Chapter 5
Smart Monitoring of Farmland Using Fuzzy-Based Distributed Wireless Sensor Networks

Anagha Rajput, Vinoth Babu Kumaravelu and Arthi Murugadass

Abstract Agricultural research is practiced globally as farming contributes to national revenue of many countries. The embryonic technologies can be intelligently used to help farmers in automating farming operations for better productivity and reduced human efforts. Recent agricultural researches emphasize majorly on agro-meteorology, wireless sensor network-based Internet of things systems for land surveillance, and geospatial technology for drought assessments. Large farmlands need to be monitored continuously to evaluate soil fertility, crop moisture and protect from crop raiders. This research work proposes an idea of smart monitoring of farmland using wireless sensor networks. The timely collected data by the network will assist the farmers to take precise agronomic decisions. The main constraint of wireless sensor networks is its limited lifetime because sensor nodes are battery-driven devices. The major energy consumption is due to long-distance radio communications. To prolong the lifetime of nodes and reduce the transmission distances, a fuzzy-based distributed clustering protocol is proposed. The network is clustered using fuzzy-c-means algorithm. The cluster head selection in each cluster is then carried out based on perception probability model. The protocol is simulated using MATLAB. The simulation results are obtained for different coverage areas. The proposed protocol outperforms the recent conventional protocols in terms of energy savings and network sustainability. The results indicate that the proposed protocol is scalable and sustainable. Hence, it can be efficiently used in farmland monitoring systems.

Keywords Fuzzy-c-means (FCM) clustering · Farmland monitoring · Perception probability · Wireless sensor networks (WSNs)

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5.1 Introduction

Agriculture serves nations food products, and many of the developing countries rely on agriculture for their annual revenues. Agriculture is one of the most prompted applications of wireless sensor network (WSN)-based Internet of Things (IoT) systems. The embryonic of IoT and WSN for precision agriculture has the potential to provide automated systems and quick services to farmers and experts. WSN is considered as an important and sustainable technology to realize the monitoring infrastructure of IoT systems because the future Internet is visualized to be a large omnipresent network where people, objects, or anything will be connected at any time [1]. This has encouraged the agricultural research in a new direction, where traditional agrarian methods are being replaced by automated techniques. Farmlands need to be monitored incessantly to protect the field from crop raiders, monitor soil quality and irrigation requirements for better harvest productivity and crop development.

Agricultural activities can be categorized like seed sowing, irrigation system, crop growing, soil fertilizing, and so forth. At each phase of farming, the field climate, soil, and crop growth are to be monitored in order to get a good yield. For instance, plant growth is affected by different facets like climatic conditions, soil mineral contents, a quantity of composts used, water supply. For better productivity, attaining accurate estimations of these facets is a basic need of the agriculturist [2]. Another aspect of observing the farmlands is to protect the harvests from crop raiders like mammals and birds. The wildlife is hazardous to farmers as they damage the plants, destroy the grains, and at times harm the human beings. There are several traditional methods used by farmers to safeguard their farms like wire fencing, helikites, dog guarding. In any case, these are not safe and economical provisions. Subsequently, farmland monitoring is a vital and critical issue challenged by farmers [3].

In precision agriculture, systems like smart irrigation, cattle monitoring, controlled fertilization are been developed [4–6]. The real-time field information is gathered by sensors, which are embedded on microprocessor circuits. Such large number of sensor nodes deployed in the farm can quickly capture the farm conditions and transmit information to the required recipient. These information gathered from deployed sensors are utilized by farmers, experts or computerized control systems to take decision on agricultural policies like scheduling water supply to crops, soil composting. Here, agrarian fields can spread over large acres of land. Thus, WSN is well suited to automate the farming process, where wireless sensor nodes can be placed over large open space. WSNs are ad hoc and infrastructure less networks intended for specific applications. Thus, the deployment of WSN differs from one application to another.

The sensor nodes deployed for farmland monitoring to realize precision agricultural operations are portrayed in Fig. 5.1. The sensor nodes are deployed in the farming region where parameters like ambient temperature, humidity, soil moisture, carbon content are to be measured. The sensors are smart devices with radio circuit embedded on the device. These sensors can communicate with the gateway node

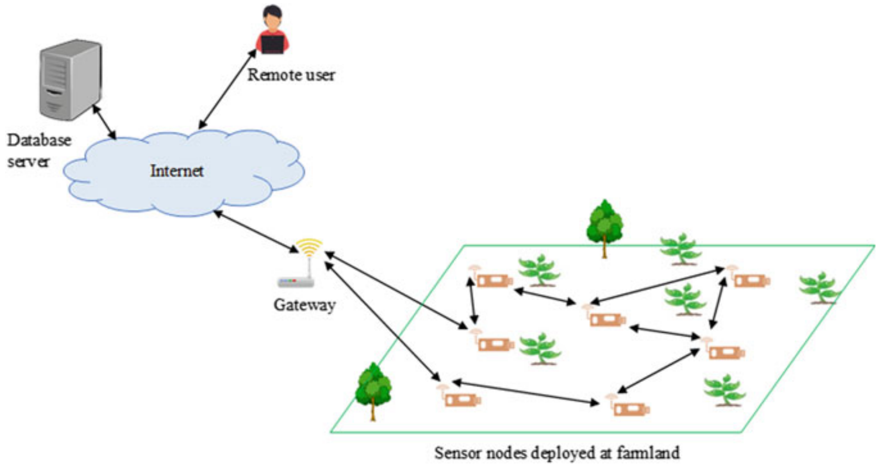

Fig. 5.1 WSN-based IoT system for precision agriculture

(also called as sink) to transmit the sensed data either periodically or on demand. The gateway node is the intermediate device that forwards sensor data into the Internet database system. Once the data is available at Internet database system, it can be retrieved by any users for knowledge acquisition or data analysis. A remote user can monitor the field and control the sensors and actuators [7, 8]. For instance, the valve of water pump can be controlled remotely by the user, when an alarm is given by on-field deployed water level indicating sensors. As the data is instantly available on Internet, the end user can use any of the devices like computer, laptop, or mobile phone to get access to the data. The remote user is connected to Internet via base stations of the cellular network. The recent research concentrates on the sustainability of WSN because the network can be large in size but restricted to the short battery lifetime. WSNs are designed for specific applications, and therefore, the network deployment has to satisfy application-based requirements [9].

Rest of the paper is organized in the following order: Sect. 5.2 discusses the potential of WSN for agricultural applications. Section 5.3 represents the literature studied. Section 5.4 illustrates the proposed clustering protocol based on fuzzy-c-means (FCM) algorithm and perception probability. Simulation results and discussions are presented in Sect. 5.5. The paper is concluded in Sect. 5.6.

5.2 Potential of WSN for Agricultural Applications

In precision agriculture, sensor nodes are deployed to capture the climate conditions of the field. These sensor nodes communicate with each other and form a network that works collaboratively to collect the environmental data. WSNs are ad hoc and

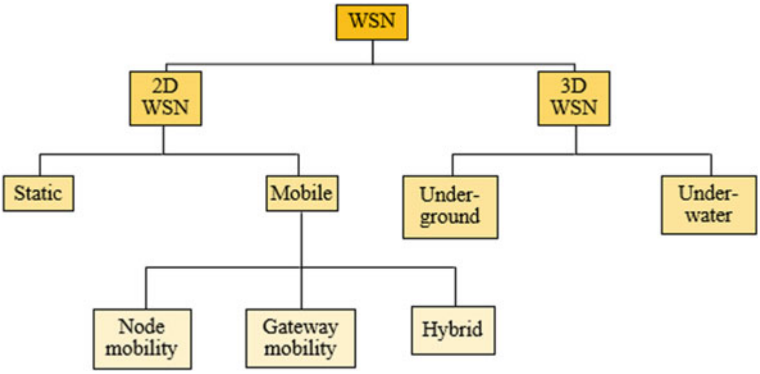

Fig. 5.2 Classification of WSN in context to the sensor node deployment

infrastructure less in nature. This gives them the flexibility to organize themselves into a network that will effectively send information from field to the remote user. The classification of WSN in context to the sensor node deployment is shown in Fig. 5.2. Broadly, WSN is classified as two-dimensional (2D) and three-dimensional (3D) network.

5.2.1 2D WSN

In 2D WSN, sensor nodes are deployed on or above the ground surface as shown in Fig. 5.1. The location tracking of such nodes is done using two geographical axes. Thus, the network formed by these nodes is called as 2D WSN. It is also called as terrestrial WSN in [2]. It is further classified into static and mobile networks.

5.2.2 Static 2D WSN

In this type, all the sensor nodes are assumed to be static after their deployment on the field. The gateway node that collects network data is also static at a particular location. Many WSN protocols are implemented considering its static nature [10–12]. This type of network is suitable for monitoring system, which can be used to observe climatic conditions, controlling pump valves, cattle monitoring, etc. The network performance in static scenarios is improved by constructing hierarchical layers of the network. Every WSN protocol design considers energy-efficient utilization of the nodes to enhance the lifetime of the network.

The more number of layers, the better is the energy savings. This is illustrated by implementing modified version of low-energy adaptive clustering hierarchy protocol

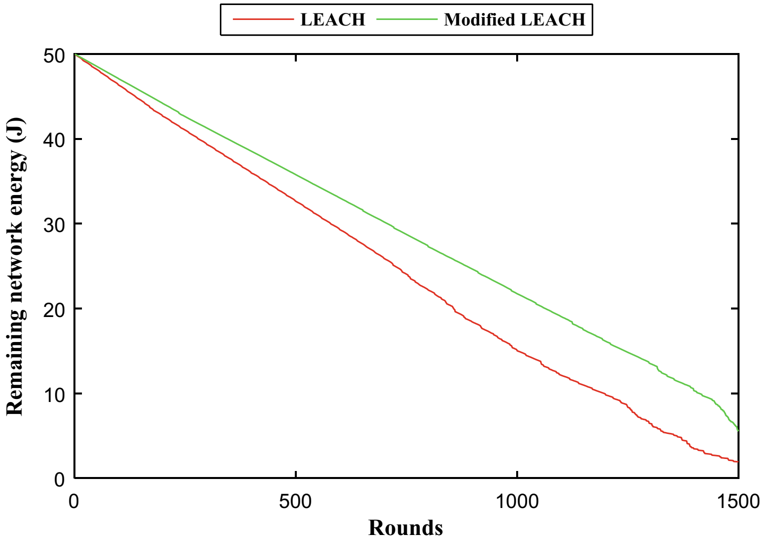

Fig. 5.3 Remaining network energy of LEACH and Modified LEACH protocols

(LEACH) [11]. In modified LEACH protocol, an additional hierarchical level of super cluster head (SCH) is introduced. All the cluster members send their data to their respective cluster head (CH). One SCH is elected among all the CHs for every round. The CHs transmit their cluster data to SCH. SCH further forwards the whole network data to the gateway. A comparison plot of total remaining network energy of modified LEACH and conventional LEACH is shown in Fig. 5.3. Due to the consideration of one more hierarchical level for data forwarding, the network load distribution is balanced and hence resulted in less number of death nodes compared to its conventional protocol. This is proved by measuring number of alive nodes for every round as shown in Fig. 5.4. The energy model for transceiver and simulation parameters is similar as in [11] and listed in Table 5.1.

5.2.3 Mobile 2D WSN

In this type of WSN, network devices have mobility. The network may not be 100% mobile but can have partial mobility among the devices. As illustrated in Fig. 5.2, mobility can be observed in three different forms:

Node Mobility: The sensor nodes themselves can be mobile, and the mobility completely depends on the application for which the network is established. In case of agriculture, the WSN with node mobility can be used in cattle monitoring system [12]. Here, the network should often re-organize itself to operate effectively.

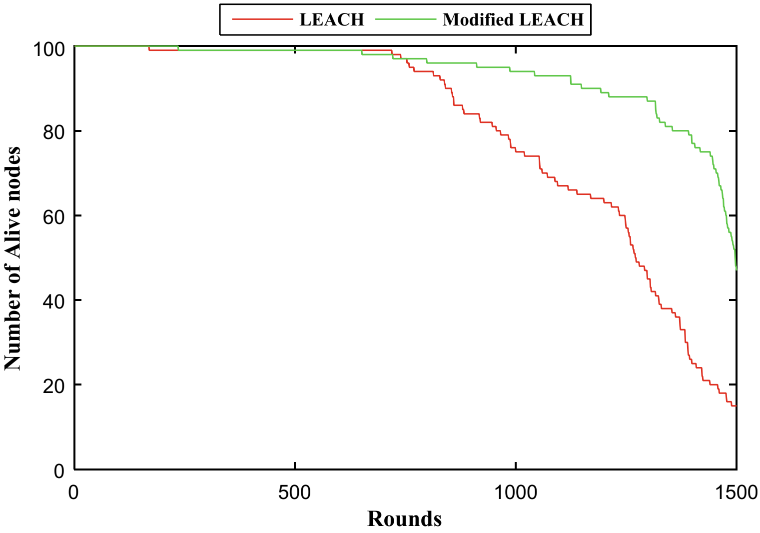

Fig. 5.4 Number of alive nodes of LEACH and modified LEACH protocols

Table 5.1 Parameters used for simulation

Parameters	Values
Monitoring area	100 m × 100 m
Number of sensor nodes	100
Gateway's location	(50,150)
Initial energy of sensor node	0.5 J
Electronic circuit's energy	50 nJ
Data aggregation energy	5 nJ/bit/message
Free space communication energy	10 pJ/bit/m^2
Multipath communication energy	0.0013 pJ/bit/m^4
Control packet size	200 bits
Data packet size	2400 bits

The trade-off occurs between the cattle speed and the energy required to attain the functionality of the network.

Gateway Mobility: The gateway is the node that collects data from the deployed sensor nodes. The mobility of gateway is rarely implemented, but in precision agriculture, mobility of gateway node can make a user-flexible system. The farmers can use personal digital assistants (PDA), while moving through field, which can be connected wirelessly to the nearby nodes for data collection. The option of communicating to all the nodes or few nodes at the farm relies on the design of an appropriate protocol.

Hybrid: This is a category with both sensor nodes, and gateway has mobility or one of the either becomes mobile as per requirement. Such type of network must be completely autonomous and independent to dynamically self-organize frequently. The monitoring drones are the example of such networks [13]. The issue faced in such mobility scenarios is the communication range required to deliver data toward gateway. Also, the hostile climatic conditions may erupt the communication. Another hybrid mobility is the mobility of the event occurring. The animal tracking at forests and crop raiders at farms are the examples of WSN, where event (crop raiders) is moving. In this case, to track the movement of event, sufficient number of sensor nodes are required to cover the event at all the time. An attempt by [14] is done to detect the crop-raider entering into farm by using ultrasonic sensors.

The communication protocols designed for such mobile cases should be rendered by appropriate support of the existing technology. The hybrid mobility is very uncommon compared to other mobile WSNs, but in real-time scenario, mobility of events and sensor nodes cannot be restricted.

5.2.4 3D WSN

The necessity for monitoring the environment has been increased substantially in the past few decades. The factors like climatic changes, decrease in water resources, and increase in livelihood habitats are motivating the need to monitor the environment and apply better policies to protect the scar resources. 3D WSN is the network that is been researched to monitor the changes occurring deep into the soil or the water [2, 9, 15]. Based on this research, 3D WSN is categorized as underground and underwater sensor networks. The 3D WSN applications are ocean monitoring, soil monitoring, disaster prevention, estimating burials and excavations, pipeline monitoring, etc. These types of networks are inherently three dimensional. The depth at which the sensor node is immersed into water [16] or soil [17] will become the third direction to track the location of the sensor node. The location tracking of these nodes is one of the challenging tasks due to two main reasons: The underwater sensor nodes are subjected to mobility often. Thus, tracking such nodes is tedious. The second reason is the communication interference caused by soil or objects under water. The issues faced by underwater WSN due to mobility are more than the underground WSN. The wireless communication used for underground WSN and underwater WSN is electromagnetic waves and acoustic waves, respectively. The challenges faced in using these communication systems are listed as follows:

- Lower propagation speed;
- Noise;
- Path loss due to various physical obstacles.

The above issues degrade the signal. Thus, reliable communication protocols need to be developed for these WSNs. For agricultural application, the WSNs are deployed

Table 5.2 Difference between 2D and 3D WSN

S. No.	2D WSN	3D WSN
1	Sensor is placed on the surface	Sensors are immersed into soil/water
2	Communication range is up to 100 m [2]	0.1–10 m [2]
3	High-frequency communication is efficient	High-frequency communication is attenuated by the soil. Thus, lower frequency communication is preferred
4	Frequency used is 868/915 MHz and 2.4 GHz [17]	Frequency range used is 433 MHz and 8–300 kHz [17]
5	Energy consumption is less	Energy consumption is more compared to 2D
6	Installation cost is lower	Installation cost is higher

underground, where sensors are mainly used to measure moistness, minerals, and compost proportion present in the soil. The sensor nodes are buried in two layers—-topsoil and subsoil. The communication links of the nodes are affected by the soil. High-frequency signals suffer severe attenuation compared to lower frequency signals [18]. Due to this, communication range of the sensor nodes gets limited. Thus, more number of nodes is required to cover the large farmland.

The advantage of 3D over 2D is that the soil mineral and moisture in depth can also be monitored so that the fertilizers and compost will be adequately used as per the requirement. The water supply can also be made precise for drought-affected agricultural lands. The major differences between 2D and 3D WSN are listed in Table 5.2.

5.3 Study of Literature

The literature on clustering protocols is studied and summarized in this section. The nearby sensor nodes form clusters using various techniques like query-driven model, probability-based model [19–25]. The appropriate formation of clusters will reduce intra-cluster transmission distances required to forward the sensed data to CH. In [19], a distributed cluster computing energy-efficient routing scheme (DCCEERS) is implemented. A node is eligible to form cluster if its random counter becomes zero. The node form clusters using queries exchanged between the sensor nodes within its transmission range. The center of gravity of the clusters is then calculated and used to determine the centrality of the sensor nodes. The CHs are elected in each round based on remaining energy of the node and its centrality. The protocol does not limit the number of clusters formed in the network because any node in the network can start cluster formation on the condition of random counter.

The WSN is used for potato crop monitoring in Egypt as explained in [20]. Potato fields are mostly affected by fungal disease called as phytophtora. The preferable land for good quality potato cultivation is loamy and well-aerated soil. The soil must not contain high level of calcium carbonate. This affects the starch quality of potatoes. The project used adaptive threshold sensitive energy-efficient sensor network (APTEEN) protocol for routing the sensed data [21]. APTEEN is the hierarchical cluster-based routing protocol. The field is assumed to be divided into small tubs of one carat area. Every carat will have two nodes deployed at the central region with a separation distance of approximately six meters. Also one node is deployed at the edges of the carat so as to communicate with another carat node.

In [22], the monitoring of cotton plant vigor to enhance its productivity and protect from damage is illustrated. Here, low-power sensor nodes are used to monitor potency in terms of chlorophyll concentration of the leaf. The sensor nodes sense the leaf information. This data is transmitted to sink node. The sink node forwards the data to remote host computer through universal serial bus (USB). The plants are separated evenly into small bunches. Every bunch has a sensor node deployed. The images of the leaves captured are judged for its strength. In minor abnormal situation also, an alarm is given. This makes the system fully flexible and avoids human efforts of manually observing the plants. The data collected can be used by experts to analyze the cultivation crop. The WSN is thus used in agriculture to enhance the crop protection as well as improve the farming techniques to achieve better productivity and quality.

Another initiative taken by the institute of agriculture and natural resources under University of Nebraska, Lincoln, used crop canopy sensors to measure liquid rate of nitrogen as per plant need [23]. The objective of the project is to manage nitrogen spray rate depending on the need of the crop using crop canopy sensors mounted on the node. This node can be fitted to the existing liquid nitrogen applicator, which uses electronic spray. The node also consists of electronic flow meter, pump speed hydraulic valve, and global positioning system (GPS). The monitoring central system receives sensor data along with GPS location. The data is processed using sufficiency index algorithm, and the desired nitrogen rate is provided to the rate controller. Thus, the pump valves control the flow of nitrogen spray.

A dynamic CH selection method (DCHSM) [24] forms clusters using Voronoi cells. The mean point of each Voronoi cell is used to determine centrality of the sensor node, while selecting a CH for every cluster. Two sets of eligible nodes are selected in a cluster. CH is then selected from first set initially. The second set is utilized only after the death of all the nodes in the first set. This results in unbalanced energy distribution among the network because every Voronoi cell does not have uniform number of nodes. In saving energy clustering algorithm (SECA) [25], mean points of the clusters are calculated using pre-defined single central point of the monitoring region and the average distances between the central point and the sensor nodes. The mean points are then determined iteratively by shifting away from the central point. The mean points depend on the number of sensor nodes in the cluster and their positions in the monitoring region. The change in number of cluster members will change the mean point location of that cluster. Thus, determining mean point of the region within a group of sensor nodes is likely to be ambiguous in nature.

Fuzzy-based clustering protocols also find tremendous scope in improving network performance. FCM is one of the optimization algorithms to categorize given objects [26, 27]. The nodes in the network are clustered using FCM. A fuzzy logic-based clustering protocol is proposed in [28]. To balance the network load and minimize hot spots in the network, unequal clustering is implemented. The fuzzy logic-based efficient clustering hierarchy (FLECH) is proposed in [29]. The CHs selected in the network are based on fuzzy logic system. The inputs to this system are remaining energy of the node, its centrality and distance toward gateway. It uses network dimension and number of one-hop neighbors to calculate the centrality of the sensor node to its associated cluster.

Based on the above literature, it is inferred that the cluster formation has major effects on the network performance. The nodes in a cluster must be near located nodes so that the intra-cluster distances are reduced. If the distances are considerably large, then energy consumption is also more. This ultimately reduces the overall network lifetime.

5.4 Proposed Clustering Protocol

An energy-efficient distributed cluster computing protocol is proposed in this work for farmland monitoring. The crops are grown on large surface region, and they are to be monitored using sensor nodes. Thus, the WSN deployed must be scalable. The sensor nodes are battery driven, and therefore, their energy must be utilized in proper manner so that the network can monitor the farmland for long period of time. Thus, the WSN must be sustainable and maintain alive nodes in the network for long duration. In the proposed protocol, an attempt is made to fulfill both—scalability and sustainability of the network.

In this work, FCM algorithm is used to determine mean points among the randomly deployed sensor nodes in the farmland. The clusters are formed within t iterations of the FCM algorithm. Once clusters are formed, every sensor node calculates its perception probability, which depends on the distance between node and mean point of the associated cluster. A set of eligible nodes is formed based on the perception probability of these nodes. All the CH-eligible nodes then calculate their perception value (V) and energy ratio (E) and broadcast to other nodes in the cluster. A node with highest V or highest E value will declare itself as CH.

The communication model decides the energy utilization of the sensor node because the major energy consumption is due to radio transmissions. The communication model used in the proposed protocol is similar to the model used in [11]. The energy required to transmit Q bits of data is given as,

$$E_{\mathrm{Tx}} = \begin{cases} Q\left(E_{\mathrm{elec}} + E_{\mathrm{fs}} D^2\right); \; D < D_{\mathrm{ref}} \\ Q\left(E_{\mathrm{elec}} + E_{\mathrm{mp}} D^4\right); \; D \geq D_{\mathrm{ref}} \end{cases} \tag{5.1}$$

where E_{Tx} is the energy utilized for transmission. Q is the number of bits. E_{elec} is the energy required by hardware for processing and data aggregation. E_{fs} is the energy utilization due to free space channel propagation. E_{mp} is the energy required due to multipath fading channel propagation. D is the distance between transmitter and receiver nodes. D_{ref} is the reference distance used to choose the propagation model for data transmission. The energy required at the receiver end to receive Q bits is calculated as,

$$E_{Rx} = QE_{elec} \tag{5.2}$$

where E_{Rx} is the energy utilized for data reception. The proposed cluster formation and the CH selection are explained in the following subsections. It is assumed that the nodes are familiar with their node locations. It is also assumed that all the distances calculated are based on the received signal strength (RSS).

5.4.1 FCM-Based Clustering

The locations of sensor nodes and number of mean points are the inputs to FCM algorithm. Let us consider X number of sensor nodes in the network. These are grouped into Y clusters. The node location is denoted by two coordinates. FCM computes membership values between 0 and 1 as illustrated in this subsection. A value of 0 indicates no membership and 1 indicates complete membership. In between values indicate proportionate membership. The sum of the membership values for each sensor node to all clusters will be equal to 1. Also, different membership values show the probability of each sensor node to different clusters. A node is associated with that cluster mean point, whose corresponding membership value is highest. The first input data, i.e., node locations, is given as

$$\boldsymbol{A} = \{a_1, a_2, \ldots, a_i, \ldots, a_X\} \tag{5.3}$$

where X is total number of sensor nodes in the network. $\boldsymbol{A}$ is a matrix of dimension $X \times 2$. a_i is the node location of the ith node. Similarly, the matrix of mean points, $\boldsymbol{M}$, is given as,

$$\boldsymbol{M} = \left\{m_1, m_2, \ldots, m_j, \ldots, m_Y\right\} \tag{5.4}$$

where Y is total number of clusters to be formed in the network. m_j is the mean point of the jth cluster. Initially, random mean points are considered for the first iteration. These mean points are shifted in the next iteration as per the objective function. The objective function with respect to membership value Z_{ij} and the distance D is formulated as

$$F = \sum_{i=1}^{X} \sum_{j=1}^{Y} \left(Z_{ij}\right)^{\alpha} D\left(a_i, m_j\right)^2 \tag{5.5}$$

where F is the objective function. Z_{ij} is the degree of membership that the ith sensor node pertains to the jth cluster mean point. $\alpha \in [1, \infty]$ is the fuzzy factor. Practically, many studies show that α value is considered to be [2, 2.5] [26]. In our work, α is considered to be equal to 2. $D\left(a_i, m_j\right)$ is the distance between ith sensor node and jth mean point. For every iteration, Z_{ij} and m_j are calculated as,

$$Z_{ij} = \frac{1}{\sum_{k=1}^{Y} \left(\frac{\|a_i - m_j\|}{\|a_i - m_k\|} \right)^{\frac{2}{\alpha - 1}}} \tag{5.6}$$

$$m_j = \frac{\sum_{i=1}^{X} Z_{ij}^{\alpha} a_i}{\sum_{i=1}^{X} Z_{ij}^{\alpha}} \tag{5.7}$$

In order to minimize the objective function F, partial derivative of F with respect to Z_{ij} and m_j is performed iteratively using Eqs. (5.6) and (5.7). m_k is the mean point calculated in the past iteration for the jth cluster. The iterations are performed subject to the following conditions,

$$\sum_{j=1}^{Y} Z_{ij} = 1, i = 1, 2, \ldots., X \tag{5.8}$$

$$0 \leq Z_{ij} \leq 1, i = 1, 2, \ldots, X \text{ and } j = 1, 2, \ldots, Y \tag{5.9}$$

The condition in Eq. (5.8) is used to remove node isolation issue in the network. Every node has some membership toward each cluster within value one. After optimum iterations, each node is associated with one cluster, whose corresponding membership value is the highest. The condition in Eq. (5.9) restricts membership value within the given range so as to satisfy Eq. (5.8). The algorithm is halted in two cases—algorithm has reached either minimum threshold or maximum iterations. The proposed FCM algorithm for cluster formation is given as follows:

FCM algorithm for cluster formation

Initialization:

1. *Initialize minimum_ threshold;*
2. *Initialize maximum iterations (t_{max});*
3. *Initialize cluster mean points;*

Input:

4. *Node locations;*

Main function:

```
5.  For each iteration (t)
6.      If t < t_max
7.          Calculate objective function (F);
8.          Improvement = absolute F^t – absolute F^(t−1);
9.          If improvement > minimum_ threshold
10.             Update Z_ij and m_j;
11.         Else
12.             Break;
13.         End
14.     Else
15.         Break;
16.     End
17. End
```

5.4.2 CH Selection Using Perception Probability

After clusters are formed in the network, each sensor node is associated with a mean point of its cluster. All the nodes then calculate perception probability using,

$$P\left(a_i, m_j\right) = \begin{cases} 1, & D\left(a_i, m_j\right) < S - \tau \\ e^{-\vartheta D_i}, & S - \tau \le D\left(a_i, m_j\right) < S + \tau \\ 0 & D\left(a_i, m_j\right) \ge S + \tau \end{cases} \tag{5.10}$$

where $P\left(a_i, m_j\right)$ is the perception probability of ith node with respect to its mean point m_j. a_i is the ith node location associated with jth cluster. $D\left(a_i, m_j\right)$ is the distance of the ith sensor node from its mean point m_j. S is the sensing range of the sensor node. τ is the uncertainty factor of the sensor hardware circuit, and ϑ is the exponent factor. D_i is the term used as an exponential variable and calculated as,

$$D_i = D\left(a_i, m_j\right) - (S - \tau) \tag{5.11}$$

where D_i affects the probable value of node proportionately to the sensing range of the sensor hardware circuit. The use of sensing range assures node's coverage over other nodes within the cluster. This assures that none of the node is isolated. Then, a set of redundant nodes are found, whose perception probability is greater than 0.3 and less than 1. This range is selected because the perception probability model is distance based. The nodes having probability less than or equal to 0.3 are reasonably away from center point compared to other cluster members. Such nodes have comparatively less reach ability or cluster coverage, which affects the average transmission distance of the nodes in the cluster.

The redundant nodes are the eligible nodes that can become CH for the given round. For each redundant node, V is calculated. At initial round, all nodes have equal energy level. Thus, for the initial few rounds, CH is selected based on V value. It is calculated as,

$$V_q = \frac{P\left(a_q, m_j\right)}{\sum_{l=1}^{q} P\left(a_q, m_j\right)} \tag{5.12}$$

V_q is the perception value of qth node in the jth cluster. The node with highest V_q value is selected as CH. After few rounds, the energy of the nodes apparently becomes heterogeneous in nature. Hence, for further rounds, CH is selected based on perception probability and remaining energy of the node. The E value is calculated as,

$$E_q = P\left(a_q, m_j\right) \frac{E^q_{\text{residual}}}{E^j_{\text{average}}} \tag{5.13}$$

where E_q is the energy ratio of the qth node of jth cluster. E^q_{residual} is the remaining energy of qth node. E^j_{average} is the total average energy of all the q nodes of jth cluster. The node having maximum E_q value is selected as CH. The total average energy of all the nodes in the cluster is considered to calculate energy ratio, because it will estimate the accurate perception of the node with respect to all its cluster members.

Once the CH is selected for every cluster, a time division multiple access (TDMA) scheduling is done at every CH node. Cluster members transmit their sensed data to CH in their allocated time slots. When all the cluster data is received, CH performs data aggregation to form a single data packet. This aggregated data packet is then transmitted to gateway. For every round, new CH is elected by comparing the V and E values among the cluster members.

5.5 Simulation Results and Discussions

In this section, the simulation results of the proposed clustering protocol are presented. The MATLAB R2017b is used to implement the proposed protocol. A WSN for given monitoring region consists of 200 sensor nodes and one gateway. All the network devices are static after deployment. The sensor nodes are randomly deployed, while gateway is located at (0, 0). The clustering protocol is executed for increasing monitoring area, and the corresponding network performance metrics are observed. The simulation parameters used are listed in Table 5.3.

Table 5.3 Simulation parameters

Parameters	Values
Monitoring region	100 m × 100 m, 200 m × 200 m
Number of sensor nodes	200
Gateway's location	(0,0)
Initial energy of sensor node	0.5 J
Energy consumed by electronic circuits	50 nJ
Energy for data aggregation	5 nJ/bit/message
Energy of free space propagation	10 pJ/bit/m^2
Energy of multipath fading channel	0.0013 pJ/bit/m^4
Packet of control bits	200 bits
Packet of data bits	2400 bits
Fuzzy factor (α)	2
Uncertainty factor of sensor node (τ)	0.2
Exponent factor (ϑ)	0.1
Improvement threshold of objective function	1×10^{-5}
Termination threshold for FCM ($t_{\max}$)	100

The performance of proposed protocol is compared with LEACH [11], DCCEERS [19], DCHSM [24], and FLECH [29] in terms of remaining network energy and number of alive nodes. It is evaluated for two scenarios.

5.5.1 Scenario 1: Monitoring Region of 100 m × 100 m

The comparative plot of total remaining network energy and number of alive nodes with respect to number of rounds is shown in Figs. 5.5 and 5.6, respectively. The proposed protocol outperforms the conventional protocols because of efficient cluster formation using FCM algorithm, which reduces the intra-cluster transmission distances of the sensor nodes significantly. The centrality of the sensor node in the cluster is decided by the perception probability, which is based on factors like S, ϑ, and distance between sensor nodes and cluster mean point. Due to consideration of all above-mentioned factors, proper CH is been elected and the network load distribution among the sensor nodes is done in efficient manner. Therefore, the network sustains for long duration with more number of nodes alive as shown in Fig. 5.6.

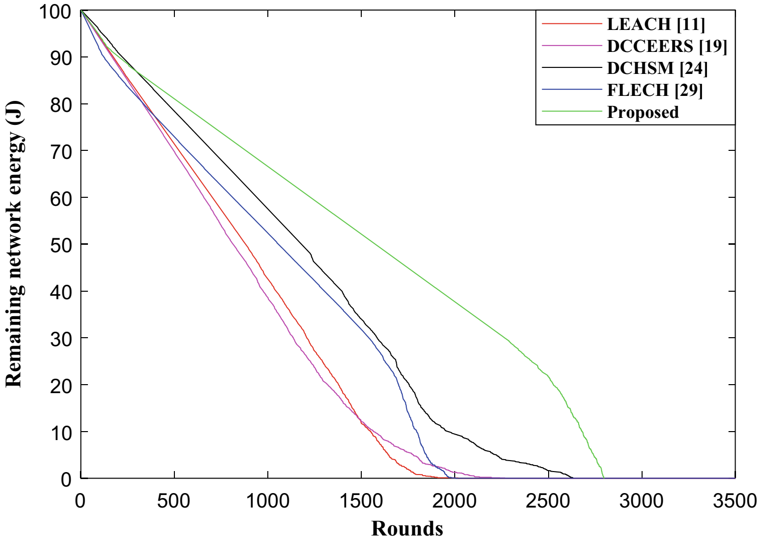

Fig. 5.5 Remaining network energy for monitoring region of size 100 m × 100 m

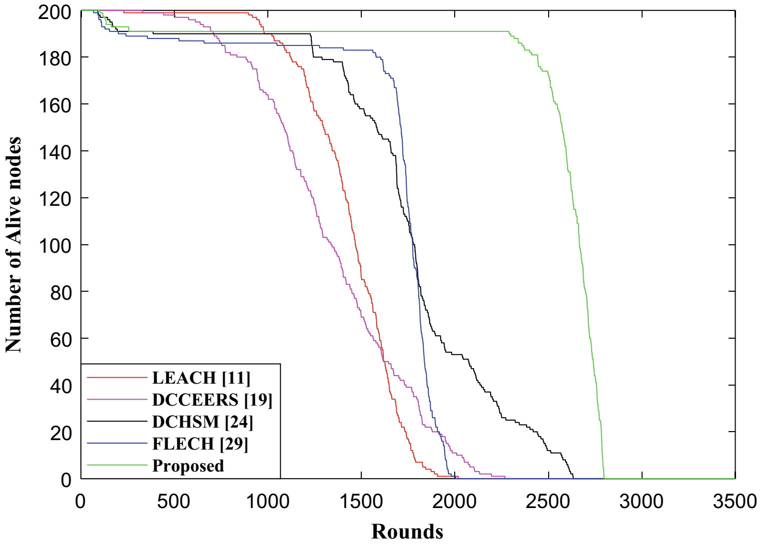

Fig. 5.6 Number of alive sensor nodes for monitoring region of size 100 m × 100 m

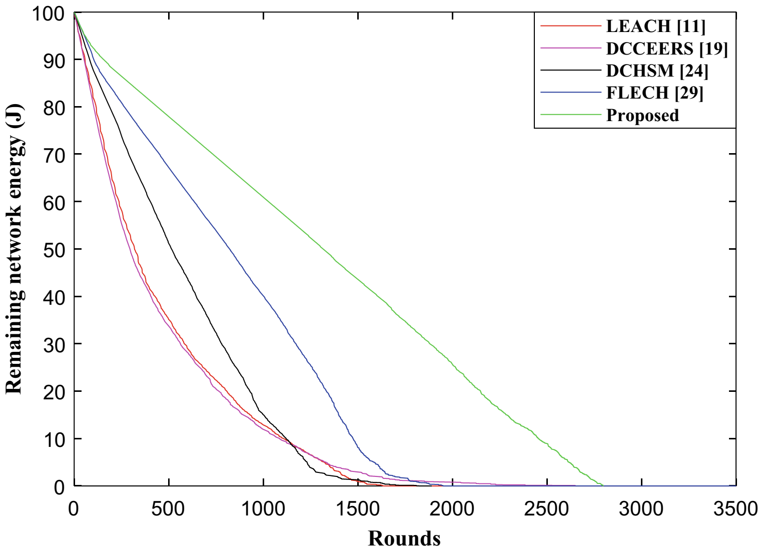

Fig. 5.7 Remaining network energy for monitoring region of size 200 m × 200 m

5.5.2 Scenario 2: Monitoring Region of 200 m × 200 m

As the proposed protocol is simulated for farmland monitoring system, it is also tested for increase in coverage area. In this scenario, 200 sensor nodes are deployed in the area of 200 m × 200 m. The protocols are executed, and the results are plotted as shown in Figs. 5.7 and 5.8. The results obtained proved that the proposed protocol performs better than other conventional protocols even for scalable scenario.

The proposed protocol is further analyzed for the sustainability in terms of first node dead (FND), half of the nodes dead (HND), and last node dead (LND). The round at which FND, HND, and LND occurred for all the simulated protocols is observed for five different WSN deployments. The readings for these set of WSN deployments are observed for both scenarios. The readings are listed in Tables 5.4 and 5.5 for 100 m × 100 m and 200 m × 200 m, respectively.

The average values of HND and LND readings are calculated and plotted as shown in Figs. 5.9 and 5.10, respectively. The HND value indicates 50% of the WSN to be alive. From Fig. 5.9, it is seen that the proposed protocol sustains with 50% alive nodes for more number of rounds compared to other protocols in both the scenarios. This is because, as nodes start exhausting their energy, CHs are elected based on centrality as well as energy ratio values determined by Eqs. (5.10) and (5.11). The result for LND also holds better as seen from Fig. 5.10. Thus, the proposed protocol is energy efficient as well as sustainable and thus can be implemented for agricultural applications. The FND values of the proposed protocol occur at very early rounds because at the initial few rounds, the CHs are elected based on only distance parameter. Thus, the node that

Table 5.4 Network lifetime in terms of FND, HND, and LND (monitoring region = 100 m × 100 m)

WSN	LEACH [11]			DCCEERS [19]			DCHSM [24]			FLECH [29]			Proposed		
	FND	HND	LND	FND	HND	LND	FND	HND	LND	FND	HND	LND	FND	HND	LND
1	308	1437	1832	363	1380	2510	63	1742	2219	93	1669	1978	124	2671	2799
2	209	1489	1865	361	1367	2982	60	1699	2329	79	1732	1989	105	2685	2799
3	204	1421	1762	414	1380	2520	78	1733	2659	90	1693	1977	98	2697	2796
4	211	1514	1992	338	1411	2422	68	1770	2282	80	1773	1992	112	2664	2798
5	230	1467	2018	330	1336	2269	91	1778	2633	68	1774	2004	102	2666	2799
Average	232.4	1465.6	1893.8	361.2	1374.8	2540.6	72	1744.4	2424.4	82	1728.2	1988	108.2	2676.6	2798.2

Table 5.5 Network lifetime in terms of FND, HND, and LND (monitoring region = 200 m × 200 m)

WSN	LEACH [11]			DCCEERS [19]			DCHSM [24]			FLECH [29]			Proposed		
	FND	HND	LND	FND	HND	LND	FND	HND	LND	FND	HND	LND	FND	HND	LND
1	119	675	1632	92	635	2650	25	866	1892	94	1402	1950	26	2309	2795
2	117	650	1584	91	616	2473	26	905	2056	92	1418	1959	29	2391	2792
3	120	679	1674	70	668	2030	27	885	1600	93	1463	1955	38	2469	2796
4	124	589	1747	91	560	2345	27	893	1756	86	1391	1968	36	2371	2786
5	100	524	2049	66	556	2536	26	857	2249	95	1365	1939	31	2400	2793
Average	116	623.4	1737.2	82	607	2406.8	26.2	881.2	1910.6	92	1407.8	1954.2	32	2388	2792.4

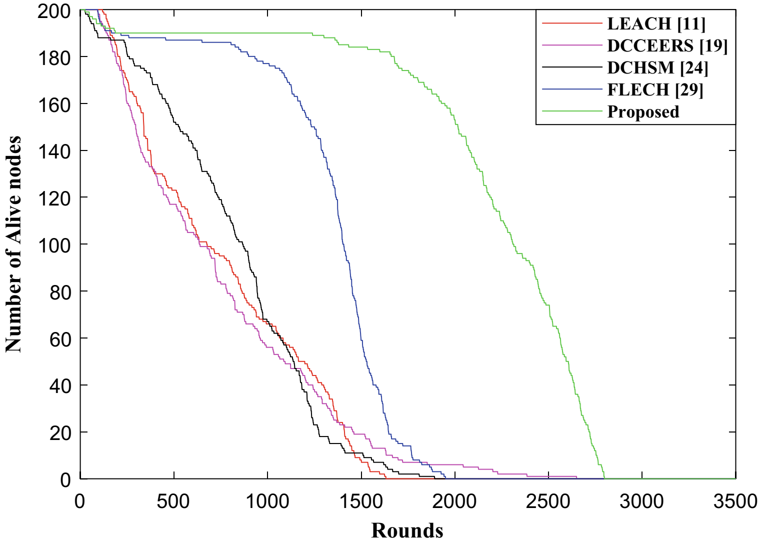

Fig. 5.8 Number of alive sensor nodes for monitoring region of size 200 m × 200 m

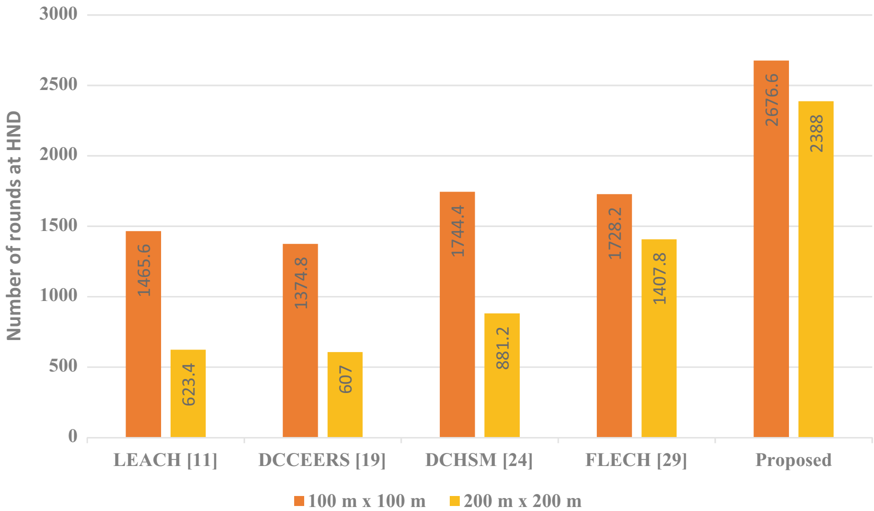

Fig. 5.9 Effect of monitoring region on HND of simulated protocols

is more central to the cluster gets repeated chance to become CHs in the initial few rounds. These nodes deplete their energy very soon ultimately decreasing the FND metric. In later rounds, the network load is distributed evenly based on distance as well as energy parameters. Hence, the HND and LND are attained at higher rounds, prolonging the network lifetime.

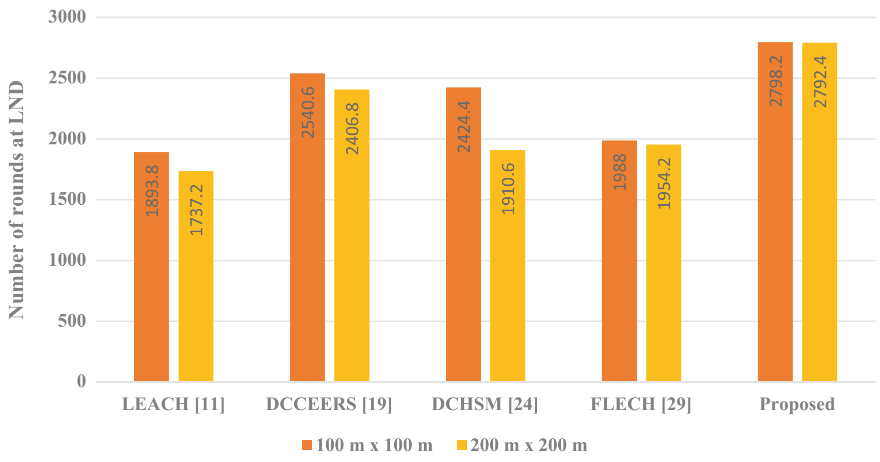

Fig. 5.10 Effect of monitoring region on LND of simulated protocols

5.6 Conclusions

A sustainable WSN clustering protocol is proposed using FCM algorithm and the perception probability. The protocol aims at increasing network lifetime, while increasing coverage area. This paper discussed the basic requirements of the WSN-based IoT system for smart monitoring of the farmlands. In the literature framework, 2D and 3D WSNs are illustrated in detail, focusing the implementation aspects. A modified LEACH is implemented to demonstrate the effect of hierarchical levels in clustering techniques.

The proposed clustering protocol outperforms the existing conventional protocols in terms of energy saving and network lifetime. Due to FCM algorithm, proper clusters are formed with significantly reduced intra-cluster distances. The appropriate selection of CH based on perception probability distributed the network load evenly among the nodes. For monitoring applications in agriculture, a maximum number of nodes are required to be functional till the crop development period. The proposed protocol sustains more than 50% of nodes for long period of time making it suitable for agrarian monitoring systems. The results observed in terms of alive nodes indicate that the proposed protocol is energy efficient and sustainable.

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