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Fuzzy Logic Based Cluster Head Election Led Energy Efficiency in History Assisted Cognitive Radio Networks

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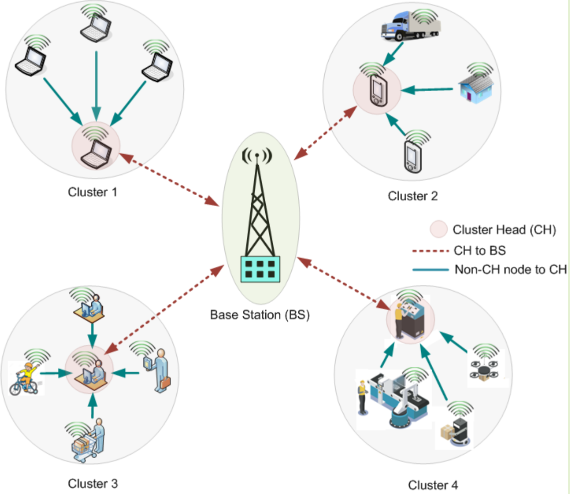
***Abstract*—The performance and the network lifetime of cooperative spectrum sensing infrastructure based Cognitive Radio (CR) networks is hugely affected by the energy consumption of the power constrained cognitive radio nodes during spectrum sensing, followed by data transmission and reception. To overcome this issue and improve the network lifetime, clustering mechanisms with several nodes inside a single cluster can be employed. It is usually the cluster head (CH) in every cluster that is responsible for aggregating the data collected from individual cognitive radio nodes before it is being forwarded to the base station (BS). In this paper, an energy efficient fuzzy logic based clustering algorithm (EEFC) is proposed which uses novel set of fuzzy input parameters to elect the most suitable node as CH. Unlike most of the other probabilistic as well as fuzzy logic based clustering algorithms, EEFC increments the fuzzy input parameters from three to four to obtain improved solutions employing Mamdani method for *fuzzification* and Centroid method for *defuzzification*. It ensures that the best candidate is selected for the CH role by obtaining the crisp value from the fuzzy logic rule-based system. While compared to other well-known clustering algorithms such as LEACH, CHEF, EAUCF and FLECH, our proposed EEFC algorithm demonstrates significantly enhanced network lifetime where the time taken for first node dead (FND) in the network is improved. Moreover, EEFC is implemented in existing history assisted energy efficient infrastructure CR network to analyse and demonstrate the overall augmented energy efficiency of the system.**



***Index Terms*—Sensing, Fuzzy logic, Cognitive radio, History-assisted, Energy efficiency.**

I. INTRODUCTION

PORTABLE wireless nodes are usually small and low-powered that have the capability to sense the channel, process the data and communicate with other nodes and base station (BS). The communication activities have higher overhead traffic and throughput for data transmission [1], [2]. This increased overhead traffic increases complexity and energy consumption [3], [4]. Prolonged usage of the power constrained wireless nodes results in reduced lifetime which has a profound effect on the overall network lifetime and network performance. Network lifetime is said to be high when energy of the overall network is high, and the number of alive nodes is high. The network lifetime is based on the number of alive nodes in relation to the number of rounds. It is directly proportional to the number of alive nodes per round. Therefore, when the network has maximum number of alive nodes, the energy is high and thereby extends the network lifetime.

Power consumption issues in wireless nodes have been addressed in many research works where different mechanisms of cooperative spectrum sensing (CSS) schemes have been employed [5]. Cluster-based CSS technique is the most popular and widely utilised scheme. In clustering mechanism, nodes are assembled into a number of small groups called ’clusters’. Every cluster has a cluster head (CH) as shown in Fig. 1. CH is usually responsible for collecting the data from the non-CH nodes, aggregating the collected data and forwarding it to the BS. CH selection is a challenging task since every network has its own characteristics and limitations.

Appropriate selection of CH is vital as key network operations of data aggregation, processing, computation, and data communication relies on it. Frequent (re)selection of CHs will result in energy wastage. This problem arises when an

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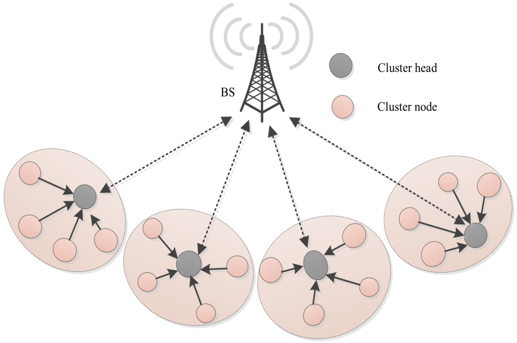


Fig. 1. Cluster based cooperative spectrum sensing.

inappropriate node is selected as the CH or where the same node is selected repeatedly as the CH. This causes the node to drain its power and results in first node dead (FND). A completed power drained and dead CH node is detrimental for both the network performance and network lifetime. Therefore, it is essential for CHs to exhibit higher levels of energy. Since, lower FND numbers give highly stable systems, choice of CH is a decisive factor. Selection of best candidate for CH role is, therefore, made based on certain parameters such as residual energy level, distance between CH and non-CH CRs, distance between CHs and BS, node density and node centrality.

The conventional clustering algorithm that is widely employed for cluster head selection and cluster formation is the low-energy adaptive clustering hierarchy (LEACH) protocol. LEACH is an energy efficient clustering algorithm that uses probabilistic approach to select CHs randomly [6], [7]. Research suggests that the energy levels and received signal strength indicator (RSSI) parameters can be employed for cluster head selection [8]. The optimal number of nodes has been used by Shakhov *et al.* to create clusters based on the OR- and AND-rule [9]. Particle swarm optimisation (PSO) has also been found beneficial for CH selection [10], whereas fuzzy logic-based mechanisms are also applied to select CHs [11], [12]. Fuzzy logic is a non-numerical, simple, flexible, cost effective control system approach which integrates the input parameters and manipulates linguistic rules to provide appropriate solutions.

The main motive for this work is to develop an energy efficient cluster-based system for improving the network lifetime of infrastructure based cognitive radio system. The proposed approach adopts clustering and selection of one of the CR nodes as the CH in order to avoid the high communication cost between individual CR nodes and the BS. The proposed energy efficient clustering algorithm, EEFC, employs the fuzzy logic rule-based system having linguistic variables instead of mathematical values to evaluate the correlation of criteria. Since, fuzzy logic model is computationally faster and easier to implement compared to mathematical and other CH selection models, it reduces the computation overhead [12]. As the computation complexity reduces, the energy required for computation reduces which in turn improves the network lifetime. Fuzzy logic is implemented for dynamic selection of the CHs for every cluster in the network using various parameters such as residual energy, node centrality and distance between CH and BS. These parameters act as the fuzzy input to the fuzzy inference system giving the decision for CH selection as the outcome.

Following this introduction, the rest of the paper is organized in five sections. Section II briefly discusses the related work further highlighting need of the proposed EEFC method. Section III explains system model with details of fuzzy logic system and the employed energy model. Section IV provides description of EEFC, whereas Section V analyses the usability and performance of EEFC. The paper is concluded in Section VI.

II. RELATED WORK

Traditional clustering mechanisms are usually based on some predetermined criteria where selection of CH follows grouping of neighbouring non-CH sensor nodes into clusters. For cluster-based CSS, most of the published research is exploits means to extend the lifetime of wireless networks, such as wireless sensor networks. For CH selection and cluster formation, most of these algorithms use either one or combination of parameters including residual energy, node degree, distance between CHs and BS, distance between non-CH sensor nodes and CH, distance between CHs, received signal strength (RSSI), positioning of nodes, node centrality, node density, etc. [13]

Low energy adaptive clustering hierarchy (LEACH) is the most popular hierarchical clustering protocol which aims to extend network lifetime and improve power consumption. For CH selection, the process is broken down in multiple rounds where each round starts with every sensor node selecting a random number r between 0 and 1. Referring to Equation 1, if this randomly selected value is less than the threshold value $T(n)$, then the node selected as the CH in current round will never be selected as CH again until all the other nodes got a chance to become CH in the next rounds. $T(n)$ is calculated as follows:

$$T\left(n\right) = \begin{cases} \frac{p}{1-P*\left(r mod \frac{1}{P}\right)} & if\ n\ \in G \\ 0 & otherwise \end{cases} \tag{1}$$

Where P is the probability a node becoming a CH, r refers to the current round, n is the given number of nodes and G is the set of nodes that did not become CH in the previous $1/p$ rounds. A random number is generated between 0 and 1 for each node in the cluster, if that number is less than the threshold in the current round then that node will become the cluster head. Once a node is elected as a CH then it cannot become CH again until all the nodes of the cluster have become cluster head once. The threshold value $T(n)$ of a node is set to zero when that node becomes a cluster head so that it will not be elected as CH again. Once the CH is selected, it advertises its status and non-CH nodes get associated with the nearest CH using the allocated time division multiple access (TDMA) slots forming clusters. Interestingly, LEACH performs really well when all nodes have the same energy levels. However, its performance degrades in selection of an appropriate CH when the nodes have different energy levels. Since, LEACH is a purely probabilistic model and does not use parameters such as residual energy and distance for CH selection, there is a possibility that a CR with low energy is selected as CH, selected CHs may located close to each other and some CHs may lie at the edge of network. These limitations subsequently result in inefficient clustering. Also, for every round, a random number is generated and a threshold value is calculated which increases the central processing unit (CPU) cycles. However, many research works have built their approaches to overcome these limitations considering LEACH algorithm as basis [14]. Some of these methods include centralised LEACH-C in which the BS selects the CH; energy efficient centralised LEACH-EP which uses residual energy for CH selection and LEACH-DT that employs distance from BS as the criteria to select CH [15].

Fuzzy logic has been widely used in clustering algorithms for its comparatively reduced computational load, less processing requirements, effective implementation and for the improvement in network lifetime [16]–[19]. Fuzzy logic-based clustering algorithms reduce the overhead in selecting CHs. Some of the clustering algorithms that employ fuzzy logic include fuzzy logic based clustering algorithm for the formation of a uniform size clusters in an ad hoc networks (FUSA) [18], cluster head election using fuzzy logic (CHEF) [20], fuzzy based master cluster head election LEACH (F-MCHEL) [21], fuzzy logic based energy efficient clustering hierarchy (FLECH) [22], and energy aware unequal clustering using fuzzy logic (EAUCF) [23].

A. CHEF

Cluster head election using fuzzy logic (CHEF) is a distributed clustering algorithm, that uses both probabilistic approach and parameters to select CHs. CHEF does not require the BS to gather all the characteristics of the sensor nodes. Interim CH candidates are selected based on the probabilistic approach of LEACH and then fuzzy logic is implemented which utilises the fuzzy input parameters such as residual energy and local distance to calculate the output parameter chance as to which interim CH candidate will become the CH. The drawback in this method is that the local distance is not a suitable parameter for selecting efficient CHs and will result in re-clustering overhead in every round.

B. EAUCF

Energy aware unequal clustering using fuzzy logic (EAUCF) employs probabilistic approach to select interim CHs and the final CHs are selected through fuzzy logic scheme. It uses only two fuzzy logic inputs which are residual energy and distance to BS and the output is the competition radius. Only those interim CHs that fall in the competition radius range will become CHs. If more than one interim CH is in the radius then the residual energy is used to determine the CH. The main limitation of this algorithm is the selection of the fuzzy input parameters where essential parameters such as node centrality and node density that define suitability of a CH much better are not used. Also, the energy is depleted at the CH node which has detrimental effect on the network [24].

C. FLECH

Fuzzy logic based energy efficient clustering hierarchy (FLECH) includes both probabilistic approach and sensing parameters for CH selection. FLECH blends probabilistic approach and metric-based approach for CH selection. FLECH links vital parameters such as residual energy, node centrality, and distance to BS for selecting the most appropriate sensor nodes as CH and increases the network lifetime [22].

Interestingly, these fuzzy logic-based clustering algorithms suggest to improve network lifetime. However, due to their shortcomings, appropriate CHs may not be selected and thus, there will be no proper assignment of CH role among the nodes. Due to random selection of CHs, the frequency of same nodes becoming CH again may increase which affects the network lifetime adversely.

D. Motivation for Proposed EEFC Technique

The limitations of the well known clustering algorithms discussed in preceding sections craft a need and require a solution which can effectively address these deficiencies. This paper, therefore, proposes a novel energy efficient fuzzy logic-based clustering (EEFC) algorithm. Generally, the fuzzy logic-based clustering algorithms demand comprehensive information of node attributes and occurrence of intra-cluster communication becomes very expensive in terms of energy consumption [25]. Therefore, it is preferred to employ a centralised approach in EEFC that would let the BS handle the estimation of node location. Majority of the fuzzy-based clustering algorithms utilise only two or three fuzzy input parameters for CH selection estimation. Interestingly, increase in the number of fuzzy input parameters can result into the network lifetime increment [26], [27]. Therefore, in the proposed EEFC algorithm considers four input parameters and one output parameter to compute the possibility of electing a node as a suitable CH. Use of four fuzzy input parameters is first of its kind effort. The employed fuzzy input parameters determine which node is selected as CH (i.e., the required outcome) include *node residual energy*, *distance between CH and BS*, *neighbour node average energy* and *node centrality*. Higher the value of outcome, greater is the chance for that node to become a CH. A high value of FND will require frequent selection of CH which will result in higher energy consumption. EEFC aims to select the most suitable CR as CH to reduce the dead nodes ratio.

III. SYSTEM MODEL

This section describes the proposed fuzzy logic approach for optimal selection of CH. A cognitive radio network of n collaborating nodes and a BS is considered. The CR nodes are indiscriminately distributed in the spectrum sensing field which is considered to have an area of $200m \times 200m$ and limited power. The network is treated to be homogeneous with energy levels at par for all the wireless nodes. The BS is aware of the position of the CR nodes in the network. Generally, the received signal strength indicator (RSSI) is used to estimate the distance between the nodes and BS and this information is shared by BS using small HELLO messages. To establish

TABLE I
ENERGY CONSUMPTION VALUES

No.	Notation	Values
1	$E_{mp(Multipath\ loss)}$	0.0013 $pJ/bit/m^4$
2	$E_{fs(Free\ space\ loss)}$	10 $pJ/bit/m^2$
3	$E_{e(Electronics\ energy)}$	50 nJ/bit nJ/bit
4	*Initial energy*	1J

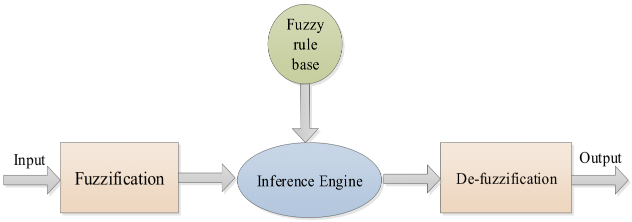


Fig. 2. Fuzzy logic system.

communication link, all nodes have a minimum signal to noise ratio (SNR) threshold. There is intercommunication between BS and CHs and intra-cluster communication between CH and non-CH nodes. A free space propagation model is considered for intra-communication between non-CH nodes and CH, since the distance between them is small. The distance and the number of neighbour nodes can be estimated by the individual nodes by using the HELLO messages that are broadcasted by all nodes initially. These messages contain node ID, communication radius and its other performance metrics. Complete drain of power of wireless nodes will lead to first node dead (FND). Table I shows the energy consumption values of the system.

A. Fuzzy Logic System

Fuzzy logic has proven to be an effective technique to solve the uncertainty issues pertaining to wireless networks based on multi-valued human decision-making linguistic variables. Generally, fuzzy clustering algorithms merge different fuzzy input parameters for CH election in various types of low energy wireless networks. The fuzzy logic system (FLS) consists of three major blocks, the *fuzzifier, fuzzy decision block (FDB)*, and the *defuzzifier.* The FDB block comprises of an inference system and a fuzzy rule base. The Mamdani controller is the most widely used fuzzy inference system [28]. Fig. 2 shows the FLS system block diagram which is incorporated in the proposed model.

The input descriptors which are crisp values are fed into the fuzzifier, where fuzzified values or fuzzy set which are in the form of understandable linguistic variables are generated. The rule base is basically the IF-THEN statements that provide antecedents and consequents based on numerical data. The fuzzified FDB maps the linguistic variable of input and the output using the rule base and fuzzy inference system (FIS). The input parameters to fuzzifier includes the node residual energy, distance between CH and the BS and node CHs for the selection of a suitable CH. Based on these parameters the potential CH is identified. The output has got just one variable, namely outcome and the fuzzy set is now defuzzfied to get the crisp output value. Greater the value of the outcome, higher is the probability of selecting that node as CH. Any node in the wireless network that has adequate power and suitable processing capability, can become a potential CH candidate.

B. Energy Consumption Model

Residual energy of the wireless sensor nodes is one of the main criteria for the selection of CH. The CH require higher energy levels compared to the non-CH nodes since it has additional activities to perform. The network lifetime will shrink drastically and end sooner if the energy of the CH node is fully depleted, leading towards the node death. Energy is largely consumed when nodes perform data communication. The energy E_{Tx} consumed during inter-communication between CH and BS and during intra-communication between non-CH nodes and CH is formulated as in (2) [22]:

$$E_{T_x} = E_{CH-BS} + E_{non-CH-CH} \tag{2}$$

For the CR network, Heinzelman's energy model which considers micro-controller processing, radio transmission and receiving related energy, is applied [29]. The energy consumption, E_{Tx} during data transmission includes the size of the data, l in bits and the distance d, between the transmitter and the receiver.

$$E_{T_x} = l \times E_e + I \times E_{fs} \times d^2 \qquad if\ d < d_0 \tag{3}$$

$$E_{T_x} = l \times E_e + I \times E_{mp} \times d^4 \qquad if\ d > d_0 \tag{4}$$

If the distance between transmitter and receiver is short then free space loss E_{fs} (as in (3)) is considered otherwise it is treated as multipath loss E_{mp} (as given in (4)). Therefore, for long distance data transmission, (4) is used and for short distance data transmission, (3) is employed to calculate the energy consumed during the data transmission process. E_e is electronics energy and d_0 is the threshold calculated using (5):

$$d_0 = \sqrt{\frac{E_{fs}}{E_{mp}}} \tag{5}$$

The distance, however, is not considered during reception of data. The energy consumed during receiving the l bits data is calculated using (6):

$$E_{R_x} = l \times E_e \tag{6}$$

The CH collects data from the non-CH nodes in that particular cluster and then aggregates the data. It is only the CH that communicates with the BS and sends the aggregated data to the BS. The energy consumed during data aggregation is calculated as:

$$E_{DA} = l \times E_{DB} \tag{7}$$

The node centrality depicts the closeness of a node to the cluster. Initially, every node sends a HELLO message in the network. The neighboring nodes calculate the number of neighbors based on the of the received signal. The degree of centrality can thus be calculated by computing the distance between neighboring CRs. The distance the CHs and the BS is calculated using the RSSI. The CHs receive a signal from BS and an estimate value of power level can be measured. Using this value, it is possible to get an estimate of distance between CH and BS.

IV. ENERGY EFFICIENT FUZZY LOGIC BASED CLUSTER HEAD (EEFC) ELECTION

The preliminary phase of cluster formation process does not include any CHs. Cognitive radios exchange their initial state at the current round and store the data in their local storage. The proposed clustering algorithm EEFC, uses fuzzy logic to elect suitable CHs to improve energy consumption and network lifetime of the CR system. The parameters *node residual energy* (N_{re}), *distance between CH and BS* (d_{CH-BS}), *neighboring nodes average energy* (N_{AE}) and *node centrality* (N_C) are augmented as input to the fuzzifier. The residual energy of a node is the existing remaining energy of the node. This particular parameter is most vital for CH election. A potential CH is the CR node which has high energy value to carry out the data collection, data aggregation and data forwarding functionalities. Average energy of neighboring nodes is a strong parameter depicting the energy level of the nodes. If average energy level of neighboring nodes has a low value, then it impacts the communication between CH and non-CH nodes negatively. Cognitive radio node that has neighboring nodes with higher average energy can become a good candidate for being selected as a CH. Distance between CHs and BS should be optimum so that the energy that is used in data communication is not high, and this distance can be calculate using RSSI. Node degree shows the density of nodes within the communication radius and node centrality defines how close a node is located to the middle of the neighboring nodes [22]. A node that is centrally located has connections to most of the other nodes and thereby, improves the efficiency of communication between them. Consequently, lower the value of node centrality, higher is the possibility of that node to be selected as CH. It is a crisp value which determines which node is eligible to become the CH.

The fuzzified linguistic input values or the fuzzy set are converted into crisp values of system output by the inference system after defuzzification. The fuzzy rule base consists of the membership functions and the IF-THEN rules for fuzzy logic analysis. The linguistic variables N_{re}, N_{AE} and N_C has various membership degrees as given below (for example, the membership degree function of node residual energy, $T_1(N_{re})$ is given as *"low", "medium" and "high"*):

$$T_1(N_{re}) = \{low, medium, high\};$$
$$T_2(d_{CH-BS}) = \{near, medium, far\};$$
$$T_3(N_{AE}) = \{weak, normal, strong\};$$
$$T_4(N_C) = \{adjacent, accessible, remote\};$$

The fuzzy linguistic variable of outcome O_V would have the following membership degrees:

$$\begin{aligned} O_V &= \{very\ low, low, fairly\ low\}; \\ &= \{low\ medium, medium, fairly\ medium\}; \\ &= \{fairly\ high, high, very\ high\}; \end{aligned}$$

Table II shows the IF-THEN mapping rule set created by using the fuzzy input parameters. For example, if the residual energy is low, distance between CH and BS is far, average energy of neighboring nodes is strong and the node centrality is remote, then the outcome is indicated as very low. Subsequently, the chances of that node to become CH is very low and it is classified as the non-CH node. It then broadcasts the $potential_{CH}$ message packet that contains the node identification number and the outcome value obtained by using the fuzzy input parameters. The other nodes can compare this value and decide to whether contend the CH election or not. If the received value is greater than its own value, the node will not enter the election but will wait to join the CH to form a cluster. If the received value is lower than its own value, it enters the election process. If the tentative CH receives another node's $potential_{CH}$ message and if that value is greater than the present tentative CH, then it broadcasts a $exit_{CH}$ message and exits from the election contention. The node that has the higher value of outcome is elected as the CH.

Elected CH advertises by sending the $invite-to-join$ message. The non-CH nodes join the CH by sending the $request-to-join$ message after they receive invite message from the CH. The nodes that join the CH are in the communication radius within its range. Primarily, the elected CH allocates the TDMA schedule for the non-CH nodes in its cluster for data communication. The non-CH nodes transmit the data in allocated time slot and the CH collects the data, aggregates it, and forwards the aggregated data to the BS. Algorithm 1 shows the pseudocode of the proposed EEFC algorithm, where the nodes enter election process to select the best candidate for CH.

V. PERFORMANCE ANALYSIS

The fuzzy logic toolbox in MATLAB is utilized to implement the EEFC algorithm. The input variables follow the *triangular* and *trapezium* membership function. Mamdani model is used as the fuzzy inference system to map the fuzzified linguistic variables and the output linguistic variable. The defuzzification method that is widely used by researchers is the centre of area (COA), also known as the centroid. Since the fuzzy system has a rule base and overlapping output member functions, the output outcome is a continuous one and any minor change in the input fuzzy parameters does not cause major changes in the system [33]. Therefore, the continuous COA method is used in the proposed scheme for defuzzification instead of the discontinuous Mean of Maximum (MOM) method. Centroid method is used for the defuzzification of the output variable to obtain a crisp output value that clearly dictates which node is suitable to be the CH. The number of input variables are 4, each having 3 linguistic degrees. The total number of rules created are, therefore, 27 as shown in the fuzzy rule base in Table II. Fig. 3 shows the fuzzy

TABLE II
FUZZY INPUT PARAMETERS

No.	Residual Energy (N_{re})	Distance (d_{CR-BS})	Neighbor Node Average Energy (N_{AE})	Node Centrality (N_C)	Outcome (O_V)
1	Low	Near	Weak	Adjacent	Fairly low
2	Low	Near	Weak	Accessible	Low
3	Low	Near	Weak	Remote	Very low
4	Low	Medium	Normal	Adjacent	Fairly low
5	Low	Medium	Normal	Accessible	Low
6	Low	Medium	Normal	Remote	Very Low
7	Low	Far	Strong	Adjacent	Fairly low
8	Low	Far	Strong	Accessible	Low
9	Low	Far	Strong	Remote	Very low
10	Medium	Near	Weak	Adjacent	Fairly medium
11	Medium	Near	Weak	Accessible	Medium
12	Medium	Near	Weak	Remote	Low medium
13	Medium	Medium	Normal	Adjacent	Fairly medium
14	Medium	Medium	Normal	Accessible	Medium
15	Medium	Medium	Normal	Remote	Low medium
16	Medium	Far	Strong	Adjacent	Fairly medium
17	Medium	Far	Strong	Accessible	Medium
18	Medium	Far	Strong	Remote	Low medium
19	High	Near	Weak	Adjacent	Very high
20	High	Near	Weak	Accessible	High
21	High	Near	Weak	Remote	Fairly high
22	High	Medium	Normal	Adjacent	Very high
23	High	Medium	Normal	Accessible	High
24	High	Medium	Normal	Remote	Fairly high
25	High	Far	Strong	Adjacent	Very high
26	High	Far	Strong	Accessible	High
27	High	Far	Strong	Remote	Fairly high

Algorithm 1: EEFC Pseudocode.

```
input : $N_{re}, d_{CH-BS}, N_{AE}, N_C$
output: $O_V$
nodes calculate the probability of becoming CH using
  fuzzy input parameters through FIS;
  $O_V = ProbCH \leftarrow FIS(N_{re}, d_{CH-BS}, N_{AE}, N_C)$
nodes send $potential_{CH}$ message to neighbouring
  nodes containing node ID and outcome value;
  $potential_{CH}(node_i, O_V)$
nodes compare the chance of becoming CH with
  neighbouring nodes; // CH election
for all neighbouring nodes do
    if $Prob^i{}_{CH} > Prob^i{}_{CH}$ then
        $node_i \leftarrow potential_{CH}$
        send to $node_j$
        $exit_{CH}$ election
    else
        // Exit from CH election
        $node_i \leftarrow non - CH$
        $exit_{CH}$ election
    end
    // CH elected
    if $potential_{CH} \leftarrow true$ then
        send $invite - to - join$
    end
end
// Cluster formation
listen to $invite - to - join$ message;
send $request - to - join$;
// data transmission
CH allocates TDMA to $non - CH$ nodes for data
  transmissions.
```

inference system used in the proposed model. Figs. 4(a)-(d) give the membership functions of the input variables while Fig. 4(e) shows the membership function plot for the output fuzzy variable.

Fig. 5 is the rule viewer used to look at the entire implication process. As the input values change by moving the line indices, a new output value is obtained as the system recalibrates accordingly. It is observed that when the residual energy is high (0.942), distance between CH and BS is less (3.37), neighbor node average energy is high (0.853) and node centrality is low (1.21) making the probability for that node to be elected as CH also high (0.949).

Fig. 6 is the surface viewer which has two-input one-output instance. The selected input parameters are residual energy N_{re} and distance d_{CH-BS} while the output parameter considered is outcome O_V. It can be inferred from the surface viewer that as the residual energy increases and distance between CH and BS reduces, the outcome value becomes higher.

Performance evaluation and validation of EEFC is done based on FND. Network lifetime is calculated in terms of the round number when the first node dead occurs in the network. The proposed EEFC algorithm is simulated in MATLAB and its performance is compared with the conventional LEACH and other fuzzy clustering algorithms including CHEF and EAUCF as illustrated in Fig. 7. The results reveal that the FND occurs in round 995 in LEACH, whereas it occurs in round 1280 in the proposed EEFC scheme. Since, LEACH does not consider parameters for CH selection and implements only probabilistic approach, it clearly shows the poor performance of LEACH in comparison to EEFC. The network lifetime attained by EEFC is also improved by 28% compared to

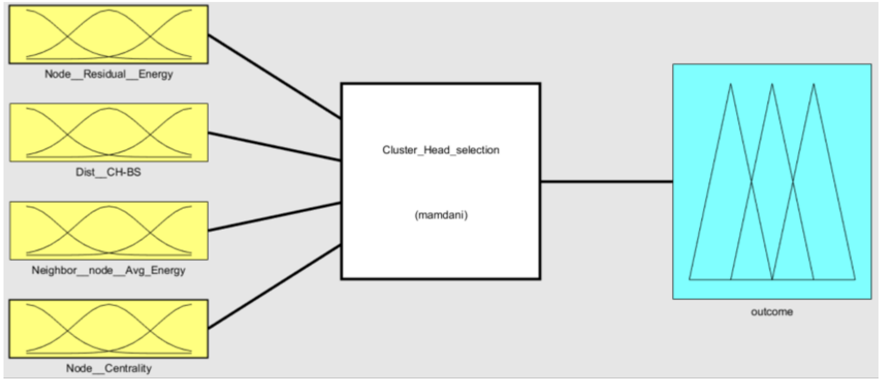
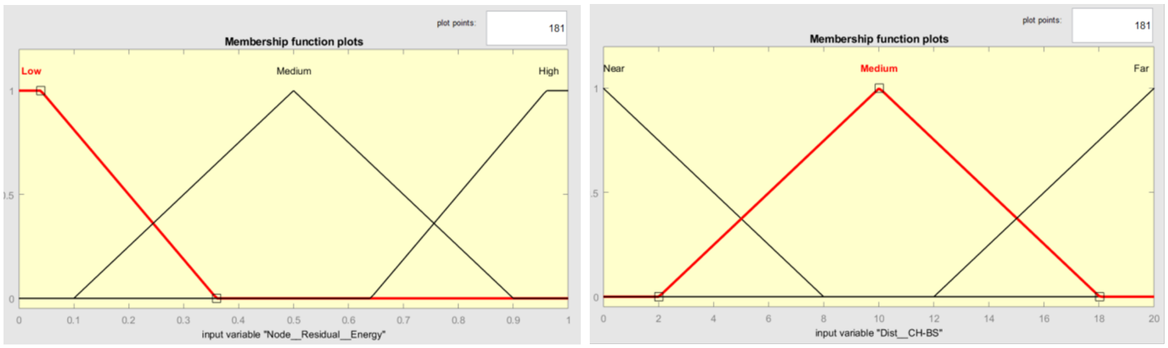
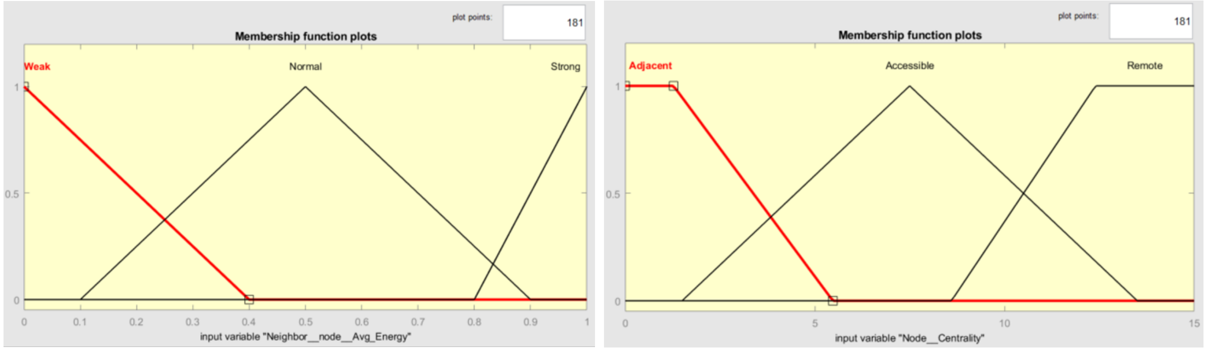


Fig. 3. Fuzzy inference system.



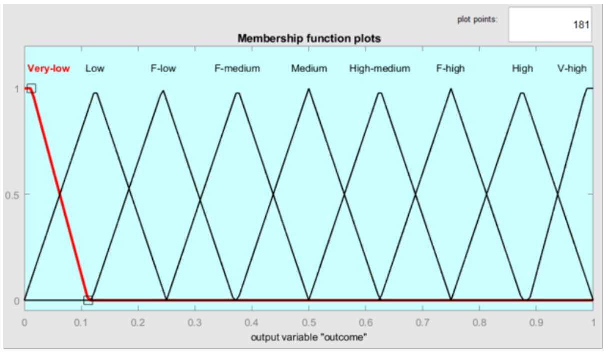
(a) Membership function for N_{RE}

(b) Membership function for d_{CH-BS}



(c) Membership function of N_{AE}

(d) Membership function for node centrality N_C



(e) Membership functions for output variable O_V

Fig. 4. Membership functions of input and output fuzzy variables for the proposed EEFC technique.

the other clustering algorithms. The proposed algorithm also exhibits better performance as compared to CHEF and EAUCF in all departments. Therefore, the network performance is significantly enhanced by using EEFC by having superior energy conservation and considerably longer network lifetime.

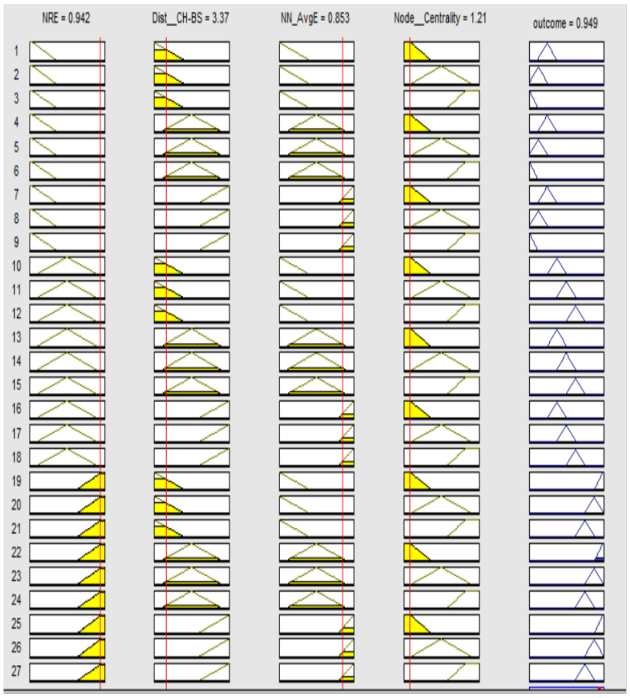


Fig. 5. Rule viewer for the selection of CH.

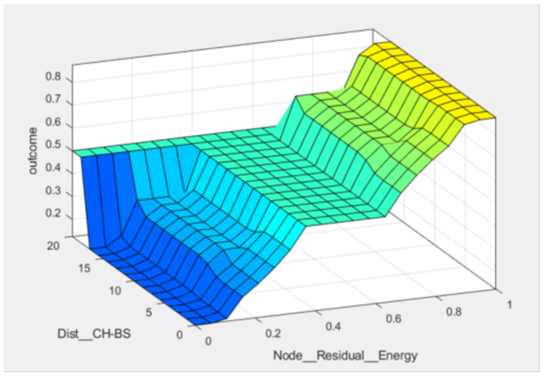


Fig. 6. EEFC – Surface Viewer.

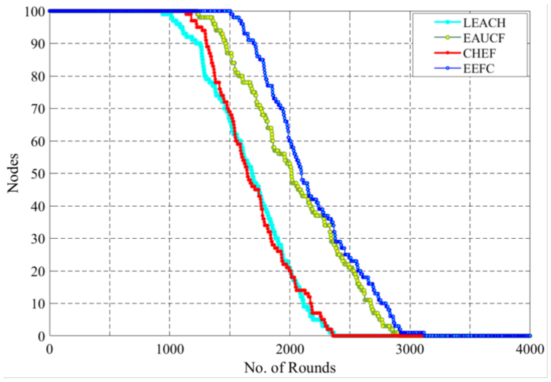


Fig. 7. Network lifetime comparative analysis.

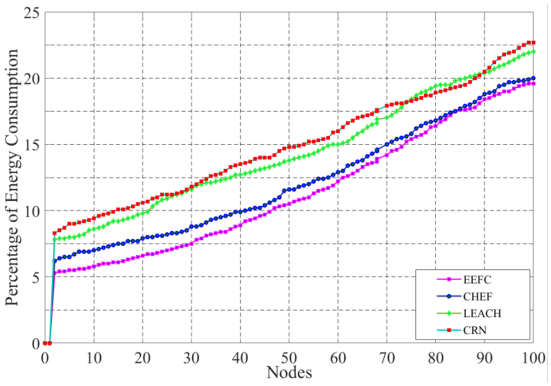


Fig. 8. EEFC implementation in history assisted energy efficient CR system.

A. Energy Efficiency Augmentation in History Assisted CR through EEFC

The performance of the EEFC clustering algorithm is further analyzed by implementing it in authors' another salient research work aimed at infrastructure-based CR network which uses history data for energy efficient spectrum sensing [30], [31]. In infrastructure-based CR system, every CR communicates with the BS for data transmission and reception. The energy consumption related to communication activities is higher than the energy consumed for spectrum sensing because of increased overhead traffic and throughput for data transmission compared to that required for spectrum sensing. The CR senses the spectrum using the traditional energy detection sensing mechanism and stores the data in its local storage. This spectrum sensed data of every CR in the network is transmitted to the BS for processing. The energy consumed during data transmission between CRs and BS can further be greatly reduced by employing clustering techniques [32], where only the elected CHs are allowed to communicate with the BS. Cognitive radio systems have CRs that are battery operated having limited power, therefore for a longer network lifetime, energy consumption efficiency is vital. The analytical engine database in the CR system [30] processes the sensed data and generates a rich history data set. This result set has to be transmitted to the CRs and sensed data from the CRs to the database via BS. If a selected CH is far from CRs, considerable energy is dissipated during data transmission. CHs must be in ON state throughout the round in order to collect, aggregate and transmit data from non-CH CRs to BS. This overhead results in increased power consumption. The overhead due to data communication could increase the energy consumption of already energy constrained CR devices. This issue can be solved by clustering the nodes and selecting a suitable CH through EEFC. The non-CH CRs associate with the nearest CH to form clusters. The CH collects and aggregates the sensed data from all other CRs from its cluster. It then coordinates and reports the received local sensed data from the CH to the BS.

Cluster based co-operative sensing has proven to save energy consumption by allowing only the CHs to communicate with the BS. The non-CH CRs transmit their data only to the CH which further transmits it to the BS. However, the communication overhead between the CRs and the BS results in increased energy consumption. Therefore, it is this energy consumption that must be reduced which can be addressed by introducing the concept of clustering. Therefore, the proposed EEFC clustering algorithm is implemented in history assisted infrastructure cognitive radio networks to analyze the performance of the overall CR system. Fig. 8 shows that by implementing EEFC in authors' own history assisted energy efficient system [30], the energy consumption is reduced tremendously by 33.3%. The reason being the fact that elected CH allocates time slots for the CRs in the cluster for data transmission. The non-CH CRs can only communicate with the CH and therefore, during their allocated time slots, they transfer the data to CH. Using clustering mechanism, the communication between the non-CH CRs and BS is prevented, thereby greatly reducing the energy consumption.

VI. CONCLUSION

Battery operated wireless devices desire to achieve prolonged operating time by reducing energy consumption. Clustering mechanism in wireless sensor networks saves more energy compared to the flat architecture of non-cluster systems. Compared to the well-known and widely used algorithms such as LEACH, CHEF, EAUCF, the proposed clustering algorithm EEFC has attempted to mitigate the shortcomings by employing fuzzy logic with four fuzzy variable inputs N_{re}, d_{CH-BS}, N_{AE}, N_C and one outcome O_V. Higher the value of outcome for a sensor node, higher is the chance for that node to become the CH in the wake of cluster formation. Performance analysis has shown that the network lifetime and ebergy conservation is improved by using the proposed fuzzy logic-based EEFC scheme compared to the traditional LEACH algorithm and other fuzzy-based clustering algorithms CHEF and EAUF. Results has also exhibited the tremendous impact of the proposed EEFC method when implemented in history assisted energy efficient cognitive radio systems, with an overall of 33.3% reduced energy consumption. It makes EEFC a highly suitable technique for CR networks which employ cooperative spectrum sensing in a clustered network.

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