Signal Processing and Renewable Energy
March 2022, (pp. 83-97)
ISSN: 2588-7327
eISSN: 2588-7335

An Energy-Efficient Fuzzy Logic-based Fault-Tolerant Routing Protocol for Wireless Sensor Networks

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Received: 12-Sep-2021, Revised: 22-Nov-2021, Accepted: 24-Nov-2021.

Abstract

Routing with energy consideration has paid enormous attention in the field of wireless sensor networks (WSNs). Aiming at maximizing network lifetime in WSNs, most studies focus on minimizing energy consumption. Energy is consumed by sensor nodes to perform three important functions such as data sensing, transmitting, and relaying. Also, event-driven WSN applications require minimum end-to-end delay and medium access delay. This paper proposes an energy-efficient fuzzy logic-based fault-tolerant routing protocol (EEFRP) for routing in WSN and minimizing the energy consumption to a large extent. EEFRP takes two important parameters “residual energy” and “hop-count” into consideration. Simulation results demonstrated that the proposed algorithm could achieve better performance in comparison with IEEE 802.15.4 original protocol in terms of end-to-end delay, medium access delay, and fault tolerance, particularly in node failure cases.

Keywords: Wireless Sensor Networks, Fuzzy-logic, Fault Tolerant, Medium Access Delay.

1. INTRODUCTION

Wireless sensor networks are infrastructure-less networks that are comprised of a large set of sensor nodes to monitor a wide region with the objective of monitoring, gathering, and measuring environmental parameters then sending them to the base station. Wireless sensor nodes are small size devices that have limited energy, processing power, radio communication range, and low bandwidth. These tiny sensor devices could collaborate to achieve great goals (Akyildiz, et al. 2002;

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Cheikhrouhou, et al. 2012; Yick, et al. 2008).

To have an operational wireless sensor network, the designed protocols for WSN should concentrate on reducing energy consumption. Developing cross-layer protocols which take the information from two or more layers into consideration could achieve good results in such scenarios. Also, medium access schemas should be optimized to shorten the processing delay in the MAC layer to overcome energy limitations. The routing in WSNs is a crucial problem and designing an efficient routing protocol could enhance the performance and energy consumption of the network. Many previous types of research for routing in WSNs are not suitable to perform in situations where the fault tolerance is required (Demirkol and Ersoy 2009).

As stated before, sensor nodes have a limited energy level; hence, they lose a significant amount of energy by transmitting data packets to neighbor nodes or base stations. When a node completely loses the energy, it fails and could not take a role in data transmitting and all links ended in that particular node will fail. Node failure causes route changes frequently. When a node in the path to the destination fails, the route must be changed. Developing an intelligent route construction method that could handle such complicated situations could enhance the performance of the network (Brahma, et al. 2005). Hop count is the most commonly used metric when selecting a route from the source to the base station. However, this metric may perform poorly in networks that topology changes frequently or nodes have limited battery. It is possible to have routes with minimum hop count to the destination, but nodes in the path may have little energy or their leading links have little bandwidth; resulting in poor performance (Tabatabaei, et al. 2015). Many researchers focus on developing new routing protocols for routing in wireless sensor networks. Authors (Nam and Cho 2015) consider a method called LEAP as the base which investigates the different types of packets exchanged between the nodes to prevent attacks. Authors claim that the LEAP method is suitable for performing secure connections but the node's energy limitation in the path to the destination is not considered. Based on this assumption they proposed a fuzzy logic-based method to opt for the next forwarding node aiming at allowing an efficient path construction for packet routing. (Demirkol and Ersoy 2009) proposed a new method to optimize energy consumption and network delay in wireless sensor networks. They suggest a method to estimate contending nodes since the individual wireless sensor nodes do not have this information readily. Authors (Qiu, et al. 2009) with the information of tree routing (TR) which is a low-overhead routing protocol, propose an enhanced tree routing (ETR) method for sensor networks that have structured node address assignment schemes. ETR in adaption to parent-child links considers the link between same level nodes for tree construction. (Raghavendra and Mahadevaswamy. 2020), modeled the energy consumption and identified the most important parameters affecting the lifetime of the network such as data sensing rate, data transmission rate, and data relay rate of nodes. they use the fuzzy membership function at multiple levels to optimize the parameters of variables affecting the lifetime. The simulation result shows that the proposed method can enhance energy efficiency and the lifetime of the network.

for improving the quality-of-service (QoS) necessities in (Alqahtani. 2021) research are proposed which Used multipath Routing Protocol (IQMRP) for Wireless Multimedia Sensor Networks. It uses the Ant Colony Optimization (ACO) technique to choose the multi-path. Using multi-path routing will enhance the capability to handle these failures and can serve to balance traffic load, also can extend the network lifespan. The proposed method, using route preference possibility is measured based on node residual energy, bandwidth as well as next-hop accessibility. Whereas the sender desires to communicate the information towards the recipient, it selects the multiple routes with maximum path preference probability. Simulation results illustrate that the IQMRP offers better throughput, and reduces both the network delay and routing load in the network.

In (Mazinani, et al. 2021), a semi-distributed fuzzy-based method was proposed for clustering nodes in wireless sensor networks. The proposed method uses multi-criteria remaining energy, distance to the base station, and centrality as the fuzzy logic parameters to choose the best nodes as cluster heads and includes two-phase, the first phase is done in a centralized approach by the sink node and selecting the initial cluster heads and determining virtual grids. The second phase includes a distributed approach that all nodes can Participate in the cluster head selection. The simulation results showed that the proposed method could save more energy by decreasing the number of control messages and prolonging the network lifetime.

In (Hajipour, et al. 2021), an energy-efficient layered routing protocol (EELRP) is proposed. This method divides the network into some concentric circles of different radii and circles which are divided into eight equal sectors. Each section contains some sensors nodes, and the most suitable one is selected as the agent. The nodes send the sensed data to their agent. Next, the agent adds error detection and correction codes and sends the data to the agent of the lower sector of the same section. The procedure continues until the information reaches the base station. Applying error detection and correction causes increased reliability and prevents resending packets. The simulation result shows the EELRP provides an improvement in the network lifetime, energy consumption, packet delivery rate, and the number of path hops. (Tabatabaei, et al. 2015) suggest a fuzzy-based on-demand routing protocol (FBORP) for MANETs. The proposed scheme uses the fuzzy logic system to select a stable route to enhance system performance. The fuzzy logic system is based on the residual energy of the nodes, available bandwidth, node mobility, and hop count. Similarly, (Baklizi, et al. 2014) proposed a controller technique for early-stage congestion detection at the router buffer in the networks. The proposed technique extends the well-known gentle random early detection (GRED) algorithm. Unlike GRED, which relies on parameter settings, such as min-threshold, max-threshold, and double max-threshold, to obtain satisfactory performance, GRED depends on a fuzzy logic system which reduces the large dependency on parameter settings. The proposed technique uses the average queue length and the delay rate as input linguistic variables for a fuzzy logic system. The utilized fuzzy logic system produces a single output that represents a packet dropping probability, which in turn controls and prevents congestion in the early stage. In another study, authors (Shafigh, et al. 2012) proposed two methods to improve the performance of on-demand multicast routing protocol (ODMRP). Fuzzy logic-based on-demand multicast routing protocols to establish a small, efficient, and high-quality forwarding group. The main proposed method tries to establish a small, efficient, and high-quality forwarding group. This is achieved by augmenting the join query packets with additional information such as speed, the power level of the node, and link bandwidths. Besides, the control overhead is further reduced by restricting the domain of control packet flooding.

The present work proposes an energy-efficient fuzzy logic-based fault-tolerant routing protocol (EEFRP) to enhance network lifetime in WSNs. We need to develop energy-efficient routing protocols to enhance the lifetime of WSNs. We suggest a fuzzy logic technique for route construction because fuzzy logic is flexible and it is capable of enhancing layers' functionality. The rest of the paper is organized as follows: Section 2 describes the details of the proposed method. Section 3 evaluates the performance of our proposed algorithm. Finally, section 5 concludes the paper.

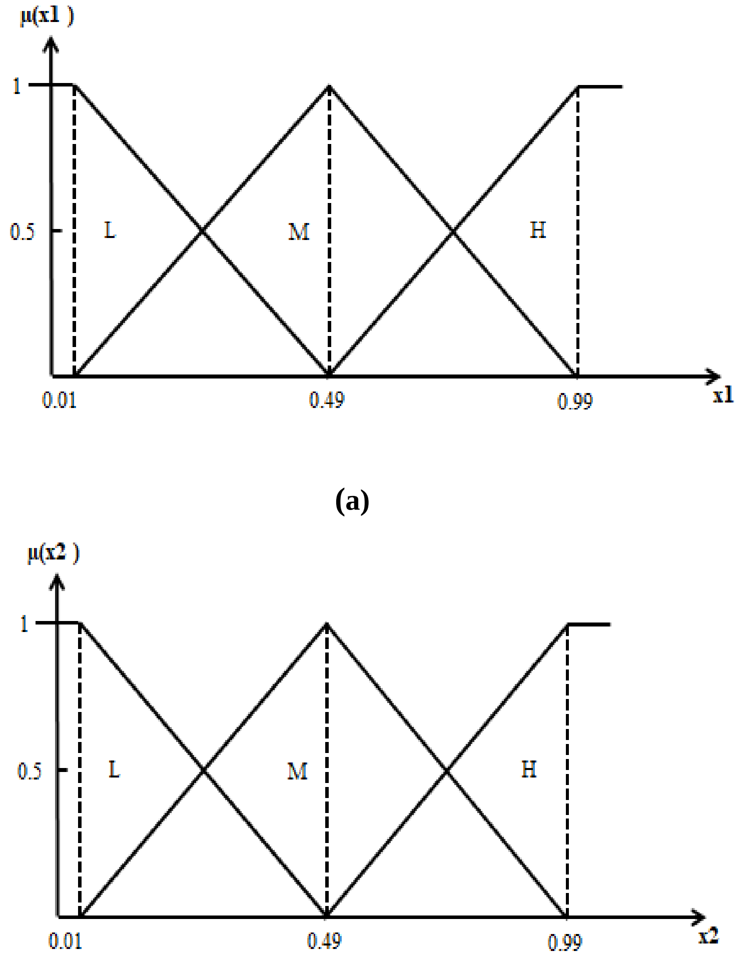
2. ENERGY-EFFICIENT FUZZY LOGIC-BASED FAULT-TOLERANT ROUTING PROTOCOL (EEFRP)

This paper proposes an energy-efficient fuzzy logic-based fault-tolerant routing protocol (EEFRP) for WSNs. The goal is to improve the lifetime of WSNs and increase the quality of the path to the destination using the available information and access data in the network. Choosing a stable path decreases the overhead and optimizes the use of powerful and energetic paths. The proposed method considers two important parameters to select more reliable routes to the destination.

- **Residual energy (RE):** This parameter accounts for the reminded energy of a node for data transmission.
- **Hop count (HC):** Distance (in hops) between the sensor nodes.

2.1. Fuzzy Logic

Fuzzy logic is a logic type that can recognize more than simple “true” and “false” values. In other words, it could be used for modeling the uncertainty of natural language (Zadeh 1996). The main idea behind fuzzy logic is to indicate truth values and membership functions by a value in the range of [0, 1]. Unlike classical set theory according to which each element either fully belongs to the set or is completely excluded from the set, elements in a fuzzy set can take values between 0 and 1. A membership function is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. We define three triangular membership functions



(a)

(b)

Fig. 1. Fuzzy membership functions. (a) Residual energy. (b) Hop count.

for each input variable (“H” Height, “M” Medium, and “L” Low). Fig. 1 shows the membership functions for residual energy and hops count.

A generalized block diagram of a fuzzy inference system (FIS) is shown in Fig.2. A fuzzy inference system is a mechanism that employs fuzzy logic concepts to carry out such tasks as control and decision-making. In this study, FIS was used to determine the optimum value of link stability. The inputs to FIS are real numbers, but it processes them in linguistic forms. This conversion is performed by a FIS element called Fuzzifier. Fuzzifier produces membership functions which can be regarded as fuzzy inputs to the fuzzy inference engine. The fuzzy rule base is made up of fuzzy rules in the form of IF-THEN statements. This is the main part of the fuzzy system since the other components of the system are there to implement the rules appropriately. The inference engine decides how to process the rules in the knowledge base using the fuzzy inputs from the

Fuzzifier. The fuzzy inference engine uses fuzzy rules to compute the stability of the links. We have used the most commonly used fuzzy inference technique called the Mamdani method (Negnevitsky 2005). Three variables are defined for each input parameter which results in 9 fuzzy rules. Table 1 shows the fuzzy logic rule base. Conceptually, the task of the demulsifier is to specify a crisp point in the output space that best represents the fuzzy set. The demulsifier decides how to convert the fuzzy result from the inference engine back into a crisp value.

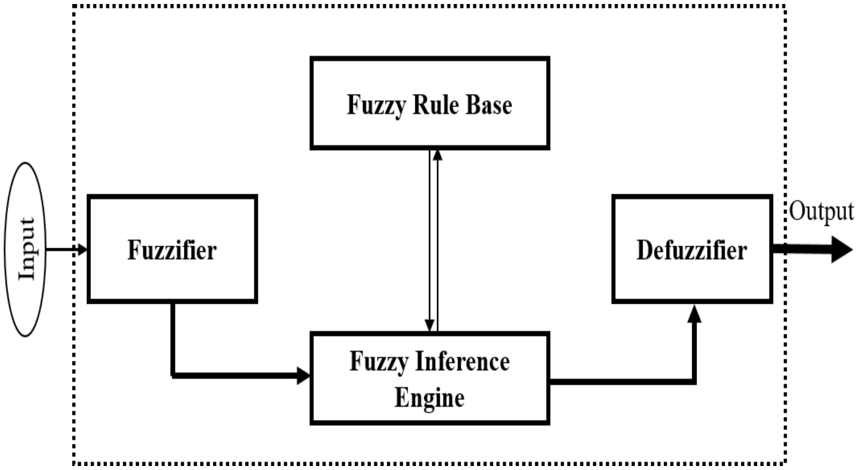


Fig. 2. Block diagram of the fuzzy inference system.

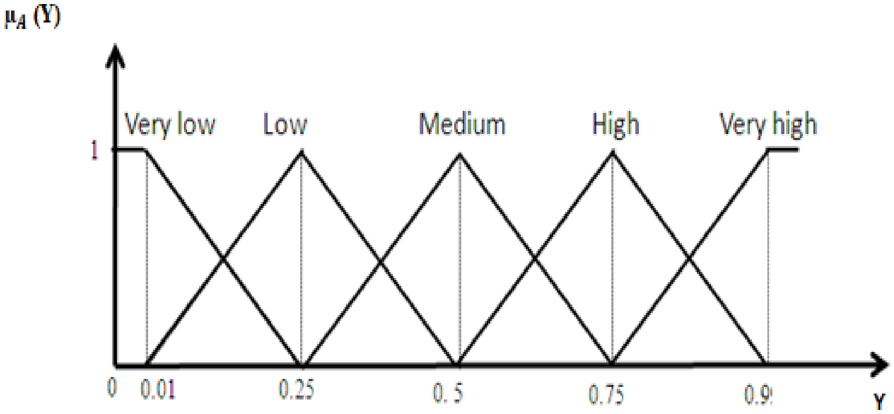


Fig. 3. Fuzzy membership functions for output variable Y (Congestion Rate).

The fuzzy rule base contains 9 rules which are presented in table 1. For example following rules determines the link stability for sender nodes.

R1: If residual energy and hop count of sensor nodes are L, then link stability is M.

R2: If residual energy is L and hop count of sensor nodes is M, then link stability is L.

. . .

R9: If residual energy is H and hop count of the sensor is H, then link stability is M.

Table 1. ***Fuzzy Rule Base.***

HC RE	L	M	H
L	M	L	VL
M	H	M	L
H	VH	H	M

Five triangular fuzzy membership functions are used for the output variable (Fig. 3). The following notations are used to show variable bounds: VL (Very Low), L (Low), M (Medium), H (High), VH (Very High). Then, the output of the fuzzy system is applied to the EEFRP algorithm as the criterion for updating the routing table.

2.2. EEFRP Route Discovery

The operation of EEFRP is similar to IEEE 802.15.4 protocol. Two metrics are utilized for routing decisions in WSNs which are residual energy and hop count. Mainly, existing routing protocols use one metric for routing in WSNs. For example, IEEE 802.15.4 tries to select nodes with maximum residual energy as forwarding nodes in the path to the destination. We suggest combining residual energy and hopping count as two important metrics to choose the most stable routes; therefore, it is expected that our proposed algorithm archives more robust and stable routes in comparison with IEEE 802.11.4 protocol. The decision about data broadcast in the network will be determined by a fuzzy logic system to get the data of the sensor being applied to a Fuzzifier and map them into fuzzy sets. The fuzzy sets are used to estimate each parameter as being “Low”, “Medium”, or “High” and then assign them a value between [0, 1]. These evaluations are passed to the fuzzy inference engine, then applying them a set of fuzzy rules which determine whether a link is suitable for data transmission or not.

Due to the broadcast nature of route discovery strategy, it is possible to have excessive network resource utilization which leads to the selection of unstable paths. Unstable paths are classified as those that have a large associated signal loss, low-energy nodes, a high number of hops, or paths spread over a large distance between a source node and the sink node. Therefore, to eliminate unsuitable paths from the route discovery/reply process and to optimize sending decisions, broadcast transmissions are only continued if a sensor’s fuzzy system indicates that it is valid to do. The route discovery process is initiated whenever a sensor node wants to communicate with another node. The source node initiates route discovery by broadcasting a Route Detection (RD) packet to its neighboring nodes. If the node has already received an RD packet it is verified using a defined fuzzy rule-based system. The route discovery steps are presented below. The pathfinding table structure of EEFRP is similar to that of the IEEE 802.15.4 protocol. When a source node wants to send data to an away node, the following steps must be followed:

a) When source S receives a packet from the transport layer in the direction of sink node D, it checks to see if a route exists to the sink. If it already has a route, it transmits the packet to the next-hop node; otherwise, it transmits an RD packet to its neighboring nodes and initializes the hop count to zero.

b) When a sensor node X receives an RD packet with source node S and destination node D, Node X for-wards a Route Reply (RREP) packet including a MAC with the result of the fuzzy logic system and 9 rules in table1 which specifies the link that the RD packet has received through this route is suitable or not. In the end, if the link was considered to be suitable, then a new efficient path is configured between S and X.

c) Source node S transmits the data to X along the path. These processes are repeated until the report arrives at the sink.

2.3. EEFRP Route Maintenance

Considering the limited power of sensor nodes in WSNs, links are easily broken. The sensor nodes monitor their neighbor-hood. When a node in an active route gets unavailable, a route error (RE) packet is generated to notify the other nodes on both sides of the link about the unavailability of the intendant node. Sensor nodes that receive the RE packet will find this failure in their route cache and increase their error count by one. Upon receiving a RE packet, the source node initiates a new route discovery process to find an alternative path to the destination. The proposed algorithm can be summarized as follows:

Assume that source node “S” in Fig. 4 wants to find a path to the sink node “D” and nodes “I” and “J” are chosen to be the transmitting nodes (forwarding nodes) and the link between node “I” and “J” is broken. When the link between “I” and “J” is broken, node “I” receives a RE packet.

If “I” detects the failure of the link to the next node (J) then:

1. “I” sends the RE packet.
2. “S” receives the RE packet.
3. “S” stops sending the data.
4. “S” restarts the route discovery process and finds an alternative path to the destination; Otherwise, Node “I” continues to send the data.

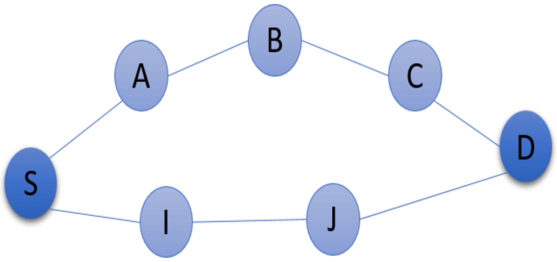
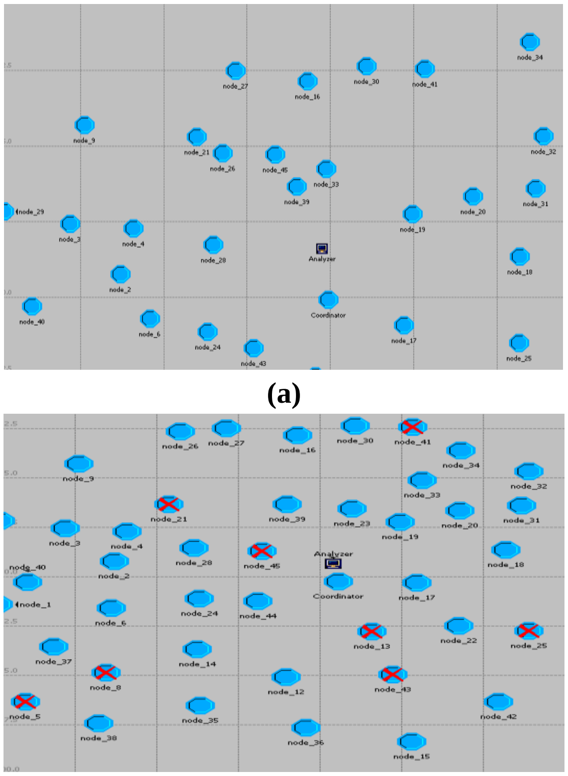


Fig. 4. An example for route error process.

3. PERFORMANCE EVALUATION

In this section, in an attempt to compare the performance of the proposed EEFRP with the IEEE802.15.4 protocol the simulation experiments are presented. OPNET modeler 11.5 (Modeler 2009) is used as a network simulator to verify the performance of the proposed algorithm. Assumptions about the parameters of the system architecture were made in the simulations. The network is modeled in a 100m × 100m area with 46 sensor nodes. In each run, 20 constant bit rate (CBR) sessions were simulated with random source and sink pairs. Each CBR session generated 20 packets per second with data packets of 512 bytes. The simulation time was 30 seconds. The initial positions of the nodes were uniformly distributed throughout the network. A simple topology for no failure state and node failure state was used, as shown in Figs. 5 (a) and (b), respectively.



(a)

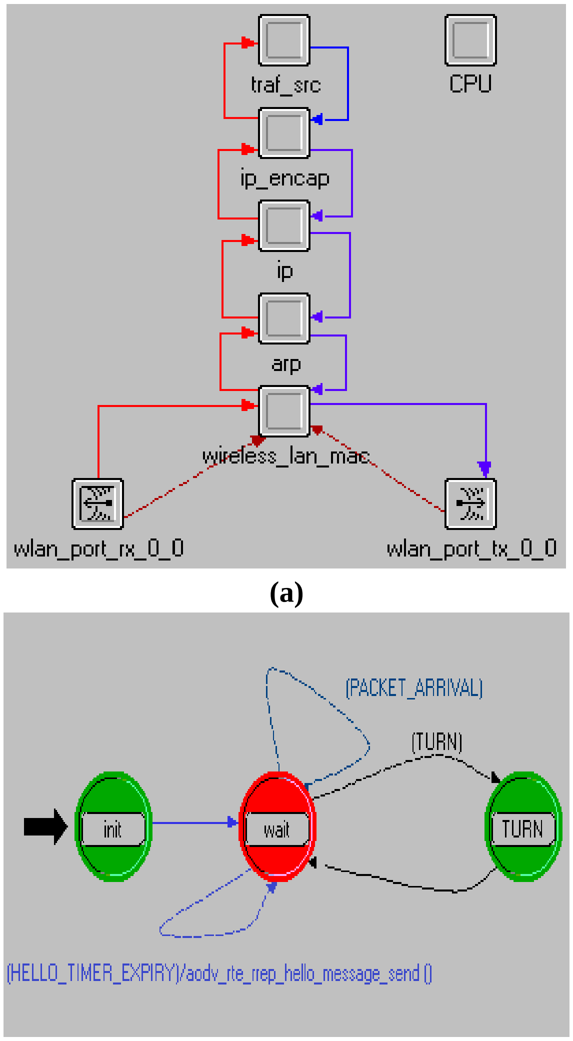
(b)

Fig. 5. Network topology (a) No failure state, (b) Failure state.

The node model and process model used in our simulation are shown in Fig. 6 (a) and (b), respectively.

The following metrics are used to measure the performance of the proposed work.

- Probability of success in the sink: also called packet delivery ratio (PDR) is the ratio of the number of received packets by the CBR sink to the number of sent packets by the CBR source, both at the application layer. Packets that are sent but not received are recognized as lost packets in the network due to malicious activities, route failures, congestion, and wireless channel losses.
- Average end-to-end delay: This is the average delay of all packets that are correctly received. Lost packets are not included in this measurement since their packet delay is infinite.



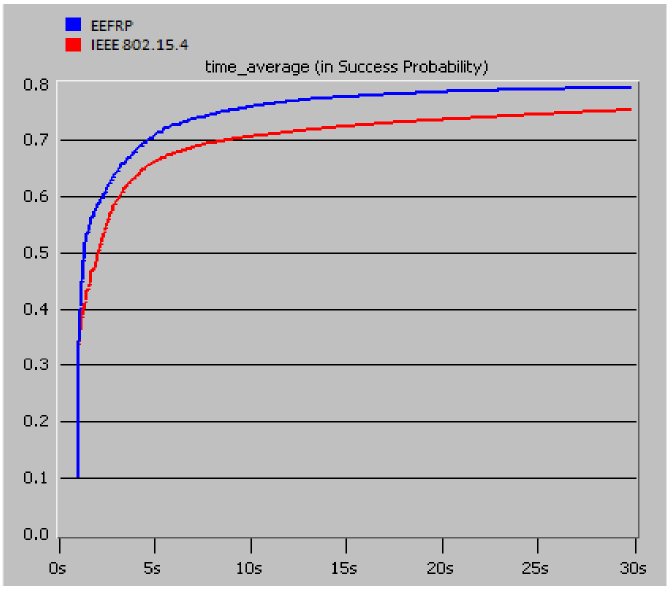
(a)

(b)

Fig. 6. (a) Node model for sample topology, (b) Process model for sample topology.

- Medium access delay: the time from when the data reaches the MAC layer until it is successfully transmitted out on the wireless medium.
- Consumed energy: the amount of consumed energy.

Fig. 7 (a) and (b) show the comparison of the average performance of EEFRP and IEEE802.15.4 protocols in terms of probability of success in sink nodes for different simulation times in a network consisting of 47 nodes. The simulations in Fig. 7 (a) indicate that EEFRP performed better than IEEE 802.15.4. Most routing protocols presuppose the presence of bidirectional links between the sensor nodes in the network. In reality, a wireless sensor network may consist of heterogeneous nodes with different power capabilities and varying transmission ranges. When this is the case, a given node might be able to receive the transmission of another given node but might not be able to successfully transmit



(a)

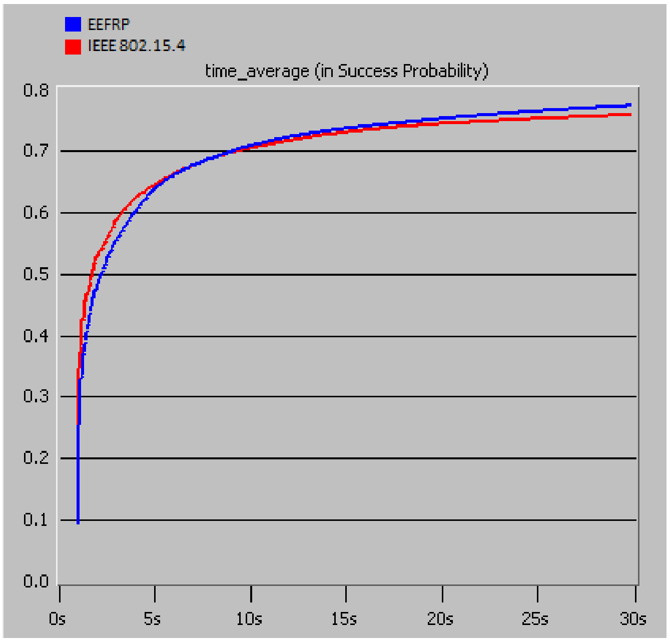


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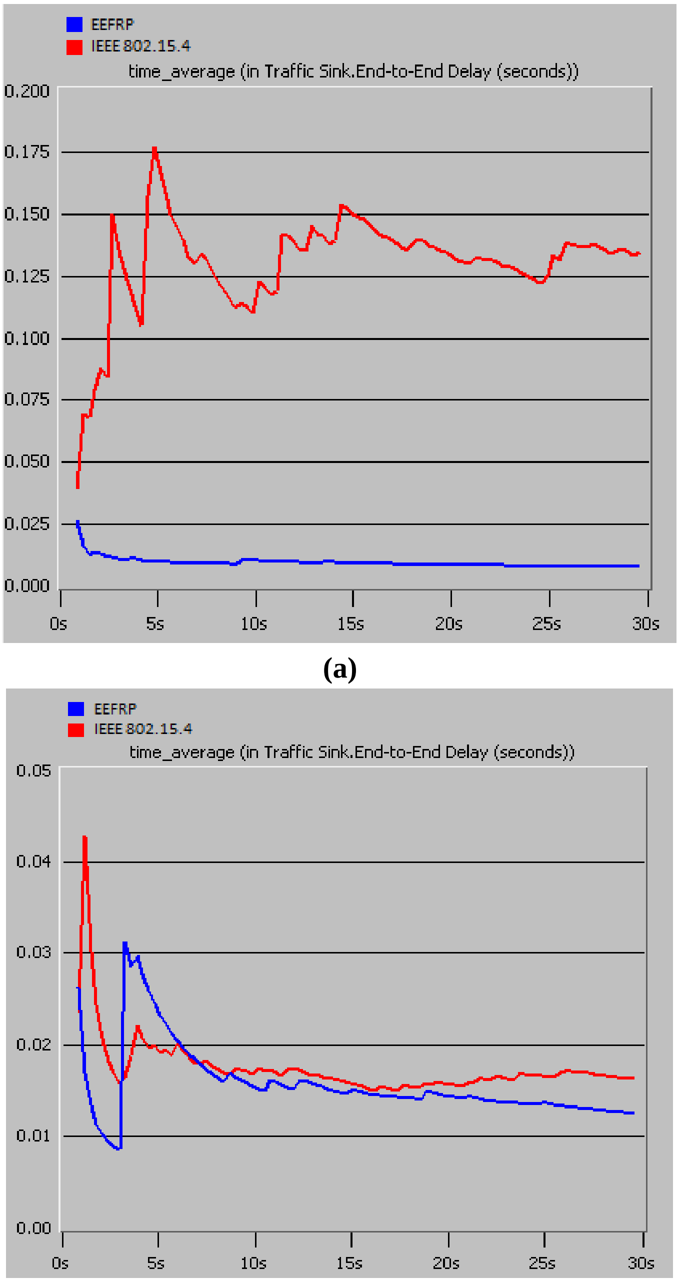
Fig. 7. Probability of success in sink node in different simulation times for 47 sensor nodes. (a) No failure state (b) Failure state.



(a)

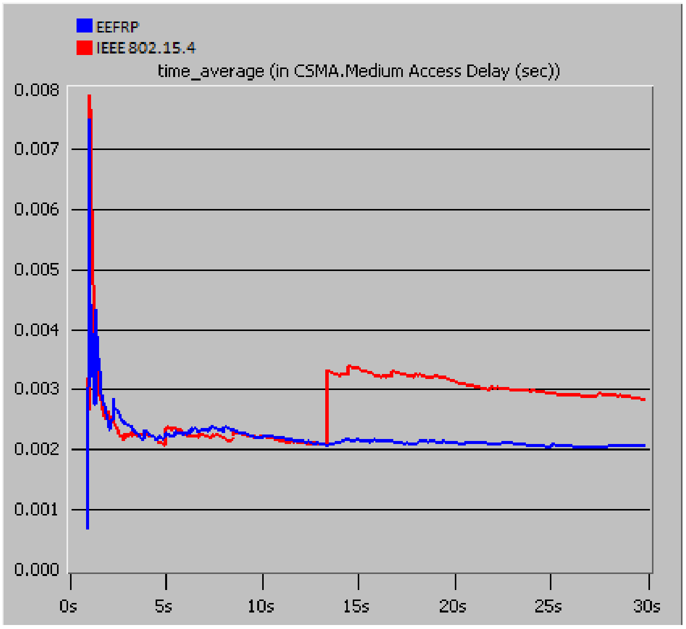
(b)

Fig. 8. End-to-end delay is different simulation times for 47 sensor nodes. (a) No failure state (b) Failure state.

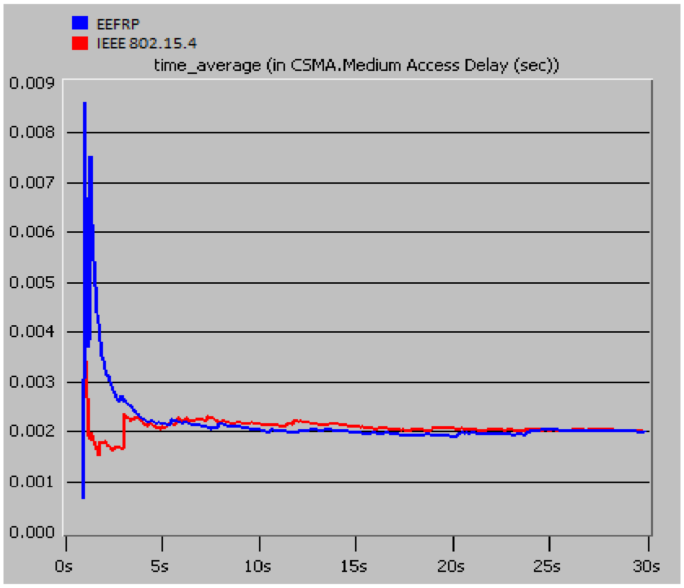
data to it (Wang, et al. 2007). In the EEFRP protocol, using the fuzzy logic-based algorithm the suitability of the link is determined, and if the link was suitable, a given node was able to successfully transmit data to it. Thus, the success probability of the proposed algorithm was higher than that of the IEEE 802.15.4 algorithm.

Fig. 8 (a) and (b) illustrate the comparison of the average end-to-end delay for EEFRP and IEEE 802.15.4 protocols in different simulation times. The IEEE802.15.4 protocol in Fig. 8 (a) can be explained by the fact that the number of dropped packets was larger for the IEEE 802.15.4 protocol than for the EEFRP protocol and that the dropped packets were not taken into account in the average delay calculation. When a packet was not dropped and was delivered with a large delay, the total average delay increased. However, if EEFRP increased, the network reliability and average end-to-end delay decreased.

Fig. 9 (a) and (b) illustrate the comparison of the average medium access delay of EEFRP and IEEE 802.15.4 protocols for different simulation times. This figure

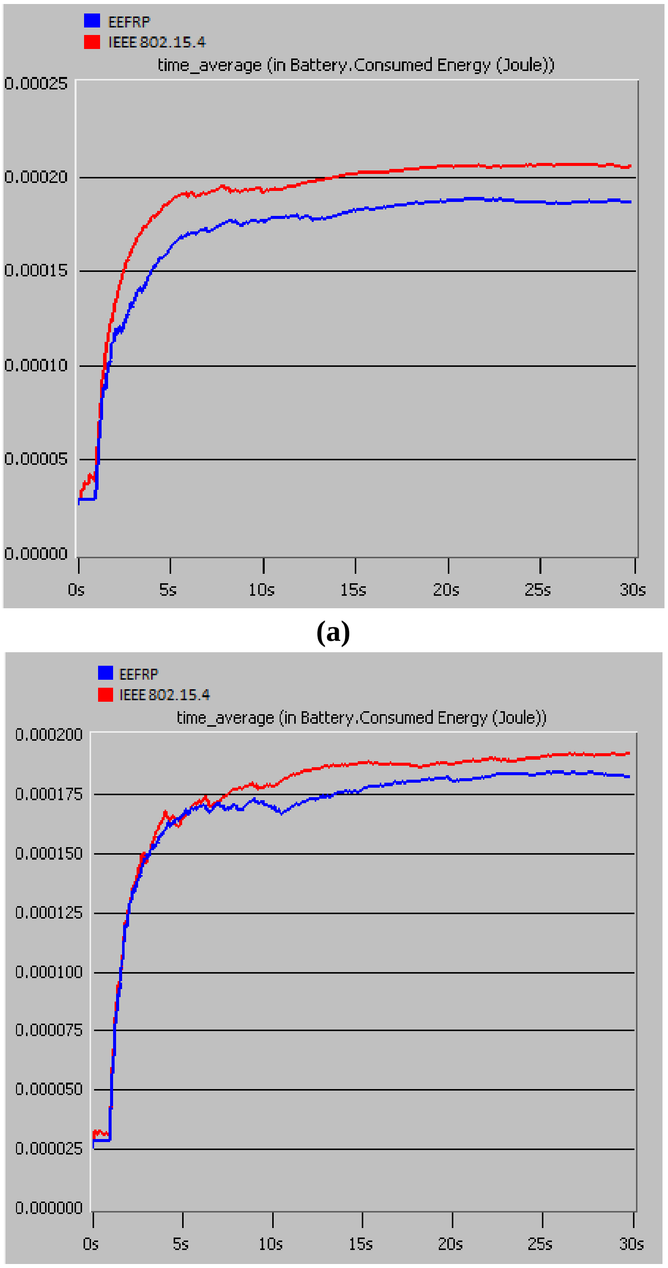


(a)



(b)

Fig. 9. Medium access Delay in different simulation times for 47 sensor nodes. (a) No failure state (b) Failure state.



(a)

(b)

Fig. 10. Energy consumption in different simulation times for 47 sensor nodes. (a) No failure state (b) Failure state.

indicates that EEFRP performed better than IEEE 802.15.4.

Fig. 10 (a) and (b) depict the comparison of the consumed energy rate of EEFRP and IEEE 802.15.4 protocols for different simulation times. The IEEE 802.15.4 protocol in Fig. 15 can be explained by the fact that the number of dropped packets was larger for the IEEE 802.15.4 protocol than for the EEFRP protocol. In the EEFRP protocol, if the link was suitable, a given node was able to successfully transmit data to it and decrease the energy consumption rate.

4. CONCLUSIONS

In this paper, we proposed a new fuzzy logic-based routing protocol called EEFRP for WSNs. The EEFRP protocol employs the fuzzy logic strategy to select a stable route to enhance system performance. For this reason, two parameters are used in EEFRP to calculate the link stability of the feasible path: residual energy, and hop count of sensor nodes. The selection mechanism for choosing the appropriate route in this protocol is based on the fuzzy logic-based of each feasible path. Both IEEE 802.15.4 and EEFRP protocols were implemented in the OPNET and their evaluation was accomplished based on important metrics, including success probability of sink, end to end delay, medium access delay, and energy consumption rate. Simulation results indicated that the EEFRP outperformed the IEEE 802.15.4 protocol considering all the above-mentioned metrics. These results showed that the fuzzy logic strategy could learn to make efficient routing decisions owing to granting mechanism.

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