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A New Routing Approach for Mobile Ad Hoc Systems Based on Fuzzy Petri Nets and Ant System

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ABSTRACT Mobile ad hoc network (commonly called MANET) comprises a large and relatively dense population of mobile units that move in any territory, and its only means of communication is the use of wireless interfaces without using pre-existing infrastructure or centralized administration. Moreover, routing should provide a strategy for sending data at any time between a pair of nodes (i.e., source and destination) across a network. However, the main problem is to determine an optimal routing of packets across the network. The main objective of the proposed protocol is to find the least-cost investment in nominal capacities that ensures the routing of nominal traffic and guarantees its survivability in case of any arc or node failure. In this context, the fuzzy synchronized Petri net is substantially adopted in the modeling of the routing and detection/decision functions that use a synchronized fuzzy transition approach, where the ant system is used to find a solution for the problem of uncertainty events in ad hoc networks. The obtained results show the effectiveness of the proposed synchronized Fuzzy Ant System (SynFAnt) protocol compared to four protocols. The SynFAnt routing protocol improves the packet delivery ratio, the throughput, the end-to-end delay, and the acceptance rate of the QoS flows.

INDEX TERMS Routing, ad hoc, fuzzy Petri net, ant system.

I. INTRODUCTION

In the recent years, the evolution of wireless communication technologies and the emergence of mobile devices (laptops, smartphones, etc.), made the access of these devices to the network possible anywhere and anytime without connecting the communicating devices to an infrastructure as shown in Fig. 1. An undeniable advantage of these wireless technologies is the ability to be mobile while staying connected.

Wireless communication is less reliable than communication in wired networks. The propagation of the signal undergoes perturbations (e.g., transfer errors, micro-break, timeout, etc.) due to the environment, thereby altering the transferred information. This process results in an increase in message transit time due to the increase in the number of retransmissions. The connection can also be broken or altered by the mobility of the sites when the user leaves the receiving area or enter a high interference zone. In the mobile ad hoc network (MANET), mobile users are obliged to implement the routing of the actual data due to the lack of infrastructure in this type of network. When the destination is outside of the radio range of the source, each mobile of the network serves as a relay by retransmitting the data to another mobile unit until the destination is reached. The frequent instability of the path due to mobility and radio resource constraints (e.g., variable throughput, limited bandwidth, etc.) presents major challenges for this type of routing.

MANET is a special case of mobile networks, and new concepts have been emerged to improve the routing reliability to ensure the quality of information in a network containing mobile nodes. However, gain mobility is imperfect in other aspects such as speed of communication and quality of service. Compared to wired interfaces, only a few wireless interfaces offer fast throughput. As a result, routing consists of finding a path between the different elements of the

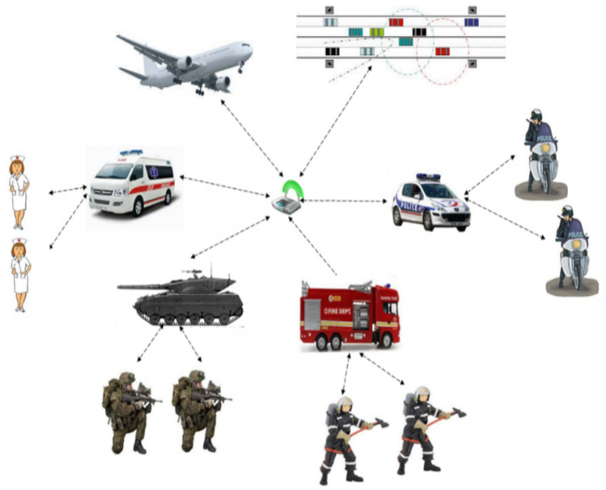

FIGURE 1. Examples of MANET applications.

network to send a message between two elements that do not communicate directly with each other.

Routing protocols are classified into three categories in the uncertain knowledge associated with the monitoring of ad hoc systems requires specific reasoning and modeling methods that are adapted to a logic different from classical logic.

Fuzzy logic (in the ''ambiguous'' sense of the term) has been developed to circumvent the impossibility or the extreme difficulty of modeling certain problems. In opposition to the Boolean logic that does not tolerate intermediate states, the idea is then to determine the veracity of a proposition as being a real number situated in the interval [0, 1]. It is inspired by classical human reasoning, which is often based on incomplete data. It is said that fuzzy logic makes it possible to make the link between symbolic modeling and numerical modeling. Used in artificial intelligence, fuzzy logic also finds applications in fields as varied as robotics, seismology, medicine, and even routing in ad hoc networks [2], [3].

The two main categories of the Fuzzy Petri Net (FPN) models generated by three logical types (i.e., classical, fuzzy, or linear) are as follows:

-In the models used by a fuzzy expert system, FPN is interfaced by the information that arrives through the sensors of the system under surveillance and includes a fuzzy controller for this system.

- The second class is modeled by FPN and models a physical system by applying a linear logic to the transmission of information. The current study is based on the second class.

This study will use an extension of FPN, which integrates the aspect of delay [4], to model the routing protocol and monitoring function. Timed Fuzzy Petri net (TFPN) [5] is oriented for the modeling of a basis of the fuzzy logic rules that result from the logical expression of the fault tree, which is identified a priori at the level of the system monitored. TFPN evidently models the intersection of a set of rules that defines a logical reasoning. The analysis aspect offers us refined information at the level of each defect by the transfer of the signals of the temporally synchronized defects. Accordingly, TFPN highlights the characteristics of a few critical points that materialize the critical path in the strategy of prognostic function.

The question that will arise and presents a limit for the basic TFPN model is the interval between the detection of an event and injection of the latter into the network. In a TFPN network, the event automatically validates the transition, which is a limitation of the TFPN tool.

A. MOTIVATION

Communications in ad hoc networks are essentially based on radio transmission. If the wireless environment offers great flexibility, it causes many problems such as frequent disconnections and variable debits. New techniques have been developed to overcome these problems, but some problems still persist despite miniaturization and cost reduction efforts. These problems are mainly related to terminal mobility where topological changes can cause the unavailability of communications services. The existing works [23]–[30] use a heuristic or optimization techniques but they do not refer to the notion of fault detection in routing protocols (please check this) With the proposed protocl, we seek to maximize the Packet Delivery Ratio (PDR) or equivalently minimize the Frame Loss Rate, maximize network capacity, and reduce end-to-end delays, taking into consideration bandwidth constraints, lifetime and reliability. The fuzzy synchronized Petri net (SynFPN) based on synchronized fuzzy transition approach, is substantially adopted in the modeling of the routing and detection/decision functions, where the ant system is used to find a solution to the problem of uncertainty events in ad hoc networks.

B. CONTRIBUTIONS

The work carried out in the framework of this paper consists in proposing an ad hoc network routing protocol with communication constraints and at the same time studying mechanisms of repair of connectivity. SynFAnt protocol is based on fuzzy logic and ant system. The main contribution of this paper is summarized in the following points :

- Defining the types of nodes located at the network at the time 't' and the changes in each node over time using fuzzy petri net reasoning.

- Defining several parameters or indicators (e.g. hopcount, packet, residual energy, delay, and distance).

- Choosing the best close node based on the confidence value provided by neighboring nodes, which depends on the fuzzy logic in the calculation.

- Proposing a new detection procedure based on the ant system, this procedure aims to reduce the extra cost of the signaling.

- The integration of the detection procedure in the routing protocol helped to reduce mutual inference between the nodes and minimized broken routes. Finally, by using several network metrics, the Packet Delivery Ratio (PDR) and the network lifetime (LT) are increased, and the end-to-end delays is reduced.

C. ORGANIZATION OF THE PAPER

This paper is organized as follows : In section 2, a state of the art of ad hoc network routing is presented. Sections 3 and 4 provide the details of this tool. Section 5 presents the application of our SynFAnt in ad hoc networks and how it is very efficient as a routing protocol. Finaly, the simulation results and discusion are provided in section 6.

II. RELATED WORKS

Many approaches have been proposed in the literature. Das *et al*. [6] used the hop count as a parameter or method to select the best route; however, this study disregards other routes. Once the best route is selected, maintaining the information of these routes can solve the problem of link failures. Son *et al.* [7] proposes a routing protocol for the mobile conditions (displacement of the nodes in the network zone), but if the network becomes static these mobility metrics have no advantage, and they take a high complexity compared to the simple methods of measurement of mobility. Chiang *et al.* [8] proposed a knowledge-based inference approach for a new path of discovery for multicasting. A fuzzy Petri net agent, which is a special expert system, is introduced at each node to learn and adjust itself to fit the dynamic conditions in a multicast ad hoc network. A new concept based on the ant Systems is currently being used in computer networks. It is used in conventional wireless networks and yields positive results [9]. Li and Leu [10] used the clustering concept of Weakly connected dominating set-assisted ant (WCDS) to propose an improved ant-based on-demand clustering routing protocol for wireless ad hoc networks. Das and Tripathi [11] propose an Intelligent Energy-aware Efficient Routing protocol for MANET (IE2R), using a Multi Criteria Decision Making (MCDM) technique based on entropy and Preference Ranking Organization METHod for Enrichment of Evaluations-II (PROMETHEE-II) method to determine efficient route MCDM technique combines with an intelligent method, namely, Intuitionistic Fuzzy Soft Set (IFSS) which reduces uncertainty related to the mobile node and offers energy efficient route. The proposed protocol helps to reduce the mutual interferences between nodes and eliminate uncertainties related to route selection. Moreover, the same authors propose a novel routing formation algorithm called Geometric programming [12] based Energy Efficient Routing protocol (GEER) for the hybrid ad hoc network. It optimizes two sets of objectives: (i) maximize the network lifetime and throughput, and (ii) minimize the packet loss and routing overhead. The stated optimizations are done by the fusion of multi-objective optimization, geometric programming, and intuitionistic fuzzy set. Fathy *et al.* [13] proposed an adaptive cross-layer product routing protocol (ACRP), this protocol uses fuzzy logic as a means to adapt to the types of mobility and communication system applications. The proposed model is able to switch between the two types of active and proactive routing. Chettibi and Chikhi [14] propose an improved routing approach to determine the probability of routing a node based on two criteria, residual node energy, and energy drain rate. The proposed model arrives at maximizing the network lifetime by applying fuzzy logic only but it increases the complexity of the network layer of a node. Another method proposed by [15] based on the application of metric self-adaptive routing for MANET ad hoc networks. The nodes in this model are able to detect whether the model is in a static or mobile state using a global positioning system GPS. Yadav *et al.* [16] proposed a routing protocol based on fuzzy reasoning, in this mechanism all the network metrics of the routes are converted into a single metric. The path choice is based on the value obtained by each link, the optimal path is that which has a minimum fuzzy cost. Kaliappan *et al.* [17] used dynamic genetic algorithms such as Elitism-based Immigrants Genetic algorithm (EIGA) and Memory Enhanced Genetic Algorithm (MEGA) to solve Rooting in Load balancing in Mobile Ad hoc Network. Clausen *et al.* [18] Studies the routing protocol Lightweight On-demand Ad hoc Distance-vector Routing Protocol - Next Generation - (LOADng) support for smart route requests and expanding ring search, designed to enable efficient, scalable and secure routing in low power and lossy networks. Naimi *et al.* [19] Introduce an algorithm that predicts metric values a few seconds in advance, in order to compensate the delay involved by the link quality measurement and their dissemination by the routing protocol in ad hoc network.

III. FUZZY SYNCHRONIZED PETRI NET

The work presented in [14] will provide good support to develop our protocol because it is adapted to the modeling of the static information bases. This approach is effective for the control but is unsatisfactory for the monitoring and control of the flow of the dynamics of data. Thus, we propose the SynFPN optimized fuzzy synchronization as an extension of FPN for the modeling and diagnostics/monitoring of ad hoc communication systems.

A. DEFINITION OF THE TOOL

The synchronized fuzzy Petri nets (SynFPN) is a tool defined as the n-tuple presented in Fig. 2:

SynFPN $= <P, T, E, I, O, F, Sync, D, M_0>$, where

$P = \{p_1, p_2, p_3 \ldots.. p_n\}$ Finite set of places;

$T = \{t_1, t_2, t_3 \ldots.. t_n\}$ Finite set of transitions;

$E = \{e_1, e_2, e_3 \ldots.. e_n\}$ Finite set of external events;

$I : T \rightarrow P$ Input function in the places;

$O : P \rightarrow T$ Output function of the places;

$F(t) : T \rightarrow [0, 1]$ Associative function that establishes a time-varying credibility value $\mu = F(t)$ for each transition $t_i \in T.\mu$ represents the degree of truth of the proposition corresponding to the transition.

The instant t corresponds to the time instant $t \in d$ when the external event E_i will be received by the modeled system. $Sync : T \rightarrow E \cup e$ Application on the set of transitions with

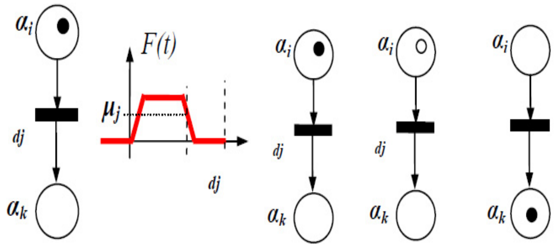

FIGURE 2. Representation of a fuzzy Petri net.

values on the set of events E combined with the event e, which is the event with permanent appearance.

$D = \{d_1, d_2, d_3 \ldots . d_n\}$ Set of durations associated with external events that represent the time window for their receptions. These times represent the same time as the timings associated with transitions synchronized with external events.

M_0: Initial network marking.

In the SynFPN network, a transition can be crossed when it is valid. The assumption is that the monitored system is modeled by a timed fuzzy Petri net (TFPN), which transmits the information as an external event. This event is expected in time window di. During time t, the token exhibits the token status reserved for the transition T_i as shown in Fig. 3. This feature is the T-timed aspect of the *SynFPN* network. At this instant, the transition transfers to the token the value $\mu_i = F(t)$, which represents the degree of credibility associated with the possibility of occurrence of the external event. The token that arrives in the succeeding place will be loaded with the fuzzy value $\alpha_k = \alpha_i.\mu_i$

B. FUZZY PETRI NET REASONING

The computational approach described in this study is the Mamdani fuzzy Petri net (MFPN) [20], which is able to overcome the drawbacks specific to pure Petri nets.

Each transition corresponds to a fuzzy rule and has associated a function $\mu_i = F(t)$, which describes the possible crossing time. The function $\mu_i = F(t)$ represents the membership function of the fuzzy variable t to the fuzzy set defined by the linguistic variable "event appearance E_i". The credibility value μ, which is variable over time and corresponds to the rule modeled by the transition, prints a dynamic credibility character to each rule. The interval $[0, d_j]$ represents the total time analyzed and the time interval associated with the transitions.

If the event occurs in the time window $[0, d_j]$, then the shooting of the transition will follow after the d_j duration. During the interval $[t, d_j]$, the token of the place P_i is the reserved token in the square; hence, such token is unavailable for any other transition that can be crossed.

Our approach considers the operators

$T(u, v) = \min(u, v)$ and $\perp(u, v)$. The generalized modus ponens operator $T_{probabilistic}(u, v) = u.v$.

The structures presented in Fig. 3 show that the evolution of the marking is natural but the fuzzy values associated with the tokens of the following places are determined based on the following definitions:

Fig. 3 (a) $\alpha_k = min\left(\alpha_1, \alpha_2, \ldots, \alpha_j\right).\mu_j$

Fig. 3 (b) $\alpha_1 = \alpha_2 = \alpha_3 = min(\alpha_1, \alpha_2, \ldots, \alpha_j).\mu_j$.

Fig. 3 (c) $\alpha_k = max(\alpha_1\mu_1, \alpha_2\mu_2, \ldots, \alpha_j\mu_j)$

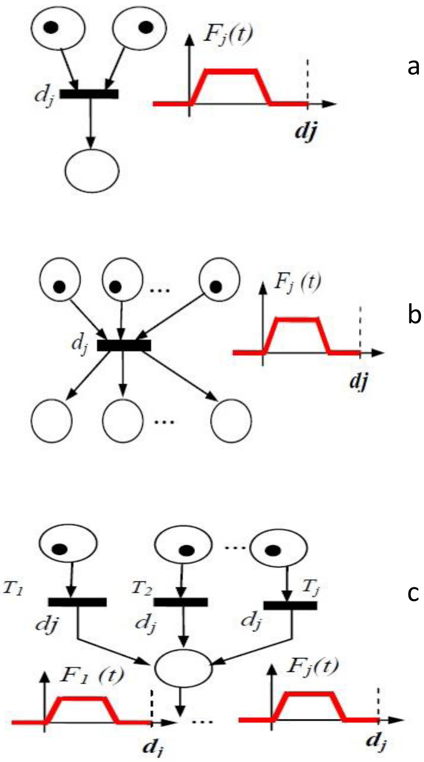

FIGURE 3. Modeling the logical rules: (a) $p1 \wedge p2 \rightarrow p1'$, (b) $p1 \wedge p2 \wedge ..pi \rightarrow p1' \wedge p2' \wedge ..pk'$, and (c)$(p1 \rightarrow pk) \vee (p2 \rightarrow pk) \vee .. (pi \rightarrow pk)$.

IV. ANT SYSTEM

The Ant System, which was introduced by Colorni, Dorigo, and Maniezzo and used in ad hoc communication systems [21], [22], is a distributed metaheuristic for hard combinatorial optimization problems and was used on the well-known Traveling Salesman Problem (TSP).

The described behavior of real ant colonies can be used to solve combinatorial optimization problems by simulation: artificial ants that search for a solution space simulate real ants that search in their environment. The objective values correspond to the quality of the food sources and an adaptive memory corresponds to the pheromone trails. In addition, artificial ants are equipped with a local heuristic function to guide their search through a set of feasible solutions [23].

For artificial ants, a few changes are made to the capabilities of the ants described in [5].

- They have a memory.

-They are not completely blind.

To prevent an ant from retracing its steps, it maintains a list of cities it has already crossed. This list, which is called a

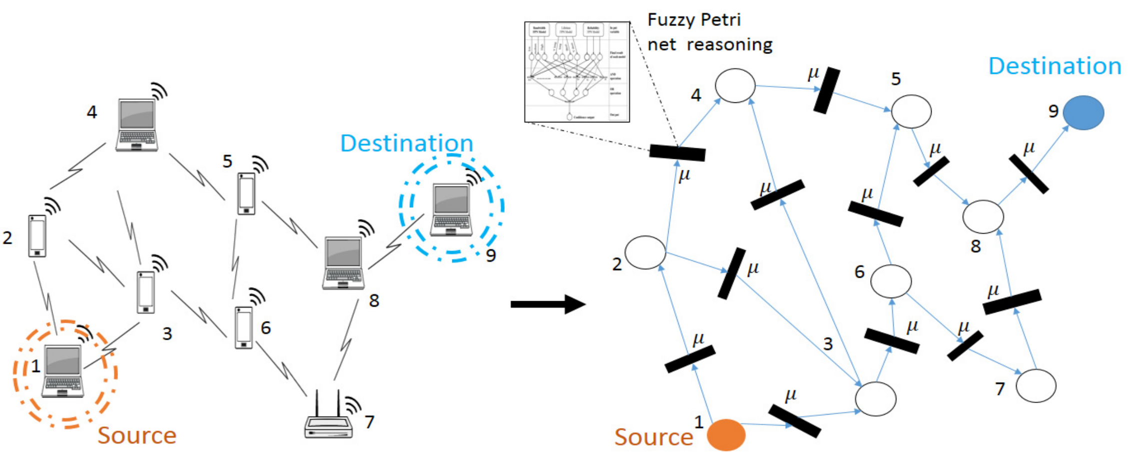

FIGURE 4. Modeling of the ad hoc communication system with Fuzzy Petri net.

taboo list, is reset each time the ant has completed a tour. The taboo list is the memory of the ant.

The pheromone values are modeled by variables $\tau_{ij}(t)$ given the intensity of the trace on the path (i, j) at time t. The probability of transition from vertex i to vertex j by ant k is provided as follows:

$$P_{ij} = \begin{cases} \dfrac{[\tau_{ij}]^{\alpha}[\gamma_{ij}]^{\beta}}{\sum_{l \notin L_{K(i)}}[\tau_{ij}(t)]^{\alpha}[\gamma_{ij}]^{\beta}} & if\ j \notin L_k(i) \\ 0 & otherwise \end{cases} \quad (1)$$

where $Lk(i)$ represents the taboo lis–ant k located at the top, and i, v_{ij} is a measure of visibility that corresponds to the inverse of the distance between cities i and $j.\alpha$ and β are the two parameters that modulate the relative importance of pheromone and visibility.

The pheromone update is performed after all ants have gone through all directions:

$$\tau_{ij} \leftarrow \tau_{ij}(1-p) + \sum_{k=1}^{m} \Delta\tau_{ij}^{k} \quad (2)$$

where p is a coefficient that represents the evaporation of the pheromone and $\Delta\tau k_{ij}$ represents the strengthening of the arc (i, j) for ant k:

$$\Delta\tau_{ij}^{k} = \begin{cases} \frac{\mathrm{Q}}{\mathrm{L^K}} & \text{if the ant k passed through the arc} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

with Q a constant and L_k, the length of the path traveled by the ant k and the initial value τ_{ij} is τ_0.

V. ROUTING PROTOCOL DESCRIPTION

This section presents our conceptual vision for the implementation of a routing protocol based on the Ant Systems and fuzzy Petri net. That is, to determine a path between the various network elements to send a message–packets–between two elements that do not directly communicate with each other. Fig. 4 presents an ad hoc network and the equivalent representation with the Petri nets. Each host on the network must have the following elements to implement an ad hoc network based on fuzzy reasoning and Ant Systems. Agent software provides the best neighbor of the host from all its neighbors. The previous field's purpose is to know the host that last sent a packet.

A list of all hosts and distances between neighbors is provided. The host has an agent and the agent software can be based on a single jump. It's a function that's called BestHop (described in Section D.1) and its primary role is to use fuzzy rules to select the best neighbor node S from all its other neighbors.

In the ad hoc network, the timing durations are different for each transition and are matched with the duration of the communication. A substantially different marking evolution is proposed if the resources of a communication system are modeled. After the shooting of the transition, each token will have associated the fuzzy value $\alpha_k = \alpha_i.\mu_j$.

Each token will independently have the reserved token status during the interval [0 di] associated with the transition.

A. SynFAntPN FOR MODELING THE RESOURCES OF COMMUNICATION SYSTEMS

In this part, a description of the metrics associated with the routing problem in our protocol is presented.

1) BANDWIDTH MODEL

To ensure the flow of the stream QoS [24], we estimate the available bandwidth that can allocate them. The estimate must be distributed and consider the different phenomena specific to ad hoc networks (e.g., interference, collisions, etc.). The basic principle of most protocols is that nodes monitoring support the radio in determining the occupancy rate of a radio channel. Subsequently, an estimate of the timing of the transmitter and receiver mobile, as well as the collision rate, is performed to determine the residual bandwidth links.

However, estimating these protocols does not consider the transmission type (or Best Effort QoS) in the network. Thus, we add it to the ADOV protocol [25], which is a mechanism to differentiate hopcont and the neighbor hosts as two criteria of the bandwidth model.

The hosts that have a few neighbors are the ideal ones because they have a high communication rate.

The most efficient flow is between the two nearest nodes because the energy required to perform an operation between two near nodes is less than that of a further distance. Accordingly, we refer to the quality of the system and conservation of energy.

2) LIFETIME MODEL

In the second control block, we used fuzzy logic to estimate the lifetime LT for each route. Consequently, we focus on two criteria: the number of packets sent by the route and the lowest energy consumed by the route nodes.

One of the most important criteria in optimizing sending time is to control the number of packets sent by a node at time t and the number of packets received. This factor is significant in evaluating the quality of the inkier. If one of the nodes is congested by a certain number of packets, then the shared bandwidth would be reduced in such a way that the unitary becomes unstable and loses packets.

For energy consumption, which is significant in the routing domain, we consider the energy characteristic channel as a means of evaluation. The rate of energy consumption is the parameter used to calculate the power condition of an arbitrary node. The method used is simple and substantially detailed in [17].

3) RELIABILITY

Let M be the set of multicast members. Assuming that for the multicast member $n \in M$, the router n_i has stored p_i, $q(t)$ number of routes (as much node disjoint as possible) till time t , established at time stamps

$\tau s_i, q\,(1), \tau s_i, q\,(2), \ldots, \tau s_i, q\,(p_i, q\,(t))$, in its route cache capable of storing at most C_i routes, the reliability $rl_i(t)$ of therouter n_i at time t is given by,

$$\mathrm{rl_i}\,(\mathrm{t}) = \left(\frac{1}{|\mathrm{M}|}\right) \sum_{\mathrm{n_q} \in \mathrm{M}} \left(\frac{\mathrm{P_{i,q}}\,(\mathrm{t})}{\mathrm{C_i}}\right) \times \left\{ \prod_{1 \le \phi \le \mathrm{P_{i,q}}(\mathrm{t})+1} (1 - \tau s_{\mathrm{i,q}}\,(\phi)\,/\mathrm{t} \right\}^{\frac{1}{\mathrm{P_{i,q}}(\mathrm{t})+1}}$$
$$n_q \in M 1 \le \Phi \le p_{1,q}\,(t) + 1 \quad (4)$$

In the above formulation, it is assumed that if n_i has not stored a route to a multicast member nq then the value of Φ will be limited to 1 only and $\tau s_{i,q}\,(\Phi)$ will be 0.

Hence, if n_i doesn't already have any stored path to any multicast member, then its reliability will be 0. Please note that, for any router n_i, $rl_i(t)$ lies between 0 and 1. Reliability of a router acquires a high value if a large number of recent routes are stored in route cache of n_i at time t corresponding to a huge number of multicast members belonging to the multicast group M. The utility of storing multiple paths, as much node-disjoint as possible, to a multicast member is that, if a path breaks in the middle of the multicast communication, another stored path may be tried instead of initiating a new route discovery session to newly discover a route to the multicast member. This helps to reduce the message cost in the network [26].

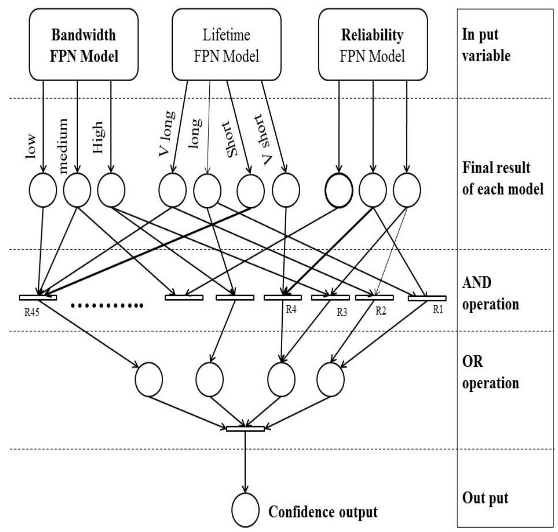

FIGURE 5. Block diagram of fuzzy inference reasoning structure.

Fig. 5 shows an overview of the fuzzy modeling process. This schematic indicates the components that have to be defined for our routing protocol, including the inputs considered in the model (i.e., bandwidth, lifetime, and reliability). Accordingly, the fuzzy confidence value can be inferred in terms of the following degrees: very low (*VL*), low (*L*), medium (*M*), high (*H*), and very high (*VH*).

B. DESCRIPTION OF FUZZY REASONING OF SYNFANT ROUTING PROTOCOL

Conventionally, the inner workings of a fuzzy system are based on the structure shown in Figure 6 which includes 5 blocks or layers:

1) THE KNOWLEDGE BASE

Presented by layer 1 in figure 6, it contains the definitions of the membership functions (forms and parameters) associated with the input/output variables as well as the set of fuzzy rules. In the proposed protocol, the neighbor hosts and efficient throughput are inputs for the bandwidth model, and its output is expressed by the confidence value of the bandwidth. Similarly, the energy and the number of sent and received packets are inputs for the lifetime model, and its output is the confidence value of the lifetime. Furthermore, the two outputs bandwidth and lifetime confidences values are the inputs

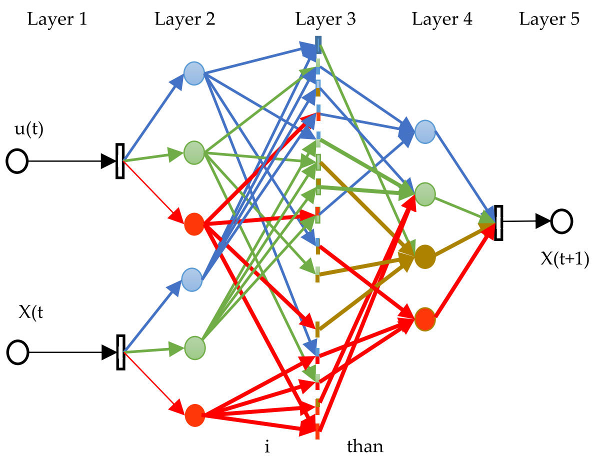

FIGURE 6. The Fuzzy layer structure of Mamdani fuzzy Petri net nodes.

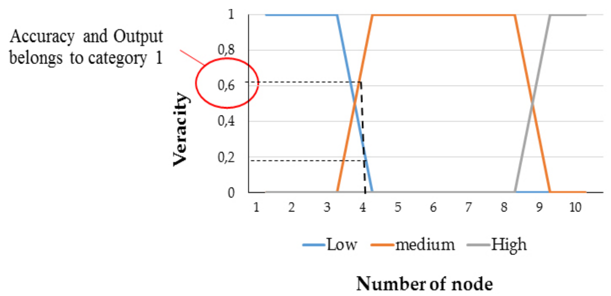

FIGURE 7. Fuzzy sets of the neighbor host input with an initial number of 10.

for the global model of fuzzy inference reasoning structure presented in Fig. 5.

2) THE FUZZIFICATION

The first step consists in transforming the variables (input and output) into linguistic variables as depicted in the layer 2 of Fig. 6. The universe of speech (i.e. the range of values that the variable can take) is defined. Then, each variable is divided into categories called linguistic variables. These variables are expressed in words that give them meaning by using the human language (linguistic values).

Fig. 7 shows the mechanism of how to modify the variable, for instance, the neighbor hosts of a node are divided into modalities (an individual with 4 neighbor hosts is low at 20%, medium at 60%, and high at 0%). This process is similar to the definition of a priori laws in Bayesian statistics, this example a prior law (0.2, 0.6, 0). The difference in this framework is that the sum of the truths is not required to be worth 1.

From Fig. 7:

- **Speech universe**: is the number of the nodes, it can be represented by an integer [0-10].

- **Linguistic variable**: is the name of the output variable (number of the node).

- **Language values**: "Cat1" (low), "Cat2" (medium) and "Cat3" (high).

3) FUZZY INFERENCE

a: Constructing a rule set

Based on previously performed categories, a set of rules is constructed. As shown in Fig. 6, each of the variables $u(t)$ and $x(t)$ is divided into 3 categories (high, medium, and low).

A veracity for each of the rules is then calculated. The construction of these rules, mainly based on the logical operators "AND" and "OR" is mathematically translated in this way.

The output link of layer 2, represented as the membership value, specifies the degree to which the input value belongs to the respective label. Linguistic rules can be formulated that connect the linguistic labels for $x(t)$ and $u(t)$ via an IF-part, called an antecedent of a rule and the THEN-part, also called a consequent of the rule which determines the resulting linguistic label for $x(t+1)$. The structure of a single rule can thus be presented by equation 5:

$$\text{IF (x(t) is Ax(t)) AND (u(t) is Au(t)),} \quad \text{THEN (x(t+1) is Ax(t+1))} \tag{5}$$

where $Ax(t)$, $Au(t)$, *and* $Ax(t+1)$ are the linguistic labels for $x(t)$, $u(t)$, *and* $x(t+1)$, respectively, generated for the data points.

b: Implication: Calculation of the activation rule

It remains to define an activation rule in order to obtain a single answer. This step is called the implication. The Mamdani method presented in layer 3 in Fig. 6 is used in the proposed method.

$$\text{Mamdani:} \mu_{ConcluRi} y \rightarrow MIN_y \left(\mu_{Ri}\left(X_0\right), \mu_{ConclusRi}\left(y\right)\right) \tag{6}$$

Let $x_0 = (variable\ 1,\ variable\ 2)$ is the characteristics of the individual.

where

- $\mu R_i(x_0)$ is the degree of activation of the rule;

- $\mu_{Conclusio}(y)$ is the membership function of the output fuzzy set according to the decision rule.

c: Aggregation

In this step, all the rules are grouped. This grouping is therefore based on logical operator "OR". We use the MAXIMUM compositions to characterize the set of outputs by a membership function equal to the maximum of the membership functions of the fuzzy subsets. The aggregation step is presented by layer 4 in Fig. 6.

4) DEFUZZIFICATION

This step is presented in layer 5 in Fig. 6 where the final activation curve obtained during the aggregation step is transformed into a real value. The center of gravity method (CoG) is used, since it is preferable (and more consistent with the principles of fuzzy logic) in the sense that it incorporates the fact that an individual can belong to two categories at the

TABLE 1. Rating scale for assessing neighbor hosts, efficient throughput, energy, number of sent and received packets, and reliability of the Coif criteria (i.e., L (Low), M (Medium), H (High), and VH (Very High)).

Parameters	Low	Medium	High	Very High
Neighbor hosts	[0, 3]	[2, 6]	[5, 10]	[9, 14]
Efficient throughput	[0, 4]	[3, 8]	[7, 12]	[11, 16]
Energy (joules)	[0, 0.4]	[0.4, 0.7]	[0.5,0.9]	[0.8, 1.5]
Number of sent & received packets	[0, 3]	[2, 5]	[4, 8]	[7, 10]
Reliability coef	[0, 0.45]	[0.40, 0.7]	[0.65, 1]	/
Bandwidth	[0, 0.33]	[0.2, 0.75]	[0.60, 1]	/

same time.

$$CoG : X_G = \frac{\int_U X\mu_x d_x}{\int_U \mu_x d_x} = \frac{\sum_{i=0}^{n} x_i\mu_{xi}}{\sum_{i=0}^{n} \mu_{xi}} \tag{7}$$

Where U is the universe of the speech of the output variable.

This amounts to considering the expectation related to the density $d = \frac{\mu}{\int_U \mu_x d_x}$ associated with the function of veracity. The bandwidth model in Fig. 5 is taken as an example, which is an input in the model of fuzzy inference reasoning structure. The mechanism for estimating bandwidth confidential value is also based on the fuzzy reasoning as shown in Fig. 8. It is clear that the reasoning for estimating the confidence value for such a node for the metric bandwidth is a fuzzy reasoning, i.e. a hierarchical fuzzy network is run at the level of two models of the bandwidth and lifetime.

The membership function for neighbor hosts, efficient throughput, energy, number of sent & received packets, bandwidth, lifetime, and reliability are presented in table 1 as well as the linguistic expressions used for the fuzzification.

C. ANALYSIS OF SynFAntPN

To optimally maximize the proposed tool, our study is essentially based on a probabilistic formula that is used to calculate the best probability to move from one node to another based on the previously cited parameters. Our study focuses on transitions, particularly on transitions with competing places.

1) BASIC FUNCTION 'BESTHOP'

The goal of this function is to select the best neighbor node N among others. Its essential function is based on a probabilistic formula that is used to calculate the best probability to move from one node to another based on the parameters cited in section (V.A).

The algorithm for presenting this function is as follows.

2) FUZZY ANT SYSTEM ROUTING ALGORITHM ILLUSTRATION

The illustration of the fuzzy ant system routing algorithm (SynFAnt) may be presented using a pseudo-algorithm, the goal of which is to show the general operation of the protocol.

Algorithm 1 BestHop

Begin

BS: Best Step

if S has no neighbor, then

Node S is out of range BS $\leftarrow -1$

Return (BS)

if not

Select the best node and its neighbors using the fuzzy rules model

STEP 1: Enter the required variables (amount, distance. . . .) for the fuzzy rule in the model for the nodes connector.

STEP 2: Calculate the degree of adhesion of the proposition of the variables based on the trapezoidal formula.

STEP 3: Use the compound operator AND (min) to calculate the firing strength.

STEP 4: Use the OR (MAX) composition operator to define the maximum firing force.

The function returns the node that has the best value.

/ / Return (BS)

Proposition 1: A constant function F (t) = 1 is associated with each transition that does not have external events detected

Proposition 2: An unstable marking will be recorded after the crossing of an event by a transition, which has not associated a time delay d and that has a duration equal to 0.

end if

End

The detailed description of the proposed routing algorithm is given by:

Phase 1: Discovery of neighbors

All nodes in the network broadcast "*Hello*" message containing their addresses periodically. The node that receives this packet declares the sending node as a neighbor and adds it to the neighbor's table. Then, the *BestHop* function is automatically triggered by this node to classify the new node in the routing table according to the assigned confidence value.

Phase 2: Route discovery

Whenever a source node S wishes to transmit data to a destination node D, it periodically sends a number of forwarding ants to find the best route. The periodic sending of these packets allows us to find better routes that will be used in the sending of data packets, and at the same time provide the route maintenance. As the Forward ant advances to the destination, it records the address of the visited nodes, the minimum bandwidth, the delay of the route, and its reliability. Each Forward ant chooses a new node to visit among its neighbors based on a probability called transition probability defined by equation 1.

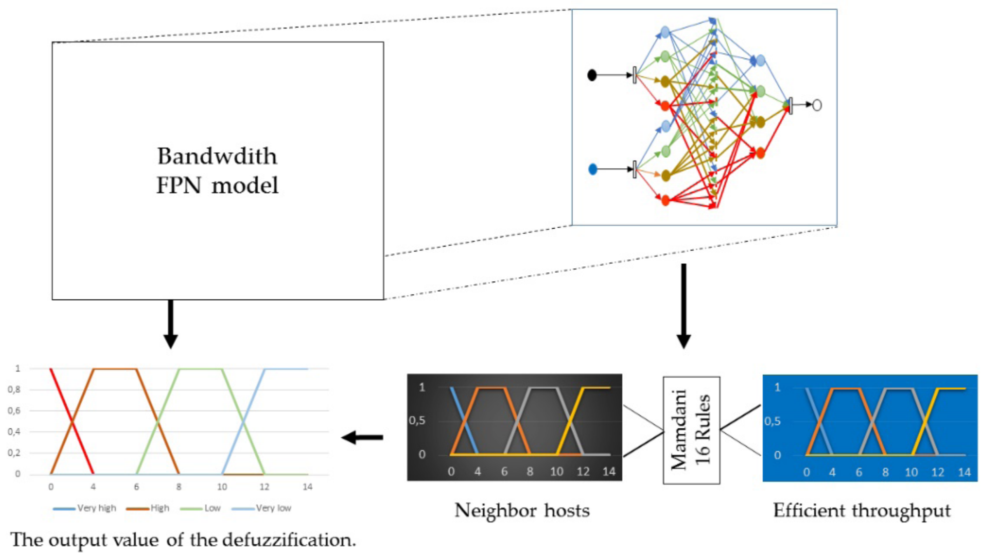

FIGURE 8. Fuzzy control of bandwidth model modeled by Petri net.

For each node N chosen, the Forward ant will check if this node already visited. If so, then, there is a cycle which should be avoided by deleting all the successor nodes of k in the list of visited nodes (Forward ant packet field). Then, the Forward ant chooses a new intermediate node based on the transition probability.

If the node is not yet visited, the Forward ant checks whether this node is the desired destination. If this is not the case, then, it is an intermediate node that has not been visited before, the protocol will perform the following tasks:

- Add this node to the list of visited nodes.

- Check if the throughput of this link is inferior to the Forward ant rate field.

- Toggle this value to this field if this is the case.

- Add to the delay field the delay value of this link (Delay = Delay + delay of the link).

- Check if the stability of this link is lower than the registered stability in the ant table (*Stab*).

- Assign this value to this field if it is the case (Stab = link stability).

If the Forward reaches the desired destination, it gives birth to the Backward ant and transfers all the information it has conveyed (speed, delay, stability, the list of nodes visited, and the sum of the pheromones of all links).

Finally, this Forward ant will be killed. The procedure to find the optimum route is depicted in Fig. 9.

Phase 3: Calculation of the amount of pheromone to be added to the links

The destination node "*D*" detects a new neighbors "*N*" for each time, which will be added to the node's neighbor table. Then, the value of the link pheromone *(S, Ni)* will be assigned to a constant. Then, this value is updated when a Backward ant passes. At that moment, this value is added to a pheromone amount calculated according to the quality of the route traversed by the Forward ant. This quantity denoted $\Delta\tau(S, D)$ is expressed by the equation (8):

$$\Delta\tau(u_i, u_j) = \frac{B(R)_B^{\beta} + T(R)_T^{\beta}}{D(R)_D^{\beta}} \tag{8}$$

Where:

- $B(R)$ is the bandwidth of the route R. This is the minimum bandwidth of all the links forming R because it is a concave metric.

- $D(R)$ is the delay of the route R. It is the sum of the delays of all the links forming R because it is an additive metric.

-$T(R)$ is the stability of the route R. This is the minimum stability of all the links forming R because it is a concave metric.

- β_B, β_T and β_D are weights, representing the relative importance of each of the metrics during the update of the pheromone on the R route links. In order to respect the principle of evaporation of pheromone, the quantity of pheromone on all the network bonds is periodically multiplied by the evaporation factor p, knowing that $0 < p < 1$.

The amount of the pheromone specifying the quality of the found route is also calculated on the arrival of the Forward ant node destination. This quantity is stored in the Pheromone field of the routing table.

Phase 4: Response to the Forward ant

The Backward ant takes the opposite path from the one borrowing by the Forward ant. It uses the list of nodes visited by the Forward ant in the opposite direction. As the Backward ant approaches to the source node, it updates the tables of the traversed nodes.

3) BEHAVIOR OF SYNFANT ALGORITHM AT THE DIFFERENT NODES

The proposed protocol is implemented as a routing agent running on all the nodes of the network. Several functions

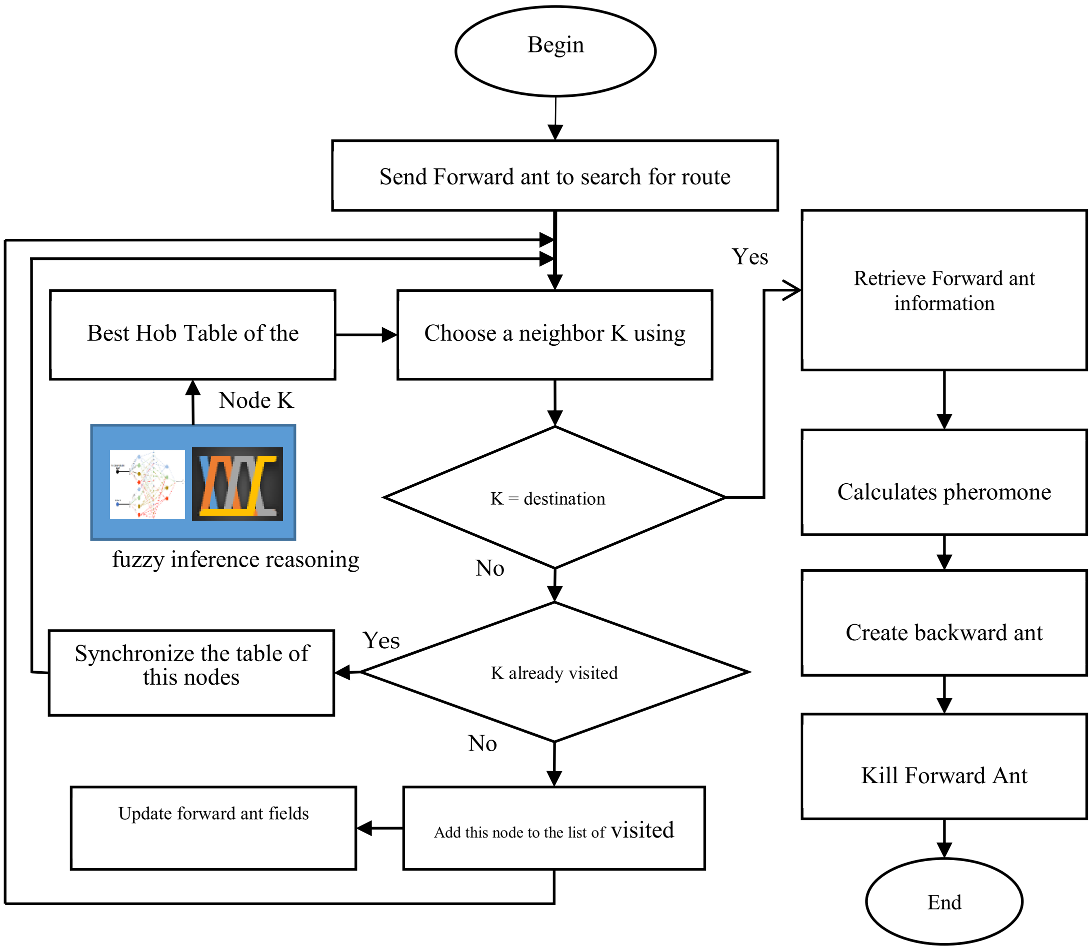

FIGURE 9. Route search flowchart.

are implemented as described in Fig. 10. The invocation of its functions depends on the nature of the node (source node, destination node or intermediate node)

At the source node

According to Fig. 10, the source node S could be a route requestor to send data to a destination node D. Moreover, the node S can also receive a Backward ant from the other nodes previously visited by a Forward ant. The behavior of the source node in each case is described in the following algorithms.

At the intermediate node

The intermediate node behaves differently depending on the nature of the received packet:

At the destination node

Whenever a node receives a Forward ant packet, it tests whether it is the destination node. If so, it will proceed as follows:

VI. SIMULATION AND COMPARISON

We evaluated the SynFAnt performance using the NS-3 simulator. We have compared our protocol with four other recent models, which are reputation-based trust models, as a communication medium: EFMMRP [16], EELB-Mega [17], LOADng [18] and ETX-Ant [19]. The scenario to test our protocol in NS2 simulator is detailed in table 2. The number of nodes in the network considered varies from 10 to 200 and are randomly positioned on a square of 1000 m × 1000 m.

TABLE 2. Scenario for NS-2 topology.

Parameters	Values
Number of simulated Nodes	20-80-120-160-200
Area size of topography x(m	1000 m
Area size of topography y(m)	1000 m
Wireless range	250 m
Packet size	512 bytes
Pause Time (s) at simulation	0s
Node placement	Random
Mobility model	Random way point
Speed node	[5-10-15-20-25-30] m/s
Simulated Routing Protocols comparing with	EFMMRP,EELB-Mega, LoaDng and EXT

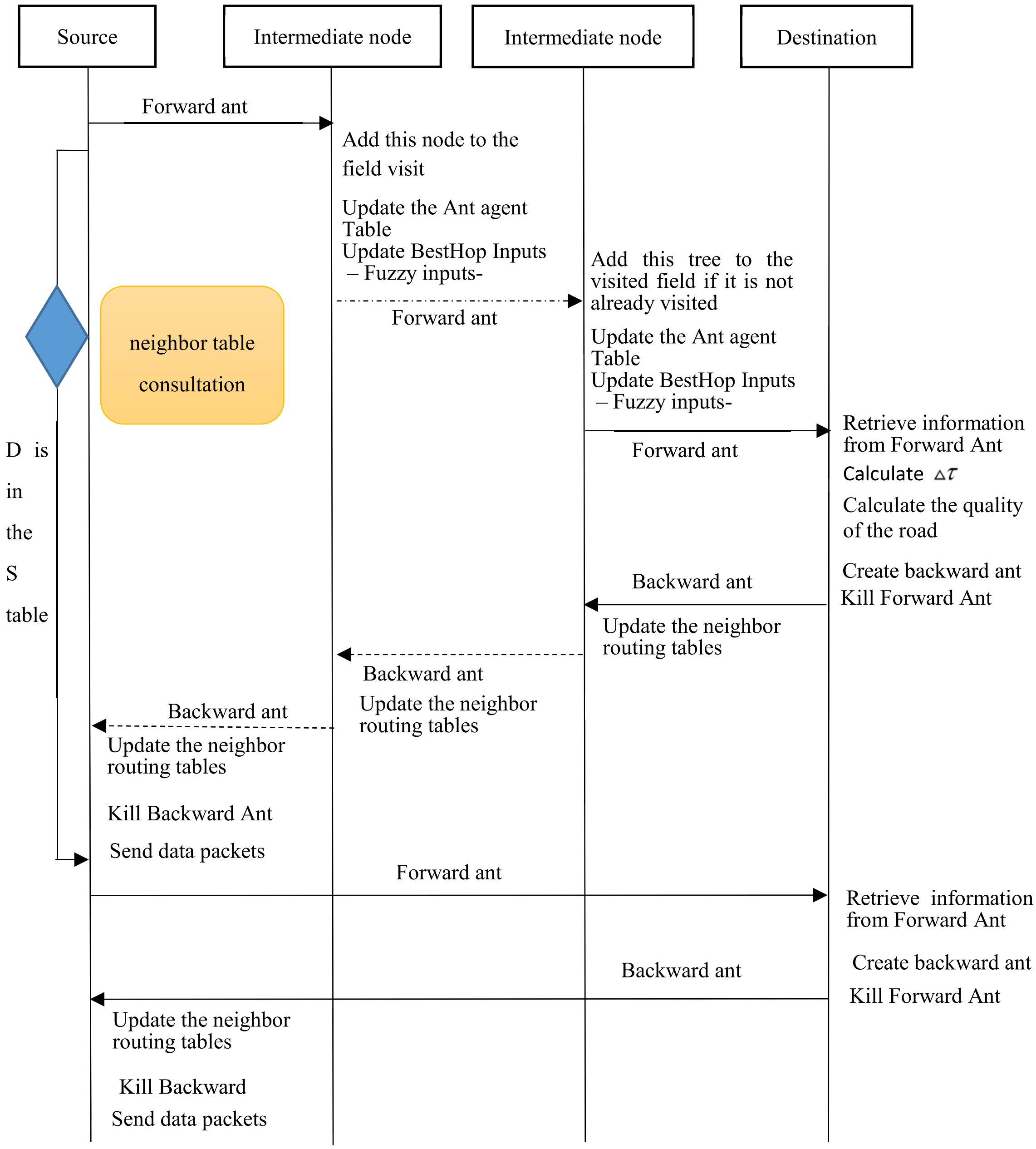

FIGURE 10. **The different functions of the SynFAnt algorithm at the different node.**

The communication range is 250 m, while the carrier detection range is 250 m. A total of 10 CBR streams, including 5 Best Effort and 5 QoS, are established between the source and randomly selected destination nodes. Each simulation lasts 100 s, and the results presented represent the average of 30 simulations for a defined node number.

In order to compare the performance of the different routing metrics. These criteria are performance metrics that depend on the criteria sought by the routing protocol. In this study, we seek to maximize the Packet Delivery Ratio (PDR) or equivalently minimize the Frame Loss Rate, maximize network capacity, and reduce end-to-end delays.

So we use Packet Delivery Ratio PDR, capacity, end-to-end delay, and the acceptance rate of the QoS flows as performance metrics.

A. PACKET DELIVERY RATIO

Packet Delivery Ratio (PDR) is the ratio of the number of data packets received by the destination, to the number of data packets sent by the source. The PDR is calculated as follows:

$$PDR = \frac{\sum \text{packets Received}}{\sum \text{packets sent}} \tag{9}$$

Algorithm 2 SynFAnt

S = source;
D = destination
Node table: contain stability (*Stab*), neighbor hosts, confidence value calculated by *BestHop* fuction.
Begin

1. The rule basis R is a collection of logical rules deduced from the logical expression from fuzzy inference reasoning and table 1.
2. Each place P models a possible communication and is matched with a logical proposition di: "the sign i is in the process of occurring."
3. Each transition t_i models a logical rule R_i, which expresses the appearance of a new communication by combining the logical propositions.
4. If a transition models the evolution of a communication, that is, knowing the duration d of the activity capable of generating this communication, then the coefficient of the truth of this event is fuzzified.
5. A communication can be described as a conjunction / disjunction of the link already produced. The truth coefficient for the corresponding logical variable respects the meeting or intersection rules applicable for fuzzy sets.

if (Best hop (S) $\neq$ -1) **then**
// sends a message between S and the best neighbor
Initialization: $\tau_{ij} \leftarrow \tau_0 \tau$ij$\leftarrow \tau 0$
(i, j) ∈ {1... n}, each ant randomly places a direction node for
$t = 1$ to $t = t_{max}$ do
for each ant k do
Build a path $\tau_k \tau$(t) with the transition rule 1.
Calculate the length Lk (t) of the route
end for
Let T + find the best path and the corresponding length L +. Update the pheromone according to Rule 2
end If
Return T + and L +
/ / Destination found, return and mark the table of each node Ant (S, D)
Replay of the algorithm Otherwise
if (Best hop (S) = −1) then
if (NbNear [S] = 0) then
Node S is out of range Communication error
else
The node D is directly connected with S Ant (S, D)
end if
end if
End

The performance of the four protocols SynFAnt, EFMMRP, LOAdng and EELB-mega is shown in Fig. 11. It is observed that the packet delivery ration PDR increases relatively with the number of nodes in the network. It can be clearly seen that there is a greater chance of having a more stable routing with a network that contains more nodes compared to a network with fewer nodes.

Algorithm 3 SynFAnt Function at Source node

S = source;
D = destination
Visit List: Table
Begin
if S wants to send data to D that is not in the routing table **then**
Create Forward ants and send them on the route search.
end if
if node S receives a Backward ant sent by D then
Update tables (routing and neighbors)
Kill the Backward ant
Send data
end if
End

Algorithm 4 SynFAnt Function Intermediate Nodes

Begin
if the received packet is a Forward ant **then**
if this node k visited (node not already visited) **then**
Add this node to the list of visited nodes
Update Forward ant fields:
$Debit \leftarrow min(Debit, linkrate)$
$Delay \leftarrow Delay + delay\ of\ the\ link$
$Stab \leftarrow min(Stab, linkstability)$
Send Forward ant to the chosen node based on the probability transition (equation 1)
else
Remove the cycle and send the Forward ant to another node according to the probability of transition given by BestHop Function.
end if
if not
if the received packet is a Backward ant **then**
Update the tables (neighbors table and routing table)
Send the Backward ant to the next node in the Visit list.
end if
end if
End

SynFAnt protocol surpasses other protocols; Even though the EFMMRP protocol uses fuzzy logic for the control of uncertainties, the control block neglects the lifetime of the links that play a very important role in ensuring the packet delivery. The LOADng protocol does not take into account the uncertainties for multipath selection for packet transmission; which explains the degradation of the PDR as a function of the number of nodes of this protocol.

Algorithm 5 SynFAnt Function at the Destination Node

Begin
  if the received packet is a Forward ant then
      Calculate the amount of pheromone to be added to the arches (equation 2).
      Create a Backward ant
      Send the Backward ant to the destination node
      Kill Forward ant
  end if
End

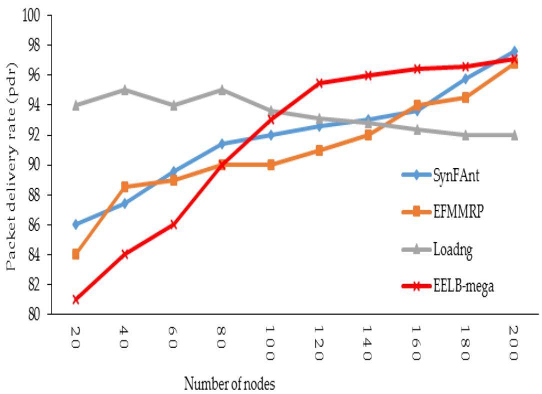

FIGURE 11. Packet delivery ratio vs. number of nodes.

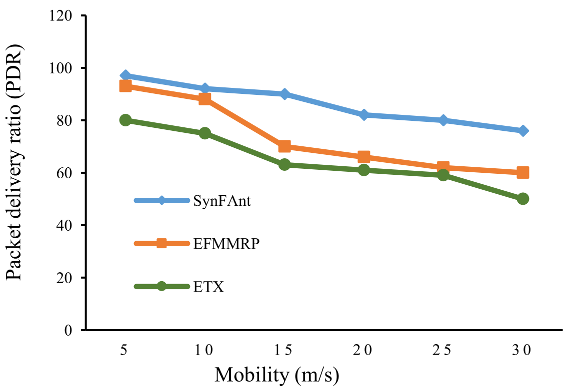

FIGURE 12. Packet delivery ratio vs. mobility.

Fig. 12 shows the PDR for different protocols by varying the speed of nodes. It is observed that the value of PDR decreases as a function of speed, mainly because of the delay between the values taken into account by the routing protocol and the actual values of the metrics. The performance of the proposed SynFAnt protocol is better than the EFMMRP and ETX protocols because SynFAnt prefers the routes with lower losses and high capacity. ETX is the worst metric because it chooses the longest paths.

B. CAPACITY

The Capacity is the amount of passed traffic sent by all nodes (N) of the network during the simulation time. This metric represents the maximum amount of traffic that can flow through the network. The larger capacity of the network

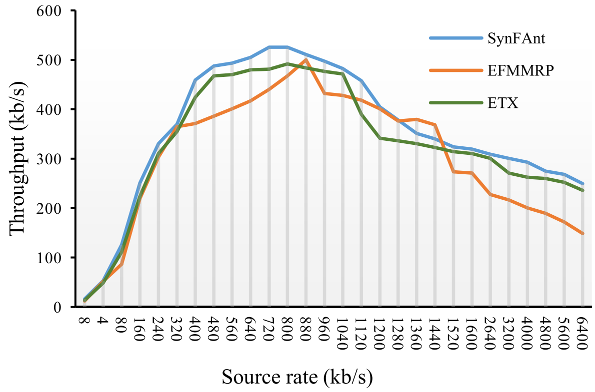

FIGURE 13. Throughput vs. Source rate.

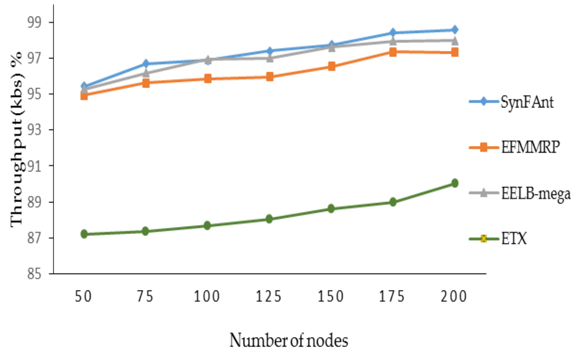

FIGURE 14. Throughput vs. number of nodes.

provides a better quality of service to a larger number of users. This metric is calculated as follows:

$$\text{Capability} = \frac{\sum_{n \epsilon N} |\text{Packets received}|}{\textit{Time of application}} \tag{10}$$

The flow expressed in Kb/s according to the flow rate of the source expressed in Kb/s for a fixed speed of 25km/h is plotted in Fig. 13. This figure illustrates the capacity of the SynFAnt, EFFMRP, and ETX metrics for the random topology. It is observed that the performance of SynFant and EFFMRP is better than that of ETX, because they choose the routes with high capacities and fewer losses. Moreover, SynFAnt throughput exceeds 515Kb/s. In addition, the capacity of the metrics is measured according to the number of nodes. The obtained results of the throughput for the protocols SynFAnt, EFMMRP, EELB-Mega, and ETX are presented in Fig. 14. In the proposed protocol the average throughput is improved to 98.4% by the variation of a number of nodes from 50 to 200, with a rate of 33 +/− 0.38%, the EELB-Mega protocol reaches a rate of 28% and EFMMRP a rate of 31.5%. For the ETX protocol, it does not reach a remarkable rate because it does not take the measure of energy in the criteria of the routing algorithm.

C. AVERAGE DELAY

The end-to-end delay is the average time between the sending of a packet and its reception. It includes the routing delay

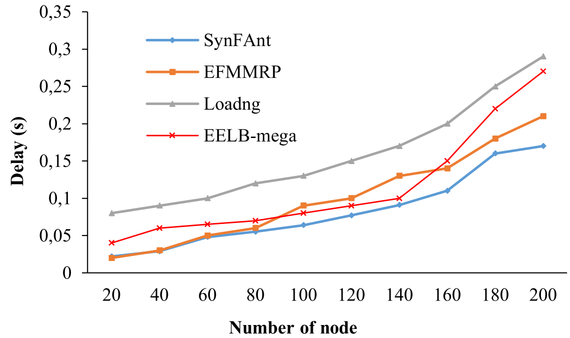

FIGURE 15. Packet delivery delay vs. number of nodes.

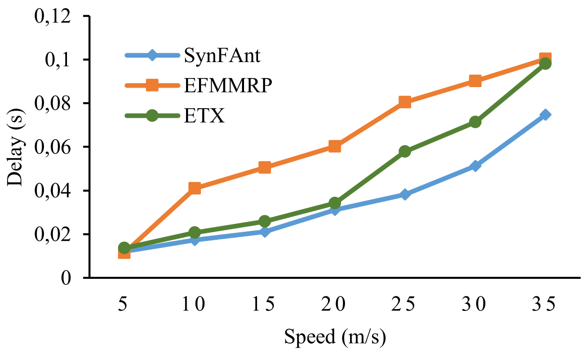

FIGURE 16. Packet delivery delay vs. mobility.

and other miscellaneous delays, such as transmission delay, propagation delay, and queue delay. The end-to-end delay is calculated as follows:

$$\text{Delay} = \frac{\sum_{n\epsilon N} Delay}{\sum \text{packets Received}} \quad (11)$$

The measured values of the delay are represented as a function of the number of the nodes in the network. From Fig.15, it can be clearly seen that the delay varies proportionally with the number of nodes. Indeed, since the scenarios are generated with the same density of nodes, the simulation surface increases with the number of nodes. Subsequently, as the routing traffic increases, the data packets are increasingly delayed in the queues of the intermediate nodes which is reflected directly by a huge increase in the response time. These factors (the number of nodes and the number of the sent packets) are the main cause of the large delay given by the LOAdng protocol. Since EELB-Mega generates the largest overhead, it produces the greatest delay compared to the other protocols. On the other hand, soliciting some nodes over others in the routing of data packets can cause bottlenecks in the data paths. Thus, the delivery time of the packages increases considerably. This effect explains the significant response time generated by LOAdng protocol. The SynFAnt and EFMMRP protocols generate delays close to and much shorter than those recorded by the LOAdng and EELB-Mega protocols. With its lower overhead and the variety of paths used, SynFAnt produces the lowest end-to-end delay.

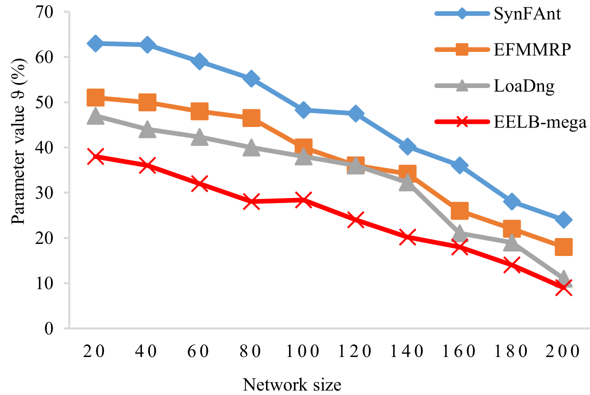

FIGURE 17. Acceptance rate of the QoS flows with the SynFAnt, EFMMRP, LOADng, and EELB-meg protocol.

Fig. 16 shows the simulation of the end-to-end delay depending on the velocity variation. It can be clearly seen that the end-to-end delay caused by EFMMRP and ETX is larger than SynFAntPN protocol. A very small increase in delay for the protocol and ETX between the two speeds 5 and 15 m/s is observed, after this point, the delay increases for the three protocols. Moreover, the speed of mobility is proportional to the motion of the nodes, hence the frequent destruction of paths must be followed by a triggering of the route maintenance process. This affects the delivery time of transmitted packets as it will take a longer time to get to their destination.

D. ACCEPTANCE RATE OF THE QOS FLOWS

We introduce a new metric (ϑ), which represents the acceptance rate of the QoS flows and is defined as follows:

$$\vartheta = \frac{Number\ of\ QoS\ flows\ allowed\ correctly}{Total\ number\ of\ QoS\ flows\ in\ the\ network} \quad (12)$$

A correctly accepted QoS stream is one that has not suffered over 5% degradation of its throughput during transmission [24]. Therefore, this situation implies that the estimation of the differential residual bandwidth and the admission control phase are reliable. This metric will also enable us to estimate the reliability of the differential estimation of the residual bandwidth. An erroneous estimate would lead irremediably to a degradation of the flow rate of the QoS flows and consequently result in a decrease in the value of the variable ϑ.

Fig. 17 shows the protocol parameter value used. Evidently, the denser the network, the lower the acceptance rate φ of the QoS fluxes because the residual bandwidth of the links becomes considerably small (i.e., the capacity remains constant while the number of links increases). When the network is low density (i.e., between 10 and 20 nodes), the acceptance rate φ is relatively high for our protocol (63%), whereas the EFMMRP protocol carries approximately 51% of the QoS flows. Thus, the two mechanisms of the differentiation of flow and differentiated estimation of the residual bandwidth enable an increase in the rate of acceptance of the

QoS flows. However, when the network is moderately dense (i.e., between 80 and 120 nodes), the acceptance rate of the QoS fluxes of all the protocols begins to decrease. However, the SynFAnt protocol still delivers up to 50% of the QoS flows present. Lastly, when the network is very dense (i.e., between 140 and 180 nodes), then a reduction in the flow rate of the Best Effort flows are insufficient to guarantee resources for the QoS flow given that the residual bandwidth of the links becomes very low. However, with SynFAnt, 26% of the QoS flows are still routed with the required conditions, whereas the other protocols carry at least 17% of these flows.

VII. CONCLUSION

In this paper, a new routing protocol based on synchronized Fuzzy ant system, for ad hoc networks is proposed. The basic idea is to propose an adaptive solution to reduce congestion and end-to-end delay by checking the confidence values for each link in the network. The protocol uses parameters such as bandwidth, lifetime and reliability. Moreover, a new formula that considers energy, neighbor hosts number, efficient throughput and number of sent & received packets to estimate confidence values for each node, is proposed.

The process to find the best routes in the proposed protocol is based on fuzzy logic and ant system. The latter is a heuristic inspired by a biological field interested in the study of ant behavior. The proposed solution uses both systems due to their intelligence and ability to be adapted to the environment changes. This proposed solution to intelligently control the flow in MANETs has the following advantages: the control is preventive and quickly adapted to the changes that occur, and the proposed protocol can also detect faulty nodes and speedily propose new routing tables, to avoid large transmission delays that lead to packet losses.

The contribution of this work is: firstly, to integrate a new concept of routing by controlling the flow of the in information

(Quantity and nature) to reduce the congestion and packet losses within an ad hoc network. Secondly, is to propose a new formula for real-time diagnosis for ad hoc communication networks.

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