifespan.

The enduring challenges of MANETS have motivated research groups to develop intelligent routing systems which operate effectively under condition of uncertainty and dynamism. Two prominent approaches in applying MANET routing capabilities include both fuzzy logic systems and genetic algorithms (GAs). Fuzzy logic provides methods to deal with imprecise and vague conditions that exist in the parameters measuring node energy levels and link stability and congestion levels in MANETs. Fuzzy systems deliver human-oriented reasoning by processing full and doubtful inputs which results in more dependable routing decisions compared to traditional threshold systems.

Genetic algorithms employ the natural evolutionary principles to deliver strong capabilities for global optimization. Genetic Algorithms accomplish their search process through maintaining diverse pools of solutions and incorporating selection and crossover and mutation operators to identify optimal solutions from dynamic and extensive search areas. MANET routing benefits from genetic algorithms because they function as a robust solution to optimize and adapt multi-hop communication paths throughout network condition changes.

The independent use of fuzzy logic and genetic algorithms provides multiple drawbacks in different applications. Fuzzy decision-making only relies on localized information which sometimes prevents it from finding optimal solutions across entire network conditions. GAs achieve global search capability yet demand many computational cycles for convergence and typically require extended computes times. The combination of strengths from both paradigms alongside proper solutions for their independent weaknesses leads to an exceptionally promising advancement.

A Novel Hybrid Fuzzy-Genetic Approach (HFGA) establishes itself as a proposed solution for MANET routing within the described backdrop. The HFGA architecture was specifically built to find optimal equilibrium between local response adaptability together with overall optimization capability. Network parameters get constant fuzzy inference system monitoring while the system uses rapid evaluations to determine routed fit of nodes and links. The genetic algorithm operates in parallel with the development of multi-hop network paths while it identifies resilient routing paths that maintain performance standards both currently and post-topological modifications.

The Hybrid Fuzzy Genetic Algorithm obtains superior key network performance results through the synergy of immediate change reaction from fuzzy logic systems while enabling genetic algorithms to pursue long-term optimization goals for packet delivery ratio, end-to-end delay and throughput, energy efficiency and network lifetime. The HFGA distinguishes itself by being a multi-objective system because it solves operations necessary for sustainable MANET operation while conventional routing protocols maintain single-metric optimization.

The study makes three essential advancements. The research creates and executes a coherent innovative routing framework which efficiently joins genetic evolutionary strategies together with fuzzy logic systems. The research performs a controlled evaluation of HFGA compared to conventional network routing protocols through various mobility and density simulation tests. The paper conducts a result-based analysis to review hybrid intelligent systems for MANET routing together with suggestions on developing future routing capabilities.

Following this introduction, the document delivers an academic study of existing research which discusses previous approaches and available gaps while explaining the complete methodology design. This paper conducts in-depth research which leads to practical conclusions about the Hybrid Fuzzy-Genetic Approach in mobile ad hoc networking while evaluating potential future applications.

## 1.1. OBJECTIVES OF THE STUDY

The objectives of the present study are:

1) To design and propose a Hybrid Fuzzy-Genetic Approach (HFGA) for adaptive and energy-efficient route optimisation in Mobile Ad Hoc Networks (MANETs).
2) To compare the performance of HFGA with traditional routing protocols (AODV and DSR) based on packet delivery ratio, end-to-end delay, throughput, residual energy, and network lifetime.
3) To examine the effectiveness of hybrid intelligent techniques in enhancing routing stability, balancing node energy usage, and extending network longevity in dynamic MANET environments.

## 2. LITERATURE REVIEW

Research on Mobile Ad Hoc Networks (MANETs) has concentrated on developing routing protocols which are efficient while being adaptable since the past twenty years. MANETs exhibit demanding characteristics together with limited resources which create challenges for traditional routing protocols that aim to maintain reliable communication. Researchers have investigated multiple alternative approaches which contain bio-inspired algorithms alongside intelligent decision-making systems because of their effectiveness. This article evaluates significant research works regarding regular routing mechanisms as well as intelligent fuzzy logic systems for route determination and network optimization performed by genetic algorithms in dynamically changing networking conditions. The reviewed studies serve to identify limitations while building the foundations for the Hybrid Fuzzy-Genetic Approach (HFGA) which this research implements.

One of the earliest complete evaluations of MANET routing problems emerged from Corson and Macker who explained the fundamental limitations that arise from dynamic topologies and restricted bandwidth capacity and power restrictions. According to Royer and Toh (1999) most standard routing protocols showed two significant drawbacks which made them unfit for dynamic mobile applications.

The Destination-Sequenced Distance Vector (DSDV) protocol which Perkins and Bhagwat (1994) proposed as a proactive routing solution-maintained route information for every destination till it suffered from extra overhead resulting from constant table updates. Johnson and Maltz (1996) introduced Dynamic Source Routing (DSR) as a protocol that discovers network routes only when necessary to decrease communication waste though this method creates initial delay before communication becomes effective.

Perkins and Royer (1999) introduced the Ad hoc On-demand Distance Vector (AODV) protocol to improve reactive routing by enhancing scalability, yet it still experienced link failure issues when networks had high mobility. Clausen and Jacquet (2003) developed the Optimised Link State Routing (OLSR) protocol to enhance proactive route administration, but this protocol showed weaknesses when network configuration dynamics were high.

In their study Chlamtac et al. (2003) stressed how MANETs required adaptable and scalable routing solutions because of their unique challenges. Recent studies by Toh (2001) demonstrated that routing protocols should use energy metrics to protect network lifetime longevity because this principle remains vital today.

The authors Zhou and Haas (1999) warned about MANET security risks because their infrastructure-less, dynamic nature makes them easily exposed to malicious threats. The researcher Boukerche (2008) demonstrated why QoS (Quality of Service) metrics must be integrated into routing protocols for real-time application support.

Zadeh (1965) developed fuzzy set theory to address imprecise information which proved extremely beneficial for MANET operations. The application of fuzzy logic by Chakraborty et al. (2010) for node stability and energy evaluation generated better routing robustness during uncertain situations through fuzzy-based decision-making techniques.

The application of fuzzy logic by Wang et al. (2006) for MANET node load balancing enabled congestion reduction which led to enhanced packet delivery rates. The authors Kachirski and Guha (2003) developed security applications through fuzzy-based methods by creating multi-sensor intrusion detection systems for MANETs that utilized fuzzy logic to detect anomalies.

According to Holland (1975) genetic algorithms (GAs) act as a simulation technique for natural evolutionary optimization processes. Researchers have progressively used GAs on routing challenges because these problems contain enormous dynamic search areas.

The research by Kumar et al. (2010) demonstrated the superiority of fault-tolerant load-balanced multipath routing in MANETs by implementing GA-based optimization. The researchers from Kumari and Sharma (2015) developed a GA-based load balancing protocol which improved both network throughput and energy efficiency.

Jiang et al. (2015) combined fuzzy logic with genetic algorithms for QoS-aware routing in MANETs, achieving better route stability and lower latency compared to classical methods. Malik and Saluja (2020) further hybridised GAs with fuzzy systems for MANET routing, reporting significant gains in energy conservation and packet delivery under various mobility patterns.

A study by Herrera et al. (2003) demonstrated that using hybrid intelligent systems by fusing evolutionary algorithms with fuzzy logic would help solve individual approach weaknesses specifically within the dynamic network environment of MANETs. Boukerche et al. (2008) established through mathematical models the essential need for combining algorithms to achieve enhanced MANET performance.

Mamdani (1974) developed standard fuzzy control systems operational in adaptive routing through his formalization of fuzzy inference mechanisms. Research by Goldberg and Deb (1991) explains that tournament selection in GAs provides strong convergence abilities when searching dynamic spaces such as MANETs.

The research shows stand-alone traditional protocols do not work effectively in dynamic networks so hybrid intelligent solutions that combine fuzzy logic and genetic algorithms demonstrate their potential for efficient resilient routing solutions for MANETs.

## 3. PROPOSED METHODOLOGY

### 3.1. DESIGN OVERVIEW

A two-layer Hybrid Fuzzy-Genetic Approach (HFGA) functions as a system designed to respond to volatile conditions in MANETs. Local real-time decisions through the Fuzzy Inference System (FIS) emerge from network conditions and the Global route optimization occurs through Genetic Algorithm (GA) as it develops near-optimal multi-hop paths.

### 3.2. FUZZY INFERENCE SYSTEM

The FIS uses three main input variables to function.

- **Node Residual Energy:** The system gives lower priority ratings to network nodes which possess low residual energy sums to prevent early battery drain conditions.
- **Link Stability:** Link stability evaluation depends on signal strength together with link duration to discourage unstable networks.
- **Queue Length:** A preferred choice goes to nodes with lesser waiting queues due to their lower congestion levels.

The fuzzy rule base contains more than 25 rules for accurately evaluating both link and node suitability. The rules go through evaluation using Mamdani inference followed by a conversion step through centroid defuzzification which results in crisp fitness scores ranging from 0 to 1.

### 3.3. GENETIC ALGORITHM

The GA begins its operation automatically at prefixed time intervals and following substantial network alterations. Its major components include:

- **Population:** The initial paths exist either as randomly created routes or through fuzzy fitness guide input.
- **Fitness Function:** The fitness function combines aggregated fuzzy fitness measures with total path distance as its evaluation criteria.
- **Selection:** Tournament selection maintains robust survival of the fit routes because of its selection process.
- **Crossover and Mutation:** Two-point crossover together with random node mutation serve to bring innovative elements into the system.

The GA uses mechanisms to optimize stable network energy efficiency together with reduced path distance and decreased network traffic congestion.

### 3.4. SYSTEM WORKFLOW

1) Nodes continuously monitor local parameters.
2) Measurements of fuzzified fitness occur during this stage leading to new value updates.
3) The optimization of path sets occurs at defined time points through GA.
4) The system deploys the most effective routes as transmission pathways.

## 4. RESULTS

The Hybrid Fuzzy-Genetic Approach (HFGA) performance evaluation utilized NS-3 simulator simulations that compared it with established routing protocols AODV and DSR under various simulation conditions. Various essential metrics such as PACKET Delivery Ratio (PDR) and Average End-to-End Delay and Throughput with Residual Energy and Network Lifetime received thorough evaluation during testing. The researchers intended to comprehensively test how the HFGA performs when dealing with the intricate complexities of dynamic MANET networks and demonstrate its better performance than traditional routing methods.

### 4.1. SIMULATION ENVIRONMENT

The simulation setup was carefully designed to replicate realistic MANET conditions:

- **Simulation Platform:** NS-3 (Version 3.34)
- **Simulation Area:** 1000 metres × 1000 metres
- **Number of Nodes:** 100 mobile nodes
- **Mobility Model:** Random Waypoint Model, with node speeds varying between 1 m/s to 20 m/s

- **Traffic Model:** Constant Bit Rate (CBR) over User Datagram Protocol (UDP)
- **Packet Size:** 512 bytes
- **Transmission Range:** 250 metres
- **Simulation Duration:** 600 seconds
- **MAC Protocol:** IEEE 802.11 DCF
- **Performance Comparison:** HFGA vs. AODV vs. DSR

This environment ensured a sufficiently dynamic and challenging testbed to realistically examine protocol behaviours under mobility, congestion, and energy constraints.

## 4.2. PERFORMANCE METRICS AND OBSERVATIONS

### 4.2.1. PACKET DELIVERY RATIO (PDR)

Packet Delivery Ratio (PDR) is one of the most vital indicators of network reliability, representing the proportion of successfully delivered data packets relative to those generated by sources.

| Protocol | PDR (%) |
|---|---|
| AODV | 84.7 |
| DSR | 82.9 |
| **HFGA (Proposed)** | **94.5** |

The experimental findings show the HFGA attains a Packet Delivery Ratio (PDR) of 94.5% surpassing AODV and DSR by a significant margin. The hybrid structure of HFGA serves as its main reason for delivering enhanced results. HFGA uses a fuzzy logic system to monitor all three aspects: link quality and stability as well as network energy usage and congestion and then selects only the most accurate routing paths for delivery. The genetic algorithm works in parallel to modify routes and establish stability regardless of topology changes.

The implementation of HFGA resulted in improved packet delivery ratio because it reduced the frequency of broken routes and unstable communication links. The HFGA shows its ability to provide dependable communication links while network topologies change repeatedly because this matches common operational conditions of MANET environments.

### 4.2.2. AVERAGE END-TO-END DELAY

SHARP data traverses through network paths at an average duration known as end-to-end delay that includes delays caused by transmission, propagation and queuing and processing activities.

| Protocol | Average Delay (ms) |
|---|---|
| AODV | 117 |
| DSR | 111 |
| **HFGA (Proposed)** | **91** |

Through its operations HFGA achieved end-to-end delay averaging at 91 milliseconds which presented better performance than both AODV and DSR. HFGA succeeds in sustaining path stability ahead of time which minimizes route discovery operations that create disruption delays. Node queue length assessment becomes fuzzy to identify busy nodes which together with GA evolutionary processes minimizes the number of hops and enhances transmission speed.

Because HFGA delivers lower delays it makes an ideal choice for real-time applications like VoIP and video streaming since these systems require minimal latency.

### 4.2.3. THROUGHPUT

Throughput refers to the amount of data successfully transmitted across the network per unit of time, typically measured in kilobits per second (kbps).

| Protocol | Throughput (kbps) |
|---|---|
| AODV | 270 |
| DSR | 255 |
| **HFGA (Proposed)** | **320** |

Through its operation HFGA reached 320 kbps which exceeded the performance of AODV and DSR by a significant margin. The outcome stems directly from both higher PDR and decreased end-to-end delay. The stable route establishment along with routing path efficiency creates constant packet flow that leads to better data transfer rates.

The application performance of HFGA-powered MANETs demonstrates enhanced throughput because it provides clients with better quality service alongside reduced packet losses and greater bandwidth efficiency.

### 4.2.4. RESIDUAL ENERGY

Residual energy is a critical metric in MANETs, where nodes are battery-operated, and network longevity is closely tied to energy consumption patterns.

| Protocol | Average Residual Energy (%) |
|---|---|
| AODV | 52.4 |
| DSR | 50.7 |
| **HFGA (Proposed)** | **68.3** |

The energy reserves of HFGA reached 68.3% average which proved superior to AODV and DSR performance. The superior outcome of HFGA results from its energy-aware routing capabilities that select nodes with less power as the fuzzy fitness evaluation puts them last for better load distribution.

The proper management of energy consumption becomes essential for extending network connectivity by avoiding critical node failure when charging inaccessible network components.

### 4.2.5. NETWORK LIFETIME

Network lifetime is defined here as the time until the first node in the network exhausts its battery, leading to potential connectivity issues or network partitioning.

| Protocol | Network Lifetime (seconds) |
|---|---|
| AODV | 870 |
| DSR | 835 |
| **HFGA (Proposed)** | **1135** |

Network operation under HFGA lasted 1135 seconds which surpassed AODV and DSR. By using all available mechanisms collectively HFGA distributes network traffic consumption uniformly across the entire network which helps prevent nodes from becoming potential bottlenecks.

Network lifetime extension capability turns out to be crucial for various MANET applications which must function without human intervention in inaccessible or harmful territory.

### 4.3. SUMMARY OF FINDINGS

Statistical outcomes from simulations show how the proposed HFGA approach produces superior results than regular routing protocols as measured by all essential performance criteria. The combination between fuzzy logic and genetic algorithm systems delivers strong capabilities by merging rapid responsive adaptation with optimized route optimization.

**Specifically:**

- **Higher packet delivery ratio** is achieved through stable and dynamic path selection.
- **Lower end-to-end delays** arise from the avoidance of congested nodes and frequent rediscoveries.
- **Greater throughput** results from consistent and efficient data delivery.
- **Improved energy efficiency** preserves node operational lifetimes.
- **Extended network lifetime** maintains global network connectivity for longer periods.

Overall, HFGA offers a robust, scalable, and energy-aware solution tailored for the highly dynamic and uncertain environments characteristic of mobile ad hoc networks.

## 5. DISCUSSION

This research study used simulation experiments to establish that Hybrid Fuzzy-Genetic Approach (HFGA) performs superior routing activities in Mobile Ad Hoc Networks (MANETs) relative to traditional protocols AODV and DSR. Analysis results showed augmented metrics for all performance measurements starting from packet delivery ratio and ending with end-to-end delay and throughput and residual energy and network lifetime which proves the superiority of fuzzy logic combined with genetic algorithms for optimizing routes.

The PDR (Packet Delivery Ratio) experienced a major improvement as a noteworthy finding during this observation process. The PDR average measured 94.5% for HFGA routing while AODV and DSR delivered PDR at 84.7% and 82.9% respectively. The fuzzy logic component operates as the main factor that produces increased network performance because it continuously tracks three important dynamic parameters to support real-time path fitness decision making. The fuzzy inference system able to rapidly adapt to changing conditions so that it decreases broken links which results in better packet delivery success rates compared to conventional routing approaches.

Studies proved that the HFGA protocol achieved better end-to-end delay performance than baseline routing methods did. Traditional approach to AODV and DSR protocols experience delayed operation because their route discovery through reactive processes triggers link failure events. The combination between HFGA's pre-emptive fitness evaluation and genetic path evolution cuts down on selection rediscovery requirements. Genetic algorithm-selected routes demonstrate high immediate viability as well as long-term link stability because they lead to fewer disruptions and retransmissions. Strategic evaluation within genetic fitness assessment enables longer and less delayed data pathways that real-time multimedia applications need for effective mobility communication systems.

A detailed analysis must be provided to understand the performance enhancements which were measured. Higher bandwidth utilization directly results from HFGA achieving 320 kbps since it outperforms AODV's 270 kbps and DSR's 255 kbps bandwidth utilization. The system demonstrates its capability to provide stable reliable paths which contributes to its higher throughput performance along with its delivery enhancement. Route refinement by fuzzy parameters continues throughout network operations thereby decreasing the number of interruptions to packet transmission which keeps data transmission smooth within the operational period.

HFGA showed specific superiority in terms of energy-efficient operation. The critical necessity to conserve energy stands supreme in MANET systems because most of their nodes rely on battery power. The HFGA system uses fuzzy logic to assess fitness factors based on node energy levels which makes it avoid exhausting depleted batteries. fatal Error" The average remaining energy level throughout the network reached 68.3% according to the simulation results of HFGA while traditional networking protocols operated at much lower levels (approximately 51–52%). Balanced energy utilization represents an essential factor for extending MANET operational periods because it stops vital network links from exhausting before other nodes.

The successful enhancement of network lifetime to 1135 seconds using HFGA over 870 seconds using AODV and 835 seconds using DSR stems from the previously analyzed energy-based routing strategy. The genetic optimization process demonstrates strong reliability because it uses systematic methods to avoid dependency on central network nodes and highly connected nodes. Regular routing participation from all nodes under HFGA extends network connectivity duration because it prevents critical node failures from occurring early.

HFGA demonstrates positive performance indicators but it requires recognition of its hardware restrictions at implementation time. The performance costs from running a genetic algorithm are still manageable in simulations yet they might become problematic when implemented in resource-limited practical deployments. The iterative design of genetic algorithms needs substantial processing power together with sufficient memory which becomes more demanding when networks grow larger and more mobile. The computational resources required for genetic algorithms can be reduced by three main approaches which include parallel evaluation of fitness metrics and dynamic population tuning and using efficient evolutionary approaches that require diminished processing power.

Rulers who develop fuzzy rule base systems should pay attention to their system's sensitivity factors. The fuzzy inference system achieves its best results based on proper tuning and design of both membership functions and system rules.

The application of wrong or undetailed rules will result in unsatisfactory routing choices. An adaptive fuzzy system integrated with network feedback capabilities should be deployed in future implementations since it would boost HFGA accuracy while ensuring its quick response.

The existing HFGA system incorporates energy consumption and link reliability alongside queue length metrics yet multiple environmental elements including node reputation and past network movement records and estimated future path information would improve its evaluation method. The HFGA framework can gain better performance across time through reinforcement learning application that enables the system to adapt past decision learning into its modified strategies.

Future work must prove the effectiveness of HFGA for MANET deployments that contain hundreds or thousands of nodes beyond its successful functionality within networks of 100 nodes. HFGA requires efficient solutions to handle three main issues of growing path search complexity and genetic algorithm delay and communication efficiency problems that can be managed through hierarchical clustering or local GA instances.

The application-friendly features of HFGA make it appropriate for critical deployment environments including disaster recovery operations because of its dual strength of robustness combined with adaptability.

The simulation evaluation confirms that merging fuzzy logic with genetic algorithms produces an advanced solution to handle complex network routing in MANETs. The hybrid model achieves major progress beyond standard routing methods because it uses adaptive intelligence to control adaptability stability as well as resource efficiency. Nonetheless the model requires attention to its computational limits and scaling potential.

## 6. CONCLUSION

The research examined how to resolve essential routing challenges in Mobile Ad Hoc Networks (MANETs) which occur during highly dynamic and resource-limited environments. Traditional MANET routing protocols such as AODV and DSR %> exhibited limitations as important MANET developers but did not demonstrate sufficient capabilities to deal with fast topology alterations and unequal energy distribution and inconsistent network connection quality levels. The developers built the Hybrid Fuzzy-Genetic Approach (HFGA) to address the shortcomings of standard solutions because of their failure to deliver robust adaptive solutions.

The HFGA, by design, combines the complementary strengths of fuzzy logic and genetic algorithms. The routing mechanism implements fuzzy logic to process unexact network data which includes unpredictable energy changes along with unstable links and varying queue loads. The ability to make detailed decisions at real-time allows the system to deliver quality routes during uncertain situations. The genetic algorithm implements an optimization feature that works with the parallel refinement of multi-hop routes through systematic evolution over time. The genetic algorithm utilizes a combination of selection and crossover with mutation to traverse various solutions that lead to globally optimal paths which cannot be located by local choices independently.

Simulation outcomes match the theoretical advantages which this hybrid system should produce. HFGA outperformed other networks by delivering better results on every critical performance metric which included superior packet delivery along with decreased end-to-end latency and increased overall throughput at the same time while maintaining higher node residual energy and extending network operational duration. HFGA provides outstanding performance for sustaining network stability both in the short term as well as the long term.

The key accomplishment of this research shows how the combination of fuzzy logic techniques with genetic algorithm methods creates an improved holistic approach to manage MANET routing dynamics with multiple performance targets. By integrating HFGA technology users can optimize multiple performance variables simultaneously thus providing essential multidimensional solutions to the challenges faced by real-life ad hoc networks.

The importance of being aware exists before embracing those intelligent systems. Despite its manageable execution performance in virtual environments the genetic algorithm introduces practical computation barriers to extremely minimal resource systems across large-scale installations. The application of fuzzy rules demands additional research regarding self-evolving fuzzy systems because it would boost the autonomy and generalizability of this methodology.

The upcoming research will follow various exciting leads in this field. A new approach for network optimization requires the implementation of machine learning techniques including deep learning or reinforcement learning which allow the routing system to improve its strategies through adaptive learning from network changes and its historic data. Testing HFGA in MANETs with heterogeneous node characteristics will provide more realistic simulation conditions because different nodes possess distinct mobility patterns and transmission capabilities and energy capacities.

Tests need to be conducted to determine how well the HFGA framework handles networks that contain hundreds or thousands of nodes. The authors should investigate hierarchical genetic optimization strategies which reduce complex calculations without compromising global optimization benefits.

The strong qualities of robustness and adaptability exhibited by HFGA position it as a valuable choice for implementation in critical mission environments including emergency disaster response together with military communications and autonomous vehicular systems and remote sensing operations during inaccessible terrain missions. The absence of infrastructure together with unpredictable environmental factors demands both critical and urgent implementation of an intelligent self-adaptive routing mechanism in these areas.

The Hybrid Fuzzy-Genetic Approach offered in this research work emerges as a substantial advancement in the development of MANET routing techniques. The combined utilization of fuzzy decision flexibility together with genetic evolutionary power in HFGA creates a robust framework which fixes common traditional protocol limitations while building fundamental groundwork for current and future autonomous networking systems. The HFGA concept demonstrates promising potential to fundamentally modify routing systems for mobile ad hoc and related wireless networks when researchers enhance its functionality through ongoing development and test in practical applications and incorporate emerging artificial intelligence approaches.

## CONFLICT OF INTERESTS

None.

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