Wireless Pers Commun
DOI 10.1007/s11277-017-4631-3

Fuzzy Logic-Based Sink Selection and Load Balancing in Multi-Sink Wireless Sensor Networks

Mohammad Masdari[1] · Farah Naghiloo[2]

Abstract Using multiple sink nodes in wireless sensor networks can greatly improve the lifetime and throughput of the network. One of the important issues in multi-sink wireless sensor networks is the congestion problem in sink nodes which reduces the effectiveness of data processing in sink nodes and increases the energy consumption of the sensor nodes. To prevent congestion in the sink nodes, in this paper, a distributed fuzzy logic-based sink selection algorithm is presented for one-hop sensor networks which makes each sensor node able to independently select a sink node based on the congestion situations in all the sink nodes. This scheme can effectively prevent congestion in the sink nodes and provide load balancing among them. Moreover, it reduces the delay of successful data transmissions to the sink nodes and improves the lifetime of wireless sensor networks by reducing the number of packet retransmissions. Simulation results indicate the effectiveness of our proposed solution.

Keywords Wireless sensor network · Multiple sink · Load balancing · Fuzzy logic · Congestion · Energy

1 Introduction

Wireless sensor networks or wireless sensor networks consist of many small, inexpensive, sensor nodes that communicate wirelessly. Each sensor node has a limited resource [1] and collaborates with other nodes to perform operations such as environment monitoring or

✉ Mohammad Masdari
M.Masdari@Iaurmia.ac.ir

Farah Naghiloo
F.Naghiloo@urmia.ac.ir

1 Department of Computer Engineering, Urmia Branch, Islamic Azad University, Urmia, Iran

2 Department of Computer Engineering, Urmia University, Urmia, Iran

target tracking etc. [2, 3]. Also, various applications of WSNs are proposed for E-Healthcare systems [4–6]. Limited battery power is one of the main limitations of the wireless sensor networks and almost all schemes and algorithms designed for these networks should consider this limitation [7–13]. When sensor nodes recognize any event in their perimeter they can forward their sensed data to the sink [14]. In this process, based on their distance to the sink and network topology, they may send their data to the sink, directly or through one or more relaying sensor nodes [15]. The sink node can transmit the sensor nodes data to other networks and even to a cloud-based system for further processing [16–19].

Regarding the number of sink nodes in the network, wireless sensor networks can be classified as single sink wireless sensor networks and multi-sink wireless sensor networks [20]. But wireless sensor networks, which utilize one sink node, are prone to hotspot problem near the sink and due to the high node density and converge cast communication pattern [21–23], congestion may happen in the sink node.

Deployment of multiple sinks is a promising solution for wireless sensor networks to alleviate the congestion in the sink nodes and to improve the reliability of wireless sensor network communications [24]. Moreover, extra sink nodes help to mitigate the unbalanced energy consumption among the sensor nodes and improve the lifetime of the network [25]. Furthermore, multi-sink wireless sensor networks provide a higher level of fault tolerance and are able to tolerate the inaccessibility or failures of the sink nodes [26, 27].

Congestion is one of the critical problems in the sensor networks which increases the packet loss rate and the power consumption of network. In the wireless sensor networks, the congestion problem can happen because of irregular deployment of sensor nodes, buffer overflow, transmission channel contentions, transmission rate, dynamic time variation transmission channel and many-to-one data transmission schemes [28]. Generally, congestions can be classified as node-level congestions and link-level congestions. In the node-level congestion, the congestion is created because packet arrival rate is higher than the packet service rate. Also, node-level congestion can happen in the sensor nodes and in the sink nodes, in this paper, focus is on the latter case.

To deal with congestion in the sink nodes, it should be detected and then notified to the sensor nodes somehow. Finally, the congestion should be mitigated by performing appropriate actions in the congestion mitigation phase [29].

Although some robust researches have been conducted for congestion control and load balancing in multi-hop and multi-sink wireless sensor networks, few researches have been performed on these issues in the multi-sink one-hop wireless sensor networks. For example, in [30] Jain et al. present a centralized solution to balance the request load among multiple sink nodes by restructuring the wireless sensor network based on the decisions taken by the sinks themselves. However, this scheme does not prevent congestion in sink nodes and requires network restructuring to be performed by the sink nodes to provide load balancing. Such centralized congestion prevention and load balancing schemes are prone to a single point of failure and incur some overheads to the sink nodes.

To mitigate these problems, in this paper, a distributed fuzzy logic-based sink selection scheme is presented for one-hop wireless sensor networks. This scheme is aimed to prevent congestion in sink nodes and distribute the sensor nodes loads among multiple sink nodes. For this purpose, each sensor uses a fuzzy inference system which receives factors such as distance to the sink node, remaining energy of the sensor node and the average load on each sink node. By using the proposed solution, each node can select the nearest uncongested sink node to transfer its sensed data. The results of the extensive simulations indicate that our proposed fuzzy scheme can mitigate congestion in the sink nodes and is able to balance the sensors loads on the multiple sink nodes. Moreover, it can reduce the energy consumption and delay of data transmissions by reducing the number of retransmissions required for successful packet delivery to the sink nodes.

The remainder of this paper is organized as follows: Sect. 2 discusses the existing congestion control schemes designed for the wireless sensor networks, Sect. 3 illuminates the congestion problem in the wireless sensor networks and Sect. 4 illustrates the proposed fuzzy solution for sink selection. Section 5 presents the simulation results, and finally, Sect. 6 provides the concluding remarks.

2 Related Works

In [31], the authors present a scheme called Multi-Sink Load Balanced Reliable Forwarding or MLBRF, which is a cross-layer geographic multi-hop forwarding scheme to provide reliable and energy efficient video delivery in a multi-sink WNS. To provide load balancing among the sinks, MLBRF provides a fuzzy logic-based sink selection mechanism for frame forwarding which evaluates the traffic density in the direction of each sink node. This scheme uses dynamic criteria such as the number of contenders and the buffer occupancy levels in the neighborhood with the static distance criterion.

An efficient data routing from multiple sources to multiple sink nodes is presented in [32]. This decentralized scheme is based on the periodic adaptation of the message routes to minimize the number of exploited network links.

Also, an adaptive learning solution to load balance multiple sink nodes in the wireless sensor networks is proposed by Cheng et al. [33]. In this scheme, an agent in a mobile anchor node with the directional antenna is applied to partition the network into zones associated with each sink, and the size of the zones is tuned to balance the power consumption based on the remaining energy of the sensor nodes positioned near each sink. In addition, anchor nodes are made adaptable to any traffic pattern and to discover a near-optimal control policy for the movement of the anchor for the minimization of residual energy variance among sinks and prevent the isolation of sinks.

In [34], Sitanayah et al. present two local search algorithms named GRASP-MSP (Greedy Randomized Adaptive Search Procedure-Multiple Sink Placement) and GRASP-MSRP (Greedy Randomized Adaptive Search Procedure-Multiple Sink Relay Placement) for the multiple sink and relay placement problem. GRASP-MSP minimizes the deployment cost while ensuring that each sensor node in the network, which is double-covered, supports two length-constrained paths to the two sink nodes. GRASP-MSRP deploys sinks and relays to minimize the deployment cost and guarantee that all the sensor nodes in the network are double covered and noncritical.

Most of the discussed schemes are designed for congestion control in the multi-hop networks that many intermediary nodes help the sensor nodes to forward their sensed data to the sink nodes. But, these schemes cannot be applied directly in the one-hop wireless sensor networks.

Moreover, in [30], the authors provide a centralized scheme which improves the network lifetime by network restructuring and modifying the nodes that are connected to each sink. In this scheme, only those nodes which make the total energy of the sink less than the threshold should be connected to a sink. For this purpose, when some sink nodes receive more connections, a network restructuring operation is conducted to balance energy consumption in the sink nodes and optimize the network lifetime. However, this solution does not prevent the congestion, but lets the congestion to happen and then tries to detect and solve it by restructuring the wireless sensor network. Also, centralized schemes are prone to a single point of failures and when a sink node is compromised or fails to do network restructuring, congestion occurs and the network restructuring can be prevented.

3 Congestion Control in Wireless Sensor Networks

Generally, congestion control mechanisms consist of congestion detection, congestion notification, and congestion mitigation phases. In wireless sensor networks, the following methods are proposed for congestion detection in the literature [21, 29]:

- Buffer occupancy (queue length): Each node has a buffer applied for buffering the incoming packets, and buffer occupancy is a good indication of congestion.
- Channel load: When the time frame for the transmission of a data packet exceeds the predefined threshold, congestion is detected.
- Packet service time: It refers to the time difference between packet arrival at the medium access control layer and its transmission time. This parameter is equal to one-hop node delay.
- The combination of the buffer occupancy and channel load methods.

After congestion is detected, it should be informed to the sensor nodes to select an appropriate sink to connect. Congestion information can be propagated explicitly or implicitly. In explicit congestion notification, the congested node informs other nodes, by transmitting congestion information packets. However, in implicit congestion notification, the congested nodes notify other sensor nodes by sending congestion information in a piggybacked packet header. A number of congestion control protocols apply ACK signaling to indicate the congestion state. Finally, in the rate adjustment or congestion mitigation phase, congestion should be mitigated and appropriate data rate should be selected. Congestion control and rate adjustment techniques can be categorized into the following methods [35]:

- *Traffic control* In this technique, congestion mitigates by reducing the number of packets injected into the wireless sensor networks.
- *Resource control* The disadvantages of traffic control scheme is the reduction of the data rate which is undesirable in some applications. In this case, congestion is handled by increasing other idle or uncongested network resources.
- *Priority-aware congestion control* Congestion is managed by considering different priorities and the congested nodes are provided with a prioritized channel access.
- *Queue-assisted technique* A rate adjustment technique like Additive Increase Multipartite Decrease (AIMD) is used to keep the queue length of nodes as low as possible.

4 Proposed Scheme

This section presents our proposed fuzzy sink selection algorithm for one-hop wireless sensor networks. In this scheme, it is assumed that the sensor nodes are non-uniformly deployed in the monitoring environment and there are multiple sink nodes in the transmission range of each sensor node. Also, as specified in Eq. (1), it is assumed that the total capacity of the sink nodes is more than the total number of nodes.

$$\sum_{i=1}^{Nsink} SinkCapacity_i \geq N_{sensor} \tag{1}$$

Moreover, as shown in Eq. (2), it is assumed that the number of the sensor nodes around some sink nodes is more than the capacity of the sink nodes:

$$SinkNeighbor_i > SinkCapacity_i \tag{2}$$

In this equation, $SinkNeighbor_i$ denotes the number of sensor nodes in which $sink_i$ is the nearest sink node to them and $SinkCapacity_i$ is the capacity of the ith sink node. Also, the number of the required sink nodes to support all the sensor nodes or N_{Sink} can be calculated by Eq. (3):

$$N_{sink} = \frac{N_{sensor}}{E(SinkCapacity)} \tag{3}$$

In which, N_{sensor} is the number of the sensor nodes in the network and $E(SinkCapacity)$ is the average capacity of the sink nodes. Generally, based on the location and transmission range of the sensor nodes, different number of sink nodes may be available for each node.

$$Dist\left(S_i, Sink_j\right) < R_c \tag{4}$$

In this equation, $Dist\ (S_i,\ Sink_j)$ indicates the distance between the ith sensor and the jth sink node and R_c is the sensor node transmission range.

In this scheme, time is divided into rounds and in each round the sensor nodes select one of the available sink nodes in its range to send its data to it. When a sink node receives more requests than its capacity, it will drop some of them because of the congestion. Thus, it is very important to limit the load on each sink and prevent the sink nodes from receiving more requests than its capacity (Table 1).

Table 1 Abbreviations and Acronyms

Abbreviations	Description
N_{Sink}	Number of sink nodes
N_{sensor}	Number of sensor nodes
$SinkCapacity$	Capacity of the sink node
$Dist\ (S_i,\ Sink_j)$	Distance between the ith sensor and the jth sink node
E_{tx}	Transmission energy
E_{rx}	Receive energy
N_{RE}	Number of retransmissions
E_{packet}	Energy required to deliver packet to the sink
N_{normal}	Number of normal sensor nodes
$N_{advanced}$	Number of advanced sensor nodes
Rc	Sensor nodes transmission range

To control congestion in the sink nodes, the congestion should be notified to the sensor nodes somehow. For this purpose, in each round, first, each sink node broadcasts a Hello message containing its average load in the previous rounds to the networks [36]. Afterward, each sensor node computes its distance to each sink by using the Received Signal Strength (RSS) of the received messages and uses the content of these messages to detect the average amount of the sink load in the previous rounds.

Then, it applies a fuzzy logic-based algorithm to select the nearest uncongested sink node by using factors such as its distance from the sink nodes, the average load of the sink nodes in previous rounds and its remaining energy. The proposed fuzzy sink selection algorithm is indicated in Fig. 1. After an appropriate sink is selected by the proposed fuzzy sink selection algorithm, sensor node sends its data to the selected sink.

```
Algorithm Fuzzy_Sink_Selection ( )
Input:
   RSS (Received Signal Strength) of each sink positioned in the range of the sensor node
   Congestion level of each sink positioned in the range of the sensor node
   Energy level of the neighboring sensor nodes
Output:
   ID of the selected sink node
Begin
     For  each round  Do
          Receive the broadcasted Hello message from each sink
          Determine distance to each sink based on the RSS of the Hello message received from the sink node.
          If  distance to sink < Transmission range  Then
              Add sink to the available sink list
          End If
          If  round<3  Then
              Select a random sink and connect to it
          Else
              For  each sink in the range of a sensor node  Do
                   Extract the congestion information from the Hello message.
                   If  congestion level > Sink capacity  Then
                        X=Random();  //  a random number between [0-1]
                        If  X>0.5  Then
                             Continue;
                        End If
                   End If
                   Apply fuzzy inference system based on its distance with the sink,
                   average congestion in the sink and its remaining energy
              End For
              Compare the output values
              Find the sink with maximum output
              If  more than one sink has the same output value  Then
                   If  the sinks distance is different  Then
                        Select the nearest sink
                   Else
                        Select a random sink
                   End If
              Else
                   Select a random sink
              End If
          End If
     End For
     Return the ID of the selected sink
End  Algorithm
```

Fig. 1 The proposed fuzzy logic-based sink selection algorithm

4.1 Fuzzy Inference System

As indicated in Fig. 2, the proposed distributed fuzzy sink selection solution consists of the following modules:

- *Fuzzification module* That transforms the inputs such as distance, congestion rate and remaining energy which are crisp numbers, into fuzzy sets.
- *Knowledge base* Which stores the IF–THEN rules, required to select the appropriate sink.
- *Inference engine* Simulates the human reasoning process by making fuzzy inference on the inputs and IF–THEN rules.
- *Defuzzification module* Which converts the fuzzy set obtained by the inference engine into a crisp value.

The linguistic variable Distance, indicated in Fig. 3, is used to indicate the distance between a sensor node and its connected sink. This variable is divided into three different levels which are: Close, Mid, and Far. Because energy consumption of each sensor directly depends on its distance with the selected sink, it is ideal that each sensor node connects to its nearest sink. However, in addition to the distance to each sink, congestion situation in them should be taken into account.

The linguistic variable Congestion, shown in Fig. 4, is used to represent the average congestion of a sink node in previous rounds. This variable is divided into three levels: Low, Medium and High. In the proposed sink selection scheme, the average congestion is computed from the load level of all previous rounds. It is important to note that, if this average is computed from the few last rounds then sensor nodes quickly react to the sink node status and the sink nodes may receive low and high number of requests, alternately. Figure 5 presents the linguistic variable Energy used to indicate the remaining energy of sensor nodes. This variable is divided into three levels*:* *Low*, *Medium* and *High*, respectively. One of the important components of each fuzzy inference system is the rule

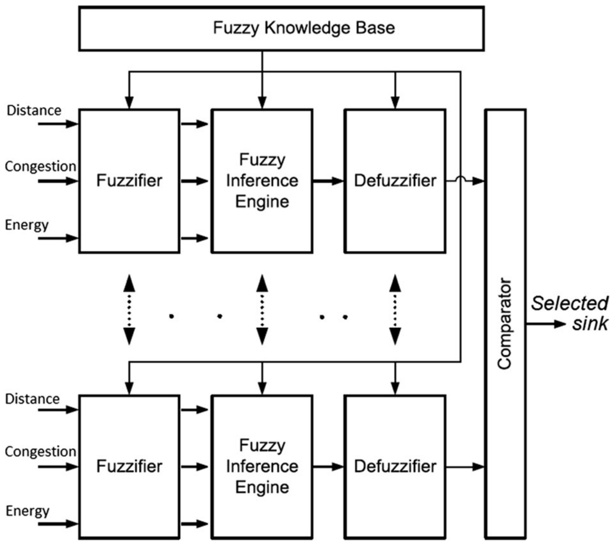


Fig. 2 Structure of the proposed fuzzy sink selection approach

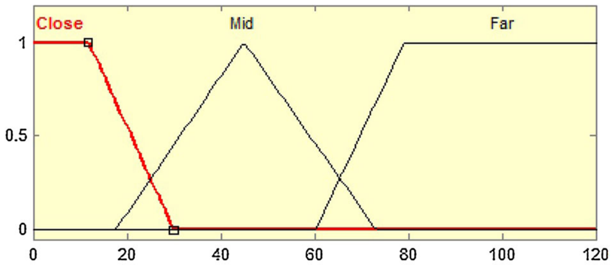


Fig. 3 Membership function for distance input variable

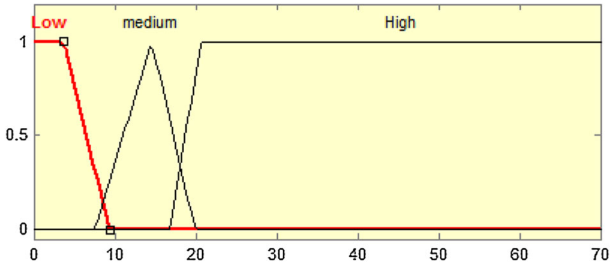


Fig. 4 Membership function for congestion variable

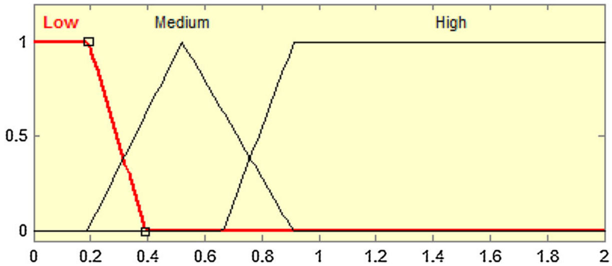


Fig. 5 Membership function for energy input variable

designed to mimic the real world behavior. As the fuzzification step is completed, the obtained membership values are applied to the IF THEN rules to determine our new fuzzy output set. Table 2 indicates the rules that are considered in this scheme for sink selection. We apply the Mamdani method as fuzzy inference technique. Since there are three fuzzy variables in a fuzzy pattern vector and based on the fuzzy classes for each fuzzy variable, our rule base contains 27 different rules for sink selection.

By using these rules, the sensor nodes which have low energy, select the nearest sink and do not care about the congestion situation in it. However, a sensor node which has Medium or High level of energy, considers the congestion situation of the sink nodes into account, and tries to select the nearest uncongested sink node. By considering the remaining energy of the sensor nodes in the sink selection process, sensors with less energy achieve more priority to select the nearest sink node and sensors with more energy may the select sink nodes located far away in the congestion situations. As indicated in Table 2, when the congestion in the sink node is high, regardless of the remaining energy in the

Table 2 Fuzzy rules applied in the knowledge base

Rule#	Distance	Congestion	Energy	Output
1	Close	Low	Low	9
2	Medium	Low	Low	6
3	Far	Low	Low	3
4	Close	Medium	Low	8
5	Medium	Medium	Low	5
6	Far	Medium	Low	2
7	Close	High	Low	7
8	Medium	High	Low	4
9	Far	High	Low	1
10	Close	Low	Medium	9
11	Medium	Low	Medium	8
12	Far	Low	Medium	7
13	Close	Medium	Medium	6
14	Medium	Medium	Medium	5
15	Far	Medium	Medium	4
16	Close	High	Medium	3
17	Medium	High	Medium	2
18	Far	High	Medium	1
19	Close	Low	High	9
20	Medium	Low	High	6
21	Far	Low	High	3
22	Close	Medium	High	8
23	Medium	Medium	High	5
24	Far	Medium	High	2
25	Close	High	High	7
26	Medium	High	High	4
27	Far	High	High	1

sensor nodes and their distance to the sink, the lowest output value is assigned to the sink node which causes the congested sink node not to be selected by the sensor nodes. On the other hand, when the sink is located very close to a sensor node and its congestion is low, the sink node will be the best choice for the sensor node.

The last step is defuzzification, where a crisp value indicating the appropriateness of the sink node is achieved and the sensor node selects the sink which has the highest value of the sink output variable. In this scheme, the Center Of Area (*COA*) is used in the centroid defuzzification. Figure 6 indicates the membership function for the sink output variable which represents each sink node to be elected by the sensor node.

4.2 Radio Model

In this article, a radio model similar to the communication model specified in the [37] is applied for communications between sensor nodes and sink nodes. In this model, $E_{tx}(l)$ or the amount of energy consumption in transmitting a packet with the size of l bits over d distance can be calculated by Eq. 5:

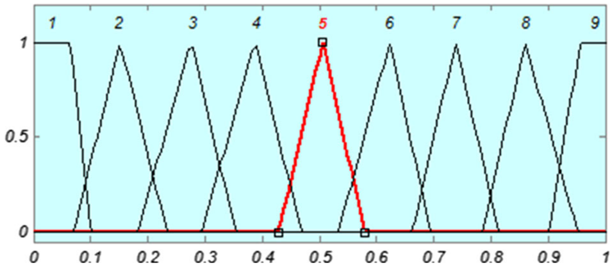


Fig. 6 Membership function for sink output variable

$$E_{tx}(l) = \begin{cases} l * \left(E_{elec} + E_{fs}d^2\right) & if \quad d < d_0 \\ l * \left(E_{elec} + E_{amp}d^4\right) & if \quad d \geq d_0 \end{cases} \tag{5}$$

In this equation, E_{elec} (unit: nJ/bit) is the amount of energy consumption per bit to run the transmitter or receiver circuitry. Moreover, the E_{fs} indicates the energy dissipation in free space propagation model and E_{amp} is the energy dissipation during multipath propagation. In these Equations, the distance d_0 can be obtained with Eq. 6:

$$d0 = \sqrt{\frac{E_{fs}}{E_{amp}}} \tag{6}$$

Furthermore, $E_{rx}(l)$ or the amount of energy consumption in receiving a packet with l bits can be calculated as follows:

$$E_{rx}(l) = l * Eelec \tag{7}$$

5 Simulation Results

This section presents the simulation results of the proposed scheme, conducted in the OMNET++ simulator software. In these simulations, the proposed fuzzy sink selection solution is evaluated against the following sink selection methods:

- Nearest sink selection method
- Random sink selection method

In the nearest sink selection method, the sensor nodes try to connect to the nearest sink node positioned in their transmission range, without considering the congestion situation at the destination sink. When the number of sensors located in the vicinity of a sink node is less than its capacity, the nearest sink selection method achieves the best results and consumes a minimum amount of energy for data transfer. However, when a sink node receives more requests than its capacity, it simply drops additional requests. Afterwards, these dropped messages should be retransmitted and this increases the delay and power consumption of the data transmissions. In the nearest sink selection method, when Eq. 8 is true, then N_{dropi} or the number of dropped packets in the ith sink node can be computed as follows:

$$ReceivedRequests_i > SinkCapacity_i \tag{8}$$

$$N_{dropi} = ReceivedRequests_i - SinkCapacity_i \tag{9}$$

Also, in the nearest sink selection method, the average energy required to successfully transmit each packet to the sink or $E(E_{packet})$ can be computed as follows:

$$E\left(E_{packetj}\right) = (1 + E(N_{RE})) * E_{tx}\left(S_i, sink_j\right) \tag{10}$$

In this equation, the $E(N_{RE})$ parameter indicates the average number of the retransmissions required to transfer each packet and the $E_{packetj}$ parameter is the amount of the energy required to transfer one packet to the *j*th sink node. When distance to the sink node is less than *d0* then the energy required to successfully transmit a packet to the *j*th sink can be computed as follows:

$$E_{tx}\left(S_i, sink_j\right) = l * \left(E_{elec} + E_{fs} * E\left(D\left(S_i, sink_j\right)\right)^2\right) \tag{11}$$

In this equation, $D(S_i, sinkj)$ is the distance from the *i*th sensor to the *j*th sink node.

In random sink selection method, sensors select a random sink node positioned in their transmission range and do not consider congestion situation at them. In this method, sink selection process does not depend on the sensor nodes deployment model and the probability of selecting each sink node can be calculated by Eq. (12):

$$P_{sinkj} = \frac{1}{N_{sink}} \tag{12}$$

In this equation, N_{sink} is the number of sink nodes deployed in the wireless sensor network and P_{sinkj} is the probability of the selecting *j*th sink node. Moreover, the probability that each sink receives requests from n_x sensor nodes (P_{nxreq}) can be calculated by Eq. 13:

$$P_{nxreq} = \left(\frac{1}{N_{sink}}\right)^{n_x} \tag{13}$$

Also, $P_{congestioni}$ or congestion probability in the *i*th sink node can be calculated by using Eq. (14):

$$P_{congestioni} = \sum_{j=SinkCapacity_i+1}^{N} \left(\frac{1}{N_{sink}}\right) j \tag{14}$$

In random sink selection method, the energy required to successfully transfer one packet is given as follows:

$$E_{packetj} = \sum_{i=1}^{NRE+1} E_{tx}\left(S_i, sink_j\right) \tag{15}$$

In which, the N_{RE} parameter indicates the number of retransmissions required to transfer the packet.

Figures 7, 8 indicates the request load on one of the sink nodes when 3 sink nodes are deployed in the wireless sensor network. In these simulations, 50 sensor nodes are randomly deployed in a 70*70 m area.

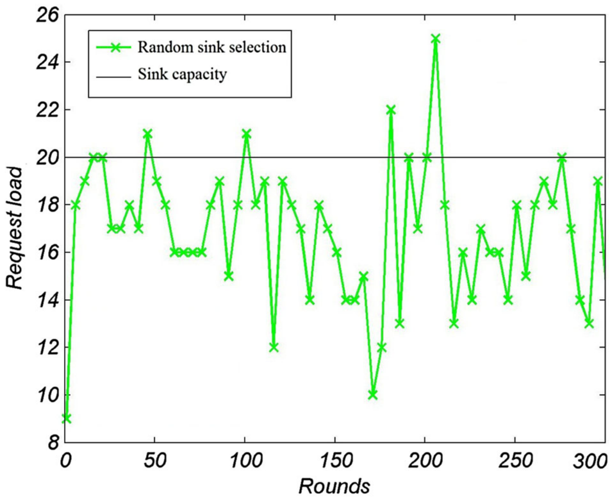


Fig. 7 Request load on a sink node when 3 sink nodes are deployed in the wireless sensor network

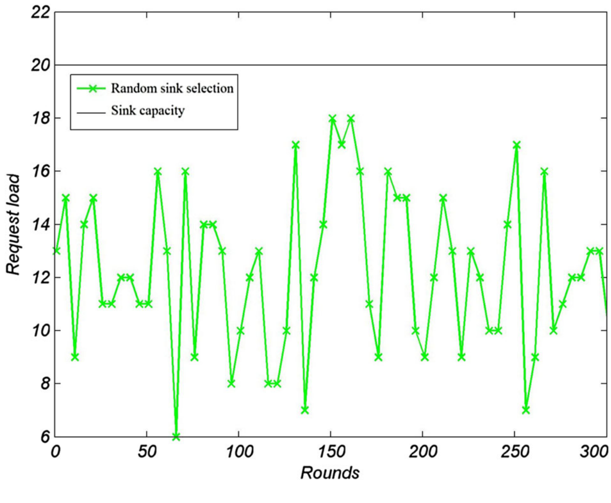


Fig. 8 Request load on a sink node when 4 sink nodes are deployed in the wireless sensor network

As it can be concluded from the previous equations and figures, when more sink nodes are applied in the network, random sink selection method can reduce the request load on each sink node. However, it increases the energy consumption, because the random sink selection does not consider the distance to the sink nodes and distant sinks may be selected.

In simulation scenarios used to evaluate our scheme, the following items area analyzed:

- The load on each sink node.
- Energy consumption of the sensor nodes for transferring a specific amount of data.
- The number of rounds required to transfer the data.
- The average distance between sensors and sink nodes.
- Remaining energy of network at each round.

In these simulations, the sensor nodes are distributed non-uniformly in the wireless sensor network, thus the density of the sensor nodes is different throughout the network. Also, in all scenarios sink nodes are homogeneous and have the same capabilities. Because energy is one of the important factors in our proposed sink selection method, three scenarios are considered in these simulations. In the first scenario, a heterogeneous wireless sensor network with 5 sink nodes is used and normal sensor nodes utilize 1 J battery power. Also, 10% of the sensor nodes are advanced nodes which apply 2 J battery power. In a heterogeneous wireless sensor network, the total number of nodes (*Nsensor*) can be obtained by Eq. 16:

$$N_{sensor} = N_{normal} + N_{advanced} \tag{16}$$

In this equation, N_{normal} is the number of normal sensor nodes and $N_{advanced}$ is the number of advanced sensor nodes having more battery power.

In the second scenario, a homogeneous sensor network is considered which sensor nodes have 1.5 J battery power. In the third scenario, a heterogeneous wireless sensor network with 4 sink nodes is considered that normal sensor nodes use 0.6 J battery power and 20% of sensor nodes are advanced nodes which have 1.8 J energy.

Figure 9 depicts the network topology applied in the first scenario in which sensor nodes are non-uniformly distributed around some sink nodes. In this configuration, 5 sink nodes are applied in the network where, for simplicity, the capacity of 20 connections is considered for all of them. Also, the sink nodes are fixed and can be placed in any position in the network. In addition, they may be mobile because their distance in each round can be computed by the received signal strength of their Hello messages.

In the first scenario, all sensor nodes are required to transfer 400 rounds of data to one of the available sink nodes but when a sensor request (packet) is dropped in a congested sink, it should be re-transmitted to a sink node decided by the proposed fuzzy logic-based sink selection scheme. Table 3 indicates the simulation parameters applied in the first simulation scenario.

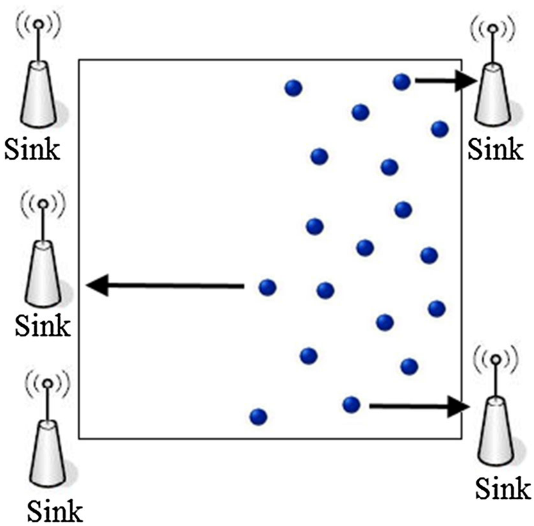


Fig. 9 Network topology in the first simulation scenario

Figure 10 indicates the request load on the 3rd sink node in the first scenario. Figure 11 presents the request load on the 4th sink node and as shown in this Figure, our solution can effectively keep the request load under the sink node capacity. As shown in Figs. 10 and 11, the nearest sink selection method incurs the highest traffic into the sink nodes and random sink selection incurs the lowest load on the sink nodes.

One of the important issues in the sink selection is the distance between the sensor nodes and the sink nodes because as outlined in Sect. 4.2, the energy consumption of the data transfers increases as the distance between the sensor nodes and sink nodes increases. Figure 12 presents the average distance from the sensor nodes to the sink nodes. As shown in Fig. 12, random sink selection method suffers from long distance between the sensor nodes and the sink nodes which result in high energy consumption. Although the nearest sink selection method provides the lowest distance between the sensor nodes and the sink nodes, it suffers from congestion in sink nodes which causes retransmission of messages, higher delay and more energy consumption for the data transfer.

Figure 13 indicates the total remaining energy of the wireless sensor network in the 400 rounds of the data transfer. As depicted in Fig. 13, our solution can preserve the sensors energy better than the random sink selection method.

However, in the first 400 rounds, the random sink selection method consumes more energy than the nearest sink selection method. But, as shown in Fig. 14, the total energy consumption of our fuzzy sink selection methods is less than the random sink selection and the nearest sink selection methods.

Figure 14 indicates the total energy consumption of the sensor nodes for transferring 400 rounds sensed data by each sensor node. As shown in Fig. 14, random sink selection

Table 3 Simulation parameters of the first scenario

Parameter	Value
Simulation area	70 m*70 m
Number of the sinks	5 sink nodes
Sinks locations	1st sink: (0, 0)
	2nd sink: (0, 70)
	3rd sink: (70, 0)
	4th sink: (70, 70)
	5th sink: (0, 35)
Congestion threshold	20 connections
Number of nodes	60 nodes
Initial energy	Normal nodes: 1 J advanced nodes: 2 J
Etx	50*0.000000001 J
Erx	50*0.000000001 J
Efs	10*0.000000000001
Eamp	0.0013*0.000000000001 J
Required data transfer	400 rounds
Network type	Heterogeneous
Sensor nodes maximum transmission range	100 m
Packet length	4000 bits

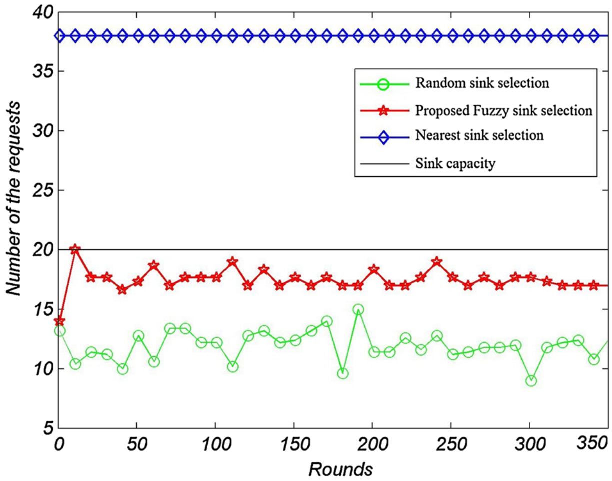


Fig. 10 Request load on the 3rd sink node in the first scenario

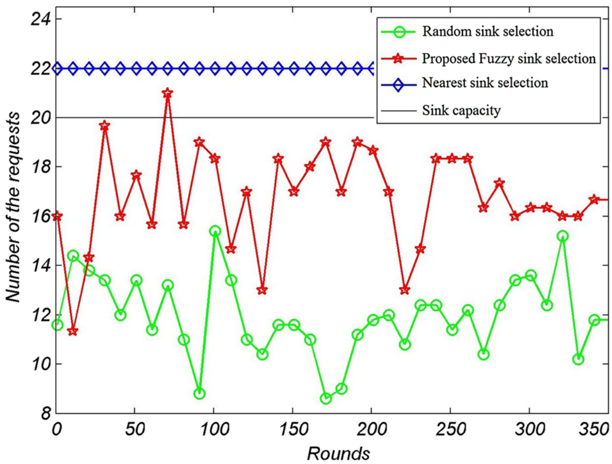


Fig. 11 Request load on the 4th sink node in the first scenario

method incurs highest energy consumption because nodes may randomly select the distant sinks. Also, the nearest sink selection method consumes more energy than our proposed solution because most of the requests sent to the overloaded sinks are dropped and should be re-transmitted until successful delivery to the sink node.

In heterogeneous wireless sensor networks, E_{total} or total initial energy of the wireless sensor network can be computed as follows:

$$E_{total} = N_{normal} * E_{initial} + N_{advanced} * E_{advinitial} \tag{17}$$

In which, $E_{initial}$ is the initial energy of the normal sensor nodes and $E_{advinitial}$ denotes the initial energy of the advanced sensor nodes. In each round, $E_{remaining}$ or the total remaining energy of the wireless sensor network can be computed as follows:

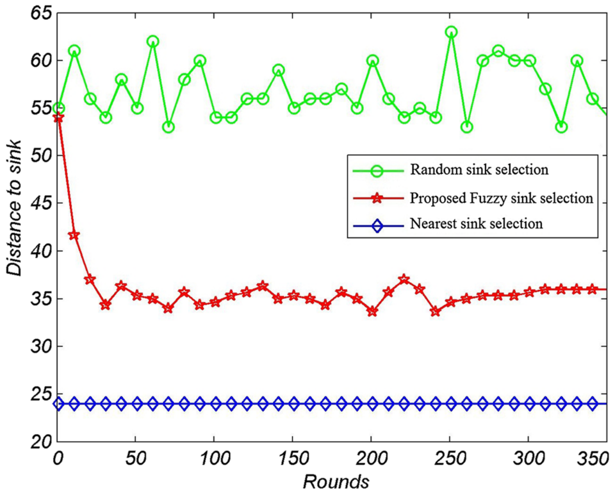


Fig. 12 Average distance from the sensors to the sink nodes in the first scenario

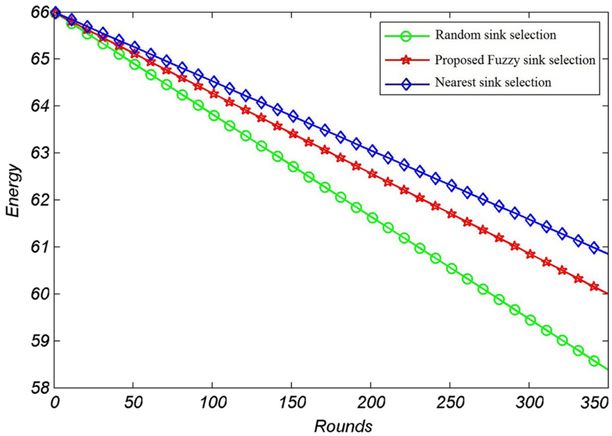


Fig. 13 Average remaining energy in wireless sensor network sensors in the first scenario

$$E_{remaining} = E_{total} - \sum_{i=1}^{N_{Sensor}} Ei \quad (18)$$

In this equation, E_{total} indicates the total initial energy of the wireless sensor network, N_{Sensor} denotes the number of live sensor nodes in the network and Ei shows the remaining energy of ith sensor node.

Figure 15 indicates the total rounds required to transfer 400 rounds sensed data. As it is shown in this Figure, nearest sink selection method can be completed near the 800 rounds of data transfer. Also, random sink selection method can incur the lowest delay in 400 rounds data transfer, but as shown in Fig. 14, it incurs high energy consumption, because nodes may select sink nodes positioned far away.

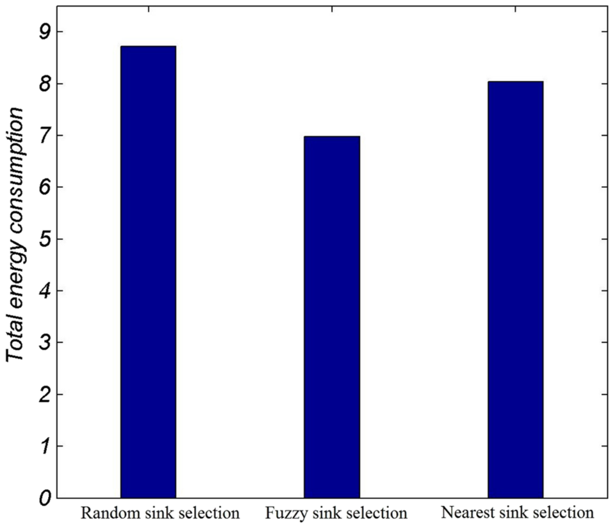


Fig. 14 Total energy required to transfer 400 rounds data by all sensor nodes in the first scenario

Table 4 indicates the simulation parameters applied in the second scenario which utilizes 5 sink nodes in different locations. In this scenario, 600 rounds data transfer should be performed by wireless sensor network nodes. Also, wireless sensor network is heterogeneous and sensor nodes use 1 J battery power. Moreover, 10% of the sensor nodes are considered as advanced nodes and utilize 2 J battery power.

Figure 16 presents the request load on the 3rd sink node and Fig. 17 presents the request load on the 4th sink node. The results of Figs. 16 and 17 indicate that our proposed fuzzy sink selection method can effectively handle the heterogeneous wireless sensor networks.

The average distance between the sensor nodes and their connected sink nodes is shown in Fig. 18. As indicated in this Figure, the fuzzy sink selection method is able to balance

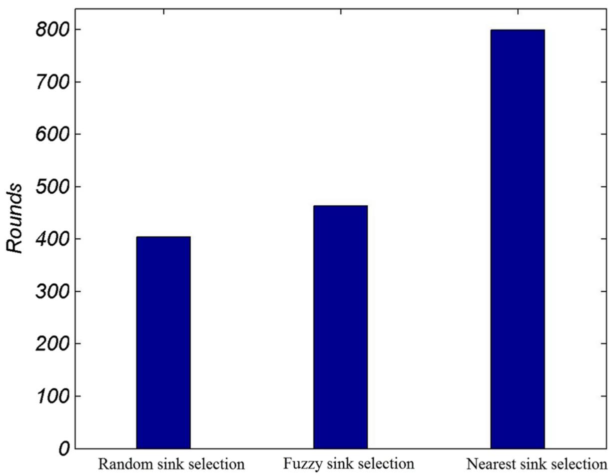


Fig. 15 Required rounds for 400 rounds data transfer

Table 4 Simulation parameters of the 3rd scenario

Parameter	Value
Simulation area	70 m*70 m
Sink location	4 corners of the simulation area
Number of nodes	70 nodes
Initial energy	1.5 J
E_{tx}	50*0.000000001 J
E_{rx}	50*0.000000001 J
E_{fs}	10*0.000000000001
E_{amp}	0.0013*0.000000000001 J
Number of the sinks	5 sinks
Congestion threshold	20 connections
Required data transfer	600 rounds
Network type	Homogeneous
Sensors maximum transmission range	100 m
Packet length	4000 bits

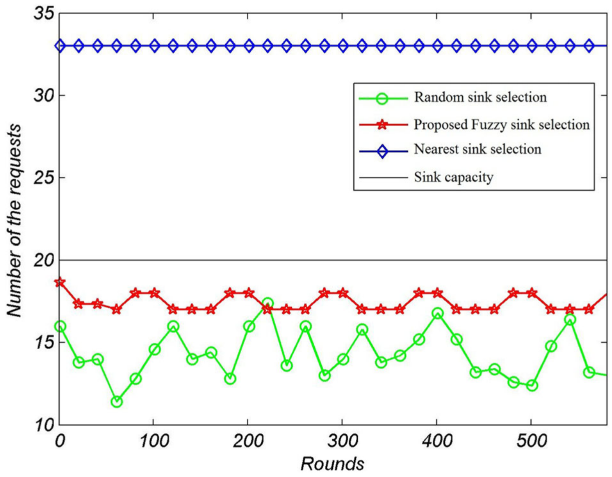


Fig. 16 Request load on the 3rd sink node in the second scenario

the load on the sink nodes, but in this scheme, sensor nodes may select a far way sink nodes when the near sink nodes are predicted to be congested. However, the proposed scheme operates better than the random sink selection method and tries to select the nearest uncongested sink node. Thus, the average distance to sink in our solution is much less than the random sink selection method. In this scenario, a homogeneous sensor network is considered that all sensor nodes have 1.5 J initial battery power. Figure 19 exhibits the average remaining energy of the sensor nodes in the second scenario which can be computed as follows:

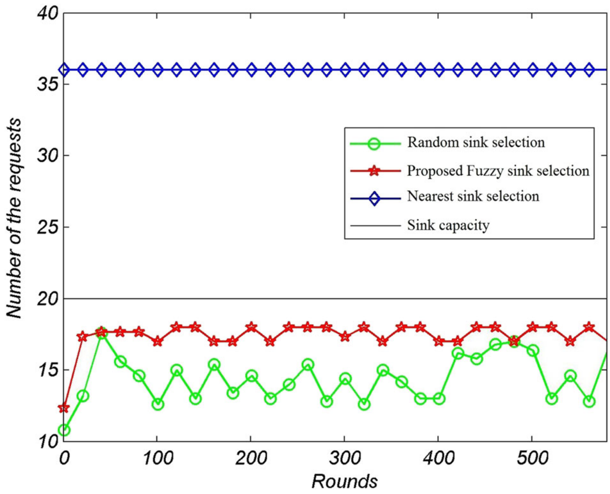


Fig. 17 Request load of the 4th sink node

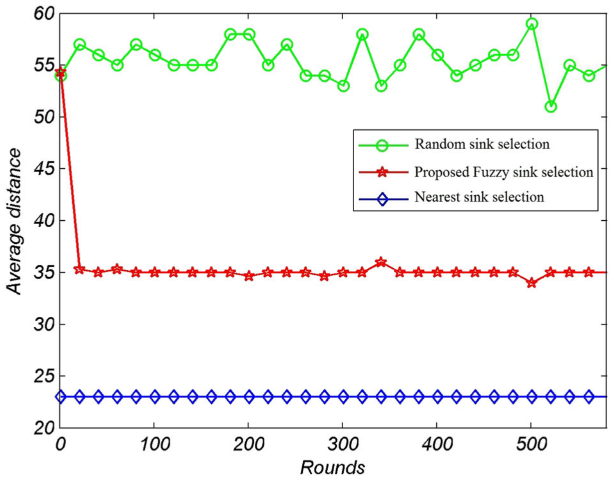


Fig. 18 Average distance of the sensors from the sink nodes in the second scenario

$$E_{average} = \frac{E_{remaining}}{N_{Sensors}} \tag{19}$$

In each round, our fuzzy sink selection method consumes less energy than random sink selection method. Although in the first 600 rounds the nearest sink selection method consumes less energy than our solution, it requires more rounds to complete its data transfer. As shown in Fig. 20, the nearest sink selection method completes 600 rounds data transfer in 1200 rounds and as indicated in Figs. 21, 22, it consumes more energy than our proposed sink selection solution.

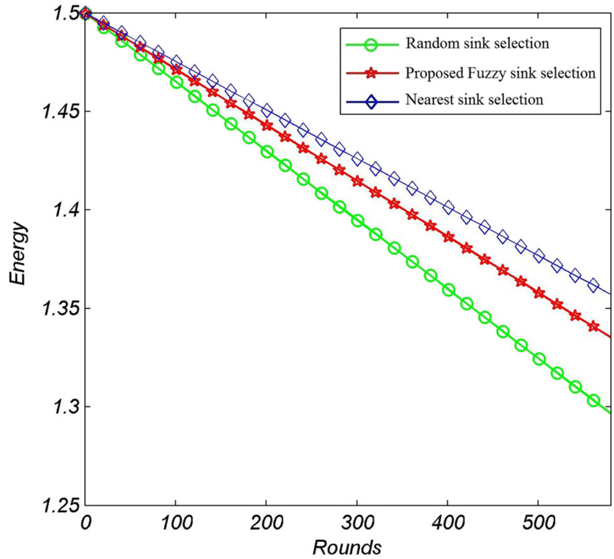


Fig. 19 Average remaining energy of wireless sensor network sensors in the second scenario

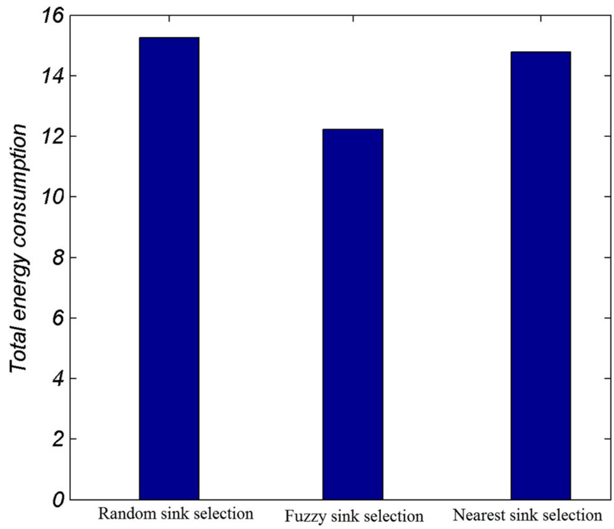


Fig. 20 Total energy required to completely transfer 600 rounds data by all nodes in wireless sensor network in the second scenario

Figure 20 depicts the total energy consumption by all the sensor nodes to successfully transfer 600 rounds data to the sink nodes. However, as indicated in Fig. 21, this process is often completed in more than 600 rounds.

Table 5 specifies the simulation parameters of the 3rd scenario that a heterogeneous wireless sensor network with 4 sink nodes positioned in the corners of the simulation area is applied. In this scenario, normal nodes have 0.6 J battery power and 20 percent of the

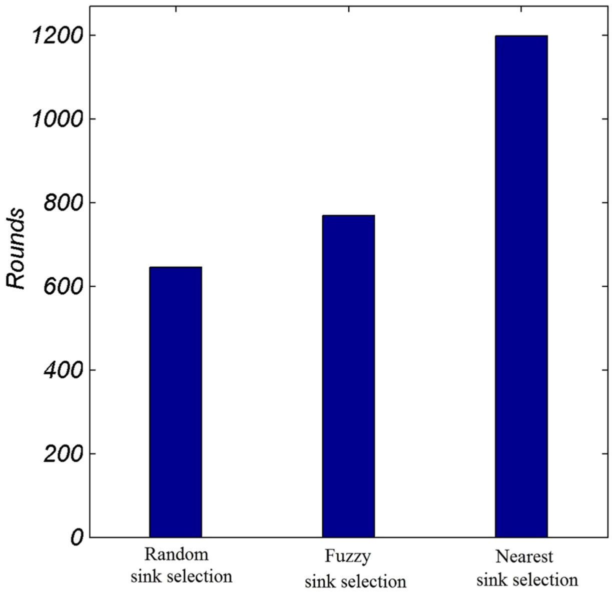
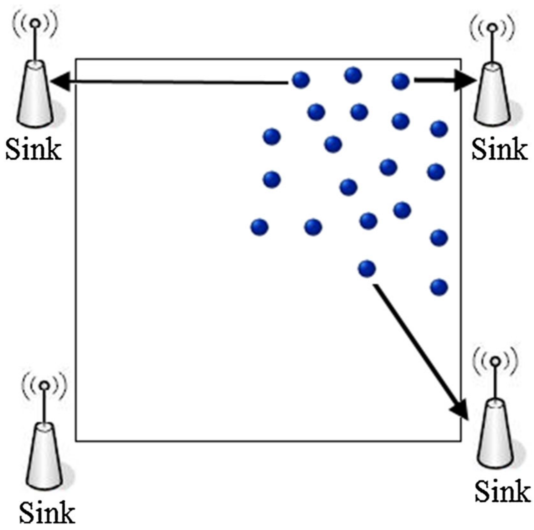


Fig. 21 Total rounds required to completely transfer 400 rounds data by all nodes in the second scenario

Fig. 22 Network topology in the third simulation scenario



sensor nodes are advanced nodes which utilize 1.8 J battery power. In this scenario, it is assumed that most nodes are non-uniformly located close to one of the sink nodes. As the simulations results indicate, even in this scenario, our solution is able to distribute the request load on all available sink nodes.

Request load of the third sink node in the third scenario is exhibited in Fig. 23. Although in this scenario 30 sensors are located near one sink node, the proposed fuzzy sink selection solution can allocate an appropriate number of sensor nodes to each sink and is able to limit the request load under the sink capacity. Thus in 600 rounds of the

Table 5 Simulation parameters of the third scenario

Parameter	Value
Simulation area	70 m*70 m
Number of sensor nodes	50 nodes
Initial energy	0.6 J
Number of the sinks	4
Sink nodes locations	1st sink: (0, 0)
	2nd sink: (0, 70)
	3rd sink: (70, 70)
	4th sink: (70, 0)
Sink capacity	20 connections
Required data transfer	500 rounds
Network type	Heterogeneous
Maximum transmission range	100 m
Packet length	4000 bits

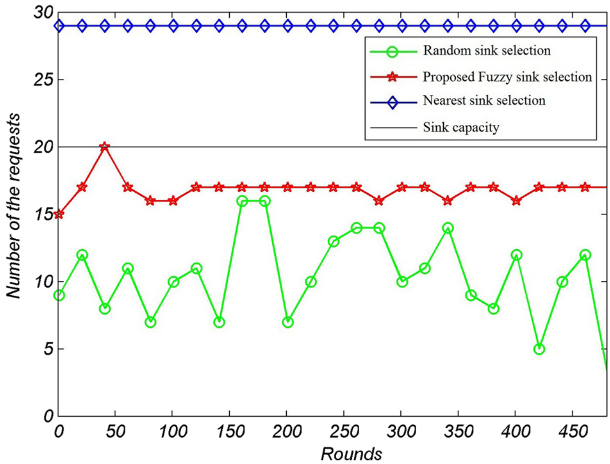


Fig. 23 Requests loads on the 3rd sink node in the third scenario

simulation, no request is dropped by the 3rd sink node and also its capacity is not abandoned unused.

Figure 24 displays the requests loads on the 4th sink node in the third scenario. As shown in this figure, the requests of the sensor nodes are effectively limited on the 4th sink nodes to prevent any congestion.

Average distance from the sensor nodes to the sink nodes in the third scenario is shown in Figs. 25, 26.

Figure 27 shows the total remaining energy of all live sensors for 600 rounds data transfer in the third scenario. As indicated in this Figure, the nearest sink selection method transfers the required data in more rounds and consequently consumes more energy than the other methods. However, the proposed fuzzy solution can better preserve the sensor nodes battery power by selecting the nearest uncongested sink in its range.

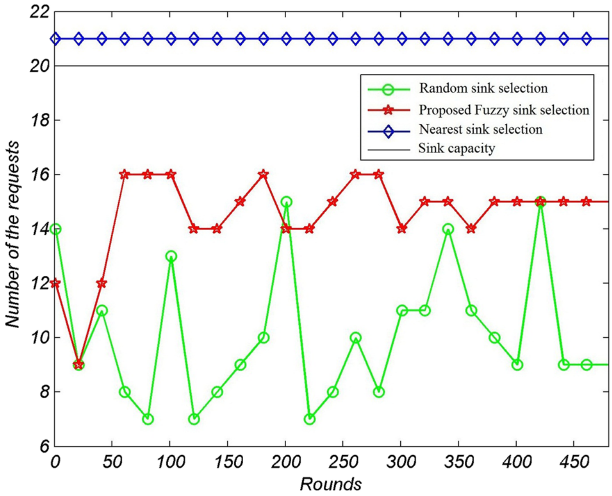


Fig. 24 Request load on the 4th sink in the third scenario

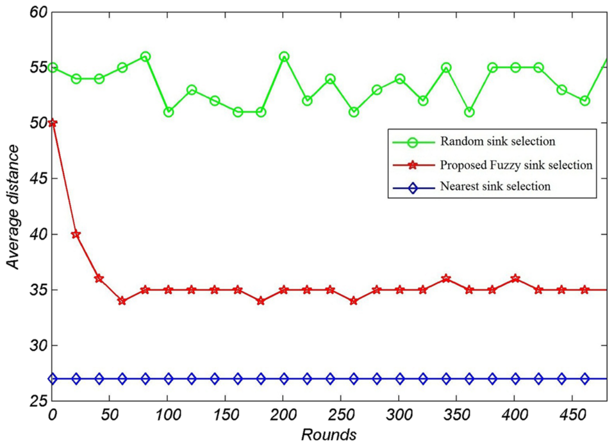


Fig. 25 Average distance from the sensor nodes to the sink nodes in the third scenario

Figure 28 exhibits the total rounds required for 500 rounds data transfer by all the sensor nodes to the sink nodes in the third simulation scenario. As indicated in this Figure, our fuzzy sink selection method produces lower delay than the nearest sink selection method and in this case, its delay is slightly more than the random sink selection method. But, as shown in Fig. 27, its energy consumption is less than both random sink selection and the nearest sink selection methods.

6 Conclusion

The lifetime of the wireless sensor networks can be improved by multiple sink nodes deployment. Congestion is an important issue in multi-sink sensor networks which mitigates the effectiveness and lifetime of the network. Irregular and non-uniform distribution

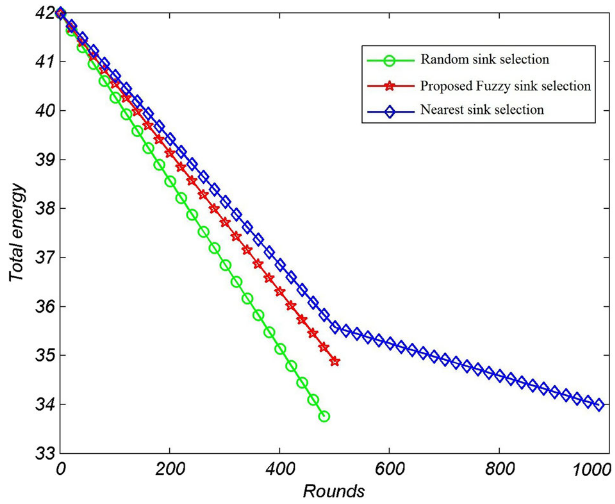


Fig. 26 Total remaining energy of the sensor nodes to completely transfer 500 rounds data in the third scenario

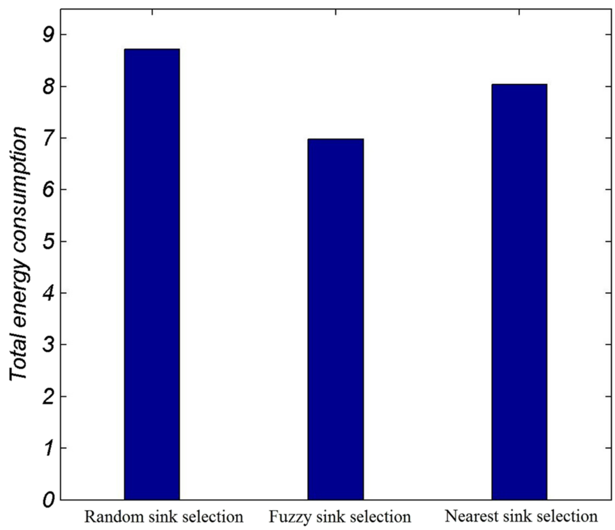


Fig. 27 Total energy required to transfer 500 rounds data by all the nodes in the third scenario

of the sensor nodes and unbalanced loads of the sink nodes are important factors which deteriorate the congestion situation in the sink nodes.

To mitigate the congestion problem in sink nodes and benefit from the multiple sink deployment, in this paper, a fuzzy logic-based sink selection algorithm is presented for one-hop wireless sensor networks. In the proposed distributed sink selection scheme, each sink node should declare its average load with a Hello message to the network. When a sensor node receives this message, it can recognize the congestion situation in the sink node and by using the Received Signal Strength of this message, it can determine its

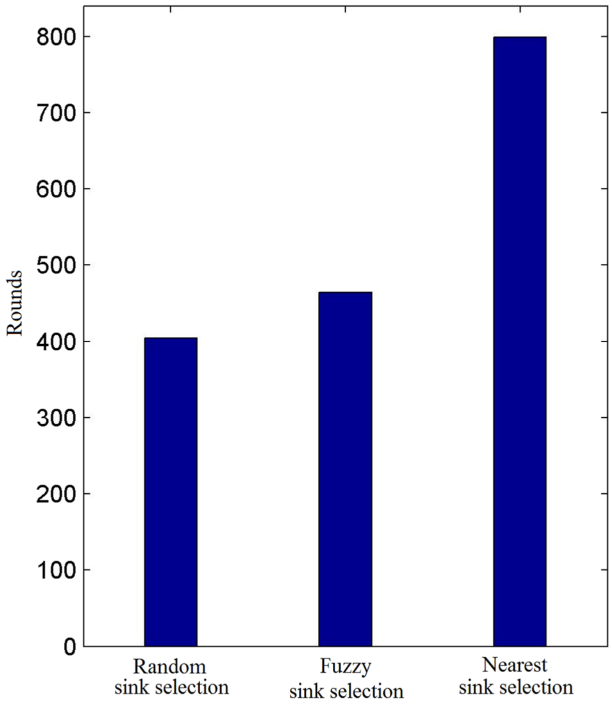


Fig. 28 Total rounds required for 500 rounds data transfer by all the sensor nodes in the third scenario

distance with the sink. Then this information along with remaining battery power are applied to a fuzzy inference system to select the nearest uncongested sink node. Extensive simulations indicate the effectiveness of the proposed solution in load balancing the sink nodes, reducing congestion in sink nodes, and mitigating the delay and energy consumption of data transmissions.

In the upcoming researches and studies, we will try to adapt our proposed fuzzy sink selection solution to the multi-hop wireless sensor networks with multiple mobile sink nodes.

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Mohammad Masdari received his B. Tech degree in Computer Software Engineering from Islamic Azad university, Qazvin branch, Iran, in 2001, and M. Tech degree in Computer Software Engineering from Islamic Azad University, South Tehran Branch, Tehran, Iran, in 2003. He received his Ph.D. degree in Computer Software Engineering from Islamic Azad University, Science and research branch, Tehran, Iran, in 2014. Since 2003, he worked a faculty member of Islamic Azad University, Urmia branch, Iran. Presently he is an Assistant Professor in the Department of Computer Engineering of Islamic Azad University, Urmia branch, Iran. His research interests include Distributed Systems and Network Security.

Farah Naghiloo received her B. Tech degree in Computer Software Engineering from Azad university, Khoy branch, Iran in 2001 and she received her M. Tech degree from Urmia University, Iran in 2013. Her research interests include wireless network security.