Energy sink-holes avoidance method based on fuzzy system in wireless sensor networks

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ABSTRACT

The existence of a mobile sink for gathering data significantly extends wireless sensor networks (WSNs) lifetime. In recent years, a variety of efficient rendezvous points-based sink mobility approaches has been proposed for avoiding the energy sink-holes problem nearby the sink, diminishing buffer overflow of sensors, and reducing the data latency. Nevertheless, lots of research has been carried out to sort out the energy holes problem using controllable-based sink mobility methods. However, further developments can be demonstrated and achieved on such type of mobility management system. In this paper, a well-rounded strategy involving an energy-efficient routing protocol along with a controllable-based sink mobility method is proposed to extirpate the energy sink-holes problem. This paper fused the fuzzy A-star as a routing protocol for mitigating the energy consumption during data forwarding along with a novel sink mobility method which adopted a grid partitioning system and fuzzy system that takes account of the average residual energy, sensors density, average traffic load, and sources angles to detect the optimal next location of the mobile sink. By utilizing diverse performance metrics, the empirical analysis of our proposed work showed an outstanding result as compared with fuzzy A-star protocol in the case of a static sink.

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1. INTRODUCTION

Wireless sensor networks (WSNs) are large-scale Ad hoc networks that consist of tiny, inexpensive, and battery-powered devices which densely distributed in the field for sensing the desired physical properties, aggregating data, and transferring it wirelessly to a center of data collector known as the base station (or sink) [1]. WSNs have widespread applications in different fields such as natural disaster prediction, military monitoring systems, healthcare systems, and so on [2].

In WSNs, extend the network lifetime has revolutionized the state of the art because data throughputs are very low in a wireless model of communications, and in most cases, thousands of limited battery-powered sensor nodes are distributed randomly in hazardous unreachable environments; thus it is difficult to replace or recharge batteries of the dead sensors [3]. Sensors in the field execute several energy consumption processes like sensing, data aggregation, packet transmission, and packet receiving [4]. Data aggregation is performed by certain data mining algorithms to refine the data by reducing the redundant data, merge some data, and get rid of frequent data [5]. The sensed information is transmitted from sensors to the sink either by direct-link (single-hop) transmission pattern or indirect-link (multi-hop) transmission pattern.

The concept “distance” plays a vital role when it comes to energy consumption issues where the quantity of energy depleted by the source sensor node increases super-linearly with the distance between the source and destination [6]. In single-hop transmission techniques, the further away sensor from a sink, the faster it drains energy. Therefore, the sensor nodes that are situated away from the stationary sink will die rapidly. In multi-hop transmission techniques, sensor nodes collaborate to forward the data packets to the stationary sink which implies that sensors near the sink take charge of forwarding the data from all over the network to the sink thus deplete their energy quickly due to enormous traffic overhead near the sink [7]. This problem was called the “energy sink-hole problem” [8], or “bottleneck problem” as in [1]. As a result of this nonhomogeneous energy consumption, if the quick death of those high overloaded relay sensors has occurred, the sink will not be able to collect any data although a tremendous number of away sensors still retain an abundant amount of energy [9]. To address the nonhomogeneous energy consumption problem, energy-efficient routing protocols and sink mobility have been targeted by researchers. Several studies [10]-[15] are some great clusters-based and flat energy-efficient routing protocols that have been developed to spread energy consumption among sensors with diverse spatial locations. Even though such protocols overcome many routing challenges such as traffic load reduction, uniform energy consumption, fault tolerance, and a minimum number of intermediate hops, the energy sink-hole problem still takes place.

On the other hand, due to the role-reversal of overloaded relay sensors, a remarkable improvement in terms of energy hole elimination has been achieved by using a mobile sink (MS) [16]. As the main objectives behind utilizing MS are gathering sensed data and overcoming the energy holes; thus, these two goals must be effectively and strictly attained by considering two constraints. The first is the data latency caused by a sensor's buffer overflow which should be as low as reasonably achievable [17]. The other factor is the reduction of energy consumed by sensors during receiving the broadcasted messages of the sink's repetitive positions. Such constraints can be defeated by detecting a thoughtful number of movements and extracting the optimal traveling distances that don’t significantly impact the network topology. To earn such goals, one category of movement behaviors is that MS comes close to every sensor node to capture its data. In large-scale sensing areas, such behavior significantly increases the data latency and overflows the sensor's data queue due to a very long traveling distance until returning to any sensor in the next tour. In general, it’s still a good moving behavior in small-scale areas [9]. The other category accurately determines a specific number of sensors called “anchors” which take on the mission of collecting data from their neighbors and deliver to MS once MS arrives next to them. The detection of anchors and construction of the shortest MS path has been considered as an np-hard problem that leads to balancing energy consumption, eradication of bottleneck problem, and reduction of end-to-end delay thus extending network lifetime [18]. Nevertheless, unlike in the case of heterogeneous WSNs, the processes of periodically selecting anchors and constructing an optimal path for MS result in high energy consumption by anchors and high data latency in the case of homogenous WSNs with limited specifications.

In this paper, we proposed a sink mobility method based on a fuzzy system and fuzzy A-star routing protocol to extend the lifetime of flat architecture WSNs. Firstly, we took advantage of the fuzzy A-star protocol proposed in [12] which performs well in terms of balancing the usage of the possible routes to the sink. Regarding the MS matter, we deal with the whole geographical area by partitioning it up into a grid-like shape based on sensors transmission range (TR) to specify and enclose the overloaded relay sensor nodes near the sink which helps the MS to make a movement decision. Lastly, based on specific parameters, MS leaves the current high traffic grid and heads to the optimal nearby grid. Thus, concealing the energy holes near the sink and distributing the energy consumption equally during the routing are the overall goals of our work.

The remainder of this paper is constructed as follows. A review of sink mobility-related works has been discussed in section 2. In section 3, the proposed work is explained. Section 4 contains the simulation and performance results. Finally, the conclusion of this paper is discussed in section 5.

2. RELATED WORKS

Using MS is a perfect tactic to enhance the lifetime in WSNs Specifically to hide the energy holes near the sink [19], [20]. Sink mobility management is a major challenge in mobile ad hoc networks due to dynamic repeated changes in network communications topologies [21]. Accordingly, continuous topological modifications may affect the multi-hop data transmission capabilities to the ideal state (or the contrary). Furthermore, mobility over a long distance inevitably raises the data latency leading to attrition of sensors resources and reduces the real-time application’s performance that makes MS route construction is a paramount subject [22]. Although the mobility patterns have been improved and classified into different categories such as random mobility, rendezvous point-based mobility, and controlled mobility [23], It is some inquiries that should be accurately achieved to get an effective mobility pattern such as when should MS decide to leave its current position? where should MS head to? and how should it move? as a result, the sink mobility issue has caught the interest of researchers last few years. The forthcoming paragraphs discuses some works regarding such matter.

Basagni *et al.* [24] provide one of the earliest mobile sink strategies by utilizing a mixed-integer linear programming model for optimizing the lifetime of WSNs by constructing a sink route path. They deeply discussed and introduced three constraints for sink mobility which were the sojourn time for MS residence at each sojourn point, the maximum distance that MS can travel from one sojourn point to another, and the cost of constructing a new route path. Then, they proposed a distributed and localized algorithm called greedy maximum residual energy (GMRE) for selecting the areas with high residual energy to be the next MS position. Motivated therefrom, Somasundara *et al.* [25] described this theme in the context of buffers by attempting to solve the (mobile element scheduling problem), thereby constructing a path through which MS trying to reach the nearly-overloaded sensors before their buffers overflow. They showed that this problem is an NP-hard with integer linear programming in formularization but unlike (TSP) problem there may be multiple visits for the same sensor during the same route. Although this approach is very effective in small sensor populations, it fails in large ones due to high computations. Substantial progress has been made by [26] as they express MS issues with the use of partitioning systems. They suggested partitioning the geographical area in the form of hexagons. After that, they discussed the sink movement in two cases, when the sink moves in Hexagon's corners, and when it moves in multiple sites on the hexagon's perimeter. As a result, they proposed a distributed and localized algorithm to discover the best energy-rich sites to be targeted by multiple MS. They showed a great energy consumption enhancement. However, this approach is computationally complex and from an economic perspective using multiple mobile sinks in each hexagon is still costly.

Evolutionary and swarm optimization algorithms also had their share of attention. Genetic algorithm (GA) was forwarded to the march of mobility. GA, proposed by [27], constructs an MS path by determining the optimum number of rendezvous sensors (RP) based on three parameters which were a minimum number of transmission nodes that are tow-hops away from RP, sink's minimum traveling distance, and traffic load in rendezvous sensors. Lu et al. [28] enhanced the artificial bee colony algorithm (ABC) by accelerating the convergence using cumulative factor and global search enhancement using a mutation operator. The authors formulated a problem based on the fact that the minimization of hops between sensor nodes and their RPs will enhance the total energy consumption in the network. By using the improved ABC for optimizing the route path of the mobile sink, they showed a great enhancement in energy efficiency and data collection in real-time performance. A well-developed and integrated system has been proposed by [29], which utilized an adaptive neuro-fuzzy system (ANFS) for cluster-head selection, and the emperor penguin optimizer (EPO) to construct a strategy to design an efficient trajectory for MS that aims to find a minimum number of RPs. They showed a great result. However, using an optimization algorithm along with an ANFS is computationally complex in large-scale areas. A shift toward the use of machine learning classification algorithms was presented in [17] as the authors proposed a new protocol for MS route planning called density-aware and energy-limited path construction algorithm for data collection (DEDC) to enhance the network lifetime. DEDC was based on two stages. At the first stage, the area was partitioned into equal size grids to construct a primary snake-like path for the mobile sink. At the second stage, by using the hierarchical clustering technique to classify grids into balanced and unbalanced grids, the path was adjusted on both types of grids using an independent approach for each. This proposition almost shows an ideal enhancement in terms of energy efficiency.

From the above works, we have been concluded that the optimal sink mobility method must be characterized by fitting well with the physical specifications of the sensors, having a moderate traveling distance, providing reasonable computation complexity, and performing well in large-scale geographical areas. Moreover, the importance and the necessity of using a mobile sink in multi-hop transmission networks grow as the transmission range of sensors decreases. To overcome the bottleneck problem near the sink with the reduction of data latency as much as possible, we proposed an integrated routing scheme comprised of merging two methods which are a mobility method for MS along with multi-hop transmission technique. This combination will result in enhancing WSN's lifetime significantly.

3. PROPOSED WORK

WSN should be clearly described for implementing the proposed work effectively. We assumed a WSN having homogeneous stationary sensors limited in terms of transmission range, energy, and buffer size are randomly deployed in a regular size topographical area along with a single energy-unlimited MS aware of its location and moving within a certain range for collecting data from nearby sensors. All stationary sensors are aware of their location coordinates by using a positioning system. Sensors are also aware of MS position and can transmit their data using a multi-hop transmission pattern. This network uses a medium access control based on time division (TDMA). The following describes the network model.

3.1. Grid formulation model

As shown in Figure 1, MS is positioned in the monitoring area. The whole topographical area is virtually partitioned by MS into equal size square-shaped grids. Initially, MS locates itself at the center of any grid. Let l be a grid side length which can be calculated using (1). For better grid formulation, we considered that the transmission range of sensors (TR) has a relationship with l that is if TR of sensors were too low, then l should be higher than the transmission range. Conversely, the higher TR, the more equal l will be to TR.

$$l \geq TR \quad (1)$$

Where TR represents the transmission range of the deployed sensors. Equation (1) has been formulated based on the MS position which is at the center of any grid. Consequently, the majority of overloaded sensors that suffer from rapid energy depletion are those situated at the current sink's grid. Those sensors are said to be critical in terms of traffic load, energy consumption, and computations. Since MS must move restrictedly over a short distance to overcome the problem of data latency and high topological changes; thus, the determination and restriction of those overloaded sensors help the sink to stay away from them in the next move. It also helps the sink to evaluate the energy status at the current grid as we discussed in the next part.

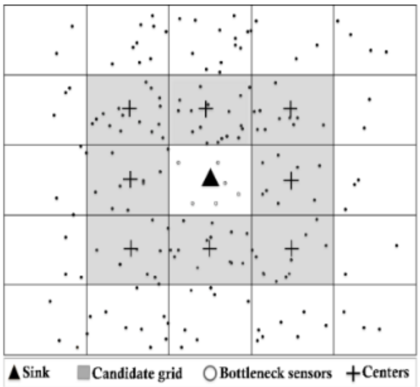

Figure 1. Network model

3.2. Multi-hop routing model

In this proposition, the fuzzy-A-star routing protocol (FA*), which is proposed in [12], is used as an energy-efficient routing protocol due to its low complexity and outstanding performance. The fuzzy approach and A* heuristic is combined to choose the optimal path from source to destination based on three decision parameters that represent the status at the source's neighbors. Those parameters are the residual energy, traffic load, and distance to sink. The more energy, the more sensors participate in forwarding data by acting as an intermediate sensor. On the other hand, the traffic load is considered to prevent the selection of candidate intermediate sensors that suffering buffer overflow. The minimum number of hops is taking into account to reduce the end-to-end delay by performing minimization on the distance between the candidate intermediate sensor and the sink. This protocol aims to maximize the evaluation function of the candidate intermediate sensors represented by (2).

$$f(n) = NC(n) + (\frac{1}{MH(n)}) \quad (2)$$

Where n is the source's candidate neighbor; $NC(n)$ represents the source's candidate neighbor cost which can be calculated using a fuzzy approach; $MH(n)$ is the distance from the candidate neighbor to the sink. The source sensor sends a broadcast message to get the parameters from all neighbors. After evaluating each neighbor, the source sensor sends its packet to the best one. This process goes on until the packet reaches the sink via one of the overloaded sensor nodes which have direct communication to the sink and are situated in the sink's current grid. Two advantages have been taken by using this routing method. First, we determine the location of overloaded sensors nearby MS. Second, we were able to balance the energy consumption by using this routing method.

3.3. Sink mobility model

The mobility of the sink in this proposition is based on controllability where MS has the control of mobility based on specific parameters belonging to the current grid and nearby grids. As previously declared, initially, the sink is located at the center of any grid. At each transmission round r, the sink executes an evaluation process at its current grid to see the situation inside. This evaluation process is based on the average residual energy $\overline{RE}_{BT}$ of the most overloaded sensors inside that grid; we called those sensors bottleneck sensors (BT). Here, BT sensors that are involved in such evaluation process are those which can communicate directly with the sink (one-hop away), in other words, the distance from those sensors to the sink is less than or equal to TR, $dis(sensor, sink) \leq TR$. Equation (3) states that if $\overline{RE}_{BT}$ exceed a specific threshold (τ), the sink will move to another nearby grid.

$$\overline{RE}_{BT_r} \leq \tau) \quad (3)$$

$$\tau = \overline{RE}_{initial} * \alpha \quad (4)$$

Where τ represents the mobility threshold that can be calculated using (4); $\overline{RE}_{BT_r}$ is the average residual energy of BT sensors at each transmission round r; $\overline{RE}_{initial}$ is the initial average residual energy of BT sensors at the beginning of MS arrival; α is a percentage value of desired energy threshold which determines the time duration for MS residence at the current grid, α is inversely proportional to the density of deployed sensors. Using (3), the sink continuously tests $\overline{RE}_{BT}$ at each transmission round r. if the condition satisfies, then the sink decides to head to the best nearby grid to prevent the occurrence of an energy hole due to high energy depletion in the current grid.

The sink mobility is a very critical movement. As the sink moves, the network topologies will be affected in terms of communications. Furthermore, the traveling distance should be suitable and not cause a major disruption to the network in terms of data latency. Based on this theory, the traveling distance of MS will be either diagonally or parallel to one of the nearby grids. As demonstrated in Figure 1, MS analyzes information about the maximum (8) nearby grids and by using the fuzzy system, MS will be able to evaluate each grid and choosing the optimal next target grid. A fuzzy system, illustrated in Figure 2, is a procedure for solving decision-making problems under incomplete information and uncertainty [30]. The objective of the fuzzy part which is based on the Mamdani model in our proposed sink mobility method is to determine the optimal grid out of a maximum (8) grids which depend on four parameters derived from each nearby grid. These parameters which represent fuzzy inputs variables are:

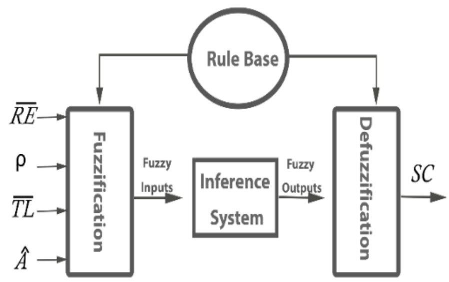

Figure 2. Fuzzy system structure

3.3.1. Average of residual energy ($\overline{RE}$)

In all lifetime enhancement various strategies, the residual energy is the most important factor to be considered in any computational intelligence approach; thus, a grid with more residual energy has the opportunity to be selected as the next target for MS. This feature has nearly 40% importance in the evaluation of rule base system.

3.3.2. Sensor’s density (ρ)

A grid with a high density has a high chance to be selected. A grid area with more dense sensors is supposed to be a high-energy grid. However, this statement is not always correct due to high sensing regions in the environment affect a specific group of sensors in those regions. This feature has nearly 20% importance in rule base system.

3.3.3. Average of traffic load ($\overline{TL}$)

A grid with less average traffic load has a high chance to be selected. Here, the traffic load represents the status in buffers of all sensors in a grid. A grid with a low traffic load has less data latency and low computations. This feature has nearly 20% importance in rule base system.

3.3.4. Source nodes angle ($\hat{A}$)

From the perspective of medium access control, which is TDMA, the source nodes represent a group of nodes situated in a specific region in the geographical area whose time has come to forward their data. As a fuzzy input, it represents how far away is the candidate grid from the center of those sources. The purpose of using this parameter is to reduce the number of transmission hops to achieve more effective data transmission and less energy consumption. The nearer grid to the source nodes the higher chances it has. This feature has nearly 20% importance in rule base system.

Each grid will be evaluated and assign a selection chance (SC) which represents the output of the fuzzy system. In fuzzy rule base, there are (375) rules for covering all possible implications. MS heads to the grid that has the highest SC result from the defuzzification by the center of gravity formula. MS locates itself in the center of that best grid and broadcasting its new location to the entire network. Figure 3 defines the inputs and output of our fuzzy system. Figure 3(a)-(e) shows average residual energy, sensor's density, average traffic load, source nodes angle, and selection chance.

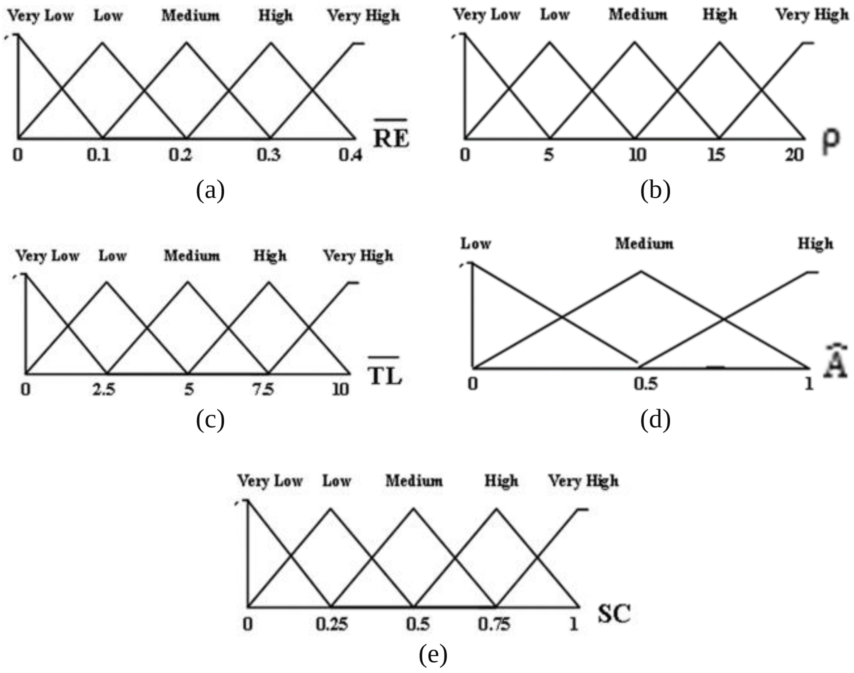

Figure 3. Membership graphs of fuzzy inputs and outputs (a) average residual energy, (b) sensor's density, (c) average traffic load, (d) source nodes angle, and (e) selection chance

4. PERFORMANCE EVALUATION

The performance of our proposed sink mobility method in homogeneous WSNs was evaluated by comparing it with the fuzzy A-star routing protocol in the case of utilizing a static sink.

4.1. Simulation setup

We have been considered the average remaining energy of the network, numbers of dead nodes, running times, and the number of transmission hops as comparison factors to show the efficiency of our proposed protocol in terms of uniform energy consumption and extending the network lifetime. For ease of expression, we called our proposed as FASM. Both FASM and (fuzzy-A*) with static sink have been implemented using Python 3.8 by Spyder IDE on the Anaconda environment.

As shown in Table 1, we considered a homogenous network where (200) sensors that have the same features were deployed randomly over a square topographical area with (200x200) dimensions. For FASM preparation, the whole area is portioned into grids. as the TR of sensors is (20 meters), which is a low range considering a (200x200) area, it's better to have a grid size higher than (20 meters. We set the grid side length (l=40) which means that MS travels (vertically/horizontally) about (40 meters) or diagonally with (56.4 meters) to the center of the best grid. Both protocols run out (14,000) transmission rounds. In each round, an equal amount of packets was generated by both. Both were exposed to the same energy consumption model defined in [31].

Table 1. Simulation parameters

Parameter	Value
Region size (meters)	200m x 200m
Node deployment	Randomly
No. of sensors	200
No. of grids	25
Transmission range (meters)	20m
Initial sensor's energy (Joules)	0.4J
A	0.97%
Control packet length (bits)	2kb
No. of transmissions (rounds)	14000
Maximum traffic in sensor's queue	10
E_{elec}	50 nJ/bit
E_{amp}	100 pJ/bit/m2

4.2. Simulation results

The majority of proposed works and literature in the field of "WSNs lifetime enchantment" are focused on the period in which the (first/last) sensor's energy runs out. Figure 4 shows the number of sensors still alive versus the transmission rounds in both protocols. A long period before the first death is the most important feature in WSNs with a long lifetime. The death of the first sensor in our protocol came after a long time than that of other protocols with static sink, besides, after (14,000) rounds, the number of nodes still alive is also larger.

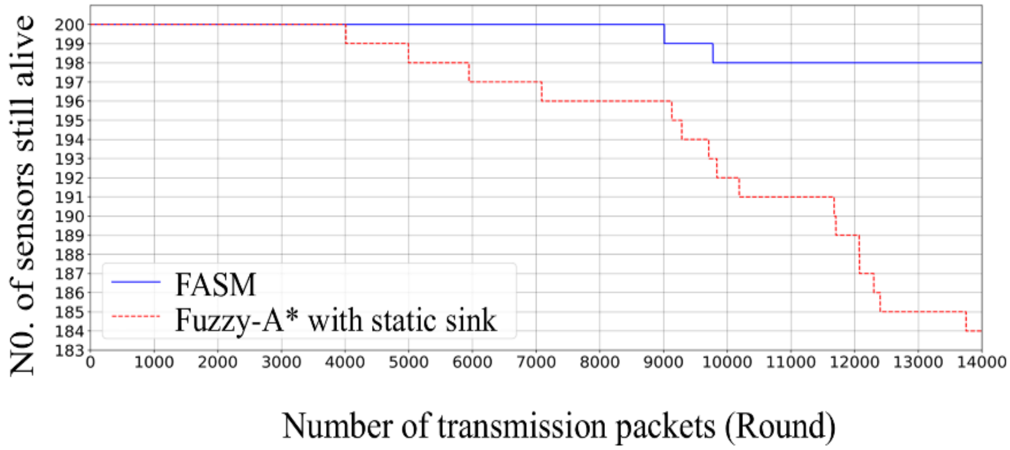

Figure 4. Number of alive nodes in each transmission round

In Figure 5, we showed the ratio of remaining energy which is an important factor that clarifies the energy consumption during each round in the entire network. The approach with the highest ratio has a priority to own a better life due to the existence of an adequate amount of energy that will be able to be used by the network for a long period. It appeared that the highest energy was conserved by the FASM and even it shows a slight difference, this is due to uniformly distributing energy consumption performed by FASM in which only two nodes were lost as shown in Figure 4.

Since less data latency (end-to-end) means more efficient energy usage and more rapid transmission, Figure 6 shows the kernel density estimation histogram of transmission hops number in (14000) transmission rounds. A low (end-to-end) transmission delay was accomplished by FASM as the dense central region of transmission hops is located between (3-7) hops.

Running time is an important factor that shows the computational complexity levels of an approach. FASM executes two approaches, one is for finding the optimal path from source sensors to MS, and the other is for the implementation of fuzzy logic to explore the new target position. As demonstrated in Figure 7, which shows the running time factors, there is a slight advantage for fuzzy A-star with static sink in such factor. However, taking into consideration the huge enhancement of WSN lifetime, the difference between the two protocols makes no high gap.

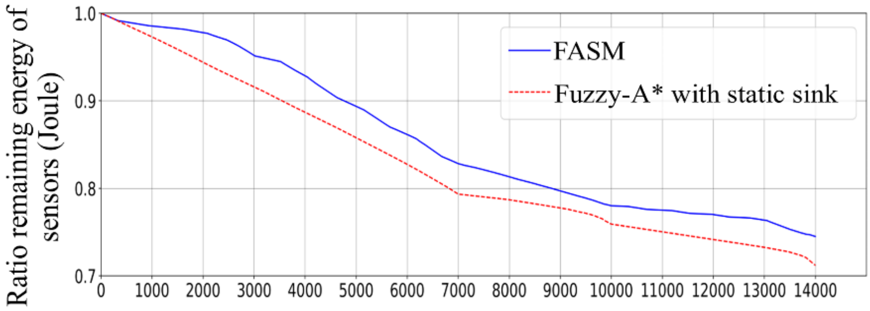

Figure 5. Ratio remaining energy of sensors

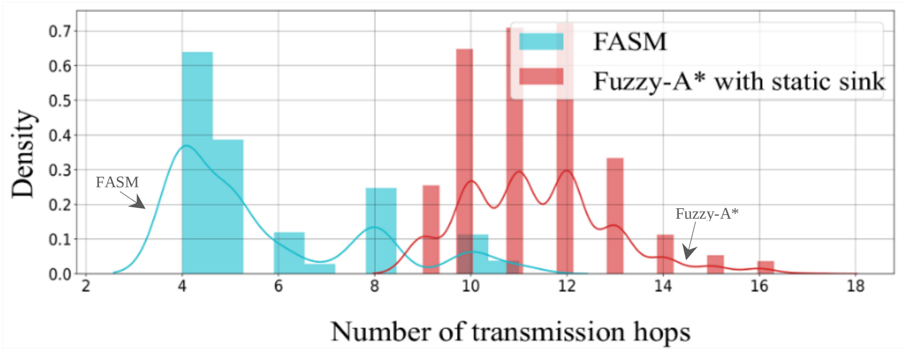

Figure 6. Kernel density histogram of number of transmission hops

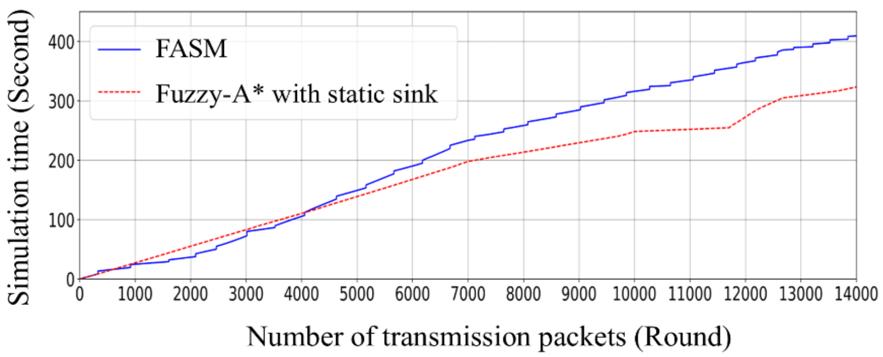

Figure 7. Simulation time in both approaches

5. CONCLUSION

A recent time, there has been much research into multi-hop routing protocols, clustering strategies, and optimal sensors deployment methods that aim to balance the energy usage in WSNs. In many of these researches, a stationary base station was employed as a sink. Thus, the energy of the sensors situated in the vicinity of the sink might be drained quickly leading to a disconnection between faraway energetically active sensors and the sink. A mobile sink can be a very powerful method to eliminate this problem. In this paper, a combination of a previously proposed fuzzy A-star routing protocol and a new grid-based fuzzy logic was proposed as a mobile sink approach. The proposed method, named FASM, initially partitions the area into grids based on the sensor's transmission range. While data is transmitted through fuzzy A-star, the mobile sink continually monitors the energy levels at its current grid every round. If the condition of moving is satisfied, the sink evaluates a maximum of (8) grids on its neighborhood using fuzzy logic, then moves to the center of the optimum grid. A comparison has been shown between this proposed and fuzzy A-star with static sink considering various parameters. The simulations indicated that relative to fuzzy A-star with static sink, the proposed approach achieved an improved efficiency. Shortly, we will try to use an enhanced swarm intelligence algorithm to control the mobile sink behavior.

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