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An Energy Efficient Fuzzy Logic Cluster Formation Protocol in Wireless Sensor Networks

Rogaia Mhemed, Nauman Aslam, William Phillips and Frank Comeau

Abstract

Despite significant advancements in wireless sensor networks (WSNs), energy conservation remains one of the most important research challenges. Researchers have investigated architectures and topologies that allow energy efficient operation of WSNs. One of the popular techniques in this regard is clustering. While many researchers have investigated cluster head selection, this paper investigates the cluster formation. In particular, we propose a novel scheme, the Fuzzy Logic Cluster Formation Protocol (FLCFP), which uses Fuzzy Logic Inference System (FIS) in the cluster formation process. We demonstrate that using multiple parameters in cluster formation reduces energy consumption. We compare our technique with the well known LEACH protocol to show that using a multi parameter FIS enhances the network lifetime significantly.

1. Introduction

Recent advancements in WSNs are predominantly motivated by developments in the micro electromechanical systems (MEMS) technology. Typically, a WSN is a collection of a large number of low cost wireless nodes that contain one or more MEMS-based sensors. Integration of sensors to wireless nodes in this manner allows them to interact with the physical world and collect data using on-board sensors [1] [2]. Moreover, sensor nodes are resource-constrained. To take advantage of these resource-constrained sensor nodes, the nodes form clusters, which are generally defined as a grouping or organizing of objects that share one or more properties.

The clustering strategy adds flexibility in achieving many goals, such as energy efficient operation, prolonging the WSN lifetime and decreasing the number of nodes that communicate with the base station (BS). Energy efficiency is an important criterion. For energy efficient operation, optimal cluster formation is necessary to ensure that energy is consumed at a balanced rate. While some studies have focused on the cluster head (CH) selection [3] [4] [5], we have focused on cluster formation. In the Low-Energy Adaptive Clustering Hierarchy protocol (LEACH) [6], each node decides which cluster it belongs to by picking the CH that requires the smallest transmission distance, indirectly by measuring the received power from a CH message. Considering only the distance between the CH and the node ignores other factors that affect the energy consumption and the network lifetime. We present a Fuzzy Logic approach for the cluster formation that uses the energy level of the CH, distance between the BS and the CH, and distance between the CH and the node as parameters. For cluster formation, each non-CH node applies the three descriptors for each CH using the Mamdani Fuzzy Inference System [7], and joins the CH that has the maximum chance value to form the cluster. We call our approach the Fuzzy Logic Cluster Formation Protocol (FLCFP) for WSN.

To demonstrate the improvement in energy efficiency of our proposed FLCFP, we compare it with LEACH. Simulation results show that our approach extends the network lifetime significantly as compared to the LEACH protocol. In addition, our simulations show that the nodes consume energy in a more uniform fashion.

The remainder of this paper is organized as follows: In Section 2, we present a brief discussion of related work. In section 3, we describe our novel approach for cluster formation. Comparison of FLCFP

with LEACH using First Node Death (FND) metric is presented in section 4. We conclude the paper in Section 5.

2. Related Work

Several clustering strategies have been proposed for WSNs in recent years [8] [9] [10]. Our proposed protocol, the FLCFP, is an extension of the LEACH protocol. Both are Hierarchical Schemes.

LEACH is the original clustering protocol for WSN. It created a foundation for many other algorithms such as those proposed by the authors of [3], [4] and [5]. In addition, it was the most important protocol that proposed to prolong the overall lifetime of the network and to decrease the overall energy consumed by the network [6]. The operation in LEACH is divided into rounds. Each round contains a set-up stage, where each sensor node picks a random number between 0 and 1 to decide whether it will become a cluster-head or not. If the number chosen by a particular node is less than the threshold value $T(n)$, the node becomes a CH for the current round. We can compute $T(n)$ as shown below in equation 1.

$$T(n) = \begin{cases} \frac{p}{1 - p \times \left(r \bmod \frac{1}{p}\right)} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Where p is the expected percentage of cluster heads, r is the round number, and G is the set of nodes that have not been a CH in the last $1/p$ rounds.

The Gupta Fuzzy Protocol [3] uses the Fuzzy Logic approach to select CHs using three parameters: energy level, concentration, and centrality; each one divided into three levels. Mainly, this protocol has taken the LEACH protocol as a basis. The difference between the two protocols lies in the set-up stage where the BS needs to collect energy level and location information for each node, and evaluate them in the designed FIS to calculate the chance for each node to become a CH. The BS then chooses the node that has the maximum chance of becoming a CH.

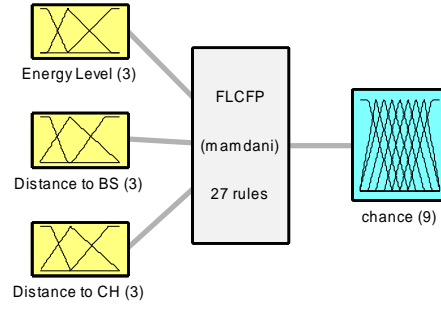
The CHEF protocol (Cluster Head Election mechanism using Fuzzy Logic in Wireless Sensor Networks) [4] uses a Fuzzy Logic approach to maximize the lifetime of WSNs. It is similar to the Gupta protocol but it does not need the BS to collect information from all nodes. Instead, the CHEF protocol uses a localized CH selection mechanism using Fuzzy Logic.

In [5] the LEACH-FL (Improving on LEACH Protocol of Wireless Sensor Networks Using Fuzzy Logic) protocol is proposed. This protocol uses Fuzzy Logic to improve the LEACH protocol by considering three different parameters: energy level, node density, and distance between the CH and the BS. This model is the same as the Gupta protocol with a set-up stage and a steady-state stage, except that in the set-up stage it chooses different parameters to apply in the designed FIS to obtain the probability value for each node.

As discussed above, a number of variations on the LEACH protocol use fuzzy logic [3] [4] [5]. However, these protocols use fuzzy logic for cluster head selection, while our algorithm, FLCFP, uses fuzzy logic for cluster formation.

3. Fuzzy Logic based Cluster Formation Protocol

Our goal is to prolong the lifetime of WSNs by using the Fuzzy Inference System (FIS), which provides a method for formulating the mapping from input(s) to output(s). Our fuzzy clustering formation operates in rounds similar to LEACH. Each round is composed of a set-up stage and a steady-state stage. The main difference between FLCFP and LEACH lies in the cluster formation phase. In FLCFP, the non-CH nodes compute a chance value for each CH by applying the FIS. The inference techniques and our Fuzzy Logic system design are illustrated in Figure 1.



System FLCFP: 3 inputs, 1 outputs, 27 rules

Fig.1. FLCFP System

In our proposed model we use the method used in [3] [4], and [5], called the Mamdani method in the MATLAB Fuzzy Logic toolbox.

3.1. FIS Parameters and Rules

We use the following equations to compute the energy that will be consumed during transmission and reception between transmitter and receiver [6]:

$$E_{TX}(l, d) = E_{elec} * l + \varepsilon_{amp} * l * d^{\lambda} \quad (2)$$

$$E_{RX}(l) = E_{elec} * l \quad (3)$$

Where λ is the path loss exponent, l is the messages size in bits, d is the distance between transmitter and receiver, ε_{amp} is the energy constant for propagation, and E_{elec} is the electronics energy. For transmissions to the CH, $\lambda = 2$ and $\varepsilon_{amp} = 10$ pJ/bit/m². For transmissions to the BS $\lambda = 4$ and $\varepsilon_{amp} = 0.0013$ pJ/bit/m⁴.

To extend the network lifetime, we divided each linguistic variable used to represent these parameters into three levels as follows. Low, medium, and high are used for the energy level of the CH; and close, medium, and far are used for the distance to the BS and the distance between the CHs and the node. We chose Triangular and Trapezoid membership functions, as identified in MATLAB fuzzy logic toolbox, to present our parameters, as shown in equations 4 and 5.

$$\mu_{A1}(x) = \left\{ \begin{array}{ll} 0, & x \leq a1 \\ \frac{x - a1}{b1 - a1}, & a1 \leq x \leq b1 \\ \frac{c1 - x}{c1 - b1}, & b1 \leq x \leq c1 \\ 0, & c1 \leq x \end{array} \right\} \quad (4)$$

$$\mu_{A2}(x) = \left\{ \begin{array}{ll} 0, & x \leq a2 \\ \frac{x - a2}{b2 - a2}, & a2 \leq x \leq b2 \\ 1, & b2 \leq x \leq c2 \\ \frac{d2 - x}{d2 - c2}, & c \leq x \leq d2 \\ 0, & d2 \leq x \end{array} \right\} \quad (5)$$

Where the values of a1, a2, b1, b2, c1, c2, and d2 used are

- energy level: low ($a_2=-1, b_2=0, c_2=0.05, d_2=0.175$), medium ($a_1=0.05, b_1=0.175, c_1=0.45$), high ($a_2=0.175, b_2=0.45, c_2=0.5, d_2=0.51$);
- distance to the BS: close ($a_2=-1, b_2=0, c_2=20, d_2=55$), medium ($a_1=0, b_1=60, c_1=160$), far ($a_2=65, b_2=130, c_2=160, d_2=161$);
- distance between the CH and the node: close ($a_2=-1, b_2=0, c_2=20, d_2=55$), medium ($a_1=0, b_1=55, c_1=142$), far ($a_2=55, b_2=122, c_2=142, d_2=143$).

To give our incidence feature flexibility we divided the linguistic variable for chance value into 9 levels as follows: very weak, weak, little weak, little medium, medium, high medium, little strong, strong, and very strong. Once again, the trapezoidal membership function represents both sides, and the triangle membership function represents other chance levels as shown in Figure 2.

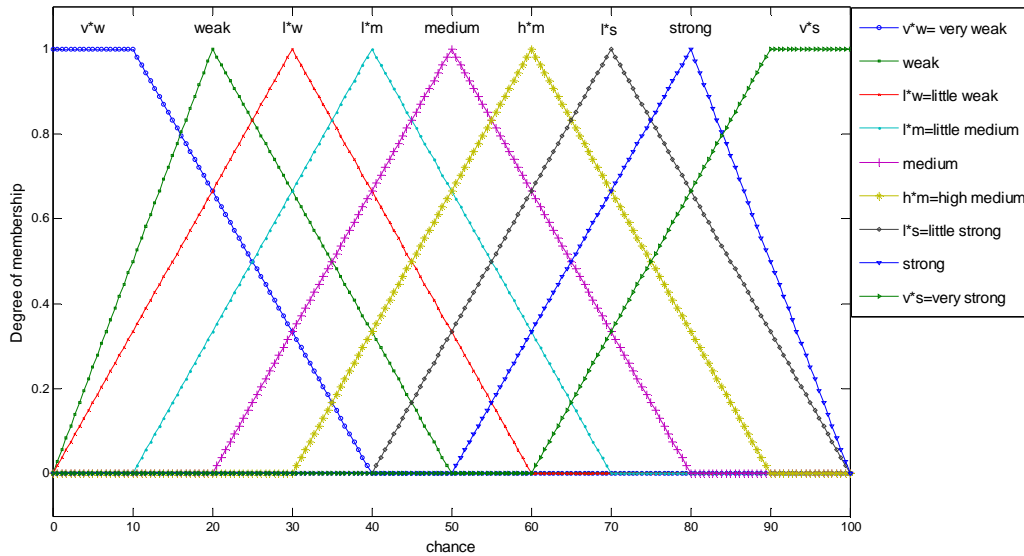


Fig.2. Degree of Membership vs. Chance Values

Since we have three parameters, each divided into three levels, $3^3=27$ possible chance values can be computed using our fuzzy IF-THEN rules. These rules fall between two extreme cases as shown in Table1:

Extreme Case 1: If (energy is low) and (distance to the BS is far) and (distance between the CH and the node is far) then (chance is very weak).

Extreme Case 2: If (energy is high) and (distance to the BS is close) and (distance between the CH and the node is close) then (chance is very strong).

Table 1. Fuzzy IF-THEN Rules

Energy level	Distance To the BS	Distance To the CH	Chance	Energy level	Distance To the BS	Distance To the CH	Chance
Low	Far	Far	Very weak	Medium	Medium	Close	High medium
Low	Far	Medium	Weak	Medium	Close	Far	Medium
Low	Far	Close	Little weak	Medium	Close	Medium	High medium
Low	Medium	Far	Weak	Medium	Close	Close	Little strong
Low	Medium	Medium	Little Weak	High	Far	Far	Medium
Low	Medium	Close	Little medium	High	Far	Medium	High medium

Low	Close	Far	Little Weak	High	Far	Close	Little strong
Low	Close	Medium	Little medium	High	Medium	Far	High medium
Low	Close	Close	Medium	High	Medium	Medium	Little strong
Medium	Far	Far	Little weak	High	Medium	Close	Strong
Medium	Far	Medium	Little medium	High	Close	Far	Little strong
Medium	Far	Close	Medium	High	Close	Medium	Strong
Medium	Medium	Far	Little medium	High	Close	Close	Very strong
Medium	Medium	Medium	Medium				

3.2. Determination of Cluster-Head Chance Value:

The concept of Fuzzy Logic is based on four steps: fuzzification, rule evaluation, aggregation, and defuzzification. These four steps are used in FIS to calculate the chance values as follows:

- Step 1: Input of Crisp Value and Fuzzification

First, we forward our inputs (crisp values), which represent our parameters: energy level of the CH, distance to the BS, and distance to the CH, to our FIS. Depending on these three crisp numbers, we determine the value of the membership function, which is the intersection point of the value of our parameters with the degree of the membership function.

- Step 2: Rule Evaluation

After the fuzzification step has been completed, we supply the membership values obtained to our IF-THEN rules to determine our new fuzzy output set. Our fuzzy IF-THEN rules have multiple inputs and the fuzzy operator (AND), which simply selects the minimum of our three membership values, is used to get a single number.

- Step 3: Aggregation of the Rule Outputs

The aggregation is a process of the union of all the outputs obtained from applying all rules (27 rules in our FIS model). Since we aggregate all our rules, we have used an OR Fuzzy Logic operator. The OR operator selects the maximum of our rule evaluation values to generate the new aggregate fuzzy set, which we use in the next step.

- Step 4: Defuzzification

The last step is de-fuzzification, where we obtain our chance value. We have used the Mamdani technique to calculate the implication value, and the Centroid defuzzification method to find the CH election chance value to form a cluster formation. Therefore, the Center Of Area (COA) will be used in the centroid defuzzification, which we can compute from equation 6.

$$COA = \int \mu_A(x) * x dx / \int \mu_A(x) dx \quad (6)$$

Where $\mu_A(x)$ is degree of membership function of fuzzy set A, which is defined in equation 7.

$$A = \{(x, \mu_A(x)) | x \in U\} \quad (7)$$

By applying the values we obtained from step 3 and calculating COA, we determine the chance value for electing a CH to form a cluster. If two CHs have the same chance value, to break the tie between them, we choose one closer to the BS. Then we use the distance to the CH.

4. Evaluation

Using this network operation model allows the network lifetime metric to be measured in data collection rounds till the very first node runs out of energy. This metric is known as first node death (FND). It has been used extensively in literature [11] [12] [13]. The configuration parameters used in our experiments are shown in Table 2.

Table 2. Simulation Parameters

Parameters	Value
Network size	(100 x 100)m ²
Base station location	(50 , 150) m
Number of nodes	100
Initial Energy	0.5 J
Data packet size	4000 bits
Probability of becoming CH	0.1

4.1. Simulation Scenario

Figure 3 shows the number of alive nodes for both the LEACH and our FLCFP algorithms. Our FLCFP outperforms the LEACH algorithm. We observe that the average value for FND for LEACH is 541, whereas, in the FLCFP, the average is 634. These improvements rely on the nature and number of parameters that have been used for each protocol.

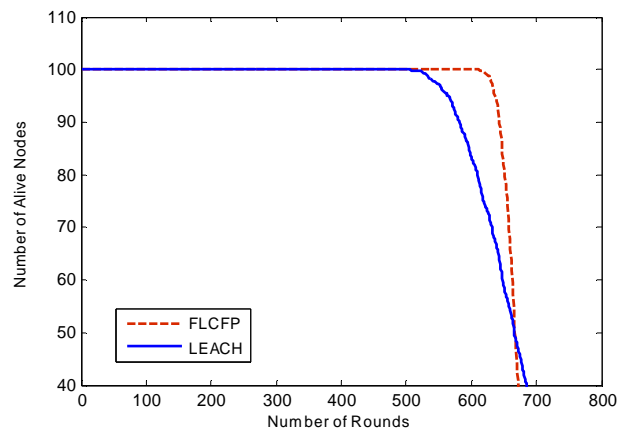


Fig.3. Number of Alive Nodes Per Round

To understand the energy consumption behavior of the sensor nodes, we monitor the residual energy level of the nodes just before the FND in FLCFP. As a result, we can see from Figure 4 below that our FLCFP helps the nodes to consume energy in a uniform way. Conversely, the energy of the nodes in LEACH is quite variable with some nodes having a high energy level and some nodes being dead. The FLCFP the node energies do not have these extremes.

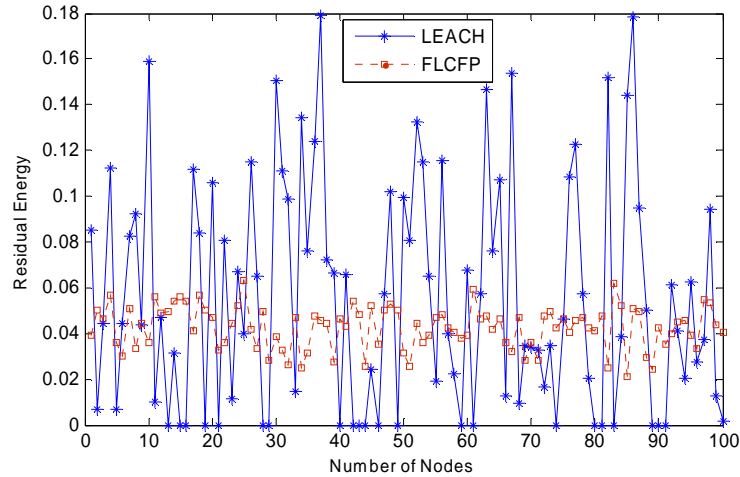


Fig.4. Residual energy of the nodes

These results show that our proposed algorithm delays FND approximately 17% as compared with LEACH, a significant improvement in network lifetime.

We confirmed the results for the FND metric using statistical analysis based on testing the hypothesis that there is difference in the results collected from simulating both algorithms using the same configuration parameters. MINITAB software was used to conduct a Paired T-test. Our testing hypotheses were:

$$H_0: \text{Difference} = 0$$

$$H_1: \text{Difference} \neq 0$$

Paired T for FLCFP - LEACH

	N	Mean	StDev	SE Mean
FLCFP	10	634.10	7.53	2.38
LEACH	10	541.80	19.22	6.08
Difference	10	92.30	16.16	5.11

95% CI for mean difference: (80.74, 103.86)

T-Test of mean difference = 0 (vs. not = 0): T-Value = 18.06 P-Value = 0.000

The MINITAB results show a p-value of zero indicating that the FLCFP network lifetime is significantly longer as compared to the LEACH protocol.

From the previous results and analysis we conclude that the FLCFP improves the time to FND because it considers three parameters in cluster formation, as opposed to LEACH, which uses only one parameter - the sensor node's distance to the CH as determined by a received power measurement. Our proposed algorithm, FLCFP, considers three parameters (energy level of the CH, distance of the CH to the BS and the distance between the CH and the node) to calculate the chance value for each CH.

5. Conclusion

In this paper, we presented a novel approach for cluster formation in WSNs that uses Fuzzy Logic to enhance network lifetime. We have analyzed the performance of our protocol through simulations, and compared its performance with the LEACH protocol using FND metrics and Paired T-Test in MINITAB, and found that our protocol improved the network overall lifetime from 12% to 19%. This improvement is

attributed to the fact that our proposed protocol uses three parameters in the cluster formation process as compared to LEACH, which uses only one parameter.

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