A Fuzzy-logic Based Energy-efficient Clustering Algorithm for the Wireless Sensor Networks

Quan Wang, Deyu Lin, Pengfei Yang, Xidian University
Schoolo of Computer Science and Technology
Xian, China
Email: Dashing_lin@126.com

Zhiqiang Zhang, University of Leeds
School of Electronic and Electrical Engineering
Leeds, UK
Email: eendl@leeds.ac.uk

***Abstract*—The clustering strategy is one of the most promising schemes to reduce the energy consumption since the power constraint still remains as a bottleneck for the Wireless Sensor Networks (WSNs). Though the energy efficiency has been improved, most of them result in too much computational expense. The fuzzy-logic based clustering algorithm outperforms others owing to its superiority in imitating the human's decision making and its ability in transforming multiple inputs into a single output. A Fuzzy-Logic based Energy-Efficient Clustering algorithm (FLEEC) is proposed in this paper. A two-level fuzzy logic system is designed to balance the energy consumption and relieve the "hot spot problem". In the first level, the Sink determines the communication radius for all the sensor nodes according to the fuzzy inputs of the Node-Density and the Distance-to-Sink. The probability to be the cluster head is calculated locally in the second level basing on the descriptors of the Residual-Energy and the Total-Distance generated in the first level. Finally, extensive experiments are conducted and the performance of FLEEC is evaluated. It is proved to be more energy efficient than other clustering schemes such as LEACH and EFCH through the results comaprison.**

Keywords*—*CHEF; Energy efficiency; Fuzzy logic control; Hot spot problem; LEACH; The wireless sensor networks

I. Introduction

Benefited from the rapid development of the Micro-Electric-Mechanical System (MEMS) and the great advancement in wireless communication, recent years have witnessed a boom in the Wireless Sensor Networks (WSNs). So far, the Wireless Sensor Networks have gained wide applications in a variety of scenarios, such as environment monitoring, habitat monitoring, industrial controlling, battlefield surveillance, structural health monitoring, infrastructure & facility diagnosis, and other commercial applications[1][2][3].

Although great improvement has been made, the energy constraint still remains as a bottleneck for WSNs. The fact that the sensor nodes are often scattered by the airplane and distributed in the harsh environment makes it impossible or even unpractical for them to be replenished. The lifetime of the WSNs can be extended if the energy efficiency is improved. Clustering strategy is one of the most energy-efficient approaches. The Cluster Heads (CHs) compress the data received from their Cluster Members (CMs) through data fusion to reduce the data redundancy, therefore the energy is saved.

Various clustering algorithms have been proposed these years, such as LEACH[4], PEGASIS[5], EDFCM[6], and so on. In spite of the ability to extend the lifetime to some extent, they only take the amount of the resdual energy into consideration when cluster forming. Besides, the process of cluster heads selection is compute-intensive. Therefore the light-weight and more energy efficient clustering algorithm is necessary for WSNs.

Fuzzy-logic based control, owing to its superiority in manipulating linguistic rules in a natural way and imitating the process of human's decision making, has found wide applications in the Wireless Sensor Networks recently[16][17]. The fuzzy-logic based controller can blend different parameters together to make a real-time decision. As for the Clustering schemes, the cluster head election process is obviously more advisable when multiple factors are taken into consideration. Hence a lots of algorithms basing on the fuzzy logic have emerged recently[7][8][9][10][11][12][13][14].

Fuzzy logic theory found its earliest utilization in the cluster head election in Ref.[14] by Gupta. He used a fuzzy-based approach which adopted three descriptors, namely energy, concentration and centrality to lessen the energy dissipation. An energy efficient scheme which used an unequal clustering algorithm and based on the fuzzy logic & improved ACO (UCFIA) and another scheme named IFUC were proposed by Mao *et al.* in [7] and [8] respectively. In order to alleviate the "hot spots problem" and extend the lifetime of the WSNs as long as possible, each node's local information, such as the distance to the Sink, the energy level and the local density were taken into consideration. Besides, Ref.[8] adopted the max-min ant colony optimization to achieve energy-aware inter-cluster routing so as to balance the energy consumption among the cluster heads. To reduce the energy expenditure of the Cluster Heads election process, Cluster Head Election mechanism using Fuzzy logic (CHEF) was introduced in Ref.[9]. In CHEF, the probability of each sensor node to become a Cluster Head was determined according to two fuzzy variables whihc are energy and local distance. An Energy-aware distributed Clustering Protocol in the wireless sensor networks which uses the Fuzzy logic (ECPF) was presented in [11]. Three strategies were utilized to lengthen the lifespan as long as possible. As a fuzzy-logic-based algorithm, ECPF used a couple of fuzzy inputs, namely the node degree and the node centrality, to generate an output.

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A Fuzzy-Logic based Energy-Efficient Clustering algorithm (FLEEC) is proposed in this paper. A two-level fuzzy-logic system is designed to balance the energy consumption and relieve the "hot spot problem"[15]. In the first level (FLC_1), the Sink determines the communication radius according to the fuzzy inputs, namely the Node-Density and the Distance-to-Sink. The probability to be cluster head is determined locally in the second level (FLC_2) basing on the descriptors of the Residual-Energy and the Total-Distance, which are the outputs of the first level. The "hot spot problem" can be alleviated since the node density, the total distance to the Sink and the residual energy are considered together. Furthermore, compared with the approaches in Refs.[8][10][14], FLEEC requires less memory and computation resources due to the reduction of the fuzzy rules used for control.

The reminder of the paper is organized as follow. The preliminaries are elaborated in Section II. Subsequently the Fuzzy-Logic based Energy-Efficient Clustering algorithm (FLEEC) is presented in Section III and Section VI conducts a lot of experiments to evaluate its performance. Finally, Section V concludes this paper and points out the research direction in the future.

II. Preliminaries

A. Network Model

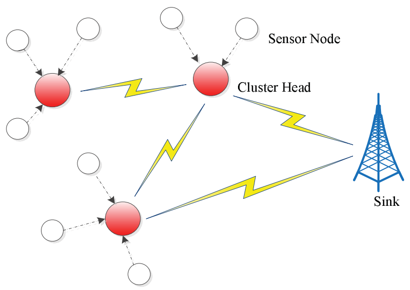


Fig.1 The network model

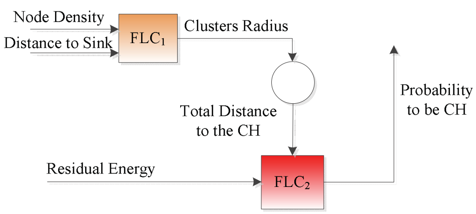


Fig.2 The system basing on fuzzy-logic which controls the clustering

Fig.1 shows the network model used in this paper. It consists of a large number of sensor nodes. Two kinds of nodes coexist in the hierarchical sensor network. They are Cluster Heads (CHs) and Cluster Members (CMs) respectively. The nodes possessing more energy (the red ones) act as Cluster Heads which are responsible for fusing the data from their cluster members (the white ones) and transmitting data to the Sink.

B. Some Assumptions

For the sake of simplicity and convenience, some assumptions is presented as follow.

1. Each sensor node keeps stationary once being deployed.
2. All the sensor nodes are assumed to be supplied with the same initial energy and left to be unattended. However, the Sink has no limitations in terms of computation capability and energy, memory capacity.
3. The nodes are capable of changing the transmission power. It enables the nodes to control the energy consumption.
4. The distance between the source and the destination nodes can be determined basing on the wireless radio the Received Signal Strength(RSS).

C. Energy Consumption Model

The energy dissipated for transmission for the node is measured as Equations(1-2), which mean the energy consumed for transmitting and receiving l bits data to distance d are E_{tx} and E_{rx} respectively

$$E_{tx} = E_{elec} \cdot l + \varepsilon_{amp} \cdot l \cdot d^{\alpha} \quad (1),$$

$$E_{rx} = E_{elec} \cdot l \quad (2),$$

where E_{elec} represents the energy dissipation per bit in the transmitter or receiver circuit and ε_{amp} is the energy consumed for amplifying radio signals. The specific values of ε_{amp} and α rely on the critical transmission distance $d_{critical}$ as Equation(3) shows:

$$d_{critical} = \sqrt{\varepsilon_{fs} / \varepsilon_{mp}} \quad (3),$$

where ε_{fs} and ε_{mp} represent the specific values of energy dissipation factor ε_{amp} for the free space and multi-path transmission models respectively [10]. The values of α can be 2 or 4 for the two transmission models respectively.

III. The Template The Fuzzy-Logic Based Energy-Efficient Clustering Algorithm (FLEEC)

A. System Model

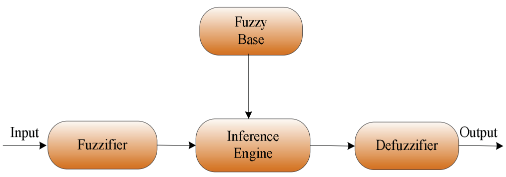


Fig.3 The structure of the fuzzy-logic controller

The system model used in this paper is shown in Fig.2, two fuzzy logic controllers comprise the fuzzy-logic system. Unlike other fuzzy-logic based schemes listed in Refs.[7-15], the first-level fuzzy logic controller (FLC_1) turns two fuzzy descriptors, namely the Node-Density and the Distance-to-Sink to be the Clusters-Radius. The Clusters-Radius acts as the inputs of FLC_2. Then the nodes calculate the total distance to their neighbors basing on the output of FLC_1. Finally FLC_2 generates the probability of the nodes to be cluster head according to the Residual-Energy and the Total-Distance-to-CH.

Fig.3 illustrates the structure of the fuzzy-logic controller. It consists of a fuzzifier, a fuzzy rules base, an inference engine, and a defuzzifier. The fuzzifier is responsible for mapping each crisp input to its corresponding fuzzy element and determining the degree of the membership for each fuzzy set. Thus, the deterministic values are transformed into the fuzzy ones. Once being fuzzified, the inputs are processed by the fuzzy-logic decision-making block which consists of an inference engine and a fuzzy rules base. The fuzzy rules base on the common experience of humans' decision making. In the inference engine of FLEEC, the authors adopted the Mamdani method to establish the rules base for further process. The Mamdani method is one of the most commonly used fuzzy-logic engine technique owing to its simplicity. The basic rules in the fuzzy rules base can be described in the Table.4 following the pattern like "If (the Distance-to-Sink is Near) and (the Node-Density is Sparse) then (the Communication-Radius is Medium)". The last part of the fuzzy-logic system is assigned to turn the fuzzy outputs generated by the inference engine to a crisp value. This process is also called defuzzification. In this paper we use the Center of the Area (COA) to conduct the process of defuzzification. The working mechanism of it is described as Equation (4):

$$probability_{COA} = (\sum \mu_{probabitlity}(x) \cdot x) \big/ \sum \mu_{probability}(x) \qquad (4),$$

where $\mu_{probabibity}(x)$ is the membership function of the set $probability$.

B. The Fuzzy-logic Based Energy-Efficient Clustering Algorithm (FLEEC)

As is analyzed in Ref.[15], the "hot spot problem" would be triggered if the clusters were formed with the same size without considering the distance of nodes to the Sink. The node nearer to the Sink, the more energy is required for communication. The phenomenon can be easily explained by Fig.1. In the FLEEC scheme, the "hot spot problem" is relieved by the fuzzy logic based system. Compared with the energy-efficient strategies proposed in Refs.[4-6], the FLC_1 uses one more decision variable, namely the Node-Density. It enables the FLC_1 capable of being applied in the situation where the sensor nodes distribute unequally. In the FLC_1 , the following two fuzzy descriptors are collected to achieve unequally cluster formation.

(1)The Distance-to-Sink, each node is able to evaluate the value in the initial stage via the message from the Sink since all the nodes are aware of their location with the help of the RSS.

(2)The Node-Density, which represents the cardinal of the neighbors set of each sensor node. The neighbor set of sensor node i can be defined as Expression(5):

$$Ne(i) = \{Node_x \mid Dis(Node_i, Node_x) \le d_{initial}\} \qquad (5),$$

where $Dis(Node_i, Node_x)$ denotes the distance between $Node_i$ and $Node_x$ and $d_{initial}$ denotes the value of the communication radius of each node.

It is worth noting that although the cluster size is calculated globally by the Sink, no much overhead is produced as the process is done on-demand. Once the FLC_1 generates the output, each node will obtain the corresponding communication radius and then the would-be cluster head computes the total distance to the neighbors within its communication radius. The total distance (denoted as Total-Distance) and the residual energy (denoted as Residual-Energy) of a node compose the inputs of the FLC_2 . The FLC_2 regulates the value of the probability of each node to be CH by considering the residual energy and its dissipation rate together.

The fuzzy sets and the membership functions of both the inputs and the outputs in FLC_1 and FLC_2 are shown in Tables(1-2) and Figs(4-9). The trapezoidal and triangular membership functions are utilized in the paper owing to its simplicity to realization. The variation range of all the elements is normalized to be 0 to 1. The value of each element reflects the degree of membership. For instance, as for the input Node-Density, the value 0.8 indicates the node density is dense.

Table.1 shows the fuzzy sets for each input variable. As is shown in Fig.2, the first two variables, namely the Node-Density and the Distance-to-Sink, constitute the inputs for the FLC_1 . The later two comprise the inputs for the FLC_2 . After fuzzy inference process and defuzzification, the two outputs is produced by the fuzzy logic system and they are shown in Table.2.

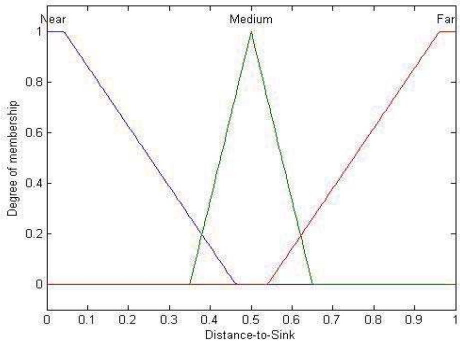


Fig.4 The membership function for the Distance-to-Sink

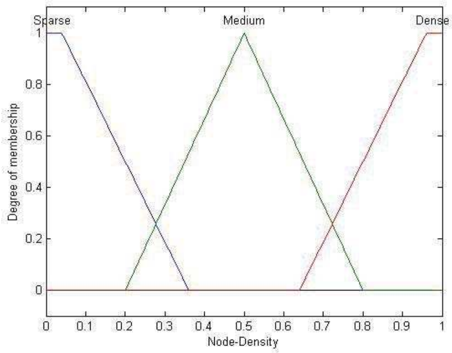


Fig.5 The membership function for the Node-Density

The fuzzy rules base is a vital part for the fuzzy logic controller. It consists of numerous expert knowledge or heuristic rules which base on the practical experience. The fuzzy rules used in this paper are listed in Tables.(3-4). From Table.3, the conclusion can be drawn that the Communication-Radius depends on both the distance-to-Sink and the Node-Density. For example, Rule.3 indicates that if a node is close to the Sink and lies in an area where the nodes are rather dense, then it should cut down the communication range. It is reasonable owing to the fact that the nodes lying in the "hot spot" bear heavier traffic burden. So the fuzzy logic rules is helpful to relieve the "hot spot problem" and balance the energy consumption.

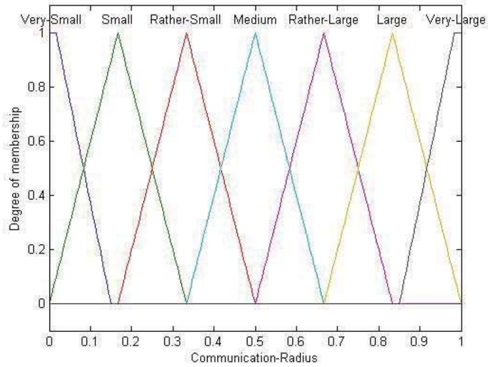


Fig.6 The membership function for the Communication-Radius

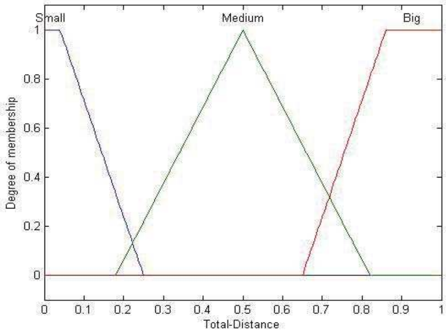


Fig.7 The membership function for the Total-Distance

TABLE 1 THE FUZZY SETS FOR INPUTS VARIABLES

Input Variables	Fuzzy Sets
Node-Density	Sparse, Medium, Dense
Distance-to-Sink	Near, Medium, Far
Total-Distance	Small, Medium, High
Residual-Energy	Low, Medium, High

TABLE 2 THE FUZZY SETS FOR OUTPUTS VARIABLES

Output Variables	Fuzzy Sets
Communication-Radius	Very Small, Small, Rather Small, Medium, Rather Large, Large, Very Large
Probability-to-be-CH	Very Low, Low, Rather Low, Medium, Rather Hgh, High, Very High

TABLE 3 THE FUZZY RULES USED IN FLC_1

Distance-to-Sink	Node-Density	Cluster Head Radius
Near	Sparse	Medium
Near	Medium	Small
Near	Dense	Very Small
Medium	Sparse	Rather Large
Medium	Medium	Medium
Medium	Dense	Rather Small
Far	Sparse	Very Large
Far	Medium	Large
Far	Dense	Medium

Table.4 shows the fuzzy rules for FLC_2. According to the rules listed in Table.4, the energy consumption balance and reduction are considered together. Following this rules, the nodes with more neighbors and higher energy have higher probability to be responsible for acting as CHs.

C. Cluster Formation

FLLEC consists of three main phases, namely the cluster radius determination phase, the probability to be cluster head determination phase and the cluster head selection phase.

1) The cluster radius determination phase

In the initial phase, the Sink sends an initial message to all the sensor nodes in the form of broadcast. Once receiving the initial message, the sensor nodes calculate the distance to the Sink according to the Received Signals Strength (RSS). Subsequently, the sensor nodes send an initial ACK message which contains the ID, the region location and the residual energy to the Sink. Then the Sink establishes a list which records the node ID, residual energy, the distance to the Sink respectively. Besides, it also calculates the node density distribution of different regions and keeps it in its memory. Finally, the sensor nodes calculate their corresponding cluster radius through the first level fuzzy logic FLC_1 and keep the value in their memory.

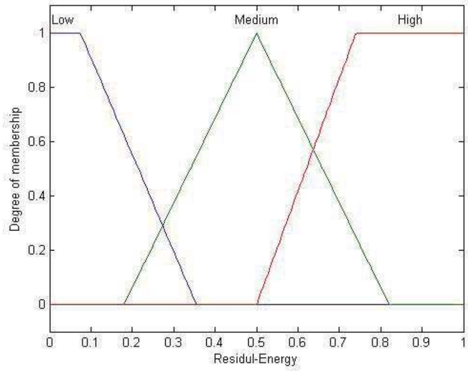


Fig.8 The membership function for the Residual-Energy

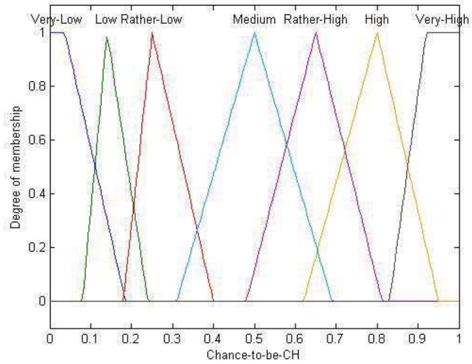


Fig.9 The membership function for the Chance-to-be-CH

TABLE 4 THE FUZZY RULES USED IN FLC_2

Total-Distance-to-CH	Residual-Energy	Probability to be CH
Small	Low	Low
Small	Medium	Medium
Samll	High	Very High
Medium	Low	Rather Low
Medium	Medium	Medium
Medium	High	High
Big	Low	Very Low
Big	Medium	Medium
Big	High	Rather High

2) The probability to be cluster head determination phase

Once obtaining the cluster radius, each node sends the neighbor discovery message in the form of broadcast. The nodes reply with a neighbor discovery message acknowledge once receiving the neighbor discovery message. Subsequently, the nodes calculate the total distance to their neighbors according to the Received Signals Strength. Finally all the nodes input their residual energy and the total distance to the FLC_2 to generate the probability to be CHs basing on the fuzzy rules stored in the fuzzy rules base.

3) The cluster head selection phase

The node sends the HELLO message to all its neighbors in the form of broadcast which contains its value of both the probability to be CH and its ID. Other nodes also do this at the same time. Once the network converges, all the nodes compare their own probability-to-be-CH and those of their neighbors. If the value of its own is bigger, it then replaces the role of CH. Otherwise, it just acts as a cluster member. Once a node is determined to be CH, it broadcasts an advertisement(ADV) message. Sometimes some CMs may receive serveral ADV messages. In this case they decide which CHs to join. Subsequently, they send join request message[6] to the best CH for them. At last, the process of cluster formation terminates. Then the CH acts as the local control center to coordinate the data transmission. Besides, in order to relieve the energy burden of the cluster heads, the cluster formation takes place round by round in a certain period T.

TABLE 5 THE PARAMETERS USED IN THE SIMULATION

Network Space	100×100
The Position of the Sink	(50,50)
The Number of the Sensor Nodes	100
The Initial Energy of Each Node	2J
E_{elec}	50nJ/bit
ε_{amp}	13pJ/bit/m^2
Packet Length	500bits
Simulation Time	3600Seconds
d	34m
r	20

IV. SIMULATION RESULTS AND ANALYSIS

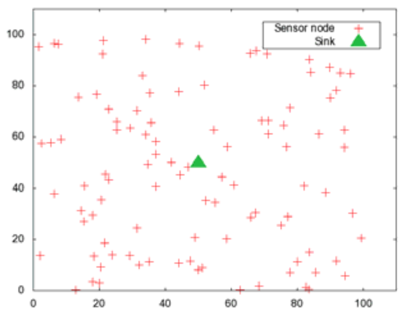


Fig.10 The topology of the network

In order to evaluate the energy performance of FLEEC, a set of experiments were conducted. The comparisons with the classical clustering algorithms and the fuzzy-logic-based schemes were made. Specifically, FLEEC is compared with LEACH and CHEF algorithms, which are the classical clustering algorithm and fuzzy-logic-based algorithm respectively.

A. Experiment Environment

The experiment was conducted basing on a network simulation software, namely NS2[18]. The network topology and the parameters used in this paper are shown in Fig.10 and Table 5 respectively.In order to quantitatively evaluate the energy performance of the FLEEC, some metrics are defined firstly.

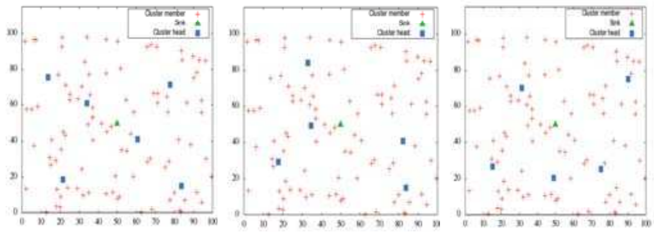
FND: the time when the first node dies. It reflects the network lifetime when the applications which are strict with node's distribution, such as the endangered species tracking applications.

HND: the time when half of nodes in the network have run out of their energy.

LND: the time when all of nodes exhaust their energy.

B. Simulation Results

The Fig.11 shows the distribution of cluster heads in three scenarios. It is apparent that the cluster heads are distributed more uniformly when FLEEC is adopted. As the cluster heads are selected randomly in LEACH, the situation in Fig.11(b) is common. We can see from Fig.11(b) that the nodes at the top right corner need to join the cluster heads far away. It goes against the goal of extending the life of the network. CHEF tries to control the cluster heads selection to avoid the defect of LEACH. Fig.11(c) shows that the heads are distributed more reasonably.



(a) The cluster head distribution in FLEEC (b) The cluster head distribution in LEACH (c) The cluster head distribution in CHEF

Fig.11 The cluster heads distribution comparison

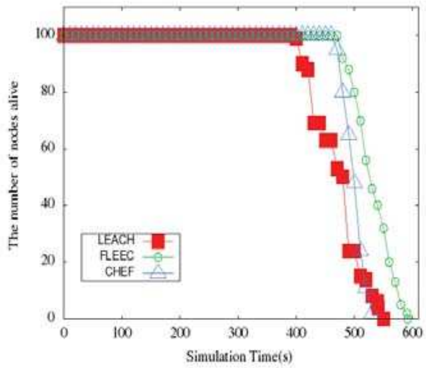


Fig.12 The number of nodes alive

For WSNs, the lifetime of the network is one of the most important performance metrics. Hence it is reasonable to discuss the lifespan when comparing the performance of the FLEEC with other cluster algorithms. Fig.12 indicates that in spite of its improvement in extending FND, CHEF is unable to postpone the LND. FLEEC, however, is capable of prolonging the lifetime in terms of the FND, HND and LND. Fig.13 shows that the FLEEC algorithm outperforms LEACH and CHEF in terms of the FND, HND, and LND.

According to the energy comparison shown in Fig.14, it is obtained that since the number of nodes decreases rapidly in CHEF after FND, the amount of energy consumed rises accordingly. Whereas that of FLEEC increases in a relatively gentle way. The reason for this is that distance to the Sink has also been taken into consideration at the beginning of cluster formation.

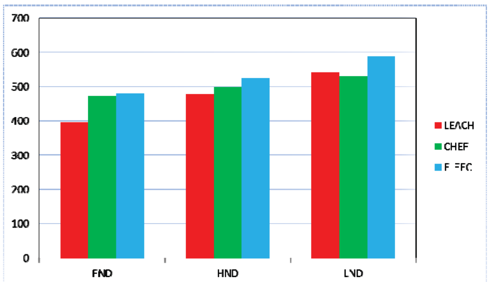


Fig.13 The comparison of lifetime in terms of the FND, HND, and LND

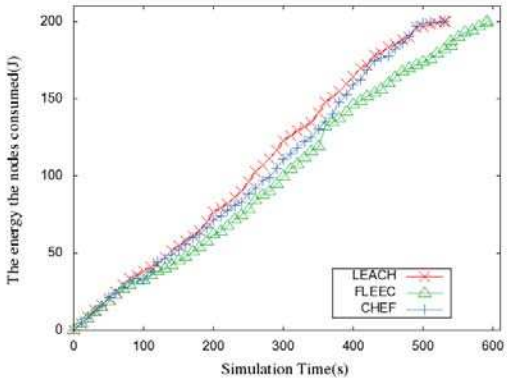


Fig.14 The comparison of the energy consumed for the three algorithms

V. Conclusions

The related works on how to balance the energy consumption and extend the lifespan of WSNs were described firstly. The shortage of the clustering algorithms was then analyzed. Based on this analysis, a Fuzzy-Logic based Energy-Efficient Clustering algorithm (FLEEC) was proposed. The algorithm was evaluated via simulation software NS2. The results shown that it is more effective than other clustering algorithms such as LEACH and CHEF in the energy efficiency. The longevity of the WSNs still remains as a key research topic. As for the authors, the further study will focus on the topics on how to achieve transferring energy and information simultaneously for WSNs[19-23] and how to route effectively among the cluster head.

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