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A Survey on Successors of LEACH Protocol

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ABSTRACT Even after 16 years of existence, low energy adaptive clustering hierarchy (LEACH) protocol is still gaining the attention of the research community working in the area of wireless sensor network (WSN). This itself shows the importance of this protocol. Researchers have come up with various and diverse modifications of the LEACH protocol. Successors of LEACH protocol are now available from single hop to multi-hop scenarios. Extensive work has already been done related to LEACH and it is a good idea for a new research in the field of WSN to go through LEACH and its variants over the years. This paper surveys the variants of LEACH routing protocols proposed so far and discusses the enhancement and working of them. This survey classifies all the protocols in two sections, namely, single hop communication and multi-hop communication based on data transmission from the cluster head to the base station. A comparitive analysis using nine different parameters, such as energy efficiency, overhead, scalability complexity, and so on, has been provided in a chronological fashion. The article also discusses the strong and the weak points of each and every variants of LEACH. Finally the paper concludes with suggestions on future research domains in the area of WSN.

INDEX TERMS LEACH, Wireless Sensor Network, Clustering Protocol, Cluster Head, Routing.

I. INTRODUCTION

A Wireless Sensor Network (WSN) is a collection of large numbers of sensor nodes with limited sensing, computing and communication capabilities. These sensors are deployed over a large area with one or more than one Base Station (BS). WSN has wide application possibilities, such as temperature, pressure, humidity and habitat monitoring, disaster management, military reconnaissance, forest fire-tracking, security surveillance and many more [1]–[3]. In most scenarios, sensor nodes are randomly deployed with limited battery power. The selection of routing techniques is an important issue for the efficient delivery of sensed data from its source to the destination. The routing strategy used in these type of networks should ensure minimum energy consumption as battery replacement in sensors are often not possible. A lot of energy-efficient routing protocols have been proposed and developed for WSN, depending on their application and network architecture. Designing a routing protocol is full of challenges, mainly due to limited power, low bandwidth, low computational power, no conventional addressing scheme, computational overheads and self-organization of the sensor nodes.

According to Pantazis *et al.* [4], routing protocols can be classified in four schemes: Network Structure Scheme, Topology Based Scheme, Communication Model Scheme and Reliable Routing Scheme. Further based on the deployment of nodes in the network, the network structure schemes can be divided into two types: Flat routing and Hierarchical routing. In flat routing protocols, all sensor nodes play identical roles and functionalities in the network. The popular flat routing schemes are Flooding and Gossiping [5], Directed diffusion [6], Rumor [7], SPIN [8], etc. The main problem of these types of networks is scalability as they are used for small area networks. Since this paper provides a survey on LEACH and its variants, our discussions will be limited to hierarchical routing protocols. Hierarchical routing provides better energy efficiency and scalability due to its architecture. In this type of protocol, the whole network is divided into clusters and some nodes are chosen as special nodes based on certain criteria. These special nodes called cluster heads (CHs) collect, aggregate and compress the information received from neighbour nodes, and finally transmit the compressed information to the BS. The CH provides additional services to other nodes in the cluster and hence consumes more energy as compared to other nodes of the cluster. Cluster rotation is a common method deployed to balance the energy dissipation within a cluster. The first hierarchical routing protocol was proposed by Heinzelman *et al.* [9] known as LEACH. In LEACH, clusters are formed on the basis of the strength of the signal received by the sensor

TABLE 1. List of the previous surveys on LEACH variants.

Year	Contributions	Limitations	References
2010	Compared six hierarchical routing protocols (HRPs) with a comparision graph in terms of energy consumption and network lifetime.	Only six protocols are compared and only one parameter, namely network lifetime, is used.	Lotf et al. [17]
2011	Six HRPs with 12 parameters were compared.	Proper parameters are not used and discussed protocol are outdated.	Xu et al. [18]
2012	LEACH was compared with M-LEACH, MH-LEACH and sLEACH in terms of energy consumption.	Only four HRPs are analysed under energy consumption parameters.	Aslam et al. [19]
2013	Various LEACH-related protocols are discussed and their basic techniques comapred CH selection, improvement over LEACH and their disadvantages.	Limited number of comparision parameters are taken.	Hani et al. [20]
2013	Classified all LEACH variants into three categories: modified CH selection algorithms, energy aware algorithms and optimization in CH selection.	Smaller number of HRPs compared with some selected parameters.	Madheswaran et al. [21]
2014	Security-related LEACH variants are presented.	Only security-related protocols and issues are discussed.	Rahayu et al. [22]
2015	Successors of LEACH protocols in alphabetical order are discussed and compared.	Only four parameters are considered and analysed without considering the energy consumption parameters.	Mahapatra et al. [23]
2016	Variants of LEACH and other HRP protocols are discussed with four parameters.	Only four parameters and few HRPs are considered and analysed.	Arora et al. [24]

nodes. The local CHs are used as routers to the BS. LEACH is discussed in more details in section II. A number of hierarchical clustering protocols have been developed by considering LEACH as the basic protocol and applying different factors over it. Popular clustering routing algorithms in WSNs include LEACH [9], HEED [10], PEGASIS [11], EECS [12], EEMC [13], TEEN [14], PANEL [15] and T-LEACH [16].

Several surveys [17]–[24] have been conducted on LEACH and its variants for WSN as shown in Table 1. Aslam *et al.* [19] have examined only the enhancements of energy efficiency and throughput of LEACH, Multi-hop LEACH, M-LEACH and solar aware LEACH protocols. Hani and Ijjeh [20] provide an insight into various LEACH-related protocols. The paper also reviews and compares a limited number of LEACH and its successors with the help of a table showing the advantages, disadvantages, CH selection criteria and assumptions for each protocol. Madheswaran and Shanmugasundaram [21] group LEACH-based protocols into three categories: modified CH selection algorithms, energy-aware algorithms and optimization in CH selection. The area of discussion in the paper is limited to CH selection and energy efficiency-related parameters. Soni *et al.* [23], have presented a survey on the successors to LEACH protocol in alphabetical order. The survey is based on some selected features like the clustering method, data aggregation, mobility and scalability. Arora *et al.* [24] have reviewed different types of hierarchical routing protocols based on LEACH. The authors have discussed and compared only four protocols(LEACH [9], C-LEACH [25], MOD-LEACH [26] and SEP [27]) based on the round number when the first node dies, the percentage of dead nodes and parameters when the last node dies. However, all of the surveys mentioned in Table 1 shed light on a limited number of LEACH variants and their comparisions are based on a few parameters and without any consideration for their limitations. As far as we know, the work presented in this paper is the most comprehensive survey. It covers a large number of available literatures on LEACH and its variants and compares them against different parameters related to WSN. we believe that this paper will help a researcher, to gain insight into the working of routing algorithms and how they have developed over the years to perform in energy efficient way.

In order to streamline this survey, we have classified all the variants of LEACH in two categories: single hop communication and multi-hop communication based on data transmission from the CH to the BS. In the data transmission phase of WSN, data is transmitted in two different communication modes: intra cluster communication and inter cluster communication. In intra cluster, cluster members communicate with the CH within a cluster and in inter cluster CHs communicate with the BS. The intra cluster communication is always single hop. However, the inter cluster communication may be single hop or multi-hop. Many hierarchical clustering routing algorithms have been developed by using these two types of communications. The phases and their classification of LEACH and its variants are shown in Figure 1.

Objectives of LEACH and its Variants: LEACH and its successors are developed with different objectives and purposes in WSN. The most common and important objective of these protocols is energy conservation. Figure 2 shows an overview of some of the most common objectives of LEACH and its successors. This paper has attempted to prioritize the objectives of the research community developing LEACH over the years. The number along with objective in Figure 2 shows the priority order on a scale from 1 to 8 where the lower value denotes higher priority.

The rest of the paper is organized in the following manners: Section II describes basic LEACH protocol architec-

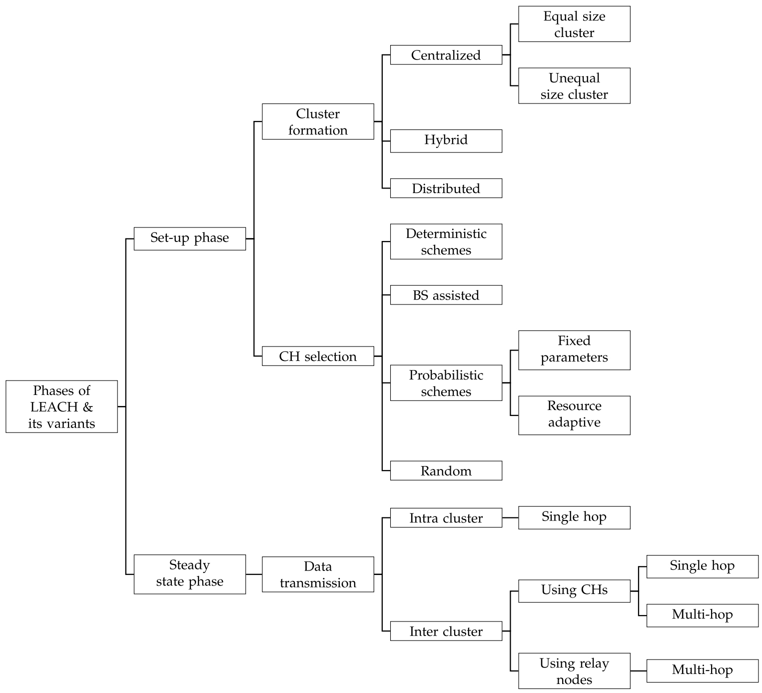

FIGURE 1. Phases of LEACH and its variants in WSN.

ture in detail along with the advantages and disadvantages. Section III presents a detailed survey of various successors of basic LEACH protocol based on single hop communication. The LEACH successors based on multi-hop communication are discussed in Section IV. In Section V, a comparative analysis of LEACH and its successors have been presented. Some important future research areas in LEACH are proposed in Section VI. Finally, Section VII concludes the paper.

II. LEACH (LOW ENERGY ADAPTIVE CLUSTERING HIERARCHY) PROTOCOL

LEACH is a pioneer clustering routing protocol for WSN. The main objective of LEACH is to increase the energy efficiency by rotation-based CH selection using a random number. The LEACH protocol architecture is shown in Figure 3.

The operation of LEACH consists of several rounds where each round is divided into two phases: the set-up phase and the steady state phase as shown in Figure 4. During the set-up phase, CH selection, cluster formation and assignment of a TDMA (Time Division Multiple Access) schedule by the CH for member nodes are performed. In CH selection, each node participates in a CH election process by generating a random priority value between 0 and 1. If the generated random number of a sensor node is less than a threshold value $T(n)$ then that node becomes CH. The value of $T(n)$ is calculated using Equation 1.

$$T(n) = \begin{cases} \frac{P}{1-P*(r \mod \frac{1}{P})} : & if\ n \epsilon G \\ 0 : & otherwise \end{cases} \quad (1)$$

Where P denotes the desired percentage of sensor nodes to become CHs among all sensor nodes, r denotes the current round and G is the set of sensor nodes that have not participated in CH election in previous $1/P$ rounds. A node that becomes the CH in round r cannot participate in the next $1/P$ rounds. In this way every node gets equal chance to become the CH and energy dissipation among the sensor nodes is distributed uniformly. Once a node is selected as the CH, it broadcasts an advertisement message to all other nodes. Depending on the received signal strength of the advertisement message, sensor nodes decide to join a CH for the current round and send a join message to this CH. By generating a new advertisement message based on Equation 1, CHs rotate in each round in order to evenly distribute the energy load in the sensor nodes. After the formation of the cluster, each CH creates a TDMA schedule and transmits these schedules to their members within the cluster. The TDMA schedule avoids the collision of data sent by member nodes and permits the member nodes to go into sleep mode. The set-up phase is completed if every sensor node knows its TDMA schedule. The steady state phase follows the set-up phase.

In the steady state phase, transmission of sensed data from member nodes to the CH and CH to the BS are performed using the TDMA schedule. Member nodes send data to the CH only during their allocated time slot. When any one member node sends data to the CH during its allocated time slot, another member node of that cluster remains in the sleep state. This property of LEACH reduces intra cluster collision and energy dissipation which increases the battery life of all member nodes. Additionally, CHs aggregate data received from their cluster members and send it directly to the BS. Transmission of data from the CH to the BS is also performed with the help of the alloted TDMA schedule. The CH senses the states of the channel for sending its data. If

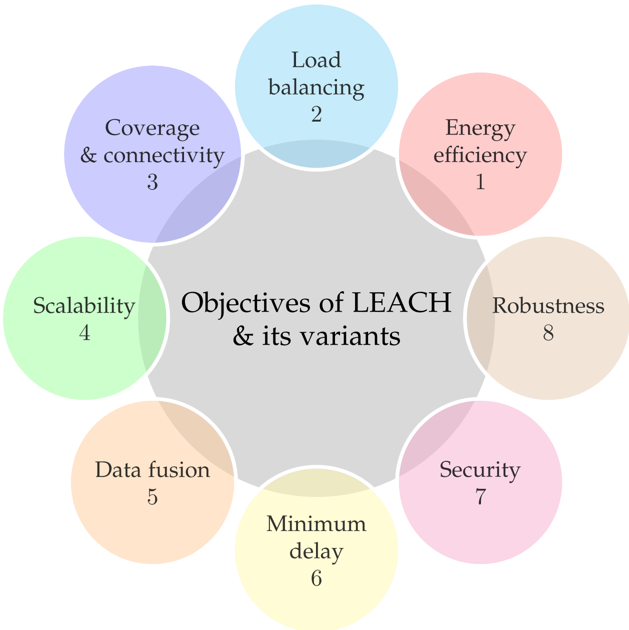

FIGURE 2. Objectives of LEACH and its variants with a increasing priority.

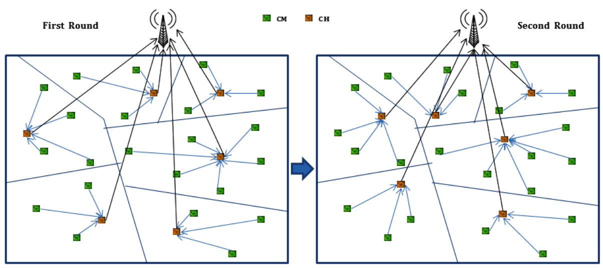

FIGURE 3. Illustration of the LEACH protocol with two different rounds with different CH.

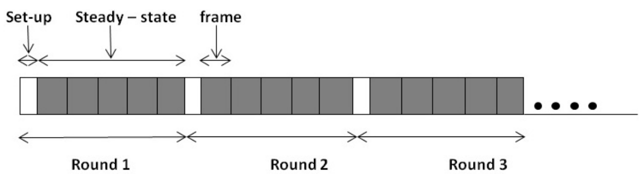

FIGURE 4. Time line of LEACH operation: the set-up and steady state phase.

the channel is busy i.e. it is being used by any other CH then it waits; otherwise it uses the channel to transmit the data to the BS.

A. ADVANTAGES OF LEACH

LEACH is a complete distributed routing protocol in nature. Hence, it does not require global information. The main advantages of LEACH include the following:

1) Concept of clustering used by LEACH protocol enforces less communication between sensor nodes and the BS, which increases the network lifetime.
2) CH reduces correlated data locally by applying data aggregation technique which reduces the significant amount of energy consumption.
3) Allocation of TDMA schedule by the CH to member nodes allows the member nodes to go into sleep mode. This prevents intra cluster collisions and enhances the battery lifetime of sensor nodes.
4) LEACH protocol gives equal chance to every sensor node to become the CH at least once and to become a member node many times throughout its lifetime. This randomized rotation of the CH enhances the network lifetime.

B. DISADVANTAGES OF LEACH

However, there exist some disadvantages in LEACH which are as follows:

1) In each round the CH is chosen randomly and the probability of becoming the CH is the same for each sensor node. After completion of some rounds, the probability of sensor nodes with high energy as well as low energy becoming the CH is the same. If the sensor node with less energy is chosen as the CH, then it dies quickly. Therefore, robustness of the network is affected and lifetime of the network degrades.
2) LEACH does not guarantee the position and number of CHs in each round. Formation of clusters in basic LEACH is random and leads to unequal distribution of clusters in the network. Further, in some clusters the position of the CH may be in the middle of the clusters, and in some clusters the position of the CH may be near the boundaries of the clusters. As a result, intra cluster communication in such a scenario leads to higher energy dissipation and decreases the overall performance of the sensor network.
3) LEACH follows single hop communication between the CH and the BS. When the sensing area is beyond a certain distance, CHs which are far away from the BS spend more energy compared to CHs which are near to the BS. This leads to uneven energy dissipation which ultimately degrades the lifetime of the sensor network.

III. SUCCESSORS OF LEACH WITH SINGLE HOP COMMUNICATION

In single hop communication, the CH collects data from its member nodes and directly sends this data to the BS. LEACH protocol follows single hop communication which plays a major role in achieving better performance. If the network area is not very large, single hop communication is useful due to minimum overhead and minimum delay. Due to direct communication, it is not necessary to communicate/set-up a path with other relay nodes or the CH, thus minimizing communication cost and network delay and increasing network lifetime. There are several improvements that have been made to LEACH protocol considering single hop communication. The researchers mainly enhanced the CH selection process, cluster formation and intra cluster communication in single hop LEACH successors. This section describes various improvements over LEACH in terms of energy efficiency, better CH selection, overheads and scalability. All these improvements against LEACH protocol exhibit excellent performance enhancement.

1) **LEACH-C (LEACH-Centralized)**
LEACH-C is a centralized protocol [25] in which all decisions such as the CH selection, cluster formation and distribution of information into the network are performed by the BS. LEACH-C produces excellent clusters by scattering the CH throughout the sensor network. Since the steady state phase is completely executed at the BS, there is no overhead for sensor nodes during the formation of clusters. The set-up phase of LEACH-C is the same as the LEACH protocol. In the set-up phase, initially each sensor node transmits its position (determined by Global Positioning System (GPS) receiver) and residual energy information to the BS in every round. In order to create better clusters, there should be uniform distribution of energy among all sensor nodes. For this the BS calculates the average energy of sensor nodes and the nodes having less than the average energy are prohibited from participating in the CH selection process for the current round. For sensor nodes whose energy is greater than average energy, the BS creates K optimal cluster using a simulated annealing algorithm [28]. The average energy of the netwok E_{avg} can be calculated by using Equation 2.

$$E_{avg} = \frac{\sum_{i=1}^{N} E_i}{N} \tag{2}$$

Where E_i is residual energy of i^{th} node and N denotes the number of sensor nodes.
The optimal number of clusters K can be calculated using Equation 3, if there are N sensor nodes uniformly deployed in a $M * M$ sensing area.

$$K = \sqrt{\frac{N}{2\Pi} \frac{\epsilon_{fs}}{\epsilon_{mp}} \frac{M}{d_{toBS}^2}} \tag{3}$$

Where d_{toBS} is the average distance between CHs to the BS. ϵ_{fs} and ϵ_{mp} are parameters of the transmission and receiver circuit in free space and multi path fading respectively. Simulated annealing algorithm minimizes the energy dissipation of normal nodes within the cluster by shortening the squared distance between all normal nodes to their respective CHs. When the process of selecting CHs and clusters is over, the BS broadcasts this information in the sensor network. The BS sends the CH id to every sensor node, and if the CH id matches any sensor node that node becomes CH, otherwise it acts as a normal node. The steady state phase of this protocol is the same as LEACH protocol. The CHs broadcast the TDMA schedule to all sensor node of their clusters. On the basis of the TDMA schedule, data transmission begins in all clusters.
In centralized LEACH, the complete process is managed by the BS, so it is very much energy efficient compare to LEACH. For location information, every nodes require GPS which is a costly device and it consumes extra energy. Though it is centralized it is less scalable.

2) **LEACH-DCHS (LEACH-Deterministic Cluster Head Selection)**
This protocol is proposed by Handy *et al.* [29] for prolonging the network lifetime. This is acheived by making two modifications in LEACH protocol: (i) modify the threshold $T(n)$ value for CH selection by multiplying the remaining energy factor which can be shown in Equation 4 and (ii) using a new approach to define the network lifetime. This paper presents a deterministic cluster-head selection algorithm with low energy consumption.

$$T(n) = \frac{P}{1 - P * (r \bmod \frac{1}{P})} * \frac{E_{n_{current}}}{E_{max}} \tag{4}$$

Here, $E_{n_{current}}$ is the current energy and E_{max} is initial energy of the node n. But the problem of this modification is that after a certain numbers of rounds the network gets stuck, although nodes with sufficient energy are available. Further, this can be expanded by using a factor that increases the $T(n)$. The new threshold $T(n)_{new}$ can be written as given in Equation 5.

$$T(n) = \frac{P}{1 - P * (r \bmod \frac{1}{P})} * [\frac{E_{n_{current}}}{E_{max}} + (r_s div \frac{1}{p})(1 - \frac{E_{n_{current}}}{E_{max}})] \tag{5}$$

r_s are the consecutive rounds in which a node has not been selected as the CH; once elected then it is set to 0. In the second modification, authors have considered three new metrices: (i) First node dies (FND), (ii) Half of the nodes alive (HNA) and (iii) Last node dies (LND) for the comparision of network lifetime over other protocols.
These two modifications increase by 30% the network lifetime compare to LEACH but frequent cluster formation degrades its performance.
By considering the frequent cluster formation in [29] as a major disadvantage for network lifetime, Liu *et al.* [30] have proposed a new cluster maintenance protocol called LEACH-DCSH Cluster Maintenance (LEACH-DCSH CM). In this new protocol, only the steady state phase is modified by introducing a fit factor H_i. Each node generates a random number r between 0 to 1. If a generated number r is less than the minimum threshold then that node will act as the CH for the current round. Then the node will broadcast an advertisement message to all the neighbouring nodes to be elected as a cluster member. When all the nodes get the advertisement message from the CH, it will reply to the CH if the member nodes are free. In this way, all the nodes join the cluster as a cluster member. If any two nodes have tie in joining the cluster, nodes that have

a higher received signal strength indicator (RSSI) will join the cluster. In the steady state intra cluster communication phase, each nodes in intra cluster computes the H_i using Equation 6.

$$H_i = \frac{e_{j_{current}}}{Pow_{j_{current}}} \tag{6}$$

Here,$e_{j_{current}}$ and $Pow_{j_{current}}$ are current energy and current transmiting power of CH j respectively. CH nodes select the highest H_i nodes for inter cluster node communication for transmitting data to the BS. After the failure of a certain number of nodes, the cluster maintenance phase starts.

This protocol is simple but very effective for network lifetime improvement due to its cluster maintenance and choosing the minimum distance for inter cluster communication. The main problems that needed to be improved in this protocol are finding the certain number of failed nodes in each cluster and control overheads.

3) **sLEACH (Solar Aware-LEACH)**

Energy Harvesting with external power sources to the sensor nodes is an important way to increase the network lifetime of the WSN. Voigt *et al.* [31] have proposed an idea, where some sensor nodes are assisted by solar power, that sensor nodes play the role of CHs based on solar power status. The concept of solar power can be applied in a distributed as well as a centralized clustering algorithm. In solar aware centralized clustering, each sensor node sends its residual energy and solar power status to the BS. Normally, the BS chooses solar operated sensor nodes with higher energy. If the number of solar nodes increases, the network performance increases to a great extent. Network lifetime of solar aware LEACH completely depends upon the sun duration. There is a cluster handover mechanism in solar aware LEACH, if the sun duration is small. If a sensor node operated with battery acts as the CH in a cluster, a member node sends data with a flag during the steady state phase. The solar power node's power levels increase and it is ready to serve as the CH in place of a former CH. In solar aware distributed clustering, solar operated sensor nodes have high probability to become the CH.

Assisting some nodes with solar power and selecting them as cluster head provides better performance in terms of lifetime than the LEACH and LEACH-C protocol. Due to harvesting by solar panel, the cost and complexity of the network increases.

4) **SLEACH (Security based LEACH)**

SLEACH [32] is first protocol which added security features using SPINS protocol [33] in LEACH. This protocol uses lightweight cryptographic techniques for WSN. In WSN, providing security with the cryptographic method is a challenging task due to the limited the resources of sensor nodes. In WSN, sensor nodes have high security threats from insiders as well as outsiders. This protocol provides security only from outsiders' attacks and assumes the BS is trusted. The authors have added two important security features to LEACH: data authentication and data freshness. In data authentication, the recipient of the message can authenticate its originator. Data freshness shows whether the message is old or new. In predeployment stage, each node loaded with two keys Xx, a master symmetric key for sharing with the BS and a group key k_n is shared by all nodes in the network. Each node also shares a counter C_x with the BS for freshness purposes. The whole process of SLEACH is divided into two phases: the set-up phase (advertisement, cluster joining and confirmation) and the steady state phase. Once a CH is selected in the set-up phase, a node n broadcasts a sec_{adv} message concatenated with its id and a MAC value produced using the key holders drive K_x. The BS receives all the advertisement messages and verifies their authenticity. μTESLA symmetric key building block is used for broadcast authentication. If the advertisement message is valid, the BS keeps the CH id into the list V of authorized CHs. The BS broadcasts the compiled V list along with computed MAC of V list. The MAC is computed with the help of a key chain k_j and this chain is the only chain that is not disclosed to the network yet. The whole network holds the key k_{j+1} and checks the validity of k_j using key k_{j+1}, when the BS revealed the key k_j. In cluster joining, each node sends $join_{req}$ (join request) message to its CH. When CHs receive all the $join_{req}$, they broadcast the TDMA time slots to their cluster members.

After the completion of cluster formation, the steady state phase starts and each node sends their sensed data to the CH, according to their TDMA schedule. The message contains sensor node id, MAC of the sensor node and counter. The MAC is calculated by member nodes using a key which is shared with the BS. The counter is used to check the freshness of the messages. After receiving all the messages from its cluster members, the CH aggregates these messages and creates a packet containing its id, aggregated data and their MAC. The created message is sent to the BS by including its counter shared with the BS. The CH sends a second message to the BS containing MAC array of its cluster members. In the final step, the BS matches each MAC of the sensor nodes and if it finds any invalid MAC, then it will drop the whole packet and sends back the unauthorised list of sensor nodes to the corresponding CH, so that the CH can blacklist them in the next round.

This protocol is the first protocol which uses security in LEACH for protecting the network from outside attacks using a lightweight security algorithm. This protocol has some limitations which are mentioned below.

a) It does not provide security at the time of cluster formation; anyone can send $join_{req}$ to any CH without any authentication.
b) The sensed data sent by the cluster member is not secure.
c) There is no key update provision.
d) It does not prevent insider threats to the network.

Further, this protocol's limitations are resolved by Essam and Shaaban in their papers [34] and [35] to some extent. They presented an enhanced version of SLEACH [32] named MS-LEACH. They provide data confidentiality and source authentication in sensor nodes to CH data transfer using pairwise keys shared between cluster members and their CHs.

MS-LEACH shows overall performance improvement over SLEACH in terms of security, network lifetime, energy consumption, normalized routing load and network throughput. The major problems of this protocol are: not providing proper counter, no authentication process for join message and pairwise key for schedule messages which consumes more energy of a CH.

5) **Sec-LEACH (Security-LEACH)**

Sec-LEACH [36] is a security-based LEACH protocol which mainly protects the network with many kind of attacks like sinkhole and selective forwarding attacks. At the deployment, a large number of key pools and their ID_s are generated by Sec-LEACH. In pseudo-random fashion, a ring of key pools is assigned to each node with pair-wise key shared with the BS. The CH selection is similar to LEACH and selected CHs broadcast their ID_s and a nonce. After the computation of CHs ID_s by the other sensor nodes, they select the nearest CH and send a join request message. CHs send a TDMA schedule to their cluster member. The communication between sensors and the CH are protected by a same shared key used in the join request message generated by MAC. A value computed from the nonce is used to prevent the reply including reporting cycle. The CH aggregates the decrypted message and sends it to the BS using a symmetric key shared with the BS for protection from attacks.

Sec-LEACH as its name implies is very good for security prospects. It is more secure against several attacks compared to SLEACH. It provides security but increases its energy consumption and due to that it fails to perform better in terms of network lifetime.

6) **Q-LEACH (Quadrant Cluster based LEACH)**

Q-LEACH [37] is a quadrant-based routing protocol which combines the characteristics of Q-DIR [38] routing techniques and LEACH protocol. Q-DIR routing is the intregation of location-based routing and restricted flooding. The coverage area is divided into four quadrants, and in each quadrant clusters are formed. The CHs of each cluster communicate with each other using route request packets (RREQ) and also determine the shortest routes between source and destination. This protocol enhanced the network lifetime but increased delay and congestion in the WSN.

In Q-LEACH, CHs are not selected on the basis of residual energy and the CH changes in every round. This limitation is further improved by a new protocol, namely Enhanced Q-LEACH [39]. It uses threshold residual energy for the CH changes. In this protocol, the CH does not change in every round. If the residual energy of the CH is less than threshold residual energy, it starts the process of new CH selection.

One more protocol, Quadrature LEACH [40], published by Manzoor et al., used a similar approach [37] of splitting the entire sensing region into four quadrants. For a better coverage area of the entire sensor network, Q-LEACH uses such a partition. Each sensor node in the sensor network transmits its location information to the BS. Based on it, the BS partitions the entire network into four quadrants (a1, a2, a3 and a4) in such a way that each quadrant has an optimal number of sensor nodes for better coverage. In division, some nodes are selected as the CH on the basis of threshold. In LEACH, formation of the CH is dynamic and if member nodes are far from the CH, then more energy will dissipate. Whereas in Q-LEACH protocol clustering is performed within each quadrant and sensor nodes join the CH based on RSSI.

Q-LEACH enhances the network lifetime and the stability period of the sensor network by distributing energy evenly among the sensors. The partition into four quadrants and selection of the CH increases the control overhead.

7) **ME-LEACH (More Energy Efficient-LEACH)**

Chen and Shen [41] extended LEACH by minimizing the communication distances among sensor nodes. They named their proposal ME-LEACH. They proposed this scheme to balance the load of sensor nodes. In this way, it becomes more energy efficient compare to original LEACH. However, it also support single hop communication between any nodes and the BS like LEACH. In large scale networks, this will not be feasible due to higher cost and powerful radio. So, authors further extended the work to accomodate large scale networks and named it ME-LEACH-L [42]. It tackles two major problems of previous works: channel allotment to neighbour clusters and cooperation between clusters during data collection. Each round of MELEACH-L comprises four sequential phases. In first phase, CH selection is done on the basis of a timer T_i and it is calculated with the help of Equation 7.

$$T_i = [\alpha \frac{E_{start} - E_{residual.i}}{E_{start}} + random(0, 1)]\delta \tag{7}$$

E_{start} is the initial energy of each sensor, $E_{residual.i}$ is residual energy of node i, α is a constant and δ is the time duration for CH selection. In the second phase, a backbone tree is constructed with the help of an energy-aware virtual backbone tree (EAVT) [43] by selecting some non-CH nodes. After the selection of EVAT nodes, the third phase starts where each CH selects its closest EVAT node as a relay node towards the BS. Non-CH nodes select a CH as a leader and intra cluster communication trees are formed. Finally, the data communication phase starts, where each sensor node transmits its data to the CH and sends aggregated data to the parent(root) node of the EVAT tree.

This protocol uses the communication channels more efficiently and increases the lifetime of large scale networks. The drawbacks of this protocol are overhead due to tree construction and finding EVAT nodes and transmission delay.

8) **TB-LEACH (Time Based-LEACH)**

Junping *et al.* [44] presented a time based LEACH to overcome the problems of LEACH. In this protocol, the CH is selected on a time interval based threshold. The nodes which have the shortest time interval win the competition to become the CH. To get the specified constant value of CHs, there is a counter. Each node generates a random number at the begining of a round. When the timer expires, nodes check their advertisement message; if it is less than the constant value of CHs, that node announce itself as a CH and broadcasts a CH advertisement message by using a CDMA MAC protocol. After the seletion of the CH the rest of the process is similar to LEACH. It is a totally distributed algorithm because it does not require global information for cluster formation.

It provides a significant amount of improvement in energy consumption to form a constant number of clusters compared to LEACH. The authors experimentally proved that it provides longer lifetime of the network compared to LEACH. Due to the direct communication between the CH and the BS, it is not suitable for large scale networks.

9) **A-LEACH (Armor-LEACH)**

To resolve the energy efficiency problem of Security-LEACH [36], Abuhelaleh *et al.* [45] proposed a new secure protocol by addding the features of Security-LEACH and Time-Controlled Clustering Algorithm (TCCA) [46]. The new protocol is called Armor-LEACH and it is more secure and energy efficient. The initial keys and the distribution of ID_s in the network after deployment is the same as [36]. Here, CH selection is also based on random number generation between 0 and 1 but the threshold T(n) calculation is different. The modified T(n) value can be calculated with the help of Equation 8.

$$T(n)=\begin{cases} max(\frac{P}{1-P*(r \bmod \frac{1}{P})} * \frac{RE}{E_{max}}, T_{min}) : & if\ n\epsilon G \\ 0 : & otherwise \end{cases} \tag{8}$$

Where, p is the desired percentage of CHs, T_{min} is the minimum threshold to avoid the remaining energy shortage, RE and E_{max} are residual energy and maximum energy of the network respectively. After the selection of the CH, it broadcasts an advertisement message containing CH-ID, Time to live (TTL), timestamp, nonce, remaining energy, and the advertisement message to its neighbours. Each sensor nodes replies to the CH with a request message containing sensor ID, CH-ID, join request message, original advertisement message timestamp, the remaining TTL value and sharing key ID when it receives the advertisement message. The nodes also send the encryption of sensor ID, CH-ID, sharing key ID and the nonce sent by CH to produce the message authentication code. Timestamp helps the CH to estimate the approximate distance of member nodes which helps in multi-hop data transmission. In transmission phase, each sensor sends a report message to its CH in a time slot alloted by the CH. The report message contains sensor ID, CH-ID, sensor report; the encryption of sensor ID, CH-ID, sensor report; and the nonce with its reporting cycle within the current round. The CH sends an aggregated report message to the BS containing CH-ID, BS-ID, aggregation reports of sensors, encrypted aggregation report and sharing key between the CH and the BS.

In Armor-LEACH, Sec-LEACH provides a high level of security against several attacks and TCCA provides less energy consumption in the network. It protects from spoofing, jamming, replay attacks, sinkhole and selective forwarding attacks. Simulation results show that it is three times better than LEACH and Sec-LEACH in terms of energy efficiency and high level of performance. The main demerits of this protocol are bandwidth wastage due to the large number of control packets exchanged and message overhead.

10) **ALEACH (Advanced-LEACH)**

In ALEACH [47], a new technique for CH selection in every round is proposed. The technique for selection of CH depends on two terms: current state probability (CS_p) and general probability (G_p). Thus, the threshold value to become a CH depends on both terms in each round. So the threshold value $T(n)$ can be calculated by Equation 9 and the value of G_p and CS_p are derived from Equations 10 and 11 respectively.

$$T(n) = G_p + CS_p \tag{9}$$

here,

$$G_p = \frac{K}{N - K * (r \bmod \frac{N}{K})} \tag{10}$$

and

$$CS_p = \frac{E_{current}}{E_{n-max}} * \frac{K}{N} \tag{11}$$

Where $E_{current}$ is current energy of a node, E_{n-max} is the initial energy of the network, K is expected number of CHs in a round, r is current round and N is the total number of nodes in the sensor network. So after putting the value of G_p and CS_p in Equation 9, the final threshold value will be represented by Equation 12.

$$T(n) = \frac{K}{N - K * (r \, mod \frac{N}{K})} + \frac{E_{current}}{E_{n-max}} * \frac{K}{N} \tag{12}$$

The steady state phase of ALEACH is the same as the LEACH protocol.

Since the CH nodes are chosen as the most appropriate nodes in terms of their current state and general probability, the network lifetime of the sensor nodes is better compared to LEACH. This protocol follows the direct communication between the CH and the BS, so it is not suitable for large scale networks.

11) **T-LEACH (Threshold-LEACH)**

Hong *et al.* in [16] have proposed a clustering protocol for replacement of the CH in WSN based on threshold energy of the sensor nodes called T-LEACH. In most of the existing protocols, the CH changes in every round, resulting in a sigificant amount of energy consumption as message exchange. T-LEACH minimizes the CH selection and replacement process using a threshold energy scheme. In this protocol, CHs are fixed for some rounds. When the residual energy of a CH becomes lower than the threshold energy, a new CH selection process is started.

It enhances the lifetime of the network by using threshold energy for changing the CH. It suffers from uneven energy consumption. The calculation of threshold energy for CH change is not clearly defined by the authors.

12) **LEACH-H (LEACH-Hybrid)**

In order to enhance the network lifetime, Wang *et al.* [48] exploited the advantage of LEACH and LEACH-C algorithms and proposed a new protocol named LEACH-H. This protocol solves one major problem of LEACH, where the uncertain number of CHs are choosen in every round. In this protocol, the number of CHs are fixed for each round. In the first round, the BS determines the optimal number of CHs set and forms the optimal cluster with the help of a Simulated Annealing algorithm. In this protocol, the selection of CHs is an iterative process; collection c represents the current CH list and collection $c^{'}$ represents the new CH list. The next CH list is selected by using Equation 13.

$$P_k = \begin{cases} e^{\frac{-(f(c^{'})-f(c))}{\alpha_k}} : & if\ f(c^{'}) \geq f(c) \\ 1 : & f(c^{'}) \leq f(c) \end{cases} \tag{13}$$

In Equation 13, P_k is the probability of selecting a new CHs list, $f(c)$ and $f(c^{'})$ stand for the energy consumption of the network whose CHs list is collection c and collection $c^{'}$. α_k are the control parameters used to ensure the convergence of the CH selection algorithm. The collection $c^{'}$ assign the CHs list for the next round in LEACH-H, if $f(c^{'}) <= f(c)$. Otherwise, the next CHs list will be determined using the probability P_k as shown in Equation 13. $f(c)$ can be calculated by using Equation 14.

$$f(c) = \sum_{i=1}^{N} mid \;\; d^2(i, c) \tag{14}$$

The current CHs will select the next round of new CHs in their cluster based on location information and residual energy.

LEACH-H routing protocol ensures a more even distribution of CH than LEACH and LEACH-C routing protocol. Amalgamation of the characteristics of LEACH and LEACH-C protocol gives a better solution in terms of lifetime. LEACH-H is the appropriate solution for the large scale WSN. This protocol suffers from large overhead due to the selection of a new CHs list by current CH.

13) **U-LEACH (Unequal Clustering-LEACH)**

Ren *et al.* [49] have proposed an unequal LEACH clustering scheme for reducing the hotspot problem in single hop communnication like LEACH. In single hop clustering all CH transmit their aggregated data to the BS directly; due to this CHs distant from the BS consume more energy compared to nearer CHs. Energy consumption of the transceiver is directly propotional to distance. In this protocol, authors considered unequal sizes of concentric circles as a cluster. The size of the cluster decreases as we go far from the BS. In the CH selection phase, they have considered some extra parameters like weight factor, residual energy and distance with classical LEACH threshold function $T(n)$. This protocol improves the network lifetime and balanced the energy but suffers from intra cluster communication in clusters near the BS.

14) **LEACH-B (LEACH-Balanced)**

LEACH-B protocol [50] resolves the issue of unbalanced clusters of basic LEACH. It uses both the desired percentage of cluster nodes and the residual energy of sensor nodes for formation of balanced clusters and selection of CH. It uses the concept of the second selection of CH for modifying the CH at set-up phase in each round. After deciding the desired percentage of sensor nodes to become the CH, LEACH-B proposes another competition for CH selection. According to LEACH-B, CHs in each round should be a constant number $N * P$, where P is the desired percentage of CHs and N is the number of sensor nodes. In this protocol, first CHs are selected randomly based on LEACH protocol, then each CH broadcasts its status and residual energy to each sensor node. Now there are two possibilities. First, if the number of randomly selected CHs is less than $N * P$, then some normal nodes with less time interval are selected as CHs into a CH set and these selected CHs broadcast their CH status to the network. The time interval is calculated by $t = K/E$ where E represents residual energy of an individual sensor node and K is a constant factor. Second, if randomly selected CHs are more than $N * P$, then exclude some CHs with low energy to maintain the CH set equal to $N*P$. To achieve this, all the CHs are arranged in descending order based on their residual energy. The CHs that are ranked lower than $N * P$ convert into normal nodes.

LEACH-B is a distributed protocol, which improves the energy-load balance problem of the cluster and reduces the energy consumption of sensor nodes in WSN compared to LEACH. The message overhead, scalability and complexity are the main demerits of this protocol.

15) **LEACH-GA (Genetic algorithm based LEACH)**

LEACH-GA proposed by Liu and Ravishankar [51] is a genetic algorithm (GA) based adaptive clustering protocol with an optimal probability for cluster formation and CH selection. Initially, all sensor nodes participate in the candidate CH (CCH) selection process by generating a random number r and comparing this r with threshold $T(s)$. If the value of r is less than $T(s)$, based on a probability value p_{sat}, then the node is selected as CCH. In our protocol, the value of p_{sat} is set as 0.5. After the selection of initial CCH, all nodes send their status messages containing their node-id, location information and CCD information. Based on this information, the BS finds the optimal probability P_{opt} for formation of optimal clusters K_{opt} with the help of GA. The GA searches the solution space to determine the P_{opt} using an evolutionary optimization process including probabilistic transitions and non-deterministic rules with crossover and mutation operators. After selecting P_{opt} using Equation 15 the BS broadcasts the value of P_{opt} to all sensor nodes n. The set up and steady state phases are the same as in LEACH.

$$P_{opt} = \frac{K_{opt}}{n} \tag{15}$$

The performance of this protocol is compared in two scenarios based on the BS position. In the first case, the BS is located in the centre of the network and in the second case, it is situated outside of the network. In both cases, LEACH-GA performs better than LEACH in terms of energy efficiency but it suffers from message overhead and scalability.

16) **FL-LEACH (Fuzzy Logic based LEACH)**

Al-Maaqbeh *et al.* [52] have proposed a fuzzy logic based LEACH protocol called FL-LEACH. This protocol has used the Mamdani interference method and comprises a fuzzifier, a fuzzy inference system, rules and a defuzzifier. Initially, the fuzzification process is started with two input variables to determine their fuzzy sets and membership values. In fuzzified inputs, fuzzy rules are applied and the output fuzzy sets of output variables are aggregated. Lastly, the centre of gravity (COG) defuzzification method is applied to get the crisp value. Fuzzy logic is applied on two variables: the number of sensor nodes in the network and the network density, to find out the initial CHs.

The main advantage of this protocol is in the calculation of the optimal number of CHs before network deployment. This protocol outperforms in terms of network lifetime compared to LEACH. The main drawbacks of this protocol are uniform node distribution and not considering energy as a parameter for CH selection.

17) **LEACH-SWDN (LEACH with Sliding Window and Dynamic Number of Nodes)**

LEACH-SWDN is proposed by Wang *et al.* [53] using a sliding window on the current cycle of nodes that have not already been cluster heads, and dynamically changing the number of nodes in the threshold calculation model. In the set-up phase, each node randomly generates a number between 0 and $\frac{E_{Average_n}}{E_{Max_i}}$; the node becomes CH if the number is less than the threshold (P_i). $E_{Average_n}$ is the average energy level of the nodes that have not already been cluster heads and E_{Max_i} is the initial energy of node i. The node that is not a CH in the current round sends its residual energy information to the CH in the last slot alloted to it. The frame received by the CH with residual energy information is transmitted to the BS for average energy caculation $E_{Average_n}$. Before the begining of the next round the BS calculates the $E_{Average_n}$ and the number of nodes alive in the network, and broadcasts these to all nodes. After receiving this information, nodes updates their random number interval and the number of nodes alive.

They showed through simulation that in terms of FND and HNA there is a 41% and 36%, 17% and 26%, and 22% and 21% improvement over LEACH, LEACH-DCSH and ALEACH respectively. One major problem of this protocol is that network load increases due to sending residual energy information.

18) **EP-LEACH (Energy potential-LEACH)**

EP-LEACH [54] has improved the lifetime of LEACH by using EH-WSN (Energy Harvesting WSN) [55]. In EH-WSN, sensor nodes have a rechargeable battery and battery power is harvested from the environment. The EP-LEACH operation is similar to LEACH, except the CH selection process. It has two modifications over LEACH. In the first modification, sensor nodes with more energy-harvesting potential should have more chance to became a CH. According to the second modification, a node can become a CH any number of times. Based on these two modifications, the LEACH threshold Equation 1 can be reformulated as Equation 16.

$$T_k(i) = \frac{F_k(i)}{\sum_{r \epsilon N_k} F_r(i)} * P * |N_k| \tag{16}$$

Here, $T_k(i)$ is the probability of selecting node k as a CH at slot i. $F_k(i)$ is the EP function for EH-WSN and its value ranges from 0 to 1. 0 indicates the sensor node's energy is completely exhausted and 1 means it has sufficient energy to work as a CH. P is the optimal number of clusters in the network. $N_k(i)$ denotes the N neighbours node of node k and it can be calculated by using Equation 17.

$$N_k = [r | D(r,k) < D_t] \quad (17)$$

Where $D(r,k)$ is a measurement of the distance between node r and node k. D_t is a threshold distance under which two nodes are neighbours. The steady state phase is similar to LEACH.

EP-LEACH with EH-WSN outperforms LEACH with respect to network lifetime. Due to the energy harvesting sensor nodes, cost will be a matter of concern in this type of network. The protocol performs poorly in terms of complexity and message overhead compare to LEACH.

19) **I-LEACH (Improved-LEACH)**

Performance factor such as network lifetime, load distribution and energy efficiency directly depends on the selection of the CH. I-LEACH [56] protocol suggested a new idea for selection of the CH. The CH in I-LEACH protocol is selected by considering residual energy, the number of neighbouring nodes and position of the node from the BS. A sensor node can calculate the number of its neighbours with neighbourhood radius R_{ch}, which is written in Equation 18.

$$R_{ch} = \sqrt{\frac{(M*M)}{(\pi*K)}} \quad (18)$$

Where, $M*M$ is the area of nodes deployed and K is the number of clusters. The optimal number of CHs has been selected using Equation 3. All sensor nodes generate a random number between 0 and 1 like LEACH in each round. The improved threshold $T(n)$ has been derived as shown in equation 19. Comparing the randomly generated number to $T(n)$, if the number is less than $T(n)$, that node will become the CH for the current round, otherwise it remains in normal node.

$$T(n) = \begin{cases} \left(\frac{P}{1-P*(r \bmod \frac{1}{P})} * \frac{E_c}{E_{avg}} * \frac{Nbr_n}{Nbravg} * \frac{d_{to}BS_{avg}}{d_{to}BS_n}\right): & if\ S \epsilon G \\ 0: & otherwise \end{cases} \quad (19)$$

Where, E_c is the current energy of a sensor node and E_{avg} represents average energy of the network. Nbr_n and Nbr_{avg} are the number of neighbours for n and the average number of neighbouring nodes in the network respectively. $d_{to}BS_{avg}$ and $d_{to}BS_n$ denote the average distance of sensor nodes to the BS and distance of individual sensor nodes from the BS respectively. I-LEACH protocol organizes all the sensor nodes in the network in such a way that it increases network lifetime and minimizes the average energy consumption per sensor node.

It has improved the performance in terms of energy consumption and packet delivery ratio compare to LEACH and LEACH-C.

20) **MOD-LEACH (Modified-LEACH)**

To overcome the problems of LEACH protocol, Mahmood *et al.* [26] have proposed a new variant of it called Modified LEACH (MOD-LEACH). This protocol uses two different signal amplifications for intra and inter cluster communications. It uses a low amplified signal for intra and a high amplified signal for inter communications. In this way authors save a significant amount of energy, whereas in LEACH for both types of communication (intra and inter) the same signal amplification is used. One more modification made by the authors is in CH changes. Like LEACH, a similar CH selection algorithm is used and a new CH is selected but not in every round. After the completion of every round, the CH checks its residual energy and if it is less than a predefined energy threshold, the CH changes and new CH selection procedure starts. If the residual energy is higher than the energy threshold, the CH remains as CH for the next round. This is how energy consumption reduces: by not selecting a new CH in every round.

MOD-LEACH has modified in two main weaker sections of LEACH: CH changes in every round and using the same amplification signal for inter and intra communications. It performs better in terms of energy consumption and network lifetime compare to LEACH. One major problem of this protocol is the amplification of signals in two different modes and their synchronisation.

Further, Singh and Nayak [57] have improved this protocol by using dual transmitting power level and efficient CH replacement schemes. The new protocol is known as Enhanced Modified LEACH (EMOD-LEACH) and it performs better in terms of energy consumption and network lifetime. This protocol is not suitable for periodically sensing data in WSN.

21) **W-LEACH (Weighted-LEACH)**

W-LEACH [58] is a new data aggregation algorithm presented by Abdulsalem et al. for WSNs that can handle uniform and non-uniform networks. They have assigned a weight w_i based on residual energy e_i and the density d_i to each sensor S_i. The d_i is the ratio between all alive nodes in the range r of a sensor node S_i with all alive nodes in the network. The w_i can be calculated using Equation 20.

$$w_i = \begin{cases} e_i * d_i: & if\ d_i > d_{thres} \\ d_i: & otherwise \end{cases} \quad (20)$$

Where, d_{thres} is a density threshold. Sensors with less than d_{thres} density are selected for the data transmission. So, all the nodes of a cluster not needed to activate and take part in each round of communication, like LEACH. In this way, authors increase the average lifetime of sensor nodes and enhance the network lifetime. Abdulsalam and Ali [59], have extended their work by introducing a dynamic W-LEACH using CH density d_{CH}. The d_{CH} is calculated using Equation 21.

$$d_{CH} = \frac{number\ of\ alive\ sensors\ in\ Cluster_i}{total\ number\ of\ alive\ sensors} \tag{21}$$

These algorithms improve the network lifetime as well as average lifetime of individual sensor nodes. The main problems with these protocols are scalability and control message overhead.

22) **LEACH-G (LEACH-G)**
In order to minimize the deficiency of LEACH that is the uncertain number of CHs and their position, Chen *et al.* [60] have proposed a protocol called LEACH-G, which ensures a certain number of CHs and their even distribution. Due to the random selection of CHs and clusters, LEACH does not guarantee the optimal number of CHs and the optimal position of CHs. According to the LEACH-G protocol, the optimal number of energy efficient CHs can be found by Equation 22.

$$K = \sqrt{\frac{N}{2\Pi}}\sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp} - d_{toBS}^4}M} \tag{22}$$

Equation 22 is based on the radio energy model, where N is the number of sensor nodes and M is the area of the sensor network. ϵ_{fs} is the amplifier energy of the free space radio model and ϵ_{mp} is the amplifier energy of the multi-path radio model. d_{toBS} indicates the average distance from CHs to the BS. Equation 22 gives the optimal number of clusters and helps to provide even distribution of energy among the sensor nodes, which avoids the early death of sensor nodes. LEACH-G routing protocol adopts a centralized as well as a distributed approach for the selection of CH and for the formation of clusters. LEACH-G ensures the optimal number of clusters and even distribution of CHs in each round by using the combined centralized and distributed approach.
LEACH-G outperforms the classical LEACH in terms of network lifetime and energy consumption. It suffers from scalability and hotspot problems.

23) **EC-LEACH (Enhanced Centralized-LEACH)**
EC-LEACH is a new variant of LEACH proposed by Bsoul *et al.* [61] using a centralized and multi-hop clustering approach. The main modification of this protocol over LEACH is in CH selection. The BS calculates a thresold $T(n)$ by using Equation 23.

$$T(n) = \frac{R_E(n)}{\sum_{i=1}^{m} \frac{d(i,n)}{R_E(i)}} \tag{23}$$

Where, $R_E(n)$ is the residual energy of the sensor node n, m is the number of sensor nodes in the network, $d(i, n)$ is the distance between node i and node n and $Res_E(i)$ is the residual energy of node i. After calculating of all nodes $T(n)$, the BS selects the highest $T(n)$ node as the first CH and compares the distance to the second highest $T(n)$ node. If the distance is greater or equal to the minimum distance between every CH and the next (MDCH), then the second highest $T(n)$ node becomes the CH. The BS does not select two consecutive CHs if the distance between them is less than MDCH. After selecting all the CHs, the BS broadcasts the CH list to all sensor nodes. The residual energy avoids selecting a low energy node as a CH.
Due to the proper distribution of CHs in a centralized manner, it saves a significant amount of energy to enhance the network lifetime. It performs better in terms of FND and average residual energy compared to LEACH. The problems with this protocol are extra overhead and scalability.

24) **LEACH-CE (LEACH-Centralized Efficient)**
LEACH-CE [62], a centralized algorithm, is a modified version of LEACH-C protocol, which minimizes the problem of LEACH-C [25]. In LEACH-C algorithm, the BS finds k optimal CHs whose energy are greater than the average energy of the network by using a simulated annealing algorithm. There may be a chance that some nodes accompanied by higher energy cannot be chosen as CHs and CHs accompanied by less energy die early in some rounds. So LEACH-C protocol does not ensure the balance of energy consumption during the selection of CHs. LEACH-CE chooses higher energy nodes as CHs in every round and eliminates the problem of early death of low-energy CHs. According to LEACH-CE protocol, the first round CHs and their associated clusters are chosen by the BS in the same way as in LEACH-C. When clusters are formed, the BS selects the final CH by choosing the node which has maximum energy among the initial CHs. When all clusters find their final CH, the BS sends this information to the sensor network and the steady state phase starts which is similar to LEACH.
The performance of LEACH-CE protocol is better than that of basic LEACH and LEACH-C protocol. Since location information is not considered in the CH selection, it results in uneven energy consumption and increases intra cluster communication cost.

25) **FT-LEACH (Fault Tolerance LEACH)**
Fault tolerance is an important issue which negatively affects the performance of LEACH and its variants [63]. To reduce the fault tolerance issue in LEACH, Cheraghlou and Haghparast [64] have proposed a fault tolerance LEACH called FT-LEACH. The major changes that FT-LEACH considered are: each sensor

node sends its residual energy as a packet header to the CH; the cluster members do not send similar data in two consecutive rounds to the CH. Hence, CHs are always aware of faulty nodes and live nodes, and not sending duplicate data saves a significant amount of energy. LEACH follows only global re-clustering but FT-LEACH uses both a Local and global re-clustering mechanism based on the CH's energy. Re-clustering reduces the network partition in every round which minimizes energy consumption. On the basis of the energy value sent by the sensor nodes to the CH and the CH to the sink, this protocol detects the fault. If the fault is in a member node of a cluster, it can be traced back to its energy value and residual energy level. By deleting this node from the cluster, the network will be repaired. Recovery of the CH is similar to that of member nodes by replacing the CH using local re-clustering. The rest of the work is similar to LEACH.

FT-LEACH outperforms LEACH in terms of fault tolerance and energy consumption. It has some limitations, such as how the energy level detects the faulty nodes, which is not clearly explained by the authors. Local re-clustering is also not clear and how duplicate data is managed by using a threshold is not discussed clearly.

26) **IB-LEACH (Intra-Balanced LEACH)**

Salim *et al.* [65] have proposed a protocol to minimize the energy gap between the CH and cluster members of LEACH called intra-balanced LEACH (IB-LEACH). The main goal of this protocol is to reduce intra cluster communication costs and minimize the load of CH by dividing the task among the CH and its cluster members. The operation process of IB-LEACH consists of several rounds and each round is split into three phases: set-up, pre-steady and the steady state. The set-up phase is similar to basic LEACH. In the pre-steady state phase, sensor nodes of a cluster are divided into three categories: CH, sensing nodes and aggregators. Sensing nodes sense the environment and send sensed data to the aggregators. The aggregators aggregate the received data and send it to the BS. This reduces the energy consumption of CHs. CHs maintain and manage the cluster activities. They create and broadcast the TDMA schedule to all cluster members. CHs also select the aggregator nodes in a frame and broadcast its list to all cluster members. The steady state process is divided into frames. Each cluster member sends its data in each frame according to their time slots. The aggregator aggregates this data and sends it to the BS.

Due to the uniform energy distribution in the cluster, the performance of this protocol is significantly increased. The simulation results show that it performs better than LEACH, E-LEACH, T-LEACH, VR-LEACH [66] and LEACH-B in terms of energy consumption and network lifetime. There are two major problems in this protocol. The first one is control message overhead for selecting aggregators and CHs. The second problem is scalability due to direct communication from aggregators and the BS.

27) **CogLEACH (Cognitive LEACH)**

The literature [67] presented a spectrum aware algorithm for the cognitive radio sensor network (CRSN), called cognitive LEACH (CogLEACH). It uses the number of idle channels as a weight in the probability of each node to become a CH. The probability P_i can be determined by using Equation 24 and the total number of channels in a band C_t will be determined using Equation 25.

$$P_i = min(K\frac{C_i}{C_t}, 1) \tag{24}$$

Where,

$$C_t = \sum_{i=1}^{n} C_i \tag{25}$$

K denotes the number of CHs in each round of a network. n is the number of nodes in the network and C_i represents the number of idle channels in node i. Based on this P_i each node decides whether it becomes a CH or not. When a node becomes a CH, it broadcasts a CH tentative announcement message with node id and C_i over the common control channel (CCC). The normal nodes which are in the range of CH send a CH tentative join request message including their id with sensed idle channels over the CCC. After the cluster formation, the intra and inter cluster communication are similar to LEACH.

CogLEACH improves the lifetime and throughput compared to basic LEACH but it suffers from uneven energy consumption and load balancing due to not considering the residual energy of individual nodes during CH selection.

Latiwesh and Qiu [68] mitigate the problem of uneven energy consumption of CogLEACH by introducing the centralized cognitive LEACH (CogLEACH-C). In this protocol, besides idle channels, nodes' residual energy is also used as a parameter for the CH selection which balances the energy load of the network. Since, it is a centralized protocol, the BS handles the complete process of this algorithm. So, the probability P_i can be rewritten as Equation 26.

$$P_i(t) = min(K * n * \frac{C_i * E_i}{C_t * E_t}, 1) \tag{26}$$

Where, E_i and E_t are the residual energy of node i and the network respectively.

CogLEACH-C improves the lifetime of the network and provides better network coverage compared to CogLEACH. It is not suitable for large scale networks.

28) **V-LEACH (Vice Cluster LEACH)**
In basic LEACH protocol, the CH is selected based on a probability without any consideration for the energy of nodes. This leads to a poor selection of CH because some CHs may die before completion of the current round due to very low energy. To address this problem, Sasikala and Sangameswaran [69] suggested an idea of a vice CH that plays the role of CH when the original CH dies before the completion of the current round. The selection procedure of the original CH is the same as in basic LEACH protocol and the sensor node with the most residual energy acts as vice CH. So in V-LEACH protocol every cluster has three types of sensor nodes: CH (which receives data from member nodes), member nodes (which sense the environment) and the vice CH (which acts as CH when the original CH dies). The steady state phase of V-LEACH is similar to basic LEACH protocol.
This protocol ensures the data delivery success rate as it uses two CHs compared to LEACH. The problems of this protocol are overhead and scalability owing to one extra CH and single hop communication between the CH and the BS respectively.

29) **EHA-LEACH (Energy Harvested Aware LEACH)**
Tang *et al.* [70] have improved the performance of LEACH by using energy harvested sensor nodes and presented a new protocol, named energy harvested aware LEACH (EHA-LEACH). They have formulated a max-min optimization problem for maximizing the minimum energy conservation of each node in the EHWSN. The node with high energy harvesting capacity and low energy consumption has more chance to become a CH. The total energy harvested E_h by a node v can be represented with the help of Equation 27 in a time interval $[0, T]$.

$$E_h(v, 0 <= t <= T) = \beta * \int_0^T p_h(v, t)dt - \int_0^T p_{leak}(v, t)dt \quad (27)$$

Where, $p_h(v, t)$ is the harvested rate of node v in a ambient environment and $p_{leak}(v, t)$ denotes the leakage power of node v at time t. Here, T is a non-negative time unit: it may be one hour, one day or more. The process of cluster formation and the CH selection mechanism are modified over basic LEACH by considering the node's harvesting measurement and energy-consuming status. The energy potential function $F(u)$ of a node u can be formulated as shown in Equation 28.

$$F(u) = \frac{\exp^{\frac{(E(u,0)+E_h(u,0<t<T)-M)}{A}}}{1 + \exp^{\frac{(E(u,0)+E_h(u,0<t<T)-M)}{A}}} \quad (28)$$

Where, M and A are the mean and variace for the energy of each node in the network respectively and these can be calculated using Equation 29.

$$\begin{cases} M = \sum_{u\epsilon V} (E(u, 0) + E_h(u, 0 < t < T) - M)|V| \\ A = \sum_{u\epsilon V} (E(u, 0) + E_h(u, 0 < t < T) - M)^2|V| \end{cases} \quad (29)$$

Each node randomly generates a number between 0 and 1 like LEACH and is compared with the pre-defined threshold $T(U)$. If the generated number by node u is less than threshold $T(u)$, it declares itself as a CH for the current round. The pre-defined threshold $T(u)$ can be reformulated from Equation 16 to 30, where p is the desired percetage of CH nodes.

$$T(u) = \frac{F(u)}{\sum_{v\epsilon L(u)} F(v)} * p * |L(u)| \quad (30)$$

From Equation 30, it can be derived that the higher energy consumption nodes have more chance to become a CH. After the selection of CHs, the rest of the process is similar to LEACH.
Due to using energy harvesting nodes and energy consumption rate it outperforms LEACH and EP-LEACH in terms of energy efficiency and network lifetime. The authors achieve 18.41% and 29.19% more rounds compared to EP-LEACH and LEACH. Higher cost and complexity are the main problems of this protocol.

30) **LEACH-MAC (LEACH-Medium Access Control)**
Most of the LEACH variants use dynamic, randomness and distributed approaches for clustering and thus an optimal number of clusters does not form in the network. LEACH-MAC [71] protocol is designed to mitigate the randomness problem by restricting the number of cluster head advertisements. The optimal number of CHs k is calculated based on Equation 3. When the CH selection process starts, a variable CHheard initialises to 0 and is incremented by 1 if it receives a CH advertisement message. In the threshold function, nodes select a uniform random time from the time interval [0 to total adv time], where total *adv time* is the time required for the CH transmission and reception. Suppose the selected time is R_t, so the CH advertisement sending time t_{adv-CH} can be calculated using Equation 31.

$$t_{adv-CH} = \frac{R_t}{Current\ Energy} \quad (31)$$

Now, node checks the value of CHheard variable at time t_{adv-CH} that it has updated at the time the advertisement was received. If the value of CHheard varible is less than the optimal number of clusters, then it will declare itself as a CH and sends a CH advertisement; otherwise it declares itself as a normal node. In the steady state phase, the nodes send their sensed data to the CH in their alloted TDMA schedules. The total energy consumed by CH can be calculated using Equation 32.

$$E_{CHMAC} = lE_{elec}\frac{N}{K'} + lE_{DA}\frac{N}{K'} + l\epsilon_{mp}d^4_{toBS} \quad (32)$$

Where, E_{CHMAC} is the energy consumed by the cluster head in receiving, aggregating and transmitting data to the BS in LEACH-MAC protocol. K' is the number of CH advertisements in the proposed approach, l is the data bits, E_{elec} is energy dissipated due to electronic circuitry and d is the distance. The energy consumed by non-CH nodes can be represented with the help of Equation 33 in LEACH-MAC.

$$E_{Non-CHMAC} = lE_{elec} + l\epsilon_{fs}\frac{1}{2\pi}\frac{M^2}{K'} \quad (33)$$

The LEACH-MAC performs better in terms of overall lifetime compared to LEACH, ALEACH and LEACH-DCHS. This protocol improved the FND time and LND time by 21% and 24% over LEACH, 10 and 20% over ALEACH and 5% and 35% over LEACH-DCHS. The major problems with this protocol are complexity due to energy calculation and message overhead.

IV. SUCCESSORS OF LEACH WITH MULTI-HOP COMMUNICATION

In multi-hop communication, the CH sends its data via some intermediate nodes to the BS. Intermediate nodes are either some relay nodes or other CHs which forward received data towards the BS. According to the radio model, the energy dissipation by a transceiver is directly propotional to the distance between the source and destination. If the distance goes beyond a threshold distance, the energy consumption increases in distance to the power four: d^4. So, the main purpose of multi-hop communication is to keep the distance at a minimum or less than the threshold distance. In successors of LEACH with multi-hop communication, researchers have mainly focused on inter and intra cluster communication, CH selection, cluster formation and scalability. These improvements achieve energy efficiency and scalability in WSN. This section discusses about all the multi-hop LEACH successors and their merits and demerits in detail.

1) **LEACH-B (LEACH-B, a new strategy for CH selection and cluster formation)**
LEACH-B [72] introduces some new strategies for cluster formation and CH selection in WSN. The authors have taken an assumption that N_{TOT} number of nodes are uniformly deployed in an MXM square area. If there are N_c clusters, then on average there are $\frac{N_{TOT}}{N_c}$ nodes per cluster with one CH and ($\frac{N_{TOT}}{N_c}$ -1) non-CH nodes present. The CH selection is performed on the basis of an indicator function $C_p(t_i)$ in the current round t_i. If ($C_p(t_i)$ = 0), node p has been selected as the CH. LEACH-B also uses a threshold function $T_p(t_i)$ like classical LEACH but in a different way. The modified threshold function is shown in Equation 34.

$$T_p(t_i) = \begin{cases} \frac{N_c}{N_{TOT}-N_c(r \bmod \frac{N_{TOT}}{N_c})} : & C_p(t_i) = 1 \\ 0 : & C_p(t_i) = 0 \end{cases} \quad (34)$$

The node p chooses a random number from 0 to 1 and takes its decision to become a CH or not. If the choosen number is less than the threshold value $T_p(t_i)$, the node p declares itself as a CH for the current round. The elected CH broadcasts a notification message to the rest of the nodes. The non-CH nodes join their nearest CH which has low energy dissipation between its complete routing path. Finally, sensor nodes send their sensed data to their CH according to their TDMA schedules and the CH sends it to the BS via optimal relay CH.
This protocol utilises total routing path energy dissipation between the node and the BS using the retransmission energy, own packets energy and broadcast energy of all CHs which helps to select the optimal CH for data transmission. LEACH-B outperforms LEACH and LEACH-A in terms of network lifetime. Its main disadvantages are uniform distribution of sensor nodes and not performing aggregation task at the CH.

2) **LEACH-B+ (LEACH-B+)**
Buratti *et al.* [73] have proposed an energy-efficient protocol named LEACH B+ which is an extension of LEACH B [72]. Four versions of this protocol have been presented by the authors in two different scenarios which can be distinguished by different channel fading rates. Two out of four versions of this protocol are implemented through a cross layer design approach, where physical and network layers are interact with MAC layer. The other two are modified versions of LEACH-B in CH selection and cluster formation sections. The LEACH B+ routing process is divided into two phases: the set-up phase and the data transmission phase. In the set-up phase, CH selection and cluster formation processes are carried out in self organized mode. The CH selection procedure in this protocol is also based on an indicator function $C_p(t_i)$ and a threshold value $T_p(t_i)$ like [72]. The only change is, instead of changing CH in every round, it changes after two or more than two rounds based on a counter value R. The modified $T_p(t_i)$ equation for CH selection is shown in Equation 35.

$$T_p(t_i) = \begin{cases} 0 : & C_p(t_i) = 0 \\ \frac{N_c}{N_{TOT} - N_c(r \bmod \frac{N_{TOT}}{N_c})} : & C_p(t_i) = 1, R < R^* \\ 1 : & C_p(t_i) = 1, R = R^* \end{cases} \quad (35)$$

Where R is a counter variable which is incremented at each round and becomes zero when either node becomes CH or it reaches R^*. The R^* is the number of rounds represented by ($\frac{N_{TOT}}{N_c}$ -1). The random number generated by node p is compared with $T_p(t_i)$ and, based on Equation 35, it is selected as CH or remains in its current state. The frequency of CH changes is maintained by considering the energy dissipation of each node which acted as CH last time. In the cluster formation phase, each sensor node select its CH by calculating the energy consumed in the complete path between itself and the BS. The sensor nodes choose the lowest energy loss paths and CHs to send their packets. If a sensor node does not receive any broadcast message for total energy path loss evaluation, it is forced to send it directy to the BS.

In cross layer design, authors have uses two different techniques in two different scenarios called Cross Layer Design version 1 (CLV1) and Cross Layer Design version 2 (CLD v2). The CLD v1 is designed with a proposed power control algorithm which helps in the interaction between MAC and physical layers by considering the number of retransmissions. The CLD v2 includes all the features of CLD v1 plus some additional techniques: the first two retransmissions are used in the second round to make the decision to change the CH and cluster structure.

The simulation results performed in both scenarios show a significant improvement over LEACH and LEACH-B in terms of network lifetime and packet loss rate. A large number of message overheads due to total routing path loss energy evaluation for each node and high complexity owing to the cross layer design are the main demerits of LEACH B+.

3) **MH-LEACH (Multi-hop-LEACH)**

According to the radio energy model, if the distance between the CH and the BS is greater than a certain threshold distance, energy dissipation of the CH is directly proportional to distance to the power four: d^4. So in large sensing regions and far distance between CHs and the BS, CHs dissipate their large amount of energy and die quickly. The basic LEACH protocol is not appropriate for this type of situation. Multi-hop LEACH routing protocol [74] solves this problem. Multi-hop LEACH routing protocols improve the performance in terms of energy efficiency by adopting multi-hop communication between CHs and the BS. The set-up phase of multi-hop LEACH protocol is similar to the basic LEACH protocol in that it is completely distributed in nature. In the steady state phase, CHs which are far away from the BS are chosen as intermediate nodes to transmit data to the BS (multi-hop communication) and the CHs which are near to the BS transmit data directly (single hop communication) to the BS. The inter-cluster communication and the intra-cluster communication are two types of communication used in multi-hop LEACH. In intra-cluster communication, member nodes communicate with the CH and in inter-cluster communication one CH communicates with the other CH to send information to the BS. The CHs that are far away from the BS choose a best route with the minimum hop count in order to deliver the information to the BS efficiently.

MH-LEACH is more energy efficient and highly scalable than basic LEACH but due to multi-hop transmission via relay nodes it became more complex and increases network overheads.

4) **TL-LEACH (Two Level-LEACH)**

For efficient energy consumption and even distribution of energy load in large area networks, Loscri et al. [75] have proposed a two-level hierarchy of clusters. Information sensed by sensor nodes is transmitted to the BS over two different hierarchies. Two levels of clustering facilitates more sensor nodes to use shorter distances and far fewer sensor nodes to use longer distances for transmitting data to the BS. In TL-LEACH protocol, upper level CHs are known as primary CHs and lower level CHs are known as the secondary CH. Each CH at the secondary level performs partial local computation of data and each CH at the primary level performs complete local computation, from where data is transmitted directly to the BS. TL-LEACH extends the lifetime of a sensor network by even distribution of energy among sensor nodes. For high density nodes and large area networks this protocol performs better compared to LEACH and LEACH-C. The primary level CHs which are near to the BS suffered from a hotspot problem.

5) **E-LEACH (Energy-LEACH)**

The CH selection and data transmission between the CH and the BS have been improved in Energy-LEACH (E-LEACH) [76] over the LEACH protocol. The main selection criteria of the CH in Energy-LEACH is residual energy of the sensor nodes. The working operation of Energy-LEACH is similar to basic LEACH. The probability of becoming a CH in the first round is same for all sensor nodes. So randomly $n = p * N$ number of sensor nodes are selected as the CH. Where n is the number of CHs in the first round, p is the probability of becoming CH and N represents the total number of sensor nodes in the network. After completion of the first round, the residual energy of every sensor node is not the same. So, sensor nodes with higher residual energy are chosen as CHs and sensor nodes with less energy act as member nodes. In multi-hop LEACH, CHs select the nearest node as an aim node which is energy efficient and situated in one hop range. CH transfers the aggregated data to the aim node. This process is repeated until the CH which is nearest to the BS receives the data. Finally, this CH sends data to the BS. Selecting the high energy nodes as a CH in each round provides better lifetime of the WSN. Data is transmitted in a multi-hop optimal path which reduces the energy consumption and enhances the network lifetime. This protocol selects the CH based on residual energy only, which results in uneven cluster sizes and load balances in the network.

6) **LEACH-M (LEACH-Mobile)**

Kim and Chung [77] have proposed a LEACH-based protocol for mobile nodes named LEACH-Mobile. This protocol comprises two phases: the set-up and

the steady state phase. In the set-up phase, cluster formation and CH selection are done in a similar way to LEACH. The main changes are made in the steady state phase during the data collection by CH from cluster members. At the end of every frame, the CH checks with a time slot list whether or not sensed data has been received according to the allocated TDMA time slots. If a non-receiving node is captured then this is marked in the time slot list. In the next frame, if data is not received again from a previously marked node, the CH removes it from its TDMA schedule and may allot this time slot to a newly joined node. The CH assumes that the nodes not responding to data-request messages have changed its place and moved to another cluster. In a new cluster the mobile node will associate with the CH based on RSSI of the advertisement message. After confirmation of the new member (mobile node), the CH updates its TDMA schedule and cluster membership list and broadcasts updated TDMA schedules to its cluster members.
The LEACH-Mobile protocol has improved the data transfer success rate compared to LEACH but leads to increased energy consumption due to high control overheads.

7) **LEACH-ME (LEACH-Mobile Extended)**
LEACH-ME [78] is an extension of [77] which supports the mobility issue of CH as well as member nodes. In this protocol, initially it is assumed that the BS is fixed, all the sensor nodes are homogeneous and know their current position using GPS. The selection of CH in LEACH-ME is different from the basic LEACH protocol. LEACH-ME selects CH on the basis of mobility of nodes and attenuation model. It selects a node as CH, which has less mobility and lower attenuation power. All selected CHs broadcast their status to all other sensor nodes in the network. Based on the RSSI, nodes select their CHs. The mobility issue of sensor nodes is solved by a handover mechanism. During the steady state phase, if a CH and a member node change their position and move away, the handover mechanism should be triggered. According to the handover mechanism, a member node sends a DIS-JOIN request message to the current CH and at the same time it sends a JOIN-REQ to a new CH. After joining new members and disjoining existing member, CHs allocate a new TDMA schedule for member nodes.
The protocol suits large areas where the BS is far away from the network because of adopting multi-hop transmission. Since, all mobile nodes are equipped with GPS, the cost will be increased and it also suffers from network overheads.

8) **A-sLEACH (Advanced Solar aware LEACH)**
Islam *et al.* [79] have presented a protocol named Advanced Solar aware LEACH (A-sLEACH) which is an extension of sLEACH (Solar aware LEACH) [31]. The authors have introduced five new techniques: a scan based CH selection, a FIFO priority scheme for data gathering, efficient radio energy model, a heuristic approach to select a CH within a cluster and a collision minimized Carrier Sense Multiple Access (CSMA). The BS selects the CH using a scanning technique in a cluster. A set of N sensor nodes of a cluster form a convex hull containing a maximum number of sensor nodes. The BS broadcasts an advertisement message containing CH ID. The cluster members use a TDMA schedule for data transmission to the CH and the CH aggregates received data using the enhanced First In First Out (FIFO) priority technique and sends it to the next level of CH towards the BS. In the next stage, solar assisted nodes are choosen as the CH by the current round CH. A-sLEACH uses a priority-based data gathering scheme using shortest path routing. It also applies a heuristic search approach for CH selection.
This protocol has 19.58% more network lifetime compare to sLEACH and performs better in terms of energy efficiency compare to LEACH. Because of using several approaches in the protocol, the overhead and complexity increases to a great extent.

9) **LEACH-L (Advance Multi-hop Low Energy Adaptive Clustering Hierarchy)**
LEACH-L [74] is an advanced multi-hop routing protocol in which the CH away from the BS selects other CH as a relay node. The selection critera for the relay node is distance to the BS and energy. So a CH which is closer to the BS and has more energy is selected as the relay node. The CH near to the BS transmits data directly. Selection of clusters and formation of clusters is similar to the basic LEACH. LEACH-L balances energy load in the network and decreases energy dissipation of the network, which in turn increases the lifetime of the network. The authors show that LEACH-L performs better than basic LEACH protocol when the target area of the sensing network is large.
The selection of the most suitable relay node, in terms of energy and distance from the BS for multi-hop transmission, results in equal energy distribution in the network. It enhances the lifetime of large WSN, where the BS is far away from the network. In this protocol, each node requires location information which is a complex process and also costly.

10) **MS-LEACH (Multi-hop And Single Hop Routing LEACH)**
Based on the analysis of energy consumption of single hop transmission and multi-hop transmission within a single cluster, Qiang *et al.* [80] presented the concept of the critical value for cluster size. MS-LEACH proposes a combination of single-hop and multi-hop communication within the clusters based on the critical value of cluster size. The set-up phase of MS-LEACH protocol is similar to the basic LEACH protocol. In the steady state phase, the critical value of the cluster area

is determined. Based on critical value, it is decided whether data will transmit through single-hop communication or multi-hop communication between CH and member nodes within the cluster. With the knowledge of the total number of nodes and their position within the cluster, the CH computes the critical value of a cluster size. Suppose a critical and approximate value of a cluster size is A. If the value of A is less than the value of a critical value then the CH does nothing and receives information from member nodes; otherwise the CH determines a routing path tree using a Dijkstra algorithm and broadcasts this information within the cluster. Simultaneously each member node sets a timer value and waits for the routing path tree. If the value of the timer is positive, then the CH determines the next hop with the help of the routing path tree; otherwise it sends data directly to the BS.

MS-LEACH adopts single-hop transmission as well as multi-hop transmission within the cluster which gives better performance in terms of network lifetime and scalability compare to LEACH. It suffers from a hotspot problem and network overheads in the cluster as well as in the network.

11) **WST-LEACH (Weighted Spanning Tree clustering routing algorithm based on LEACH)**

To resolve the two main issues of LEACH: (i) random selection of CH and (ii) direct communication between CH and the BS, Zhang *et al.* [81] have proposed a new clustering routing protocol based on LEACH called WST-LEACH. In this protocol, the authors make some changes in CH selection for forming a weighted spanning tree. The modified $T(n)$ formula for CH selection in this protocol is mentioned in Equation 36.

$$T(n) = \frac{P}{1 - P * (r \, mod \frac{1}{P})} * [w_1 * \frac{S(n).E}{E_0} + (w_2 * \frac{S(n).Nb}{p * N}) + (w_3 * \frac{1}{S(n).ToBs})] \quad (36)$$

In Equation 36, w_1, w_2 and w_3 are the coefficients, $S(n).E$ is the residual energy of node n, E_0 is the initial energy, $S(n).Nb$ is the neighbours node of n, N is the total number of sensor nodes, $S(n)$. $ToBs$ is the distance of node n from the BS and p is the probability to become the CH. In WST-LEACH, CH does not directly communicate with the BS. It follow a multi-hop communication by constructing a spanning tree based on the assigned weight to the CH. Equation 37 denotes the weighted formula for assigning weight to the CH for constructing a spanning tree.

$$W(i,j) = \frac{C(i).E}{E_0} * \frac{N}{C_i.Mb} * \frac{1}{d(i,j)^{\beta}} \quad (37)$$

Here, $W(i,j)$ denotes the weight of $CH(i)$ and $CH(j)$; the maximum value of i and j CHs join the spanning tree. $C(i).E$ is the residual energy of $CH(i)$ and $C(i).Mb$ is its member nodes. $d(i,j)$ is the distance between two CHs i and j and β variable depends on distance between CHs and CH to BS i.e 2 or 4 respectively. All maximum weight CHs join and form a spanning tree for data communication from the CH to the BS.

WST-LEACH enhances the lifetime of a network by optimizing the communication path. The authors have shown 80% less energy consumption in 100 rounds compared to LEACH. The drawbacks of this protocol are control packets overheads and scalability.

12) **MR-LEACH (Multi-hop Routing-LEACH)**

In order to minimize consumption of energy and prolong the network lifetime, MR-LEACH [82] is proposed by Farooq et al. It divides the entire area into various layers and forms the hierarchy of different layers of clusters. MR-LEACH produces the same size of clusters in each layer that means any normal node sends data to the BS in an equal number of hops. For this the BS allocates a time slice for each CH by using TDMA scheduling. Based on the TDMA schedule received from the BS, every CH allocates its own TDMA schedule for its member nodes. The CH in MR-LEACH is selected based on maximum residual energy. Each adjacent upper layer CH assists the lower layer CH during the data transmission to the BS.

MR-LEACH protocol increases the network lifetime by adopting multi-hop transmission from lower layers to the upper layer. It is highly scalable compare to basic LEACH. Hotspot is the main problem in this protocol.

13) **Coop-LEACH (Cooperative-LEACH)**

Asaduzzaman and Kong [83] have proposed a new variant of LEACH with a simple modification, named Energy Efficient Cooperative LEACH (Coop-LEACH). In this protocol, the authors have introduced a multiple CH concept in a single cluster. After formation of the cluster and selection of CH based on original LEACH, (M-1) additional Cooperative CH (CCH) are selected with minimum distance from the main CH. A cross layer design approach is also used to overcome the limitations preventing transmitting and receiving at the same time in a full duplex channel. Therefore, the CH and CCH can collect data at the same time independently without exchanging any cooperation data. To transmit the data of CH and CCH at the same time with the same frequency, authors have proposed a virtual Multiple Input and Multiple Output (MIMO) communication architecture with distributed space time block code (DSTBC).

Coop-LEACH reduces a significant amount of energy consumption of sensor nodes and transmission delay in the network and outperforms LEACH in terms of network lifetime. It uses MIMO and CCD which increases its complexity and network overheads.

14) **LEACH-D (LEACH based on Density of node distribution)**

In order to achieve better network lifetime, Liu *et al.* [84] introduced LEACH-D which consists of three different approaches. The first step is for the selection of CHs. LEACH-D protocol considers the density distribution of sensor nodes as well as residual energy for the selection of CHs. In LEACH-D protocol, the sensor node that has a high residual energy and is located in high density is selected as the CH. Secondly, based on degree of connectivity and distance to the BS, the CH determines its cluster radius. By adopting this approach, the CH reduces energy consumption. Based on the energy of the CH and the distance from the CH to the BS, other sensor nodes join the CH and form clusters. Lastly, the CH uses multi-hop transmission in order to deliver sensed data to the BS.

In LEACH-D, the most appropriate sensor nodes are selected as the CH with the help of a threshold value calculated by connectivity density factor and energy factor. It performs better in terms of scalability and energy consumption compared to LEACH. Since CHs are selected on the basis of the distance from the BS, a hotspot problem arises.

15) **UWSN-LEACH (Underwater WSN based LEACH)**
An energy effiicent cluster-based routing has been developed for mobile underwater WSN (UWSN) by Huang *et al.* [85] in a 3-D scenario. The basic idea of clustering in this protocol is inspired by LEACH. For CH selection, it considers three parameters: the location of the sensor node, energy status of the sensor node and whether the node has been selected as the CH or not in the past. Initially candidate CHs are selected using radio range R of the sink. All the nodes coming between half-ring redii $R - \frac{R}{n}.(i-1)$ and $R - \frac{R}{n}.i$ are considered as candidates for CH. Here n represents the number of half rings and i denotes the index for the half-ring that the candidates for the CH are placed in; initially its value is one. The most outer half-ring is checked first to determine some nodes in this ring are eligible for CH or not. If more sensor nodes are required for the CH, the second most outer half-ring is checked during the second repetition, and so forth. The coverage of each CH can be represented with hemisphere in a 3-D plane and whose flat surface is calculated by tangent using Equation 38.

$$max_{r_1, r_2, <=R} \; r_i^2 = (x_i - x_c)(x - x_c) + (y_i - y_c)(y - y_c) + (z_i - z_c)(z - z_c) \tag{38}$$

Where R represents the transmission range of CH, and (x_c, y_c, z_c) and (x_i, y_i, z_i) are coordinates of the current CH and the i-th CH neighbour. The new CH is selected on the basis of a minimum overlapping range of two or more clusters. The overlapping range is the intersection between two or more hemispheres. A candidate node becomes a CH only if the overlapping range is smaller than a pre-defined value λ. The nodes which can not find a suitable CH, select their nearest neighbour node as an interim head. The sensed packets collected and aggregated by the CH are transmitted to the sink via the other cluster's CH along the way to the sink.

This protocol performs well in terms of energy consumption and data aggregation in 3-D scenario of UWSN. The main problems in this protocol are minimizing the overlapping range, complexity of algorithm and control overheads.

Another protocol has been developed for the study of clustering in an underwater acoustic sensor network called LEACH-L [86]. This protocol uses the methods of conventional LEACH with some modifications. The CH selection process includes the residual energy and it considers coverage area an important parameter for the CH.

It is mainly designed for large scale networks in UWSN and performs better than LEACH in terms of overheads and complexity. This paper suffers from many problems such as managing mobile nodes in UWSN and this protocol is for large scale networks but the protocol uses single hop communication from the CH to the BS.

16) **FZ-LEACH (Far Zone-LEACH)**
To reduce one of the major drawbacks of LEACH that is large variations in cluster size, which affects the performance of the protocol, FZ-LEACH was proposed. Katiyar *et al.* [87] have presented the idea of a far zone to reduce the intra cluster communication in large size clusters. The CH selection in this protocol is similar to LEACH. After CH selection and cluster formation, the far zone selection process starts. All non-CH nodes send their $MinPwr_i$ to the CH. The CH computes the average minimum reachability power (AMRP) with the help of Equation 39.

$$AMRP = \frac{\sum_{i=1}^{N} MinPwr_i}{N} \tag{39}$$

N is the total number of nodes in a cluster. Far zone nodes are identified by AMRP value. The node's energy level below AMRP is considered in the far zone. After formation of the far zone, the node having maximum residual energy is selected as the Zone Head (ZH) and collects data from far zone nodes and transmits aggregated data to the BS.

This protocol solves the problem arising due to the difference in cluster sizes of LEACH and enhances the lifetime of the network. The main drawbacks of this protocol are far zone and ZH selection, which are improved by Kim *et al.* [88] with a new protocol called improved far zone LEACH (IFZ-LEACH). In this protocol, initially the CH divides the area into far zone and non far zone and selects the ZH from the far zone based on maximum residual energy and a threshold distance. This protocol outperforms FZ-LEACH and LEACH in terms of network lifetime but it suffers from scalability and network complexity.

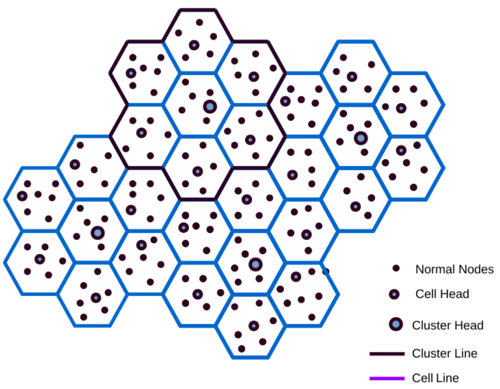

FIGURE 5. Hexagonal cells and seven nearby cells form the cluster.

17) **C-LEACH(CELL-LEACH)**
In cell LEACH [89], the entire network is partitioned into several hexagonal cells for better network coverage. Every cell has many sensor nodes. Seven nearby cells form a cluster in the network. Every cell has a special sensor node called a cell head and sensor nodes within the cell called cell members. Each cluster of seven cells has its own CH. Cell heads and CHs are changed randomly in every round. The cell head allocates a time schedule to cell members using TDMA. Each cell member transmits data during its allocated time slot. A similar concept is used for transmission of the data from cell head to the CH. During data transmission the entire cell is turned-off except a cell member that transmits data to the cell head. The cell head receives data, aggregates it and sends this aggregated data to its respective CH. The aggregated data is transmitted from the CH to the BS by selecting the shortest path between the two. Figure 5 shows the partioning of the sensor network into hexagonal cells and the formation of clusters with seven nearby cells. Data transmission from cell members to cell head and from cell head to the CH to the BS is shown in Figure 6. This protocol has better network coverage due to creation of hexagonal cells. It is highly scalable and energy efficient compare to LEACH and LEACH-C due to adopting of multi-hop communication. Due to the different head nodes (cell head and CH) the complexity and control packets overhead increases.

18) **WLEACH (Wise-LEACH)**
WLEACH [90] overcomes the deficiencies of LEACH by introducing three techniques. The first one is the consideration of energy, the second one is multi-hop communication and the third one is adding dormancy of the CH node. The first approach of WLEACH deals with an energy constraint parameter to become a CH node. For this, WLEACH considers the average energy of the sensor network as the threshold parameter. The second approach, geographical routing and multi-hop routing are used in order to overcome the problem of LEACH (single-hop communication). It uses prims algorithm to set up the minimum spanning tree. The last approach measures the network performance based on the transmitting frequency of the sensor nodes and processing frequency of the BS. There is much burden on the sink node if the transmitting frequency of the sensor nodes is very high. In some situations, sensed information is transmitted only when it is more than a threshold. WLEACH protocol adds a dormancy factor to take the decision whether to transmit data or not.
By adding these three approaches in basic LEACH, the network lifetime has been improved by a significant amount. Its main problem is high network delay.

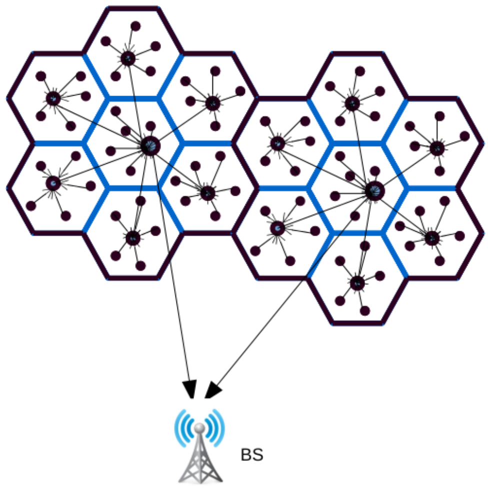

FIGURE 6. Data packets collected by the cell head are transmitted to the CH. The CH transmits these packets to the BS.

19) **E-LEACH (Enhanced-LEACH)**
Performance of cluster-based hierarchical routing protocol depends on the selection of optimal numbers of CHs. In order to distribute energy equally in the network and to increase the network lifetime, Xu *et al.* [91] devised the idea of selecting the optimal number of sensor nodes as CHs and varying the round time in every round. They have considered the energy dissipation of the transmission of an entire network, instead of the individual sensor nodes. The selection of the CH in each round of the E-LEACH protocol considers two additional constraints: the first one is the residual energy of sensor nodes and the second one is energy consumption for sending data to the BS. The main advantage of considering these two constraints is to distribute energy across the network uniformly. So, the sensor node is selected as a CH based on higher residual energy and minimum energy consumption for transmitting data in the E-LEACH protocol. In order to send sensed data from CHs to the BS efficiently, E-LEACH protocol uses the minimum spanning tree for the shortest path among CHs. The CH with highest residual energy is selected as the root node of the minimum spanning tree.

The E-LEACH protocol is highly scalable and more energy efficient compare to basic LEACH but it suffers from delay and control packets overhead.

20) **DAO-LEACH (Data Aggregation based Optimal-LEACH)**
In order to reduce the energy consumption of sensor nodes and optimize the use of resources, Saminathan and Karthik have proposed a new variant of LEACH called DAO-LEACH [92]. The entire process of DAO-LEACH is divided into four stages: node deployment, cluster formation, optimal numbers of CH selection and node aggregation via data ensemble. For better network coverage, nodes are deployed according to the gaussian normal distribution formula which is written in Equation 40.

$$f(a,b) = \frac{1}{2\pi\sigma_a\sigma_b} e^{-\left(\frac{(a-a_i)^2}{2\sigma_a} + \frac{(b-b_i)^2}{2\sigma_b}\right)} \tag{40}$$

Where σ_a and σ_b are the standard deviation for the a and b dimentions. a_i and b_i are the deployment point coordinates. Cluster formation and selection of CHs depends on residual energy of neighbour nodes and their receiving message's time duration. In node aggregation, an aggregator node, known as a macro node M, is selected for data aggregation purposes. Path definition and a macro node M (a combination of more than one node) are used to complete the aggregation process. The efficient aggregation process is done by the macro node through conditional probability. After accomplishment of all the stages, an energy-efficient path has been established to transmit aggregated data from the source node to the BS.
The optimal deployment of nodes and CH selection improves the load balance of the network. The data aggregation through conditional probability and aggregator node increases the network lifetime in reference to LEACH. Due to several stages with different techniques, this protocol is more complicated and also increases network delay.

21) **LEACH-SAGA (LEACH-Simulated Annealing and Genetic Algorithm)**
Zhang *et al.* [93] have presented the LEACH-SAGA routing protocol that is based on optimization techniques of simulated annealing and genetic algorithms for better energy distribution among the sensor nodes in the WSN. The LEACH-SAGA routing protocol is a completely centralized control algorithm which is executed at the BS. Initially it forms optimal numbers of clusters accomplished by simulated annealing and genetic algorithms. After the formation of clusters, the BS calculates the centroid of each cluster. In the selection of the CH, the BS considers the residual energy of the sensor nodes and the distance of the sensor node from the centroid. The sensor nodes with energy greater than the average energy of the cluster become the set of possible CHs in each cluster. The BS selects the final CHs from the possible CHs set based on the minimum distance from the centroid. In the steady state phase, member nodes of the clusters communicate with their respective CHs and CHs then transmit the aggregated data to the BS via other CHs.
The LEACH-SAGA routing protocol outperforms LEACH in terms of network lifetime. It also claims even distribution of the CH in the network with less energy consumption. The main issues with this protocol are scalability, delay and complexity.

22) **P-LEACH (Prediction based Cluster-LEACH)**
P-LEACH [94] is an improvement over LEACH in WSN with mobile sinks. It uses a cluster-based prediction technique to reduce the energy consumption by activatiing a small number of nodes during the sink tracking. In P-LEACH, the network area is virtually divided into three regions: partition cluster (PC), communication quadrangle (CQ) and structure with four PCs. A PC is a circular area with radius r and one cluster centre (CC), four partition nodes (Pns) and four gate nodes (Gns). The maximum energy node is considered the *CC* and resides in the centre of the PC. The Four *Pns* and four *Gns* are located on the perimeter of the PC circle. The *Gns* transfer collected data from the sensor as well as monitoring the presence of mobile sinks. A *Gns* sends a condition message to the remaining *Gns* when it detects a mobile sink and they change their state from deep sleep to sleep. If a mobile sink comes near to the PC, Gns change their states to ready and wait for a resolution message. After receiving a resolution message they change state from ready to work. In work state all sensor nodes are awake and transmit their data to a mobile sink through one of the Gns in the cluster. When a sink leaves the PC, sensor nodes change their state from work to deep sleep and transmission stops. Authors have compared this protocol with STUN (scalable tracking using networked sensors) [95] and DMSTA (dynamic distributed tree-based tracking algorithm) [96] protocols and show that it is two times more energy efficient.
P-LEACH is an enhancement over conventional LEACH and it has better energy conservation, stability and more accurate mobile sink tracking capability compare to existing techniques. Its complexity and message overhead have been increased because of sink mobility.

23) **EEM-LEACH (Energy-Efficient Multi-hop-LEACH)**
To reduces the problems of direct communication from CH to the BS and poor CH selection in LEACH, an energy-efficient multi-hop LEACH (EEM-LEACH) [97] has been designed by Antoo and Mohammed. The main changes made in this protocol for better performance are: (i) CH selection based on residual energy and average energy consumption of nodes, (ii) inter communication path from the CH to the BS with minimum cost and (iii) direct comminication

by nearer nodes of the BS. In CH selection, they have calculated a threshold $T(n)$ like LEACH by adding one more parameter: residual energy of node $P(RE)$. The modified $T(n)$ and $P(RE)$ calculation formula can be shown in Equations 41 and 42.

$$T(n) = \begin{cases} \frac{P}{1 - P * (r \, mod \, \frac{1}{P})} * P(RE) : & if \; n \in G \\ 0 : & otherwise \end{cases} \tag{41}$$

$$P(RE) = \begin{cases} \frac{E_{res} - E_{avg}}{E_{res}} : & if \; E_{res} > E_{avg} \\ 1 - E_{avg} : & otherwise \end{cases} \tag{42}$$

Each CH computes the communication cost metric c whenever it receives a CH advertisement message from the CH or the BS. The cost metric c of a node u can be found by using Equation 43.

$$c = \begin{cases} C(u) + d_{uv}^4 : & d_{uv} >= d_0 \\ C(u) + d_{uv}^2 : & d_{uv} < d_0 \end{cases} \tag{43}$$

Where $C(u)$ is the communication cost metric of u and d_{uv} is the distance between nodes u and v. The cost metric at node v is derived from Equation 44.

$$C(v) = min(C(v), c) \tag{44}$$

The $C(u)$ helps to construct the data transmission path from the CH to the BS.

Since, EEM-LEACH has followed multihop and single hop communication in inter cluster data communication, it saves a significant amount of energy. This protocol performs better in terms of energy consumption and good packet delivery compared to LEACH. Control packets and packet delay significantly increase due to computing maximum residual energy nodes for relay nodes and the communication cost of each node for CH selection.

24) **EE-LEACH (Energy Efficient-LEACH)**

The main drawbacks of traditional LEACH are random selection of CH and single hop communication from CH to the BS. To overcome these problems, Arumugam and Ponnuchamy [98] have proposed a new idea called EE-LEACH. It provides an optimal cluster formation and efficient data aggregation which saves a significant amount of energy. This protocol uses the Gaussian distribution model for better coverage of the network, and for aggregation it uses conditional probability theorem. The optimal clusters are formed on the basis of neighbours' information and their residual energy information. The optimal probability of CH selection is based on the function of spatial density. This helps to prolong the network's lifetime, increases reliability of data forwarding and decreases the latency for data transmission in heterogeneous networks. The energy efficient routing is performed by selecting the maximum residual energy nodes for forwarding the data to the BS.

The experiment results show that EE-LEACH performs better than LEACH in terms of better data delivery, less end-to-end delay and reduced energy consumption. It consists of several techniques and due to that its complexity increases. It lacks integrity of data and scalability scope.

25) **LEACH-1R (LEACH One Round)**

LEACH-1R is proposed by Omari and Fateh [99] for enhancement of LEACH to increase the lifetime over a multi-hop network. In this protocol, the authors have modified MR-LEACH [82] and MS-LEACH [80] with LEACH-1R. Instead of changing every round, the CH only changes when it runs out of energy. When current CH energy goes below the threshold, it selects the strongest received signal node as the CH and sends the new CH message to that node. After getting the CH message, the node transmits the CH message to its neighbours containing the CH id, location information and residual energy.

Simulation results of MR-LEACH-1R and MS-LEACH-1R outperform MR-LEACH and MS-LEACH in terms of network lifetime and energy efficiency. It also presents a better distribution of cluster formation in each round. The main problem of this protocol is that changing the CH after it runs out of energy can create an energy hole after some rounds.

26) **O-LEACH (Orphan-LEACH)**

O-LEACH [100] provides a high connectivity rate with great area coverage of the network. The sensor nodes which are not connected to any CH are considered orphan nodes. Authors have discussed this protocol in two different scenarios. In the first scenario, a cluster member of a cluster acts as a gateway for orphan nodes. The orphan nodes join the gateway node and send their data to it. The gateway node aggregates data and sends it to the BS in a single hop like a CH. In the second scenario, sensor nodes residing in an uncovered area are known as orphan nodes. These nodes form a sub-cluster and select a CH based on the shortest distance to the gateway nodes. The new CH of the sub-cluster informs all orphan nodes and collects data from them, aggregates it and forwards it to the gateway node.

O-LEACH provides better coverage, connectivity rate, energy and scalability compared to basic LEACH. The main problem with this protocol is finding the orphan nodes' information. Data delivery delay and control overhead are also some issues that need to be removed.

27) **CL-LEACH (Cross Layer-LEACH)**

Marappan and Rodrigues have proposed a novel idea called CL-LEACH [101] by exploiting the cross layer techniques in WSN for enhancing the lifetime of the network. The complete operation of this protocol is divided into four phases: (i) cluster formation, (ii) routing mechanism, (iii) CL-LEACH model and (iv) route maintenance.

In cluster formation, initially each nodes select their CH based on residual energy and distance from the BS. The routing mechanism process is divide into two different phases: (i) route discovery and (ii) distance calculation. In route discovery, the source node checks its route cache before sending the data to the destination node; if there is no path in the route cache then it will accomplish a source route to the destination using this routing mechanism. To discover the route from source to the BS and other nodes, The distance D is calculated using Equation 45. Where, (x_1, y_1) are the coordinates of the source node and (x_2, y_2) are the coordinates of the node from which the distance is calculated.

$$D = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{45}$$

This paper proposes a CL-MAC model which works by taking as input the residual energy, threshold value of the node. The node with residual energy greater than the threshold value is considered the relay node for multi-hop communication. Route maintenance detects broken links along the source node to the destination node. The damaged routes are maintained by substituting some new paths in the existing route.

This protocol performs better in terms of message cost, live nodes and energy consumption compared to LEACH. The main drawbacks of this protocol are message overheads and complexity.

28) **DL-LEACH (Dual-hop Layered-LEACH)**

DL-LEACH [102] protocol mitigates the limitation of LEACH arising due to two-hop transmission distance structure using two layers of multi-hop routing technique. The nodes closer to the BS reside in the lower layer. In DL-LEACH, the CH selection process is similar to LEACH. By consuming energy, the network is divided into several layers. In the transmission phase, lower layer nodes compare their distance from the CH and the BS. These nodes directly send their data to the BS if the distance is shorter than to the CH, otherwise it sends the data via the CH. The far nodes transmit their data through the CH; the CH then passes these aggregate data from the relay nodes or the CH to the BS.

This protocol has achieved a great improvement in energy consumption of the network compared to LEACH but it suffers form short node lifespan in large scale networks.

V. COMPARATIVE ANALYSIS

A comparative analysis of single hop and multi-hop LEACH successors has been presented as shown in Tables 2 and 3. These clustering protocols are compared based on different parameters such as routing type, energy efficiency, location information, mobility, scalability, overhead for cluster creation and approach for cluster formation (distributed or centralized or both (Hybrid)). All these protocols are arranged in chronological order in Tables 2 and 3. The basic LEACH is energy efficient but it has some major limitations as discussed in Section II. To resolve these issues, more efficient successors of LEACH have been developed which are discussed in Sections III and IV. These protocols exhibit better performance than basic LEACH in several aspects such as energy efficiency, scalabilty, CH selection and cluster formation.

From this survey and comparison tables, some conclusions will be summarized as follows.

1) Most of the LEACH variant protocols are designed to minimize energy consumption, since sensor nodes are energy constraints. However, there are a lot of areas which are not fully explored in variants of LEACH like cross layer techniques, optimization, data transmission, duty cycle etc.
2) Security-related issues are discussed in some variants of LEACH but improved security is achieved at a cost of high energy consumption which is not acceptable in WSN. Researchers should try to achieve better security with minimum energy consumption using new lightweight cryptographic techniques.
3) Optimization techniques are mainly used for finding optimal numbers of clusters and selecting optimal numbers of CHs in all proposed LEACH successors. Optimization can be used for optimal placement of sensor nodes and the routing path from nodes to the BS.
4) Energy harvesting is a new and promising research area in WSN. Only one solar energy harvesting technique is used in a LEACH-based protocol, namely solar-LEACH. Harvesting has not been properly utilized in WSN or variants of LEACH due to the cost of extra hardware. Different sources of energy harvesting that may be used are solar power, thermal energy, wind energy, salinity gradients, kinetic energy, wireless charging etc.
5) Mobility in WSN is an emerging field of research in contrast to its well-established antecedent. It is much more flexible than static sensor networks as it can be deployed in any scenario and managed with fast topology changes. But in variants of LEACH this field has not been exploited. We can try to propose new schemes in mobility WSN related to the mobile BS and CHs.
6) Network coverage, one important area of WSN, is not extended that much in LEACH variants. Network coverage-related problems in LEACH-based protocols require more attention.
7) Most of the centralized variants of LEACH use GPS for location information which is costly and energy consuming. The optimal localization techniques need to be developed and used.

RESEARCH DOMAINS

LEACH routing protocol has attracted a lot of attention over the last 16 years. It was proposed to enhance the lifetime of the network by offering the equal load distribution among all

TABLE 2. Comparative analysis of Single-hop LEACH and its successors.

Leach & its successor	Year	Clustering	Overhead	Scalability	Energy efficiency	Loc. Req.[1]	Load Bal.[2]	Complexity	Delay
LEACH	May 2000	Distributed	high	low	moderate	no	bad	low	small
LEACH-C	Oct 2002	Centralized	low	low	high	yes	moderate	moderate	small
LEACH-DCHS	Sept 2002	Distributed	high	low	high	yes	good	moderate	small
Solar-LEACH	June 2004	Hybrid	high	moderate	very high	yes/no	moderate	high	small
SLEACH	April 2005	Distributed	high	moderate	very high	yes	moderate	high	small
LEACH-Mobile	June 2006	Distributed	very high	low	low	yes	bad	high	small
Sec-LEACH	July 2006	Distributed	very high	high	low	no	moderate	very high	small
A-sLEACH	April 2007	Distributed	high	moderate	high	no	good	high	high
Q-LEACH	May 2007	Distributed	high	high	high	yes	good	high	small
Energy LEACH	Oct 2007	Distributed	high	moderate	high	no	good	high	high
LEACH-L(UWSN)	Dec. 2007	Distributed	moderate	high	moderate	yes	good	low	small
ME-LEACH	July 2008	Distributed	low	low	moderate	yes	bad	high	small
Armor-LEACH	Aug 2008	Distributed	very high	low	low	no	good	very high	small
TB-LEACH	Sept. 2008	Distributed	high	moderate	moderate	no	good	high	small
LEACH-ME	Dec 2008	Distributed	very high	low	moderate	no	bad	high	small
ALEACH	Dec 2008	Distributed	high	moderate	high	no	good	very high	small
T-LEACH	June 2009	Distributed	moderate	high	high	yes	good	high	small
LEACH-H	Nov 2009	Hybrid	high	moderate	high	yes	moderate	high	high
U-LEACH	March 2010	Distributed	low	low	high	yes	good	high	small
LEACH-B	Aug 2010	Distributed	high	low	high	yes	good	high	high
LEACH-GA	April 2011	Distributed	high	low	high	yes	low	high	small
MS-LEACH [34]	June 2011	Distributed	very high	high	low	no	bad	low	small
FL-LEACH	April 2012	Distributed	low	high	low	yes	good	high	small
LEACH-SWDN	May 2012	Distributed	moderate	high	low	yes	moderate	high	small
EP-LEACH	April 2013	Distributed	high	low	very high	no	good	high	small
I-LEACH	May 2013	Distributed	moderate	high	high	yes	good	high	small
MOD-LEACH	June 2013	Distributed	low	moderate	high	yes	good	high	small
Weighted-LEACH	Aug 2013	Distributed	high	high	high	yes	good	high	small
LEACH-G	Oct 2013	Hybrid	low	high	high	yes	good	high	small
EC-LEACH	Nov 2013	Centralized	low	high	high	yes	good	high	small
LEACH-CE	Dec 2013	Centralized	low	low	very high	no	good	moderate	small
FT-LEACH	March 2014	Distributed	high	low	moderate	yes	bad	high	small
IB-LEACH	Aug 2014	Distributed	high	low	high	no	good	high	small
CogLEACH	Oct 2014	Distributed	high	high	moderate	no	bad	moderate	small
V-LEACH	June 2015	Distributed	high	low	very high	no	good	very high	high
CogLEACH-C	Aug 2015	Centralized	high	low	high	yes	good	moderate	small
EMOD-LEACH	Sept 2015	Distributed	high	low	high	yes	good	moderate	small
EHA-LEACH	Feb 2016	Distributed	high	high	very high	yes	good	high	small
LEACH-MAC	July 2016	Distributed	high	moderate	high	yes	good	high	small

Loc. Req.-Location Required and Load Bal-Load Balance

nodes to rotate the role of data collection, aggregation and transmission. But, in LEACH, random CH selection, position of CH and single hop communication from the CH to the BS are the main hurdles to prolong the network lifetime. Further, several modification and improvements are being done on LEACH to overcome these issues. LEACH has been extended to diverse variants in various research domains as shown in Table 4. It is observed that the primary research domain is energy efficiency in most of the LEACH variants. In recent time, security and energy harvesting domains are gaining a lot of attention. Table 4 also describes the main contributions of the LEACH variants along with challenges.

VI. FUTURE DIRECTIONS

All the clustering protocols related to LEACH have the same common objective: to reduce energy consumption and extend the network lifetime. To achieve this goal, a variety of approaches have been used by different LEACH variant protocols. Most of the protocols are distributed clustering in nature, but in some cases (small area network) centralized approach is more appropriate. There is still a number of open research issues needed to be addressed in the future.

However, the major goals for proposing LEACH variants protocols for WSNs are the following:

- Energy efficient communication in WSN.
- Improvement in scalability.
- Increasing the security in WSN.
- Minimization of network delay.
- Reduction of complexity.
- Assurance of connectivity under various scenarios.
- Equal load distribution over entire network.
- Improvement of the overall performance in WSN.

The reviewed literature and presented tables clearly indicate that the design of a proper LEACH-related protocol mainly depends on a user's requirements and their applications. However, LEACH has been broadly investigated by researchers in different domains, yet still many aspects of LEACH are not appropriately explored. Here, the paper proposes some areas for future work.

A. HARVESTING TECHNIQUES

Batteries are the main power source of sensor nodes in WSN. The nodes will die once their energy is exhausted. In most applications, replacement of the node's battery is not feasible.

TABLE 3. Comparative analysis of Multi-hop LEACH successors.

LEACH Successors	Year	Clustering	Overhead	Scalability	Energy efficiency	Loc. Req.[1]	Load Bal.[2]	Complexity	Delay
LEACH-B	April 2003	Distributed	high	low	high	yes	good	moderate	moderate
LEACH-B+	May 2005	Distributed	high	low	very high	yes	good	very high	small
Multi-hop LEACH	May 2005	Distributed	moderate	high	high	Yes	good	high	high
TL-LEACH	Sept. 2005	Distributed	low	low	high	no	bad	low	small
LEACH-M	Dec. 2007	Distributed	high	high	low	no	moderate	high	small
ME-LEACH-L	Oct. 2008	Distributed	high	very high	moderate	yes	good	high	high
LEACH-DCHS-CM	June 2008	Distributed	high	high	high	yes	good	moderate	small
LEACH-L	Nov. 2008	Distributed	high	high	high	yes	good	high	high
MS-LEACH [82]	May 2009	Distributed	high	very high	very high	yes	good	high	high
WST-LEACH	May 20010	Distributed	high	high	very high	yes	good	moderate	small
MR-LEACH	July 2010	Distributed	high	high	high	no	good	high	high
Coop-LEACH	Aug. 2010	Distributed	high	low	high	no	good	high	high
LEACH-D	Sept. 2010	Distributed	high	very high	very high	no	good	very high	low
UWSN-LEACH	Jan 2011	Distributed	very high	low	moderate	yes	good	very high	high
FZ-LEACH	May 2011	Distributed	high	high	high	yes	bad	high	high
Cell-LEACH	Feb. 2012	Distributed	very high	very high	moderate	yes	good	very high	moderate
IFZ-LEACH	Sept. 2012	Distributed	high	high	very high	yes	good	high	high
Wise-LEACH	Nov. 2012	Distributed	high	high	very high	no	good	low	small
Enhanced LEACH	May 2012	Distributed	high	very high	high	no	good	high	high
DAO-LEACH	July 2013	Distributed	high	moderate	high	yes	good	high	high
LEACH-SAGA	March 2014	Centralized	moderate	high	high	yes	good	very high	small
P-LEACH	March 2014	Distributed	very high	high	very high	yes	good	very high	small
EEM-LEACH	July 2014	Distributed	high	moderate	very high	yes	good	very high	small
EE-LEACH	March 2015	Distributed	high	very high	high	yes	good	high	small
LEACH-1R	March 2015	Distributed	low	low	high	yes	bad	high	small
O-LEACH	April 2016	Distributed	high	high	high	yes	good	high	high
CL-LEACH	March 2016	Distributed	high	moderate	high	yes	good	high	high
DL-LEACH	July 2016	Distributed	moderate	high	high	yes	good	low	moderate

Recently, EHWSN has gained more attention due to high energy efficiency in WSN. The sensor nodes of EHWSN are equipped with some harvesters, which can charge batteries from the environment. The main harvesting sources of energy are solar, wind, vibration etc. The nodes which have more harvesting power play the role of CH in solar LEACH [31], [79] or can work as a relay node in multi-hop communication [103]. In LEACH only sloar-assisted nodes are considered; various harvester domains need to be explored and how to used them in LEACH-related protocol is an open research issue.

B. ROUND LENGTH

The number of Rounds is considered as an important factor in LEACH and its variants but all these protocols remain quiet on round length. One complete round consists of cluster formation, CH selection and data transmission phases. In one round all sensor nodes of the WSN transfer their sensed data to the BS through different phases. The total time taken in a complete round is called round length. The number of Rounds is also considered as a powerful parameter for performance measurement in WSN. TB-LEACH [44] and Variable Round LEACH (VR-LEACH) [66] protocols have used time factor for CH selection and variable round time respectively but round length is not clearly discussed. Hence, finding the optimal round length is an open challenge in LEACH and its variants.

C. 3D SCENARIOS

Most of the real world applications are related to 3D scenarios, even though sensor nodes are usually deployed on a 2D surface. Underwater WSN-based LEACH (UWSN-LEACH) [85] and LEACH-L [86] are proposed using the hierarchical clustering techniques for underwater WSN. The main challenge in 3D UWSN is to manage mobile nodes moving with the ocean currents. The major issues that need to be considered while designing a UWSN are extreme water conditions, hardware constraints, transmission issues, etc. However, clustering techniques are not fully exploited in the 3D environment due to their highly sparse deployment and this provides a great challenge for the researchers to design a better protocol.

D. MOBILITY

Mobility is an important open research issue for investigating the effect of mobile nodes in hierarchical clustering routing or LEACH-related protocols. In clustering, all three parts of the network, non-CH nodes, the CH node and the BS, can be mobile. Lotfinezhad *et al.* [104] have investigated the effect of a mobile BS in a clustering-based WSN. Another valuable analysis [77] supports the non-CH and CH. Both the mobile and least mobile nodes are selected as CH. The network topology changes and control packets overhead due to mobile nodes are the major challenges to handle. Cluster formation and stable time for estimation of link establishment time are also very challenging tasks.

E. SCALABILITY

LEACH is not efficient for large scale networks, since its CH communicates directly with the BS. In large scale networks, single hop communication uses higher radio range which consumes more battery power. To mitigate this prob-

TABLE 4. List of research domains of LEACH variants. *(To be Continued)*

Research Domains	Protocols	Main contributions	Challenges
Energy Efficient	Energy-LEACH	CH selection based on residual energy.	Uneven energy consumption.
	EE-LEACH	Gaussian distribution for node deployment, conditional probability for data aggregation and residual energy used for CH selection and relay node selection.	High complexity and fails to provide data integrity.
	EEM-LEACH	Maximum residual energy for CH and relay node selection. Multi-hop and single hop inter cluster communication.	High complexity and overhead.
	EC-LEACH	CH selection based on a maximum threshold distance between two CHs. Completely centralized	More control overhead and less scalable.
Security	Security-LEACH	Lightweight cryptographic techniques and SPINS optimized security building blocks are use.	It is only effective for inside attackers and it is not energy efficient.
	SecLEACH	Random Key predistribution.	Security is acheived at the cost of higher energy consumption.
	Armor-LEACH	Combined SecLEACH and TCCA protocols functions.	More overhead and energy consumption.
	MS-LEACH	Provides data confidentiality and cluster members to CH authentication.	More control overhead and energy consumption.
Dual-hop layered	DL-LEACH	Two different transmission schemes are used for short-range and remote communications.	Hotspot problem increases.
Optimization	LEACH-GA	Genetic algorithm is used to find optimal probability p in CH selection process.	Sensor node with GPS enabled or use of geographical routing algorithms for location coordinates; in both cases extra energy consumption added.
	FL-LEACH	Fuzzy logic is applied to find the optimal value of CHs by using two linguistic variables: number of sensor nodes in the network and the network density.	Energy is not considered as a parameter for CH selection and nodes distribution is uniform.
	LEACH-SAGA	Simulated annealing and genetic algorithms are used for optimal number of clusters formation. CH selection is based on residual energy and minimum node distance from cetroid of a cluster.	More overhead and highly complex.
Energy Harvesting	Solar-LEACH	Some nodes are assisted with solar panels and most of the time these nodes play the role of CHs.	Solar panel-assisted nodes totally depend on Sun duration and due to extra harvesting hardware, costs increase.
	A-sLEACH	Convex Hull with maximum number of sensor nodes used for cluster and solar power-aware nodes are selected as CH.	Large control overhead and more complex.
	EP-LEACH	More energy potential sensor nodes become CHs.	High cost and highly complex.
	EHA-LEACH	Max-min optimization used for maximizing the minimum energy conservation.	More delay and highly complex.
Cognitive Radio	CogLEACH	Spectrum-aware protocol which uses idle channels as a parameter for CH selection.	Energy is not considered for CH selection so it has uneven energy distribution.
	CogLEACH-C	Idle channels and residual energy are used for CH selection.	Due to it being fully centralized it is not highly scalable.
Data aggregation	IB-LEACH	More energy potential sensor nodes become CHs.	High cost and highly complex.
	DAO-LEACH	Gaussian distribution for node deployment, macro node used as a data aggregator.	Due to aggregators packet overheads and delay increases.
Mobility	LEACH-Mobile	Mobility-centric protocol for mobile nodes ensures the connection between mobile nodes and CH.	More overheads due to mobile nodes connection. CHs selection can be improved.
	LEACH-ME	Fewer mobility sensor nodes selected as CHs. The data transfer success rate is high between CH and member nodes.	Due to the rescheduling of the TDMA, more control packets are generated.

TABLE 4. List of research domains of LEACH variants. *(To be Continued)*

Scalability	LEACH-L	Depending on the threshold distance of the first order radio model, routing switches from single hop to multi-hop.	Clusters formation and CH selection are the same as LEACH.
	ME-LEACH-L	Timer is used for CH selection. Spanning tree is constructed using EVBT node.	Delay and complexity increases.
Cross Layer	LEACH B+	MAC and routing layers aspects are jointly considered and optimized for cluster formation.	Nodes are uniformaly distributed and not fit for large scale networks.
	CL-LEACH	Routing and physical layers are marged with MAC layer. CHs are selected based on residual energy and distance of the node from the BS.	Not scalable and, due to cross layer network complexity increases.
Tree Based routing	WST-LEACH	Weighted spanning tree is constructed by considering residual energy, nodes distribution density and distance from CH to the BS.	Each node's location information required. Less scalable.
	ME-LEACH-L	Timer is used for CH selection. Spanning tree is constructed using EVBT node.	Additional control packets and More complex.
Unequal Clustering	U-LEACH	Unequal clusters are formed and clusters nearer to the BS are bigger than farther clusters.	Reduces hotspot problem but intra cluster communication increases.
Multi-CH in a cluster	Vice-LEACH	Apart from the main cluster, one vice cluster is selected for backup purposes if main CH dies or fails.	Ensures data delivery but extra energy consumed for vice CH.
	Q-LEACH	One extra sub cluster is formed to finish the task of a round if main CH fails in the middle of a round.	Uniform distribution and additional control packets.

lem, several multi-hop LEACH variants are proposed, some dedicated to large networks [42], [88]. In scalability, the main challenges are adjusting radio range and finding the optimal path in multi-hop communication.

F. SECURITY

Incorporating security in LEACH-based protocols is a difficult task due to the lack of resources in a sensor node. Existing solutions for wireless ad hoc networks are not relevent here. Like other protocols, LEACH is at high risk of security attacks including spoofing, replay, hello flood, sybil etc. Since it is a cluster-based protocol, CHs are the first target for attackers due to the potential for most damage. The CHs should perform the security protocols and data acquisition and at the design level data link-layer encryption and authentication should be considered. SPINs [33], SLEACH [32] and SecLEACH [36] protocols are based on LEACH and they have contributed different light-weight security approaches in hierarchical clustering protocols. The major open research challenges in this domain are designing light-weight cryptographic algorithms, thereby minimizing the message overheads and reducing energy consumption.

G. HEURISTIC AND METAHEURISTIC OPTIMIZATION TECHNIQUES

Biologically inspired algorithms have been used for formulating solutions to optimization problems in WSN. Heuristic and metaheuristic techniques have been applied to address clustering issues such as node deployment, CH selection, optimal number of CHs selection, localization and data aggregation. A load-balancing algorithm [105] using GA has been proposed for distribution of equal and optimal load in the network. Some more LEACH-related protocols [51], [52], [93] have been designed to optimize the different operations. Most of the proposed protocols related to hierarchical clustering routing have used optimization techniques only for CH selection or finding the optimal number of CHs in WSN. Incorporating optimization methods in LEACH and its variants is not an easy task: it has several major issues such as parameter estimation, finding a relevant optimization algorithm and minimizing the complexity of the optimization operation. Heuristic-based clustering approaches require more attention by researchers. However, these methods are centralized and time consuming.

H. FAULT TOLERANCE MANAGEMENT

Fault tolerance is one of the most important issues in LEACH and its variants due to temporal link failures. Since, in WSN, sensor nodes are deployed in an inhospitable environment and remain unattended, the failure of a node's components is practically unavoidable. In cluster-based protocols, failure of the CH causes more damage in the network because it directly affects their member nodes. This issue is discussed and an attempt at resolution is made by an efficient re-clustering method in [106]. LEACH-FT [64] has been developed to increase the network's dependability and fault-tolerance capacity and also reduces energy consumption. In fault tolerance management, the major challenges are fault detection and its recovery. Implementing fault-tolerance schemes in LEACH and its associated protocols have several issues that need to be considered such as managing frequent link breaks, re-clustering, selection of new CH incase of CH failure and minimizing the message overhead.

I. QUALITY OF SERVICE (QoS) BASED COMMUNICATION

QoS pertains to several WSN performance issues such as end-to-end delay, bandwidth, throughput and latency [107]. In most of the WSN protocols, energy efficiency is considered a key design issue to improve the network lifetime. However, due to the emergence of the latest multimedia and imagining sensors that are used in new WSN applications, QoS-aware energy-efficient protocols need to be developed. [108] and [109] provide some better QoS schemes in clustering routing protocols to ensure minimum delay and path loss.

J. COGNITIVE RADIO

A new paradigm of communication has emerged after the integration of cognitive radio and WSN. Cognitive radio provides a solution for the scarcity of the available radio spectrum due to massive demand. In [110], cognitive radio was first integrated with the sensor network and further it has been used as an extension of LEACH in [67] and [68]. WSNs work on the unlicensed band and this band is also utilized by other wireless communications, which affects its performance. This new spectrum-aware technique in WSN opens the portal to a new class of applications like multimedia and indoor sensing applications. In this area, finding the vacant channels of a band is a big challenge. However, the energy and computational constraints are also an important issue in WSN, which needs to be addressed.

K. ADDITIONAL IMPORTANT ISSUES

Finally, some more important areas and their issues which require more attention by the researchers are mention here. Coverage and connectivity are important open issues for all researchers in LEACH-related protocols. Random deployment of sensor nodes in harsh environments and limited resources are the main challenges for network coverage. Limited work has been done in this area, so it requires more awareness. One more challenging area in LEACH and its variants is localization which requires more study by the researchers. From this survey it is clear that most LEACH variants are distributed in nature and location information is very important for them. To find the location of each sensor node, GPS is not a good choice due to its cost and extra energy consumption. So, several localization algorithms [111] are designed to find the position of nodes without using GPS in WSN. Localization algorithms using clustering techniques and LEACH-related protocols or use of localization in LEACH and its variants have not been fully exploited. A lot of work is required in this important field to improve LEACH. Cross layer design in LEACH-related protocols is another major issue which needs to be discussed and worked on. [101] and [73] have provided some cross layer design schemes for LEACH.

VII. CONCLUSIONS

The paper presents a comprehensive and state-of-the-art survey of LEACH and its successors. We have discussed and compared more than 60 LEACH related protocols covering both single hop and multi-hop communication. Further, these protocols have been comparatively analysed on various parameters like energy efficiency, overheads, scalability etc. These analyses have also been presented in tabular formats for easy reference. It is evident that the different successors of LEACH are an improvement over the basic LEACH protocol. A major goal of any newly designed protocol in WSN is energy efficiency apart from performance factors.

The findings of this survey show that most of the discussed protocols are distributed in nature and require location information. Finding location coordinates through either GPS device or localization techniques is expensive and it consumes a significant amount of energy. Multi-hop clustering routing protocols suffer from more overheads and delay due to path set-up and relay nodes as compared to single hop clustering routing protocols. Only few protocols have considered the consumption of energy during the CH selection and cluster formation in their simulation. In CH selection, energy is an important parameter but apart from this, researchers have considered many other parameters for it such as location of the node, node density, distance from the BS, mobility, energy harvesting nodes, optimal number of CHs etc. Security is a major concern as WSN is also used in military and hostile scenarios. Most of the proposed protocols for security in WSN are doing so at the expense of energy efficiency as there is a trade-off between security and energy efficiency. Hence, it is challenging to improve both energy efficiency and security at the same time.

In recent years deterministic clustering approaches have gained more popularity in WSN as they are more reliable than probabilistic clustering approaches. However, the deterministic clustering methods increase the complexity and energy consumption, as they use different approaches like fuzzy-logic based, weight-based, heuristic-based, and compound based approaches. The most important design objectives are detailed with priority in Figure 2 to help the reader evaluate the different design parameters used by researchers in developing LEACH. We have highlighted some research domains based on discussed protocols, which is mentioned in Table 4.

LEACH has been a creative field of research over the years. All LEACH-related protocols discussed in this paper offer a promising improvement over conventional LEACH; however, there is still much room for developing convenient and efficient LEACH variants. This paper proposes some open issues in Section VI, which can be considered as important areas in the future for designing a new LEACH-related protocol. Among the proposed open issues, QoS-based LEACH-inspired routing needs to be addressed more in the near future, mainly in multimedia and real-time applications in WSN.

Another interesting area is EHWSN which will require more attention in LEACH-based protocols by the researchers in the near future. Furthermore, the cluster formation in heterogeneous network should be considered as an important problem due to different communication and processing capabilities. Based on the reviewed literature, presented tables and discussions, it is clear that the design of a suitable LEACH variant depends on the specific application and user's requirements. We believe that this comprehensive survey will pave the way for the researchers to have an in-depth understanding of WSN routing protocols and help them in designing more effective routing algorithms in WSN.

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