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Article

FQ-AGO: Fuzzy Logic Q-learning Based Asymmetric Link Aware and Geographic Opportunistic Routing Scheme for MANETs

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Abstract: The proliferation of mobile and IoT devices, coupled with the advances in the wireless communication capabilities of these devices, have urged the need for novel communication paradigms for such heterogeneous hybrid networks. Researchers have proposed opportunistic routing as a means to leverage the potentials offered by such heterogeneous networks. While several proposals for multiple opportunistic routing protocols exist, only a few have explored fuzzy logic to evaluate wireless links status in the network to construct stable and faster paths towards the destinations. We propose FQ-AGO, a novel Fuzzy Logic Q-learning Based Asymmetric Link Aware and Geographic Opportunistic Routing scheme that leverages the presence of long-range transmission links to assign forwarding candidates towards a given destination. The proposed routing scheme utilizes fuzzy logic to evaluate whether a wireless link is useful or not by capturing multiple network metrics, the available bandwidth, link quality, node transmission power, and distance progress. Based on the fuzzy logic evaluation, the proposed routing scheme employs a Q-learning algorithm to select the best candidate set toward the destination. We implement FQ-AGO on the NS-3 simulator and compare the performance of the proposed routing scheme with three other relevant protocols: AODV, DSDV, and GOR. For precise analysis, we consider various network metrics to compare the performance of the routing protocols. Our simulation result validates our analysis and demonstrates remarkable performance improvements in terms of total network throughput, packet delivery ration, and end-to-end delay.

Keywords: Fuzzy logic, Q-learning, routing protocol, mobile ad hoc network (MANETs), opportunistic network.

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1. Introduction

Mobile ad hoc networks (MANETs) have been attracting great interest in the past twenty years. Due to the movement of the intermediate nodes, limited wireless resources, the heterogeneity of nodes transmission power, and the lossy characteristics of a wireless channel, the routing problem of establishing an efficient stationary path between a source and a destination through multiple mobile intermediate relay nodes is very challenging. The efficiency of a route is dependents on the cooperation of all intermediate nodes participating in data transmissions. These restrictions make the route selection problem particularly difficult; thus, researchers have developed several routing algorithms for mobile ad hoc networks MANETs [1].

In MANETs, since the network environment varies, the routing protocol needs to be adaptable enough to work in highly dynamic environments. In MANETs, a wireless communication link between nodes is impairment due to nodes mobility and susceptibility to being affected by the fading of the wireless channel. The quality of a wireless link between nodes highly depends on multiple factors,

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such as the available bandwidth of participating nodes, the transmission power, node mobility, and the link quality. In the next-hop forwarder selection process, these factors should be considered jointly to develop a stable and robust routing scheme. Therefore, a flexible design that can consider all these metrics is required. Accordingly, it is challenging to develop a mathematical model to evaluate the wireless link, since these metrics may conflict with each other. Also, the network connectivity and routing performance are dependent on all the direct wireless links constituting the source-destination paths. Therefore, we form the next-hop forwarder selection algorithm from a multi-hop perspective.

There have been a great number of routing protocols proposed based on traditional wire routing techniques for MANETs [2,3]. In general, they establish an end-to-end path from the source to the destination before forwarding data packets in MANETs and then transmit data packets via the predetermined route. With the popularity of global positioning system (GPS), many of the proposed routing algorithms [4–6], utilize position information to find a route. In geographic routing algorithms, network nodes able to exchange location information where a forwarder node can select next-hop that close to a destination. The drawback of geographic routing algorithms is that they do not take into account wireless link quality or throughput. All these protocols are developed based on conventional routing metrics. Several wireless network issues have been ignored, such as the heterogeneity of nodes transmission power, nodes mobility, and fading of the wireless signals. Therefore, we cannot easily adapt conventional MANETs routing protocols with the new generation of wireless networks.

To solve the problems mentioned above and to exploit the broadcast nature and spatial diversity of the wireless medium to enhance routing performance, the Opportunistic routing OPRNETs has been proposed [7]. The main idea of OPRNETs is that, instead of establishing an end-to-end path and rely on pre-selecting a single specific next-hop to forward the packets, multiple nodes can potentially serve as the next-hop forwarders. In the opportunistic routing algorithms, there is no specific next-hop node. In this paper, we propose FQ-AGO, fuzzy logic Q-learning based asymmetric link aware, and geographic opportunistic routing scheme for MANETs. The proposed routing scheme relies on fuzzy logic [8] to evaluate a wireless link by considering multiple routing metrics, such as the available throughput, distance progress, node transmission power, and link quality. The proposed scheme also employs a Q-learning algorithm [9] to learn the best next-hop forwarder by using control messages. Fuzzy logic can analyze different metrics even if they are imprecise and uncertain and may opposing and conflict with one another. The proposed routing scheme employs fuzzy logic to evaluate wireless link status information and find a trad-off between the different routing metrics the routing scheme considered without deriving a mathematical model. Based on the fuzzy logic evaluation, the Q-learning algorithm chooses a potential next-hop forwarder with a highly reliable link. FQ-AGO is different from existing OPRNETs routing schemes for MANETs. In every step of FQ-AGO, we infuse a stable strategy. From the candidate selection phase, the FQ-AGO forwarder node evaluates the direct wireless links in its vicinity. It makes the selection of the next-hop forwarder on-the-fly by employing the Q-learning algorithm as a means to improve network connectivity and routing performance. The proposed routing scheme is scalable since there are no overwhelming overhead control packets required to move the data packets towards the desired destination. Also, it can be adapted by varieties of MANETs networks such as vehicular ad hoc networks (VANETs), and wireless sensor networks (WSNs). The flexibility of FQ-AGO enables its adaptability. We modify the fuzzy logic membership functions and rules to include other network metrics.

In this paper, we make the following contributions:

1. We propose FQ-AOG fuzzy Q-learning opportunistic routing scheme that learns and makes the route decisions on-the-fly by considering one-hop performance.
2. The proposed scheme takes into account the available throughput, distance progress, asymmetric link, and link quality in the candidate selection process.
3. The proposed protocol is flexible because we can easily tune the protocol to work for different MANETs networks by modifying the fuzzy membership functions and fuzzy rules.
4. We implement and test the proposed routing scheme in the $ns-3$ simulator [10].

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5. We evaluate the performance of the proposed routing scheme and compare it with three state-of-the-art MANETs routing protocols, namely destination sequenced distance vector routing (DSDV) [2], ad hoc on-demand distance vector (AODV) [3], and and geographic opportunistic rout-ing protocol (GOR) [11].

The remainder of this paper is organized as follows: In Section 2, we review the related literature, focusing mostly on the opportunistic routing on MANETs. In Section 3, we describe the system model and the assumptions. A detailed description of the proposed scheme and its objective function and features is in Section 4. In Section 5, we discuss the routing scheme implementation as well as the simulation setup and performance evaluation. Finally, Section 6 concludes the paper.

2. Background & Related Works

Opportunistic Routing (OR) Figure 1 has been proposed in the context of multiple applications and scenarios including mobile ad-hoc networks [12], wireless mesh and sensor networks [13], Delay Tolerant Networks [14], and for smart grids applications [15]. While traditional MANETs protocols fail with high mobility of the nodes and their heterogeneity, OR exploits the broadcast nature of the wireless medium and pre-selects a set of candidate nodes and delegates the packet forwarding, hop-by-hop and on the fly, to these relays [16]. Thus, the packet can be traverse from the source node to the destination node through a set of potential routes. This dynamic selection of route improves the transmission reliability and throughput of the network.

While the MANETs algorithm is concerned with the end-to-end path between the source and the destination and deals with frequently link failures due to connections and disconnections by applying route management and recovery strategies. Opportunistic Routing (OR) constructs the route online by pre-selecting a set of neighbor's relays on a routing protocol metric within the radio frequency transmission range of the source node. These neighbor nodes are called relay nodes or candidate sets.

Extensive research and surveys have been conducted on OR aspects. OR reduces the number of transmissions of a message to a destination by taking advantage of the broadcast nature of the wireless medium. Success on reducing transmission number to a packet between source and destination can improve network performance by reducing end-to-end delay, and the energy consumption of network nodes [17]. The broadcast nature of the wireless medium replicates a packet to multiple nodes per transmission, and the choice of relay nodes affects the efficiency of OR. The source nodes utilize the available network information to calculate the OR metric, which is ordering and assigning a probability to the potential candidate set. The node with a higher probability becomes the new custodian node. One can classify the network information to be utilized to compute the OR metrics as local or global. Local network information mainly depends on the information of neighbors, such as the geographic location of nodes or the link delivery probability. On the other hand, the former one mainly relies on the end-to-end information of the network topology by taking into consideration the number of hops from each neighbor to the given destination [4,17]. The OR algorithms that consider the network topology information to select and prioritize the candidate set outperform OR algorithms that depend only on the local information of the neighbors. However, the computation cost of the global network information could impact the network performance, especially, and network scalability because of the significant overhead.

In [7,18], the hop-count utilized as a metric parameter where is the network nodes need to know the network topology information to construct a path to the desired destination. OR adopts the hop-count as a metric. In a conventional wire routing protocol, the network nodes exchange control packets periodically to share network information, which allows any network node to build a route to any destination with a small number of hops. EXOR [7], one of the first proposed OR protocols utilized that average number of transmissions (hop-count) of a packet on a bath, to a given destination as a metric. EXOR quantitatively provided a significant reduction in the number of transmissions of a packet. Another popular, widespread metric in mesh OR networks is Expected Any-path Transmission (EAX) [18]. In wired networks, connection media is relatively reliable between network nodes.

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Table 1. Hello Packet Format

Parameter	Value
Packet Sequence Number	2 bytes
Originator ID	4 bytes
Originator Position	16 bytes
Transmission Range	1 byte

However, in multi-hop mesh wireless networks, a predetermined single-path approach is not a perfect model due to the broadcast nature of the wireless communication medium. Traditional wireless routing protocols focused on finding a single shortest route between any two given network nodes, which led to network performance degradation and may even collapse. The EAX metric selects and prioritizes candidate set nodes relay on the expected number of transmissions for a single-path paradigm without taking into consideration the closeness between nodes under opportunistic forwarding. On the other hand, EAX captures the expected number of transmissions in EAX, and considers the multi-path paradigm between nodes under opportunistic forwarding which provides loss-free communication. This metric has been utilized in developing several candidate selection algorithms, such as Least-Cost Opportunistic Routing (LCOR) [19], and Minimum Transmission Selection (MTS) [20].

With the popularity of global positioning systems (GPS), the geographic location information of the neighbors has been considered as a metric to select and sort the candidate set nodes [21,22]. Accordingly, depending on the Distance Progress (DP), the forwarder node compute the euclidean distance between potential candidate nodes and the given destination, the closest node to the geographic location of the destination has higher priority to become the potential next-hop forwarder. Utilizing the DP metric, source nodes can estimate the distance from each potential candidate node to reach the destination. Expected distance progress (EDP) [21] improved the performance of DP by including the link delivery probability between the current custodian node and the candidate set nodes. Selecting the closest nodes to the destination is not always the optimal choice, especially when the link delivery probability ratio is low. In such a case, multiple re-transmissions of the same packet will be attempted until it is received by one of the candidate nodes. When the DP metric fails to select reliable candidate nodes, EDP will overcome the DP shortcoming by selecting reliable candidate nodes by taking into consideration the same delivery probability, and that will reduce the number of re-transmissions of a packet significantly.

While multiple OR protocols have been proposed, most of these solutions consider a homogeneous network consisting of similar wireless nodes equipped with the same wireless capabilities, moving at the same speeds. In this paper, however, we consider OR in a hybrid scenario, where we leverage, detect, and select nodes equipped with high transmission range wireless antenna, from which they allowed to construct eventual shortcut paths towards the destination.

3. Fuzzy Logic Q-Learning Routing Scheme with Asymmetric Link Aware

3.1. System Model And Assumption

The network model simulates a typical multi-hop urban environment composed of a large number of mobile nodes N. The topology of a network is a directed graph $G(V, E)$, where V is the set of all mobile nodes, and E is the set of wireless links in the network. Among these mobile nodes, few are equipped with long-range (N_L) transmission capabilities, and others use the common short-range (N_S). Each node is equipped with a wireless radio transceiver. A wireless link exists between any two nodes A and B, if and only if B locates within the transmission range of A. A link is bidirectional if $A \rightarrow B \in E$ and unidirectional if $B \rightarrow A \notin E$. Each node is equipped with a GPS device that provides information about its position and speed. Also, every node can obtain the destination position when needed using

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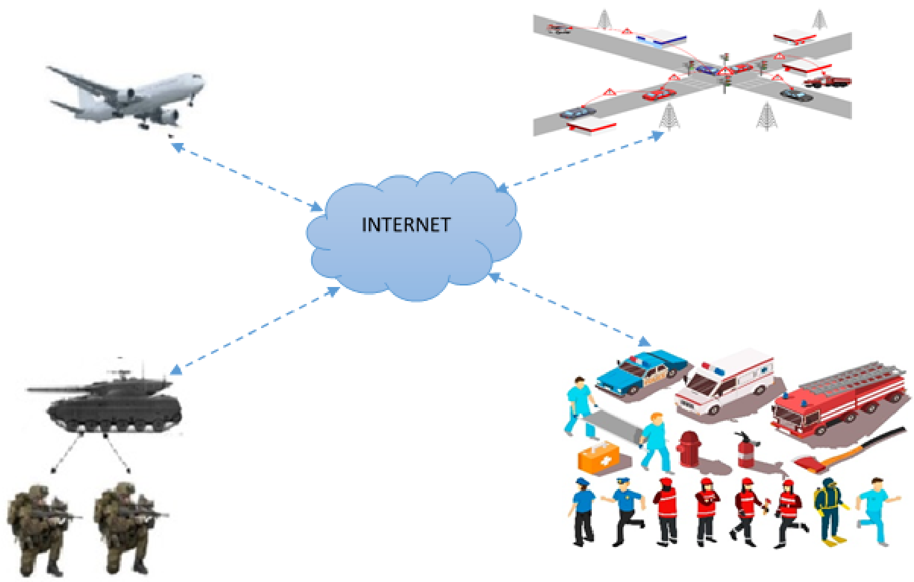

Figure 1. Examples of MANETs communication applications.

a location service such as Region-based Location Service Management Protocol (RLSMP) [23], and Mobile Group based Location Service Management (MG-LSM) [24]. Network nodes obtain neighbors information through broadcasting a Hello message periodically at predefined intervals $(\tau + jitter)$, to control traffic storm, and to avoid potential collisions. Table 1 shows the format of a Hello message used in FQ-AGO, which includes the sender's ID, which identifies each node in the network, a unique sequence number that reflects the freshness of the neighbors' information, the current position, and node velocity also included in the Hello messages. Each network node maintains a local view of its neighbors by constructing a neighbors' table (NT able) to manage neighbor's information obtained from exchanging Hello packets. We define the set of neighbor's nodes from which forwarder node can select next-hop to relay its packet as the Candidates Set denoted by C_n. A candidate node from C_n is selected to relay the forwarder packet to its corresponding destination according to the neighbor evaluation strategy of our proposed fuzzy logic-based scheme. To avoid situations where a selected candidate might be out of the forwarder communication range, Hello packet transmission interval can be tuned based on the network environment requirements. However, the Hello packet transmission interval should be small, to get the current location information about C_n. Accordingly, there is a trade-off between the routing protocol performance and the network overhead. After conducting a set of initial simulation experiments, we found that setting the Hello message transmission interval in our scheme to 1-second is sufficient in most cases because the mobile node relative movement during this amount of time is much smaller than the transmission range [25].

3.2. Proposed Scheme

The design of the proposed protocol FQ-AGO uses multi-hop ad hoc wireless communication without relying on any network infrastructure units. The proposed scheme is an opportunistic routing that employs a fuzzy logic-based approach Figure 2 to evaluate each direct wireless link of neighbors in the candidate set. Each node evaluates its candidate set members based on their distance to destination, transmission power, link quality, and available throughput. These metrics are jointly evaluated, utilizing a fuzzy logic analysis system. The wireless links evaluation values of the candidate set nodes are stored in the neighbor table Figure 2 and maintained this evaluation values up-to-date. Whenever a forwarder node has a packet for forwarding, based on the destination's current location, the forwarder applies a Q-learning algorithm to the candidate set, and the candidate that reveals the highest Q-Learning value is considered the next-hop forwarder.

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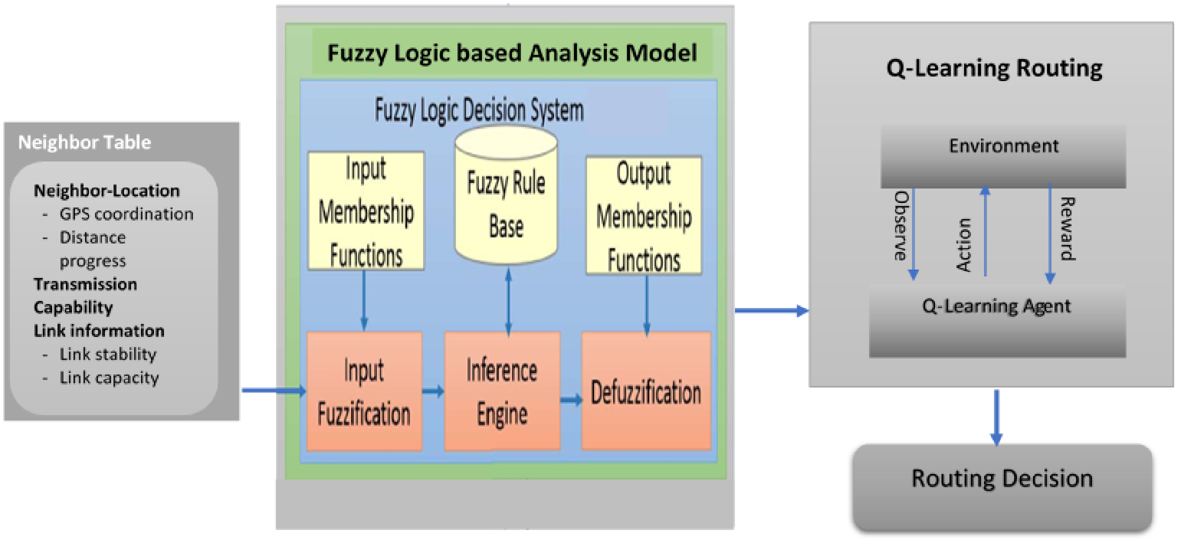

Figure 2. FQ-AGO system architecture

For each packet, that the forwarder node has to forward, the candidate forwarding node with the maximum Q-learning value is selected as a next-hop forwarder. The membership functions and fuzzy rules used by the fuzzy logic system are easy to modify and tune to make the protocol more suitable for a particular network environment and condition. Therefore, the proposed protocol can provide a practical and intelligent solution for routing in varieties of ad hoc networks, such as VANETs, and Wireless sensor network (WSN). In FQ-AGO, if a local minima problem is detected, the forwarder node will select a new next-hop forwarder, and a re-transmission of the packet is required to progress the transmission packet operation.

3.3. Neighbors Evaluation Criteria

The proposed model is an opportunistic routing scheme that relies on fuzzy logic and Q-Learning for routing decision making. The proposed routing scheme is designed to work in a variety of mobile wireless networks. Several configuration parameters of FQ-AGO are adjustable so that it is adaptive to different network environments. One of the characteristics of the proposed routing scheme is that the routing decisions depend on the proposed metric value, which simplifies network setting-up operations where there is no need for any network layer system management. Consequently, this will alleviate the network's overall end-to-end delay. In this section, we define multiple network metrics concerning mobile ad hoc networks to improve online routing decisions [26].

3.3.1. Link Quality Estimation Using ETX

Link instability has a significant impact on network connectivity, routing performance and significantly affects packet delivery ratio, network throughput, and increase end-to-end delay. Wireless links are directly affected by signal attenuation and fading. Thus, to elevate forwarding reliability and minimize packet re-transmissions and delay, we consider the link quality between the current forwarding node and the potential next-hop candidates. To estimate link quality, we utilize the well-known Expected Transmission Count (ETX) module [25,27], to select the most reliable wireless links. Mainly ETX measurement depends on dedicated probe packets. Instead, we considered Hello packets, which is a fundamental factor of an opportunistic cooperative awareness scheme, and it is also used by our routing protocol to discover direct neighbors.

We defined the probability of successfully receiving data packet d_{packet} and d_{ACK} is the probability of receiving an ACK packet, respectively, ETX can be defined as:

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$$ETX(V_n, C_i) = \frac{1}{d_{packet} \cdot d_{ACK}} \tag{1}$$

Every node estimates link quality for its direct neighbors by calculating d_{packet} and d_{ACK} using the ratios of Hello packets that have been successfully received (HRR). The forwarder maintains a counter of each neighbor to calculate the number of received Hello messages within a sliding window size of w seconds. Therefore, the ratios of the successfully received Hello packets (HRR) is calculated at any given time instance (t) by using the following equation:

$$HRR_{hello}(t) = \frac{counter(t - w, t)}{w/\tau} \tag{2}$$

where, $count(t - w, t)$ is the number of Hello packets that have been delivered at time t during the sliding window w, and w/τ indicate to the total number of Hello packets that should have been received during time t.

For the calculation of the HRR(t), ETX model relays on the sequence number that exists in every received Hello packet, which is used to determine the number of received and lost Hello packets. The packet is either received or lost in the current window size, w, based on a Hello packet sequence number. This determination happens through a comparison process between the sequence number of the freshly received packet with the sequence number of the last packet sequence number recorded in the neighbors' table Figure 2. Accordingly, a node can detect any lost Hello packet, and the HRR value is calculated by updating the numerator and denominator, respectively, in equation 2.

3.3.2. Available Throughput Estimation

Recruiting a subset of neighbors as a potential candidate without taking into consideration their available throughput, will highly impact routing performance and might result in high packet delays and loss. Therefore, we define the Available Throughput Estimation (ATE) as a mean to predict the maximum amount of data that could be transmitted successfully by each candidate node C_i during a specified time period [25]:

$$ATE(C_i) = \frac{NBits_{suc}}{DTT} \tag{3}$$

Where NBits indicates the number of bits that is successfully transmitted, and DTT is the Data Transmission Time which is total amount of time a forwarder node requires to transmit packet. The DTT includes total time of both success or failed transmission attempt that a forwarder node conducts:

$$DTT_{total} = \sum_{k=1}^{N_{success}} DTT_{success(k)} + \sum_{k=1}^{N_{failed}} DTT_{filed(k)} \tag{4}$$

The number of attempts a forwarder takes to transmit a packet k successfully is $N_{Tx}(k)$, and we define the time duration that it takes a packet to be successfully transmitted as:

$$DTT_{success(k)} = \sum_{x=1}^{N_{Tx}(k)} (\overline{CW_i} + T_\varphi) + (\overline{CW_{N_{Tx}(k)}}) + T_s \tag{5}$$

Where $N_{Tx}(k)$ is the number of transmissions attempts it takes a packet to be transmitted successfully, $\overline{CW_i}$ is the estimate of contention window size for the $x\check{}th$ transmission attempt, $\overline{CW_{N_{Tx}(k)}}$ is the estimate contention window size for the last successful attempt of transmitting that packet, T_φ and T_s are defined as follows:

$$T_\varphi = T_{AIFS_{AC}} + T_{Header+Data} + T_{SIFS} + T_{ACK} + 2\delta \tag{6}$$

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$$T_s = T_{AIFS_{AC}} + T_{Header+Data} + T_{SIFS} + T_{ACKTout} + \delta \quad (7)$$

where, T_{SIFS} indicates the short inter-frame space, $T_{AIFS_{AC}}$ is the arbitration inter-frame space and tuned based on access categories (AC), $T_{AIFS_{AC}}$, and time slot T_{Slot} duration is as defined as follows:

$$T_{AIFS_{AC}} = AIFS[AC] \times T_{Slot} + T_{SIFS} \quad (8)$$

$T_{Header+Data}$ is the transmission time of the payload of a packet, T_{ACK} is the transmission time of the ACK frame, δ is the propagation delay, and $T_{ACKTout}$ is the ACK timeout duration:

$$T_{ACK_{Tout}} = T_{Slot} + T_{SIFS} \quad (9)$$

Similarly, the time spent in re-transmissions (NT_{xmax}) a packet before it dropped which considered as a failed transmission attempt define as:

$$DTT_{failed(k)} = \sum_{x=1}^{N_{Tx}(k)} (\overline{CW_i} + T_{\varphi}) \quad (10)$$

Assuming that the selected contention window size is uniformly distributed in the range [0, CW_i], where CW_i is the current window size for the ith transmission attempt, the average contention time for any transmission attempt can be defined using the following equation:

$$\overline{CW_i} = \frac{min(CW_{max}, 2^i \times (CW_{min} + 1) - 1) \times T_{Slot}}{2} \quad (11)$$

where, CW_{max}, and CW_min are the maximum and minimum contention window sizes IEEE 802.11p access defined. The dynamic topology in MANETs due to rapid nodes mobility and the wireless signal impairments, such as fading, interference, and obstacles cause instabilities in node's data transmission rates. To cope with wireless communication impairments in dynamic environment, we use the exponentially moving average (EMA) to calculate the available bandwidth estimation accuracy as follows:

$$ATE_{c_i} \leftarrow (a - \alpha) \times ATE_{t-1} + \alpha \times ATE_t \quad (12)$$

where, α is a simulation parameter considers to evaluate the estimation of the accuracy and responsiveness due to rapidly changing in network topology and fluctuating on wireless communication conditions. Based on our simulation experiments, we found that the best value of α is 0.7.

3.3.3. Asymmetric Link

There have been two different models for considering the extra wireless transmission capabilities of heterogeneous nodes in MANETs routing [28]. One is trying to use a long-range asymmetric link, and the other avoids it. The former exploits the long-range wireless link to transmit data. There have been many attempts to accomplish this [29–31]. There are several benefits of considering transmission over long-range links, such as reducing the number of hops on the path and increasing the lifetime of network nodes with limited energy. This reduces latency and improves network connectivity and routing efficiency, which makes the path more robust. The latter model tried to avoid the use of a remote connection to transmit data. Such solutions include [32,33]. They consider the use of long-range transport may increase energy consumption and reduce overall network throughput.

In conventional homogeneous wireless ad hoc networks, a network node can only communicate with other nodes in its transmission range. In contrast, in heterogeneous wireless ad hoc networks, some network nodes can reach other nodes within a broader transmission range. Therefore, the

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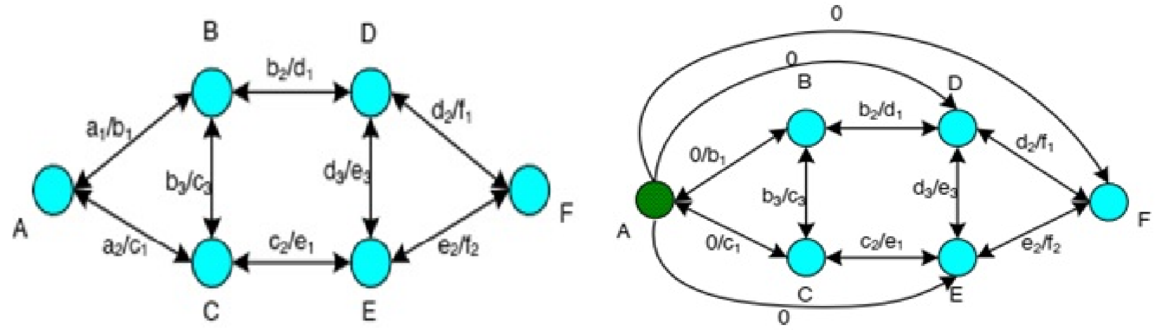

(a) Topology in Heterogeneous scenario.

(b) Topology in Homogeneous scenario.

Figure 3. The network topology in homogeneous and heterogeneous wireless communication.

network topology and routing mechanisms are quite different from those in homogeneous networks. As an example, a homogeneous network topology without asymmetric links is depicted in Figure 3a where all wireless links are symmetric and labeled with transmission costs on both directions. For example, a1/b1 show that the wireless link cost from node A to node B. In contrast, if a node, say, A, has high transmission power and has ability to reach much further in the network, more wireless asymmetric links may be added as shown in Figure 3b. We label asymmetric links from node A to its neighbors with cost 0 to represent node A's has high transmission power.

Therefore, on the one hand, a packet should be forwarded to a candidate C_i has higher transmission power. On the other hand, communications in the networks should avoid using candidate nodes with a short transmission, if possible, Figure 4. For these purposes, it is desirable to allow a candidate with high transmission capability to relay forwarder packet to cover a larger transmission area, which can statistically reduce the number of intermediate nodes involved in the packet forwarding process.

3.4. Evaluation of one-hop neighbor wireless link status based on Fuzzy logic model

Fuzzy logic-based systems have been attracted considerable interest and widely accepted in many industrial systems and research communities to develop communication applications [8,25,34], due to its capability to simulate human brains reasoning in interpretation uncertain information. The fuzzy logic model performs well to handle imprecise and uncertain information when the boundaries are not clear. Uncertainty in a classical set theory arises, however, when an attempt is made to define a measurement value as either member or non-member, instead, values in the fuzzy logic set theory can have different degrees of membership [8,25]. Accordingly, the fuzzy logic model can handle imprecise and uncertain information by approximating data rather than precise information analysis. Therefore, fuzzy logic can perform well in decision making and analyzing different metrics.

In the opportunistic network, wireless communication links are vulnerable due to nodes mobility and wireless signal impairment. Accordingly, an evaluation of neighbors' wireless links status is required to improve network connectivity and routing performance. The neighbor's wireless links status depends on multiple factors, such as transmission range capability, available throughput, link stability, neighbor mobility, etc. Therefore, the attempt to derive any mathematical model facilitating the selection of the forwarding candidate set by taking into consideration multiple network metrics is a complex and challenging task, and the solution would be inflexible.

For routing in MANETs, a fuzzy logic model capable of cope with unreliable and uncertain information about candidate nodes due to rapid nodes mobility and wireless channel conditions. Whenever a forwarder node has a packet to forward, a fuzzy logic model is used to evaluate each candidate's wireless link status and select the most suitable next-hop for forwarding the packet. The proposed fuzzy logic model is developed to combine all considered network metrics discussed in

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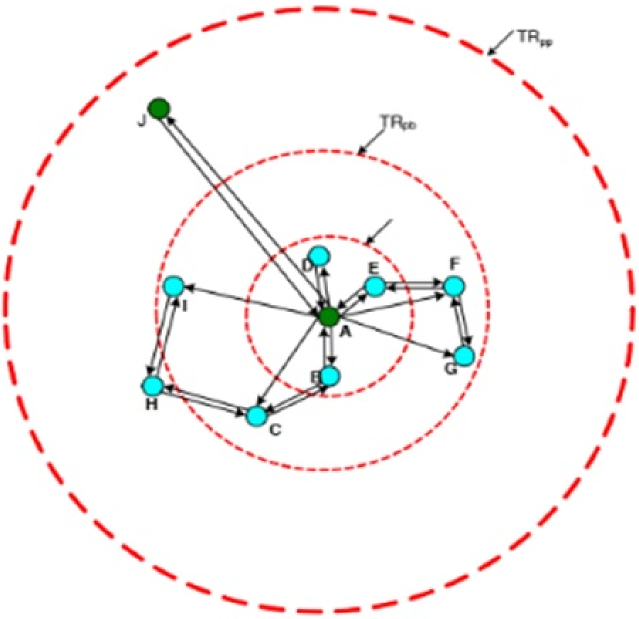

Figure 4. An example of the candidate selection process

Section 3.3 to contribute to improve the efficiency and reliability of selecting a next-hop forwarder from the potential next-hop candidate. Figure 2 illustrates the fuzzy logic structure that evaluates the neighbors' wireless link status. It consists of three phases: fuzzification, fuzzy inference, and defuzzification. In the first phase, numerical values accepted as inputs get converted into nonnumerical linguistic variables to express the facts. Then the defined fuzzy rules are used to drive a linguistic output. The final phase interprets the linguistic output into a numerical value that represents the fuzzy weight of each neighbor. The phases that illustrate the calculation operation of the fuzzy logic weight for candidate nodes C_i are elaborated in the following subsection.

3.4.1. Fuzzification

Fuzzification is the process of accepting and converting crisp numerical input values into fuzzy linguistic values by employing a predefined membership function to each network metric. For the sake of accurate evaluation of the considered metrics, their values are normalized by considering Min-Max feature scaling normalization, which improves the sensitivity of the metrics to every negligible variation on the neighbor link status. The following equation shows the normalization of the expected distance progress metric:

$$DP_{c_i}^{c_x,d} = \frac{DP^{c_x,d} - DP_{min}}{DP_{max} - DP_{min}} \tag{13}$$

where, $DP_{c_i}^{c_x,d}$ is the normalized distance value of the potential candidate to destination, and $DPmax - DP_{min}$ are the maximum and minimum measured distance span values to destination of all potential candidates C_i. Figure 5a illustrates the membership function of candidate distance progress evaluation. The forwarder node employs the developed membership function to map the normalized metric value into the predefined linguistic fuzzy set and measure the degrees of belonging to the linguistic variables. Thus, the fuzzy set degree values for the distance progress metric input belongs to {VeryClose, Close, Far}.

The fuzzy membership function for the node transmission power is shown in Figure 5b. The forwarder node uses the membership function to evaluate the neighbor transmission range based on the information included in the exchanged hello packets. Thus, the forwarder node calculates which

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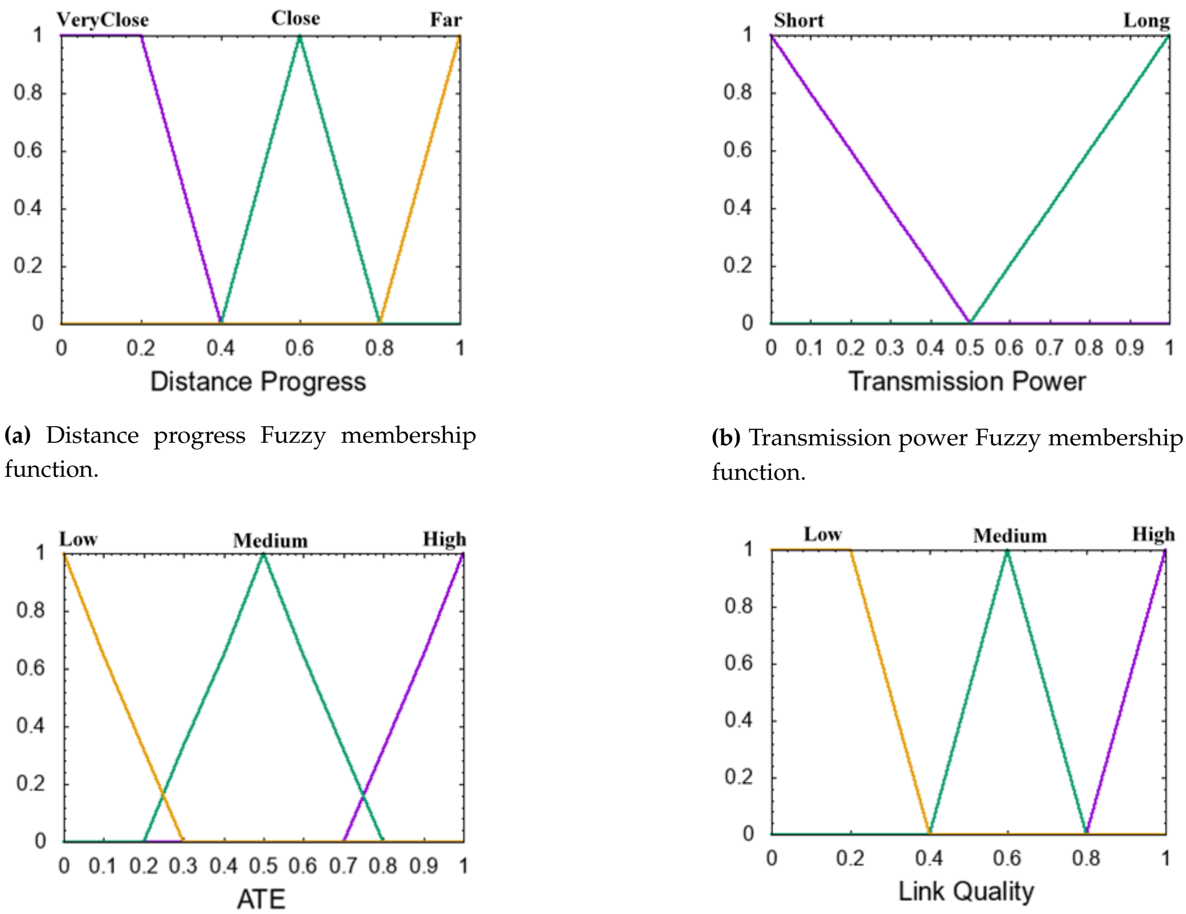

(a) Distance progress Fuzzy membership function.

(b) Transmission power Fuzzy membership function.

(c) ATE Fuzzy membership function.

(d) Link quality Fuzzy membership function.

Figure 5. Fuzzy membership functions plots.

degree the transmission range of a candidate forwarder belongs to {Long, Short}. The membership function of the ATM metric depicts in Figure 5c. The forwarder node uses the membership function and the normalized metric to calculate which degree the available throughput value of a candidate node belongs to {Low, Medium, High}, where low represents low achievable throughput and high represents high achievable throughput.

Figure 5d depicts the fuzzy membership function of the wireless link quality metric. The metric defined in equation (1) is normalized using min-max normalization as in equation (15). The current forwarding node uses the fuzzy membership function and the normalized value to calculate which degree the metric value belongs to {Good, Average, Bad }.

3.4.2. Rule-based and Inference Procedure

The intelligence of evaluating wireless link status in this work comes from the developed fuzzy inference engine [25]. After mapping the numerical values of the input metrics into a fuzzy set variable, the forwarder node employs the predefined combination of ***IF-THEN*** rules to convert the fuzzy values into fuzzy output, which rank the wireless link between the forwarder node and each potential candidate. The linguistic variables of the rank are defined as {Perfect, Good, Acceptable, Undeferrable, Bad, VeryBad}. The fuzzy rule-base construction requires a clear and profound understanding of the nodes' behavior in dynamic environments and the ways input metrics values can affect the ranking output. The fuzzy rule-base consists of a set of ***IF-THEN*** rules applied to infer output ranking values. The fuzzy rule-base of FQ-AGO composes of 54 rules. A few sample rules are shown in Table 2. The first four columns show the four input variables considered in FQ-AGO fuzzy analysis system, and

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Table 2. EXAMPLES OF FUZZY RULES

Rules	ATE	LQ	DP	TP	Fuzzy Weight
Rule1	High	High	VeryClose	Long	Perfect
Rule2	High	High	Close	Short	Good
Rule3	High	High	Far	Long	Good
Rule4	High	Medium	VeryClose	Short	Acceptable
Rule5	High	Medium	Close	Long	Good
Rule6	High	Medium	Far	Short	Unperformable
Rule7	High	Low	VeryClose	Long	Good
Rule8	High	Low	Close	Long	Good
Rule9	High	Low	Far	Short	Unperformable
Rule10	Medium	High	VeryClose	Long	Good
Rule11	Medium	High	Close	Short	Acceptable
Rule12	Medium	High	Far	Short	Acceptable
Rule13	Medium	Medium	VeryClose	Long	Acceptable
Rule14	Medium	Medium	Close	Short	Unperformable
Rule15	Medium	Medium	Far	Long	Acceptable
Rule16	Medium	Low	VeryClose	Short	Bad
Rule17	Medium	Low	Close	Long	Unperformable
Rule18	Medium	Low	Far	Short	Bad
Rule19	Low	High	VeryClose	Long	Bad
Rule20	Low	High	Close	Short	Unperformable
Rule21	Low	High	Far	Long	Bad
Rule22	Low	Medium	VeryClose	Short	VeryBad
Rule23	Low	Medium	Close	Long	Unperformable
Rule24	Low	Medium	Far	Short	Bad
Rule25	Low	Low	VeryClose	Long	VeryBad
Rule26	Low	Low	Close	Short	Bad
Rule27	Low	Low	Far	Long	VeryBad

the last column contains the output fuzzy ranking values. Each rule consists of an IF component and a THEN component. The IF component is applied to constructs conditions by employing predicates and logical connections, while the THEN component gives the degree of membership that the fuzzy variable corresponds to. For example, in Table 2, the first rule defines the best candidate for relaying the forwarder packet as follows:

IF ATM is High, LQ is High, DP is VeryClose, and TP is Long ***THEN*** , the candidate rank is Perfect. In contrast, The worst candidate node for forwarding can be defined using the following rule:

IF ATM is Low , LQ is Low, DP is Far, and TP is Short ***THEN*** Rank is VeryBad.

3.4.3. Defuzzification

Defuzzification is the process of generating a crisp numerical result based on fuzzy membership functions. And the corresponding output membership function. Here, we considered the center-of-gravity (COG) method, since it is the most common defuzzification method that is widely used in real applications to produce the fuzzy output Figure 6. It ranges from (0) to (1), where the Highest value represents the best candidate node in C_n. In the situation where more multiple candidate nodes have the same rank value, the candidate with the high transmission range is selected as a next-hop forwarder.

3.5. Q-Learning Routing Decisions

3.5.1. Q-Learning Model

Q-Learning [9] is one of the early form breakthroughs of a reinforcement learning algorithm that does not rely on a model of its environment and learns by directly interacting with its dynamic

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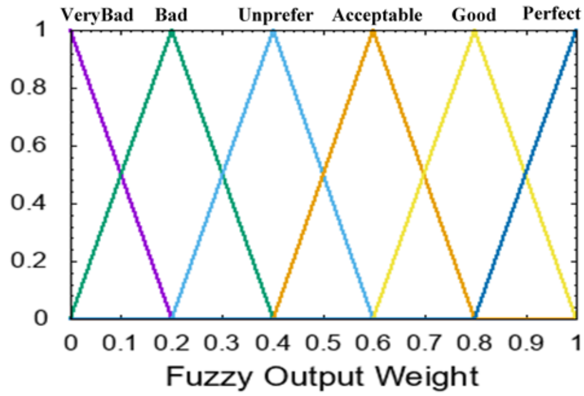

Figure 6. Fuzzy membership function plots for neighbor fuzzy weight.

environment Fig. 2. Q-learning works by trial-and-error for estimating the values of state-action pairs. The Q-value Q(s, C_i) (s ∈ S, a ∈ A) in Q-learning is utilized to directly approximates the optimal action-value function (Q*) for the value of future rewards if the agent performs a particular action (a) when it's in a particular state (s) [35,36]. By exploring the environment, the agents build a table of Q-values for each environment state and each possible action. The Q-Learning control algorithm in FQ-AGO is defined as follows. The opportunistic network is the entire environment. The mobile nodes are the learning agents, where they observe and learn the dynamic environment by exchanging Hello messages with neighbor agents. The set of all nodes in the network is the state space. The action that a forwarder node can perform is to select the best next-hop candidate to relay the data packet. Therefore, the set of one-hop neighbors is the possible actions that allowed at each forwarder [35,37]. A state transition is the process of delivering a packet from the forwarder node to the selected candidate node. There is a set of state transition P(s | s, a) that model the probabilities of transiting from state (s) to state (s') by performing the action (a). Every node maintains a Q-Table, which consists of Q-value, where it is ranging from 0 to 1.

3.5.2. Updates of the Q-Values

Each node maintains a wireless link status fuzzy logic evaluation [Fuzzy(s, C_i) in (14)] for candidate nodes. These evaluation values are used as an input for the Q-learning to select the next-hop forwarder online. Accordingly, the fuzzy evaluation value must be fresh enough at each node to reflect the up-to-date topology information in its vicinity. Thus, it frequently updates upon the reception of Hello messages and eradicates stale neighbor information in the absence of new advertisements of neighbors [35,37]. In an Asymmetric fading environment, a node may receive Hello packet from a node that is not in its one-hop neighbor list. Since each node is only required to maintain the information about its vicinity and traffic source nodes, the proposed protocol is scalable. Each entry of Q-values is initialized to 0. when a forwarder node has a data packet to send. It selects the best next-hop forwarder candidate by applying the Q-Learning algorithm as follow:

$$Q_{C_i}^{c_x,d} \leftarrow (1-\alpha) \times Q_s^{C-i,d} \alpha \times Fuzzy_{C_i} \times \{R_{t+1} + \gamma \times \max_{a \in A} Q(C_i, d)\} \tag{14}$$

where, $Fuzzy_{C_i}$ is the Fuzzy logic evaluation value of the best candidate wireless link between the forwarder and the next-hop forwarder. We set the learning rate α to 0.8, and the discount-rate parameter γ to 0.9. The possible reward values R_n is calculated as follows:

$$R = \begin{cases} 1 & d = C_i \\ 0 & otherwise \end{cases} \tag{15}$$

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Table 3. Summary of our simulation parameters

Parameter	Acronym	Value
Number of nodes	N_i	100
Long transmission nodes ratio	–	20%
Simulation Area	–	1500m x 1500m
Long Transmission Range	$R_T(LR)$	200-400m
Short Transmission Range	$R_T(SR)$	200m
Maximum speed	v_{max}	5-30m/s
Packet size	S_p	512B
Data rate	DR	10pps
Buffer size	BS	0packets

4. Simulation And Evaluation

In this section, we detail the simulation setup of our proposed techniques and evaluate our techniques compared to what exists in the literature.

4.1. Simulation Setup

To evaluate the performance of FQ-AGO, we implement our scheme in the NS-3 simulator. We simulate a network with 100 nodes randomly deployed in a 1500 $\times$ 1500m area. In our simulations, all network nodes are capable of roaming randomly in the network according to the modified Random Way Point (RWP) mobility model [38] at a predefined uniformly distributed speed (V_{min}, V_{max}), where V_{min} is fixed to be 5 m/s, and V_{max} assumes various values to reflect various network mobility levels. No group mobility models are considered in this simulation.

In the simulation, we consider a constant bit rate (CBR) data sessions between a randomly selected source and destination pairs. The source nodes generate a constant bit rate (CBR) traffic at a constant time interval with a packet payload size of 512 bps at a rate of λ packets per second.

We study networks with 20% of the nodes with long transmission range. These nodes are randomly deployed. By varying the number of nodes, the maximum moving velocity, and the CBR source rate, we can study the performance of FQ-AGO under various network configurations. We perform a set of 15 runs for each experiment to plot the average result for each simulation configuration, and each run is executed for 500 seconds of simulation time.

We use the following network performance metrics in our comparisons: the average hop-count, packet delivery ratio (PDR), average packet end-to-end delay, and available throughput. The remaining simulation parameters are listed in Table 3. Note, we define the average hop-count as the total number of intermediate network nodes that cooperated in the transmission process to deliver the source packet to the corresponding destination. And, we define the packet delivery ratio (PDR) as the ratio of delivered data packets to those generated by the sources.

4.2. The Impact of the Nodes Mobility

Figure 7 illustrates the evaluation of the routing protocols' performance of the average number of hop-count as a function of the node's speed. In AODV, the average number of hop-count increase as nodes mobility increase due to the requirement of re-computation of the route when the original route lost. On the other hand, DSDV hop-count is constant comparing to AODV, DSDV constructs a path to a destination relies on shortest path metric with periodic route maintenance for accurate routing and link stability. However, geographic routing makes the routing decision on-the-fly, and thus, node mobility has no significant impact on it. The proposed routing scheme, however, performs better than all due to utilizing an asymmetric link to relay the data packet, which has a substantial impact of reducing the total number of intermediate nodes involved in moving the data packet to the intended destination.

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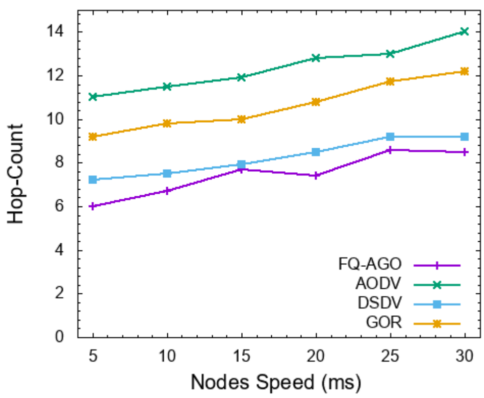

Figure 7. Hop-Count versus nodes speed.

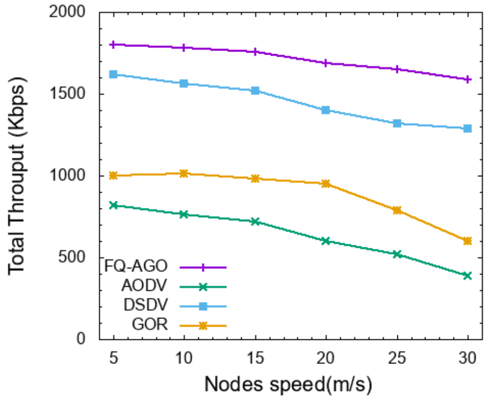

Figure 8. Throughput versus nodes speed.

The impact of nodes speed mobility on network throughput depict in Figure 8. Overall, the mobility of the nodes has a direct effect on the network throughput due to frequently wireless losing communication between neighbor nodes. Routing protocols such as AODV faced a severe reduction on throughput as nodes mobility increases due to frequent path loss to the destination and increased of routing overhead to find a new path to the destination. On the other hand, the geographic routing achieves better throughput than the previous routing protocol due to less path lost since the routing decision does not rely on a single fixed path to the destination. However, the proposed routing scheme always performs better than Geographic routing, DSDV, and AODV; this is due to select the best candidate node along the path to the destination. For example, the throughput in DSDV and AODV drops when the nodes mobility increase, while the proposed scheme exhibits stable throughput under high node mobility.

Figure 9 shows the average packet delay as a function of nodes' speed. We observe that for AODV, the delay grows more significantly as the mobility of the nodes increases. This is because nodes' mobility significantly affects the routing protocol, and the route to the destination may be lost since the routing protocol relies on one next-hop only. Therefore, once the relay node becomes out of the sender transmission range, the sender initiates a search by broadcasting a Route Request packet to find a new route to the destination at the cost of additional delay. On the other hand, DSDV performed better than AODV, as speed increases, the routing protocol gradually starts losing the available routes to the destination, in some situations, a packet travels through a long path to the destination. In the worst-case, the current packet custodian drops the packet. The Geographic routing protocol outperforms AODV in terms of average packet delay, and it is not affected directly by increase nodes mobility since it relies on its neighbors' local geographic position for routing decisions. It makes the routing decision on-the-fly when a network node has a packet to send. It instantaneously selects the neighbor with the highest distance progress toward a given destination to forward the packet. The main factor that has a direct impact on the packet delay performance of the geographic routing protocol is the local minima phenomena. This occurs when a sender becomes the closest node to a destination, and no further progress towards the destination can be made. In such a scenario, the packet will simply be dropped, and that will increase the packet delay. Finally, the proposed routing algorithm outperforms all the routing protocols in this study, by taking advantage of the broadcast medium and involves all the available next-hop nodes into the candidate set, to choose the most reliable like as a next-hop forwarder. Furthermore, the select candidate node with a high transmission range has a direct impact on minimizing the packet delay transmission due to the long-distance progress it can achieve.

Figure 10 illustrates the impact of the independent factor node mobility on the packet delivery ratio. We observe that the packet delivery ratio decreases drastically at higher node mobility in DSDV and AODV. The frequent breaking of links requires initiating a route search to update the routing table.

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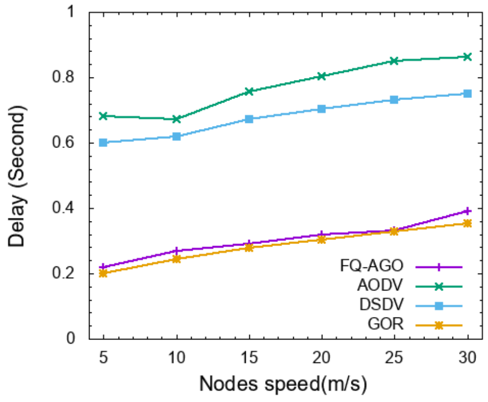

Figure 9. End-to-End Delay (Second) versus nodes speed.

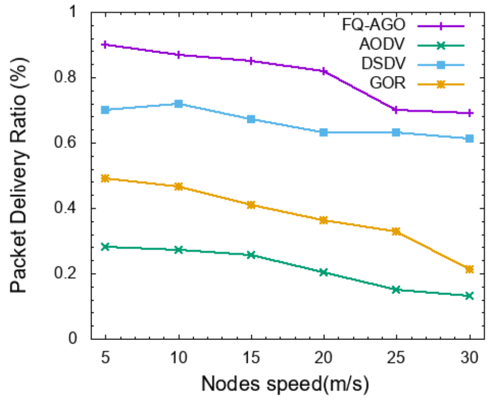

Figure 10. Packet Delivery Ratio (%) versus nodes speed.

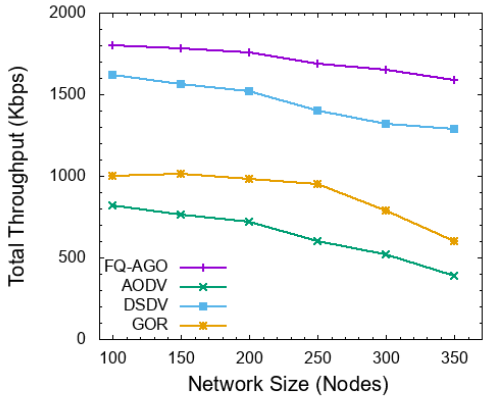

Figure 11. Total Throughput versus Number of Nodes.

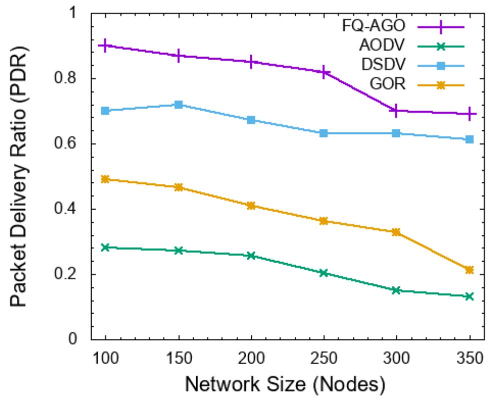

Figure 12. Packet Delivery Ratio (%) versus Number of Nodes.

This increases the control message overhead and creates congestion in the network, the time-out it takes to update the routing table increases the end-to-end packet delay and decreases the network throughput. Furthermore, taking into account a real-time application where the source node generates a high constant bit rate traffic, increasing the number of packets injected into the network. Thus, DSDV and AODV are unable to tolerate the packets streams with limited nodes' memory resources. Consequently, the ratio of the dropped packets is high due to high node mobility. On the other hand, the proposed protocol is more resilient to frequent topology changes, thanks to the candidate selection mechanism, which allows the construction of path on-the-fly, and that makes it independents of node mobility. Moreover, the presence of DE nodes creates shorter paths toward the destination, and that increases the probability of reaching the destination. Overall, the FQ-AGO outperforms all other protocols due to link stability along the path, and its independents from any network topology change.

4.3. The Impact of Network Size

The network throughput is the critical metric that illustrates the network's scalability. For the scalability of a network, its capacity should grow linearly with the number of nodes. Furthermore, increasing the network size should not lead to performance degradation [16,39]. The main reason for the lack of scalability in routing protocols that run on multi-hop wireless networks is that the packet has to travel long distances, roughly $n^{1/2}$ hops, causing the bandwidth consumption per packet to rise rather quickly as number of nodes increase [26].

Figure 11 shows the throughput performance evaluation as a function of the number of nodes. The FQ-AGO shows a considerable advantage over other routing protocols. FQ-AGO considers the

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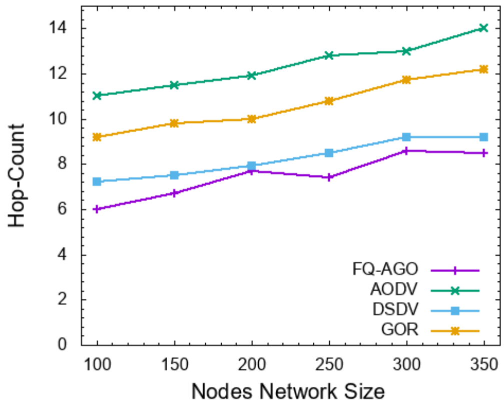

Figure 13. Hop-count versus Number of Nodes.

distance progress, available throughput, transmission power, and node-link quality in the candidate selection process. Accordingly, that enhances the network performance by maximizing the one-hop node performance along the path, as one hop performance improvement contributes to the end-to-end performance. On the other hand, the throughput on AODV is low due to the rapid loss of wireless connections with neighbors. As the network size grows, the routing control messages drastically increase, which generates considerable overhead in DSDV and AODV. This behavior is a consequence of the reduction in the pre-computed routes to the destinations due to the rapid changes in the network topology. Therefore, the throughput decreases linearly as the number of nodes increases. Regarding the PDR, Figure 12, FQ-AGO demonstrate consistent performance in all network environment configuration due to the efficiency of the candidate selection algorithm to select the most stable and effective candidate along the path to the destination. By contrast, DSDV and AODV, the packet delivery ratio decreases drastically. That is because of the frequent link breakage, which requires initiating a route search to update the routing table. This increases the control messages' overhead and congests the network, the time-out it takes to update the routing table increases the end-to-end packet delay and decreases the network throughput.

Figure 13 shows the average hop-count as a function of increasing the network size. Intuitively, the hop-count relying on the packet increases as the network size increases. However, FQ-AGO takes advantage of the presence of nodes that can transmit the packet for long distances. in other words, nodes with large transmission ranges can reach the destination in less number of hops. On the other hand, DSDV and AODV, both show an increased number of hop-counts to relay the transmitted packet. For example, DSDV calculates the shortest path to the destination; however, with the rapid change in the network topology, a massive overhead initiated by intermediate nodes to find the shortest path to the destination. Calculating the shortest path to the destination comes with the extra cost of increasing delays and launching high overhead which leads to network congestion and, in the worst case, the percentage of dropped packets increase consequently.

5. Conclusions

We have proposed FQ-AGO, a fuzzy logic Q-learning opportunistic routing protocol for MANETs. FQ-AGO employs fuzzy logic to evaluate candidate wireless links and uses a Q-learning-based approach to select a next-hop candidate in a way that can provide reliability and stability. FQ-AGO learns the best next-hop by using Hello messages. FQ-AGO can be performed efficiently in various dynamic environment scenarios by modifying the fuzzy membership functions and fuzzy rules. FQ-AGO provides a flexible and practical solution for routing in MANETs.Through experimental results and computer simulations, we have confirmed the advantages of FQ-AGO over other relevant routing schemes.

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We have performed ns-3 simulation and compared the performance of FQ-AGO with existing routing scheme DSDV, AODV and GOR. We have considered the hop-count, the available throughput, latency and packet delivery ratio for performances comparison. Simulation results demonstrate that our proposed FQ-AGO significantly outperforms the other protocols. FQ-AGO achieves up to 15% and 50% and 45% higher throughput compared to DSDV, AODV and GOR, respectively, while reduced 50% end-to-end latency and the average number of hop-count. Our simulation results demonstrate that FQ-AGO improves various network performances, particularly in case of increasing the network size and higher nodes mobility.

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