A Genetic-Algorithm-Based Optimized Routing Protocol in Mobile Ad Hoc Networks

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Abstract. Mobile ad hoc networks (MANETs) are decentralized wireless systems in which nodes communicate without any fixed infrastructure. Their dynamic topology, limited bandwidth, and energy constraints present significant challenges for achieving efficient and reliable routing. To address these issues, bio-inspired optimization techniques have attracted growing interest due to their adaptability and robustness in complex environments. In this paper, we propose a multipath routing protocol based on a bio-inspired Genetic Algorithm (GARP). The multiple paths generated by the route discovery mechanism are optimized using the genetic algorithm to identify the most efficient path to the destination node. The path with the highest routing value evaluated based on node energy and link stability constraints is selected as the optimal solution. The proposed protocol is compared to existing approaches, namely AOMDV and AODV. To assess its performance, several key metrics are considered, including packet delivery ratio, routing overhead and energy consumption.

Keywords: MANET · Routing · Genetic algorithms (GA)· Energy node · Stability link.

1 Introduction

Wireless networks represent a fundamental paradigm shift in modern communication systems, allowing devices to transmit data over the air without the need for fixed infrastructure. These networks offer high mobility, rapid deployment, and flexible connectivity, which makes them suitable for a wide range of applications, from urban smart environments to healthcare and disaster management [1, 2]. Among the various types of wireless networks, mobile ad hoc networks stand out due to their self-organizing and infrastructure-less nature. In an ad hoc network, each node functions both as a host and a router, enabling data to be transmitted across the network through multi-hop communication. These networks are highly adaptable to dynamic environments and are especially valuable in scenarios where fixed infrastructure is unavailable or impractical [3].

Despite their advantages, ad hoc networks face several technical challenges, with routing being one of the most critical [4]. Routing in such environments must cope with constantly changing topologies, limited node energy, and unreliable wireless links. Traditionally, single-path routing protocols such as AODV (Ad hoc On-demand Distance Vector) [5] and DSR (Dynamic Source Routing) [6] have been employed, selecting only one path between source and destination. However, these protocols are sensitive to path failures and may lead to frequent route rediscoveries. To improve reliability, multi-path routing protocols like AOMDV (Ad hoc On-demand Multipath Distance Vector) [7] and SMR (Split Multipath Routing) [8] have been introduced, enabling redundancy and load balancing by establishing multiple simultaneous paths. Nevertheless, both categories of protocols commonly rely on hop count as the primary routing metric, which is not well-suited to the dynamic and constrained nature of ad hoc networks [9].

Using hop count as a routing metric ignores important performance parameters such as node energy, link stability, bandwidth, and latency. This often leads to the selection of unreliable paths that quickly break down or drain critical network resources. In response, researchers have developed multi-metric routing protocols that incorporate diverse parameters into the route selection process. These protocols aim to enhance the quality and sustainability of paths by balancing energy consumption, mobility patterns, and quality of service (QoS) metrics. Notable examples include RMQS-ua (Reliable Multipath Routing Protocol based on Link Quality and Stability in Urban Areas) [10], which integrates link quality and Stability, and FT-AORP [11], which adapts paths based on rate of EC, its mobility, and the strength of its radio signal. These intelligent, context-aware protocols represent a significant evolution in routing strategies for ad hoc networks.

In this context, bio-inspired optimization algorithms have emerged as promising approaches for solving complex multi-objective routing problems. Their ability to explore large solution spaces and adapt to dynamic conditions makes them well-suited for routing in ad hoc environments [12] [13].

In the following, we explore various implementation approaches of routing protocols tailored to mobile ad hoc networks (MANETs), aiming to meet key performance criteria such as Packet Delivery Ratio (PDR), Energy Consumption (EC), Overhead (OH), and End-to-End Delay (E2ED). The primary objective is to optimize the reliability and efficiency of communications between nodes by considering multiple parameters that influence the selection of the most appropriate paths between a source and destination nodes.

In [14], the authors proposed an innovative QoS-oriented routing protocol for Mobile Ad-hoc Networks (MANETs), incorporating a bio-inspired optimization approach to enhance efficient packet transmission. Their work targets environments such as Volunteered Computing MANETs and the Tactile Internet, where energy conservation and communication reliability are critical concerns. The authors introduced a novel performance modeling strategy along with an efficient buffer management mechanism to better handle the limited resources of network nodes and prolong their operational lifespan. Central to their contribution is the Optimized mutual MAC (OMAC) process, an adaptive switch-state mechanism that promotes optimal utilization of available nodes prior to resource depletion. This approach aims to bridge the gap between network performance and energy efficiency by reducing overhead while maintaining strong Quality of Service (QoS). Simulation results provided in the study demonstrate significant improvements in latency, node availability, energy consumption, and network stability when compared to existing systems. This protocol underscores the value of adaptive strategies in addressing the trade-offs between network longevity and data transmission quality in MANET environments. However, this solution does not take into account node mobility, so the buffer management mechanism and energy optimization techniques could introduce additional overhead, potentially affecting throughput, especially in resource-constrained nodes.

In [15],the authors proposed an enhanced version of the AODV protocol, referred to as the Multi-objective Optimized AODV, specifically designed for Mobile Ad Hoc Networks (MANETs). The main objective of their work is to improve the robustness of AODV's route recovery mechanism, which is frequently challenged by node mobility and recurrent link failures. To address this, the authors introduced a dynamic strategy based on the optimization of four key parameters: SW1 and SW2, which determine the weights associated with the source-initiated repair mechanism, and LW1 and LW2, which control the local repair decision. These parameters guide the protocol in selecting the most appropriate route recovery strategy depending on real-time network conditions. The base protocol used in their approach is AODV, which was modified to integrate node connectivity information directly into routing control packets, through three alternative implementations (AODV-C1, C2, and C3). The bio-inspired optimization process leverages three multi-objective metaheuristics: NSGA-II, SMPSO, and SPEA2. The fitness function used to evaluate the candidate solutions incorporates four Quality of Service (QoS) metrics: routing delay, packet loss ratio (PLR), normalized routing load (NRL), and energy consumption (EC). The proposed solution was benchmarked against the original AODV, a mono-objective optimized AODV, and four additional well-known routing protocols. Experimental results demonstrated notable performance improvements, with average reductions in route load, routing delay, packet loss ratio, and energy consumption, validating the effectiveness and competitiveness of the multi-objective optimization approach. Although the proposed solution by Santana et al. shows promising improvements, several limitations should be considered. First, the solution is only compared to basic routing protocols, without including more advanced or optimized protocols that could better reflect real-world scenarios. Additionally, the network used for testing was relatively small (50 nodes), which raises concerns about its scalability in larger networks or high-density environments.

To address the instability of path estimation caused by frequent link failures and node mobility in MANETs, the authors in [16] proposed a bio-inspired routing protocol named AIFSORP (Ambient Intelligence-based Fish Swarm Optimization Routing Protocol). This protocol is based on the Fish Swarm Optimization (FSO) technique, enhanced with principles of ambient intelligence, to dynamically identify the most efficient routes with reduced time and energy costs. In AIFSORP, nodes promptly notify their neighbors upon discovering a potentially viable route, and only those paths that meet a predefined threshold condition are selected for data transmission. The approach employs an objective (fitness) function inspired by fish swarm movement patterns to evaluate route quality, although specific constraint parameters are not explicitly detailed. The performance of AIFSORP was compared against two protocols, APDRP and MARP, using metrics such as latency, node availability, and energy consumption. The results showed that AIFSORP more effectively reduces delays and energy usage. However, a limitation of the proposed protocol is that it does not explicitly consider the residual energy constraint of nodes in its route selection process.

In [17], the authors proposed an enhancement of the AOMDV routing protocol for Mobile Ad Hoc Networks (MANETs), taking into account critical constraints such as energy consumption, network congestion, and random packet loss. Two variants were introduced: AOMDV-FFn, which relies solely on a fitness function, and AOMDV-GA, which incorporates a genetic algorithm. These approaches aim to optimize path selection among those initially discovered by AOMDV, favoring paths with minimal distance, maximal residual energy at intermediate nodes, and minimal congestion. The genetic algorithm, used as a bio-inspired method, follows the conventional steps of population initialization, selection, crossover, mutation, and survivor selection. The fitness function combines three constraints: residual energy (Fe), distance (Fd), and a congestion factor (Fc), the latter being computed using the TCP CERL (Congestion Control Enhancement for Random Loss) mechanism, which distinguishes packet loss due to congestion from that caused by random factors. The simulation scenarios consider node mobility, equal initial energy across nodes, and the dynamic nature of distances and links. The protocol's performance was evaluated through simulation by comparing it to classical versions of AOMDV, DSR, and DSDV. The results demonstrated significant improvements in terms of reduced end-to-end delay, increased packet delivery ratio, better energy efficiency, and higher throughput, particularly under conditions of random loss and congestion. However, the proposed solution was only benchmarked against basic routing protocols such as AODV and AOMDV, without comparison to more recent or optimized techniques. Furthermore, the simulations were conducted in a relatively simple environment, characterized by a limited number of nodes and low mobility, which restricts the generalizability of the findings to more dynamic and dense network scenarios.

2 Implementation of GARP Protocol

2.1 Problem Statement

Efficient energy management is a central challenge in the development of wireless ad hoc networks, due to the limited energy resources of nodes, which are typically battery-powered. This energy constraint directly affects the routing capacity of nodes, degrades the quality of service, and reduces the overall network lifetime. Since advancements in battery technology are progressing at a slower pace compared to rapid developments in electronics, it becomes crucial to implement strategies that limit energy consumption. One of the most effective approaches is to select short routes with low traffic load, in order to minimize transmission delays, reduce congestion, and thereby extend network availability. In this context, integrating an intelligent routing protocol based on optimization mechanisms for path selection appears to be a relevant solution to ensure efficient communication while preserving the network's energy autonomy.

2.2 Proposed Solution

In the reactive AOMDV routing protocol [7], when the source node attempts to establish a connection with the destination node, it broadcasts a routing request (RREQ) to discover available paths. There may be multiple potential paths between the two endpoints. However, AOMDV selects only the path with the minimum hop count, without considering the quality of the route. To improve this approach, we introduce a new routing function (RFn), which will be used within a genetic algorithm (GA) framework [18]. Consequently, we propose a new multipath routing solution called GARP, which incorporates the genetic algorithm.

In this approach, when an RREQ is broadcast and multiple paths are received, the source node must choose the path that offers the optimal combination of better energy consumption and improved link stability. In other words, the RFn will integrate the following constraints:

- The residual energy of the nodes included in the path,
- The stability of the links included in the path,

The selection of the optimal path for data transmission will be determined by the maximum routing value of the path. The main criteria used to identify the optimal path are: (a) the highest residual energy level, and (b) the lowest instability of the links.

In the proposed architecture, mobile nodes are randomly distributed to form a MANET. The network assumptions are as follows:

- The network consists of mobile nodes, each having a unique identifier and random energy levels.
- The nodes possess mobility capabilities, which result in constant changes in the distances between them.
- Node mobility may cause link failures.

2.3 Routing Function

In this work, we introduce a novel routing function composed of two distinct constraints: the node energy and the link stability [19].

Node Energy Function The energy evaluation of a path is based on the analysis of the residual energy of the nodes that compose it. At a given time t, this function is determined by the lowest residual energy among all nodes along the path, thus identifying the most energy-constrained link. Its formula is

$$fep_j(t) = \min_{i=1}^{n-1}(fen_{i,j}(t)) \quad (1)$$

The energy function for a node n_i is expressed as

$$fen_{i,j}(t) = \frac{Elev_{i,j}(t)}{DR_{i,j}(t)} \quad (2)$$

$Elev_{i,j}(t)$ denotes the energy level of node n_i, which is part of path P_j, and is calculated as follows

$$Elev_{i,j}(t) = \frac{E_{i,j}(t)}{E_{average,j}(t)} \quad (3)$$

$E_{average,j}(t)$ represents the average residual energy of the nodes involved in path P_j. For each node, a drain rate, denoted as $DR_{i,j}(t)$, is assigned based on its energy consumption and participation in the path.

Link Stability Function Numerous studies on ad hoc networks have highlighted the impact of node mobility on routing. In this work, we will leverage real-time node coordinates to assess the mobility of a link. The stability function of a path P_j is determined by the highest value among the stability functions of the links that constitute the path, its formula is

$$fsp_j(t) = \max_{i=1}^{n-1}(fsl_{i,j}(t)) \quad (4)$$

The link stability function $fsl_{i,j}(t)$ is a normalized metric used to assess the dispersion of a probability distribution. Its value ranges from 0 *to* 1, and it is calculated as follows

$$fsl_{i,j}(t) = \frac{SDl_{i,j}(t)}{Ml_{i,j}(t)} \quad (5)$$

where $Ml_{i,j}(t)$ represents the average of nn distances computed between two nodes, determined using the following formula:

$$Ml_{i,j}(t) = \frac{\sum_{t=t_1}^{t_n} D_{i,j}(t)}{n} \quad (6)$$

The distance $D_{i,j}(t)$ between two nodes ni, located at coordinates (x_i, y_i), and n_j, located at (x_j, y_j), at time t, is computed using the Euclidean distance formula:

$$D_{i,j}(t) = \sqrt{(x_i(t) - x_j(t))^2 + (y_i(t) - y_j(t))^2} \tag{7}$$

To analyze the distribution of the recorded distance data, we use the average absolute deviation between nodes, denoted by $SDl_{i,j}(t)$, and defined as follows

$$SDl_{i,j}(t) = \frac{1}{n} \times \sum_{t=t_1}^{t_n} |D_{i,j}(t) - Ml_{i,j}(t)| \tag{8}$$

The Routing Function Our routing function is calculated based on two constraints: the energy function and the stability function. Its formula is

$$fp_j(t) = \alpha \times fep_j(t) + \frac{\beta}{fsp_j(t)} \tag{9}$$

3 Methodology

In this work, it is assumed that each mobile node in the wireless network has a random initial energy. The operational scheme of the proposed algorithm is illustrated in Figure 1. Initially, the AOMDV protocol is used to identify multiple possible paths between a source node S and a destination node D. Subsequently, a genetic algorithm is implemented following a structured five-step process: initial generation, evaluation via a performance function, selection of individuals, crossover operations, and finally, mutation operation. Data transfer is then carried out through the optimal best path.

Initialization: This step involves defining the necessary parameters for the Genetic Algorithm (GA) and configuring the simulation conditions, which are based on Algorithm 1. At this stage, six parameters are specified:

- *Genes* represents the number of individual nodes in a path.
- *PopSize* refers to the total number of paths discovered between the source and the destination.
- P_c is the probability that a pair of paths will undergo crossover.
- P_m is the probability that a node in a path will undergo mutation.
- *SurvivorSel* defines the path with the best performance (the one with the highest routing value) which will be returned as the search solution.
- *GensNoChange* is the termination criterion, indicating the number of generations that can pass without the elite path changing before it is returned as the solution. The elite path is the one with the highest routing value.

Routing: At this stage, the routing function value is computed for each discovered path. It is determined by integrating two key constraints: the residual energy of the nodes and the stability of the links. The set of routing values is then evaluated within the selection process, allowing the identification of the elite path of the generation. In our proposed solution, this routing function is defined by Equation (9).

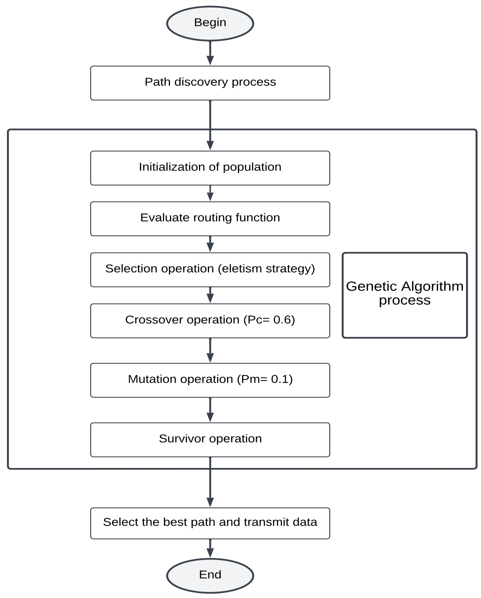

Fig. 1. Flowchart of our routing protocol (GARP).

Selection: During the selection phase, paths with the lowest routing values are discarded, while the others are retained. Our protocol incorporates an elitism strategy, which consists in preserving half of [20] the paths with the highest routing performance. This approach aims to promote the progression of the most efficient paths to the next stage, while reducing the need for additional crossover and mutation operations. The least effective paths are thus eliminated, and new candidate paths will subsequently be generated using Algorithm 1.

Crossover: This operation pairs all paths (except the elite path) for crossover, with a probability P_c, by applying Algorithm 1. The crossover process involves exchanging nodes between each selected pair of paths, typically focusing on segments with higher routing values. Specifically, the segments located on either side of the crossover point are swapped between the two paths. In practice, the crossover probability generally ranges between 0.6 and 1 [21].

Mutation: represents the final stage of the process, following the crossover phase. Each node within the paths (excluding the elite path) may undergo mutation, which involves altering the order of nodes within the same path, according to a mutation probability P_m. Once the crossover and mutation operations are completed, the entire set of paths is re-evaluated as part of the survivor selection process.

Algorithm 1 GA Algorithm

Require: Collection of discovered paths
Ensure: Efficient path E

$P_c \leftarrow 0.6$
$P_m \leftarrow 0.1$
$Ep \leftarrow \emptyset$
$Nc \leftarrow \emptyset$
$Oc \leftarrow \emptyset$
$R_f \leftarrow$ Routing function
$POP \leftarrow$ Apply R_f to multiple paths
for all routes in POP **do**
  while $P_p \leftarrow GP(POP)$ **do**
    $Nc \leftarrow$ Crossover(P_p, O_p, P_c)
    $Nc \leftarrow$ Mutation(P_n, h_c, P_m)
    $Nc_f \leftarrow$ Routing(Nc)
  end while
  for all paths in Nc_f **do**
    if $Nc_f \geq Oc_f$ **then**
      $Ep \leftarrow Nc_f$
    end if
  end for
end for
return Ep

Survivor Selection: In this step, each newly generated path (offspring) is evaluated using Equation (9). If the offspring path exhibits a higher routing value than its parent paths, it is retained as a potential candidate for data packet forwarding. Otherwise, it is added to the table of efficient paths. This table is then sorted in descending order of routing values to prioritize the most performant paths.

4 Performance Evaluation

In this section, we present the performance metrics and evaluation parameters employed in the simulation to assess the effectiveness and reliability of the proposed GARP multipath routing protocol. The performance of our approach is compared against two proactive routing protocols: AOMDV and AODV.

4.1 Performence Parameters

The performance evaluation of routing protocols will be conducted using the NS-2.35 network simulator. To generate and analyze node mobility scenarios, the BonnMotion tool will be utilized. The simulation parameters are summarized in Table 1.

Table 1. Simulation parameters.

Parameters	**Value**
Routing protocols	GARP, AOMDV, AODV
Mobility model	RWP
Transport agent	UDP
Traffic type	CBR
simulation time	200 s
Terrain range	$800 \times 800\ m^2$
Number of nodes	$50 - 100$ $nodes$
Speed interval	$5 - 20$ (m/s)
Energy interval	30 to 100 J
Size of packets	512 $bytes$
P_c	0.6
P_m	0.1

4.2 Performence Metrics

To assess the effectiveness of the proposed routing solution, we adopt the following performance metrics:

- **Packet Delivery Ratio (PDR):** This metric represents the ratio between the total number of data packets successfully received by the destination node and the total number of data packets transmitted by the source node. It reflects the reliability of data transmission within the network.
- **Overhead (OH):** Defined as the ratio of the total number of control packets generated by all nodes to the total number of data packets received at the destination. This metric quantifies the additional communication cost incurred to maintain and discover paths.
- **Energy Consumption (EC):** refers to the total amount of energy expended by all network nodes throughout the simulation duration.

5 Experimental Results

5.1 Packet Delivery Ratio (PDR)

Figure 2 presents the packet delivery ratio (PDR) of the three routing protocols under two network scenarios comprising 50 and 100 nodes, respectively. In each scenario, nodes are subject to varying mobility speeds. The results indicate that the PDR decreases as the mobility speed increases, highlighting the sensitivity of routing performance to node dynamics. Nonetheless, the proposed protocol consistently outperforms AOMDV and AODV across all configurations. This improved performance is attributed to its efficient path selection mechanism, which leverages the genetic algorithm guided by a fitness function that jointly considers two critical parameters: link stability and node energy.

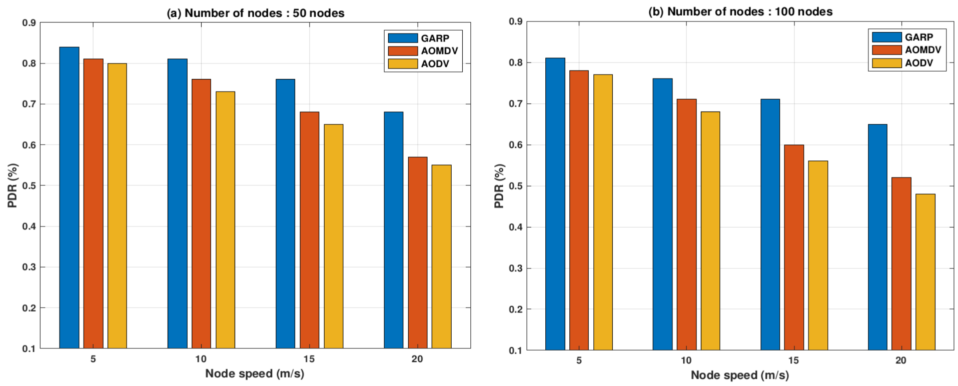

Fig. 2. Packet Delevery Ratio vs node speed.

5.2 Overhead (OH)

Figure 3 illustrates the routing overhead observed in two scenarios involving varying node speeds. The proposed GARP protocol exhibits a significantly lower number of control packets compared to AOMDV and AODV. This improvement is primarily due to the integration of the link stability metric within the fitness function, which enables GARP to proactively avoid unstable paths. In contrast, AOMDV and AODV rely solely on hop count for path selection, without considering link stability. As a result, they experience a higher frequency of route failures, particularly under high-mobility conditions, leading to increased control packet generation.

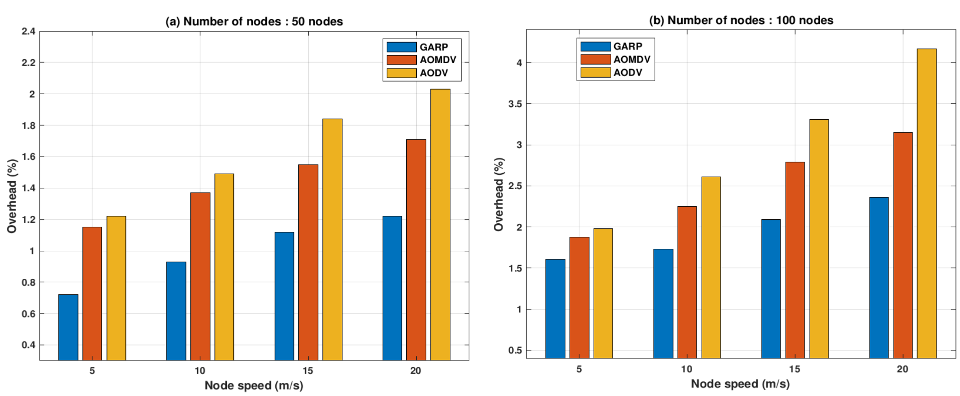

Fig. 3. Overhead rate vs node speed.

5.3 Energy Consumption (EC)

Figure 4 illustrates the energy consumption of the three routing protocols under varying mobility conditions. As expected, energy consumption tends to increase with higher mobility due to more frequent link disruptions and route rediscoveries. However, the proposed GARP protocol demonstrates lower energy consumption compared to AOMDV and AODV. This efficiency is primarily attributed to its ability to select paths with a longer lifetime, thereby reducing the frequency of route discoveries and the overhead associated with control packets. The path selection process in GARP is guided by a fitness function that incorporates both residual energy and link stability, leading to more sustainable routing decisions.

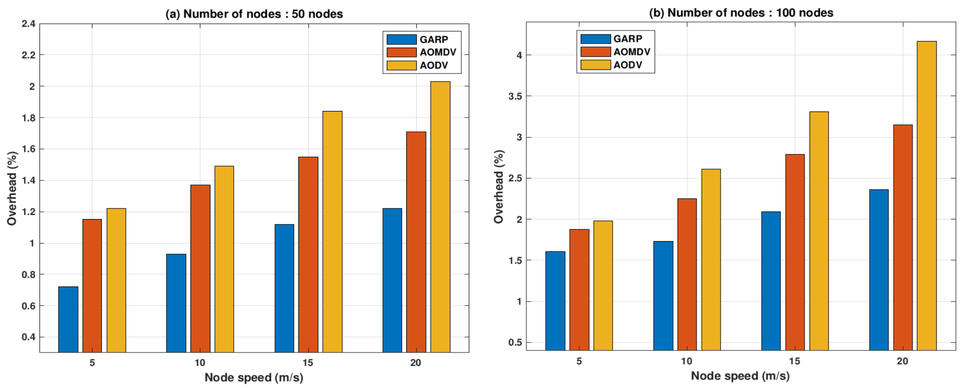

Fig. 4. Energy consumption vs node speed.

6 Conclusion

In this paper, we addressed the routing challenges inherent to mobile ad hoc Networks (MANETs), which are highly dynamic environments where frequent link failures and path disruptions occur. To enhance network reliability and optimize energy consumption, we proposed a novel multipath routing protocol, GARP (Genetic-Algorithm-based Routing Protocol). GARP leverages the GA algorithm to identify optimal communication paths between source and destination nodes. The path selection process is guided by a fitness function that simultaneously considers two critical objectives: node energy and link stability. In anticipation of potential path failures, GARP also precomputes alternative paths to ensure continuous data transmission. Performance evaluations demonstrate that GARP significantly improves MANET routing efficiency compared to existing protocols in the literature. For future work, we plan to extend this protocol by incorporating additional concerns such as Quality of Service (QoS), security mechanisms, and load balancing strategies. Furthermore, we intend to explore new performance metrics to further refine our simulation framework and enhance protocol robustness.

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