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Multipath Routing Protocol Using Genetic Algorithm in Mobile Ad Hoc Networks

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ABSTRACT Mobile ad hoc network (MANET) is a cluster of wireless mobile gadgets that creates a temporary network without seeking support from any infrastructure or central management. Energy consumption should be considered as one of the foremost vital limitations in MANETs because the mobile nodes do not possess a constant power supply and its shortage will minimize the network's lifetime. MANETs get energy from the batteries which get exhausted very quickly because of issues like node mobility, computation power, frequent data retransmissions needed in wireless communication, etc. Secondly, there is a data packet loss caused by different reasons such as traffic congestion or random loss as a result of nodes mobility or noise. This data loss, in turn, would delay packets delivery degrading data transmission in real-time applications. This paper provides management for this combination of major problems in MANETs. We present a new fitness function (FFn) used in the Genetic Algorithm (GA) to obtain the optimized route from those routes offered by the Ad hoc On-demand Multipath Distance Vector (AOMDV) routing protocol. Accordingly, we propose a routing protocol titled as AOMDV with FFn (AOMDV-FFn). We also integrate the AOMDV mechanism with the genetic algorithm (AOMDV-GA). These protocols provide an optimization process to select the efficient routes that have the highest fitness values implementing the shortest route, maximum residual energy, and less data traffic even if a random loss of data packets happens. In this regard, we introduce a mechanism where the TCP Congestion Control Enhancement for Random Loss (TCP CERL) can be utilized in the FFn to optimize the efficient route. The performance of the proposed mechanisms is compared with other preferred protocols proposed in this area.

INDEX TERMS Congestion control, energy-efficient protocol, fitness function, genetic algorithm, mobile ad hoc network, multipath routing, shortest distance.

I. INTRODUCTION

With progress in Information and Communication Technology (ICT), mobile ad hoc networks (MANETs) can support high network capacity and increasing modern multimedia services, such as video-on-demand, online shopping, entertainment, and virtual surgeries, etc. The domain of IEEE 802.11-based wireless MANETs is becoming popular because of its significance in non-traditional applications like vehicular ad hoc networks (VANETs), health surveillance, military units, disaster rescue operation, etc. MANETs provide an infrastructure-less environment enabling mobile devices to act as a wireless sender, receiver, and router. In contrast, Wireless Fidelity (Wi-Fi) networks or other ad hoc networks need an access point for functioning. A huge amount of energy is utilized in MANETs with the traffic that comes from the comprehensive access and multimedia applications with Quality of Service (QoS) requirements. For the network's sustainability, a plentiful amount of energy is required at each node. For this reason, energy which is usually driven by batteries with finite capacities is considered as an elite asset in mobile devices. Moreover, the advancement in battery technology is still progressing and expected to enhance in the future [1]. Therefore, for efficient utilization of energy at mobile nodes and to sustain the lifespan of the network, research work has been pursued in [2], [3]. Nonetheless, these researches just get in the way of the requirement for energy reload or energy harvesting [4]. Energy harvesting from different sources (e.g., vibration, thermal, radio-frequency, solar, and flow-based) for the consistent activity of mobile agents have been taken into consideration. However, it has a limited implementation in the real world because of the

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predictability complications and the excessive infrastructure needed. If we examine, most of the traditional routing protocols are proposed by the Internet Engineering Task Force (IETF). Most of these protocols establish the routes based on the least number of hops from the source to destination, less energy consumption, or a few of the QoS parameters [5]–[7].

The Power-Aware Routing (PAR) protocols specifically handle the reduction of the power depletion of the batteries of the mobile agents. The main idea behind these protocols is to transmit the traffic through the nodes which have the highest amount of residual energy. Hence, this mechanism enhances the performance and the lifespan of the network [8]. Energy-aware routing protocols have been proposed by taking into account the remaining energy on each router and establishes the best route for traffic delivery. Many routing expenses and route selection algorithms have been studied and researched for the sole objective of improving the energy efficiency in the MANETs [9].

On the other hand, constant high traffic in the mobile ad hoc networks consumes a lot of energy while degrading the performance of the network through creating congestion and likely causing data loss. Random node mobility and the unreliability of wireless medium makes routing in MANETs even more difficult. Most of the existing routing protocols make only the best effort to find the shortest route for transmission through solving these problems separately without considering various parameters of QoS performance [10].

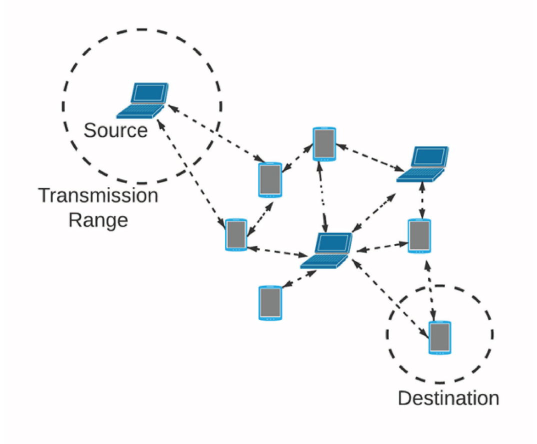

FIGURE 1. **Mobile Ad hoc networks.**

As shown in Fig. 1, nodes in MANETs are capable of making random movements that result in constantly changing and self-governing network topologies. One of the prevailing reasons for packet loss in MANETs is the link breakage. This is primarily owing to node mobility characteristic which usually varies dynamically during the network life [11]. Transmission Control Protocol (TCP) New-Reno implementation in wireless ad hoc networks approaches the packet loss as a sign of congestion either in the case of buffer overflow or connection breakdown. It demotes the congestion window capacity to half of its current size [12].

Multipath routing protocols enable the source node to select the most suitable route amongst multiple routes during a single route discovery process. This process in multipath routing minimizes the number of route discovery processes as long as there is a pool of routes already available. The extra routes can be utilized in the event of any type of failure in the route, and therefore they will reduce the end-to-end delay and energy wastage while extending the network lifetime [13]. Motivated through technological progress in wireless systems and portable gadgets, the concurrent multipath transfer is a valuable way of efficient routing in MANETs. This routing technique can be utilized in applications such as streaming high-quality mobile videos in heterogeneous access medium [14].

In this paper, we introduce a new fitness function (FFn) as an optimization technique to obtain the best route from the source to the destination using Ad hoc On-demand Multipath Distance Vector (AOMDV) routing protocol. Next, we propose a routing protocol titled as AOMDV with FFn (AOMDV-FFn). We also propose a combination of the AOMDV mechanism with the genetic algorithm (AOMDV-GA) based on the FFn. AOMDV-FFn is only using fitness function and not going into any of the GA steps like the crossover, mutation, etc. The FFn selects the best route among those devoted to the multipath algorithm. In this work, we pursue three parameters to select the most suitable route from source to destination. The selected route should have the least distance to the final destination passing through nodes having the highest residual energy and also where the route has less traffic to avoid congestion. In this regard, we develop the TCP Congestion Control Enhancement for Random Loss (TCP CERL) in [15] to be utilized in the fitness function. TCP CERL is capable of distinguishing between the random loss and the congestion loss in the selected efficient route.

Based on the results of the simulation, our routing protocols based on the proposed fitness function outperform other routing mechanisms in terms of throughput, packet delivery ratio, energy consumption, and end-to-end delay. Our protocols perform excellently in case of random loss and congestive network.

The rest of the paper is arranged as follows: Section II covers a survey on a literature review. Section III discusses the routing problem and its solution by explaining the used fitness function. Section IV introduces the proposed AOMDV-FFn and AOMDV-GA algorithms. Section V outlines the performance evaluation. Section VI presents the experimental results. Section VII explains the complexity of the proposed protocols. Section VIII concludes the research results.

II. LITERATURE REVIEW

AOMDV is the most recognized multipath on-demand routing mechanism and it is the advancement of the standard AODV protocol. AOMDV finds multiple routes from the source to the destination where all the routes are loop-free and link-disjoint. On the contrary of AODV, AOMDV protocol avoids the route phase discovery needed in case of

Destination
Sequence number
Advertised_hopcount
Route_list {(next_hop$_1$, hop_count$_1$), (next_hop$_2$, hop_count$_2$),…}
Expiration timeout

FIGURE 2. Routing table structure of AOMDV.

links failure. AOMDV mainly uses the hop count metric to determine the optimized routes. Fig. 2 depicts the routing table entry structure of AOMDV [16]. Advertised_hopcount is used instead of the traditionally used hop_count in AODV. A route_list stood as a replacement for the next_hop; this change is significantly determining multiple next_hops with corresponding hop counts. All next_hops, though, are still assigned the same destination sequence number. Every time the sequence number gets refreshed, the advertised_hopcount is initialized [16]. AOMDV finds the multiple routes and transmits the packet using the route with the minimum hop_count without even considering the energy usage or the traffic in that specific route, which can be regarded as the major drawback of this protocol. For example, in Fig. 3, the multiple routes from S (source) to D (destination) can be S-E-C-F-D and S-A-C-B-D, etc, using the AOMDV protocol.

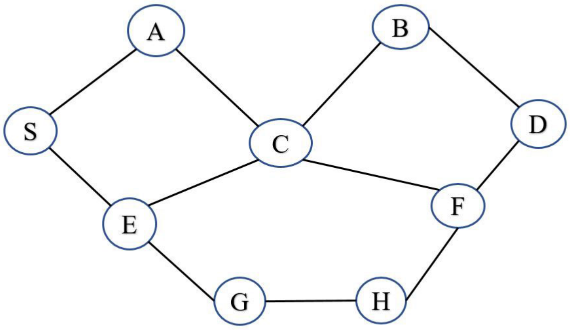

FIGURE 3. AOMDV routing protocol.

GA algorithm generally has different phases such as initializing the set of routes, calculating the fitness of all the routes, choosing the best one based on the highest fitness value, performing crossover and mutation on the routes, then evaluating the condition and repeating until the termination condition is obtained [17], [18].

The genetic algorithm is assumed from the natural selection which supports the fittest people of a population. These individuals are more likely to reproduce, thus producing more successors in the next generations. Because of the less operating costs, ease of implementation, and easy parallelization, GA has been implemented in numerous optimization problems [19]. Several approaches and terminologies from biology are applied as a theoretical base in GA. The terminologies that are used in the genetic approach are gene, chromosome, parents, children, and fitness function. A gene is defined as an optimization variable that is expressed in a coded form. A chromosome denotes a limited number of genes that represent an individual. Parents are the individuals who are decided by the method of natural selection to become candidates in the reproduction procedure. Children are the resulting individuals of this operator, and the value of one's fitness function depicts the degree of suitability of specific individuals in the conditions in which they exist [20].

The basic procedure of a GA in networking can be described in the following steps [20]:

- Initialize the process through having a set of individual routes which is called as a population,
- Calculate the fitness outcome of each route,
- Select the fittest routes to participate in creating a new route, i.e., reproduction process. The crossover operator makes the permutation of the genetic material of the selected routes (parents) and generates new routes (children) with probability P_c. New routes are submitted to mutation with probability P_m,
- The GA terminates when getting a route with the highest fitness score where further offspring routes will not have higher fitness values than the prior generation.

In simple words, multiple paths are taken as population, and the paths with the high fitness value are paired, then crossover and mutation are performed. For instance, in the "initialize" section, it will start with the multiple routes. As shown in fig. 3, there are multiple paths from S to D. Lets consider route A as "S-A-C-B-D", route B as "S-E-C-F-D" and route C as "S-E-G-H-F-D". In the "evaluate fitness" section, it will compute the fitness for every single route from S to D. For example; route A got 9.6 fitness value; route B got 9.5 fitness value, and route C got 3.4 fitness value. The routes with the bad/worse fitness value are discarded. In this case, route C will be rejected. Routes with the best fitness value are selected in the "selection" section, and they are paired and crossed over in the "p airing and crossover" section. And finally, they are mutated. As in our example, route A and route B will be paired because they have high fitness value, and then they are crossed over and mutated. And we get new paths, for example, S-A-C-F-D and S-E-C-B-D. In the "Survivor selection", it is checked that the fitness of the crossed and mutated route is higher or lower than the previously calculated fitness value of the existing routes. If it is higher, then the new route is selected as an efficient path; otherwise, the existing route with the highest fitness value is selected.

Authors in [21] proposed a Topological change Adaptive Ad hoc On-demand Multipath Distance Vector (TA-AOMDV) routing protocol, which focuses on minimizing the data traffic with the use of QoS. The limitation of this protocol is that it does not work well in dynamic layouts which require both route stability and node density. Generally, this protocol provides a little performance improvement where other protocols in many cases do way better.

Periyasamy *et al.* [22] proposed a protocol called Link Reliable Multipath Routing (LRMR). The pair of metrics used in this protocol is route length and Route-Link Quality Estimator (P-LQE) which produce multiple link reliable routes. It also minimizes the probability of routing interruptions in wireless ad hoc networks. Resources of a node such as residual energy and the available bandwidth are not taken into account so the QoS metric can only be useful to some extent. Furthermore, the End-to-End Link Reliable Energy Efficient Multipath Routing (E2E-LREEMR) protocol was proposed to deal with the faulty links and route breakages. This mechanism suggested the use of P-LQE and Route-Node Energy Estimator to find multiple steady energy-saving routes [23]. However, E2E-LREEMR slightly improves the network performance compared to AOMDV.

FF-AOMDV was proposed in [24] which presented the concept of selecting the efficient route that has a minimum energy consumption and the shortest distance. This protocol used AOMDV so in case of any failure or link breakage, the transmission will be done through the alternative route having the next shortest route in the routing table. The FF-AOMDV model considered few QoS parameters so its performance is not that high compared to AOMDV while the enhancement of the network's lifetime is quite bounded.

Authors of [25] proposed Least Common Multiple based Routing (LCMR) for load-balanced multipath routing in MANETs. The multiple routes are selected based on the minimum of calculated routing times between the sender and the receiver. LCMR has better results than the existing multipath load-balanced routing protocols like Fibonacci Multipath Load Balancing (FMLB) and Multiple AODV (MAODV) as it considers the distribution of packets along different routes. Energy consumption is the main element that drives a network, however, it is not considered in this protocol.

GA was used in [26] for the route selection though optimizing both distance and congestion metrics. This algorithm selects the route having less possibility of congestion in case of high-load traffic. However, energy consumption status is not considered. Hence, in case of a high load is flooding the network, the network lifetime is reduced.

The authors of [27] proposed a routing algorithm that enhances the quality of the network using GA. This work has considered different scenarios including mobility speed and nodes failure. The performance of the network was improved compared to other protocols. However, it was not considered the energy consumption issue.

The receiver energy-efficient congestion control algorithm was proposed in [28] which is based on the multipath transmission control protocol (EEMPTCP). Simulation results illustrate that this algorithm performs better than MPTCP as it consumes less energy and the throughput is improved. However, the proposed protocol did not consider the random loss that occurs frequently in wireless links in lossy networks. Therefore, any packets loss will be assumed as a result of congestion loss and this would shrink the congestion window and degrade the data throughput.

The authors in [29], proposed a routing algorithm that considers the energy efficiency and some of the QoS routing parameters in [30]. This algorithm relies on broadcasting the topological information to the entire network to update the nodes on the network QoS status. This information flooding would increase the overhead of the traffic, particularly with large scale networks.

In [31], it was proposed a protocol called Dynamic Energy Ad hoc On-demand Distance Vector (DE-AODV) routing protocol. The main objective is to minimize the delay in packet transmission, reduce energy consumption and hence, maximize the network lifetime. It selects the route with the shortest distance while also choosing the intermediate nodes with high residual energy and authority in the network. This protocol provides external energy to the nodes in case of any unexpected link breakage or low-energy nodes during packets transmission. Therefore, it makes the route more reliable and increases lifespan. This supply of external energy can also be counted as a limitation in terms of increasing the network cost.

Authors of [32] proposed a novel protocol called Congestion-Aware Clustering and Routing (CCR) to eliminate the congestion and clustering in Wireless Sensor Networks (WSN). Sender-side congestion control and model-based bandwidth estimation for TCP traffic over contention-free Time-division multiple access (TDMA) based MANETs was proposed in [33]. Both protocols provide good solutions for routing based on congestion avoidance, however, they did not consider the random loss which would reduce the congestion window unnecessarily.

The problem of packets random loss is a major problem in dynamic MANETs because of frequent mobility. This problem was considered in routing protocols in [34], however, other aspects such as the energy of the nodes were not touched. Even the random loss was assumed with low rates. On the other hand and to distinguish between random loss and the congestion loss, several protocols were proposed such as TCP Westwood+ [35], TCP New Jersey+ [36] and TCP mVeno [37]. In [15], TCP CERL algorithm was tested with two-way transmission and relatively heavy load connections to accommodate multiple real-time applications. CERL works efficiently to improve network performance even when a random loss occurs.

The main shortcomings of the mechanisms explained above are that several protocols are only focusing on saving the excessive amount of consumed energy while other protocols consider only the congestion control to find the best route for the data transmission. Nevertheless, these protocols ignore the effect of congestive links on the energy consumption in terms of having an excessive amount of data retransmissions which in turn would consume more energy. Moreover, nodes mobility that likely results in data random loss is not considered together with the energy efficiency and congestion control in any routing protocol up to our knowledge. This motivated us to propose a mechanism that combines solutions for all these challenges. Our solution focuses on finding the route which has the least traffic, shortest distance, and consumes less energy while supporting the nodes mobility and its consequence of having links failure and accordingly data loss.

III. THE PROPOSED PROTOCOL

A. PROBLEM STATEMENT

Power optimization is one of the significant issues on a wide range of wireless ad hoc devices. In this regard, the vast majority of the proposed research activities were generally concerned about the ad hoc network's functionality and performance over their operation time. Energy minimization is one of the primary design criteria of MANETs because nodes are battery operated. The consumption of node power reduces the node routing capacity, downgrades the performance, and critically hits the network lifetime. Also, the advancements in battery telecommunications are slow-paced compared with the growth of semiconductor technology. Hence, it is necessary to reduce the energy drain of the nodes to improve the network lifetime during data transmission. To reduce energy consumption, we need to select the efficient and optimized shortest route which consumes less energy and also passes less data traffic. The route with less traffic will transfer the packets quickly with minimal queuing delay and hence increases the throughput and network lifetime. Henceforth, a routing protocol that considers an optimized algorithm of route selection for the communication process is desired.

B. PROPOSED SOLUTION

In the AOMDV routing protocol [16], the sender broadcasts a route request (RREQ) to find the route to the receiver node and there can be more than one route available between the sender-receiver pair. Out of all the routes, AOMDV chooses the one with the minimum hop count without even considering the quality of that chosen route. In this regard, we introduce a new version of fitness function (FFn) to be used in the genetic algorithm (GA). Accordingly, we propose a multipath routing protocol called the AOMDV-FFn based on the AOMDV protocol. Next, we propose another routing protocol that uses the genetic algorithm (GA) called AOMDV-GA. In the proposed algorithm, when an RREQ is broadcast and multiple routes are received, the sender node will have to select the specific route to find the shortest and optimized route with the minimum energy consumption and less traffic taking into account the possibility of having links failure that results in random loss of data packets. In other words, the FFn will consider the following:

- The residual energy of each node in the route,
- The distance of each possible route,
- The congestion in each possible route,
- Discrimination of random loss from the congestion loss.

The selection of the route for transmission will be based on the highest fitness value of the route. The main criteria that are followed for the optimal route are: (a) that has the shortest distance; (b) that has the highest level of residual energy, and (c) that contains less traffic and higher bandwidth. The source node then sends the data packets via the shortest route with the highest energy level and less congested nodes.

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

- The network consists of mobile nodes and each node is characterized by a unique identification number,
- The MANET environment is the homogeneous representation where all mobile nodes are initialized with an equal amount of energy,
- The nodes have mobility features and so the distance between the nodes keeps on changing,
- Nodes mobility might lead to links failure.

C. FITNESS FUNCTION

Here, we develop a new fitness function that depends on three components. The first one is to consider the residual energy of the node and it can be calculated using [38] as follows:

$$F_e = E_{en}/E_{an}, \tag{1}$$

where F_e is the fitness function based on energy. E_{en} is the residual energy at each node and E_{an} is the residual energy of all the nodes.

The second component is to consider the shortest distance calculated using equation (2) [38]:

$$F_d = D_{n,n}/D_{sd}, \tag{2}$$

where F_d is the fitness function of a node based on intra-distance between nodes. $D_{n,n}$ is the distance from node n to node n in the route, and D_{sd} is the total distance from the source to the destination.

The third component is to consider the congestive links where it can be discriminated from the case of random loss of data packets. The congestion in the route is calculated using the TCP Congestion Control Enhancement for Random Loss (TCP CERL) mechanism [15]. Drawing on the Round trip time (RTT) and the Bandwidth (BW), the bottleneck queue length (L) can be calculated using the following equation:

$$L = (RTT - T)BW, \tag{3}$$

where T is the smallest RTT observed by the TCP sender, and L is updated with the latest RTT measurement every time a new RTT value is received. In CERL, the queue length L measured in equation (3) is used to estimate the congestion status of the link. Particularly, CERL set a dynamic queue length threshold of N as follows:

$$N = A * L_{max}, \tag{4}$$

where L_{max} is the largest value of L detected by the transmitter, and A is a constant between 0 and 1.

CERL makes a comparison of L and N to decide the congestive status of the network. If $L > N$, this indicates that a specific route might have packets to be dropped as a result of predicted traffic congestion at one of the nodes of such route. In this case, this route should be avoided and dropped from the optimized routes. If $L \leq N$, this indicates that the considered route can be selected to join the pool of best routes subject to the values of the other fitness function components. Even if some packets are dropped in such a route, that will be considered as a result of random loss and will not affect the fitness function nor the congestion window and therefore, the throughput will not be affected negatively. Since L and N both contain a multiple of the constant BW, we can divide both sides of the aforementioned inequalities by BW, and the resulting inequality will still be true. Therefore, estimating BW is not mandatory and it can be set to one in the CERL implementation. In short, it is generally concerned with analyzing the currently detected RTT with the minimum RTT that has been detected.

In our fitness function, we propose the mechanism where the value of the fitness function component due to congestion F_c will either have some value or reset to 0 and this is decided based on the condition $L <= N$. If $L <= N$ is true, this indicates that the route can accept packets for data transmission and the value is calculated using the equation (5) where B is the buffer size. Otherwise, the route likely has congestion in any of its nodes, and therefore, we just reset the value of F_c to zero.

$$F_c = 1 - (\frac{L}{B}), \tag{5}$$

Thus, the modified version of the fitness function is calculated using the equation as follows:

$$F = F_e + F_d + F_c, \tag{6}$$

where F is calculated for each possible route. Optimizing the routes provided by AOMDV is done though our proposed AOMDV-GA mechanism in algorithm 1. The *Fitness*() function is calculated using algorithm 2 through for the total number k of routes from source to the destination.

IV. METHODOLOGY

We assume that the same initial energy is assigned to all mobile nodes in a wireless network. The flow of the proposed algorithm is shown in Fig. 4 where we use the AOMDV protocol to find multiple routes from source S to destination D. Next, the congestion status of each route is calculated using L and N according to equations (3) and (4). In the next step, GA uses the five steps process described below of initialization, fitness function, selection, crossover, and mutation.

Initialization includes establishing the parameters for the GA, forming the mark for the simulation which is based on algorithm 1. In this stage, six parameters are determined:

- "Genes" is the number of individual nodes in a route,
- "PopSize" is the total number of routes from a set of the source to destination,
- P_c is the probability that a pair of routes will be crossed,

Algorithm 1 AOMDV-GA Routing Algorithm

```
Input: Multiple Routes using AOMDV protocol
$P_c = 0.5$
$P_m = 0.1$
$E_r$ [ ] = NULL
$N_c$ = NULL
$O_c$ = NULL
$F$ = Fitness ()
$POP$ = Multiple_Routes after applying $F$
Output: EFFICIENT_ROUTE
foreach (all routes in the POP) do
    while ($P_p \leftarrow GP(POP)$) do
        $N_c \leftarrow$ Crossover ($P_p$, $O_p$, $P_c$)
        $N_c \leftarrow$ Mutation ($P_n$, hc, $P_m$)
        $N_{cf} \leftarrow$ Fitness (set of $N_c$)
    end
    foreach ($N_{cf}$ set of routes) do
        if ($N_{cf} >= O_{cf}$) then
            $E_r[] \leftarrow N_{cf}$
        end
    end
end
RETURN $E_r$
```

- P_m is the probability that a node in a route will be mutated,
- "SurvivorSel" is the instruction which will check for the top-scoring route (the route with highest fitness value) that will return as the search answer,
- "GensNoChange" is the termination measure, which is the number of generations that may pass with no change in the elite route before that elite route will be returned as the search answer. The elite route is the route with the highest fitness value.

Fitness of each route is generated which is calculated using algorithm 2. Here, the value of the objective function for each route is calculated. The value of the objective function is described as fitness value. This is achieved by calculating the fitness of each route, which is derived from the sum of the fitness values of distance, energy, and congestion mechanism. Then, averaging the total fitness for each route. Next, all the fitness values are evaluated through the evaluation process, and the elite route of the generation is determined. In our proposed protocol, the fitness function is measured using equation (6).

Selection step will eliminate the routes with the low fitness values and hold the rest. The elitism strategy [39] is used in our proposed protocol and will save half of the routes with high fitness values. Elitism selection is an approach where a restricted number of routes with the fittest values are preferred to move to the next step, to avoid doing extra crossover and mutation steps. The worse routes will be deleted, and a new route will be created in further stages using algorithm 1.

Algorithm 2 Fitness Calculation of Each Route

```
Input: For every route received from algorithm 1:
$F_e$ is the fitness function based on the energy = NULL,
$F_d$ is the fitness function based on the intradistance
between nodes = NULL,
$F_c$ is the fitness function due to congestion = NULL
$k$: number of possible routes received from algorithm 1.
Output: Fitness function values for all possible input
        routes.
Function Fitness(F):
    foreach (i = 1; i< = k; i++) do
        $F_e(i) = $ eq. (1)
        $F_d(i) = $ eq. (2)
        if $L <= N$ then
            $F_c(i) = 1 - (\frac{L}{B})$
        else
            $F_c(i) = 0$
        end
        $F = F_e(i) + F_d(i) + F_c(i)$
        return $F$
    end
End Function
```

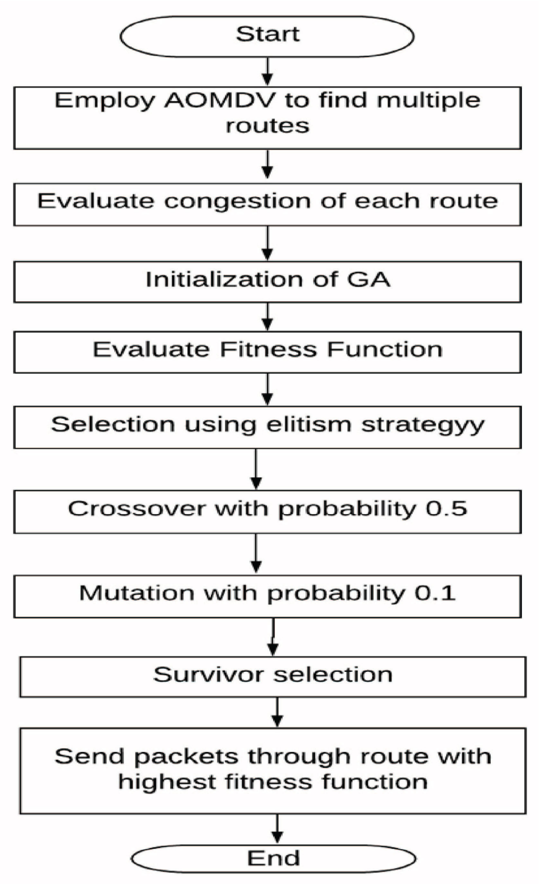

FIGURE 4. Flow chart of AOMDV-GA.

Crossover pairs up all the routes (except for the elite route) and with a probability P_c, they are crossed over using algorithm 1. The crossover is achieved by swapping nodes between every pair of selected routes having high fitness values. In doing this, the part of each node on either side of the crossover point is interchanged. Typically, the crossover probability will vary between 0.6 and 1 [40].

Mutation is the last step after the crossover. Each node of the routes (except for the elite route) will be mutated so the order of the nodes will be changed in the same route with a probability of P_m. When the crossover and mutations are done, routes are once again evaluated through the survivor selection process.

Survivor Selection is done after the crossover and mutation step. In this, the new child (route) that was created is evaluated using equation (6). If the new child route has higher fitness than the parent routes, then this child route is selected as a potential route for sending the packet; otherwise, this child route will be considered in the efficient routes array. This array will be sorted in descending order based on the fitness values.

In algorithm 1, the input is multiple routes that are obtained using AOMDV routing protocol. The P_c is the crossover probability and P_m is the mutation probability. The E_r is the final array that sorts the efficient routes in a descending order based on the highest fitness value that will be used for the data transmission. The F is the fitness function presented in algorithm 2. The POP is for the population of the total multiple routes obtained from the AOMDV protocol after applying the selection rule. The P_p is the present parent route with a high fitness taken from the POP using GP which means get the parent route from the AOMDV multiple routes. The N_c is defined as the new child route that will be generated with high fitness. O_p is for the old parent route. P_p and O_p are the two routes that were selected during the selection process and further will be used for crossover and mutation processes. The N_{cf} is where the fitness of the N_c is stored. O_{cf} is the fitness of the old child O_c or the P_p whichever is the highest. Also, we use present node P_n and hop count hc.

In short, our proposed AOMDV-GA mechanism is shown in algorithm 1 and algorithm 2. Algorithm 1 inputs are multiple routes obtained from the AOMDV protocol. Algorithm 1 uses Algorithm 2 to get the fitness values of the AOMDV routes. Algorithm 1 can be summarized as follows:

- Firstly, AOMDV generates multiple routes (initial population),
- Employ the fitness function to select parent routes with high fitness values and drop those routes having low fitness values,
- New child routes are obtained through performing crossover out of the parent routes with P_c.
- Other new child routes are obtained through performing mutation on all available child routes with P_m.
- Calculate the fitness of every new child route. If the fitness of the newly generated route, i.e., $N_{cf} >= O_{cf}$, then, keep this child route as a potentially good solution in an efficient routes array E_r,

- Repeat the process until cover all parent/child routes having high fitness values. The size of the array E_r is large enough to store all parent and child routes. The number of new child routes is determined based on the number of available routes obtained by AOMDV in addition to routes obtained by the crossover and mutation phases,
- This process terminates with an output of having an array E_r of the best routes having the highest fitness values obtained through algorithm 2,
- Sort the E_r array in descending order. The efficient route will be the one with the highest value in the array. If there is a link failure in that route, then the next one in the array will be utilized.

In algorithm 2 and for every parent route (generated by AOMDV protocol) or new child route (generated by crossover and mutation phases), the fitness function is employed to select the route with the highest fitness value. Fitness function employment is achieved for k routes using equations (1) to (6) and hence these fitness values are utilized in algorithm 1. k is determined based on the number of route reply (RREP) messages returned by the AOMDV protocol in case of parent routes. In the case of child routes, k is determined based on the number of new routes generated in the crossover and mutation phases.

We propose AOMDV-FFn as a part of our proposed AOMDV-GA algorithm, where "n" stands for new. In AOMDV-FFn, we are taking multiple routes from the AOMDV routing protocol and then apply the fitness function calculation to select the route with the highest fitness without going through the crossover and mutation processes.

Simulations are performed to run the AOMDV-FFn and AOMDV-GA protocols. In this simulation, an Object-Oriented Tool Command Language (OTcl) script has been written to describe the network parameters and topologies, such as traffic source, the total number of nodes, simulation time, routing protocols used, mobility speed and several other parameters. Two files are generated when running the simulation: a Network AniMator (NAM) to visualize the network and trace files contains a trace of several events that occur during the simulation process. In table 1, we assume the default network parameter values.

V. PERFORMANCE EVALUATION

A. SIMULATION MODEL AND PARAMETERS

Various parameters are utilized to examine the performance of our proposed protocols based on the fitness function such as the number of nodes, simulation time, percentage of the faulty/failure nodes and nodes mobility speed. In our simulation and according to table 1, 100 mobile nodes were randomly distributed in 500 meters * 500 meters network area with 100 seconds as the simulation time. To address the impact of the mobility of the nodes which in turn causes a topological change, we consider nodes having a constant mobility speed of 10 meters/second. Each node is initialized with 100 Joules of energy, and the traffic source type is taken as Constant Bit Rate (CBR) in IEEE 802.11 mobile ad hoc network [21, 24]. Probabilities of crossover P_c and mutation P_m are 0.5 and 0.1, respectively [27]. According to [15], the value of A in eq. (4) is assumed as 0.55.

TABLE 1. Default simulation parameters.

Parameters	Values
Compared Protocols	FF-AOMDV, AOMDV, AODV
Topology dimensions	500 m X 500 m
Number of Nodes	100
Simulation Time	100 seconds
Initial Energy	100 J
Mobility Speed	10 m/s
Crossover probability	0.5
Mutation probability	0.1
Number of Faulty Nodes	0%
Packet Loss Rate	0%
Mobility Model	Random Way point Model
Propagation model	Free space propagation model
Antenna Model	Omni-directional
MAC Type	802.11
Traffic Type	CBR

B. PERFORMANCE METRICS

The performance metrics used in the simulation experiments are as follows [21, 24, 41]:

1) PACKET DELIVERY RATIO (PDR)

It is the ratio of the number of delivered data packets at the destination node to the number of data packets sent from the source node. PDR shows how well a protocol is performing in delivering the packets over the network. PDR is computed as follows:

$$PDR = \frac{\sum P_d}{\sum P_s} \times 100. \tag{7}$$

In this equation, P_d represents the number of packets delivered and P_s represents the number of packets sent.

2) THROUGHPUT

It is the total number of bits that have been successfully delivered to the destination over the network expressed in megabits per second (Mbps). It is a quality and performance indicator. High throughput means fewer packets were dropped during data transmission from the source to the destination. It is measured as follows:

$$G = \frac{\sum B_r \times 8}{T} \times 10^6 \ (Mbps). \tag{8}$$

In this equation, G is the throughput, B_r is the total number of bytes received, and T is the simulation time.

3) END-TO-END DELAY (E2E)

It is the time taken by data packets to be successfully delivered to the destination node since were transmitted from the sender node. It is also called One-Way Delivery (OWD).

This consists of all types of delays. When the source node has data packet(s) to send, it consults its routing table to check if a route to the final destination is available. If there is no route, it goes through the route discovery phase where the source node sends RREQ messages to its neighboring nodes. If one of these neighboring nodes has a route to the final destination, it sends an RREP message back to the source node; otherwise, these nodes broadcast RREQ messages to further nodes. This continues until one of the nodes at least replies with an RREP back to the sender following the AOMDV protocol. The source node will calculate the optimized route based on the fitness function in equation (6) and hence packets will be transmitted through this best route to the destination node. The node maintains the optimized route during the communications process. Our proposed protocols provide alternative routes in case of links failure as being multipath algorithms. If there is no communication for a long time, the route will be deleted from the routing table [42]. During the journey of data packets transmitted from the sender to the receiver, packets have to wait in the queues of the bottleneck buffers of the intermediate nodes. Waiting times depend on several parameters such as the amount of the traffic load, the bandwidth of links, buffers size. Processing time includes all delays at the separate layers and also at the inter-layers communication times [43]. Route discovery delay is one of the primary components of the processing time. Therefore, end-to-end (E2E) delay components include transmission delay of successive packets, propagation delay over various links from the source to the destination, processing delay, and queuing delay. Time consumed to detect the communication failure, via receiving triple duplicate acknowledgments or timeout [44], and hence to retransmit data packets is another component of the E2E delay. The total E2E delay is calculated as:

$$E2E = \frac{\sum_{i=0}^{n} R_i - S_i}{n}. \tag{9}$$

In this equation, n represents the number of successfully received packets; R_i represents the time when the destination node received the ith packet; S_i represents the time when the source node sent the ith packet [45]. S_i and R_i times are counted at the application layers of the sender and receiver, respectively.

4) ENERGY CONSUMPTION

It is the total amount of energy that is consumed by the nodes in the network during the simulation time. It is calculated as follows:

$$E = \sum_{i=0}^{m} I_i - E_i. \tag{10}$$

In this equation, E is the energy consumption, I_i is the initial energy of the node i, and E_i is the node i energy at the end of the simulation time for all nodes m.

5) ROUTING OVERHEAD RATIO

It represents the number of routing packets that are required to be broadcasted for the route discovery and route maintenance to deliver the data packets. Both routing and data packets have to share the same network bandwidth most of the time. Hence, routing packets are considered as overhead. The routing overhead affects the network's robustness in terms of the bandwidth utilization and battery power consumption of the nodes. Formula (11) for routing overhead is as follows [21]:

$$RO\,(\%) = \frac{R_p}{R_p + D_p} * 100. \tag{11}$$

In this equation, RO is the routing overhead, R_p represents the number of routing packets, and D_p represents the number of data packets sent.

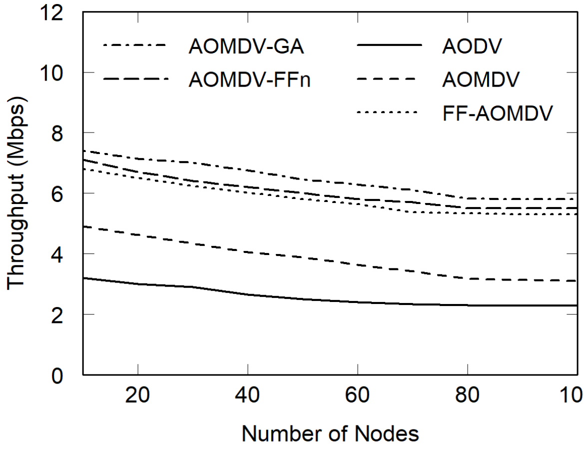

FIGURE 5. Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for throughput with number of nodes.

VI. EXPERIMENTAL RESULTS

A. THROUGHPUT

In Fig. 5, the performance analysis of the throughput for AODV, AOMDV, FF-AOMDV, AOMDV-FFn, and AOMDV-GA is shown while considering 100 nodes. Our proposed AOMDV-GA protocol is performing better than other protocols because AOMDV-GA is using a congestion control mechanism to avoid transmission through routes with excessive network traffic. Also, it sends the data packets through a route that has the highest level of residual energy and shortest distance. AOMDV-GA gains a 133%, 87%, and 8.8% throughput development over AODV, AOMDV, and FF-AOMDV, respectively. However, AOMDV-FFn gains a 115%, 77%, 4% throughput development over AODV, AOMDV, and FF-AOMDV, respectively. As we can see that AOMDV-GA outperforms the AOMDV-FFn with 4.4% throughput gain because AOMDV-GA is using the "survivor selection" for evaluating the new routes fitness after doing the crossover and mutation to achieve the highest fitness value possible. In contrast, AOMDV-FFn is not getting into those components.

On the other hand, Fig. 6 depicts the effect of varying simulation time on the throughput. As increasing the simulation time, as the data traffic enlarges in the network. Therefore, the packet loss probability increases which in turn reduces

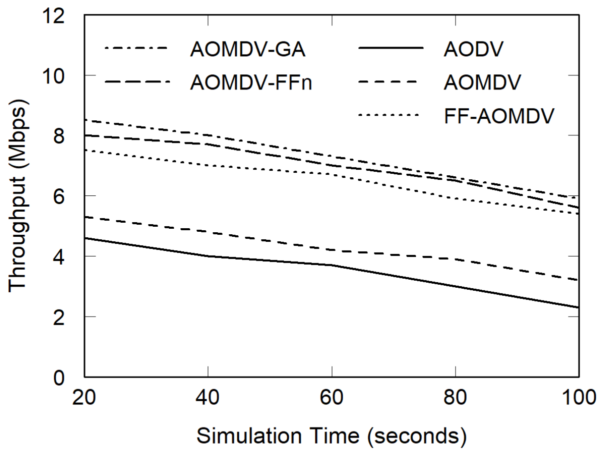

FIGURE 6. Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for throughput with simulation time.

the throughput for all protocols because of congestion. However, both AOMDV-GA and AOMDV-FFn outperform other mechanisms as the congestion control mechanism is taken into account. The AOMDV-GA has 15.25% better performance than FF-AOMDV. This is because some routes having high fitness values are not utilized in FF-AOMDV where crossover and mutation processes are not considered.

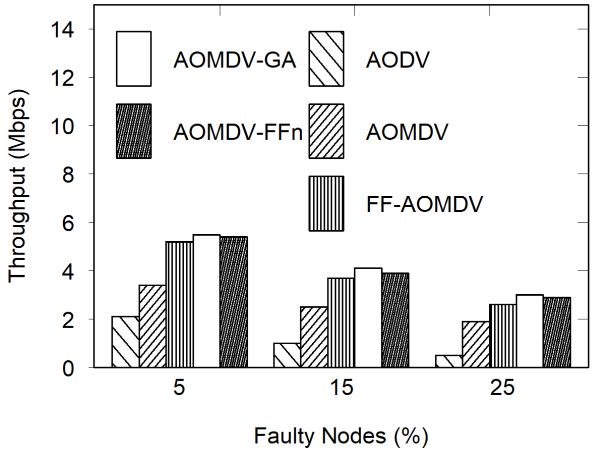

FIGURE 7. Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for throughput with faulty nodes.

Fig. 7 presents the assumption of having faulty nodes in the selected route and how different protocols perform in such a case. When the faulty nodes are present, it gets harder for the algorithms to progress with the same flow. More packets will be dropped when the number of faulty nodes increases and that, in turn, would degrade the throughput. Here, we have taken three scenarios as 5%, 15%, 25% faulty nodes out of 100 nodes. From the results, it can be seen that AOMDV-GA with 5% faulty nodes is performing better with 161%, 54%, 5% when compared with AODV, AOMDV, FF-AOMDV respectively. AOMDV-GA with 25% faulty nodes is performing better with 548%, 65%, 14% when compared with AODV, AOMDV, FF-AOMDV respectively. This shows that gains increase greatly with higher ratios of faulty nodes particularly in the case of AODV. AOMDV-FFn is quite close to AOMDV-GA in all scenarios. All protocols, except AODV, have the option to use an alternative route to the destination in case of any node failure occurrence. However, our proposed protocols seem to perform robustly with an increase in the number of faulty nodes in the network as the alternative routes are also efficient because of their high fitting values.

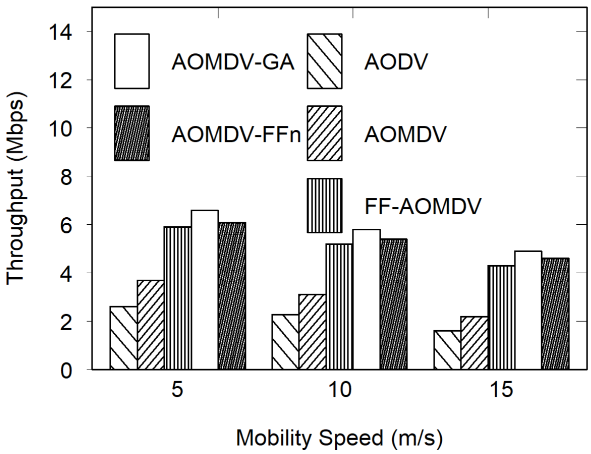

FIGURE 8. Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for throughput with mobility speed.

The performance of the different protocols with the mobility speed while taking 100 nodes with a simulation time as 100 seconds is shown in Fig. 8. All the protocols are exhibiting high throughput with low mobility speed and vice versa. The AOMDV-GA at 15 m/s mobility speed has a higher throughput with 170%, 123%, 11%, and 6.5% when compared with AODV, AOMDV, FF-AOMDV, and AOMDV-FFn, respectively. With lower mobility speeds, the throughput gain is slightly less. This shows that our protocols adapt to topological change in terms of high mobility speeds where communication links would interrupt requiring alternative efficient routes or where the random loss of packets would happen.

Fig. 9 represents the variation of the random loss for AODV, AOMDV, FF-AOMDV, and the proposed protocols AOMDV-FFn and AOMDV-GA. The packet loss rate is equal to the number of packets not received by the destination divided by the total number of packets sent by the source. The MANETs can experience packet loss caused by high Bit Error Rate (BER), unstable channel characteristics, and nodes mobility. This is used to express the reliability of a communication network route. The AOMDV-FFn and AOMDV-GA are performing well in case of packet loss because they minimize the packet loss by selecting more reliable routes based on the shortest distance, higher residual energy of the nodes and having less data traffic. Specifically, the AOMDV-GA

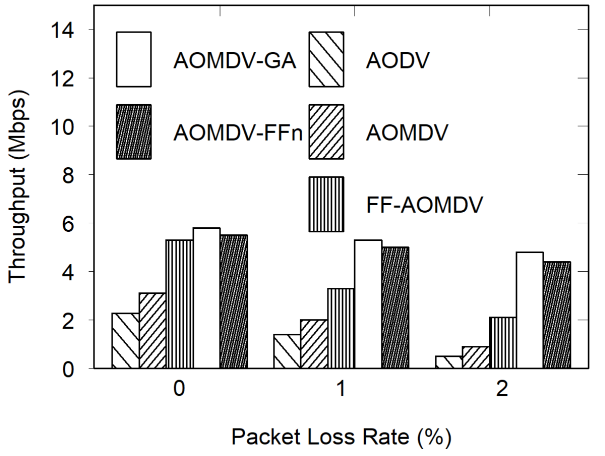

FIGURE 9. Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for throughput with packet loss rate.

at 0% random loss, has a higher throughput with 176%, 81%, 9.5%, and 6.5% when compared with AODV, AOMDV, FF-AOMDV, and AOMDV-FFn, respectively. While at 2% random loss, the AOMDV-GA, has a higher throughput gain with 1000%, 680%, 132%, and 9% when compared with AODV, AOMDV, FF-AOMDV, and AOMDV-FFn, respectively. This indicates that our protocols perform great as the fitness function considers the availability of the bottleneck buffer according to equation (5) and will not decrement the window size.

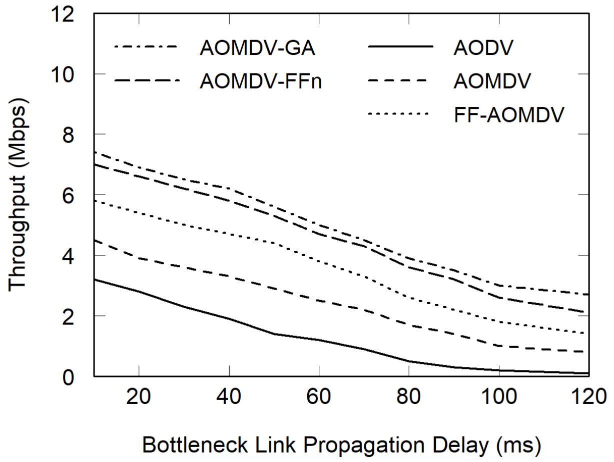

FIGURE 10. Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for throughput with bottleneck link propagation delay.

In Fig. 10, the bottleneck link propagation delay is the time delay between every pair of nodes and it can vary over the links. Owing to this long time delay, the bottleneck buffer of some nodes would undergo congestive traffic. In this case, an excessive amount of packets would drop reducing the throughput. Therefore, packets retransmission as a result of traffic congestion would deplete the nodes' energy quickly. The efficient routes selected by our proposed algorithms would avoid going through such nodes. However, at a certain point, the congestion window will grow slowly as the data acknowledgments will arrive late as a result of the increase of the propagation delay. This in turn, will reduce the amount of data transmission and the throughput gradually with the time delay increase.

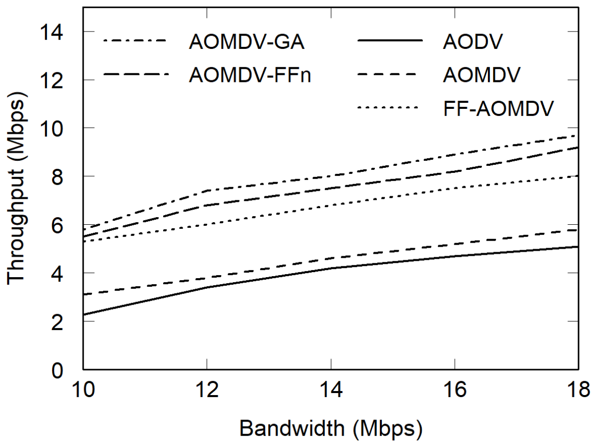

FIGURE 11. Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for throughput with bandwidth.

Fig. 11 depicts the throughput versus the end-to-end bandwidth. Nodes will allow more packets to go through them when increasing the bandwidth. This would lead to congestion, however, in our algorithms, packets will avoid passing through those congested nodes improving the throughput particularly when bandwidth increases obviously.

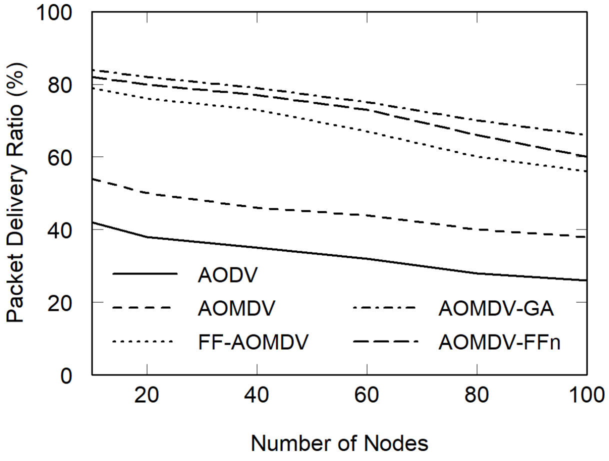

FIGURE 12. Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for PDR with number of nodes.

B. PACKET DELIVERY RATIO

The effect of PDR is shown in Figs. 12 and 13 while 10 m/s is the mobility speed. Increasing the number of nodes or simulation time duration, would increase the traffic amount

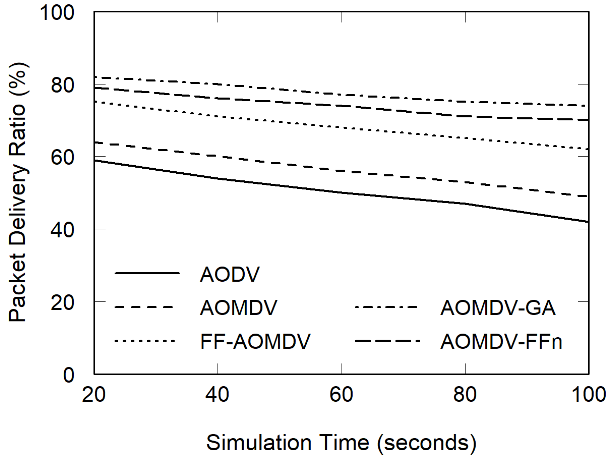

FIGURE 13. Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for PDR with simulation time.

in the network and hence enlarging the possibility of having traffic congestion. This would lead to dropping more data packets which in turn reduces the PDR. As our protocols consider the congestion problem in the fitness function so the degradation of the PDR with the number of nodes will be less compared to other protocols. The PDR for AOMDV-GA is quite close to the AOMDV-FFn mechanism.

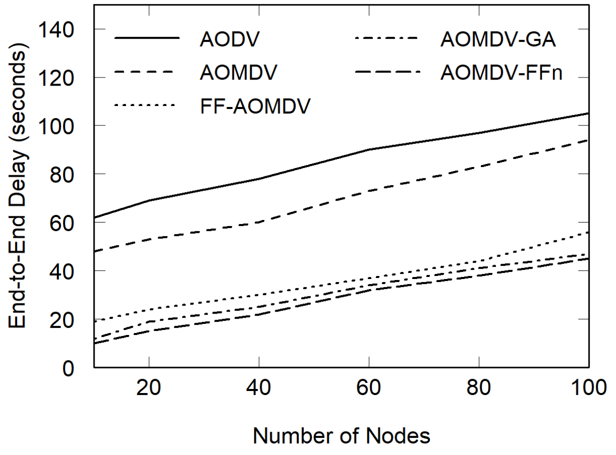

FIGURE 14. Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for end-to-end delay with number of nodes.

C. END TO END DELAY

The performance analysis in Figs. 14 and 15 are comparing protocols regarding the end-to-end delay. As explained earlier, FF-AOMDV [24] uses distance and energy metrics to calculate the best route and, therefore, its processing time should be longer than the primitive protocols including AODV and AOMDV where both use only the number of hubs metric. However, the end-to-end delay of FF-AOMDV is shorter than other protocols and this is owing to the optimized route selected by the FF-AOMDV that provides better network performance. Similarly and according to eq. (6), our protocols processing time is longer than other schemes, however, the end-to-end delay is shorter than other schemes as is explained as follows. With a mobility speed of 10 m/s, the network will have often faulty links resulting in data communications interruptions and/or data random loss. In this case, AODV needs to find a new route and this would, in turn, enlarge the E2E delay. Even those protocols where multiple routes are available including AOMDV and FF-AOMDV, packets retransmissions would often be required because of nodes mobility and/or traffic congestion occurrence. This requires a longer time delay than our mechanism where its efficient routes including the best and alternative routes would avoid congestion. Here, AOMDV-FFn is outperforming AOMDV-GA because AOMDV-FFn is not draining time delay in performing crossover and mutation processes. Consequently, the survivor selection process would have less number of available routes so processing time will be shorter.

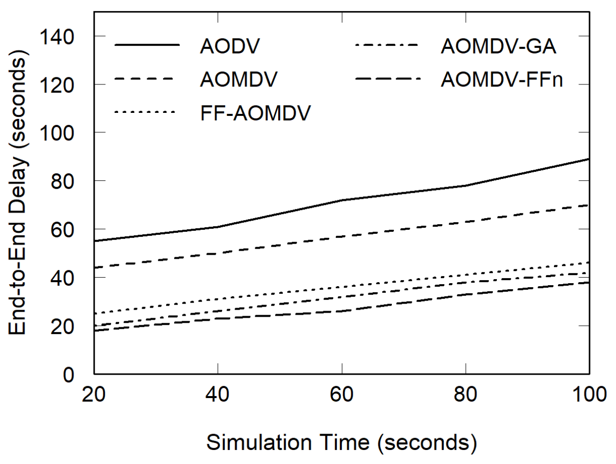

FIGURE 15. Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for end-to-end delay with simulation time.

D. ENERGY CONSUMPTION

The results for energy consumption are shown in Figs. 16 and 17. The main goal of our routing protocols is to be energy-efficient. AOMDV-GA behaves better than other protocols in the sense of saving energy. The energy in MANET nodes is mainly dissipated in sending, processing, or forwarding packets (data or routing) to the existing node's neighbors or to the final destination. Reducing the amount of data packets or routing overhead would preserve the level of residual energy. Our protocols are reactive where nodes forward packets only on demand to the destination via their neighbors and this as a result would minimize the energy consumption. Our proposed algorithms calculate the energy level in equation (1) of each node in a specific route before initiating the data transmission to obtain the route that has higher residual energy. On the other hand, the prime reason for using congestion control and the shortest distance is to conserve as much energy as possible so that the performance is improved and the network

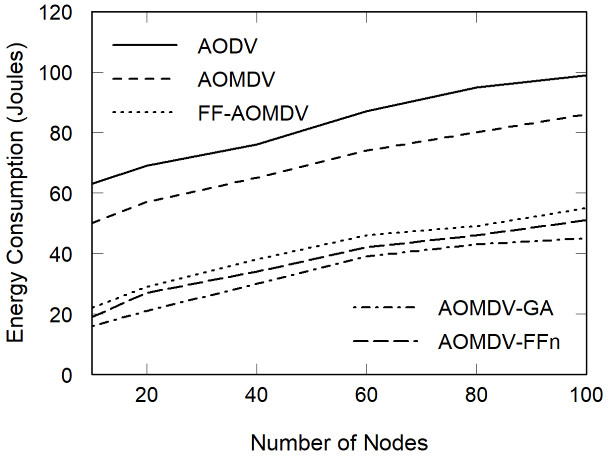

FIGURE 16. **Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for energy consumption with number of nodes.**

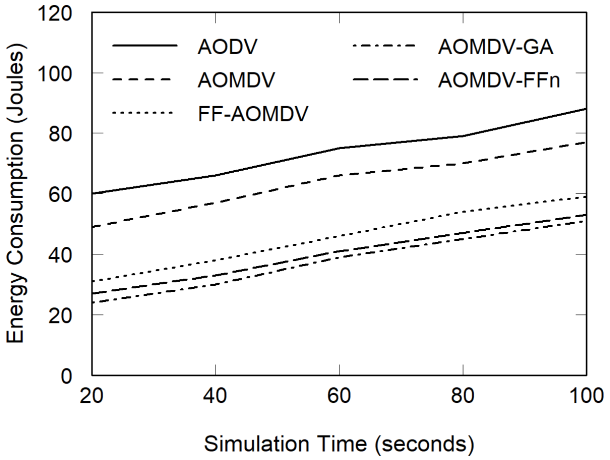

FIGURE 17. **Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for energy consumption with simulation time.**

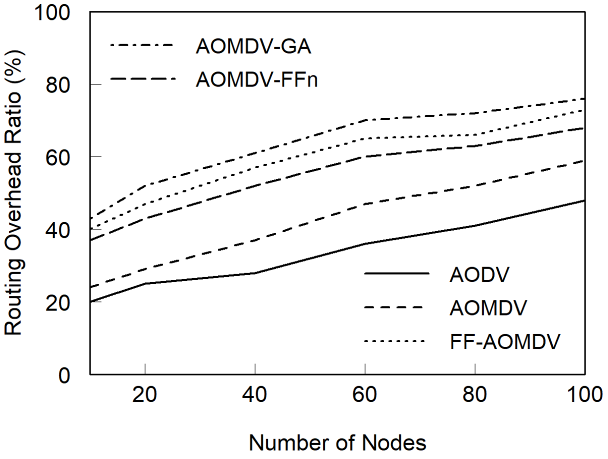

FIGURE 18. **Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for routing overhead ratio with number of nodes.**

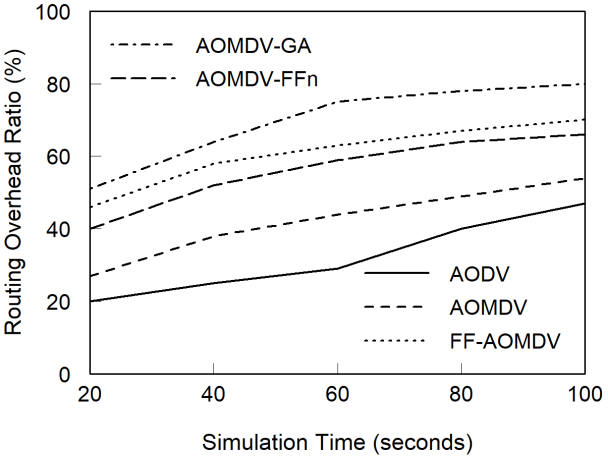

FIGURE 19. **Comparison between AODV, AOMDV, FF-AOMDV and proposed protocol AOMDV-GA and AOMDV-FFn for routing overhead ratio with simulation time.**

lifetime can be extended. Our algorithms provide efficient routes where congested links can be avoided and, therefore, alleviate the traffic in the network. This, in turn, would save energy consumption that could be wasted in the excessive packets retransmissions if the nodes congestion is not considered. Also, this would speed up the data communication and improve the throughput as the packets retransmissions are not often needed. On the contrary, other protocols do not consider the congestion problem. AOMDV-GA is slightly outperforming AOMDV-FFn as a result of the absence of the optimization method in terms of crossover and mutation processes.

E. ROUTING OVERHEAD RATIO

The amount of routing overhead packets depends on various parameters including network stability, routing algorithm, network size, and network topology. AODV finds one best route only while AOMDV discovers multiple routes and this would require more routing packets. As a result, AODV would incur less overhead than AOMDV as shown in Figs. 18 and 19 and this agrees with [46], [47]. As the algorithm requires more information on the network such as in FF-AOMDV and our algorithms where they use fitness function, the routing overhead packets would increase. However, AOMDV-GA would require more overheads than AOMDV-FFn as the former algorithm uses various components of the genetic algorithm while searching for the efficient routes which require more routing overhead packets.

We can see that our proposed protocol AOMDV-GA is performing better in the case of packet delivery ratio, energy consumption, and throughput assuming different faulty nodes, mobility speed, and packet loss rate when compared with the AODV, AOMDV, and FF-AOMDV. Besides, AOMDV-FFn is slightly less than AOMDV-GA in all these metrics. In contrast, AOMDV-GA has a poor performance in the case of the routing overhead ratio. The proposed protocol AOMDV-FFn outperforms both AOMDV-GA and FF-AOMDV in case of routing overhead and end-to-end delay.

VII. PROTOCOL COMPLEXITY

To implement reactive routing protocols such as AODV, there are three methods including Snooping, Kernel modification, and Netfilter [48]. Our proposed algorithm is integrated with the AOMDV mechanism in which it is a multipath version of the AODV protocol. Therefore, AOMDV-GA protocol will require similar routing space as needed by AOMDV. Other protocols are analogous such as FF-AOMDV [24] and DE-AODV [31].

Data communication may fail because of various reasons such as low energy nodes and nodes mobility and these result in network performance degradation in the sense of PDR and throughput. Also, end-to-end delay enlarges because of the increase in the data retransmissions rate when traffic problems such as network congestion occur. Our protocol based on the fitness function, would require more processing time to calculate the best route than other protocols; however, the optimized route generated by the GA algorithm would save time through minimizing the data retransmission rate. This is achieved as our schemes are designed to avoid the congested routes and also routes having low residual energy nodes.

In some circumstances, the optimized route would be longer than that one generated by other protocols. This is because our mechanism considers other metrics including a route having less congested nodes and higher residual energy in addition to the shortest distance. In this case, our mechanisms would provide higher performance than other protocols even the route is a bit longer.

VIII. CONCLUSION

This paper addresses an optimized algorithm for efficient routing in IEEE 802.11 MANETs. Mobility of nodes in MANETs would likely lead to links failure and accordingly random loss of data packets. This would increase the amount of data retransmissions which in turn will consume more energy. Here, we introduce the concept of a fitness function that considers the distance between the source node and the destination node, congestion control, and energy consumption. TCP CERL is a congestion control mechanism developed to be utilized in the fitness function to avoid the congested routes. This mechanism can discriminate between the congestion loss and the random loss. Through using the AOMDV algorithm, we combine our new fitness function (FFn) to select the best routes that have the highest fitness and propose AOMDV-FFn. The highest fitness route implies the shortest route, maximum residual energy, and less data traffic even if a random loss of data packets happens. We also introduced our AOMDV-GA protocol that uses a genetic algorithm (GA). Through our simulation experiments, both protocols outperform other routing mechanisms. At 2% random loss of data packets, the AOMDV-GA, has a higher throughput with 1000%, 680%, 132%, and 9% when compared with AODV, AOMDV, FF-AOMDV, and AOMDV-FFn, respectively. This shows the great enhancement in the network performance can be obtained with our proposed algorithms. Distinctly, AOMDV-GA performs slightly better than AOMDV-FFn in various network performance metrics. However, the later one has a less end-to-end delay and routing overhead than the former algorithm.

REFERENCES

[1] D. Feng, C. Jiang, G. Lim, L. J. Cimini, G. Feng, and G. Ye Li, "A survey of energy-efficient wireless communications," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 1, pp. 167–178, 1st Quart., 2013.

[2] J. Li, X. Li, Y. Gao, Y. Gao, and R. Zhang, "Dynamic cloudlet-assisted energy-saving routing mechanism for mobile ad hoc networks," *IEEE Access*, vol. 5, pp. 20908–20920, 2017.

[3] S. Hao, H. Zhang, and M. Song, "A stable and energy-efficient routing algorithm based on learning automata theory for MANET," *J. Commun. Inf. Netw.*, vol. 3, no. 2, pp. 52–66, Jun. 2018.

[4] T. Sanislav, S. Zeadally, G. D. Mois, and S. C. Folea, "Wireless energy harvesting: Empirical results and practical considerations for Internet of Things," *J. Netw. Comput. Appl.*, vol. 121, pp. 149–158, Nov. 2018.

[5] Z. Li and H. Shen, "A QoS-oriented distributed routing protocol for hybrid wireless networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 3, pp. 693–708, Dec. 2012.

[6] A. M. E. Ejmaa, S. Subramaniam, Z. A. Zukarnain, and Z. M. Hanapi, "Neighbor-based dynamic connectivity factor routing protocol for mobile ad hoc network," *IEEE Access*, vol. 4, pp. 8053–8064, 2016.

[7] M. Er-rouidi, H. Moudni, H. Mouncif, and A. Merbouha, "A balanced energy consumption in mobile ad hoc network," *Procedia Comput. Sci.*, vol. 151, pp. 1182–1187, Jan. 2019.

[8] A. M. Akhtar, M. R. Nakhai, and A. H. Aghvami, "Power aware cooperative routing in wireless mesh networks," *IEEE Commun. Lett.*, vol. 16, no. 5, pp. 670–673, May 2012.

[9] S. Chen, Z. Yuan, and G.-M. Muntean, "An energy-aware routing algorithm for quality-oriented wireless video delivery," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 55–68, Mar. 2016.

[10] P. Sra and S. Chand, "QoS in mobile ad-hoc networks," *Wireless Pers. Commun.*, vol. 105, pp. 1599–1616, Apr. 2019.

[11] P. Pal, S. Tripathi, and C. Kumar, "Bandwidth estimation in high mobility scenarios of IEEE 802.11 infrastructure-less mobile ad hoc networks," *Int. J. Commun. Syst.*, vol. 32, no. 15, p. e4080, Oct. 2019.

[12] M. Selvi and B. Ramakrishnan, "Lion optimization algorithm (LOA)-based reliable emergency message broadcasting system in VANET," *Soft Comput.*, vol. 24, no. 14, pp. 10415–10432, Jul. 2020.

[13] M. K. Marina and S. R. Das, "Ad hoc on-demand multipath distance vector routing," *Wireless Commun. Mobile Comput.*, vol. 6, no. 7, pp. 969–988, 2006.

[14] J. Wu, R. Tan, and M. Wang, "Energy-efficient multipath TCP for quality-guaranteed video over heterogeneous wireless networks," *IEEE Trans. Multimedia*, vol. 21, no. 6, pp. 1593–1608, Jun. 2019.

[15] T. Saedi and H. El-Ocla, "Improving throughput in lossy Wired/Wireless networks," *Wireless Pers. Commun.*, May 2020.

[16] M. K. Marina and S. R. Das, "On-demand multipath distance vector routing in ad hoc networks," in *Proc. 9th Int. Conf. Netw. Protocols (ICNP)*, 2001, pp. 14–23.

[17] M. Ye, Y. Wang, C. Dai, and X. Wang, "A hybrid genetic algorithm for the minimum exposure path problem of wireless sensor networks based on a numerical functional extreme model," *IEEE Trans. Veh. Technol.*, vol. 65, no. 10, pp. 8644–8657, Oct. 2016.

[18] H. Darji and H. B. Shah, "Genetic algorithm for energy harvesting-wireless sensor networks," in *Proc. IEEE Int. Conf. Recent Trends Electron., Inf. Commun. Technol. (RTEICT)*, May 2016, pp. 1398–1402.

[19] V. D. P. Souto, R. D. Souza, B. F. Uchoa-Filho, and Y. Li, "A novel efficient initial access method for 5G millimeter wave communications using genetic algorithm," *IEEE Trans. Veh. Technol.*, vol. 68, no. 10, pp. 9908–9919, Oct. 2019.

[20] S. N. Sivanandam and S. N. Deepa, *Introduction to Genetic Algorithms*, vol. 1. Berlin, Germany: Springer-Verlag, 2008.

[21] Z. Chen, W. Zhou, S. Wu, and L. Cheng, "An adaptive on-demand multipath routing protocol with QoS support for high-speed MANET," *IEEE Access*, vol. 8, pp. 44760–44773, 2020.

[22] P. Periyasamy and E. Karthikeyan, "Link reliable multipath routing protocol for mobile ad hoc networks," in *Proc. Int. Conf. Circuits, Power Comput. Technol. (ICCPCT)*, Nagercoil, India, Mar. 2015, pp. 1–7.

[23] P. Periyasamy and E. Karthikeyan, "End-to-end link reliable energy efficient multipath routing for mobile ad hoc networks," *Wireless Pers. Commun.*, vol. 92, no. 3, pp. 825–841, Feb. 2017.

[24] A. Taha, R. Alsaqour, M. Uddin, M. Abdelhaq, and T. Saba, "Energy efficient multipath routing protocol for mobile ad-hoc network using the fitness function," *IEEE Access*, vol. 5, pp. 10369–10381, 2017.

[25] A. Bhattacharya and K. Sinha, "An efficient protocol for load-balanced multipath routing in mobile ad hoc networks," *Ad Hoc Netw.*, vol. 63, pp. 104–114, Aug. 2017.

[26] K. K. Sharma and I. Kaur, "Implementation of genetic algorithm for optimization of network route," in *Proc. 2nd Int. Conf. Comput. Commun. Technol., Adv. Intell. Syst. Comput.*, vol. 381, S. Sataroutey, K. Raju, J. Mandal, and V. Bhateja, Eds. New Delhi, India: Springer, 2016.

[27] N. Muruganantham and H. El-Ocla, "Routing using genetic algorithm in a wireless sensor network," *Wireless Pers. Commun.*, vol. 111, no. 4, pp. 2703–2732, Apr. 2020.

[28] W. Wang, X. Wang, and D. Wang, "Energy efficient congestion control for multipath TCP in heterogeneous networks," *IEEE Access*, vol. 6, pp. 2889–2898, 2018.

[29] W. Jabbar, W. Saad, and M. Ismail, "MEQSA-OLSRv2: A multicriteria-based hybrid multipath protocol for energy-efficient and QoS-aware data routing in MANET-WSN convergence scenarios of IoT," *IEEE Access*, vol. 6, pp. 76546–76572, 2018.

[30] T. K. Saini and S. C. Sharma, "Prominent unicast routing protocols for mobile ad hoc networks: Criterion, classification, and key attributes," *Ad Hoc Netw.*, vol. 89, pp. 58–77, Jun. 2019.

[31] J. Deepa and J. Sutha, "A new energy based power aware routing method for MANETs," *Cluster Comput.*, vol. 22, no. S6, pp. 13317–13324, Nov. 2019.

[32] M. Farsi, M. Badawy, M. Moustafa, H. A. Arafat, and Y. Abdulazeem, "A congestion-aware clustering and routing (CCR) protocol for mitigating congestion in WSN," *IEEE Access*, vol. 7, pp. 105402–105419, 2019.

[33] P. Pal, S. Tripathi, and C. Kumar, "Bandwidth estimation in high mobility scenarios of IEEE 802.11 infrastructure-less mobile ad hoc networks," *Int. J. Commun. Syst.*, vol. 32, no. 15, p. e4080, Oct. 2019.

[34] J. Chen, Y.-Z. Lee, H. Zhou, M. Gerla, and Y. Shu, "Robust ad hoc routing for lossy wireless environment," in *Proc. MILCOM*, Oct. 2006, pp. 1–7.

[35] K. Ong, S. Zander, D. Murray, and T. McGill, "Experimental evaluation of less-than-best-effort TCP congestion control mechanisms," in *Proc. IEEE 42nd Conf. Local Comput. Netw. (LCN)*, Singapore, Oct. 2017, pp. 252–260.

[36] S. Sathya Priya and K. Murugan, "Enhancing TCP fairness in wireless networks using dual queue approach with optimal queue selection," *Wireless Pers. Commun.*, vol. 83, no. 2, pp. 1359–1372, Jul. 2015.

[37] P. Dong, J. Wang, J. Huang, H. Wang, and G. Min, "Performance enhancement of multipath TCP for wireless communications with multiple radio interfaces," *IEEE Trans. Commun.*, vol. 64, no. 8, p. 3456–3466, Aug. 2016.

[38] V. B. Trivedi and P. Nayak, "Modified AODV using genetic algorithm to minimize energy consumption in MANET," *Int. J. Innov. Technol. Exploring Eng.*, vol. 8, no. 7S2, pp. 525–530, May 2019.

[39] H. Du, Z. Wang, W. Zhan, and J. Guo, "Elitism and distance strategy for selection of evolutionary algorithms," *IEEE Access*, vol. 6, pp. 44531–44541, 2018.

[40] A. Hassanat, K. Almohammadi, E. Alkafaween, E. Abunawas, A. Hammouri, and V. B. S. Prasath, "Choosing mutation and crossover ratios for genetic algorithms—A review with a new dynamic approach," *Information*, vol. 10, no. 12, p. 390, Dec. 2019.

[41] B. Muneeswari and M. S. K. Manikandan, "Energy efficient clustering and secure routing using reinforcement learning for three-dimensional mobile ad hoc networks," *IET Commun.*, vol. 13, no. 12, pp. 1828–1839, Jul. 2019.

[42] L. Van Minh, Y. MingChuan, and G. Qing, "End-to-end delay assessment and hybrid routing protocol for vehicular ad hoc network," *IERI Procedia*, vol. 2, pp. 727–733, 2012.

[43] A. S. Tanenbaum, *Computer Networks*, 3rd ed. London, U.K.: Pearson, 2003.

[44] J. Liu, Z. Han, and W. Li, "Performance analysis of TCP new reno over satellite DVB-RCS2 random access links," *IEEE Trans. Wireless Commun.*, vol. 19, no. 1, pp. 435–446, Jan. 2020.

[45] F. A. Al-Zahrani, "On modeling optimizations and enhancing routing protocols for wireless multihop networks," *IEEE Access*, vol. 8, pp. 68953–68973, 2020.

[46] M. Ahyar, M. Yani, E. Elfisa, and R. F. Sari, "Comparison of energy efficiency and routing packet overhead in single and multi path routing protocols over S-MAC for wireless sensor network," in *Proc. 6th UKSim/AMSS Eur. Symp. Comput. Modeling Simulation*, Nov. 2012, pp. 406–411.

[47] Alamsyah, E. Setijadi, I. K. E. Purnama, and M. H. Pumomo, "Performance comparative of AODV, AOMDV and DSDV routing protocols in MANET using NS2," in *Proc. Int. Seminar Appl. Technol. Inf. Commun.*, Sep. 2018, pp. 286–289.

[48] I. D. Chakeres and E. M. Belding-Royer, "AODV routing protocol implementation design," in *Proc. 24th Int. Conf. Distrib. Comput. Syst. Workshops*, 2004, pp. 698–703.

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