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METHODOLOGIES AND APPLICATION

# Clustering-based heterogeneous optimized-HEED protocols for WSNs

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**Abstract**

Clustering-based networks play a vital role in efficient utilization of energy consumption of each sensor node (SN) in wireless sensor networks (WSNs). Furthermore, firstly, prolonged network's lifetime is observed as the key factor to analyze the protocol's efficiency. However, in critical applications, i.e., military surveillance, environmental monitoring and structural health monitoring, stability region is also an important aspect for consideration. This provides reliability of data from each SN in the network. On the other hand, once a SN dies at any region, we are not able to sense that region which leaves the region vulnerable from detection of events. With this reason, it is highly important for an energy efficient protocol to provide good stability region with prolonged network lifetime. Secondly, a protocol should be intelligent enough to handle homogeneous as well as heterogeneous nodes efficiently in the network (i.e., homogeneous and heterogeneous WSNs) because once the network executes, a homogeneous WSN is also transformed in heterogeneous WSN. This is because of different radio communication features, occurrence of random events or morphological attributes of the network field. optimized-HEED protocols are one of the most recent clustering-based algorithms which improved the various shortcomings of classical protocol, i.e., HEED and provided far efficient results in terms of energy consumption, load balancing and network lifetime. However, these demonstrated their efficiency for homogeneous WSN only. In this paper, we extend the optimized-HEED protocols for heterogeneous WSNs model on the basis of varying levels of node heterogeneity (in terms of energy), i.e., 1-level, 2-level, 3-level and multi-level, and propose these as heterogeneous optimized-HEED (Hetero-OHEED) protocols. Simulation results confirm that by increasing the level of node's heterogeneity, stability region of each Hetero-OHEED protocol enhances extremely with prolonged network lifetime. These provide a rich solution in designing of efficient protocols for those applications, where stability region and network lifetime require equal importance.

**Keywords** Clustering · WSNs · Stability region · Network lifetime · Load balancing · HEED · Optimized-HEED · BFOA · Fuzzy logic system

## 1 Introduction

Wireless sensor networks (WSNs) are one of the most popular communication technologies that have been widely appreciated in the past few years due to infrastructure-less networking. WSNs are composed of hundreds or thousands of small-sized, battery-operated sensor nodes (SNs) that have the expertise to conduct their assignments, even in hostile and challenging environments where access to human being is limited. These SNs can be easily employed for monitoring different phenomenon such as light, humidity, temperature, motion and vibration in hostile environments. These days WSNs are high in demand for various critical applications such as natural disaster forecasting, military surveillance, environmental monitoring and structural health monitoring (Akyildiz et al. 2002).

Besides this, one of the major constraints in WSN is limited battery power, given to each SN, due to which efficient utilization of limited energy resources of SNs is the prime concern in sensor networks. In this context, designing of clustering protocols can prolong the WSN lifetime with efficient utilization of each SN's energy. In clustering protocols, SNs

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are clustered into small groups. Each cluster is headed by one cluster head (CH). These CHs work like intermediate nodes between SNs and base station (BS). Each SN senses the data from environment and forwards them to the CH instead of direct communication to the BS. After reception of the data packets from SNs in its cluster, each CH combines them into a meaningful information by applying some mathematical operations, i.e., aggregation, fusion, etc. Furthermore, each CH forwards its data packet to the BS using multi-hop or direct communication. Availing this clustering approach, a WSN can easily save the improper energy dissipation of each SN and reduce excessive data packets forwarding toward BS and contributes in extension of WSN's lifetime for longer time-span (Afsar and Tayarani-N 2014; El-said et al. 2015). However, there exist some issues that require proper attention in designing of energy efficient clustering protocols, i.e., selection of best suited CHs, optimal number of CHs, ideal cluster size, proper load balancing among SNs, appropriate cluster maintenance and proficient data routing, etc., which assist to prolong the network life to maximum time-span (Kumarawadu et al. 2008; Mann and Singh 2017; Gupta and Sharma 2018a).

Furthermore, reliability of data is another aspect, where data propagation from each SN to the BS for prolonged period of time is quite important. Applications, i.e., natural disaster forecasting, battlefield surveillance and health structural monitoring, are such critical applications which require data from each SN for maximum duration for decision-making purpose. For such cases, an efficient protocol is required which must be capable of offering decent stability period (when first node dies in the network) with prolonged network lifetime in WSNs (Smaragdakis et al. 2004; Raty 2010; Gupta and Sharma 2018b).

Generally, most of the protocols are designed for homogeneous WSNs where each SN is equipped with same energy level at the beginning of network. However, during network execution, these are later transformed into heterogeneous WSNs. This is due to the variation in energy dissipation of each SN due to radio communication features, occurrence of random events or morphological attributes of the field during network execution. This reason gives birth to the fact that an efficient clustering protocol must be capable of handling both homogeneous and heterogeneous WSNs competently (Qing et al. 2006; Sharma and Sharma 2016).

In this paper, we extend the optimized-HEED protocols for heterogeneous WSNs model based on varying levels of node heterogeneity (in terms of energy), i.e., 1-level, 2-level, 3-level and multi-level, and propose these as heterogeneous optimized-HEED (Hetero-OHEED) protocols. Hetero-OHEED protocols consist of heterogeneous HEED-1 Tier Chaining (hetHEED1TC), heterogeneous HEED-2 Tier Chaining (hetHEED2TC), heterogeneous ICHB-based HEED (hetICHB-HEED), heterogeneous ICHB-based OHEED-1 Tier Chaining (hetICOH1TC), heterogeneous ICHB-based OHEED-2 Tier Chaining (hetICOH2TC), heterogeneous ICHB-FL-based OHEED-1 Tier Chaining (hetICFLOH1TC) and heterogeneous ICHB-FL-based OHEED-2 Tier Chaining (hetICFLOH2TC) protocols. In 1-level of Hetero-OHEED protocols, each node has same energy level at the beginning of the network and behaves as homogeneous WSN. It consists of het1-HEED1TC, het1-HEED2TC, het1-ICHB-HEED, het1-ICOH1TC, het1-ICOH2TC, het1-ICFLOH1TC and het1-ICFLOH2TC protocols. For 2-level of Hetero-OHEED protocols, WSN is equipped with 2-level of heterogeneous nodes which consists of two types of SNs, initialized with different energy levels at the beginning of the network. It includes het2-OHEED protocols. Likewise, 3-level of Hetero-OHEED protocols contains three types of SNs with varying energy levels initialized at the beginning of the network. It consists of het3-OHEED protocols. In multi-level of Hetero-OHEED protocols, WSN is equipped with different heterogeneous nodes under a close set of varying energy levels. It includes mul-OHEED protocols. Here, we analyze the functional behavior and performance of Hetero-OHEED protocols in heterogeneous WSNs. During the simulation results and analysis, it has been observed that on increasing the level of node's heterogeneity, the performance of Hetero-OHEED protocols improves far better. Notably, the stability region of each Hetero-OHEED protocol enhances with prolonged network lifetime. This confirms that Hetero-OHEED protocols are capable of providing a rich solution to those WSN's applications, where stability region and network lifetime have equal importance.

## 2 Related work

Being battery-operated with limited power supply and not rechargeable once deployed, efficient utilization of SNs' energy is one of the major issues in designing energy-efficient clustering protocols. A number of protocols have been designed by various authors in past two decades to efficiently utilize the energy resource of SNs and extend the network lifetime. In this field, LEACH (Heinzelman et al. 2000) is one of the initial protocols which tries to reduce the energy consumption of WSN by arranging SNs in the form of clusters. LEACH dynamically elects the CHs in round-robin fashion that allows each SN to become CH in varying rounds to evenly utilize the energy resource of each SN. CHs collect the sensed data from SNs in their clusters, do aggregation and forward them to the BS. This approach balances the energy consumption of each SN and increases the network lifetime in comparison with direct communication. LEACH-C (Heinzelman et al. 2002) was an enhancement over LEACH, in which BS itself elected the CHs. Here, each SN forwarded its residual energy and location information to the BS. Based on these statistics, BS discarded lower energy nodes from CH selection procedure. This benefitted in increasing the network lifetime. Lindsey and Raghavendra (2002) discussed PEGASIS, another extension of LEACH, where a chain was constructed among all SNs for data propagation. Each SN forwarded its data to the CH via neighboring nodes using chain. Furthermore, CH forwarded the data packet to the BS in a single-hop. Jung et al. (2007) discussed CCS, which concentrated on reducing energy consumption of PEGASIS, extending its network lifetime by dividing network in concentric circles and considering the BS location for data transmission. Gautam et al. (2009) discussed TSC, which improved the CCS by dividing the network field into tracks and sectors to further reduce the energy consumption of SNs, while minimizing the redundant data forwarding and finding the shortest path between CHs and BS for data transmission.

SEP (Smaragdakis et al. 2004) an extension of LEACH, was one of the earliest heterogeneous protocols which employed two levels of heterogeneity in terms of nodes' initial energy. This approach supported CH selection procedure by using weighted election probabilities of SNs acting as a function of residual energy for uniform usage of nodes' energies. DEEC (Qing et al. 2006) was a two-level and multi-level heterogeneity-based protocol. This protocol had employed probability-based CH selection on the ratio of residual energy and average network energy. Higher probability nodes had more chances to be CHs in the network. In Zhou et al. (2010), authors discussed EDFCM protocol which had stable CH selection scheme with reliable data forwarding algorithm for two-level heterogeneous networks. SEDEEC (Elbhiri et al. 2011) discussed the dynamic probability for CH selection by employing uniformly distributed energy consumption scheme in the two-level heterogeneous network. EECDA (Kumar et al. 2011) discussed energy efficient clustering and data aggregation protocol for three-level heterogeneous WSNs. It provided a CH selection technique with path selection procedure by applying maximum sum of residual energy nodes for data transmission instead of minimum energy consumption path. DSCHE (Kumar 2012) discussed a stable CH election protocol for refining EECDA protocol on the basis of stability region and network lifetime of heterogeneous network. In Lin et al. (2012), authors discussed a method by applying ACO technique for increasing the network lifetime of heterogeneous WSNs. SEEC (Farouk et al. 2014) discussed a stable and energy efficient clustering protocol in which each cluster was empowered with an advanced energy node. It was further extended to multi-level heterogeneous WSNs, where more power-equipped super nodes were reserved to sense long-distant areas in the network field. In Du et al. (2015), authors discussed EESSC protocol which used a special packet for updating residual energy of each node during data transmission for CH selection procedure. Lin et al. (2015) discussed an energy efficient clustering approach by partitioning a large-scale WSN into fan-shaped clusters.

In Younis and Fahmy (2004), authors discussed HEED protocol which was based on two clustering parameters, i.e., residual energy and node degree. Using this parametric combination for CH selection enabled HEED for load balancing feature and more energy efficient. Moreover, HEED was one of prominent clustering protocols in this field. However, it suffered from few drawbacks, i.e., (1) Extraneous CH formation was caused due to uncovered SNs (Aslam et al. 2011). (2) Additional overhead of packet broadcast caused by the CH selection procedure of uncovered nodes dissipated extra energy resource of the network. (3) Network suffered from hot-spots problem due to more workload on CHs, especially near BS (Wei et al. 2011; Poonguzhali 2012). MiCRA (Khedo and Subramanian 2009) was a variant of HEED, where two levels of CH selection process took place to reduce the extraneous CHs' formation caused by uncovered nodes in HEED. In MiCRA, the formation of CHs at the first level was same as HEED. However, at the second level, only first level selected CHs could participate. This process reduced the extraneous CHs' formation in the network. In Xu et al. (2014), authors discussed BEE, another variant of HEED which used the local density of CHs for providing better coverage in the network. However, it consumed more energy in data transmission due to single-hop communication between CHs and BS. To overcome this issue, authors discussed multi-hop version of BEE and named it as BEEM, which provided better performance in comparison with BEE. In Chand et al. (2014), authors discussed Heterogeneous-HEED protocols, which analyzed the performance of HEED with different levels of heterogeneity. In Xiao et al. (2015), a cell-clustered variant of HEED, i.e., CC-HEED was discussed which divided the whole network into numerous cell-shaped regions to make it more energy efficient. In Gupta and Sharma (2017), optimized-HEED protocols were discussed in which authors had resolved diverse shortcomings of HEED, which resulted in constant CHs' formation in consecutive rounds and reduced workload on CHs, minimum required data packets broadcast, even energy consumption by SNs and CHs, alleviated holes, minimized hot-spots problem and prolonged network lifetime.

In Negnevitsky (2001), authors discussed fuzzy logic system (FLS), an expert knowledge system which is capable of providing proficient results even where incomplete and inaccurate information may exist. This makes it more feasible for real-time decision making purpose (Gupta et al. 2005). In Kim et al. (2008), authors discussed a technique for reducing CH selection overhead using energy and local distance parameters through FLS module. In Mao and Zhao (2011), authors discussed UCFIA clustering protocol based on FLS with improved inter-cluster routing procedures using ACO. In Bagci and Yazici (2013), authors discussed EAUCF protocol, which used FLS to adjust CH radius and its distance to BS to overcome the cluster radius estimation issue. In Sert et al. (2015), authors discussed a multi-objective fuzzy-based clustering algorithm (MOFCA) to handle holes and hot-spots problem in WSNs. In Nayak and Devulapalli (2016), authors discussed a modification on LEACH using FLS module. In this approach, a super CH was elected based on fuzzy inference system to extend the network lifetime and stability region. In Baranidharan and Santhi (2016), authors discussed a refinement in clustering procedures of EAUCF and named it as DUCF that formed unequal clusters in WSNs which allowed better load balancing feature among CH nodes. In Gupta and Sharma (2017), authors discussed ICFLOH1TC protocol based on the combination of intelligent CH election based on BFOA (ICHB) algorithm with FLS module using residual energy, node density and distance to BS parameters for improved CH selection scheme in HEED along with intra-cluster chaining of SNs for data transmission. This resulted in better load balancing among SNs, alleviated the holes, minimized hot-spots problem and prolonged network lifetime efficiently. Furthermore, authors discussed a multi-hop variant of this protocol and named it as ICFLOH2TC. It used the inter-cluster chaining additionally for data transmission to BS which provided even energy consumption among CHs, less data packets' broadcast toward BS and delivered better stability region in comparison with ICFLOH1TC protocol.

## 3 Proposed heterogeneous optimized-HEED protocols

This section discusses the proposed heterogeneous optimized-HEED (Hetero-OHEED) protocols, an extension of optimized HEED (OHEED) protocols (Gupta and Sharma 2017) for varying levels (in terms of energy) of heterogeneous WSNs. Hetero-OHEED protocols consist of hetHEED1TC, hetHEED2TC, hetICHB-HEED, hetICOH1TC, hetICOH2TC, hetICFLOH1TC and hetICFLOH2TC protocols. The complete flowchart of proposed Hetero-OHEED protocols is shown in Fig. 1. The required heterogeneous network model, cluster formation, data collection, data transmission procedures and energy consumption model for each Hetero-OHEED protocol are discussed in this section.

### 3.1 Heterogeneous network model

The following assumptions are required for Hetero-OHEED protocols for WSNs (Younis and Fahmy 2004; Qing et al. 2006; Gupta and Sharma 2017).

- Once deployed in the network field, SNs are immobile and remain stationary.
- SNs are location unaware, because these are not equipped with GPS antennas.
- A unique identification number (UID) is allotted to each SN as an identity.
- Each SN has same capabilities for data sensing, processing and transmission, however differs in initial energy levels.
- After deployment in the field, SNs are left unattended and don't have any provision to recharge their batteries.
- The network field has a BS situated at the center which has abundant supply of energy and memory for its computational processes.
- The radio link between two SNs is symmetric, i.e., node $s_1$ consumes the same amount of energy during data transmission to node $s_2$ as node $s_2$ consumes the energy during data transmission to node $s_1$.
- Each SN is capable of data fusion of its own data with received data packet and converts it into one packet.
- *Node density* of a SN $s_1$ can be measured as the total number of nodes which respond to the reception of a broadcast message $B_{\text{msg}}$ delivered by node $s_1$. On receiving this message, nodes send a reply message $R_{\text{msg}}$ to node $s_1$. Using this message exchange, number of neighboring nodes (i.e., node density) of each node can be figured out.
- In the beginning of the WSNs, BS broadcasts a beacon message $\text{BCN}_{\text{msg}}$ intended for all SNs. On reception of this message, each SN is able to identify its *distance to BS* using received signal strength indicator (RSSI) value of this message.

Now, we discuss the different level of heterogeneity in terms of energy assignment to the SNs. The energy heterogeneity model in WSNs is based on the additional energy, which is assigned to a fraction of nodes with respect to others. For our work, we employ 1-level, 2-level, 3-level and multi-level heterogeneous models of WSNs.

In 1-level heterogeneity model, each SN is assigned with equal amount of energy $E_0$. These SNs are known as normal nodes. The total energy of 1-level heterogeneous network model $E_{\text{tot}_{\text{1-lev}}}$ is given by,

$$E_{\text{tot}_{\text{1-lev}}} = N \times E_0 \tag{1}$$

where $N$ defines total number of SNs in the network and $E_0$ indicates the energy level of each SN.

In 2-level heterogeneity model, two types of nodes are classified, i.e., normal nodes and advanced nodes in the network. The nodes initialized with $E_0$ level of energy are known as normal nodes, whereas nodes initialized with $E_0(1+\alpha)$ level of energy are known as advanced nodes. With fraction of $m$, these advanced nodes are assigned with $\alpha$ times more energy level in comparison with normal nodes. With

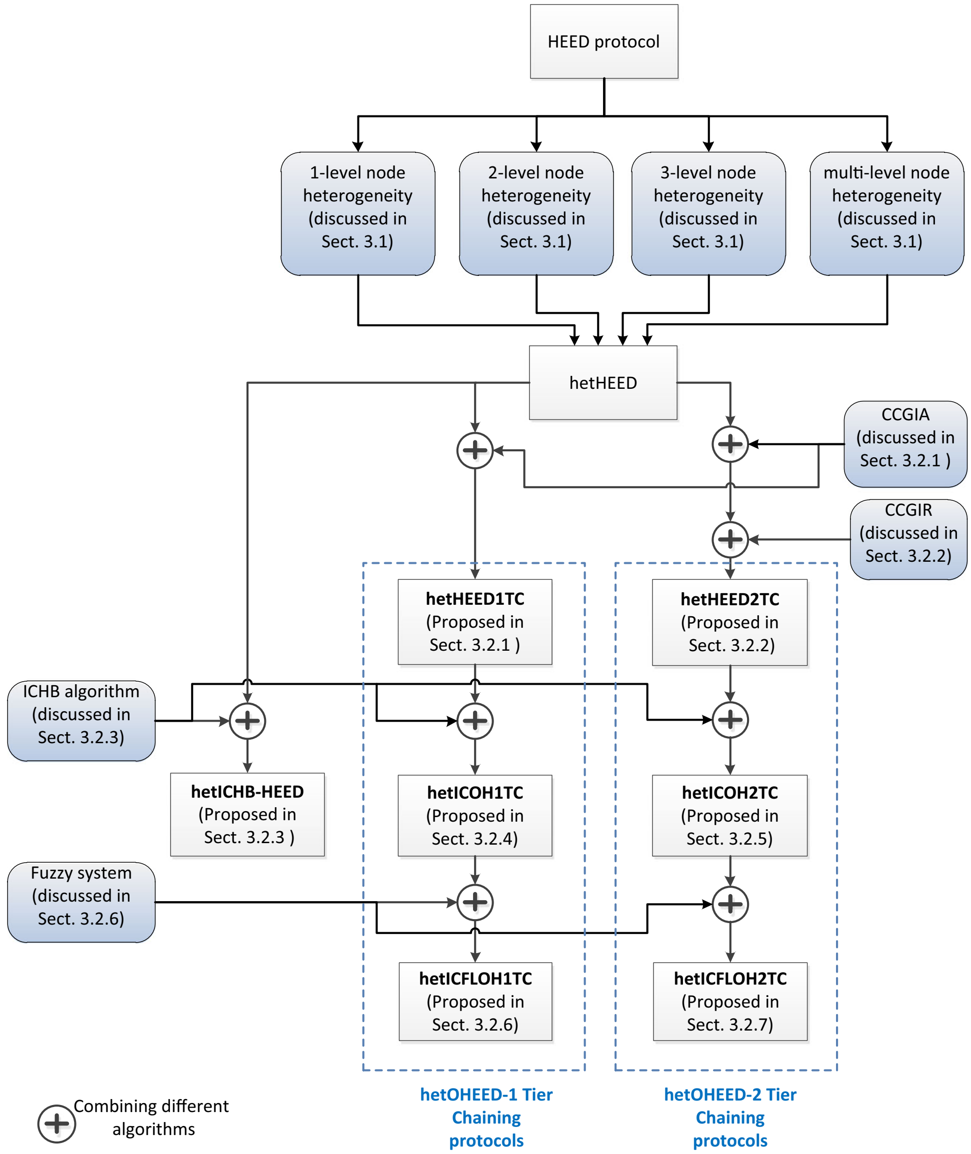


**Fig. 1** Flowchart of proposed Hetero-OHEED protocols

this effect, 2-level heterogeneous network has $\alpha m$ times more energy than 1-level heterogeneous network (Qing et al. 2006). The total energy of 2-level heterogeneous network model $E_{\text{tot}_{\text{2-lev}}}$ is given by,

$$\begin{aligned} E_{\text{tot}_{\text{2-lev}}} &= (1-m) \times N \times E_0 + m \times N \times E_0(1+\alpha) \\ &= (1+\alpha \times m) \times N \times E_0 \end{aligned} \tag{2}$$

where $(1-m) \times N$ denotes the total number of normal nodes and $m \times N$ represents the total number of advanced nodes in the network.

In 3-level heterogeneity model, three types of nodes, i.e., normal nodes, advanced nodes and super nodes are deployed in the network field. In addition to 2-level heterogeneity case, nodes that are initialized with energy level of $E_0(1+\beta)$ are known as super nodes. With fraction of $m \times m_0$, these super nodes are allotted with $\beta$ times more energy level in comparison with normal nodes. With this effect, 3-level heterogeneous network has $m(\alpha - m_0(\alpha - \beta))$ times more energy than 1-level heterogeneous network (Kumar et al. 2009). The total energy of 3-level heterogeneous network model $E_{\text{tot}_{\text{3-lev}}}$ is given by,

$$\begin{aligned} E_{\text{tot}_{\text{3-lev}}} &= (1-m) \times N \times E_0 \\ &\quad + m \times (1-m_0) \times N \times E_0(1+\alpha) \\ &\quad + m \times m_0 \times N \times E_0(1+\beta) \\ &= (1 + m(\alpha - m_0\alpha + m_0\beta)) \times N \times E_0 \\ &= (1 + m(\alpha - m_0(\alpha - \beta))) \times N \times E_0 \end{aligned} \tag{3}$$

where $(1-m) \times N$ indicates the total number of normal nodes, $m \times (1-m_0) \times N$ denotes the total number of advanced nodes

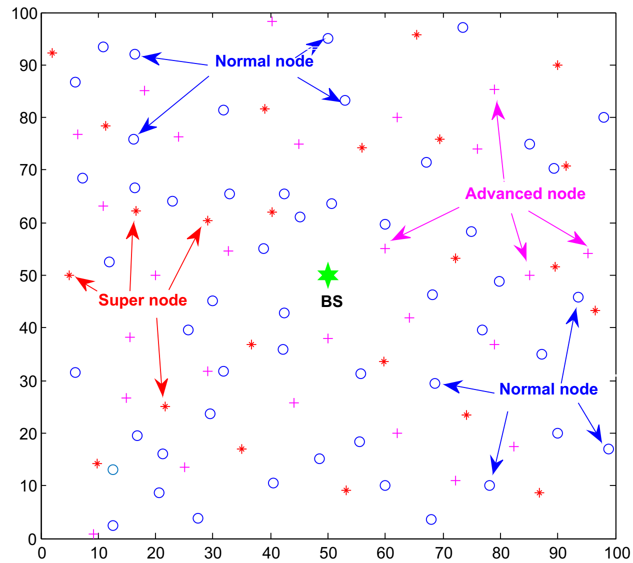


**Fig. 2** Different types of sensor nodes deployment in WSN

and $m \times m_0 \times N$ represents the total number of super nodes in the network.

In multi-level heterogeneity model, nodes are initialized with different energy levels under the close set of $[E_0, E_0(1+\alpha_{max})]$. Here, $E_0$ represents the lower limit of energy level and $\alpha_{max}$ indicates the value required in determination of maximum energy level assigned to a node. During energy allocation at beginning of the network, each node $s_j$ is empowered with $E_0(1+\alpha_j)$ energy level, which indicates that node $s_j$ has $\alpha_j$ times more energy concerning lower limit of energy level $E_0$ (Qing et al. 2006). Therefore, the total energy of multi-level heterogeneous network model $E_{\text{tot}_{\text{mul-lev}}}$ is given by,

$$E_{\text{tot}_{\text{mul-level}}} = \sum_{j=1}^{N} E_0(1+\alpha_j) = E_0\left(N + \sum_{j=1}^{N}\alpha_j\right) \quad (4)$$

Figure 2 describes the different types of SNs' deployment in WSN for 3-level heterogeneity model. Here, BS is situated at the center of the network field. Super nodes are represented by red star sign (*), advanced nodes are shown by pink plus sign (+), and normal nodes are indicated by blue circular sign (o). According to the level of heterogeneity, the count of these nodes varies for different heterogeneous WSNs.

## 3.2 Cluster formation, data collection and transmission procedures

Here, we discuss the cluster head election, cluster formation, data collection and transmission procedures for each Hetero-OHEED protocol.

### 3.2.1 hetHEED1TC

*CH election and cluster formation process*

The network is predetermined for a limited number of CHs, $C_{\text{prob}}$ (i.e., 5% of total SNs). However, during cluster formation phase, this value may vary and don't restrict final CHs in the network. hetHEED1TC protocol utilizes two clustering parameters, i.e., residual energy and node density for clustering procedure. For each round, each SN employs $\text{CH}_{\text{prob}}$ value for its selection as CH. The formulation for $\text{CH}_{\text{prob}}$ is given by (Younis and Fahmy 2004),

$$\text{CH}_{\text{prob}} = C_{\text{prob}} \times \frac{E_{\text{res}}}{E_{\text{max}}} \quad (5)$$

where $C_{\text{prob}}$ is predetermined limit of CHs, $E_{\text{res}}$ indicates the residual energy of SN, and $E_{\text{max}}$ denotes maximum allotted energy to each SN at initial stage. Based on this value, a set of SNs broadcasts an advertisement message $B_{\text{CHmsg}}$ in its communication range referring itself as a CH. Nodes hearing this message associate themselves with the respective CHs. If any node receives the broadcast message from two or more CHs, it uses the node density parameter for breaking the ties and elects the least cost CH. Least cost selected CH helps to provide better load balance among the clusters. During this phase, if any SN does not become cluster member or CH, it elects itself as the CH for that round. Rest of the clustering procedure is same as HEED. This completes the cluster formation phase for one round. This procedure continues till at least one node is alive in the network.

*Data collection and transmission process*

After the cluster formation procedure for each round, SNs are set to collect the data from the environmental surroundings and forward them to their respective CHs. In hetHEED1TC protocol before data collection, a chain has been constructed by each CH in its cluster to collect the data from its cluster members using chain construction based on greedy approach for intra-cluster communication (CCGIA) algorithm (Gupta and Sharma 2017). Using this chaining mechanism, each SN is connected to its CH via neighboring nodes. Each SN $s_i$ routes its data to the neighbor node $s_j$ via chain where node $s_j$ fuses its own data with received data packet and forwards them to the next node in the chain till it reaches the CH.

In CCGIA algorithm, chain construction procedure is initialized in each cluster, where the CH nodes broadcast a chaining message $\text{CN}_{\text{msg}}$ intended for each SN. On reception of this message, SNs determine their distances from their CH nodes using RSSI value and broadcast another message $\text{DSN}_{\text{msg}}$ in the cluster to determine their distances from other nodes. Once the SNs have measured these values, the chain construction process starts. Here, the node which is farthest

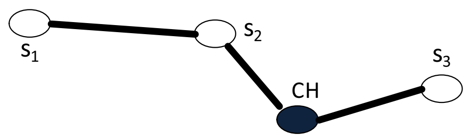


**Fig. 3** Chain-based construction process using greedy algorithm

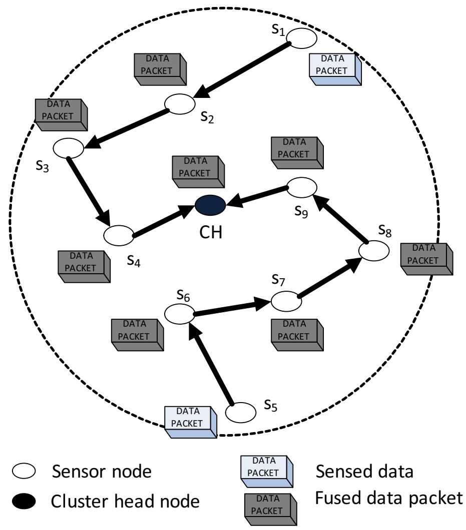


**Fig. 4** Intra-cluster data transfer from sensor nodes to its cluster head using CCGIA

from the CH selects itself as the first node in the chain. By employing measured distance of neighboring SNs, the node which is nearby to first node is selected as next SN in the chain and so on. This procedure continues till all the SNs in a cluster are not connected via chain. The CH node also joins as a member of the chain, because its location is random in the cluster. In Fig. 3, node $s_1$ is the farthest node that joins the chain as a first node. Thereafter, node $s_1$ links to node $s_2$, then it connects to CH node and CH links to node $s_3$. This represents connection establishment during chain construction process. If any SN dies or fails, reconstruction of chain is processed again after bypassing the dead node.

Once the chain is constructed, data collection process is initiated by the CHs. For this, a token-based control message passing approach is initiated by the CH. The overhead (in terms of cost) in rotation of this token is too low, because the size of token is too small. CH passes token to distant SN on either side of the chain. The SN sends its sensed data to its neighbor node that fuses its own data with received one and forwards them to the next neighbor till they reach CH. Then, CH node passes the token to another side of chain for further data collection. Figure 4 shows an instance, where SN $s_1$ sends its sensed data to its neighbor node $s_2$, node $s_2$ fuses its own data with received data packet from node $s_1$ and forwards them to node $s_3$ till they reach CH. Then, token is passed on to SN $s_5$ to collect data from that side of chain following same procedure.

Once the data packets are received by the CHs, these fuse their own data with received data packets and forward to the BS directly in single-hop.

Here, hetHEED1TC applies chain-based intra-cluster communication (IACC) in HEED with node heterogeneity, which evenly distributes the workload of a CH (i.e., data reception and data fusion of each packet) among all SNs in the cluster. This minimizes the burden of CHs, delays the death of SNs, reduces the formation of holes, minimized the hot-spots and increases the lifetime of the network.

### 3.2.2 hetHEED2TC

*CH election and cluster formation process*

The cluster head election and cluster formation procedure of hetHEED2TC is similar to hetHEED1TC.

*Data collection and transmission process*

Once the cluster formation completes for a round, each CH collects the sensed data from its cluster members employing CCGIA algorithm. After this procedure, hetHEED2TC utilizes the multi-hop routing strategy for data transmission to the BS, where it uses the chain construction process among CHs for data routing. Here, a chain has been created using chain construction based on greedy approach for inter-cluster communication (CCGIR) (Gupta and Sharma 2017). Similar to CCGIA, CCGIR algorithm follows the chain construction process among CH nodes. Here, BS also joins the inter-cluster communication (IRCC) chain. Using this chain, each CH node is connected to the BS via neighboring CH node and capable of sending its data packet to neighboring CH node. On reception of the data packet, each CH node fuses its own data and forwards this fused packet to next neighboring CH node via chain till it reaches the BS. Figure 5 shows an example, where BS sends a token to distant CH node on either side of chain. Let us suppose, token is passed to CH node $CH_1$. Now, $CH_1$ forwards its fused data packet to its neighbor CH node $CH_2$, $CH_2$ fuses its data packet with received data packet and forwards it to next neighboring CH node till it reaches the BS. Subsequently, BS passes on the token to distant CH node on another side of chain, i.e., CH node $CH_6$. $CH_6$ follows the same procedure to forward the data to BS via other CH nodes in chain as discussed earlier. Hence, all the data packets are received by the BS for analysis. Using this multi-hop scheme for data transmission from CHs to BS, problem of huge data packets flooding toward BS is highly reduced which demonstrates its effectiveness.

Here, hetHEED2TC employs chain-based IRCC in hetHEED1TC. This further results in even energy consumption among all CH nodes, improved stability region of the network and reduced data flooding toward BS (i.e., only one data packet is forwarded to BS from both sides of the IRCC chain in each round) in comparison with hetHEED1TC.

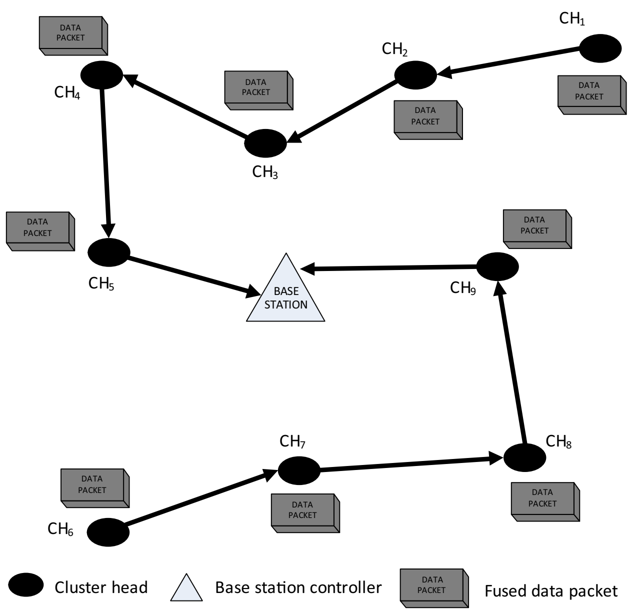


**Fig. 5** Inter-cluster data transfer from cluster heads to base station using CCGIR

#### 3.2.3 hetICHB-HEED

*CH election and cluster formation process*

hetICHB-HEED protocol modifies the CH selection procedure in HEED by employing ICHB algorithm (Gupta and Sharma 2017) on residual energy parameter. ICHB is a bio-inspired optimization technique based on BFOA (Passino 2002). ICHB algorithm efficiently searches the higher residual energy nodes in the network using a set of E. Coli bacteria. In this, an E. Coli bacterium uses chemotaxis process, where it moves from one SN to another in a specified domain in search of better nutrient gradient in the network field. The resultant higher nutrient node behaves as a tentative CH for a specific round.

*ICHB algorithm*: Assume, $G(p) = \{\beta_a^{m_a}(p) | m_a = 1, 2, \ldots, K\}$ denotes initial location of each bacterium in population $K$ at $p$-th chemotactic step. $E(m_a, p)$ indicates energy cost of the SN at which bacterium $\beta_a^{m_a}(p)$ is situated.

For this, a set of bacteria $K$ with probability $B_{\text{prob}}$ (5% of total SNs) has been initiated by few SNs in the WSNs. The position of each bacterium at $p$-th chemotactic step is represented by $\beta_a$, given as follows:

$$\beta_a^{m_a}(p) = \Phi^{m_a}(UID) \tag{6}$$

where $\{m_a = 1, 2, \ldots, K\}$ indicates population of bacterium at $p$-th chemotactic step and $\Phi$ denotes the UID of that SN at which $m_a$-th bacterium is situated.

After initialization, each bacterium $m_a$ generates a random vector $\Theta_{ma}$ which contains the UIDs of SNs $\Phi_i(UID)$ that comes under communication radius of node $\Phi^{m_a}$, where bacterium $m_a$ is located and $\{i = 1, 2, \ldots, N\}$ shows total number of SNs in random vector $\Theta_{ma}$. Furthermore, each bacterium $m_a$ shifts from one SN to another under chemotaxis process in search of higher nutrient gradient in the corresponding random vector $\Theta_{ma}$. The movement of each bacterium $m_a$ is defined as,

$$\beta_a^{m_a}(p+1) = [\Phi_{i+1}^{m_a}(UID)]^{\Theta_{ma}} \tag{7}$$

where $\Phi_{i+1}^{m_a}$ represents the shifting of $m_a$-th bacterium to other SNs, i.e., $\{i + 1, \ldots, N\}$ in the random vector. During searching process, each bacterium visits all SNs in the random vector one after another. Here, it stores the residual energy value and UID of each visited SN, compares it with the next SN during shifting process and finds the best energy SN in the random vector. Applying this procedure, each bacterium finds out the best residual energy SN in its region that may behave as CH for a specific round.

After selection of CHs, an advertisement message $B_{\text{CHmsg}}$ is broadcasted by these CH nodes in the network. SNs hearing this message associate themselves with the respective CHs. If any node receives this broadcast message from two or more CHs, it employs the node density parameter for breaking the ties and elects the least cost CH. Rest of the clustering procedure is same as hetHEED1TC. This completes the cluster formation phase for one round. This procedure continues till at least one node is alive in the network.

*Data collection and transmission process*

Once the clusters are formed, each SN senses its environmental surroundings, collects the data and forwards them to the corresponding CH. On reception of these data packets from its cluster members, CHs fuse these data packets and forward them to the BS directly in single-hop.

Here, hetICHB-HEED applies ICHB algorithm as primary parameter on HEED with node heterogeneity, which increases the fair chances of election of higher residual energy SNs for CHs' position and no uncovered SNs are left in the network as all of them are visited during searching of high residual energy SNs. This promotes the efficient utilization of energy resources in the network and extends the network lifetime.

#### 3.2.4 hetICOH1TC

*CH election and cluster formation process*

The cluster head election and cluster formation procedure of hetICOH1TC is similar to hetICHB-HEED.

*Data collection and transmission process*

Once the clusters are formed, hetICOH1TC employs the data collection and data transmission procedures same as hetHEED1TC.

Here, hetICOH1TC employs the ICHB algorithm as primary CH selection parameter in hetHEED1TC. This further improves the hetHEED1TC, allows minimum and constant number of CHs in each round, elects high residual energy SNs as CHs and extends the network lifetime.

#### 3.2.5 hetICOH2TC

*CH election and cluster formation process*

The cluster head election and cluster formation procedure of hetICOH2TC is similar to hetICOH1TC.

*Data collection and transmission process*

Once the clusters are formed, hetICOH2TC employs the data collection and data transmission procedures same as hetHEED2TC.

Here, hetICOH2TC applies chain-based IRCC in hetICOH1TC which results in even energy consumption of CHs in the network, improved stability region and less data flooding toward the BS in comparison with hetICOH1TC.

#### 3.2.6 hetICFLOH1TC

*CH election and cluster formation process*

In hetICFLOH1TC protocol, the cluster formation procedure is further modified, which uses three clustering parameters, i.e., residual energy, node density and distance to BS for CH selection procedure. Initially, a set of higher residual energy SNs has been searched out using ICHB algorithm that behaves as CHs in the network similar to hetICOH1TC protocol. Furthermore, these CHs broadcast an advertisement message $B_{\mathrm{CHmsg}}$ intended for other SNs in their communication range. On hearing this message, each SN associates itself with the respective CH. If any node receives the broadcast message from two or more CHs, it employs the probability outcome generated from Eq. 8 for breaking the ties and elects the better probability CH. The probability outcome is based on the fuzzified combination of node density and distance to BS parameters given as input to FLS module.

*FLS for Hetero-OHEED protocols*: Here, FLS consists of four major modules for its working i.e., fuzzifier, rule base, fuzzy inference engine and defuzzifier. A set of crisp numbers is given as inputs to the fuzzifier, which converts these into fuzzy sets by means of fuzzification function. Fuzzy inference engine receives these fuzzy sets from fuzzifier and IF-THEN set of rules from fuzzy rule base as inputs, does simulation-based human reasoning and generates fuzzy inference. This fuzzy inference is provided as input to defuzzifier, which converts these fuzzified values into a crisp value using centroid function for generating an output value. In our work, we have used Mamdani model (Camastra et al. 2015) as fuzzy inference engine in the development of fuzzy sets because of its wide appreciation, simplicity in use and ease in the progression of application. The working fuzzy system model for Hetero-OHEED protocols is shown in Fig. 6.

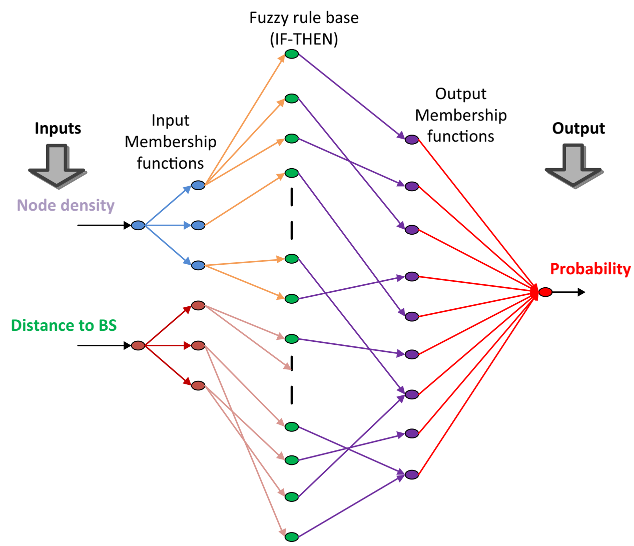


**Fig. 6** Layered fuzzy system working model for Hetero-OHEED protocols

Here, two parameters are provided for the CH selection procedure i.e., node density and distance to BS of each SN as inputs to the fuzzy system. The input variable node density corresponds three membership functions (MFs), i.e., two half-trapezoidal and one triangular MFs labeled as sparse, medium and dense, respectively. Likewise, input variable distance to BS corresponds three MFs, i.e., two half-trapezoidal and one triangular MFs labeled as near, medium and far, respectively. On providing the input parameters to the fuzzy system, it generates a crisp set of values as an output termed as probability. The probability outcome consists of nine MFs, i.e., two half-trapezoidal and seven triangular MFs labeled as very weak (VW), weak (W), little weak (LW), lower medium (LM), medium (M), higher medium (HM), little strong (LS), strong (S) and higher strong (HS), respectively. Based on this output value, the desired CH is selected. SN with higher probability has better chance to become a CH. The mathematical formulation of probability outcome (Gupta and Sharma 2017) is given as:

$$\text{Probability} = \frac{k_{nd} \times G_{nd} + k_d \times (M_d - G_d)}{k_{nd} \times M_{nd} + k_d \times M_d} \tag{8}$$

where $k_{nd}$ and $k_d$ indicate the weightages for node density and distance to BS (i.e., input parameters), $G_{nd}$ and $G_d$ denote the current level values for corresponding input parameters, $M_{nd}$ and $M_d$ represent the maximum level values for the same input parameters accordingly. The current level values for node density ($G_{nd}$) and distance to BS ($G_d$)

**Table 1** Fuzzy rule base corresponding to input parameters *Node density and Distance to BS* and output parameter *Probability* for Hetero-OHEED protocols

| Node density | Distance to BS | Probability |
|---|---|---|
| Sparse (0) | Far (2) | Very weak (0) |
| Sparse (0) | Medium (1) | Weak (1) |
| Sparse (0) | Near (0) | Little weak (2) |
| Medium (1) | Far (2) | Lower medium (3) |
| Medium (1) | Medium (1) | Medium (4) |
| Medium (1) | Near (0) | Higher medium (5) |
| Dense (2) | Far (2) | Little strong (6) |
| Dense (2) | Medium (1) | Strong (7) |
| Dense (2) | Near (0) | Higher strong (8) |

may be considered as 0 or 1 or 2 corresponding to the MFs as shown in Table 1. However, the values of $M_{nd}$ and $M_d$ indicate the maximum value which is set to 2. Furthermore, both the input parameters are given equal weightages for CH selection procedure; therefore, their values are set as $k_{nd} = k_d = 1$. The desired fuzzy set of rules for different input and output variables is clearly depicted in Fig. 7. Moreover, the corresponding relationship between these is shown in Table 1.

Rest of the clustering procedure is same as hetICOH1TC. This completes the cluster formation phase for one round. This procedure continues till at least one node is alive in the network.

*Data collection and transmission process*

Once the clusters are formed, hetICFLOH1TC employs the data collection and data transmission procedures same as hetICOH1TC.

Here, hetICFLOH1TC applies distance to BS parameter additionally in hetICOH1TC, which allows even-sized clusters in the network, further minimizes the formation of holes and hot-spots problem and extends the network lifetime to a great extent.

#### 3.2.7 hetICFLOH2TC

*CH election and cluster formation process*

The cluster head election and cluster formation procedure of hetICFLOH2TC is similar to hetICFLOH1TC.

*Data collection and transmission process*

Once the clusters are formed, hetICFLOH2TC employs the data collection and data transmission procedures same as hetICOH2TC.

Here, hetICFLOH2TC applies chain-based IRCC in hetICFLOH1TC, which results in even energy consumption of CHs, less data flooding toward the BS and extremely

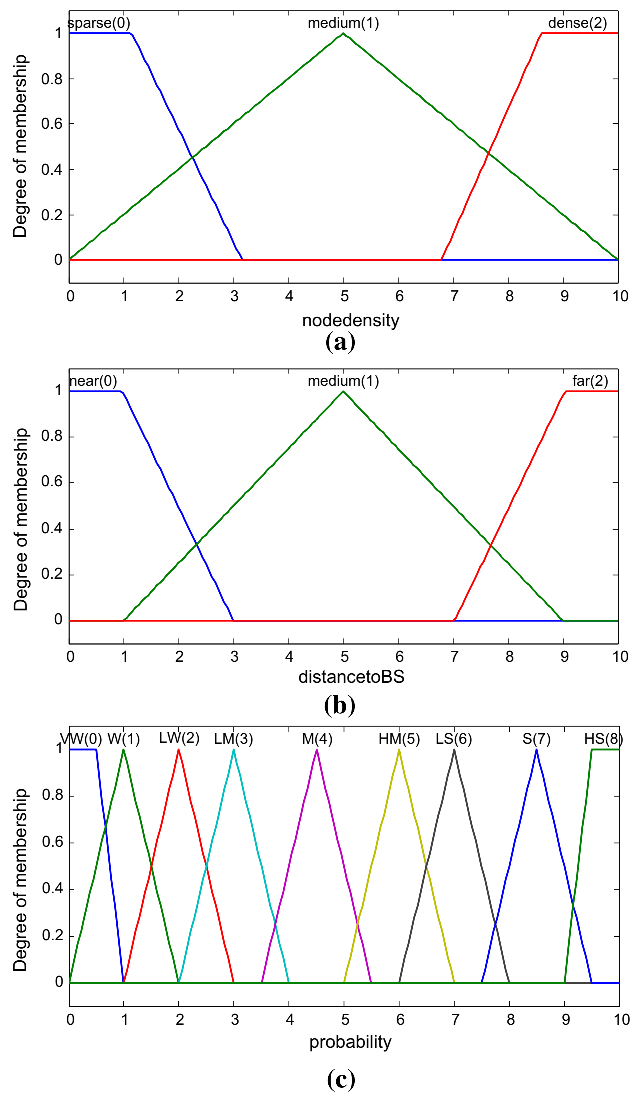


**Fig. 7** **a**, **b** Fuzzy rule sets corresponding to input parameters *Node density and Distance to BS* and **c** Fuzzy rule set corresponding to output parameter *Probability* for Hetero-OHEED protocols

enhanced stability region with prolonged network lifetime in comparison with hetICFLOH1TC.

### 3.3 Energy consumption model

During the network execution, energy is mainly consumed in data collection, data reception, data transmission and data fusion processes. These processes are done by the cluster members (i.e., SNs) and CHs at different levels in each cluster. Each process consumes a particular amount of energy during its operation.

Firstly, we illustrate radio energy consumption model to estimate the energy dissipation in each activity (Heinzelman et al. 2000; Lindsey and Raghavendra 2002). The radio trans-receiver circuitry consumes $E_{elec}$ energy (in joule) for reception or transmission of data. The energy consumed by the amplifier in transmission of signal at shorter distance $d$, ($d \leq d_0$) is expressed as $\epsilon_{fs}$, whereas for longer distance $d$, ($d > d_0$) is termed as $\epsilon_{mp}$. The energy consumed by transmitter circuitry to send L-bit data packet at shorter distance $d$ is specified as $E_{\mathrm{Tx}_S}$, given in Eq. 9 and for longer distance $d$ is shown as $E_{\mathrm{Tx}_L}$, given in Eq. 10.

$$E_{\mathrm{Tx}_S} = E_{\mathrm{elec}} \times L + \epsilon_{fs} \times L \times d^2 \;\; if \;\; d \leq d_0 \tag{9}$$

$$E_{\mathrm{Tx}_L} = E_{\mathrm{elec}} \times L + \epsilon_{mp} \times L \times d^4 \;\; if \;\; d > d_0 \tag{10}$$

The energy consumed by receiver circuitry to receive L-bit data packet is given by,

$$E_{\mathrm{Rx}} = E_{\mathrm{elec}} \times L \tag{11}$$

The distance $d$ can be measured as shorter or longer referencing to the threshold value $d_0$ is given by,

$$d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}} \tag{12}$$

The energy consumed by a node during data fusion is given by,

$$E_{\mathrm{fuse}} = 5 \text{ nJ/bit/message} \tag{13}$$

Now, we illustrate the energy consumption formulation for each SN maintaining different roles (i.e., cluster member or CH) during clustering process. During diverse roles, each SN dissipates different amount of energy in its functioning. In our work, we have major three diverse set of protocols, i.e., hetICHB-HEED, hetOHEED-1 Tier Chaining (viz hetHEED1TC, hetICOH1TC, hetICFLOH1TC) and hetOHEED-2 Tier Chaining (viz hetHEED2TC, hetICOH2TC, hetICFLOH2TC) protocols. In each set of protocols, SNs vary the energy consumption model. Here, we briefly explain the energy consumption model for each set of protocols.

#### 3.3.1 hetICHB-HEED

Maintaining uniformity in the network, we have divided $N$ number of SNs into $C$ number of clusters. Each cluster has $N/C$ number of SNs including a CH. In hetICHB-HEED, each cluster member dissipates its energy in data sensing from its surroundings and forwards the sensed data to its CH. On reception of data from each member, CH node fuses all the data packets and forwards them to the BS. This completes a round. Therefore, the network operation for one round includes data sensing by each cluster member, sending sensed data to its CH, data reception by the CH, fusion of received data packets into one and forwarding fused data to the BS.

The energy consumed by a cluster member in one round is as follows,

$$E_{\mathrm{cm}} = E_{\mathrm{Tx}_S} \tag{14}$$

The energy consumed by each CH node in one round is as follows,

$$E_{\mathrm{CH}_a} = \left(\frac{N}{C} - 1\right) \times E_{\mathrm{Rx}} + \left(\frac{N}{C} - 1\right) \times E_{\mathrm{fuse}} \times L + E_{\mathrm{Tx}_L} \tag{15}$$

here $\left(\frac{N}{C} - 1\right) \times E_{\mathrm{Rx}}$ denotes the energy consumption in data reception by the CH node from its cluster members. The next term, i.e., $\left(\frac{N}{C} - 1\right) \times E_{\mathrm{fuse}} \times L$, shows the energy consumed in data fusion of received data packets. Furthermore, the last term, i.e., $E_{\mathrm{Tx}_L}$, represents the energy dissipation in data transmission to the BS.

The total energy consumed in a cluster in one round is as follows,

$$E_{\mathrm{clus}_{\mathrm{hetICHB\text{-}HEED}}} = \left(\frac{N}{C} - 1\right) \times E_{\mathrm{cm}} + E_{\mathrm{CH}_a} \tag{16}$$

The total energy consumed by the network in one round is as follows,

$$E_{\mathrm{round}} = C \times E_{\mathrm{clus}_{\mathrm{hetICHB\text{-}HEED}}} \tag{17}$$

#### 3.3.2 hetOHEED-1 Tier Chaining protocols

In hetOHEED-1 Tier Chaining protocols, each cluster member is connected via chain for data transmission from SNs to CH. In this case, each cluster has three kinds of nodes, i.e., leaf SN, non-leaf SN and a CH. First, each cluster has at most two leaf SNs which are end nodes in the chain. In Fig. 4, nodes $s_1$ and $s_5$ are the leaf SNs. These nodes sense the data from surroundings and forward them to the neighboring node via chain. Second, nodes which reside inside the chain are known as non-leaf SNs. In Fig. 4, nodes $s_2$, $s_3$, $s_4$, $s_6$, $s_7$, $s_8$ and $s_9$ are the non-leaf SNs. These nodes sense their surroundings for the data, forward the data to neighbor nodes, receive the data packets from neighboring nodes, fuse the received data packets with their own data and forward these packets to the next neighboring nodes till the packets reach the CH. Third, there exists a CH node that receives at most two data packets from both sides of the chain, fuses the received data packet with its own data and forwards it to the BS.

The energy consumed by each leaf SN in one round is as follows,

$$E_{\text{leaf\_SN}} = E_{\text{Tx}_S} \tag{18}$$

The energy consumed by each non-leaf SN in one round is as follows,

$$E_{\text{nonleaf\_SN}} = E_{\text{Rx}} + E_{\text{fuse}} \times L + E_{\text{Tx}_S} \tag{19}$$

here $E_{\text{Rx}}$ denotes the energy dissipated by a non-leaf SN for receiving data from its neighboring node. The next term, i.e., $E_{\text{fuse}} \times L$, represents the energy consumption during data fusion of received data packet. Furthermore, the last term, i.e., $E_{\text{Tx}_S}$, shows the energy dissipation in data transmission of fused packet to the next neighbor node in the chain.

The energy consumed by each CH in one round is as follows,

$$E_{\text{CH}_b} = 2E_{\text{Rx}} + 2E_{\text{fuse}} \times L + E_{\text{Tx}_L} \tag{20}$$

here $2E_{\text{Rx}}$ denotes the energy consumed by a CH node during a data packet reception from each side of the chain. The next term, i.e., $2E_{\text{fuse}} \times L$, shows the energy dissipation in data fusion of received data packets. Furthermore, the last term, i.e., $E_{\text{Tx}_L}$, represents the energy dissipation in data transmission of fused packet to the BS.

The total energy consumed in a cluster in one round is as follows,

$$E_{\text{clus}_{\text{hetOHEED1TC}}} \approx 2E_{\text{leaf\_SN}} + \left(\frac{N}{C} - 3\right) \times E_{\text{nonleaf\_SN}} + E_{\text{CH}_b} \tag{21}$$

The total energy consumed by the network in one round is as follows,

$$E_{\text{round}} = C \times E_{\text{clus}_{\text{hetOHEED1TC}}} \tag{22}$$

#### 3.3.3 hetOHEED-2 Tier Chaining protocols

In hetOHEED-2 Tier Chaining protocols, each CH node is connected via chain for data transmission from CHs to BS for IRCC. However, at IACC level, its communication processing is same as hetOHEED-1 Tier Chaining protocols. With these reasons, this network contains four types of nodes, i.e., leaf SNs, non-leaf SNs, leaf CHs and non-leaf CHs. In this set of protocols, each cluster has leaf SNs and non-leaf SNs. Their functioning is same as in hetOHEED-1 Tier Chaining protocols. Furthermore, at IRCC level, the network has at most two leaf CHs which are end nodes in the chain. In Fig. 5, nodes $\text{CH}_1$ and $\text{CH}_6$ are the leaf CHs. These CH nodes forward their data packets to the next neighbor CH via chain. CH nodes which reside inside the chain are known as non-leaf CHs. In Fig. 5, nodes $\text{CH}_2$, $\text{CH}_3$, $\text{CH}_4$, $\text{CH}_5$, $\text{CH}_7$, $\text{CH}_8$ and $\text{CH}_9$ are the non-leaf CHs. These CH nodes receive the data packets from neighboring CH nodes, fuse the received data packets with its own data and forward them to the next neighboring node till they reach the BS.

The energy consumed by leaf SNs and non-leaf SNs in each round is similar to Eqs. 18 and 19. Furthermore, the energy consumption by each leaf CH in a round is as follows,

$$E_{\text{leaf\_CH}} = 2E_{\text{Rx}} + 2E_{\text{fuse}} \times L + E_{\text{Tx}_S} \tag{23}$$

here $2E_{\text{Rx}}$ denotes the energy consumption by a CH node in data reception during IACC phase. The next term, i.e., $2E_{\text{fuse}}, \times L$ represents the energy dissipation during data fusion of received packets. Furthermore, the last term, i.e., $E_{\text{Tx}_S}$, shows the energy consumption by the CH node in data transmission of fused packets to the next neighboring node in IRCC chain.

The energy spent by each non-leaf CH in each round is as follows,

$$\begin{aligned} E_{\text{nonleaf\_CH}} = {} & 2E_{\text{Rx}} + 2E_{\text{fuse}} \times L + E_{\text{Rx}} \\ & + E_{\text{fuse}} \times L + E_{\text{Tx}_S} \end{aligned} \tag{24}$$

here terms, i.e., $2E_{\text{Rx}}$ and $2E_{\text{fuse}} \times L$, are same as in Eq. 23 which denote the energy consumption by the CH nodes at IACC level. The next term, i.e., $E_{\text{Rx}}$, represents the energy dissipation during data reception from neighbor node during IRCC. The next term, i.e., $E_{\text{fuse}} \times L$, shows the energy consumption by the CH node during data fusion of received data. Moreover, the last term, i.e., $E_{\text{Tx}_S}$, represents the energy utilization in data transmission of fused packet to the next neighboring CH node in IRCC chain until it reaches the BS.

The total energy consumed in a cluster in one round is as follows,

$$\begin{aligned} & 2E_{\text{leaf\_SN}} + \left(\frac{N}{C} - 3\right) \times E_{\text{nonleaf\_SN}} + E_{\text{leaf\_CH}} \\ & \le E_{\text{clus}_{\text{hetOHEED2TC}}} \\ & \le 2E_{\text{leaf\_SN}} + \left(\frac{N}{C} - 3\right) \times E_{\text{nonleaf\_SN}} + E_{\text{nonleaf\_CH}} \end{aligned} \tag{25}$$

The total energy consumed by the network in one round is as follows,

$$E_{\text{round}} = C \times E_{\text{clus}_{\text{hetOHEED2TC}}} \tag{26}$$

## 4 Results and discussion

The performance of proposed Hetero-OHEED protocols is evaluated using MATLAB framework, where SNs are randomly deployed in the network field. BS is situated at center of the field (Younis and Fahmy 2004; Amini et al. 2012;

**Table 2** Simulation parameters

| Parameter description | Value |
|---|---|
| Network field | $100 \times 100$ m$^2$ |
| Number of SNs ($N$) | 100 |
| BS location | (50, 50) |
| Total number of bacteria ($K$) | 5% of total SNs |
| Total chemotactic steps | 1 |
| Length of swim | Number of SNs in random vector |
| Energy dissipation to run transmitter or receiver circuitry ($E_{elec}$) | 50 nJ/bit |
| Energy dissipation by amplifier in transmission of signal at shorter distance ($\epsilon_{fs}$) | 10 pJ/bit/m$^2$ |
| Energy dissipation by amplifier in transmission of signal at longer distance ($\epsilon_{mp}$) | 0.0013 pJ/bit/m$^4$ |
| Data fusion cost ($E_{fuse}$) | 5 nJ/bit/message |
| Message size ($L$) | 4000 bits |
| Cluster radius ($R$) | 25 m |
| Threshold distance ($d_0$) | 75 m |

Kumar et al. 2014; Gupta and Sharma 2017). Initial energies assigned to each SN vary according to different levels of heterogeneity introduced in the network field. For 1-level heterogeneity, each SN is initialized with same energy level $E_0$, i.e., 0.5 J. This works similar to homogeneous case. For 2-level heterogeneity, the network consists of $m \times N$ number of advanced nodes and $(1 - m) \times N$ normal nodes with initial energy levels of $E_0(1 + \alpha)$ and $E_0$, respectively. Using $m = 0.39$ and $\alpha = 0.6$ parametric values, the network allows 39 SNs as advanced nodes with initial energy of 0.8 J and 61 normal nodes with initial energy of 0.5 J. In 3-level heterogeneous WSNs, the network comprises $m \times m_0 \times N$ super nodes, $m(1 - m_0) \times N$ advanced nodes and $(1 - m) \times N$ normal nodes with initial energies of $E_0(1 + \beta)$, $E_0(1 + \alpha)$ and $E_0$, respectively. Considering $m_0 = 0.47$, $m = 0.49$, $\alpha = 0.6$ and $\beta = 3$ values, the network allows 23 SNs as super nodes with initial energy level of 2 J, 26 SNs as advanced nodes with initial energy of 0.8 J and 51 normal nodes with initial energy of 0.5 J. For multi-level heterogeneity case, the network is initialized with varying energy SNs under the close set of $[E_0, E_0(1 + \alpha_{max})]$. Using $\alpha_{max} = 3$, each SN is assigned with random energy level in between 0.5 and 2 J at the beginning of the network. Rest of the parameters required for the functioning of the Hetero-OHEED protocols in WSNs are described in Table 2 with their initializations. Each experiment has been simulated for 20 different random deployment scenarios and their statistics are averaged over these runs.

**Table 3** Heterogeneity parameters for het1-OHEED protocols

| Variable | Notation | Value |
|---|---|---|
| Number of SNs | $N$ | 100 |
| Initial energy of each SN | $E_0$ | 0.5 J |
| Total energy of network | $E_{tot_{1\text{-lev}}}$ | 50 J |

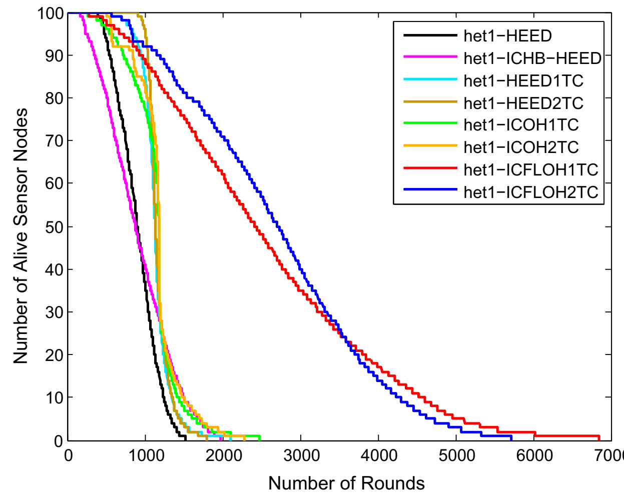


**Fig. 8** Number of remaining alive SNs after each round for het1-OHEED protocols

Hetero-OHEED protocols are fully capable in handling $n$-level of heterogeneity; however. due to space constraint, we have shown its performance for 1-level, 2-level, 3-level and multi-level heterogeneity. Furthermore, het1-OHEED protocols consist of het1-ICHB-HEED, het1-HEED1TC, het1-HEED2TC, het1-ICOH1TC, het1-ICOH2TC, het1-ICFLOH 1TC, het1-ICFLOH2TC protocols. Likewise, het2-OHEED, het3-OHEED and mul-OHEED comprise diverse OHEED protocols at varying levels of node heterogeneity.

Here, we analyze the performance of various Hetero-OHEED protocols with HEED under different heterogeneity levels for network lifetime, number of alive SNs in the network, residual energy of the network, and number of packets delivered to BS.

## 4.1 Performance analysis of het1-OHEED protocols

This section describes the comparative analysis of various het1-OHEED protocols with original HEED (i.e., het1-HEED) protocol. Table 3 shows the heterogeneity parameters required during the implementation of het1-OHEED protocols. Figure 8 illustrates the remaining alive SNs after each round. Table 4 describes the first node dies (FND), half node die (HND), last node dies (LND), stability region and network lifetime. Moreover, Fig. 9 shows the residual energy of the network after each round for het1-HEED and het1-

**Table 4** Comparison among diverse het1-OHEED protocols representing FND, HND, LND, stability region and network lifetime in terms of number of rounds

| Protocol | Increase in energy level (in %) | FND | HND | LND | Stability region | | Network lifetime | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Stability region (in rounds) | Improvement in % | Network lifetime (in rounds) | Improvement in % |
| het1-HEED | 0.0 | 394 | 908 | 1522 | 394 | 0.0 | 1522 | 0.0 |
| het1-ICHB-HEED | 0.0 | 163 | 885 | 1982 | 163 | NA | **1982** | **30.22** |
| het1-OHEED-1 Tier Chaining | | | | | | | | |
| het1-HEED1TC | 0.0 | 574 | 1135 | 2107 | 574 | 45.69 | **2107*** | **38.44** |
| het1-ICOH1TC | 0.0 | 259 | 1180 | 2479 | 259 | NA | **2479*** | **62.88** |
| het1-ICFLOH1TC | 0.0 | 287 | 2449 | 6849 | 287 | NA | **6849*** | **350.00** |
| het1-OHEED-2 Tier Chaining | | | | | | | | |
| het1-HEED2TC | 0.0 | 909 | 1140 | 1805 | **909**** | **130.71** | 1805 | 18.59 |
| het1-ICOH2TC | 0.0 | 501 | 1182 | 2283 | **501**** | **27.16** | 2283 | 50.00 |
| het1-ICFLOH2TC | 0.0 | 569 | 2729 | 5716 | **569**** | **44.42** | 5716 | 275.56 |

Bold values represent the better values in comparison to others

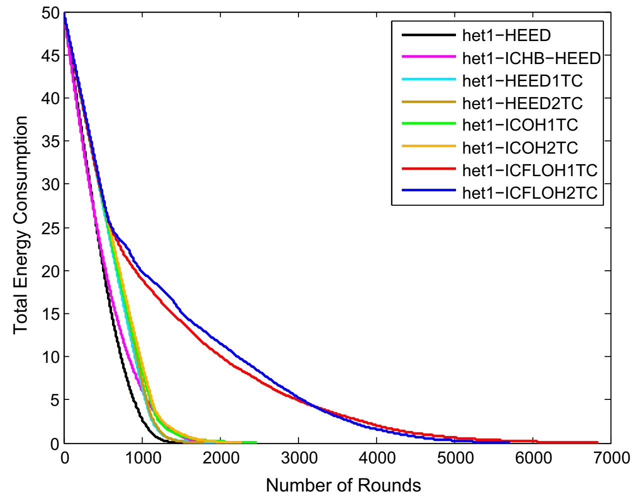


**Fig. 9** Residual energy of the network after each round for het1-OHEED protocols

OHEED protocols. Selecting only higher residual energy nodes as CHs in het1-ICHB-HEED protocol, the death rate of SNs reduces. With this reason, it improves the network lifetime by 30.22% in comparison with het1-HEED.

het1-HEED1TC uses the chain-based IACC in het1-HEED, where SNs in each cluster are connected via chain for data transmission. This process reduces the workload over CHs and evenly distributes it among all SNs. With this reason, the death of CH nodes delays, which in turn alleviates the hot-spots problem, enhances stability region by 45.69% and extends the network lifetime by 38.44% in comparison with het1-HEED. Furthermore, het1-HEED2TC implements IRCC among CH nodes for data transmission to BS additionally in het1-HEED1TC. In this process, even distribution of workload among all CH nodes occurs, which in turn dissipates similar amount of energy of all CH nodes during data transmission in chain. Therefore, het1-HEED2TC further improves the network's stability region by 58.36% and 130.71% in comparison with het1-HEED1TC and het1-HEED protocols.

het1-ICOH1TC implements the ICHB algorithm and chain-based IACC in het1-HEED which add-ons the benefits of both the techniques and results in better network lifetime by 17.66% and 62.88% in comparison with het1-HEED1TC and het1-HEED protocols while maintaining the appropriate stability region. Furthermore, het1-ICOH2TC add-ons the chain-based IRCC in het1-ICOH1TC which further improves the even distribution of load similar to het1-HEED2TC. This further enhances the stability region by 93.44% in comparison with het1-ICOH1TC.

In het1-ICFLOH1TC, three parameters, i.e., residual energy, node density and distance, to BS are used in clustering procedure, where ICHB algorithm is applied on residual energy and FLS is applied on the combination of node density and distance to BS. In addition to this, chain-based IACC is also applied for data transmission in each cluster. Using distance to BS parameter additionally for CH selection, delays the holes and hot-spots problem efficiently in the network; CHs remain well-distributed and prolongs the network lifetime to a great extent. With these reasons, the network lifetime of het1-ICFLOH1TC is improved by 176.28% and 350.00% in comparison with het1-ICOH1TC and het1-HEED protocols. Furthermore, het1-ICFLOH2TC employs chain based IRCC additionally in het1-ICFLOH1TC which helps in even distribution of workload among CHs and dissipates similar amount of energy from each CHs. This further improves the stability region of het1-ICFLOH2TC by 98.26% in comparison with het1-ICFLOH1TC.

From the above analysis, it is confirmed that het1-OHEED-1 Tier Chaining protocols provide far better network lifetime (as shown by star * in Table 4), whereas het1-OHEED-2 Tier Chaining protocols provide better stability region (as shown by double-star **) comparatively. Both types of protocols offer efficient result in different domains and can be used for diverse application-specific WSNs.

Figure 10 shows the energy consumption variation in consecutive rounds for het1-HEED and diverse het1-OHEED protocols. In case of het1-HEED, the energy consumption and its variation are maximum, because of formation of higher and uneven number of CHs in each round due to uncovered SNs that elect themselves as CHs and form additional CHs in the network. This negatively impacts on the network as it causes additional energy consumption in each round. Resolving this issue employing ICHB algorithm, constant CHs are formed in each round which minimized the energy consumption variation in ICHB-based het1-OHEED protocols (i.e., het1-ICHB-HEED, het1-ICOH1TC, het1-ICOH2TC, het1-ICFLOH1TC and het1-ICFLOH2TC). Furthermore, employing chain-based IACC and IRCC for data transmission has significantly reduced the energy consumption of het1-OHEED protocols.

Figure 11 illustrates the number of CHs formed in each round by diverse het1-OHEED protocols. Using random selection procedure on alive SNs for tentative CHs at primary stage in het1-HEED, het1-HEED1TC and het1-HEED2TC protocols forces to form varying CHs for consecutive rounds, which put adverse effect on network lifetime and energy consumption of the network. However, ICHB algorithm concentrates only on higher residual nodes without any randomized approach, which allows to form constant number of CHs per round in the network. With this reason, ICHB-based het1-OHEED protocols maintain constant CHs per round.

Figure 12 describes the number of packets sent to the BS by het1-HEED and diverse het1-OHEED protocols. As long as the network remains active with at least one SN alive, the data packets are sent to the BS. With this fact, het1-HEED, het1-ICHB-HEED, het1-HEED1TC, het1-ICOH1TC and het1-ICFLOH1TC protocols send $1.26 \times 10^4$, $1.59 \times 10^4$, $1.55 \times 10^4$, $1.72 \times 10^4$ and $3.95 \times 10^4$ number of packets to the BS till the network is alive. However, het1-HEED2TC, het1-ICOH2TC and het1-ICFLOH2TC protocols send only 3243, 3972 and 9011 number packets to the BS. This is because of using chain-based IRCC data transmission, where at most two data packets (i.e., one packet from each side of chain) are delivered to the BS in each round. This discloses the great benefits of less data flooding toward the BS by het1-OHEED-2 Tier Chaining protocols. This can be proven beneficial, where less number of data packets (with complete information) are required by the BS for data analysis purpose, in place of reception of huge number of data packets.

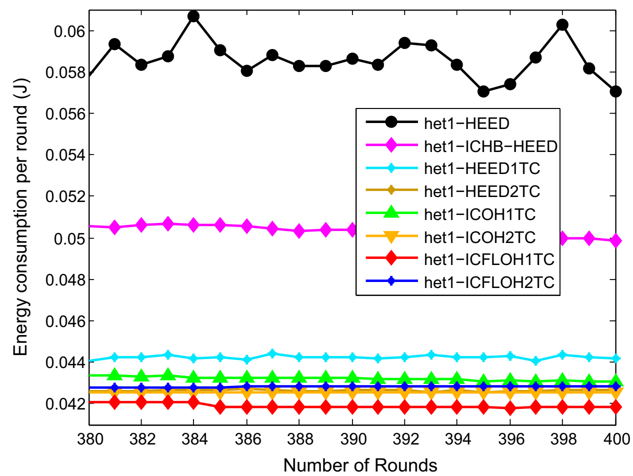


**Fig. 10** Energy consumption variation in each round for het1-OHEED protocols

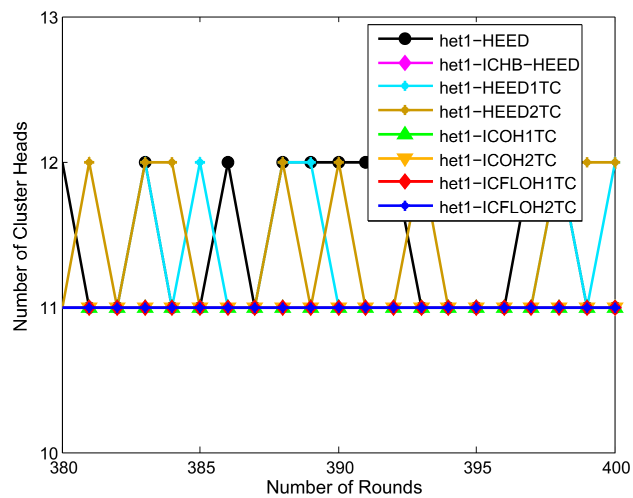


**Fig. 11** Number of CHs formed by diverse het1-OHEED protocols in each round

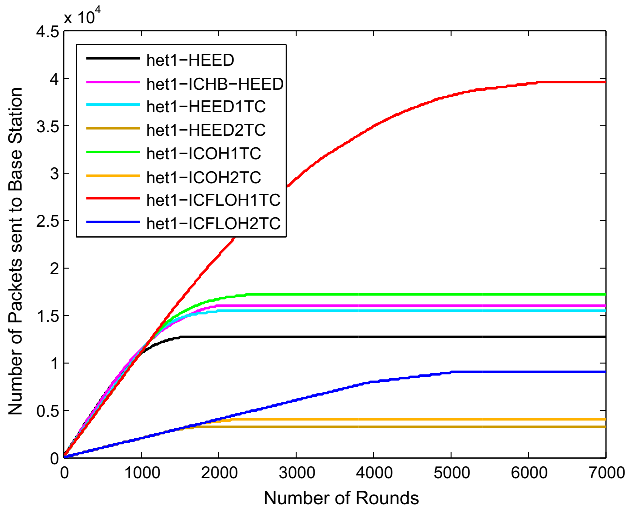


**Fig. 12** Number of packets sent to the BS by diverse het1-OHEED protocols in each round

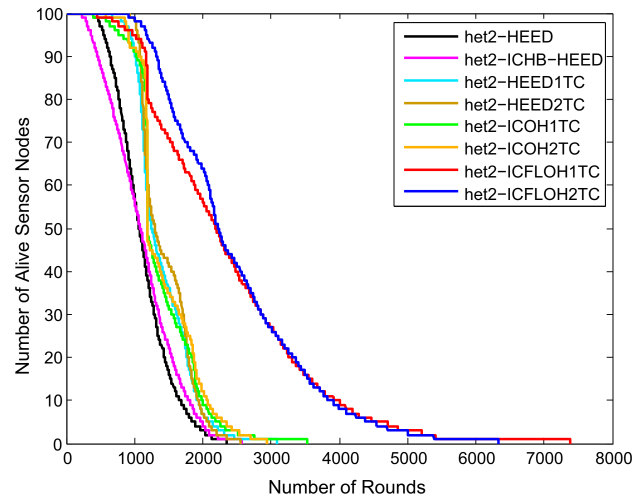


**Fig. 13** Number of remaining alive SNs after each round for het2-OHEED protocols

**Table 5** Heterogeneity parameters for het2-OHEED protocols

| Variable | Notation | Value |
|---|---|---|
| Number of SNs | $N$ | 100 $(= 61 + 39)$ |
| Number of normal SNs | $(1 - m) \times N$ | 61 |
| Number of advanced SNs | $m \times N$ | 39 |
| Energy of a normal SN | $E_0$ | $0.5J$ |
| Energy of an advanced SN | $E_0(1 + \alpha)$ | $0.8J$ |
| Total energy of network | $E_{\text{tot}_{2\text{-lev}}}$ | $61.7J$ |

## 4.2 Performance analysis of het2-OHEED protocols

This section describes the comparative analysis of various het2-OHEED protocols with het2-HEED and het1-OHEED protocols. Table 5 shows the heterogeneity parameters required during the implementation of het2-OHEED protocols. Figure 13 illustrates the remaining alive SNs after each round. Table 6 describes the FND, HND, LND, stability region and network lifetime for het2-OHEED protocols in comparison with het2-HEED and het1-OHEED protocols. Moreover, Fig. 14 shows the residual energy of the network after each round for het2-OHEED protocols. het2-OHEED protocols add-on their level of heterogeneity by means of two varieties of SNs, i.e., advanced nodes and normal nodes. Increasing the energy level by 23.40%, each protocol enhances its network lifetime with the maximum of 213.81% and 168.99%, particularly in het2-ICFLOH1TC and het2-ICFLOH2TC, respectively. This increment in network lifetime is due to the additional energy given to the WSN. Furthermore, the major effort is shown in case of stability region's increment of ICHB-based het2-OHEED protocols which include het2-ICHB-HEED, het2-ICOH1TC, het2-ICFLOH1TC, het2-ICOH2TC and het2-ICFLOH2TC. Their stability regions are improved by 46.01%, 56.37%, 59.58%, 14.97% and 59.40% along with enhanced network lifetime in comparison with ICHB based het1-OHEED protocols (as shown by star * in Table 6). This improvement is due to the following reasons: (1) ICHB algorithm which works on the searching of higher residual energy nodes allows the advanced nodes primarily for the CH selection in the WSN, which in turn delays the death of SNs and extends the stability region of the network. (2) Use of chain-based IACC and IRCC data transmissions. This promotes the load balancing feature among SNs and CHs, and alleviates the formation of holes and hot-spots, which further prolongs the stability region of the network. These reasons confirm that ICHB algorithm with chain-based IACC and IRCC procedures can provide efficient results, where enhanced stability region with network lifetime is an important aspect for homogeneous as well as heterogeneous WSNs.

Furthermore, among all het2-OHEED protocols the best results are provided by het2-ICFLOH1TC and het2-ICFLOH 2TC with stability region of 458 and 902 rounds and network lifetime of 7387 and 6332 number of rounds, respectively.

Figure 15 describes the number of packets sent to the BS by diverse het2-OHEED protocols. As long as the network remains active with at least one SN alive, the data packets are sent to the BS. With this fact, het2-HEED, het2-ICHB-HEED, het2-HEED1TC, het2-ICOH1TC and het2-ICFLOH1TC protocols send $1.76 \times 10^4$, $1.87 \times 10^4$, $2.18 \times 10^4$, $2.25 \times 10^4$ and $3.59 \times 10^4$ number of packets to the BS till the network is alive. However, het2-HEED2TC, het2-ICOH2TC and het2-ICFLOH2TC protocols send only 4608, 5222 and 8860 number packets to the BS. This is because of using chain-based IRCC data transmission, where at most

**Table 6** Comparison among diverse het2-OHEED protocols representing FND, HND, LND, stability region and network lifetime in terms of number of rounds

| Protocol | Increase in energy level than het1-case (in %) | FND | HND | LND | Stability region | | | Network lifetime | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Stability region (in rounds) | Improvement in % | Improvement in % in comparison with het1-case | Network lifetime (in rounds) | Improvement in % | Improvement in % in comparison with het1-case |
| het2-HEED | 23.40 | 404 | 1067 | 2354 | 404 | 0.0 | 2.54 | 2354 | 0.0 | 54.66 |
| het2-ICHB-HEED | 23.40 | 238 | 1092 | 2574 | **238*** | NA | **46.01** | 2574 | 9.35 | 29.87 |
| het2-OHEED-1 Tier Chaining | | | | | | | | | | |
| het2-HEED1TC | 23.40 | 679 | 1263 | 3091 | **679*** | **68.07** | **18.30** | 3091 | 31.31 | 46.70 |
| het2-ICOH1TC | 23.40 | 405 | 1190 | 3527 | **405*** | **0.25** | **56.37** | 3527 | 49.83 | 42.27 |
| het2-ICFLOH1TC | 23.40 | 458 | 2208 | 7387 | **458*** | **13.37** | **59.58** | 7387 | 213.81 | 7.86 |
| het2-OHEED-2 Tier Chaining | | | | | | | | | | |
| het2-HEED2TC | 23.40 | 927 | 1308 | 2548 | **927*** | **129.46** | **1.98** | 2548 | 8.24 | 41.16 |
| het2-ICOH2TC | 23.40 | 576 | 1190 | 2949 | **576*** | **42.57** | **14.97** | 2949 | 25.28 | 29.17 |
| het2-ICFLOH2TC | 23.40 | 907 | 2241 | 6332 | **907*** | **124.50** | **59.40** | 6332 | 168.99 | 10.78 |

Bold values represent the better values in comparison to previous protocols

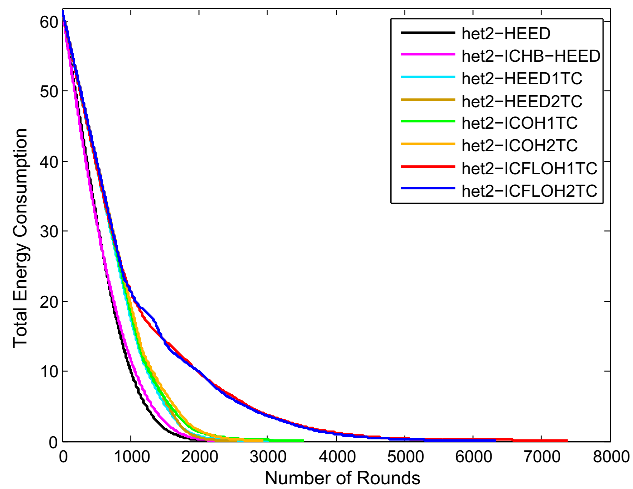


**Fig. 14** Residual energy of the network after each round for het2-OHEED protocols

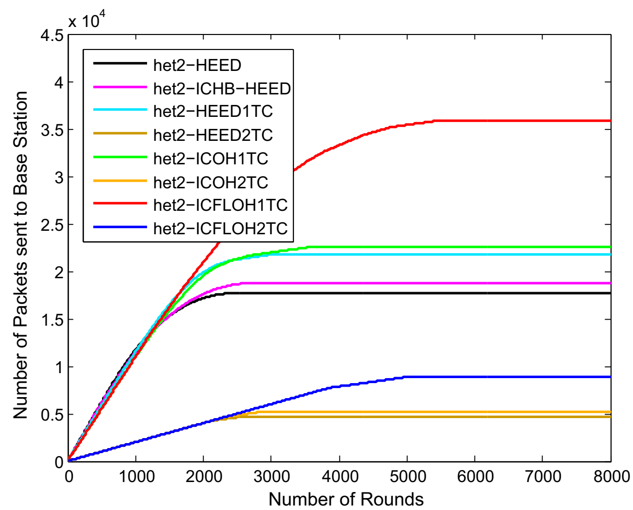


**Fig. 15** Number of packets sent to the BS by diverse het2-OHEED protocols in each round

two data packets are delivered to the BS in each round same as in het1-OHEED-2 Tier Chaining protocols.

The energy consumption variation and number of CHs per round results for het2-OHEED protocols are similar to het1-OHEED protocols. With this reason and space constraint, these graphs are omitted here.

## 4.3 Performance analysis of het3-OHEED protocols

This section describes the comparative analysis of various het3-OHEED protocols with het3-HEED, het1-OHEED and het2-OHEED protocols. Table 7 shows the heterogeneity parameters required during the implementation of het3-OHEED protocols. Figure 16 illustrates the remaining alive SNs after each round. Table 8 describes the FND,

**Table 7** Heterogeneity parameters for het3-OHEED protocols

| Variable | Notation | Value |
|---|---|---|
| Number of SNs | $N$ | 100 (= 51 + 26 + 23) |
| Number of normal SNs | $(1 - m) \times N$ | 51 |
| Number of advanced SNs | $m \times (1 - m_0) \times N$ | 26 |
| Number of super SNs | $m \times m_0 \times N$ | 23 |
| Energy of a normal SN | $E_0$ | 0.5 J |
| Energy of an advanced SN | $E_0(1 + \alpha)$ | 0.8 J |
| Energy of a super SN | $E_0(1 + \beta)$ | 2 J |
| Total energy of network | $E_{\text{tot}_{3\text{-lev}}}$ | 92.3 J |

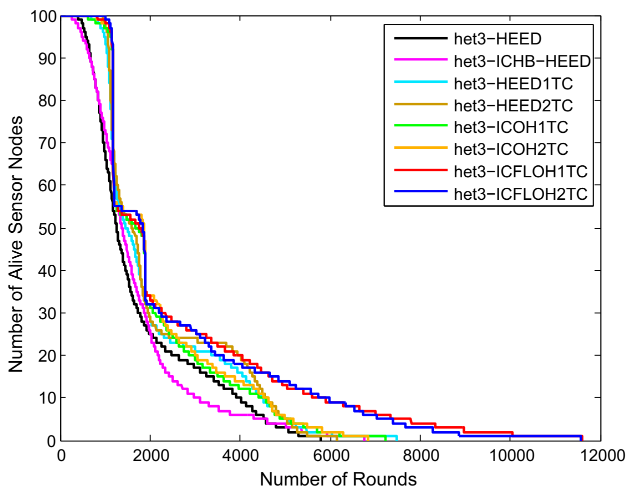


**Fig. 16** Number of remaining alive SNs after each round for het3-OHEED protocols

HND, LND, stability region and network lifetime for het3-OHEED protocols. Moreover, Fig. 17 shows the residual energy of the network after each round for het3-OHEED protocols. het3-OHEED protocols add-on its level of heterogeneity by means of three kinds of SNs, i.e., super nodes, advanced nodes and normal nodes. Increasing the energy resource by 84.60% in the network, an extremely elongated network lifetime has been confirmed by proposed protocols with the maximum increase in het3-ICFLOH1TC and het3-ICFLOH2TC by 100.35% and 99.84% in comparison with het3-HEED respectively. Besides network lifetime, proposed protocols also outperform in stability region. het3-HEED1TC, het3-HEED2TC, het3-ICOH1TC, het3-ICOH2TC, het3-ICFLOH1TC and het3-ICFLOH2TC provide 70.02%, 131.94%, 49.88%, 102.21%, 103.93% and 168.06% improvement in stability region in comparison with het3-HEED along with elongated network lifetime. Furthermore, het3-ICOH1TC, het3-ICOH2TC, het3-ICFLOH1TC and het3-ICFLOH2TC provide 135.52%, 64.27%, 189.20% and 91.74% improvement in stability region in comparison with 1-level heterogeneous case, whereas het3-HEED increases by 3.30% only (as shown by star * in Table 8). These improvements are due to the following reasons: (1) ICHB algorithm works for searching higher residual energy nodes, where it allows the super nodes primarily for the CH selection. Once super nodes energy decreases, it searches for advanced nodes and then normal nodes for CH selection process. This delays the death of SNs and contributes to prolonged stability region. (2) Use of chain-based IACC and IRCC data transmission from SNs to BS via CHs promotes the load balancing feature among SNs and CHs. Furthermore, among all het3-OHEED protocols the best results are provided by het3-ICFLOH1TC and het3-ICFLOH2TC with stability region of 830 and 1091 rounds and network lifetime of 11,600 and 11,571 number of rounds, respectively. Results confirm that providing any level of heterogeneity (i.e., 1, 2, 3, …, n) to Hetero-OHEED protocols, these produce far better stability region with prolonged network lifetime which make them far efficient and realistic in implementing for heterogeneous WSNs.

Figure 18 describes the number of packets sent to the BS by diverse het3-OHEED protocols. het3-HEED, het3-ICHB-HEED, het3-HEED1TC, het3-ICOH1TC and het3-ICFLOH1TC protocols send $4.28 \times 10^4$, $4.21 \times 10^4$, $4.51 \times 10^4$, $4.31 \times 10^4$ and $5.66 \times 10^4$ number of packets to the BS till the network is alive. However, het3-HEED2TC, het3-ICOH2TC and het3-ICFLOH2TC protocols send only 11,012, 12,015 and 16,079 number packets to the BS. This is because of using chain-based IRCC during data transmission procedure, where at most two data packets are delivered to the BS in each round same as in het1-OHEED-2 Tier Chaining protocols.

## 4.4 Performance analysis of multi-OHEED protocols

This section describes the comparative analysis of various multi-OHEED protocols with mul-HEED and het1-OHEED (i.e., homogeneous OHEED) protocols. Table 9 shows the heterogeneity parameters required during the implementation of multi-OHEED protocols. Figure 19 illustrates the remaining alive SNs after each round. Table 10 describes

**Table 8** Comparison among diverse het3-OHEED protocols representing FND, HND, LND, stability region and network lifetime in terms of number of rounds

| Protocol | Increase in energy level than het1-case (in %) | Increase in energy level than het2-case (in %) | FND | HND | LND | Stability region | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Stability region (in rounds) | Improvement in % | Improvement in % in comparison with het1-case | Improvement in % in comparison with het2-case |
| het3-HEED | 84.60 | 49.59 | 407 | 1266 | 5790 | 407 | 0.0 | 3.30 | 0.74 |
| het3-ICHB-HEED | 84.60 | 49.59 | 265 | 1386 | 6751 | 265 | NA | 62.58 | 11.34 |
| het3-OHEED-1 Tier Chaining | | | | | | | | | |
| het3-HEED1TC | 84.60 | 49.59 | 692 | 1499 | 7477 | **692*** | **70.02** | **20.56** | **1.91** |
| het3-ICOH1TC | 84.60 | 49.59 | 610 | 1749 | 7237 | **610*** | **49.88** | **135.52** | **50.62** |
| het3-ICFLOH1TC | 84.60 | 49.59 | 830 | 1817 | 11,600 | **830*** | **103.93** | **189.20** | **81.22** |
| het3-OHEED-2 Tier Chaining | | | | | | | | | |
| het3-HEED2TC | 84.60 | 49.59 | 944 | 1620 | 6148 | **944*** | **131.94** | **3.85** | **1.83** |
| het3-ICOH2TC | 84.60 | 49.59 | 823 | 1872 | 6834 | **823*** | **102.21** | **64.27** | **42.88** |
| het3-ICFLOH2TC | 84.60 | 49.59 | 1091 | 1852 | 11,571 | **1091*** | **168.06** | **91.74** | **20.29** |

| Protocol | Network lifetime | | | |
|---|---|---|---|---|
| | Network lifetime (in rounds) | Improvement in % | Improvement in % in comparison with het1-case | Improvement in % in comparison with het2-case |
| het3-HEED | 5790 | 0.0 | 280.42 | 145.96 |
| het3-ICHB-HEED | 6751 | 16.60 | 240.62 | 162.27 |
| het3-OHEED-1 Tier Chaining | | | | |
| het3-HEED1TC | **7477** | **29.14** | **254.86** | **141.90** |
| het3-ICOH1TC | **7237** | **24.99** | **191.93** | **105.20** |
| het3-ICFLOH1TC | **11,600** | **100.35** | **63.37** | **57.03** |
| het3-OHEED-2 Tier Chaining | | | | |
| het3-HEED2TC | **6148** | **6.18** | **240.61** | **141.29** |
| het3-ICOH2TC | **6834** | **18.03** | **199.34** | **131.74** |
| het3-ICFLOH2TC | **11,571** | **99.84** | **102.43** | **82.74** |

Bold values represent the improved results comparatively

the FND, HND, LND, stability region and network lifetime for multi-OHEED protocols. Moreover, Fig. 20 shows the residual energy of the network after each round for multi-OHEED protocols. In multi-OHEED protocols, different levels of heterogeneous nodes (in terms of energy) under of close set of [0.5 J, 2 J] are employed, which increase energy level by 149% (in approximation) of the network than 1-level heterogeneous case. Results confirm that increasing the energy resource by 149% of the network, each multi-OHEED protocol produces highly improved results as shown in Table 10. Furthermore among all, mul-ICFLOH1TC and mul-ICFLOH2TC protocols provide the maximum improvement in stability region by 144.60% (i.e., 702 in rounds) and 98.77% (i.e., 1131 in rounds) and prolonged network lifetime by 131.08% (i.e., 15,827 in rounds) and 162.07% (i.e., 14,980 in rounds), respectively, in comparison with 1-level heterogeneous case (as shown by star * in Table 10). These improvements are due to the following reasons: (1) ICHB algorithm searches higher residual energy nodes for the CH selection, delays the death of SNs and contributes to prolonged stability region. (2) Use of chain-based IACC and IRCC data transmission promotes the load balancing feature among SNs and CHs.

Figure 21 describes the number of packets sent to the BS by diverse multi-OHEED protocols. mul-HEED, mul-ICHB-HEED, mul-HEED1TC, mul-ICOH1TC and mul-ICFLOH1TC protocols send $4.19 \times 10^4$, $4.69 \times 10^4$, $4.65 \times 10^4$, $4.78 \times 10^4$ and $9.77 \times 10^4$ number of packets to the BS till the network is alive. However, mul-HEED2TC, mul-ICOH2TC and mul-ICFLOH2TC protocols send only 10,275, 11,228 and 23,315 number packets to the BS. This is

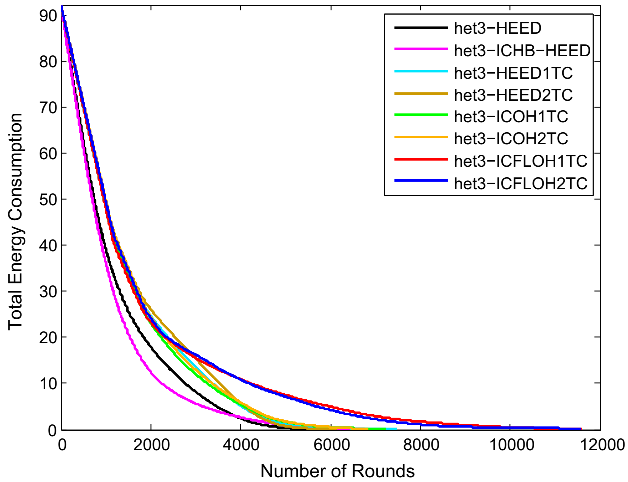


**Fig. 17** Residual energy of the network after each round for het3-OHEED protocols

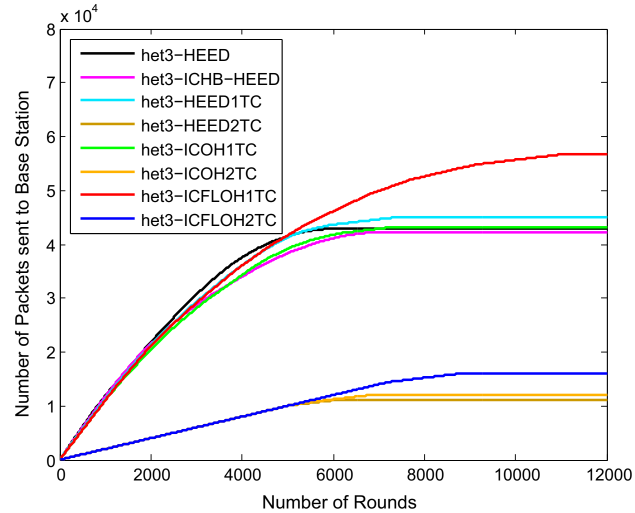


**Fig. 18** Number of packets sent to the BS by diverse het3-OHEED protocols in each round

**Table 9** Heterogeneity parameters for multi-OHEED protocols

| Variable | Notation | Value |
|---|---|---|
| Number of SNs | $N$ | 100 |
| Energy assigned to different SNs varies (in range) | $[E_0, E_0(1+\alpha_{\max})]$ | (0.5, 2 J) |
| Total energy of network | $E_{\text{tot}_{\text{mul-lev}}}$ | ≈ 125 J |

because of using chain-based IRCC during data transmission procedure, where at most two data packets are delivered to the BS in each round same as in het1-OHEED-2 Tier Chaining protocols.

### 4.5 Comparative analysis between Hetero-OHEED protocols at varying heterogeneity levels

Diverse Hetero-OHEED protocols produce different outcomes, i.e., het1-OHEED-1 Tier Chaining protocols have better network lifetime with high number of data reception at BS, while het1-OHEED-2 Tier Chaining protocols provide better stability region with very less number of packets reception at BS. These results confirm that both the categories will be advantageous for different network applications. Furthermore, on increasing the energy level (under different level of heterogeneity), Hetero-OHEED protocols enhance their network lifetime well. Meanwhile, most importantly, these protocols also extend their stability region remarkably. This shows a great confidence that Hetero-OHEED protocols are also well suited for time-critical applications, where reliability of data (i.e., data from each SN for a longer time-span) with prolonged network lifetime are very important. The complete comparative analysis of Hetero-OHEED protocols under different level of heterogeneity is given in Table 11.

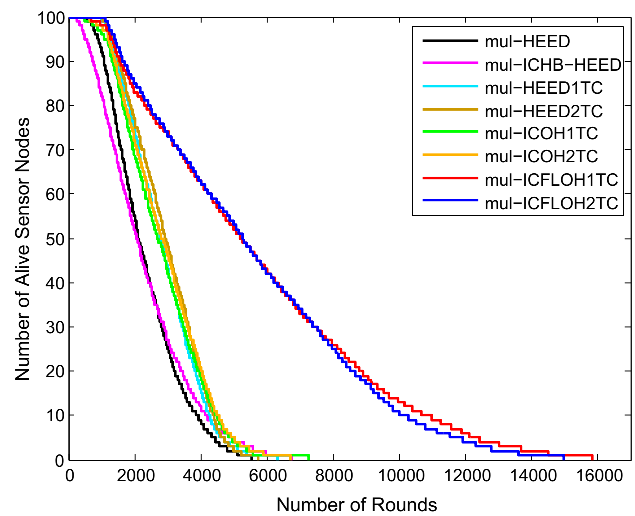


**Fig. 19** Number of remaining alive SNs after each round for multi-OHEED protocols

Furthermore, we have discussed proposed protocols with other similar kinds of existing protocols under varying levels of heterogeneity in Table 12, which confirms that Hetero-OHEED protocols, especially het-ICFLOH1TC and het-ICFLOH2TC, provide far better results comparatively in terms of combination of stability region and network lifetime.

## 5 Conclusion

This paper proposes Hetero-OHEED protocols, an extension of OHEED protocols for heterogeneous WSNs model

**Table 10** Comparison among diverse multi-OHEED protocols representing FND, HND, LND, stability region and network lifetime in terms of number of rounds

| Protocol | Increase in energy level than het1-case (in %) | FND | HND | LND | Stability region | | |
|---|---|---|---|---|---|---|---|
| | | | | | Stability region (in rounds) | Improvement in % | Improvement in % in comparison with het1-case |
| mul-HEED | 149 | 550 | 2147 | 5538 | 550 | 0.0 | 39.59 |
| mul-ICHB-HEED | 149 | 254 | 2099 | 6749 | 254 | NA | 55.83 |
| mul-OHEED-1 Tier Chaining | | | | | | | |
| mul-HEED1TC | 149 | 989 | 2816 | 6323 | 989 | 79.82 | 72.30 |
| mul-ICOH1TC | 149 | 499 | 2737 | 7272 | 499 | NA | 92.66 |
| mul-ICFLOH1TC | 149 | 702 | 5280 | 15,827 | **702*** | **27.63** | **144.60** |
| mul-OHEED-2 Tier Chaining | | | | | | | |
| mul-HEED2TC | 149 | 1040 | 2955 | 5757 | 1040 | 89.09 | 14.41 |
| mul-ICOH2TC | 149 | 658 | 2876 | 6723 | 658 | 19.63 | 31.34 |
| mul-ICFLOH2TC | 149 | 1131 | 5311 | 14,980 | **1131*** | **105.63** | **98.77** |

| Protocol | Network lifetime | | |
|---|---|---|---|
| | Network lifetime (in rounds) | Improvement in % | Improvement in % in comparison with het1-case |
| mul-HEED | 5538 | 0.0 | 263.86 |
| mul-ICHB-HEED | 6749 | 21.87 | 240.51 |
| mul-OHEED-1 Tier Chaining | | | |
| mul-HEED1TC | 6323 | 14.17 | 200.09 |
| mul-ICOH1TC | 7272 | 31.31 | 193.34 |
| mul-ICFLOH1TC | **15,827** | **185.79** | **131.08** |
| mul-OHEED-2 Tier Chaining | | | |
| mul-HEED2TC | 5757 | 3.95 | 218.95 |
| mul-ICOH2TC | 6723 | 21.40 | 194.48 |
| mul-ICFLOH2TC | **14,980** | **170.49** | **162.07** |

Bold values show the highly improved results in comparison to others

based on varying levels of node heterogeneity, i.e., 1-level, 2-level, 3-level and multi-level. Hetero-OHEED protocols consist of hetHEED1TC, hetHEED2TC, hetICHB-HEED, hetICOH1TC, hetICOH2TC, hetICFLOH1TC and hetICFLOH2TC protocols. Here, het1-OHEED-1 Tier Chaining protocols offer better network lifetime, i.e., het1-HEED1 TC, het1-ICOH1TC and het1-ICFLOH1TC protocols result in 38.44%, 62.88% and 350.00% improved network lifetime by het1-HEED, whereas het1-OHEED-2 Tier Chaining protocols offer better stability region comparatively, i.e., het1-HEED2TC, het1-ICOH2TC and het1-ICFLOH2TC protocols result in 130.71%, 27.16% and 44.42% improved stability region by het1-HEED protocol. Furthermore, results show that on increasing energy level during different heterogeneity models (i.e., 2-level, 3-level and so on), both hetOHEED-1 Tier Chaining and hetOHEED-2 Tier Chaining protocols have extremely enhanced their stability region with prolonged network lifetime, i.e., het3-HEED1TC, het3-ICOH1TC, het3-ICFLOH1TC, het3-HEED2TC, het3-ICOH 2TC and het3-ICFLOH2TC protocols have improved their stability region to a great extent by 70.02%, 49.88%, 103.93%, 131.94%, 102.21%, 168.06%, with prolonged network lifetime of 29.14%, 24.99%, 100.35%, 6.18%, 18.03%, 99.84% in comparison with het3-HEED. The stability region of Hetero-OHEED protocols is extremely enhanced because of ICHB algorithm, which searches only higher residual energy SNs during CH selection process, and chain-based IACC and IRCC data transmissions which promote the load balancing feature among SNs and CHs and alleviate the formation of holes and hot-spots in the network. This confirms that Hetero-OHEED protocols are well suited for time-critical applications, where reliability of data from each SN (i.e., stability region) with prolonged network lifetime is very important.

**Table 11** Comparison among diverse Hetero-OHEED protocols representing stability region, network lifetime and number of packets sent to BS per round

| Protocol | Stability region | | | | Network lifetime | | | | Number of packets sent to the base station | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | het1-case | het2-case | het3-case | mul-case | het1-case | het2-case | het3-case | mul-case | het1-case | het2-case | het3-case | mul-case |
| het-HEED | 394 | 404 | 407 | 550 | 1522 | 2354 | 5790 | 5538 | 12,651 | 17,666 | 42,816 | 41,965 |
| hetICHB-HEED | 163 | 238 | 265 | 254 | 1982 | 2574 | 6751 | 6749 | 15,933 | 18, 708 | 42,138 | 46,947 |
| hetOHEED-1 Tier Chaining | | | | | | | | | | | | |
| het-HEED1TC | 574 | 679 | 692 | 989 | 2107 | 3091 | 7477 | 6323 | 15,515 | 21,839 | 45,118 | 46,563 |
| het-ICOH1TC | 259 | 405 | 610 | 499 | 2479 | 3527 | 7237 | 7272 | 17,219 | 22,503 | 43,131 | 47,885 |
| het-ICFLOH1TC | 287 | 458 | 830 | 702 | 6849 | 7387 | 11,600 | 15,827 | 39,550 | 35,906 | 56,670 | 97,730 |
| hetOHEED-2 Tier Chaining | | | | | | | | | | | | |
| het-HEED2TC | 909 | 927 | 944 | 1040 | 1805 | 2548 | 6148 | 5757 | 3243 | 4608 | 11,012 | 10,275 |
| het-ICOH2TC | 501 | 576 | 823 | 658 | 2283 | 2949 | 6834 | 6723 | 3972 | 5222 | 12,015 | 11,228 |
| het-ICFLOH2TC | 569 | 907 | 1091 | 1131 | 5716 | 6332 | 11,571 | 14,980 | 9011 | 8860 | 16,079 | 23,315 |

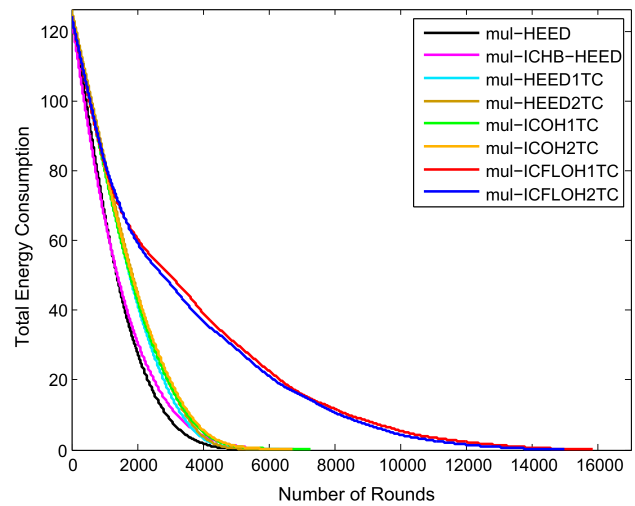


**Fig. 20** Residual energy of the network after each round for multi-OHEED protocols

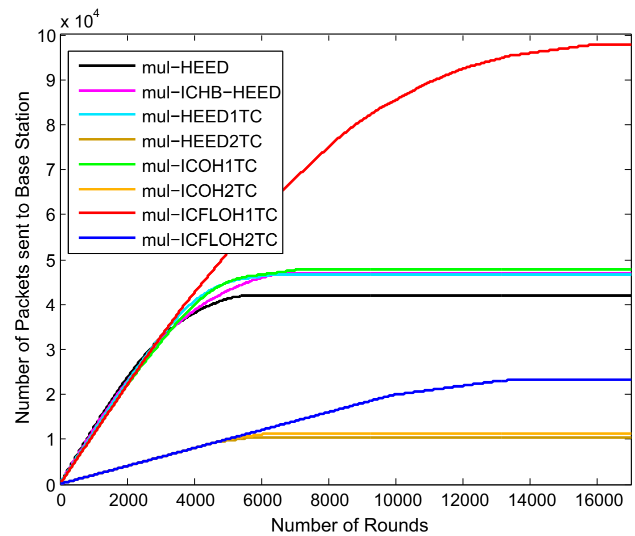


**Fig. 21** Number of packets sent to the BS by diverse multi-OHEED protocols in each round

Moreover, hetOHEED-2 Tier Chaining protocols transmit a very less number of packets toward BS which help in less data flooding toward the BS and can be proven efficient, where a less amount of data packets with complete information are required at the BS for data analysis purpose. These reasons confirm that diverse Hetero-OHEED protocols are capable of providing better-extended results for different application domains in heterogeneous WSNs.

**Table 12** Comparative analysis of Hetero-OHEED protocols with similar kind of existing protocols under different levels of heterogeneity in terms of FND, HND, LND, stability region and network lifetime

| Level for heterogeneity | Total amount of energy | Protocol | FND | HND | LND | Stability region (in rounds) | Network lifetime (in rounds) |
|---|---|---|---|---|---|---|---|
| One-level heterogeneous case (i.e., homogeneous case) | 50 J | het1-HEED (Younis and Fahmy 2004) | 394 | 908 | 1522 | 394 | 1522 |
| | | IBLEACH (Salim et al. 2014) | 426 | 1350 | 1938 | 426 | 1938 |
| | | het1-ICHB-HEED | 163 | 885 | 1982 | 163 | 1982 |
| | | het1-HEED1TC | 574 | 1135 | 2107 | 574 | 2107 |
| | | het1-HEED2TC | 909 | 1140 | 1805 | 909 | 1805 |
| | | het1-ICOH1TC | 259 | 1180 | 2479 | 259 | 2479 |
| | | het1-ICOH2TC | 501 | 1182 | 2283 | 501 | 2283 |
| | | HEEDML-FL (Singh et al. 2016) | 476 | 1602 | 3820 | 476 | 3820 |
| | | het1-ICFL-HEED | 282 | 2291 | 4368 | 282 | 4368 |
| | | het1-ICFLOH1TC | 287 | 2449 | 6849 | 287 | 6849 |
| | | het1-ICFLOH2TC | 569 | 2729 | 5716 | 569 | 5716 |
| Two-level heterogeneous case | 54.6 $J$ | DEEC (Qing et al. 2006) | 1317 | 1468 | 1665 | 1317 | 1665 |
| | | SEARCH (Wang et al. 2015) | 1021 | 1436 | 1674 | 1021 | 1674 |
| | | het2-HEED (Kour and Sharma 2010) | 419 | 979 | 1730 | 419 | 1730 |
| | | het2-ICHB-HEED | 201 | 969 | 2005 | 201 | 2005 |
| | | het2-HEED1TC | 638 | 1207 | 2319 | 638 | 2319 |
| | | het2-HEED2TC | 934 | 1255 | 2004 | 934 | 2004 |
| | | het2-ICOH1TC | 317 | 1189 | 3043 | 317 | 3043 |
| | | het2-ICOH2TC | 570 | 1189 | 2558 | 570 | 2558 |
| | | HEEDML-FL (Singh et al. 2016) | 746 | 2250 | 4814 | 746 | 4814 |
| | | het2-ICFL-HEED | 299 | 2202 | 4869 | 299 | 4869 |
| | | het2-ICFLOH1TC | 355 | 2446 | 7181 | 355 | 7181 |
| | | het2-ICFLOH2TC | 703 | 2593 | 5860 | 703 | 5860 |
| Three-level heterogeneous case | 58.7 $J$ | DEEC (Saini and Sharma 2010) | 1413 | 1583 | 1940 | 1413 | 1940 |
| | | SEARCH (Wang et al. 2015) | 1087 | 1537 | 1817 | 1087 | 1817 |
| | | het3-HEED (Kour and Sharma 2010) | 417 | 1070 | 1952 | 417 | 1952 |
| | | het3-ICHB-HEED | 229 | 1038 | 2214 | 229 | 2214 |
| | | het3-HEED1TC | 686 | 1256 | 2580 | 686 | 2580 |
| | | het3-HEED2TC | 938 | 1305 | 2304 | 938 | 2304 |
| | | het3-ICOH1TC | 388 | 1190 | 3371 | 388 | 3371 |
| | | het3-ICOH2TC | 576 | 1189 | 2753 | 576 | 2753 |
| | | HEEDML-FL (Singh et al. 2016) | 1007 | 2850 | 6186 | 1007 | 6186 |
| | | het3-ICFL-HEED | 303 | 2305 | 5628 | 303 | 5628 |
| | | het3-ICFLOH1TC | 405 | 2435 | 7318 | 405 | 7319 |
| | | het3-ICFLOH2TC | 808 | 2470 | 6130 | 808 | 6130 |

**Table 12** continued

| Level for heterogeneity | Total amount of energy | Protocol | FND | HND | LND | Stability region (in rounds) | Network lifetime (in rounds) |
|---|---|---|---|---|---|---|---|
| Multi-level heterogeneous case | 125 *J* | DEEC (Qing et al. 2006) | 2091 | 3435 | 4136 | 2091 | 4136 |
| | | SEARCH (Wang et al. 2015) | 1766 | 3272 | 5177 | 1766 | 5177 |
| | | mul-HEED (Kour and Sharma 2010) | 550 | 2147 | 5538 | 550 | 5538 |
| | | mul-ICHB-HEED | 254 | 2099 | 6749 | 254 | 6749 |
| | | mul-HEED1TC | 989 | 2816 | 6323 | 989 | 6323 |
| | | mul-HEED2TC | 1040 | 2955 | 5757 | 1040 | 5757 |
| | | mul-ICOH1TC | 499 | 2737 | 7272 | 499 | 7272 |
| | | mul-ICOH2TC | 658 | 2876 | 6723 | 658 | 6723 |
| | | mul-ICFL-HEED | 285 | 4679 | 12,008 | 285 | 12,008 |
| | | mul-ICFLOH1TC | 702 | 5280 | 15,827 | 702 | 15,827 |
| | | mul-ICFLOH2TC | 1131 | 5311 | 14,980 | 1131 | 14,980 |

## Compliance with ethical standards

**Conflict of interest** All authors declare that they have no conflict of interest.

**Ethical standard** This article does not contain any studies with human participants or animals performed by any of the authors.

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