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An Improved Multi-hop LEACH Protocol Based on Fuzzy Logic for Wireless Sensor Networks

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Abstract. As an important kind of clustering protocols in wireless sensor networks (WSNs), LEACH and its variants have been demonstrated to efficiently balance the energy consumption, simplify the routing task and extend the network lifetime. Especially, the multi-hop LEACH type protocols have proved to be effective approaches for high energy efficiency, reliability as well as scalability. However, data transmission in hop-by-hop mode increases the energy consumption and end-to-end delay. In this paper, an improved multi-hop LEACH protocol based on fuzzy logic called IMF-LEACH is proposed, which uses a fuzzy logic controller with residual energy, length of data, and distance to BS as fuzzy descriptors to determine the hop count. Moreover, the hop count is used for each CH to find its optimal next-hop intermediate CH with more residual energy and less number of members. Simulations are conducted in MATLAB to evaluate the performance of the proposed protocol, and the results show that IMF-LEACH maximizes the network lifetime and outperforms its counterparts consistently.

Keywords: WSNs, fuzzy logic control, multi-hop, energy efficiency

1 Introduction

As one of the most important and basic technologies for information collection in Internet of Things (IoT), the maturing of microelectronics and wireless communication technologies has aroused more and more scholars' attention to Wireless sensor networks (WSNs) [1]. WSNs have been widely used to measure the thermal, infrared, sonar, and seismic signals in the surrounding environments by means of various sensors built in nodes [2-4]. Saving energy to prolong the network lifespan is the most important challenge for WSNs due to their energy constrained nodes. Clustering which organizes the nodes into different groups to maximize the longevity of the WSNs has been proved to be energy efficient, robust as well as scalable [3-5]. In a cluster, a node is elected as cluster head (CH) by running a certain approach, and then the CH aggregates the collected data from its cluster number nodes (CMs) and transmits it to the base station (BS) in single- or multi- hop mode. Great efforts have been made to improve the performance of clustering approaches and expected results have been achieved during the last decades [3-11]. Low-energy adaptive clustering hierarchy (LEACH) is the pioneer clustering protocol for WSNs [7], which performs five following processes including CH election, cluster formation, schedule creation, data forwarding and re-clustering. Moreover, various improvement exerted on one or more of these five processes has been put forward in different approaches to enhance the performance of LEACH.

In LEACH, a node is randomly elected as CH only based on the suggested percentage of CHs for the network and the number of times the node has been a CH so far, which may make some nodes with low residual energy or long distance to the BS be chosen as CHs. To make matters worse, no CH is elected. Therefore, many improved approaches have been proposed to select the optimal nodes as CHs such as weight calculation [8], particle swarm optimization [9], harmony search [10] and fuzzy logic control [11]. The optimization algorithms vary from different rules and characteristics [12]. Once a node becomes a CH in LEACH, it will broadcast an advertisement message to the rest nodes announcing its CH identity, and these nodes will decide to join the clusters based on the highest received signal strength of the received messages, or in other words, the shortest distance between them. However, only considering the received signal strength or distance between CMs and CHs will form un-uniform

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clusters and deteriorate the CHs with low residual energy. Consequently, many other factors are used for CMs to join appropriate clusters such as residual energy of the CHs, distance between CM and CH, the degree of membership, distance between CM and the BS, data transmission mode and the layer number [14-16] in order to construct clusters uniformly and balance the energy consumption intra clusters. After clusters formation, each CH creates a TDMA (Time Division Multiple Address) schedule to manage the data transmission for the CMs in the cluster, and the CMs transmit data to the CH in allocated time slots and enter sleep status in other time, which save energy consumption significantly [3, 7, 11-15]. When the CH receives all the data from its CMs in LEACH, it aggregates the data and forward it to the BS in single hop mode, which may expend excessive energy when the CH appears far away from the BS and undoubtedly reduce the scalability of the network. Hence, data forwarding schemes with multi-hop [20] and hybrid (dual-hop) [17] modes have been presented to achieve energy efficiency and scalability for WSNs. Without loss of generality, for multi-hop modes, the CH sends its data by selecting proper relay nodes to the BS so as to reduce energy consumption. As for hybrid mode, the CHs forward their data to the BS hop-by-hop. Moreover, the CMs in the clusters closer to the BS than their CHs transmit their data to the BS directly. Finally, randomized rotation of the CHs based on round in LEACH is used to evenly distribute the energy consumption among the sensors in the network. But high frequency of re-clustering among nodes is bound to consume a certain amount of energy due to broadcasting messages during the cluster forming. Furthermore, using fixed round time inevitably leads to uneven energy distribution for the CHs with low residual energy. To solve the above two problems, several enhanced methods have been used to rotate the CHs such as threshold-based method in which the CH is replaced only when its residual energy is below a preset threshold without considering the round time [18], vice cluster head (VCH) or dual CHs based method in which the CH is taken over by a chosen VCH based on dynamically received CMs' information in the steady phase so as to diminish the frequency of re-clustering and prolong the time of being in the steady state phase [3, 19-20]. In addition, variable round time-based methods have been used to determine the optimal round time so as to achieve fair distribution of energy consumption [16, 21]. However, the existing schemes construct the clusters mainly by random selection of CHs or weight calculation which results in various sizes of clusters and CHs far from their cluster center. Furthermore, the proposed clustering methods seldom cope with the different uncertainty and dynamics in real network. Especially, hop-by-hop data communication increases the burden of CHs near the BS so as to cause them premature death, which results in hot spot problem [22]. In a word, the problems faced by the existing improved LEACH schemes are as follows: (I) most of them only consider the nodes with more residual energy as CHs, however, the distribution of CHs in the network may be unreasonable; (II) these schemes do not carefully consider how many hops should be required for CHs with different data, residual energy and location to reach the BS.

To solve the above mentioned problems, an Improved Multi-hop LEACH protocol based on Fuzzy logic controller (IMF-LEACH) is proposed in this paper. IMF-LEACH optimizes the cluster head threshold in LEACH by taking residual energy, node centrality and distance to BS into account in order to form a relatively stable, even distributed and energy saving cluster structure at first. Then a fuzzy logic controller is used to determine the number of hop count based on residual energy, length of data, and distance to BS. The data of the clusters is delivered to the BS according the hop count of each CH, which may lead to a further reduction in the number of hops to the BS as well as minimization of the end-to-end delay and average hop count.

The rest of the paper is organized as follows. Section 2 describes the related works. Section 3 presents the network and energy model. In Section 4, the proposed clustering method IMF-LEACH is introduced in detail, and simulation results are shown in Section 5. Finally, Section 6 concludes the paper.

2 Related Works

LEACH has been proved to have high energy efficiency and scalability by forming an optimal hierarchical structure and using a single-hop communication mode. However, it also has the following drawbacks:

•Distributed probabilistic scheme is adopted to select the CHs and non-CH nodes join a cluster according to the signal strength between itself and the CHs, which is easy to cause non-uniform clustering and load imbalance over the network, and may lead to reduced network lifetime in the end.

•Ignoring the residual energy of the nodes to form clusters may cause the nodes with low residual energy to become CHs which are prone to premature death.

•The CMs send data to their CH directly in a cluster, furthermore, the CH transfers the aggregated data to the BS over a single-hop link, no matter how far away they are, which might consume excessive energy and be resistant for energy constrained sensor nodes.

•Fixed round time is used to re-clustering so as to extend the network lifetime, however, the energy of the nodes decreases with the operation of the network, which may cause some CHs premature death resulting in data loss in these clusters.

Therefore, many variants of LEACH have been provided to improve its performance from one or more aspects mentioned above [6, 10, 13, 18, 20]. Especially, protocols based on LEACH forwarding data to the BS in multi-hop mode have been validated that they can improve the energy efficiency and scalability for WSNs much more than that of protocols in single hop communication [23]. Then, the following discussions will be limited to the multi-hop variants of LEACH.

In [24], a multi-hop routing protocol (MH-LEACH) is proposed to improve the energy efficiency of the network, whose set-up phase is the same to LEACH forming a cluster topology. In the steady state phase, the CHs far away from the BS select their next-hop CHs as intermediate nodes to transmit data according energy status and the distance to the BS. And the CHs close to the BS adopt direct transmission strategy for data forwarding. Moreover, the distance threshold of single hop or multi-hop is obtained. Compared with LEACH, simulations results show that the proposed protocol can balance network load, cut down energy consumption, enhance data collecting precision and extend the life cycle of the network. However, non-uniform clustering still exits, and hop-by-hop communication increases network burden and end-to-end delay, yet, hot spot issue has not been resolved.

In [17], an energy efficient multi-hop LEACH protocol called EE-LEACH is proposed, in which the Gaussian distribution model is used for effective coverage of the sensing network area. And unlike LEACH, it uses the function of spatial density to select the CHs, and forms optimal clusters based on neighbors' information and residual energy. Furthermore, the relay nodes with maximum residual energy are chosen to forward the data to the BS. Simulation results show that EE-LEACH yields better performance than LEACH and the other energy balanced routing protocol in terms of packet delivery ratio, end-to-end delay and energy consumption. Although the overall energy utilization is minimum and the clusters are uniformly distributed in EE-LEACH, its computational complex is high and its selection of the relay nodes only considering residual energy may increase the number of hops and the end-to-end delay. Moreover, hot spot issue has still not been resolved.

In [14], a layered multi-hop LEACH protocol named DL-LEACH (Dual-hop Layered LEACH) is proposed, in which the sensing area is divided into layers with a constant width based on the BS so as to find the next hop nodes easier than MH-LEACH and EE-LEACH. Like LEACH, DL-LEACH uses the stochastic threshold equation in [7] toelect the CHs and forms clusters in which the CH and CMs are within the same layer in the set-up phase. In the steady state phase, the source CH transmits its data to a cluster head in the adjacent lower layer than itself, and the like until to the BS. Or otherwise, the data is directly transmitted to the BS when there is no CH in the adjacent layer. Moreover, a node also transmits the data to the BS directly when it is closer to the BS than its CH. Simulation results show that DL-LEACH alleviates the problems of LEACH: a rapid decrease in the lifespan of the node as the sensor field became wider. However, the constant layer width is impractical in real deployment, and the selected relay nodes may be inappropriate only considering the layer so the network performance is deteriorated. At the same time, the end-to-end delay and hot spot issue remain unresolved because of hop-by-hop communication.

In [18], an improved layered multi-hop LEACH protocol called EM-LEACH (enhanced multi-hop LEACH) is presented, in which the layers are determined according to the setup packet propagation. Once each node obtains its layer number, it will participate in clustering as defined in LEACH. Furthermore, the residual energy constitutes another important factor for electing the suitable CHs. In the steady-state phase, CHs aggregate and forwoard data to the closest CH at lower layer till to the BS in the end, or send the data directly to the BS when there is no CH at its lower layer. Moreover, the BS computers the new round time by reading the residual energy in each node in the network at the end of this round. EM-LEACH substitutes an adaptive round time based on the total residual energy of the network for a fixed round time during the entire network operation in [14, 17, 24] so as to achieve fair energy consumption among the different rounds. The performance improvement is evaluated by simulations for EM-LEACH in terms of packet delivery and network lifetime compared to LEACH. However, it selects the relay nodes only considering the layer and hot spot issue is also neglected as DL-LEACH.

In [25], a genetic algorithm based multi-hop LEACH protocol named OMPFM (Optimal Multi-hop Path Finding Method) is proposed, in which a genetic algorithm is utilized to find an optimal path by presenting a new fitness function. Like in LEACH, each node in OMPFM is randomly selected as a CH according to the value of the modified threshold function which considers the current energy of the node, the energy average of the alive nodes, the distance from the node to the BS and the average distances between the alive nodes to the BS. And in the steady state phase, a genetic algorithm is used to find the optimal paths from the source CHs to the BS by the new proposed fitness function which considers the following four parameters: the average distance from the source CH and the BS through the intermediate CHs, the number of CHs through the path, the total number of participation in the transmission process of all CHs in the path, and the total number of member nodes in all clusters that are related to the CHs in the path. The simulation results show that OMPFM is better than the LEACH protocol in terms of the network lifetime and power consumption by approximately 50%. However, invalid individuals which are not practical in accordance with the network topology may be generated in OMPFM because of its lack of detail description of reproduction, crossover and mutation operations. In addition, the whole network information is needed for computation of the threshold value and fitness value increases the time complexity as well as energy consumption. Moreover, hot spot issue is not considered either in OMPFM.

All the proposals mentioned above give individual solutions for improving energy efficiency of LEACH by different multi-hop routing combined with various cluster head selection, clusters formation, or round time updating. At the same time, there are inevitable some drawbacks for each proposal described above. Especially, the hot spot problem is seldom considered in the successors of LEACH.

Table 1. Characteristic analysis of related works

Protocols	Cluster head selection	Route	Features	Round time
LEACH	/	/	Single hop Clustering Algorithm.	fixed
MH-LEACH	No improvement.	The transmission path is selected by calculating the shortest effective distance.	Multi-hop Clustering Algorithm.	fixed
EE-LEACH	According to the spatial density function, the optimal probability of sensor nodes is selected as CHs.	Select the relay node with the largest residual energy.	Multi-hop Clustering Algorithm.	fixed
DL-LEACH	No improvement.	Routing depends on layer.	Multi-hop layering and clustering algorithm.	fixed
EM-LEACH	The cluster head selection threshold is improved according to the residual energy of the nodes.	Routing depends on layer.	Multi-hop layering and clustering algorithm.	dynamic
OMPFM	The CHs selection process is divided into three levels according to the number of rounds.	Genetic algorithm is used to select routing.	Multi-hop Clustering Algorithm.	fixed
IMF-LEACH	The threshold is improved by considering the residual energy, the distance to the base station and the node centrality.	The route is selected according to the remaining energy, the number of CMs and layer of CHs, and combined with fuzzy control.	Multi-hop layering and clustering algorithm.	dynamic

The main objective of this paper is to solve the drawbacks of the proposals cited above, and maximize the network lifetime by finding an optimal multi-hop route from a source CH to the BS. In short, our main contributions can be summarized as follows:

- A novel threshold function for cluster heads selection which takes residual energy, node degree, node centrality and distance to BS into account so as to form a relatively stable, evenly distributed and energy saving cluster structure.
- A hop count calculation mechanism that uses fuzzy logic with residual energy, length of data, and distance to BS as fuzzy descriptors for intermediate cluster heads selection so as to solve the hot spot problem instead of traditional unequal clustering methods [22, 26].
- An energy efficient, simple and scalable multi-hop routing protocol for inter-cluster communication which selects the next-hop cluster head of a CH based on hop count, residual energy, number of cluster members, distance to the BS.

3 Network and Energy Model

3.1 Network Model

Without loss of generality as in [7, 21, 25], the network has the following attributes:

• N nodes are randomly distributed in a target area of $M \times Mm^2$ with the BS located in somewhere of the sensing field, and each node has a unique identification (ID), the set of nodes in the network is represented as $S = \{s_1, s_2, ..., s_n\}$.

• Once the nodes are deployed, their locations are fixed and can be obtained by a positioning system or and energy-efficient positioning algorithm.

• Each node has the same initial energy for being homogeneous except for the BS.

3.2 Energy Model

The same energy model as literature [21, 25] is used in this paper. The energy consumption for l-bits bits data transmission between two adjacent nodes with distance d can be calculated as follows:

$$E_{tx}=\begin{cases} l*E_{elec}+l*\varepsilon_{fm}*d^2 & d<d_0 \\ l*E_{elec}+l*\varepsilon_{mp}*d^4 & d \geq d_0 \end{cases} . \quad \textbf{(1)}$$

Where E_{elec} is the energy consumption for transmitting or receiving 1-bit data, ε_{fs} and ε_{mp} are amplifier coefficients of free space and multi-path fading respectively, d_0 is the threshold distance given by $d_0 = \sqrt{\varepsilon_{fm}/\varepsilon_{mp}}$.

The energy consumption of receiving l-bits data is:

$$E_{rx}=l*E_{elec} \ . \quad \textbf{(2)}$$

The energy consumption of *l*-bits data aggregation is:

$$E_{DA}=l*E_{pDb} \ . \quad \textbf{(3)}$$

Where E_{pDb} is the energy consumption for 1-bit data fusion.

4 Proposed IMF-LEACH Protocol

The proposed IMF-LEACH works in setup phase and stead state phase as in LEACH. Moreover, a network configuration is exerted to assign corresponding layer number to each node similar to DL-LEACH [14] and EM-LEACH [21] which has been proved to make packet forwarding easy for data transmission. In the setup phase, a new threshold function is designed for CHs selection, and a fuzzy logic controller based hop count calculation mechanism is applied to find the optimal multi-hop routing in the steady phase.

4.1 Layered Network Configuration

Splitting the network into different layers has been proved to mitigate the significant loss of energy by directly transmitting data to the BS in LEACH [14, 21]. In [14], the layers are created by a presetting constant width basing on the BS which is impractical in real deployment. In [21], the layers are formed by propagating the setup-packet across the network which overloads the network communication. For IMF-LEACH, the BS progressively broadcasts messages with different *layerID* in various transmission powers, and the *layerID* is incremented by 1 with each broadcasting from 0. Upon receiving a message from the BS, each node retrieves its *layerID* unless it has already set a lower *layerID* . The detailed flowchart of network configuration is shown as Fig. 1.

All the nodes with the same *layerID* are considered as located in the same layer, and they can forward data coming from the nodes located in the higher layer and discard data coming from the same and lower layers during the data communication.

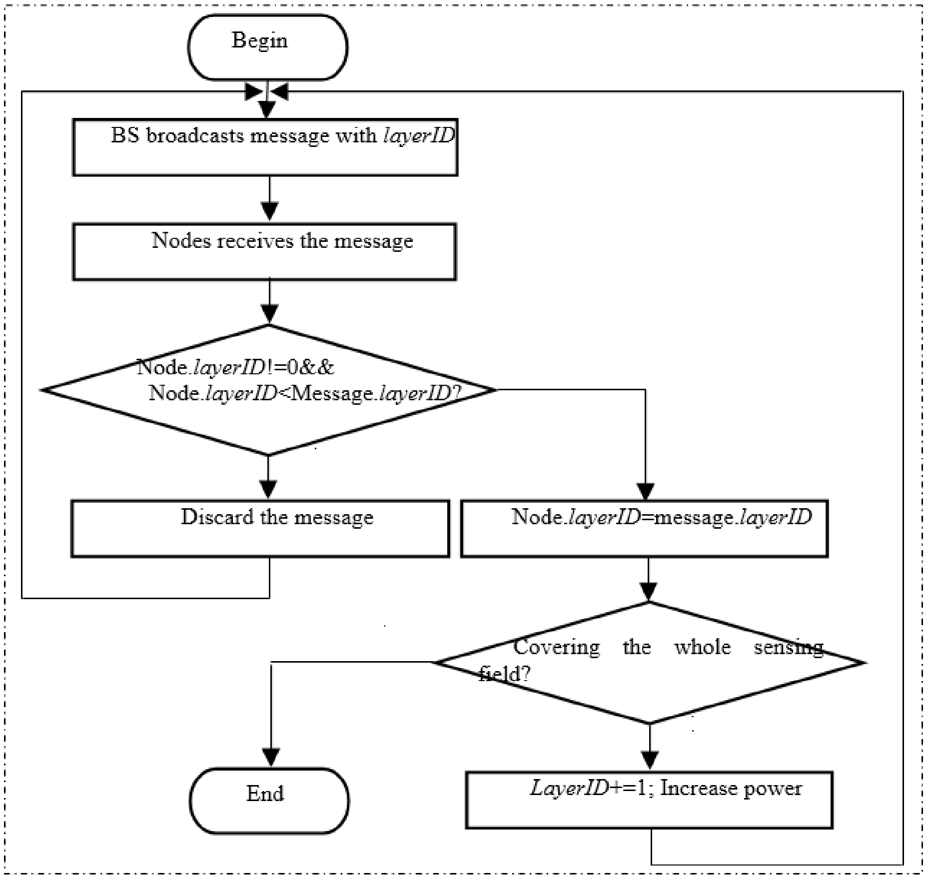


Fig. 1. Flowchart of network configuration

4.2 Clustering with a New Threshold Function

LEACH in [7] selects a node n as a CH when the random value between 0 and 1 assigned to it is less than a threshold value T(n), which can be calculated by Eq.(4).

$$T(n)=\begin{cases}\dfrac{p}{1\text{-}p*(r \bmod \frac{1}{p})};if \quad n\in G \\ 0 \qquad ;\quad otherwise\end{cases} \tag{4}$$

Where p is the desired percentage of CHs, r is the current round and G is the set of normal nodes during the previous 1/p rounds. It can be seen that nodes with low residual energy and inappropriate location may lead to premature death and uneven distribution of CHs so as to decrease the robustness and degrade the lifetime of the network. Thereupon, new threshold functions are defined in some successors of LEACH. EM-LEACH [21] considers the residual energy as another parameter for electing the CH compared to LEACH, the T(n)mod is updated as,

$$T(n)_{mod}=\begin{cases}\frac{1}{2}*\left[\beta*T(n)+(1-\beta)*\frac{E_{residual}}{E_{initial}}\right]; if \quad n\in G\\ 0 \qquad ; \quad otherwise\end{cases} . \tag{5}$$

Where Einitial and Eresidual denote the initial and residual energy respectively, and $\beta = E_{residual}/E_{initial}$. However, neglecting CHs' locations is prone to uneven distribution of CHs, so the node's location parameter is added in OMPFM [25] compared to EM-LEACH, the modified threshold function is given as follows,

$$T(n)_{mod}=\begin{cases}E(n)\geq avg(n) \quad and \quad ToBs(n)\leq avg(D); if \quad r\leq n1\\ T(n)*\left[\frac{E(n)}{E0}+\frac{1}{ToBs(n)}\right] \qquad ; \quad if \quad n1<r<n2\\ T(n) \qquad ; \quad if \quad r\geq n2\end{cases} . \tag{6}$$

Where E(n) is the current energy of node n, avg(n) is the average energy of the alive nodes, ToBs(n) is the distance from node n to the BS, avg(D) is the average distance between the alive nodes to the BS, E0 is the initial energy, n1 and n2 are the number of rounds to validate each case which depend on the application.

Like in [21, 25], a new modified threshold function based on T(n) [7] is proposed to select the optimal nodes as CHs, in which the ratio to average neighbors' residual energy, the ratio to average distance to the BS, and node centrality are considered, as shown in Eq. (7).

$$p(n)=T(n)*\frac{E_{res}(n)}{E_{nbs\text{-}res}(n)}*\frac{d_{nbs\text{-}toBS}(n)}{d_{toBS}(n)}*\frac{1}{Ncentral(n)} . \tag{7}$$

Where:

$\frac{E_{res}(n)}{E_{nbs\text{-}res}(n)}$ is the ratio to average neighbors, residual energy which can be represented as $\frac{E_{res}(n)}{E_{nbs\text{-}res}(n)}=\frac{E_{res}(n)}{\sum_{j\subset N_n}E_{res}(j)}$, $E_{res}(n)$ is the residual energy of node n. N_n is the neighbor set of node n.

The larger the ratio or the larger the residual energy of the node is, the greater the probability that it will be selected as a CH is.

$\frac{d_{nbs\text{-}toBS}(n)}{d_{toBS}(n)}$ is the ratio to average neighbors, distance to the BS, which can be described as $\frac{d_{nbs\text{-}toBS}(n)}{d_{toBS}(n)}=\frac{\sum_{j\subset N_n}d_{toBS}(j)}{|N_n|*d_{toBS}(n)}$, $d_{toBS}(n)$ is the distance to the BS of node n, and $|N_n|$ is the number of its neighbors. Moreover, the larger the ratio or the smaller the distance to the BS of the node is, the greater the probability that it will be selected as a CH is.

$Ncentral(n)$ is the node centrality whose value shows how central the node is among its neighbors proportional to the network dimension, which can be given by $Ncentral(n)=\sum_{j\subset N_n}d(n,j)/|N_n|$, $d(n,j)$ is the distance between nodes n and j. The higher the value of $Ncentral(n)$ is, the closer the node is to the center of all neighbors, and the greater the probability of becoming a CH is.

The optimal CHs can be generated by the given random numbers and the calculated threshold values in Eq. (7). Then just like in [7, 14, 21], each CH informs its neighbors by broadcasting a small advertisement message, and nodes replying with an acknowledgement message become its member nodes accordingly. Moreover, TDMA schedule mechanism is also adopted to save energy consumption.

4.3 Hop Count Determination with Fuzzy Logic

Computational intelligence techniques such as fuzzy logic [11, 27], ant colony optimization [28], particle swarm optimization [9], and genetic algorithm [25, 29] have been widely used to construct topology, select CHs, find optimal routing, and so on. Especially when there are lots of uncertainties, fuzzy logic approaches yield a better result [11, 27]. Moreover, this is the first time to use fuzzy logic to determine the hop count, as far as we know. without loss of generality, the hop count means the number of hops from the source CH to its next hop CH in layered wireless sensor network. Usually in the traditional algorithms [14, 21], forwarding data to the BS in layer-by-layer mode is adopted, namely the hop count always equals one, then the closer the CHs are to the BS, the more data forwarding task they need to undertake, which results in the spot problem [22, 26]. Consequently, different hop count is applied for each CH so as to find its optimal next hop CH based on the layered topology by layered network configuration in IMF-LEACH. Moreover, the hop count is determined by a Mamdani fuzzy logic controller like in [11, 27], which is shown in Fig. 2.

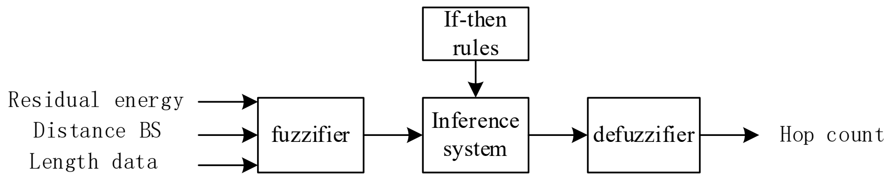
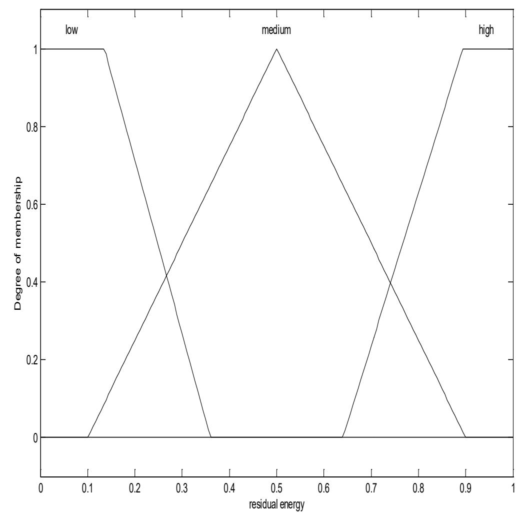
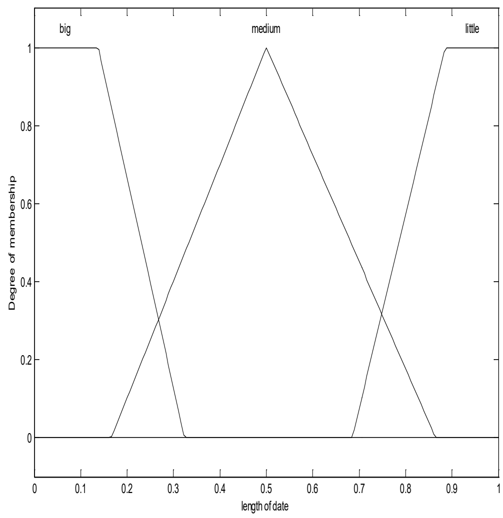


Fig. 2. Fuzzy logic controller of IMF-LEACH

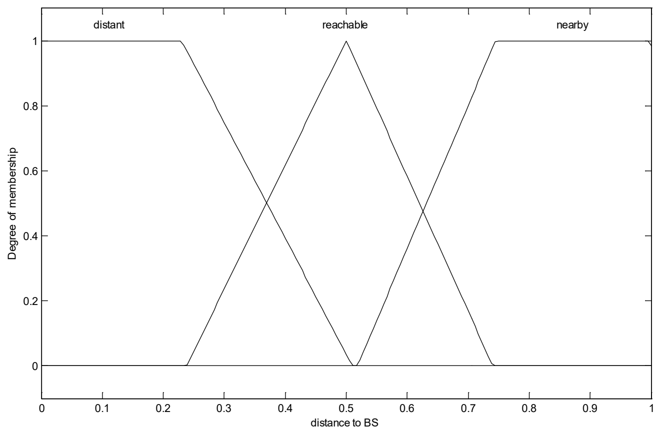
The input parameters of the fuzzy logic controller are 'residual energy', 'distance to BS', 'Length of data', which means the CH with more residual energy, further distance to BS, lower length of data can communicate with its next-hop CH by a big 'hop count'. The inputs and output have corresponding membership functions depicted in Fig. 3. Moreover, the linguistic variable for residual energy is 'low', 'medium', 'high', and the linguistic variable for distance to BS is 'distant', 'reachable', 'nearby'. At the same time, the linguistic variable for length of data is 'big', 'medium', 'little'. In addition, the output 'hop count' linguistic variables is 'very little', 'little', 'rather little', 'low medium', 'medium', 'high medium', 'rather more', 'more', 'very more'. 'Low', 'high', 'big', 'little', 'distant', 'nearby', 'very little', and 'very more' follows trapezoidal membership function, whereas the others have a triangular membership function.



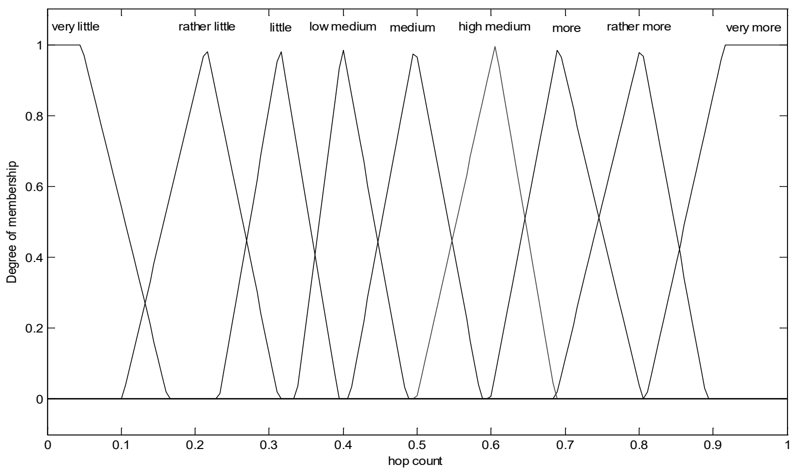
(a) Membership function for residual energy



(b)Membership function for length of data



(c) Membership function for distance to BS



(d) Membership function for hop count

Fig. 3. Membership functions for inputs and output

There are 27 if-then rules used in the fuzzy inference, which are shown in Table 2 based on the above described linguistic variables.

Table 2. Fuzzy if-then rules

No.	Input values			Output values
	Residual energy	Length of data	Distance to BS	Hop count
1	low	big	nearby	little
2	low	big	reachable	rather little
3	low	big	distant	rather little
4	low	medium	nearby	little
5	low	medium	reachable	rather little
6	low	medium	distant	rather little
7	low	little	nearby	very little
8	low	little	reachable	very little
9	low	little	distant	little
10	middle	big	nearby	medium
11	middle	big	reachable	rather more
12	middle	big	distant	Rather more
13	middle	medium	nearby	rather little
14	middle	medium	reachable	medium
15	middle	medium	distant	medium
16	middle	little	nearby	little
17	middle	little	reachable	rather little
18	middle	little	distant	rather little
19	high	big	nearby	very more
20	high	big	reachable	very more
21	high	big	distant	more
22	high	medium	nearby	rather more
23	high	medium	reachable	rather more
24	high	medium	distant	more
25	high	little	nearby	medium
26	high	little	reachable	medium
27	high	little	distant	rather more

Lastly, the crisp values of hop count are obtained by defuzzifying the output of the fuzzy inference using center of area method.

4.4 Multi-hop Routing with Round Updating

In steady state phase, a novel multi-hop routing mechanism in IMF-LEACH is used to forward data to the BS which differs from single-hop in LEACH and hop-by-hop in other multi-hop protocol [14, 26]. For each cluster, CMs send data to their CH during the assigned timeslot, and the CH aggregates and transmits the data to a close intermediate CH located in the layer lower than its *layerID* by hop count. Moreover, the chosen intermediate CH should have more residual energy and less members so as to balance energy consumption. If there is no appropriate CH in the chosen layer, another intermediate CH located in the lower layer is selected to be the next-hop. The process continues until the next hop CH is the BS. The detail description of the multi-hop routing is shown in Fig. 4.

1. Begin
2. n = total number of *CHs*, $CH = \{CH_1, CH_2, \ldots, CH_n\}$;
3. loop1: CH_i = the CH wants to forward data to the BS;
4. m = the number of neighbor *CHs* of CH_i, $nCH_i = \{nCH_1, nCH_2, \ldots, nCH_m\}$;
5. *dthi* = the difference of the maximum and minimum distance to the BS of *CHs* in the layer i, which is used to limit the range of the next-hop *CHs*
6. *HopC* = Fuzzy(CH_i);//calculate the hop count by fuzzy logic controller
7. CH_{next} = the next-hop CH;

```
loop2: j = 0;  //set a flag j to indicate whether there is a next hop CH
for k = 1 to m //to find the appropriate next hop CH in its neighbor CHs
  if CH_k.layerID = = CH_i.layerID-HopC //determine whether the neighbor CH k is located in the target layer
    if j = 0
      CH_next = CH_k;
      j = 1;   //find the first next hop CH in the target layer
    else if abs((CH_k.d_toBS-CH_i.d_toBS)-(CH_next.d_toBS-CH_i.d_toBS))<d_th  //d_toBS is the distance to the BS
      if CH_k.E_res>CH_next.E_res) && (CH_k.member<CH_next.member) //E_res is the residual energy
        CH_next = CH_k;                    //to find the optimal next hop CH
      end if
    end if
  else if CH_i.layerID-HopC<=0 //indicating the BS is the optimal next hop of CH_i
    CH_next=BS;
    goto stop;
  end if
end for
if  j = = 0 //no CH located in the target layer CH_i.layerID-HopC
  HopC+=1; //update the target layer to a lower layer
  if CH_i.layerID-HopC <= 0
    CH_next = BS;
  else
    goto loop2;//continue the process for the CHs located in the lower layer
  end if;
else
  CH_i=CH_next;   //find the optimal next hop CH of CH_i
  goto loop1;   //to find the next hop CH of CH_next
end if;
stop:end   // The BS is the destination of routing path for CH_i
```

Fig. 4. Multi-hop routing mechanism

As illustrated in Fig. 4, for any source cluster head CH_i, it can obtain its neighbor CHs nCH_i by receiving the broadcast advertisement messages of being CH. In addition, the $layerID$ also can be known by the layered network configuration. Once it wants to send data to the BS, the hop count is firstly calculated by the fuzzy controller, and the target layer is determined according to the hop count. And then, the neighbor CHs located in the target layer are selected from nCH_i, and the optimal CH with more residual energy and less distance to the BS is determined as the next hop CH CH_{next} of CH_i. Let CH_i be CH_{next} and the process continues until the optimal next hop CH is the BS. Moreover, when there is no appropriate next hop CH in the target layer, the number of target layer is reduced by one, namely $HopC$ +1. In view of the above, each CH_i in CH will find the optimal multi-hop routing path to the BS.

Besides, an adaptive round time similar to the EM-LEACH [18] is presented in IMF-LEACH according to the residual energy and number of alive nodes in the network without extra overhead by attaching nodes' residual energy in the data packets. Similar to EM-LEACH, the initial round time and the minimum round time are 200% and 50% of the LEACH round time respectively. Then the new round time is given by

$$roundt=roundLeach*\frac{\sum_{i=1}^{n}E_{res}(i)}{\sum_{i=1}^{n}E_{init}(i)}*\frac{n_{alive}}{n} \quad . \tag{8}$$

Where n is the total number of nodes in the network, and nalive is the number of alive nodes in the current round. Einit (i) are residual energy and initial energy of node i.

5 Simulation Results

MATLAB is used to evaluate the performance of IMF-LEACH compared to LEACH [7], EM-LEACH [21] and OMPFM [25]. In the simulations, n nodes are scattered randomly in a 100m×100m sensing field with the BS located at (0,0). The initial energy of each node is 1J. Packet size is between 500-4000bit, number of nodes is 100 and Cluster head ratio is 0.5. The specific parameters are given in Table 3.

Table 3. Simulation parameters

Parameters	Values
E_{elec}	50 nJ · bit^{-1}
ε_{fs}	10 pJ · bit^{-1}
ε_{mp}	0.0013 pJ · bit^{-1}
E_{pDb}	5nJ · bit
data packet size	500 bytes
control packet size	25 bytes

5.1 Average Hop Count

The average hop count denoted by the average number of hops from CHs to the BS which indicates the fast data forwarding capability is determined by the fuzzy logic controller with three descriptors residual energy, length of data, and distance. And the influence of these inputs on the hop count is tested at first, which is shown in Fig. 5.

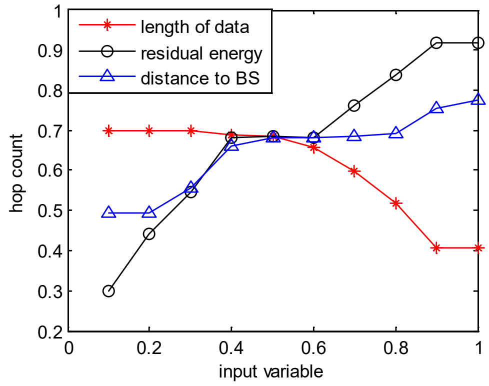


Fig. 5. The relationship between input and output of the fuzzy logic controller

It can be seen from Fig. 5 that the fuzzy value of hop count decreases with the increase of length of data when the fuzzy inputs residual energy and distance to BS are equal to 0.5. Because CHs with more CMs will receive more data, then their hop counts decrease so as to reduce the energy consumption of forwarding data. Moreover, when length of data is less than 0.5, the value of hop count remains unchanged, because distance to BS is fixed, and increasing hop count will increase the network energy consumption. When length of data and distance to BS are fixed, the value of hop count increases with the increase of residual energy, whose range is the largest among the three input variables from 0.2976 to 0.9195. This is because residual energy is one of the most important factors. With the operation of the network, the residual energy of CHs gradually decreases. In order to ensure that the data will not be lost in the forwarding process, the hop count is reduced. When distance to BS increases gradually and the other two input variables remain unchanged, the value of hop count will gradually increase and the energy consumption of CHs will be reduced by multi-hop communication. Furthermore, based on the output scale factor and deffuzzifying well as the if-then rules in Table 1 of each CH, the average hop count of CHs is evaluated, and the results is illustrated in Fig. 6.

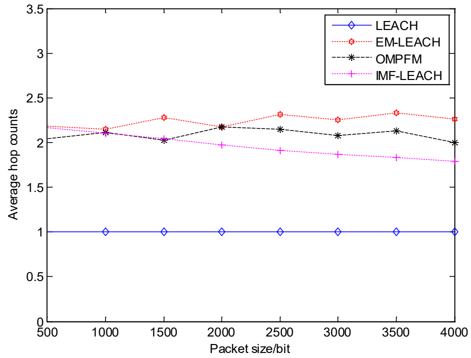


Fig. 6. Comparison of average hop counts

As seen from Fig. 6, the average routing hops of IMF-LEACH proposed in this paper are gradually reduced with the increase of data packets. This is because IMF-LEACH adaptively adjusts the hop count according to the data length by a fuzzy controller compared to fixed single-hop or hop-by-hop communication in LEACH, EM-LEACH and OMFPM. The larger the data length is, the smaller the hop count is, which reduces energy consumption as well as decreases the end-to-end delay. When OMPFM selects the paths, the distance from the CH to the BS is one of the optimal parameters, which is not enough to fully determine the best number of hops. At the same time, EM-LEACH indirectly obtains the number of hops by planning the number of rings in the network. Therefore, compared with LECH, EM-LEACH and OMFPM, the number of hops obtained by IMF-LEACH is the most appropriate.

5.2 Average end-to-end Delay

Average end-to-end delay denoted by the average time of CHs taking to send data to the BS is an important metric to evaluate the real-time performance and fast data forwarding capability. So average end-to-end delay is tested under different packet sending rate, and the results are illustrated in Fig. 7.

It can be seen from Fig. 7 that LEACH has the smallest end-to-end delay because of its single-hop communication mode, and OMPFM is better than EM-LEACH due to its global decision on finding the optimal routing paths compared to layer by layer routing of EM-LEACH.IMF-LEACH determines the optimal number of hops according to the residual energy, the distance to the BS and the data length of each CH, so that each CH has the most appropriate number of hops. Then, IMF-LEACH uses the optimal hop count to forward data until the BS, which largely decreases the end-to-end delay accordingly. Moreover, the number of nodes in the network will also affect the performance of the scheme. With the increase of number of nodes, the end-to-end delay of LEACH, EM-LEACH and OMFPM increases faster than IMF-LEACH because IMF-LEACH determines the routing paths according to the amount of transferred data.

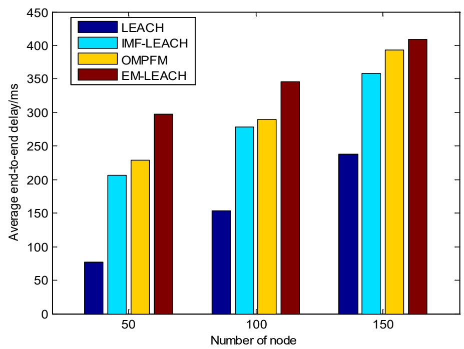


Fig. 7. Comparison of average end-to-end delay

5.3 Energy Consumption Ratio

Energy consumption ratio denoted by the percentage of total energy consumed is used to express the speed of network energy consumption. Evaluations are carried out for IMF-LEACH, LEACH, EM-LEACH and OMPFM, the results are shown in Fig. 8.

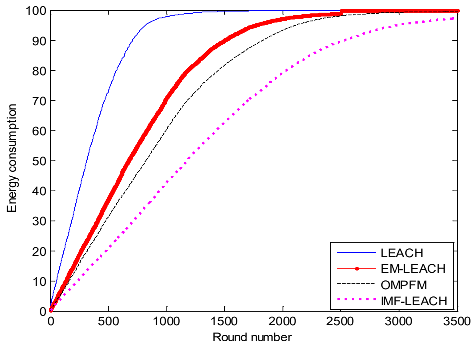


Fig. 8. Comparison of energy consumption ratio

Seen from Fig. 8, LEACH consumes 97% of its total energy in rounds 1004, while EM-LEACH, OMPFM and IMF-LEACH consume the same ratio of energy in rounds 1948, 2759 and 3452 respectively. Compared with LEACH, EM-LEACH and OMPFM, IMF-LEACH uses fuzzy control to allocate the optimal number of hops for each CH to ensure the minimum energy consumed in the process of data transmission. In addition, IMF-LEACH considers the location relationship and residual energy between nodes to complete clustering. Therefore, IMF-LEACH can effectively reduce and balance the energy consumption of intra-cluster communication.

5.4 Network Lifetime

Usually, network lifetime denoted by the number of rounds in which the last node dies is used to evaluate the overall performance of protocols. Compared to LEACH, EM-LEACH and OMPFM, IMF-LEACH forms uniform clusters and finds the optimal multi-hop routing paths as well as adaptively adjusts round time by improved threshold function and fuzzy logic controller, so the network energy consumption is reduced and balanced simultaneously. The tested results are shown in Fig. 9.

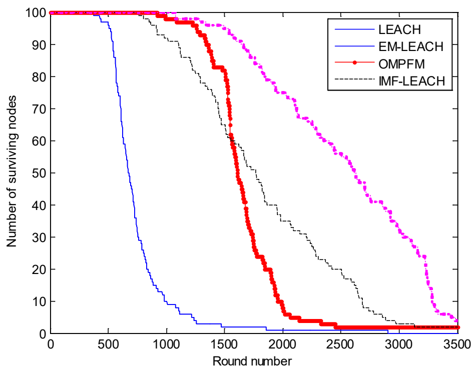


Fig. 9. Comparison of the network lifetime

As seen from Fig. 9, With 5 nodes surviving on the network, LEACH runs for 1055 round, OMFPM runs for 2134 rounds, OMFPM runs for 2926 rounds and IMF-LEACH runs for 3500 rounds. Randomly forming clusters and single-hop communication in LEACH results in the shortest network lifetime. For EM-LEACH, residual energy is considered to form clusters and find the relay nodes, especially, a new round time is calculated to rotate CHs, therefore its network lifetime is significantly extended compared to LEACH. Moreover, OMFPM considers more parameters to form clusters and find routing paths, so its network lifetime is longer than EM-LEACH.

6 Conclusion

In order to save energy and reduce delay of the network, an improved LEACH algorithm called IMF-LEACH is proposed in this paper. Considering that the CH should have more energy and reasonable location, and the distance from the CMs to the CH should be the smallest, IMF-LEACH comprehensively selects the optimal CHs according to the residual energy, node centrality and distance to the BS. Then, the remaining energy, data length and distance to the BS are used as three input parameters of the fuzzy logic controller to estimate the optimal hops for each CH. Finally, combined with the number of hops, residual energy and number of members, the optimal intermediate CH is selected to forward the data to the BS. Simulation results show that IMF-LEACH is superior to the existing LEACH, EM-LEACH, and OMPFM in terms of average hops, average end-to-end delay, energy consumption rate and network lifetime. In the future, two-level fuzzy logic controller will be designed to find the optimal hop number and optimal paths together. In addition, routing paths in multi-hop in mobile wireless sensor networks will be considered in the future.

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