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AFB-GPSR: Adaptive Beaconing Strategy Based on Fuzzy Logic Scheme for Geographical Routing in a Mobile Ad Hoc Network (MANET)

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Abstract: In mobile ad hoc networks (MANETs), geographical routing provides a robust and scalable solution for the randomly distributed and unrestricted movement of nodes. Each node broadcasts beacon packets periodically to exchange its position with neighboring nodes. However, reliable beacons can negatively affect routing performance in dynamic environments, particularly when there is a sudden and rapid change in the nodes' mobility. Therefore, this paper suggests an improved Greedy Perimeter Stateless Routing Protocol, namely AFB-GPSR, to reduce routing overhead and increase network reliability by maintaining correct route selection. To this end, an adaptive beaconing strategy based on a fuzzy logic scheme (AFB) is utilized to choose more optimal routes for data forwarding. Instead of constant periodic beaconing, the AFB strategy can dynamically adjust beacon interval time with the variation of three network parameters: node speed, one-hop neighbors' density, and link quality of nodes. The routing evaluation of the proposed protocol is carried out using OMNeT++ simulation experiments. The results show that the AFB strategy within the GPSR protocol can effectively reduce the routing overhead and improve the packet-delivery ratio, throughput, average end-to-end delay, and normalized routing load as compared to traditional routing protocols (AODV and GPSR with fixed beaconing). An enhancement of the packet-delivery ratio of up to 14% is achieved, and the routing cost is reduced by 35%. Moreover, the AFB-GPSR protocol exhibits good performance versus the state-of-the-art protocols in MANET.

Keywords: adaptive beaconing; geographical routing; AFB-GPSR; fuzzy logic; MANET; OMNeT++

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1. Introduction

Nowadays, mobile ad hoc networks (MANETs) are becoming a pivotal trend in modern life to keep pace with an accelerated world and rapid technological advances. In this context, the desire for low-cost installation and smarter and more connected devices is dramatically growing. MANETs foster a wide range of vital applications in industries, military operations, emergency situations, Intelligent Transport Systems (ITSs), intelligent health care systems, etc. [1,2]. Accordingly, MANETs are classified into various categories, such as Vehicular Ad hoc Networks (VANETs) for smart cities, Internet of Vehicles (IoV) for smart automobiles, Flying Ad hoc Networks (FANETs) for the communication of Unmanned Aerial Vehicles (UAVs), and the Sea Ad hoc Network (SANET) to communicate with Autonomous Underwater Vehicles (AUVs), vessels and boats [3–5]. Some types of wireless ad hoc networks (WANETs) and their communication applications are shown in Figure 1. This classification can be a helpful guideline for designers and researchers to understand the specific requirements, challenges, and design considerations associated with each network, in addition to the specialized routing protocols, algorithms, and system architectures [6,7].

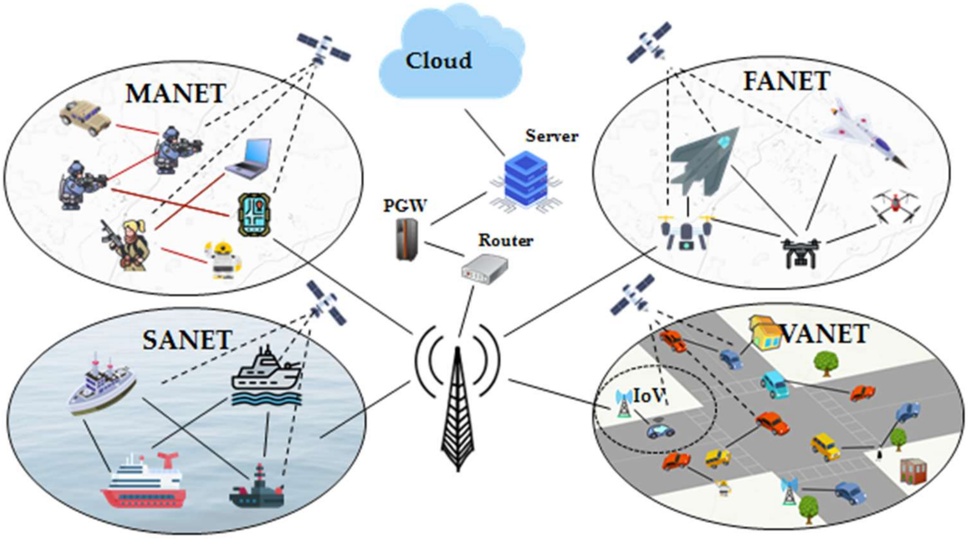


Figure 1. Examples of wireless ad hoc networks (WANETs) communication applications.

Although MANET appears simple and versatile in various applications, the design of an efficient routing protocol for data communications in such networks is still a challenging task. Since the topology of the network changes rapidly and nodes can join or leave the network at any moment, this leads to a remarkable problem in choosing the relevant forwarding node and routing the packets. To this end, the vital issue is to design efficient routing protocols that are mobility-aware to find the optimal routes between communicating nodes and ensure better routing with less overhead and high network reliability [8–10]. Typically, the traditional topology-based routing protocols are mainly classified into three categories: reactive (on-demand), proactive (table-driven) and hybrid. These routing schemes are widely developed to cope with various challenges like high node mobility and dynamic network topology, transmission power or energy restrictions [11,12]. Specifically, such schemes allow the nodes to set an entire route before forwarding data packets, causing high control overhead due to the dynamic topology of MANETs. For example, reactive routing protocols, such as AODV (on-demand routing), do not adapt well in high-mobility environments [13].

On the other hand, geographic routing protocols have been shown more interest due to their location awareness via using a Global Positioning System (GPS) device or running localization algorithms. In effect, these approaches employ non-flooding-based route discovery and offer high scalability for large-scale networks depending on the nodes' position information. This means that nodes must know their own positions before broadcasting their beacons' "Hello" messages. Also, such routing protocols do not necessitate the setup of a route management process or link maintenance [14–16]. Instead, the routing decision requires only the position information, i.e., the nodes need only maintain one-hop neighbor information for routing decision; this makes them more robust and efficient protocols for dynamic networks. However, such routing mechanisms have some drawbacks because the position information of each node may change due to network conditions such as GPS devices that may not work well in some locations like tunnels because of the absence of satellite signals. Besides that, a high mobility of nodes may change the network density from sparse to dense or vice versa. In consequence, this will increase the links' breakages of one-hop neighbor nodes and degrade the accuracy of neighbors' awareness [17,18].

Notably, owing to the rapid topology change in the network, geo-routing protocols require broadcasting the proactive beacon packets (hello packets) periodically or non-periodically to discover neighboring nodes and maintain the correctness of routing selection. However, a high beacon rate (i.e., frequency of beacons) means excessive beacon overhead, which will raise the packets' collisions and transmission delay in the network [14]. Beacons are very small messages; they include parameters such as the position, velocity, and direction of mobility of the nodes. Such key information is utilized to build the routing decisions by estimating various network measures such as geographical distance, expected transmission count (ETX), defined as the neighbor link reliability, signal strength, stability, and link lifetime (link duration) [8,15,17–19]. In sparse networks, for example, broadcasting beacons with high transmission power is essential to expand the awareness area or communicate with distant nodes in mobile wireless environments. Nevertheless, the increase in the beacon transmission power or the frequency of beacons (beacon rate) may negatively affect the routing performance due to the limitations of the wireless link's bandwidth and network resources. Therefore, the trade-off between the beacon rate overhead and the accuracy of routing information (precision) is still an open challenge in ad hoc networks [20,21].

On the other hand, the other challenges that affect the routing performance in MANETs are invoked in the following aspects [6,22]:

(i) High and rapid node mobility issues have substantial effects on the efficiency of routing algorithms; thus, the mobility increases the changes in the network topology, causing connection failure and increasing the re-initiation of the route-discovery operation.
(ii) Medium Access Control (MAC) issues are responsible for node access to the shared medium and related to node mobility, Quality of Service (QoS), bandwidth, synchronization, hidden terminals, and exposed terminal problems.
(iii) Scalability refers to the capacity of the routing protocol to expand the network with a large node density without causing any disruption or failure in data transmission or traffic loading.
(iv) Energy consumption is another significant challenge when the devices are equipped with a limited-lifetime battery. Therefore, energy management for transferring information has to be minimized in ad hoc networks.
(v) Security is a critical issue in data forwarding for randomly distributed nodes, where the data packets are more vulnerable to attacks due to the absence of centralized control.
(vi) Furthermore, packet collision, resource constraints, interference, and packet loss are other significant challenges that MANET routing has faced.

In this study, therefore, we suggest an effective strategy to improve the performance of the most commonly used geographic-based routing protocol, called Greedy Perimeter Stateless Routing (GPSR), designed by Karp and Kung [23]. To do this, an adaptive beaconing strategy is proposed to mitigate the drawback of broadcasting beacons integrated with the greedy forwarding mechanism of this protocol, in addition to lessening the problem of inaccurate routing to the appropriate neighbor.

In fact, traditional GPSR is an efficient routing protocol where the nodes' positions and destination addresses are used to make routing decisions based on (Beacon) hello packet data. Every node sends out hello packets (beacons) periodically at regular intervals of time. The beacons include the nodes' addresses (IDs) and positions, as well as information concerning its one-hop neighbors. However, the beaconing process in this traditional GPSR exhibits a few drawbacks that make it somehow unreliable for high-mobility nodes. Once the nodes' topologies change rapidly, the nodes may need to increase their beaconing frequency to obtain more accurate information on neighbors. But even so, this will eventually lead to high control-traffic overhead, excessive use of energy, an increase in data network congestion and a high delay [17,18]. Therefore, it is essential to make a balance or an adaptation in choosing the beacon interval time (BIT) value (i.e., beacon rate) according to the network's requirements and features. Hence, a higher beacon rate means higher routing overhead, interference, energy consumption, and congestion and an increase in the transmission delay. On the contrary, a lower beacon rate results in longer route discovery and energy consumption, limited support to mobility and increased route instability [20,21].

With this criterion, instead of using fixed periodic beacons, an adaptive beaconing-strategy based on fuzzy logic (AFB) is modeled in this work to adjust the beacon frequency in MANET and improve GPSR protocol. The newly proposed "AFB-GPSR", an improved GPSR protocol based on the AFB strategy, can effectively reduce the routing overhead and increase the network reliability in terms of the packet-delivery ratio and transmission delay. To achieve this, a fuzzy inference algorithm is designed to control the beacon interval's time values based on the variation of three key parameters: (i) node speed (NS), (ii) one-hop neighbors' density (OHND), and (iii) link reliability (LR) between the node and its neighbors.

In this regard, several studies have suggested different analytical models like [24,25] or intelligent schemes like [26–28] in designing the adaptive beaconing strategy for wireless ad hoc networks. As is known, Artificial Intelligence (AI)-based decision-making systems, such as fuzzy logic, are powerful tools in classification, optimization, prediction and decision-making systems [29]. A fuzzy logic system is widely employed to improve the performance of the GPSR routing protocol. It is an efficient tool used to solve complex patterns or behavioral variations based on input membership functions and a group of fuzzy rules similar to the human brain's operation. More precisely, a fuzzy logic system provides a foundation for dealing with imprecision and ambiguity that use varying degrees of truth, such as the uncertainty inherent in the nature of ad hoc networks due to dynamic topology, node mobility, resource limitations and unsteady links, where an accurate model cannot be implemented [30].

The main contributions of this study are highlighted as follows:

- An adaptive geographic routing protocol, namely AFB-GPSR, is proposed. To achieve this, an adaptive beaconing strategy based on fuzzy logic (AFB) is designed to optimize the update beacon intervals and improve the routing performance.
- The optimal beacon interval time (OBIT) is adjusted dynamically with the variations of three key network parameters: mobility of nodes, one-hop neighbors' density, and link quality of the nodes.
- Extensive simulations are carried out using OMNeT++ jointly with the INET framework to verify the AFB strategy with GPSR routing protocol. The results show that the AFB strategy reduces the routing cost and improves network reliability in terms of the packet-delivery ratio, throughput, normalized routing load and delay in comparison to traditional AODV and GPSR routing protocols.
- Moreover, the AFB-GPSR protocol exhibits good performance versus the state-of-the-art protocols in MANET environment.
- In conclusion, the AFB strategy is an effective solution in broadcasting beacons for geographical routing as it can maintain more information accuracy in the local topology.

The rest of the article is organized as follows: Section 2 introduces an overview of the classifications of routing protocols in ad hoc networks. Section 3 presents a literature review of some recent related works. Section 4 briefly describes the mechanism of conventional Greedy Perimeter Stateless Routing. In Section 5, the architecture of the proposed AFB-GPSR and fuzzy logic composition are described in detail. Section 6 defines the simulation method and performance metrics, and Section 7 presents an analysis of the results. Section 8 illustrates the performance results and comparison with existing works. Finally, Section 9 draws the conclusions and suggests future directions.

2. Classifications of Routing Protocols: Overview

In this section, an overview of routing protocols types designed for ad hoc networks is briefly presented, including the classification type, a brief description and their pros and cons. The routing of wireless ad hoc networks is still challenging owing to the absence of a centralized authority and the unpredictability of network topology. Besides that, the characteristics of self-organization, mobility, medium type and node deployment present further difficulties in the design of an ad hoc network routing protocol [31,32]. Therefore, routing protocols for ad hoc networks are categorized into various classes; the two most well-known are (a) topology-based and (b) geographic-based routing protocols.

In fact, topology-based routing protocols, like the Ad hoc On-Demand Distance Vector (AODV), are also known as traditional routing protocols because they store link information in the routing table to forward packets from source to destination nodes. On the other hand, geographic-based routing algorithms, like GPSR, are designed to cope with some of the constraints of topology-based routing by using extra strategies, where the sender utilizes a location service to figure out the destination's position. Furthermore, the information is obtained through a beaconing procedure. There are also other routing protocol classifications such as hybrid-, hierarchical-, multicast-, Geo-cast-, and cluster-based routing protocols. Table 1 briefly summarizes the main routing categories [33–37].

Table 1. Routing categories in Mobile Ad hoc Networks.

Routing Protocol	Categories	Description	Advantages	Drawbacks
Topology-based	Reactive: AODV, DSR, ACOR, DYMO	On-demand routing; routes are founded when required by establishing route requests across the network.	• Adaptable to high dynamic topologies • Support multicasting	• High latency. • Excessive flooding. • Not reliable shortest path due to nodes mobility.
	Proactive: STAR, DSDV, OLSR	The routes kept updating in a table even though there is no demand for a route (table-driven)	• Loop-free • Established route up to date	• High overhead. • Low efficiency in high density. • High rapid networks.
	Hybrid: DVRP, ZRP, HSLS	Combine Reactive and Proactive routing algorithms.	• Efficient in rapid networks • Low latency • Low energy consumption • Low overhead • Scalability	• High traffic in high-density networks. • Progress complexity.
Geographic-based	GPSR, LAR, MORA, VADD,	The path establishment is based on the node's location information from GPS equipment.	• Efficient in rapid networks • Low energy consumption • Low overhead • Low latency • Scalability	• Perimeter mode fails to determine the most effective route. • Not self-learning.
Hierarchical-based	HSR, HDVG	The nodes are organized into hierarchal groups.	• Low overhead • Low congestion • High reliability • Consistent energy dissipation	• Complexity in maintenance of the cluster head.
Multicast-based	CBM, MDR, SMORT, AOMDV	A node establishes route to a single or multiple destinations simultaneously.	• Low Processing Cost • Low bandwidth requirement	• Low reliability. • High overhead. • Route based on subscription information.
Geo-cast-based	DGR, IVG	Send messages to a single or multiple nodes based on location (combine geographic and multicast routing).	• Low overhead • Low storage load	• Multicast routing and position information may not be available at the required location.

Table 1. *Cont.*

Routing Protocol	Categories	Description	Advantages	Drawbacks
Cluster based	GBDRP, PBSM, LEACH	The protocol divides network nodes into a number of overlapping or disparate clusters and assigns cluster heads to keep track of cluster membership.	• Low energy consumption • Low storage • High scalability • Low traffic	• Complexity. • Lack of selecting optimal cluster head. • High latency. • No mobility and direction.

3. Literature Review

Recently, in the ad hoc networks community, many researchers have proposed a variety of geographic routing strategies in WANET with fixed and dynamic beaconing. Some of these studies are conducted using analytical models; others are built on intelligent approaches [38–50]. Table 2 shows some of the recent related works.

Table 2. Some related works on beaconing approaches for geographical routing.

Research	Year	Routing	Simulator	Network	Objective
Ref. [38]	2014	Contention-based Adaptive Position Update (CAPU)	NS-2	VANET	To update the positions of the nodes and improve the greedy forwarding mechanism
Ref. [39]	2015	GPSR-FLDB (Adaptive Beaconing)	NS-2	MANET	Optimizes beacon interval time in GPSR routing
Ref. [40]	2017	GPSR + Predict (Adaptive beaconing)	NS-2	VANET	To ensure that each vehicle estimates its own position for the near future.
Ref. [41]	2019	(FL-DGR) Fixed beaconing	NS-3.25 + SUMO	VANET	To increase PDR, throughput and decrease average E2ED
Ref. [42]	2019	(ABOR) Adaptive Update Beacon in Opportunistic Routing	NS-2.3	VANET	To reduce beacon overhead, channel contention To increase accuracy of the next hop and QoS
Ref. [43]	2019	Enhanced Geographic Routing with two-hop neighborhood information	-------	MANET	To deal with critical communication voids in sparse MANETs. To reduce overhead and delay against communication voids
Ref. [44]	2019	MODEL Adaptive Beaconing (Fuzzy-based)	NS-2	MANET	Maintenance of the trade-off between beacon rate overhead and routing precision
Ref. [45]	2020	AGPSR (Update Beacons) Velocity-based	Programming C#	MANET	Beacon Interval Updating periodically depends on velocity to improve greedy forwarding
Ref. [46]	2021	FL-MDLR (Fixed Beaconing)	NS-2	VANET	To establish a stable route from the source S to destination node D.
Ref. [47]	2022	LDAB-GPSR (Slow-Start Adaptive Beaconing)	NS-2.35	MANET	To optimize packet-delivery ratio and reduce average control overhead.
Ref. [48]	2022	FL-QN GPSR (Fixed Beaconing)	OMNeT + SUMO	VANET	To detect the appropriate next-hop node for packet forwarding.

Table 2. *Cont.*

Research	Year	Routing	Simulator	Network	Objective
Ref. [49]	2022	ABNT (Adaptive Beaconing)	NS-3	FANET	To establish an adaptive beacon to control the transmission in UAV networks.
Ref. [50]	2023	UP-GPSR (Fixed Beaconing)	NS-3	FANET	To select optimal next-hop (i.e., optimize greedy forwarding)
Proposed Work	2023	AFB-GPSR (Adaptive Beaconing) Fuzzy-based	OMNeT	MANET	To update optimal beacon interval to increase network reliability and reduce routing overhead

In [38], the authors develop a contention-based adaptive position update (CAPU) scheme to improve the geographic routing performance for VANETs. Two mechanisms are suggested; the first is to update the node position, and the other is to manage the contention beacon. In this scheme, the next-hop selection depends on the difference between an estimated position and the actual position of the next hop; so if the value is greater than a specific threshold, the vehicle node can update its information and send a "Beacon" message including the vehicle ID, position, velocity, and direction. Otherwise, a "Hello", as a basic message, is sent with only the vehicle ID. However, this approach increases the communication overhead and the chances of collision in the network. On the other hand, in [39], the authors modeled a fuzzy logic dynamic beaconing (FLDB) method to optimize the beaconing transmission time. In the GPSR routing protocol, where the improvement is based on the correlation between neighbor nodes quantity, node mobility speed and beacon interval time using the fuzzy logic technique.

Houssaini et al. [40] introduced an analytical beaconing approach to improve the greedy forwarding strategy of geographic routing and predict the future movement of the nodes each time the nodes broadcast the beacons periodically. The resulting scheme is the GPSR + Predict protocol in VANET. In [41], a directional geographic routing based on a fuzzy logic system, namely FL-DGR, is proposed to improve the road safety and transportation capacity in V2V. The objective is to incorporate fuzzy logic decision-making in selecting the next-hop nodes by considering multiple metrics related to the vehicle's position, direction, link quality, and available bandwidth. However, FL-DCR routing does not consider the effect of adaptive beaconing. Conversely, Nadri et al. [42] also proposed an adaptive beacon strategy for opportunistic routing in VANET. The scheme is based on two rules; the first rule is related to estimating the link establishment time between two nodes, and the second rule is to send an update beacon to neighbors if the consecutively received packet-forwarding set is changed. The aim is to reduce the beacon overhead and maintain the accuracy of the neighbor nodes' toplogy.

Moreover, Hu et al. [43] proposed a new geographic routing technique to address the communication problems in sparse MANETs. The technique uses geographic location and two-hop neighbor information to create a forwarding-node-selection policy that determines optimal relay candidates that move towards destination nodes in a network. To that aim, the proposed geographic routing strategy has the advantage of reducing routing overhead and end-to-end delay in ad hoc situations. In the contrary, Neelagiri et al. [44] introduced the MObility pattern-free Dynamic and Effective Location update (MODEL) protocol to maintain the trade-off between beacon rate overhead and routing precision in MANET. It employs the fuzzy method to allow for the least amount of inaccuracy in predicting the position rather than in nearby nodes. The Load Balanced-Dynamic Beaconing Greedy Perimeter Stateless Routing (LB-DB-GPSR) is verified using the NS-2 simulator. Furthermore, adaptive GPSR (AGPSR) is introduced in [45] to enhance greedy forwarding and routing choice. The routing model is divided into three phases—initialization, neighbor discovery, and weight value computations—and next-hop selection. The weight value is related with a variety of network characteristics such as node density, node speed, transmission range, network size, congestion level, and movement direction. The Beacon Update Interval (BUI) is determined at the source node and is connected to relative velocity in this study. When the relative velocity is very high, the BUI will be very brief, and the beacon packet will be required frequently. If the relative velocity is very low (i.e., less than 1) and the BUI value is close to the default beacon interval, no additional beacon messages are needed from the neighbor.

Rana et al. [46] presented fuzzy-logic-based multi-hop directional location routing (FLMDLR) on VANET networks. FLMDLR determines the optimum next hops using fuzzy logic to construct a stable route from the source node to the destination node. This FLMDLR is investigated using NS-2 and compared to conventional D-LAR and LAR methods. On the other hand, the authors of [47] presented Location-Prediction-with-Adaptive-Beaconing-GPSR (LDAB-GPSR) to improve the mechanism of the GPSR protocol by focusing on optimizing the packet-delivery ratio and reducing the average control overhead. Two methods were used to accomplish this; the first was the position-prediction method, which improves the greedy forwarding strategy by selecting optimal routes to forward the data, and the second is dynamic beaconing, which uses the slow-start algorithm to change the beaconing interval depending on data traffic load and node mobility rather than the periodic beaconing technique.

Similarly, Aljabry and Al-Suhail [48] suggested an FL-QN GPSR routing protocol based on an intelligent fuzzy logic control system with fixed beaconing in VANET. The proposed routing protocol incorporates two criteria to determine the appropriate next-hop node for packet forwarding: neighbor node and node speed. On the other hand, Singh et al. [49] proposed an ABNT technique for geographic routing in UAVs. To keep the neighbor data table up to date, the strategy combines adaptive beaconing (AB) and neighbor timeout (NT). NT is calculated dynamically by utilizing mobility characteristics. The fuzzy logic system uses numerous characteristics related to node mobility, remaining node energy and traffic load to determine the beaconing rate, which reduces beacon overhead, latency, delivery loss rate and energy usage.

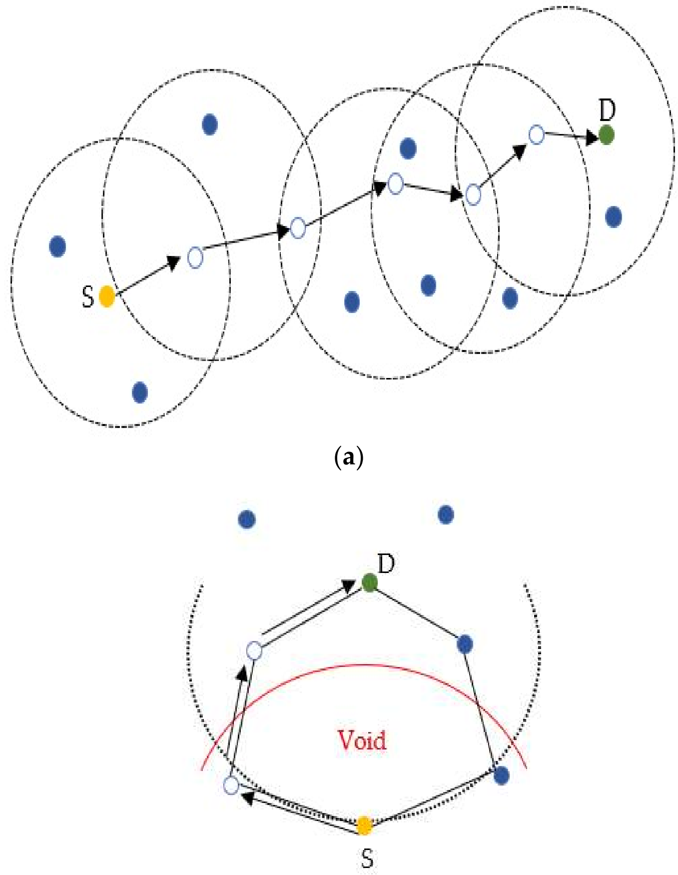
Finally, the study in [50] focuses on developing the Greedy Perimeter Stateless Routing (GPSR) protocol for FANETs. The approach is known as the Utility-Function-based Greedy Perimeter Stateless Routing (UFGPSR). The suggested method optimizes the greedy forwarding strategy by taking into account various critical factors of UAVs, including residual energy ratio, distance degree, movement direction, connection risk degree and speed. The proposed UFGPSR uses a utility function on these parameters to improve routing performance by choosing the best next hop within the transmission range.

In this paper, the GPSR is enhanced by using a dynamic fuzzy-beaconing algorithm termed AFB-GPSR in a MANET network in order to provide more adaptability to the rapid changes in node topology. The adaptive beaconing mechanism based on intelligent fuzzy logic is proposed instead of traditional periodic beaconing mechanism. Our strategy considers the network parameters of the node speed, one-hop neighbors' density, and network link stability. In brief, this technique effectively enhances GPSR performance by using a new real-time uncertainty fuzzy logic scheme to choose the best next-hop in GPSR routing.

4. GPSR Routing Mechanism

Several proposals have been studied in the literature [51–55] in order to improve geographical routing protocols by establishing stable and faster routing paths towards the destination in various network environments in MANETs and VANETs/FANETs. Most of these protocols were assigned to improve routing to select the best candidate nodes toward the destination.

In particular, GPSR routing protocol is one of the most classic location-based routing protocols; where each node is equipped with GPS unit. This will allow each node to know its location and the locations of its neighbors in addition to the location of the destination. A source node estimates the destination's location in the packet header and chooses the next hop that is the closest neighbor to the destination. It is based on calculating the optimal path to the target using an algorithm to transmit the packet until it reaches the destination [23]. However, it is called a stateless protocol in routing since each node in the network has only information about its neighbors and is unaware of the entire network nodes. The GPSR protocol uses two forwarding strategies, as shown in Figure 2, the greedy forwarding mode and the perimeter mode. Based on the state of network nodes; the greedy forwarding (GF) scheme chooses the closest neighbor to the destination in order to forward the packet. Otherwise, if no such neighbor is available closer to the destination (i.e., the void area), the perimeter routing strategy is used, where the source will consider the red-shaded area with no nodes to be a void area. Then, the source will route the packet around the void area by employing the right-hand rule to forward the packet. To accomplish this, the network nodes broadcast beacons on a regular basis. Each node sends a beacon to the broadcast MAC address, comprising its own identification number (ID/IP address) and position [52,53].



(**b**)

Figure 2. GPSR mechanism: (**a**) greedy forwarding mode; (**b**) perimeter mode.

4.1. Beaconing Approaches: Overview

To achieve high-reliability beacon communication in various network environments like MANET or VANET, many adaptive beaconing strategies have been developed to individually handle each beacon's transmission power, transmission rate, or contention window (CW) at the MAC layer, or any combination of these as hybrid techniques [38–40,42–44,47,49]. For further details, the state-of-the-art beaconing approaches with key features were addressed in [17]. Notably, the broadcasting beacons over MAC IEEE 802.11 have unique characteristics that make the broadcast more critical in finding the accurate position [43,56]:

(1) There is no acknowledgment system for the short beacon message to let the sender know when it is successfully received.
(2) A request to send/clear to transmit (RTS/CTS), a handshaking mechanism, is not employed prior to beacon transmission in order to prevent beacon broadcast collisions at the MAC layer.
(3) The fixed contention window (CW) may increase the chances of collision and degrade the performance of beacon broadcast.

Moreover, the redundant broadcasting of the beacon packets increases the amount of control traffic overhead in the network and the energy consumption at each node. This causes early disconnections in data-routing paths in wireless networks. Additionally, excessive control overhead increases bandwidth consumption and congestion in the network [35]. Therefore, beaconing techniques are classified depending on the nature of routing protocols or the emergency network status as follows:

- Periodic Beaconing: Nodes send beacons at regular intervals. For instance, this method can be utilized in topological routing such as DSDV (Destination-Sequenced Distance Vector) and AODV (Ad hoc On-Demand Distance Vector) algorithms.
- Adaptive Beaconing: Beaconing intervals are constantly modified according to the network traffic load, connection quality, or mobility patterns.
- Beaconing triggered by events: Nodes transmit beacons in response to certain events or triggers (substantial change in their network state).
- Geographic Beaconing: Nodes use their geographical position to determine when and to whom beacons should be sent.

4.2. Beaconing Interval Time

In an ad hoc network, a beacon is a periodic exchange packet that carries node status information such as ID, velocity, position and other information required by routing protocols. In the original GPSR, the nodes are defined with a geographic beaconing mechanism, which advertise beacons for their own information announcements at regular intervals known as beacon interval times (i.e., at fixed beacon rate). When a node obtains a beacon packet from a neighbor node, it makes an entry for this neighbor's information in the neighbor list. In addition, to eliminate synchronization between neighbors' beacons, a maximum jitter equal to 0.5 of Beacon Interval Time (*BIT*) has been established for each beacon's transmission. Thereby, the mean inter-beacon interval time is uniformly distributed in the range (0:5 BIT, 1:5 BIT) [22]. Then, in accordance with (1), the node schedules a beaconing timer along the simulation time (*SimTime*).

$$BT = SimTime + BIT + uniform(-1,\ 1) \times maxjitter \tag{1}$$

where *maxjitter* denotes the maximum allowable *jitter*.

If no beacons are received from the X neighbor for a specified timeout neighbor validity (*TNV*), then the node is supposed to be out of range and will be removed from the list of neighbors. The *TNV* is calculated using Equation (2).

$$TNV = 4.5 \times BIT \tag{2}$$

5. The Proposed AFB-GPSR Strategy

In ad hoc networks, it is preferable to generate beacons at a high rate to increase the freshness of the exchanged information (i.e., increase neighborhood awareness), but this may increase network congestion and resource consumption. On the contrary, transmitting fewer beacons saves bandwidth and reduces congestion. This may result in outdated information. Therefore, it is essential to employ adaptive schemes that adjust the beacon rate based on various criteria such as network topology, mobility, and link quality.

A fuzzy logic system (FLS) is described in general as a nonlinear mapping of a data input vector to a scalar output. FLS is made up of four modules [30];

(1) Fuzzification module—The system's crisp values are converted into fuzzy sets utilizing fuzzy linguistic variables and terms, as well as membership functions.
(2) Knowledge base—contains expert-provided IF–THEN rules.
(3) Inference engine—performs fuzzy inference on inputs using IF–THEN rules from the knowledge base.
(4) Defuzzification module—converts the inference engine's fuzzy set into a crisp value.

In particular, in geographical routing, each node makes forwarding decisions based on the position information contained in the neighbor database. Therefore, to accommodate the rapid topology changes in MANET, the AFB-GPSR strategy is proposed as an optimization of the original GPSR routing algorithm. The improvements are made primarily for the GPSR beaconing strategy in both GF and perimeter modes to ensure the precision and truthfulness of routing table information and ensure optimal routing achievement. Therefore, a fuzzy logic controller (FLC) is modeled to evaluate the optimal beaconing interval time (OBIT) based on the variations of three key network parameters that have a large effect on the network performance:

(i) The node speed (NS) of the current sender, regarded as the main cause of link failure;
(ii) The one-hop neighbors' density (OHND), which affects the availability of next-hop resources; and
(iii) The link reliability (LR) between the sender and its neighbors.

5.1. AFB-GPSR Architecture

The following principal steps illustrate the criteria of the network model in the proposed strategy:

1. Nodes are positioned randomly in an unimpeded area;
2. Each node is aware of its own geographical coordinates (position), IP address, speed, and direction;
3. Each node has the same transmission range and starts with an initial beacon interval for sharing information;
4. Once the node receives beacon packets from its neighbor nodes in the coverage area, it can obtain the neighbor information list and calculate one-hop neighbors' density and link reliability;
5. The fuzzy logic model is triggered to calculate a new *optimal beaconing interval time* (OBIT) based on the three network parameters defined as NS, OHND, and LR;
6. Finally, the AFB-GPSR protocol can find the optimal next-hop route decision through the new beaconing interval time jointly with the original GPSR protocol to establish the routes using the GF (greedy forwarding) mode or perimeter mode.

The routing information table for each node utilizing the proposed AFB-GPSR is defined in Figure 3. The information includes node IP, node position (X,Y), direction, speed, link reliability and neighbors' density. Each node manages this neighbor's table that holds the information obtained from a received beacon (Hello) message. The pseudocode of the AFB-GPSR algorithm is provided in Algorithm 1, and the flowchart of AFB-GPSR is also illustrated in Figure 4 to describe the two phases of beaconing and routing. Initially, each node starts broadcasting beacons with a fixed interval; once a node receives the neighbor's beacons, the routing information table is built including six parameters, node IP, node position (X,Y), direction, speed, link reliability and neighbors' density. Once the information is received, three parameters, node speed (NS), one-hop neighbors' density (OHND) and link reliability (RL) between the node and the neighbor node, are considered as input variables to fuzzy inference system (FIS) to dynamically update the new beacon for next broadcasting beacon. Later, the phase of next-hop selection for data forwarding starts either in greedy forwarding mode or in perimeter mode if there is a local max region (void region), as shown in Figure 4.

Algorithm 1. AFB-GPSR Mechanism

Input: Destination IP, Source IP
Output: BIT //BIT = Beacon Interval Time,
Initialize BIT = 1 //Start with initial value BIT = 1 s
Phase1: Beaconing Phase
For each node N do
1. Read self-address
2. Read self-position coordinates
3. Read self-speed
4. Read self-direction
5. End For
6. Broadcast Beacons
7. Update neighbors' tables information based on neighbor node (Nn) beacons' information
8. Estimate node speed (NS)
9. Estimate one-hop neighbors' density (OHND)
10.Estimate link reliability (LR)
11. Evaluate a new BIT based on FLC inputs (Self-Speed, OHND and LR)
Phase2: Routing Phase
12. If Nn is the destination Then, Send the data packet
13. Elseif
Nn the closest node to the destination Then, Switch to Greedy mode
14. Else
Switch to Perimeter mode
15. Forward the data packet
16. Update Self Table information (Address, Location, Speed and Direction)
17. Broadcast Beacons based on new FLC output BIT
18. Repeat **Phase 1** and **Phase 2** until Data Packet reach the destination

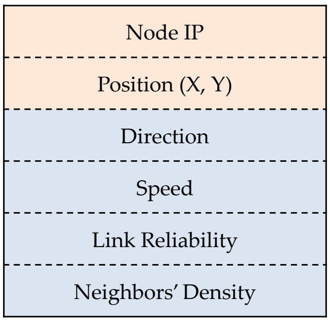


Figure 3. Routing table information in AFB-GPSR protocol.

5.2. Fuzzy Logic Composition

In an adaptive beaconing strategy, a fuzzy logic system (FLS) is used to control and predict the new beacon interval time, i.e., (Optimal BIT) by enforcing a set of rules on three multiple variables (NS, OHND and LR) as per the concept presented in Figure 5. The model is written in C++ combined with OMNeT++ to compute the imprecise data of the three input parameters.

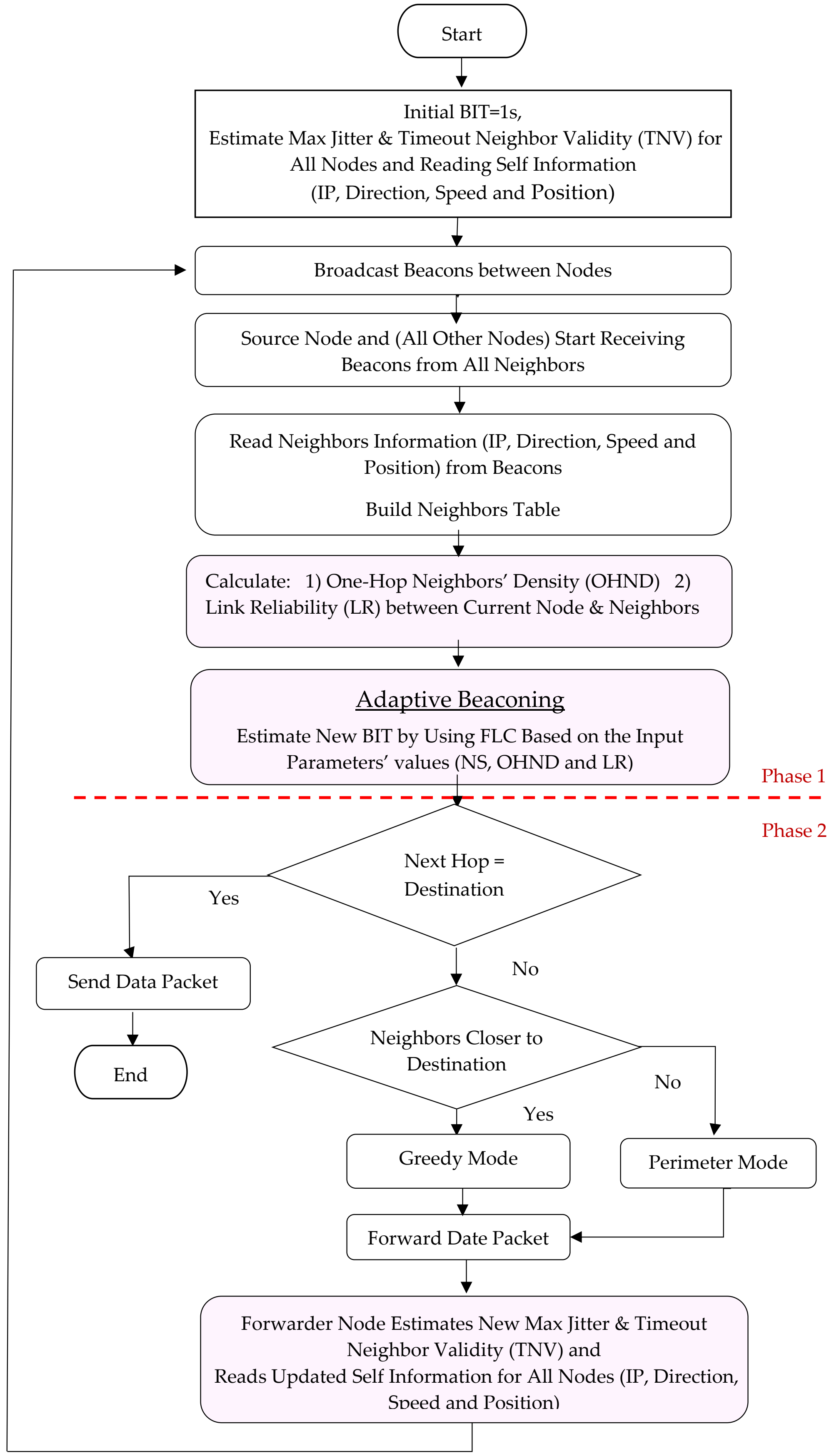


Figure 4. The flowchart of the proposed AFB-GPSR mechanism.

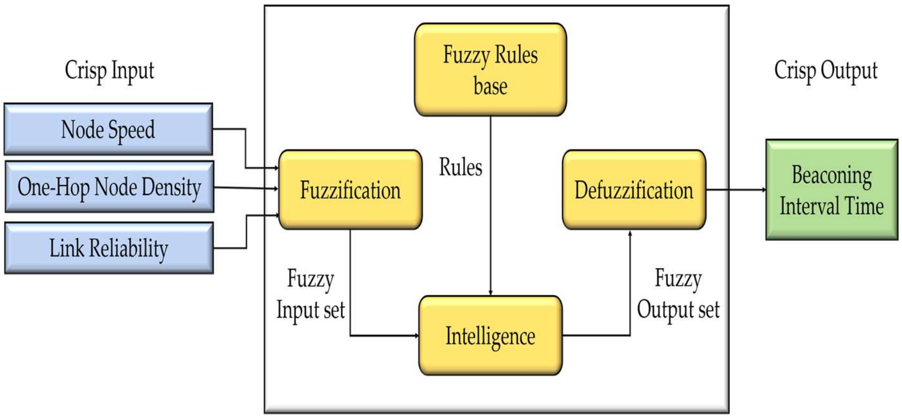


Figure 5. AFB-GPSR fuzzy logic strategy.

The fuzzy input parameters are described as follows:

- Node speed (NS): The mobility of the nodes causes the link to become unstable over time, with the increased mobility speed leading to an increase in link failure. This entails more traceability of the neighbor nodes [29,57].
- One-hop neighbors' density (OHND): The density of neighbors is determined by setting a counter for one-hop nodes that travel in the same direction as the source node, which is calculated as per (3). And the difference between the current source node angle and the neighbor angle is less than 45 degrees to be considered in the counter, where the neighbor recognized as per (3),

$$\mathrm{NN} = (|\mathrm{Sa} - \mathrm{Na}| * 180/\pi) < 45 \tag{3}$$

where NN is defined as the neighbor node Sa is source angle, and Na is Neighbor angle.

- Link reliability (LR): Link reliability has a significant impact on the network's performance in terms of the link quality metric ETX [41,58]. The establishment of communication links between nodes is influenced by changes in the network topology, and these communication links may fail due to link failures. Hence, link reliability is described as per Equation (4).

$$\text{Link Reliability} = \text{Total Received Beacons}/\text{Total Sent Beacons} \tag{4}$$

5.2.1. Fuzzification

This process fuzzifies input parameters, which are graded and assigned to the appropriate fuzzy sets. The crisp inputs have three linguistics of small, medium and large for the NS, OHND and LR as per the trapezoidal membership functions since the trapezoidal function allows for more flexibility in modeling asymmetric or irregular membership distributions. The membership value remains constant between the left and right boundaries, indicating full membership in that range.

5.2.2. Rules and Intelligent Decisions

The fuzzy evaluation rules are made up of a group of rules that contain IF–THEN, conditions to control the output based on the inputs set by using Mamdani fuzzy interference, as illustrated in Table 3. It can be observed that the value of BIT increases when NS decreases and OHND and LR increase and vice versa. For example, if the node speed is less than 10 mps, OHND value is Large; and if LR is greater than 70%, the output BIT states as Long interval. Therefore, in this model, it is preferable to avoid selecting Very Short or Very Long BIT values during the neighbor-detection process to achieve an effective neighbor table for data routing.

Table 3. AFB-GPSR fuzzy rules.

Seq	NS	OHND	LR	Output (BIT)
1	Small	Small	Small	Short
2	Small	Small	Medium	Medium Short
3	Small	Small	Large	Medium Short
4	Small	Medium	Small	Medium Short
5	Small	Medium	Medium	Medium
6	Small	Medium	Large	Medium Long
7	Small	Large	Small	Medium
8	Small	Large	Medium	Medium Long
9	Small	Large	Large	Long
10	Medium	Small	Small	Short
11	Medium	Small	Medium	Medium Short
12	Medium	Small	Large	Medium
13	Medium	Medium	Small	Medium Short
14	Medium	Medium	Medium	Medium
15	Medium	Medium	Large	Medium Long
16	Medium	Large	Small	Medium Long
17	Medium	Large	Medium	Long
18	Medium	Large	Large	Long
19	Large	Small	Small	Short
20	Large	Small	Medium	Short
21	Large	Small	Large	Medium Short
22	Large	Medium	Small	Medium Short
23	Large	Medium	Medium	Medium
24	Large	Medium	Large	Medium Long
25	Large	Large	Small	Medium Long
26	Large	Large	Medium	Medium Long
27	Large	Large	Large	Medium Long

5.2.3. Defuzzification

The defuzzification process converts the fuzzy sets into crisp output values that contain six membership functions, which are classified as Short, Medium Short, Medium, Medium Long, Long and Very Long. The output represents the beacon interval time in seconds. The inputs and output membership functions are represented in Figure 6. In the proposed system, the center of gravity or centroid (COG) is used for the defuzzification process. The centroid method is equivalent to finding the center of mass of the output composition [29].

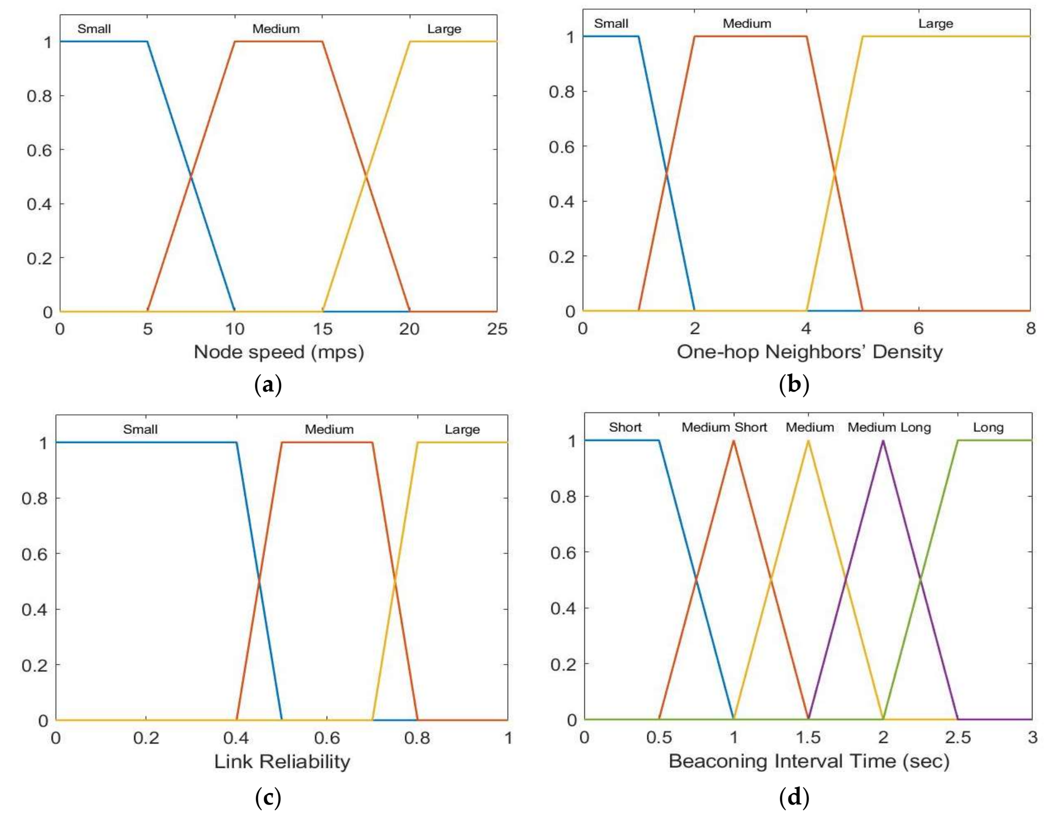


Figure 6. Inputs and output membership function (**a**) node speed; (**b**) one-hop neighbors' density; (**c**) link reliability; (**d**) output beaconing interval.

6. Simulation Setup

The simulation was performed by presenting three experimental scenarios in order to verify the QoS's performance of the proposed AFB-GPSR. The scenarios are designed to assess the impact of various MANET environmental settings on AFB-GPSR performance in comparison to GPSR [23] and topology-based AODV routing protocols [59]. The first scenario examines the performance under various node densities while holding the other simulation parameters constant, and the second scenario is tested by varying the speed of nodes. On the other hand, the third scenario presents the impact of transmission power on AFB-GPSR in comparison to the conventional GPSR with 1 s and 2 s fixed beaconing intervals.

To verify the proposed AFB-GPSR routing protocol, three extensive simulation scenarios were implemented in this section to investigate the scalability in terms of various network sizes (nodes density), the mobility metric in terms of nodes' motion speeds, and the effect of various node transmission power values on the routing efficiency through network metrics of reliability and latency.

6.1. Simulation Methodology

The simulation steps of AFB-GPSR were built and executed using the OMNeT++ simulator and the INET framework. The OMNeT++ platform built in C++ is one of the most popular software simulators, which also include NS-2, NS-3 and OPNET, as it has the features of modules connected by gates with a graphical user interface (GUI) [60–62]. Figure 7 demonstrates the simulation system's configuration for verifying the proposed AFB-GPSR protocol. Figure 8 depicts the required project architecture of the simulation model.

To verify the proposed AFB-GPSR routing protocol, the OMNeT++ simulation was run with various network sizes (node densities) and node-motion speeds in addition to various transmission power values. The experimental simulations were conducted to investigate: (i) GPSR routing protocol with fixed beacon interval times (1 s and 2 s), (ii) AODV routing protocol, and (iii) the proposed AFB-GPSR in case of adaptive beacon interval. Figure 9 shows the required network settings to establish and implement the configurations in OMNeT. The sources and destinations were chosen at random from the experimental scenario's nodes. In addition, the Random Waypoint (RWP) model is considered for the nodes' movement, where every node in the simulation environment can choose a random destination and move directly toward it. After arriving at its destination, it comes to a halt for a predetermined amount of time, identified as a pause time, and the procedure is repeated iteratively.

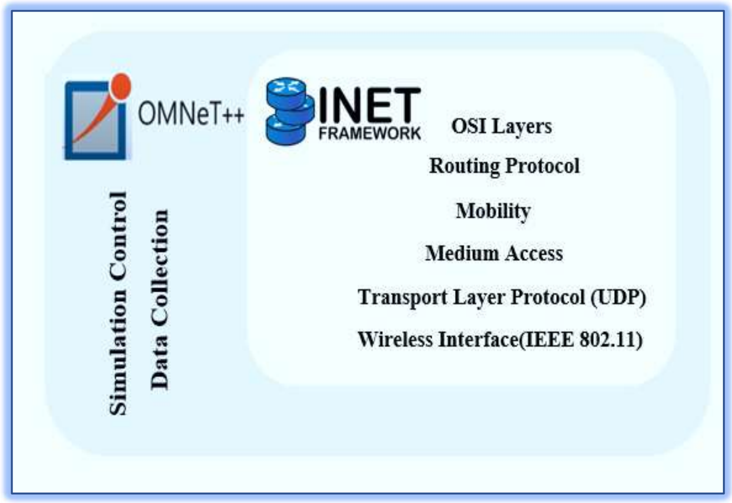


Figure 7. The simulation system configuration to implement the AFB-GPSR Protocol.

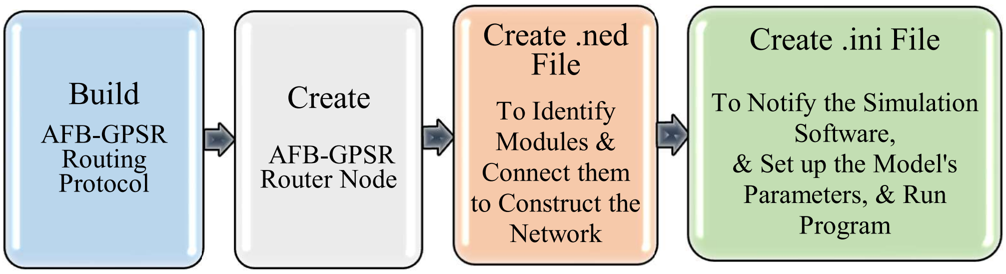


Figure 8. The OMNeT++ Project Architecture to build the AFB-GPSR routing protocol.

6.2. Performance Metrics

In the performance evaluation process of the AFB-GPSR protocol, and for comparison purposes, the following performance metrics are measured [52,55]: packet-delivery ratio (PDR), end-to-end delay (E2ED), network throughput and normalized routing load (NRL) [58].

1. PDR: This refers to the ratio of packets successfully received by the destination to the total number of packets delivered from the source;

$$PDR = (successfully\ received\ packets)/(delivered\ packets) \tag{5}$$

2. E2ED: This is the period of time occupied by a packet traveling from the source until it is successfully received by the destination;

$$E2ED = Packet\ Received\ time - Packet\ Delivered\ Time \tag{6}$$

3. Throughput (bps): This is expressed as the number of bits received successfully by the destination over a specified time period. In the case of the GPSR routing protocol, control overhead includes the total number of transmitted beacon packets.

$$Throughput = (Total\ Received\ Bits)/(Simulation\ Time) \quad (7)$$

4. Normalized Routing Load (NRL): It denotes the percentage of all routing control packets sent by all nodes divided by the number of data packets received at the destination:

$$NRL = (Total\ Sent\ Control\ Packets)/(Total\ Received\ Data\ Packet) \quad (8)$$

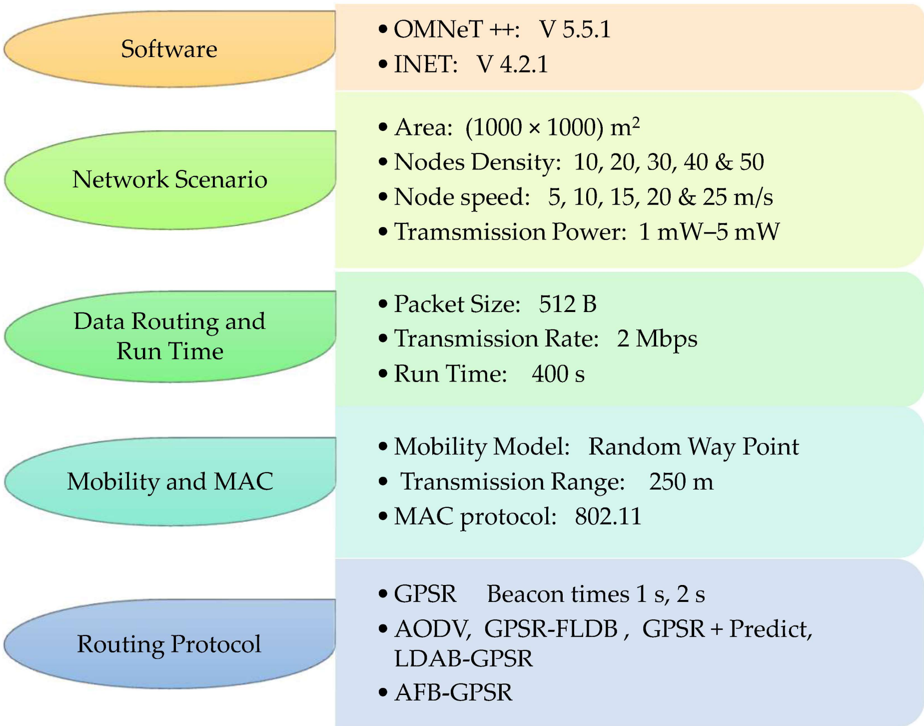


Figure 9. Simulation network settings.

7. Simulation Results and Discussion

In this section, three experimental scenarios are presented to verify the Quality of Service (QoS) performance of the proposed AFB-GPSR. Each scenario is designed to assess the impact of various MANET environmental settings on the AFB-GPSR performance in comparison to the GPSR and AODV routing protocols. The first scenario examines the performance under various node densities at a speed of 10 mps. The second scenario is tested by varying the speed of nodes for a density of 50 nodes. The third scenario examines the impact of transmission power upon GPSR in fixed and dynamic BIT statuses. In the proposed scenario, the QoS metrics in terms of packet-delivery ratio (PDR), end-to-end-delay (E2ED) and throughput are evaluated for the proposed AFB-GPSR with regard to the standard GPSR and AODV protocols.

A. Experimental Scenario (1): The Impact of Node Density

The network performance is studied for node densities of 10, 20, 30, 40 and 50. Figure 10 illustrates that the PDR grows clearly with node density, with higher node density indicating more reliable routes to the destination. However, when the node density is fewer than 11 nodes, the PDR for both the fixed GPSR and AFB-GPSR protocols is similar; however, as the node density rises, the AFB-GPSR provides a greater PDR than the GPSR and AODV.

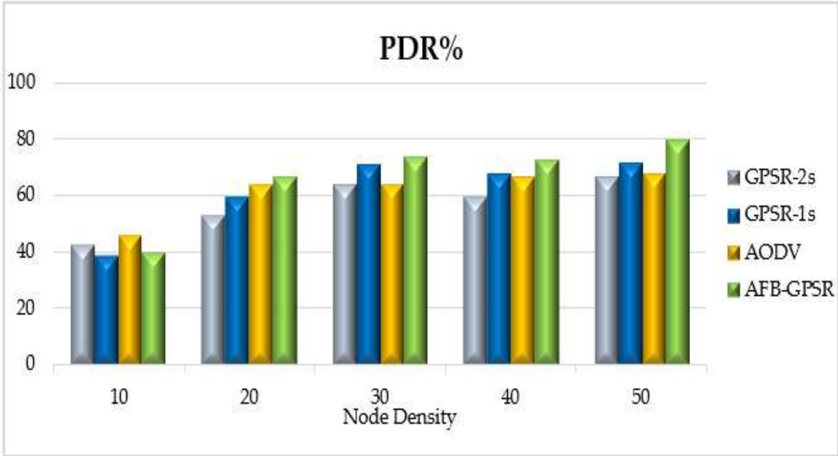


Figure 10. Packet-delivery ratio vs. node density.

On the other hand, in Figure 11, when the network density increases (i.e., more nodes are added), the resultant E2ED of AFB-GPSR achieves nearly the same E2ED in GPSR-2s; but AODV indicates the highest E2ED values when compared to GPSR-1s. This occurs due to the excessive route discovery and maintenance procedure of AODV mechanism. Furthermore, when density expands, throughput improves significantly. AFB-GPSR outperforms GPSR, whereas the route in AFB-GPSR exposes more reliable beacon intervals than GPSR at fixed beacon intervals, as illustrated in Figure 12. In addition, because AODV operates without loops and is scalable to a large number of nodes, it has the maximum throughput in comparison to GPSR and AFB-GPSR in two examples of 10 and 20 node densities, although it drops less than the other protocols as the node density rises.

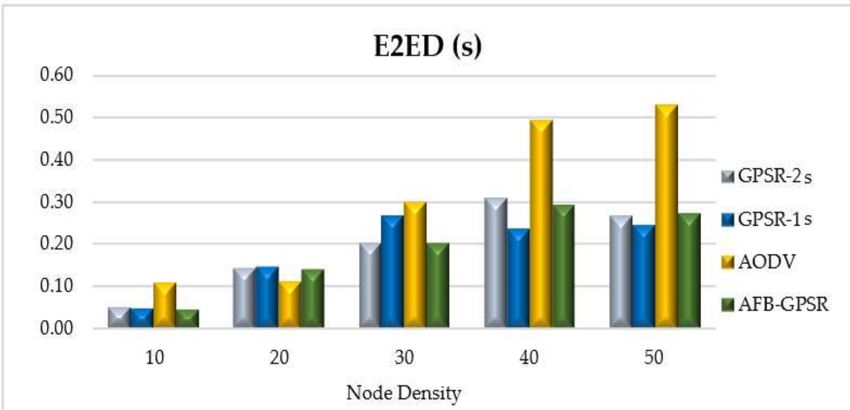


Figure 11. End-to-end delay vs. node density.

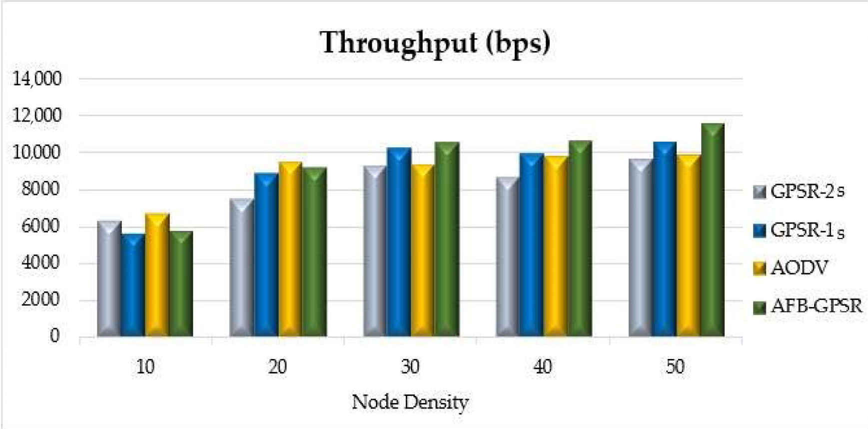


Figure 12. Throughput vs. Node Density.

B. Experimental Scenario (2): The Impact of Mobility Speed

The impact of mobility speed on network performance is investigated by testing different speed values, ranging from 0 to maximum speeds of 5, 10, 15, 20 and 25 mps, which are equal to 18, 36, 54, 72 and 90 kmph, respectively. In this scenario, Figure 13 shows that the PDR metric in AFB-GPSR clearly decreases as the maximum moving speed increases once there is a rapid change in network nodes. In contrast, it is found that this AFB-GPSR achieves a higher PDR compared to both the conventional GPSR and AODV routing protocols.

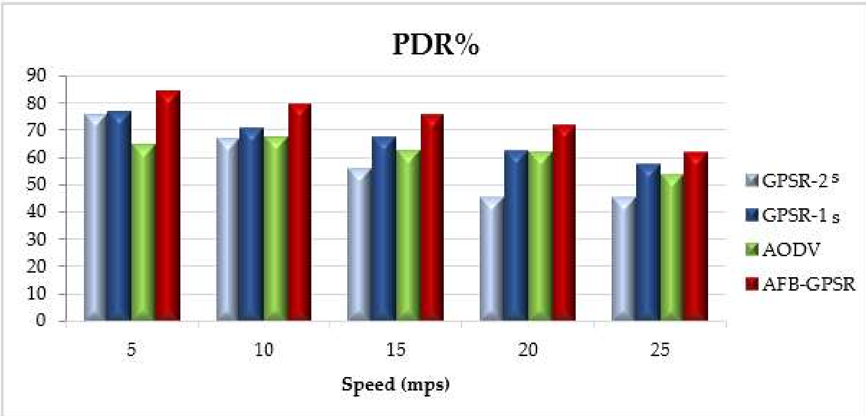


Figure 13. Packet-delivery ratio vs. node speed.

In Figure 14, AFB-GPSR also outperforms in evaluating the E2ED metric. It can maintain nearly constant E2ED with nearly 0.3 s on average when the mobility speed increases to 25 mps, and this occurs because of the randomness of the mobility. However, AODV registered a higher E2ED compared with AFB-GPSR and GPSR. That is because the AODV strategy is not easy to adapt with the dynamic nodes mobility, and it may take a longer time to find a route when the link breakage occurs.

On the other hand, Figure 15 shows that AFB-GPSR has a higher throughput than the original GPSR-1s and GPSR-2s at a fixed beaconing time and the original AODV. Meanwhile, AODV topology-based routing has a lower throughput resulting due to the high latency and excessive route discovery in AODV.

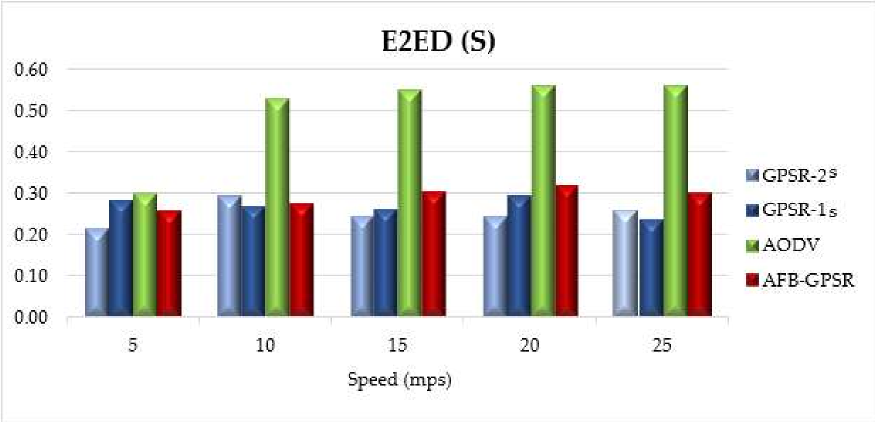


Figure 14. End-to-end delay vs. node speed.

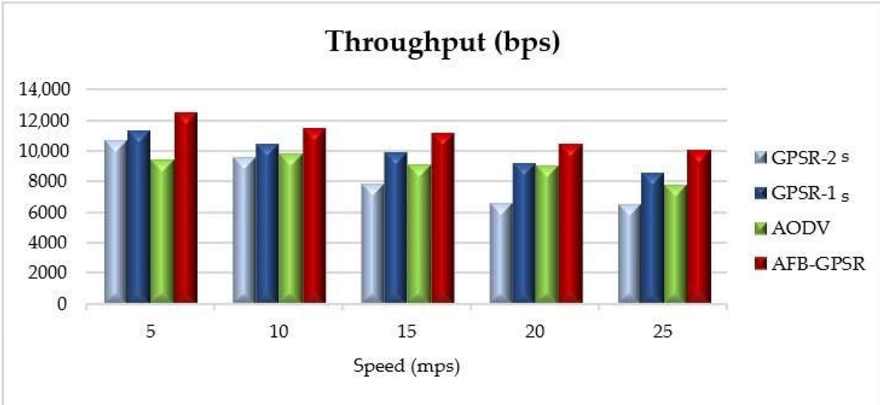


Figure 15. Throughput vs. node speed.

C. Experimental Scenario (3): The Impact of Transmission Power

This scenario was conducted for various transmission powers of 1, 2, 3, 4 and 5 mW that can cover the transmission ranges of 170, 270, 300, 353 and 390 m, respectively. The network density was set with 50 nodes (i.e., small scale network) and each node mobility speed at 10 mps. The QoS metrics in terms of PDR, throughput, and NRL were also estimated and analyzed to examine the performance of AFB-GPSR in contrast to conventional GPSR at fixed beacon times of 1 s and 2 s.

As shown in Figures 16 and 17, the PDR and throughput are increased dramatically as the transmission power increases. Increasing transmission power indicates that nodes can communicate over longer distances and form stronger links with neighbor nodes, which enhance transmission efficiency. In other words, increasing transmission power improves network reliability, allowing nodes to maintain a wider geographical area for data communication. This will definitely allow the nodes to quickly find their positions and make more efficient routes.

As noted above, AFB-GPSR significantly outperforms the GPSR-1s and GPSR-2s since it depends on dynamic beaconing time that updates the neighbors' table information properly with node movements with different transmission power values. Furthermore, in Figure 18, the proposed AFB strategy is able to reduce NRL as the transmission power increases. In this case, it means that the neighbors' connections become more robust and reliable when the transmission power is increased. Thus, longer link lifetime minimizes the chances of link failures, route interruptions and frequent topology changes. As a result, the network nodes can send more reliable data through optimal routes that were generated due to optimal broadcasted beacons at the higher transmission power value.

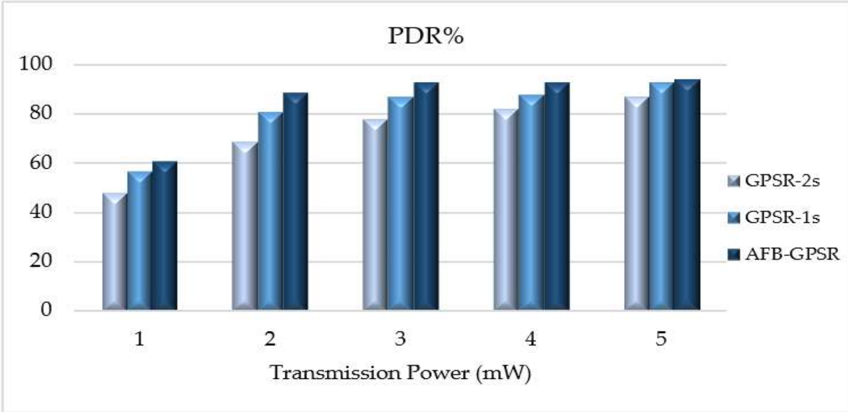


Figure 16. Packet-delivery ratio vs. transmission power.

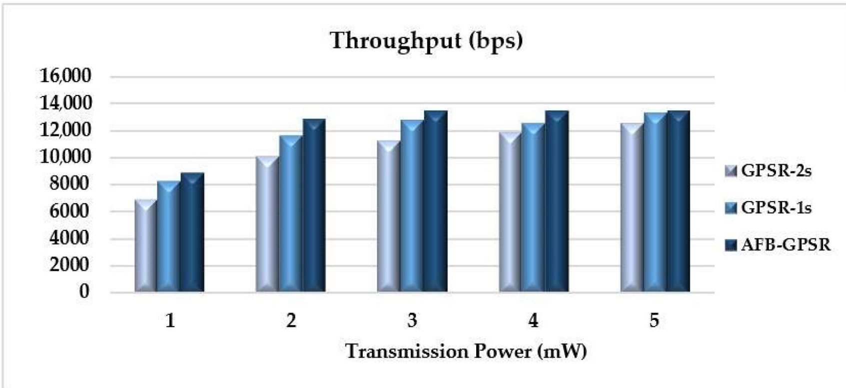


Figure 17. Throughput vs. Transmission Power.

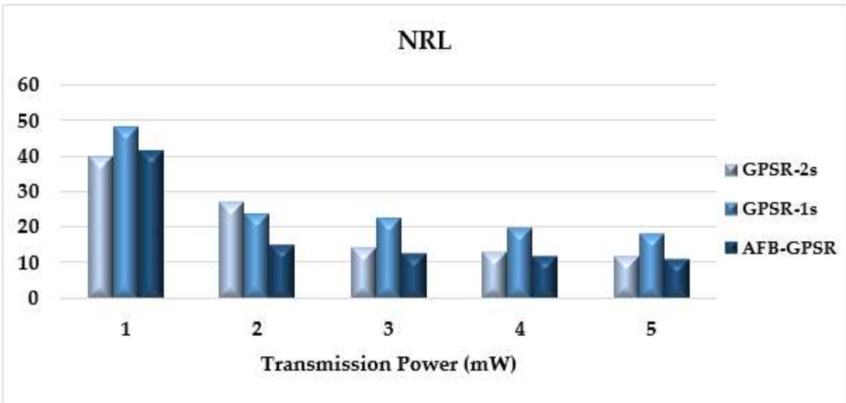


Figure 18. Normalized routing load vs. transmission power.

On the other hand, the NRL cost in AFB-GPSR has registered a lower value than the corresponding values of GPSR-1s and GPSR-2s when transmission power increases. This means the AFB dynamic beaconing strategy can allow the nodes to send their beacons only when necessary, such as when the topology changes or when a node has to update its neighbor information. Consequently, the control overhead associated with broadcasting beacons is reduced because the nodes are able to adapt to the updated beacons instead of fixed beaconing intervals. It is noticed that the GPSR with a 1 s beaconing time achieves a higher cost in NRL, where more frequent beacon messages by the nodes need more processing and forwarding times as the control packets increase.

8. Performance Comparison with Related Protocols

In this section, we firstly address the improvement ratios of the proposed AFB-GPSR compared to the conventional routing protocols AODV and GPSR with fixed periodic beaconing. In summary, in the first scenario of varying network size (i.e., small network scalability up to 50 nodes), it is found that the PDR is improved by nearly 10%, 5% and 5% on average compared to GPSR-2s, GPSR-1s and AODV, respectively. Additionally, throughput percentage of AFB-GPSR also increases by 15%, 5% and 5% on average, respectively.

Moreover, the speed-variant scenario shows the improvement in ratios of 17%, 8% and 13% on average and improvement in throughput of 35%, 13% and 23% on average compared with GPSR-2s, GPSR-1s and AODV, respectively). However, it is noticed that E2ED is approximately the same in the conventional GPSR-1 and GPSR-2 when there is an increase in the node density or node speed as well. Meanwhile, AODV has registered a higher delay than AFB-GPSR and the standard GPSRs, because AODV usually takes a longer time to establish its routes.

For the third scenario, the proposed AFB-GPSR also outperforms GPSR-2s and GPSR-1s when the transmission power varies from 1 mw to 5 mw. Higher transmission power means higher network reliability, and lower transmission power leads to low node connectivity. As a result, the AFB strategy can provide more optimal routing performance when the transmission power decreases. Furthermore, this AFB strategy can reduce the routing cost of NRL by 14% and 35% compared with GPSR-2s and GPSR-1s, respectively.

On the other hand, Table 4 summarizes the average results of the three experimental scenarios as follows. In the first scenario, with different network sizes (i.e., number of nodes varies up to 50 nodes), it is found that the PDR achieves 67% on average in AFB-GPSR compared to GPSR-2s, GPSR-1s, and AODV (57%, 62%, and 62%, respectively). In addition, the throughput value in AFB-GPSR is 9519 bps on average compared to (8243, 9015, & 9017 bps) in GPSR-2s, GPSR-1s and AODV, respectively.

Table 4. The average performance of three experimental scenarios.

Routing Protocol		Experimental Scenario (1)	
	PDR%	**E2E Delay**	**Throughput**
GPSR-2s	57%	0.193	8243
GPSR-1s	62%	0.187	9015
AODV	62%	0.308	9017
AFB-GPSR	67%	0.187	9519
		Experimental Scenario (2)	
	PDR%	**E2E Delay**	**Throughput**
GPSR-2s	58%	0.25	8276
GPSR-1s	67%	0.27	9924
AODV	62%	0.5	9056
AFB-GPSR	75%	0.29	11,161
		Experimental Scenario (3)	
	PDR%	**NRL**	**Throughput**
GPSR-2s	73%	21	10,568
GPSR-1s	81%	27	11,733
AODV	----	-----	----
AFB-GPSR	86%	18	12,462

Moreover, in the speed-variant scenario, the AFB-GPSR has registered the highest PDR of 75% on average, compared to the GPSR-2s, GPSR-1s, and AODV, (58%, 67%, and

62%), respectively. And, AFB-GPSR has the highest average throughput of 11,161 bps in various speed settings.

For the third scenario, when the transmission power varies from 1 mw to 5 mw, at fixed speed 10 mps and 50 nodes, AFB-GPS outperforms in its PDR up to 86% on average compared to the GPSR-2s and GPSR-1s (both achieve 73% & 81%), respectively. However, this AFB strategy can effectively reduce the NRL routing cost to achieve 18 on average compared with GPSR-2s and GPSR-1s; meanwhile both GPSRs reach higher routing costs, 21 and 27, respectively.

On the other hand, to verify the robustness and effectiveness of the proposed AFB-GPSR protocol, Table 5 showcases different comparative performances with other recent adaptive-beaconing-based GPSR protocols. The findings reveal that the AFB strategy exhibits a good performance in terms of the routing cost and network reliability compared to GPSR-FLDB [39], GPSR + Predict [40] and LDAB-GPSR protocols [47].

Table 5. Comparative performance with recent protocols for a density of 50 nodes.

Method	Year	Routing	Network's Parameters	PDR%	E2ED	Throughput
Ref. [39]	2015	GPSR-FLDB	Data Packet Size 512 B, Node Speed 40 m/s NS2.33	~90%	600 ms	----
Ref. [40]	2017	GPSR + Predict	Data Packet Size 64 B, Node Speed 20 m/s NS2.33	~80%	20 ms	24 Kbps
Ref. [47]	2022	LDAB-GPSR		~90%	17 ms	30 Kbps
Proposed Protocol	2023	AFB-GPSR	Data Packet Size 512 B, Node Speed 20 m/s OMNeT++	80%	270 ms	11 Kbps

9. Conclusions and Perspectives

The paper proposes an adaptive beaconing strategy based on a fuzzy logic model to enhance the common geographical GPSR routing protocol, resulting in the "AFB-GPSR" protocol. This strategy mitigates uncertainty in information update lists and ensures more reliable data forwarding in high-mobility and rapid MANET topology changes. The fuzzy logic model dynamically generates a beaconing interval based on the variations of three key network parameters: (i) node speed (NS), (ii) one-hop neighbors' density (OHND) and (iii) link reliability (LR). The Mamdani fuzzy inference system is integrated in each mobile node to generate this new optimal beaconing interval time (OBIT) value, taking into account the network status, i.e., the neighbors' status. The performance of the AFB-GPSR routing protocol was assessed through experimental simulations using the OMNeT++ and INET framework in three different environmental scenarios by varying network size, node mobility and transmission power. The findings show that the AFB strategy can reduce the routing cost in terms of transmission delay and control the routing overhead; on the contrary, it increases the network reliability in terms of network throughput and packet delivery. The achieved enhancement of the packet-delivery ratio is up to 14% and 9% compared to the standard GPSR and AODV routing protocols, respectively, on average. The routing cost decreases by nearly 35%. Meanwhile, AODV registered a higher routing cost in terms of E2ED than AFB-GPSR and the standard GPSR as well. As a result, the proposed AFB strategy can significantly enhance the geographic routing protocol, making a new AFB-GPSR routing protocol a state-of-the-art and effective protocol for ad hoc networks.

In future work, we are planning to investigate further related aspects as follows: (1) To solve the accuracy of the proposed fuzzy-beaconing approach in this study, a compressed fuzzy logic system or hybrid approaches can be considered to jointly address the effect of extra multiple network parameters such as transmission power, interference, collision rate (contention window), and routing overhead in a MANET environment. (2) AI-based approaches are also suggested to design more efficient adaptive beaconing schemes related to the contention window at the MAC layer. Finally, (3) to prove its effectiveness, the AFB strategy is eligible to be adopted in various network environments such as VANET or FANET according to the network characteristics.

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Abbreviations

AI—Artificial Intelligence; AFB—Adaptive-Beaconing-Based Fuzzy Logic; AODV—Ad hoc On-Demand Distance Vector (1999); ACOR—Admission-Control-enabled On-demand routing; DVRP—Distance Vector Routing Protocol; DYMO—Dynamic MANET On-Demand; DSR—Dynamic Source Routing; DSDV—Destination-Sequenced Distance Vector; E2ED—End-To-End Delay; ETX—Expected Transmission Count; FANET—Flying Ad hoc Network; FQ-AGO—Fuzzy-Logic-Based Q-Learning Asymmetric Geographic Opportunistic; FIS—Fuzzy Inference System; GPSR—Greedy Perimeter Stateless Routing (2000); HSLS—Hazy Sighted Link State Routing Protocol (2003); LAR—Location Aided Routing; LDAB—Location PreDiction with Adaptive Beaconing; LEACH—Low-Energy Adaptive Clustering Hierarchy; LR—Link Reliability; MANET—Mobile Ad hoc Network; NRL—Normalized Routing Load; NS—Node Speed; OHND—One-Hop Neighbors' Density; FLDB—Fuzzy Logic Dynamic Beaconing; OLSR—Optimized Link State Routing; Optimal Beacon Interval Time (OBIT); OMNeT++—Objective Modular Network Testbed in C++; PDR—Packet-Delivery Ratio; RWP—Random Waypoint; STAR—Source Tree Adaptive Routing; UAV—Unmanned Aerial Vehicle; VANET—Vehicular Ad hoc Network; VADD—Vehicle-Assisted Data Delivery (2008), ZRP—Zone Routing Protocol.

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