Routing Optimization of Satellite Wireless Sensor Networks based on Fuzzy logic and Markov chain

Omid Abolghasemi[1], Mahdi Nasiri Sarvi[2]
dept. satellite engineering
Faculty of New Technologies
Iran University of science and technology
Tehran, Iran

Abstract
In this paper, we propose a routing optimization method for satellite wireless sensor networks that utilizes both fuzzy logic and Markov chain models. Wireless sensor networks are collections of distributed sensors that are used to monitor various physical or environmental conditions, such as temperature, vibration, pressure, and sound. These networks offer advantages in terms of quick configuration and low cost, but also require careful investigation and appropriate solutions for multi-step routing.
To address this challenge, we first model the routing process using Markov chain models, which have been previously studied in literature. We then use a fuzzy algorithm to determine optimal routing based on the state matrix, which takes into account key variables that affect the stability and efficiency of the system.
Our proposed method is aimed at improving the performance of satellite wireless sensor networks by using a combination of both Markov chain models and fuzzy logic. We anticipate that this approach will lead to more efficient and stable routing in these types of networks.
Keywords: *WSN – Optimization – Sensors - Routing - Fuzzy Algorithm – Markov Chain*

1. Introduction

Wireless information transmission, particularly in the context of wireless sensor networks, is a rapidly growing field due to the emergence of new technologies and solutions. In a sensor network, the primary node collects information from the surrounding environment and, based on the network structure and topology used, delivers it to the end-user and decision maker.

Routing algorithms play a crucial role in sensor networks as the main parameters of the network are determined by the selection of these algorithms. Various studies have been conducted in this field, including the storage of the geographic location information of side nodes (geographic routing) which is efficient in terms of time and power consumption. However, geographical routing also has its disadvantages, such as the "hot route" phenomenon, where a path becomes unbalanced compared to other nodes in the network, leading to increased data traffic and power consumption, ultimately reducing the lifetime of the network.

Another method used in sensor network routing is the flooding method, which is simple to implement but less efficient due to the high repetition of information in the network.

In recent years, reinforcement learning algorithms have been developed, such as the Q-Learning algorithm, which calculates the optimal strategy using Q tables, and the DQN algorithm, which is a combination of the Q algorithm with neural networks.

In this article, we propose the use of Markov chain models and Gray modeling, which are mature theories, in combination with the particle swarm algorithm to optimally calculate the optimal bleaching coefficient to be used in routing and scheduling of nodes.

In comparison to other methods, our proposed method is shown to provide more suitable coverage and longer network lifetime. We also compare our method to the PEGASIS and LEACH methods, and demonstrate its superiority in terms of power consumption and longevity.

In the following sections, we will discuss the key technologies of the sensor network, optimization using the Markov and Gray chain models, their tests and analysis, and provide a general summary.

Wireless sensor networks often face common challenges such as power consumption and bandwidth. Other challenges include coverage, scalability, data confidentiality, and mobility.

The application of sensor networks in harsh environments with varying environmental and climatic conditions requires physical capabilities for better maintenance and operability. Additionally, due to limited bandwidth, special attention must be paid to the bandwidth used to implement such networks in a cost-effective and justifiable manner.

In Figure 1, we show the general architecture of a wireless sensor network based on satellite interfaces, where each node of the satellite interface can send information from a large number of sensors to the satellite using two conventional methods: leasing a dedicated line and SBD. The sensor information is then collected on the Internet and stored in relevant databases for display and decision making.

1.PhD Student, omid_abolghasemi@nt.iust.ac.ir
2.Assistant Professor, mnasiri@iust.ac.ir

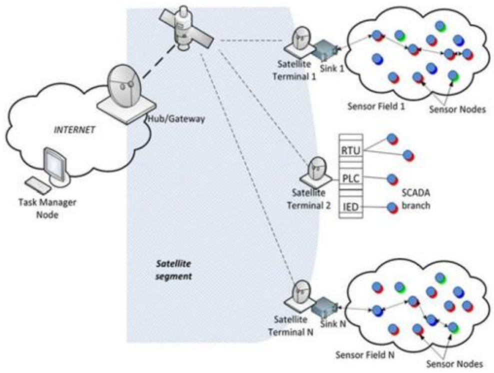


Figure 1: Satellite-based IoT Architecture [10]

2. Preliminaries

2.1. Wireless Sensor Networks

Wireless sensor networks consist of a set of randomly scattered sensors in a target area that are responsible for collecting information and relaying it to the information collection center for the purpose of monitoring and controlling the target object. The data collection module regularly collects data from target objects at specific time intervals. An analog-to-digital unit is used in all sampler modules to convert the measured parameters into numerical values. The function of these networks includes collecting, storing, and sending data.

In large sensor networks with a high number of nodes, various types of nodes such as network management nodes, main stations, and server nodes are used to ensure correct load distribution and improve reliability, coverage, and the performance duration.

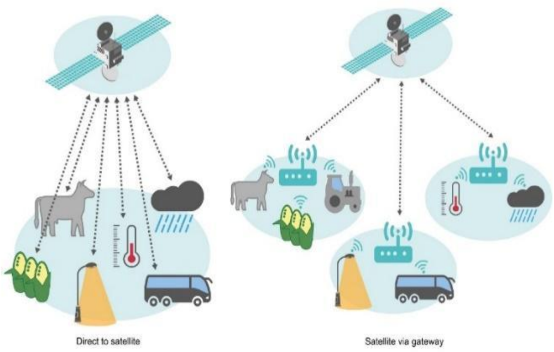


Figure 2: Two Types of Satellite-based IoT [4]

In most wireless sensor network scenarios, common challenges such as power consumption and bandwidth are faced. Other addressable challenges include coverage, scalability, data confidentiality, and mobility.

2.2. Wireless Sensor Network Architecture

The wireless sensor network architecture is composed of a set of randomly scattered sensors in a target area that collect information and relay it to the information collection center for the purpose of monitoring and controlling the target object. In large sensor networks with a high number of nodes, various types of nodes such as network management nodes, main stations, and server nodes are used to ensure correct load distribution and improve reliability, coverage, and the performance duration.

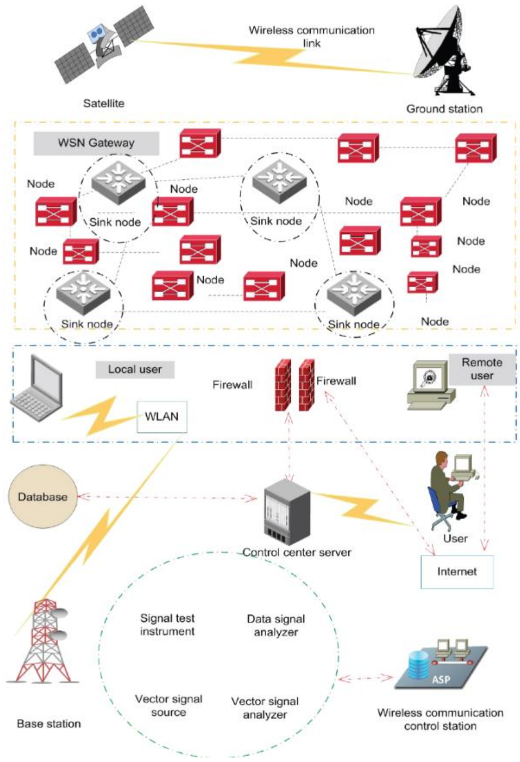


Figure 3: WSN Architecture [1]

The layered structure of the wireless sensor network is similar to the 5-layered structure of computer networks. The purpose of defining the wireless sensor network is to find the main nodes and possible communication paths between the sensors and the main station. In a flat sensor network, all the nodes have the same specifications, which makes it simple but lacks a central node. In a hierarchical sensor network, there are different types of nodes, each of which accepts different tasks from information collection to transmission and storage and a combination of them. These networks are more complex, but they provide the possibility of optimization and more suitable load distribution.

2.3. Main Challenges

The main challenges in wireless sensor networks include power consumption and bandwidth, as well as coverage, scalability, data confidentiality, and mobility. Figure 3 illustrates some of the issues related to satellite-based sensor networks.

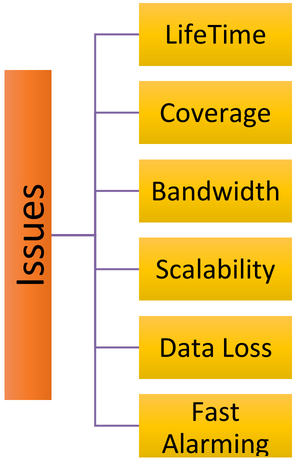


Figure 3. Issues related to Satellite-based Sensor Network

3. Proposed Methods

In this section, we will review the methods presented and propose a new routing method using a fuzzy algorithm.

2.1. A. Markov Chain Model

The Markov Chain model is a method used for the evaluation and description of a random sequence model. In this model, each state is only dependent on its previous state. The prediction of the Markov Chain model is done by calculating the transition probability between system states. This model has high prediction accuracy for data series with higher volatility. However, the Markov Chain model mainly predicts problems with a stable stochastic process, whereas most real-world forecasting problems are non-stationary processes (with a certain changing trend over time).

B. Gray Model

One of the time series estimation methods is the Gray model. Gray system modeling is a way to reduce information uncertainty by extracting and collecting primary data and then performing mathematical modeling on that basis.

The GM(1,1) method is one of the main types of this method, where a cumulative series is made from the initial series and then a linear formula is derived in terms of the cumulative series and its derivative. However, the accuracy decreases significantly as we move away from the origin and if the data is fluctuating, the error will be large.

C. Fuzzy Logic

Fuzzy logic is a method that expands the concept of set theory, where an element is either a member of the set or not. Fuzzy logic proposes the concept of graded membership, where an element can be a member of a set to some extent, not completely.

The structure of fuzzy logic systems is simple and understandable, it is widely used in commercial and laboratory scales today. It can also be used for better and more effective control of machines and cost savings. However, one of the disadvantages of fuzzy logic systems is that the decision-making process is based on established rules, and if these rules have defects or problems, the results may not be acceptable. Choosing the membership function and basic rules is one of the most difficult parts of creating fuzzy systems. Additionally, the implementation of fuzzy logic in common hardware requires numerous and time-consuming tests.

D. Fuzzy Parameters

The table below specifies the status of the entries.

TABLE I. FIS input values

Parameter Name	Range	Type
Node Battery Voltage	3.2-4.6	Volts
RSSI	30- , 80-	dBm
Nodes Count	0 ,1, 2, 3, 4, 5,...	Int

In the proposed method, fuzzy logic is used to optimize routing in a wireless sensor network using satellite interfaces. The input values for the fuzzy inference system (FIS) include the node battery voltage (Volts), the Received Signal Strength Indicator (RSSI) in dBm, and the number of nodes in the network (Int). The output range for the FIS is a probability value for the Figure of Merit (FoM) between 0 and 1. Rules are established for input and output communication based on these fuzzy parameters to make optimal routing decisions.

The following table is also considered for output.

TABLE I. FIS output range

Parameter Name	Range	Type
FoM	[0,1]	Probability

Then rules are established for input and output communication. These laws are entered in a logical way and there is the ability to give weight to each law, which is used in the case of assigning an importance coefficient to each law.

E. Fuzzy Routing Algorithm

The proposed routing algorithm combines the use of Markov Chain and Gray models to model the system and predict future states, and fuzzy logic to make optimal routing decisions based on the predicted states. The algorithm uses the state matrix, determined by the main variables that affect the stability and efficiency of the system, to select the next node in the routing path. The algorithm is then tested and compared to other methods, such as PEGASIS and LEACH, to evaluate its performance in terms of power consumption and longevity.

In conclusion, the proposed method of using a combination of Markov Chain, Gray models and fuzzy logic for routing optimization in wireless sensor networks based on satellite interfaces can improve the accuracy of predictions and make more effective and efficient routing decisions.

4. SIMULATION

In this section, we will simulate the Markov model and analyze it, and then we will simulate the fuzzy model for our problem.

4.1. Markov Model Simulation

4.1.1. Scheduling nodes based on optimization with particle swarm method

According to the graph of the coverage coefficient based on the number of nodes, the plan provided for sending information has more suitable coverage than random selection methods and the shortest distance.
Due to the displacement of nodes, the path can sometimes be longer, which is shown as high-amplitude changes in the diagram.

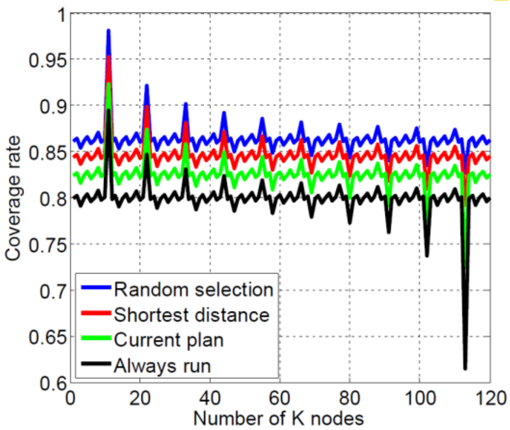


Figure 3. Practical results of rate based on node scheduling[1]

4.1.2. Optimizing the routing protocol

In this experiment to check the convergence of the algorithm, 120 nodes were deployed in the entire monitoring area. The Q value of the source node is empirically analyzed after sending data packets to the node located at (700, 700).
As it is clear in the diagram, with the increase in the number of sent packets, the network becomes more balanced with the improvement of Q, which is due to the fact that the network components know more about the optimal routes, and it shows the convergence of the algorithm in the high number of transmissions.

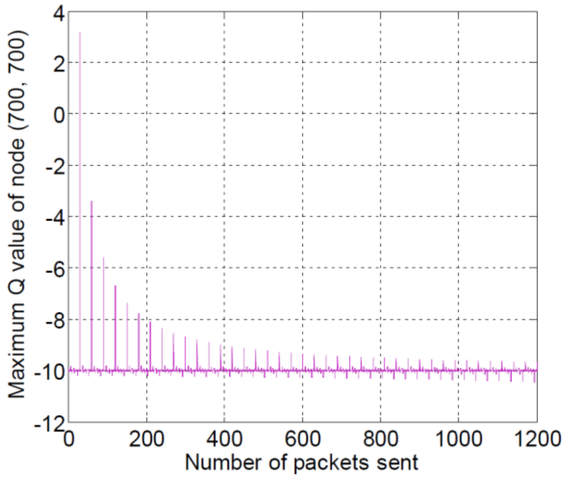


Figure 4. Q changes for Node 700,700[1]

When a node runs out of energy and communication is not possible, the network cannot fully monitor the entire area. Here, the network life cycle is defined as the time from the completion of the network deployment to the failure of the first node. We compare the life cycle when deploying 1 to 120 nodes in the entire monitoring area.
The failure time of the first node, which is the bottleneck of our problem, is very important to achieve a higher lifespan.

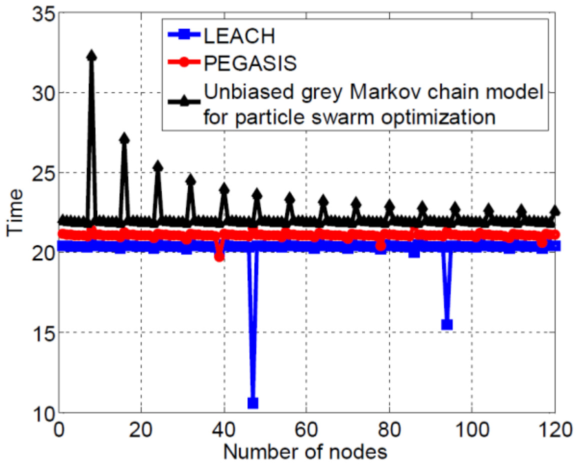


Figure 5. Comparison of the shutdown time of the first node with different routing methods[1]

In the diagram below, the changes in the remaining energy of the nodes after n transmission periods are shown, which indicates the reduction of energy consumption in the presented routing method compared to other common methods. The frequencies are due to the fact that the selected path is not necessarily the best path, and with the increase of the remaining energy round, it may have periodicity.

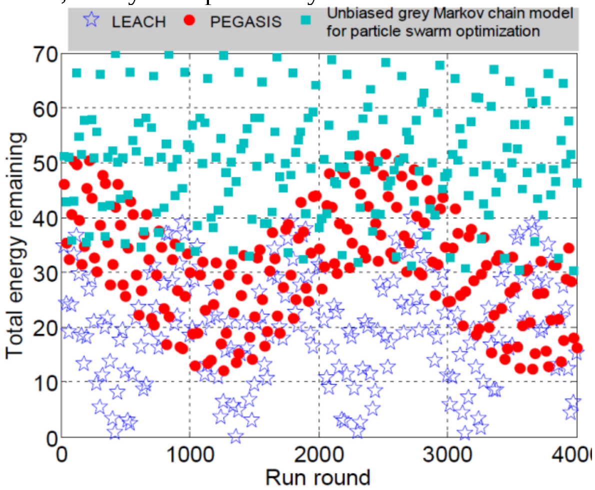


Figure 6. Comparing the remaining energy in the network with changes in execution times[1]

The number of packets exchanged in the network during its lifetime means that the network is balanced. As can be seen in the diagram below, the presented model sends more packets during its operation, which indicates the proper distribution of power consumption on the network nodes.

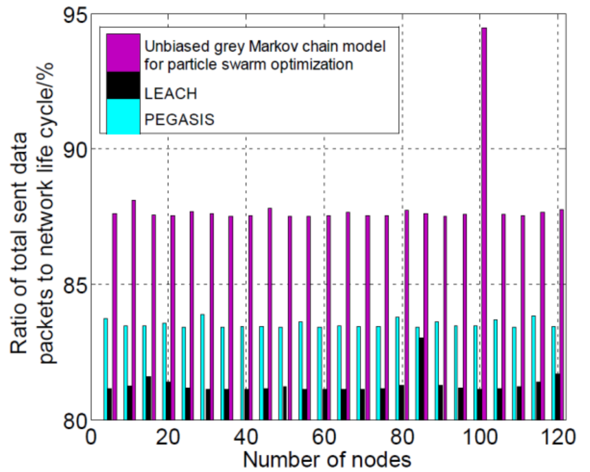


Figure 7. Comparison of network survival balance with different routing methods[1]

4.2. Fuzzy Logic Simulation

The solution used to implement this problem is the use of MATLAB software toolboxes. fis is one of the most widely used MATLAB toolboxes for fuzzy implementation of a function. In this toolbox, using the Mamdani algorithm, which is derived from fuzzy logic, the inputs are separated using the rules proposed by the user, and based on these rules, the results are given in the output. Inputs and outputs also take the desired statistical distributions of the user.

For simulation, the desired values are entered based on Figure8. These values are, respectively, the number of nodes connected to the next node, which takes values from 0 to 5, the battery of the next node, which, considering one of the nodes as the next node, must be in the range of 3.6 to 4 volts to show a good result and The strength of the next node signal, which for Wi-Fi signals is usually between -80 and -30 dBm. To select the best cluster, scoring between zero and one is considered.

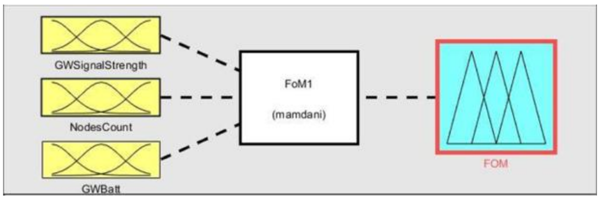
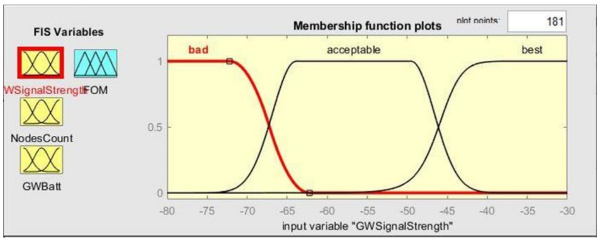
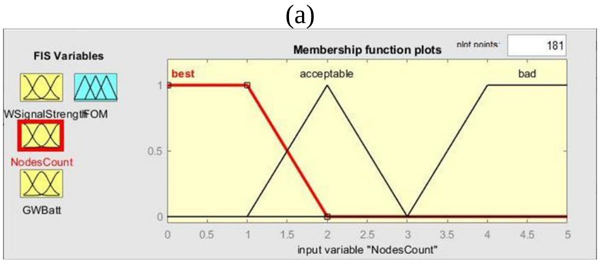


Figure 8. Fuzzy logic tool environment in MATLAB

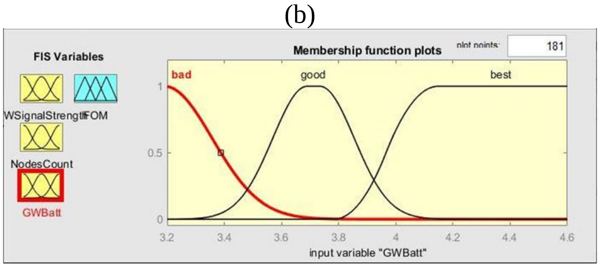
According to the figure, three inputs are given to the Mamdani algorithm and the Figure of Merit (FoM) output is output from it. Each of these entries are entered based on the following figures.



(a)



(b)



(c)

Figure 9. setting the amount of variables related to (a) gateway signal intensity (b) number of nodes connected to the gateway (c) gateway battery in the FIS environment

The output is Gaussian and takes values from 0 to 1.

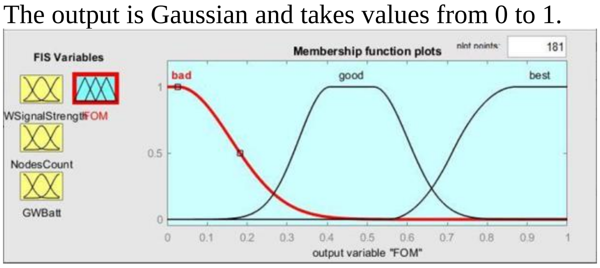


Figure 10. setting variable values related to FoM output in the range [0,1]

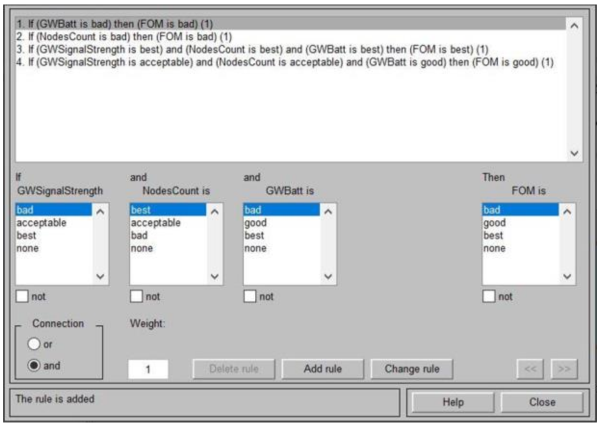


Figure 11. established rules for fuzzy logic

To check the changes in the input values, you can use the features of this toolbox and change the input values as desired so that its effects on the output can be seen. For example, in figure 10, the received signal intensity is -40 dBm, the number of nodes connected to the next node is 1, the battery level is 3.8 volts, and the value of 0.61 of 1 is given to FoM at the output.

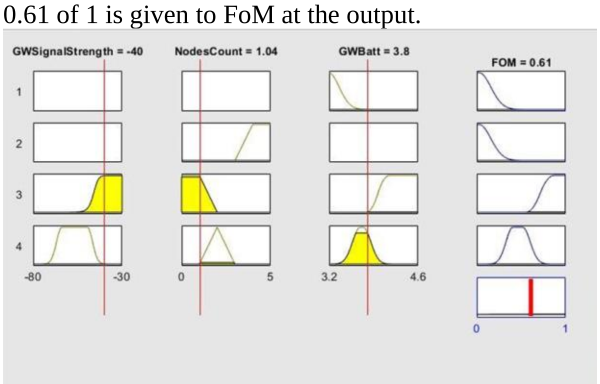
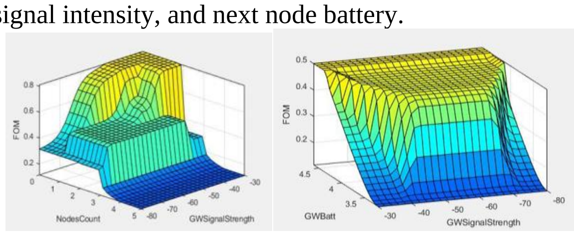


Figure 11. two-dimensional graph of FoM changes for each input change

To draw graphs related to the given values, two graphs have been drawn for FoM, respectively, in terms of signal intensity and the number of connected nodes, signal intensity, and next node battery.



(a) (b)

Figure 12. FoM diagram according to (a) number of connected nodes and gateway signal strength (b) gateway battery voltage and gateway signal strength

5. Conclusion

In this article, the aim is to investigate the modeling method to be used for modeling and routing of a wireless sensor network in natural environments and to present a new routing proposal based on the fuzzy algorithm.

One of the main differences between the fuzzy method is the use of different parameters of the nodes in the network, such as the amount of remaining power, the number of connected nodes, and the level of the connection signal to the neighboring nodes, which adds a little complexity to the structure of the packets, but in return, achieving a protocol It guarantees reliable routing with proper load distribution on all network nodes. The use of fuzzy logic according to the attitude of the problem has recently been proposed in many applications. For simulation, the MATLAB fuzzy tool that uses the Mamdani algorithm has been used, and with the rules entered into this algorithm, the node could decide which middle node to connect to and communicate with the satellite through it. This problem decided to communicate with the satellite to be accompanied by the least error.

In fact, using our method, we use the best possible node at any moment to transfer information to the next node, the advantages of this method are the instant and frequent calculation of FoM parameters to update the conditions of the surrounding nodes. This advantage makes it possible to make more appropriate decisions about moving to the next node when the nodes are mobile and the position of the nodes in the network changes regularly.

6. References

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