Evolving Systems
https://doi.org/10.1007/s12530-018-9254-8

ORIGINAL PAPER

Energy efficient clustering protocol for WSNs based on bio-inspired ICHB algorithm and fuzzy logic system

Prateek Gupta[1] · Ajay K. Sharma[2]

Received: 11 April 2018 / Accepted: 3 October 2018

Abstract
This paper explores the capabilities of Intelligent cluster head selection based on bacterial foraging optimization (ICHB) algorithm and fuzzy logic system (FLS) for searching better cluster head (CH) nodes without using any randomized algorithms in the network. ICHB-HEED is one of the recent clustering based protocol in the field of wireless sensor networks (WSNs). In this paper, the clustering procedures of ICHB-HEED is further improved by applying the combination of ICHB algorithm and FLS system based on residual energy, node density and distance to base station (BS) parameters which results in *ICHB-Fuzzy Logic based HEED* (ICFL-HEED) protocol. It alleviates the formation of holes and hot-spots in the network, delays the death of sensor nodes (SNs), minimizes the energy consumption of SNs, forms even-sized clusters and extends the network lifetime competently. The proposed ICFL-HEED protocol is compared with existing HEED & ICHB-HEED protocols and observed that the performance of ICFL-HEED is far better than these protocols.

Keywords Clustering · Wireless sensor networks · ICHB · BFOA · HEED · Fuzzy logic system · Network lifetime

1 Introduction

Wireless sensor networks is one the rapidly growing fields due to technological advancements in the field of micro-electro-mechanical-systems (MEMS) and wireless communication systems. WSNs consist of number of small battery operated devices known as SNs. These SNs are endowed with three basic principles: (1) data sense from external surroundings, (2) computation on sensed data and (3) data transmission wirelessly. WSNs comprise of such SNs which have expert solution for the environments where human intervention is extremely challenging i.e., military surveillance, structural health monitoring, natural disaster forecasting and traffic management. After deployment in the WSNs, these SNs collect the surroundings data, do computational processing on the received data and transmit it to the BS for further processing (Akyildiz et al. 2002; Kulkarni et al. 2011; Fei and Wang 2018).

Being small sized, SNs are equipped with limited power back-up, storage capabilities and computational potentials. Once deployed in the network field, these SNs are left unattended which endows the primary concern of efficient utilization of each SN s energy. With this motive, designing of energy efficient protocols can help in proficient energy consumption of each SN to ensure the longevity of network. Organizing these SNs into small groups to form clusters, play a significant role in the development of such efficient protocols. In clustered network approach, a WSN is divided into small clusters. Each cluster consists of few SNs and a cluster head (CH) that acts as a leader. All SNs send their sensed data to its respective CHs, which further transmit data to the BS. Due to this, proper CH selection, optimum number of clusters, cluster maintenance and data routing to BS are main issues in the development of clustering based energy efficient protocols (Kumarawadu et al. 2008; Sharma and Sharma 2016).

A number of clustering protocols have been designed by various authors concerning the above issues. However, acknowledging these clustering issues is not the only concerned, whereas maintaining quality of service (QoS) and trade-off among contradictory issues i.e., lifetime, coverage

✉ Prateek Gupta
cseprateek@gmail.com

Ajay K. Sharma
vcptu13@gmail.com

[1] Department of Computer Science and Engineering, Dr B R Ambedkar National Institute of Technology, Jalandhar, Punjab, India

[2] I. K. Gujral Punjab Technical University, Jalandhar, India

and throughput should also be handled competently. In recent years, bio-inspired or meta-heuristics techniques and expert systems have drawn much attention to handle these issues (Adnan et al. 2013; Chu and Fei 2017; Fei and Lu 2018; Fang et al. 2018).

In past recent years, various energy efficient protocols have been designed for either homogeneous or heterogeneous networks. Conventionally, homogeneous networks comprise of SNs possessing same energy resources at the beginning of network whereas in heterogeneous networks, SNs are equipped with varying energy resources. A homogeneous model is a special kind of WSN possessing same energy resources by each SN at the beginning but later transforms into heterogeneous model once the network executes. Because each SN cannot dissipate same amount of energy resource due to radio communication characteristics, occurrence of random events or morphological characteristics of the network field. Notably, it shows a great challenge to design an energy efficient protocol which can proficiently work for both homogeneous and heterogeneous networks (Qing et al. 2006; Sharma and Sharma 2016; Gupta and Sharma 2018). In this paper, we have proposed an algorithm considering for both homogeneous as well as heterogeneous network models.

Taking inspiration from above statistics, Gupta (2017) have designed ICHB algorithm which relies on residual energy of each SN for clustering procedure in WSNs. ICHB algorithm is fully-capable of searching higher residual energy nodes in the network field without any randomized or estimation based algorithms. This makes ICHB algorithm a unique approach for finding actual higher residual energy nodes in the WSNs. Further, authors have employed ICHB algorithm on HEED and designed ICHB-HEED protocol. However, it suffers from uneven-sized clusters, uneven load balancing among clusters, holes & hot-spots problem in the WSNs. Resolving these issues, this paper proposes *ICHB-Fuzzy Logic based HEED* (ICFL-HEED) protocol, where we have used the combination of ICHB algorithm with expert knowledge system i.e., fuzzy logic system (FLS) on different clustering parameters viz. residual energy, node density and distance to BS. Here, ICHB algorithm is employed on *residual energy* of each SN as primary parameter and FLS is applied on the combination of *node density* and *distance to BS* as secondary parameters for CH selection in clustering procedure of ICFL-HEED protocol. Simulation results confirm that by employing the combination of ICHB algorithm and FLS on different clustering parameters provide better outcome in terms of even-sized clusters, alleviation of holes & hot-spots problem with improved network lifetime of WSNs.

Rest of the paper is organized as: Sect. 2 discusses related literature. Section 3 defines the network model. Section 4 reveals the proposed ICFL-HEED protocol. Section 5 depicts the simulation results and its discussion. In last, Sect. 6 concludes the paper.

2 Related work

Clustering procedure has been proven a prominent feature in designing of energy efficient protocols in WSNs. Many clustering based protocols has been designed in past two decades i.e., LEACH (Heinzelman et al. 2000), LEACH-C (Heinzelman et al. 2002), LEACH-M (Mhatre and Rosenberg 2004), HEED (Younis and Fahmy 2004) etc.

LEACH is served as a benchmark and ascendant of most of the protocols in this field. LEACH is a self-organizing, distributed clustering protocol, which works on equal energy consumption by each SN in the WSN. The working module of LEACH is divided into two phases, setup and steady phase. In setup phase, CH election procedure is conducted based on probabilistic approach by each SN. In steady phase, once clusters are formed, each SN senses its surroundings to collect data and forwards it to the respective CH. Each CH fuses the received data from its cluster members and sends to the far away situated BS via direct communication. LEACH-C is a centralized variant of LEACH, where CH selection process is undertaken by the BS. In the beginning of each round, all SNs send their location information and current energy level to the BS. Based on this, BS calculates the average energy of the network and allows only those SNs for CH selection, whose value is greater than average value for current round. Once CHs are selected by the BS, it broadcasts the locations of CHs in the network and all other SNs join its nearest CH. However adopting the centralized approach, LEACH-C suffers from the scalability issues. LEACH-M is a multi-hop approach of LEACH. In this approach, authors inspected the performance of multi-hop communication scheme with single-hop communication scheme between CHs and BS. Results clearly showed that performance of LEACH-M is better than LEACH.

HEED being one of the prominent protocols in this field, is a hybrid, distributed and iteration based clustering protocol. In this scheme, CH selection is based on hybrid combination of residual energy and intra-cluster communication cost. At initial stage, CHs are elected based on the residual energy. Once a set of CHs are chosen, a message is broadcasted by CHs intended for the SNs for cluster formation. At this stage, on hearing messages from multiple CHs, SN uses the intra-cluster communication cost for selecting better CH. This approach helps in proper load balancing among clusters. If any SN does not hear this message, it elects itself as a CH at the end of each round. However first, HEED suffers from formation of large number of clusters. Second, due to random election of CHs at initial stage, high variation in number of

CHs in consecutive round. In Huang (2005), provided an extension on HEED. In HEED, SNs which left uncovered by the CHs and forced to elect themselves as CHs created additional CHs in the network. This problem was overcomed by using re-election algorithm on uncovered SNs and improved the efficiency of HEED. MiCRA (Khedo and Subramanian 2009) is another advancement on HEED, which applies two level hierarchy on CH selection procedure. At first level, CHs selection is same as HEED, whereas at second level, only those CHs can participate for CHs selection procedure, which are elected at first level. This type of hierarchical cluster formation helps in energy balancing among SNs in the network. In Sabet and Naji (2015), proposed a distributed clustering approach with multi-hop routing algorithms which can efficiently minimize the energy consumption caused by control packets. In Du et al. (2015), proposed an EESSC protocol which used residual energy parameter for clustering procedures and took help of a special packet header for updating SNs residual energy during data transmission in the network. In Gupta (2017), proposed an ICHB algorithm based on BFOA (Passino 2002) for CH selection procedure. ICHB is fully capable in searching higher residual energy nodes in the network with the help of artificial bacteria. ICHB is fully-distributive algorithm which does not require centralized support (i.e., BS) for its initialization. Furthermore, authors have proposed ICHB-HEED protocol, where ICHB algorithm has been executed on HEED, which showed the efficient performance in selection of better CHs (in terms of residual energy), optimal and stable CH count per round and prolonged the network lifetime in comparison to HEED.

Fuzzy logic system (FLS) is rule based expert system that has the capabilities to produce efficient results even when incomplete information exists. FLS is highly capable in generating real-time decisions by manipulating semantic set of rules to provide cutting edge features (Wang 1997; Negnevitsky 2001). In Gupta et al. (2005), discussed a clustering approach for WSNs based on FLS using battery level, node concentration and distance parameters. In Kim et al. (2008), used FLS based on energy level and local distance parameters for reduction of overheads generated during CH selection procedures in LEACH. In Mao and Zhao (2011), discussed an UCFIA protocol based on unequal clustering procedure using FLS and improved ACO for inter-cluster routing procedures. In Xie et al. (2015), authors discussed a type-2 FLS for clustering procedures with improved ACO, where this procedure has been followed for inter-cluster communication. DUCF (Baranidharan and Santhi 2016) presented a distributed unequal clustering procedures based on FLS in the formation of unequal sized clusters for providing better load balancing feature in the network.

3 Network model

This section discusses various network modeling assumptions required by proposed work for both homogeneous and heterogeneous WSNs.

3.1 Homogeneous WSNs

In homogeneous WSNs, following assumptions have been incorporated for proposed protocol.

- N_{sn} number of SNs are scattered in $K \times K$ network field with uniformity.
- Each SN is equipped with same initial energy level, E_0. With this fact, the total energy of the network is given as,

$$E_{hom} = N_{sn} \times E_0 \tag{1}$$

- SNs remain stationary after deployment and have similar capabilities of data sensing, data processing and data communication.
- SNs are location unaware because they are unequipped with GPS-capable antenna.
- In the network field, BS is situated in the middle and have sufficient energy & computational resources.
- In network startup, BS broadcasts a $HELLO_{BStoSN}$ message in the network. On reception of this message, all SNs calculate its distance to BS using received signal strength indicator (RSSI) value. Further, all SNs broadcast a $HELLO_{SNtoSN}$ message in its transmission radius. On reception of these messages, each SN calculates its neighboring nodes i.e., node density.
- Radio links between two SNs are symmetric, i.e., two SNs are capable in communicating each other using same transmission power level.

3.2 Heterogeneous WSNs

The proposed protocol is further analyzed for two-level and three-level heterogeneous model.

For two-level heterogeneous WSNs, two types of SNs are employed in the network. These are classified as normal and advanced nodes. Normal nodes are initialized with E_0 energy level, whereas advanced nodes are equipped with $E_0(1 + \Psi)$ energy level. With fraction of μ, advanced nodes have Ψ times higher energy level than normal nodes. Therefore, the total energy of two-level heterogeneous WSNs is defined as (Qing et al. 2006),

$$E_{two-lev} = (1 + \mu\Psi) \times N_{sn} \times E_0 \tag{2}$$

For three-level heterogeneous WSNs, three types of SNs are employed in the network. These are classified as normal, advanced and super nodes. Here, normal nodes are initialized with E_0 energy level, advanced nodes are equipped with

$E_0(1+\Psi)$ energy level and super nodes are initialized with $E_0(1+\Theta)$ energy level. With fraction of $\mu \times \mu_0$, super nodes have Θ times higher energy level than normal nodes. Therefore, the total energy of three-level heterogeneous WSNs is defined as (Kumar et al. 2009),

$$E_{three-lev} = (1 + \mu(\Psi - \mu_0(\Psi - \Theta))) \times N_{sn} \times E_0 \tag{3}$$

4 Proposed work

This section discusses the proposed ICFL-HEED protocol based on the refinement in clustering procedure of ICHB-HEED protocol. The flowchart showing its working procedure is presented in Fig. 1. Further, the complete cluster formation, data collection and transmission procedures are discussed below.

4.1 ICFL-HEED protocol

In ICFL-HEED protocol, we enhance the CH selection procedure by using three clustering parameters of each SN; (1) residual energy, (2) node density and (3) distance to BS.

- *Residual energy* of a node s_1, can be defined as total energy of that node at the beginning of a specific round. Once network executes, the residual energy of a node depletes in each round due to data sensing, data processing and data transmission features.

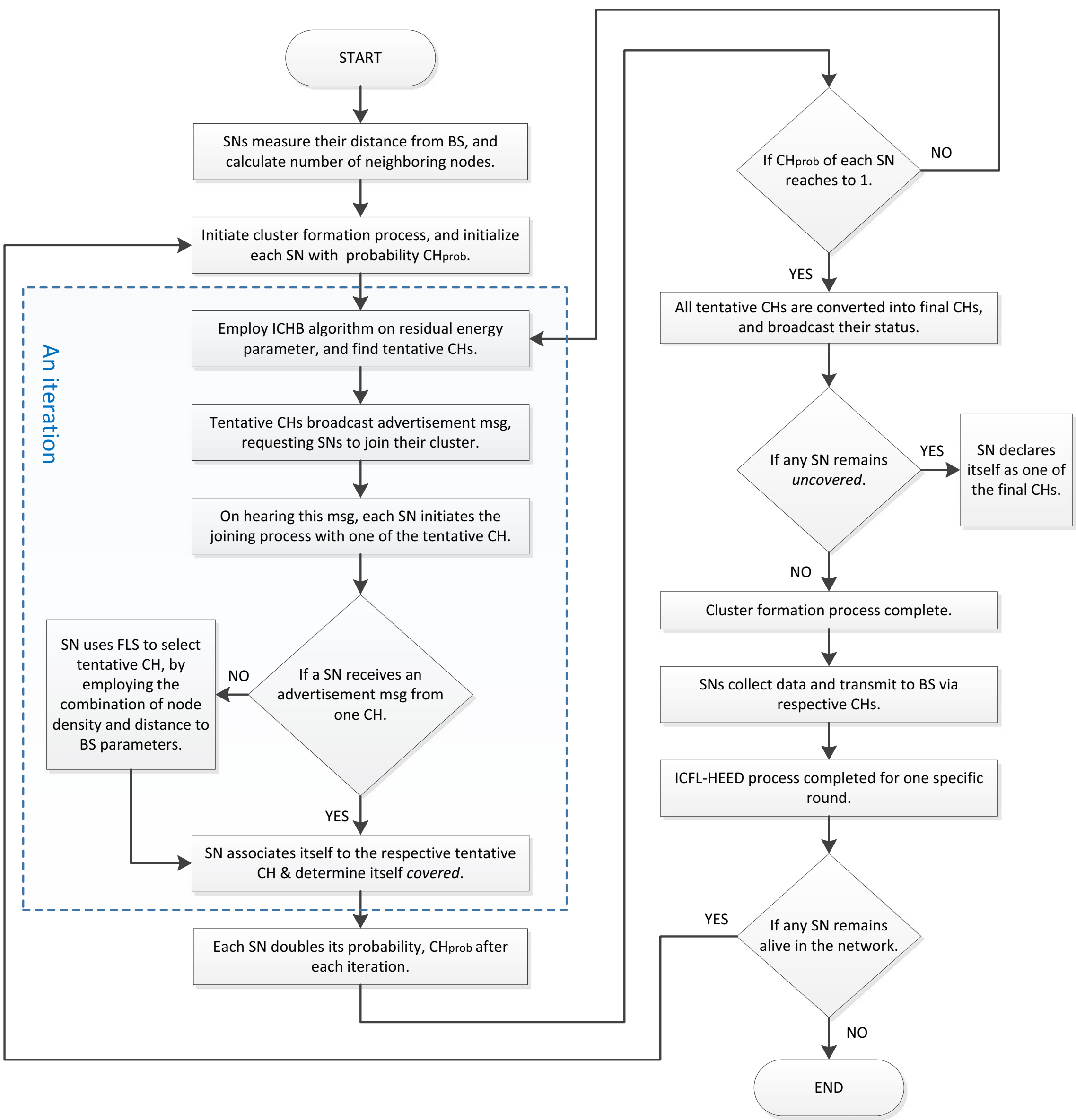


Fig. 1 Flowchart of ICFL-HEED protocol

- *Node density* of a sensor s_1, can be calculated as number of SNs s_i, ($2 \leq i \leq N_{sn}$, where N_{sn} expresses total number of SNs in the network field) which lie under the transmission radius in single-hop distant.
- To determine *distance to BS* parameter, a beacon message BCN_{msg} is broadcasted by the BS in the beginning of the network. On receiving BCN_{msg}, each SN calculates its distance to the BS using the received signal strength of this message.

The network has the pre-determined limit in selection of total number of CHs, C_{prob} (i.e., 5% of total SNs). Meanwhile, this constraint only works at the beginning of protocol execution, however it does not guarantee the number of final selected CHs in the network. Each *uncovered* SN applies the CH_{prob} probability to elect itself as a CH. An uncovered SN is a node which is neither CH nor a cluster member. The mathematical formulation of CH_{prob} probability is given as below,

$$CH_{prob} = \left(C_{prob} \times \frac{E_{res}}{E_{max}}, P_{min} \right) \tag{4}$$

where, E_{res} is residual energy of a SN, E_{max} denotes the maximum allocated energy to a SN at the beginning and P_{min} is pre-determined threshold value (i.e., $P_{min} = 10^{-4}$).

Primarily, a set of tentative CHs (S_{TCH}), with higher residual energy has been elected using ICHB algorithm based on *residual energy* parameter.

ICHB algorithm: For this, it requires *chemotaxis procedure* to search the higher residual energy SNs in the network, where a set of artificial bacteria (in the form of control message) moves from node to node in search of higher energy node in the network field.

In this context, initialize variable $P(j) = \{\lambda^b(j) | b = 1, 2, \ldots, S_{pop}\}$ that contains current location λ^b of each bacterium b at j-th chemotactic step. S_{pop} defines the population of total number of bacteria in the network. $E(b, j)$ signifies energy cost of the SN at which b-th bacterium resides at j-th chemotactic step.

Under chemotaxis procedure, ICHB algorithm requires swim method that shifts bacterium from one SN to another in a specified region in search of better energy node for the selection of tentative CH.

Initially, in a particular iteration of a round, a population of bacteria S_{pop} is initiated at few SNs with probability B_{prob} (i.e., 5% of total SNs) randomly in the WSNs.

The position of each bacterium b is indicated by λ^b under j-th chemotactic step is given as,

$$\lambda^b(j) = \tau^b(UID) \tag{5}$$

where τ^b indicates the unique identification number (UID) of SN at which b-th bacterium resides.

Once bacteria are located in the field, these start searching for better residual energy SNs in their surroundings for tentative CHs. For this, each bacterium creates a random vector Δ_b that store the UIDs of SNs that reside in the communication radius of the SN s_i at which bacteria is itself situated.

Furthermore, each bacterium b shifts from one node to another node in its corresponding random vector Δ_b in search of better energy cost $E(b, j)$. The movement by a bacterium b under chemotaxis process is defined as,

$$\lambda^b(j+1) = [\tau^b_{r+1}(UID)]^{\Delta_b} \tag{6}$$

where, τ^b_{r+1} denotes movement of b-th bacterium to other SNs $\{r+1, \ldots, N_{sn}\}$ in its corresponding random vector Δ_b.

During the shifting process, each bacterium b stores the energy value $E(b, j)$ of visited SN in E_{last} at j-th chemotactic step along with its UID for future comparison and shifts to next node in random vector Δ_b. During shift, if bacterium finds better energy node $E(b, j+1)$, updates $E_{last} = E(b, j+1)$ with current SN's energy value and stores its UID. Otherwise, shifts to next SN in random vector Δ_b without any changes for further search. The pseudo-code of ICHB algorithm is given in Algorithm 1.

ICHB parameters: During execution of ICHB algorithm, the parameters required are, S which denotes the population of total number of bacteria in the field, is kept 5% of total SNs. N_c shows the number of chemotactic steps, where during searching for better energy SNs, all SNs are visited by the population of bacteria in a chemotactic step. With this reason, number of chemotactic steps $N_c = 1$ are sufficient. Further, N_s defines the length of swim where, each bacterium shifts to total number of SNs in the random vector Δ_b.

Algorithm 1 ICHB algorithm

Initialize parameters S_{pop}, N_c, N_s.
Initiate bacteria λ^b, $\overline{=}1, 2, ..., S_{pop}\}$ on few SNs with probability B_{prob} randomly in network field. Initialize variable $(j = 0)$ that denotes the chemotaxis process. All updates to λ^b are automatically updated in variable P.

1. Chemotaxis loop: $j = j + 1$

a. For each bacterium b, a chemotactic step is given as:
b. Compute energy cost function $E(b, j) = e(\lambda^b(b, j))$ for the bacterium b at j-th chemotactic step. e indicates energy cost value corresponding to the SN where bacterium b resides.
c. Let $E_{last} = E(b, j)$ stores energy cost value, since bacterium i can find better value via run.
d. Generate random vector Δ_b containing UIDs of SNs $\tau_r(UID)$.
e. Swim:
   i. Let $m = 1$ (counter required to shift bacterium b to all SNs in random vector Δ_b.
   ii. Shift, $\lambda^b(j+1) = [\tau_{r+1}(UID)]^{\Delta_b}$ results a shift in bacterium to next SN $\tau_{r+1}(UID)$ stored in random vector Δ_b.
   iii. Compute $E(b, j+1) = e(\lambda^b(b, j+1))$.
   iv. While $m \leq N_s$ (continue searching for better residual energy node till all SNs are not visited in the random vector Δ_b)
      - $m = m + 1$
      - If $E(b, j+1) > E_{last}$ (if finds better energy node) $E_{last} = E(b, j+1)$ and $\lambda^b(j+1) = [\tau_{r+1}(UID)]^{\Delta_b}$ updates the E_{last} value by current SN $E(b, j+1)$ energy value, stores its UID and shifts to next SN in random vector Δ_b for further search.
      - Else, $\lambda^b(j+1) = [\tau_{r+1}(UID)]^{\Delta_b}$ shifts bacterium to next SN in random vector Δ_b for further search.
f. Start again this process for $(b + 1)$ bacterium till $(b \neq S_{pop})$, go to step 1b.

2. Continue above procedure till $j < N_c$, (i.e., go to step 1).

Applying ICHB algorithm, the population of bacteria is able to recognize the best SNs (in terms of residual energy) in the network field and elect them as tentative CHs. Each tentative CH broadcasts its status through an advertisement message. Each SN that hears this message associates itself to the respective CH and determines itself as *covered*.

If more than one such message from different CHs is received by a SN, it selects the CH with better probability using Eq. 7. This probability is an outcome generated by the FLS module taking *node density* and *distance to BS* as input parameters in selection of better CH node. This accomplishes the cluster formation for an iteration.

Fuzzy logic system: It consists of fuzzifier, inference engine, rule base and defuzzifier significant modules for its functioning. It takes inputs as a crisp values, which are converted into an appropriate fuzzy linguistic variables. These fuzzified values are provided to fuzzy inference engine as inputs, and IF-THEN set of rules from fuzzy rule base. Here, fuzzy inference engine does human reasoning based simulation and generates fuzzy inference. Furthermore, this fuzzy output is provided to defuzzifier for converting it into crisp output value. In FLS, we use the well-known Mamdani model (Negnevitsky 2001) as inference engine. It includes node density and distance to BS as input parameters and generates *probability* as an outcome. The working module of fuzzy inference system for ICFL-HEED protocol is shown in Fig. 2. The formulation for calculating the probability is given below,

$$Probability = \frac{\vartheta_{nd} \times Q_{nd} + \vartheta_d \times (M_d - Q_d)}{\vartheta_{nd} \times M_{nd} + \vartheta_d \times M_d} \tag{7}$$

where, ϑ_{nd} & ϑ_d signify the weightages, Q_{nd} & Q_d show the current level values and M_{nd} & M_d indicate the maximal defined values for node density and distance to BS parameters respectively. Furthermore, node density has level values 0, 1, 2 as the representation of sparsely, medium and densely membership functions (MFs), whereas distance to BS has level values 0, 1, 2 as the representation of near, medium and far MFs respectively as shown in Figs. 3 and 4. The probability outcome generates nine MFs rules as very weak (VW), weak (W), rather weak (RW), lower medium (LM), medium (M), higher medium (HM), little strong (LS), strong (S) and very strong (VS) with level values of 0, 1, 2, 3, 4, 5, 6, 7, 8 respectively as shown in Fig. 5. These rules are based on the IF X and Y THEN Z. Here X, Y and Z signify node density, distance to BS and probability outcome respectively as given in Table 1. Furthermore, Q_{nd} & Q_d may consider their current level values as 0 or 1 or 2, while M_{nd} & M_d are set to 2 as maximum value. Moreover, providing equal weightages to node density and distance to BS parameters, ϑ_{nd} & ϑ_d values are set to 1 (i.e., $\vartheta_{nd} = \vartheta_d = 1$).

Using node density parameter for CH selection procedure, ICFL-HEED generates even-sized clusters, which in turn helps to provide better load balancing among SNs. Applying distance to BS parameter for CH selection, ICFL-HEED is able to select nearby SNs to the BS, which act as CHs. Due to this, the energy consumption during data transmission from CHs to BS minimizes, which in turn prolongs the network lifetime.

After each iteration, each SN double its CH_{prob} probability, starts identification of new tentative CHs using ICFL-HEED algorithm and add them in the set of tentative CHs, S_{TCH}. During this procedure, SNs may change their associativity among different CHs. Iterations continue till CH_{prob} of each SN reaches to 1. The status of all tentative CHs at this moment convert to final CH and broadcast their updated status as $final_{CH}$. However, at this point, if any SN exists uncovered, advertises a message allowing itself as a final CH and updates its status

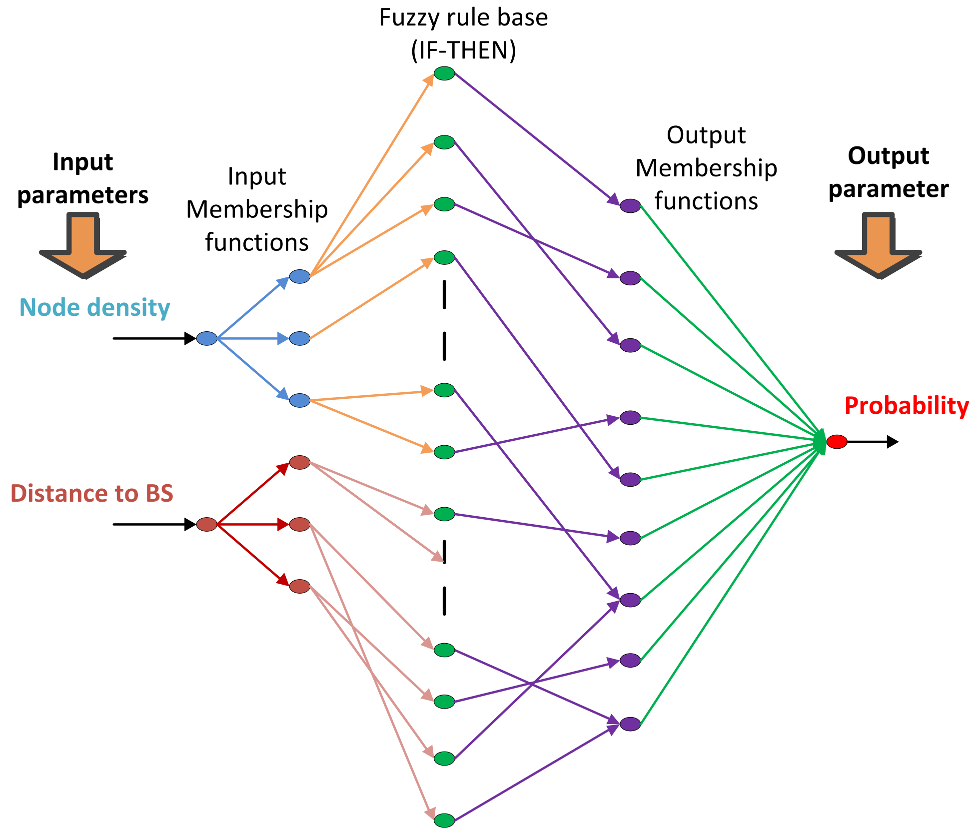


Fig. 2 Fuzzy inference system for ICFL-HEED protocol

Table 1 Fuzzy rules defined for ICFL-HEED

Node density	Distance to BS	Probability
Sparsely	Far	Very weak (VW)
Sparsely	Medium	Weak (W)
Sparsely	Near	Rather weak (RW)
Medium	Far	Lower medium (LM)
Medium	Medium	Medium (M)
Medium	Near	Higher medium (HM)
Densely	Far	Little strong (LS)
Densely	Medium	Strong (S)
Densely	Near	Very strong (VS)

as $final_{CH}$. This accomplishes the cluster formation for a specific round. The above discussed procedure is allowed to continue till at least one SN remains alive in the WSN.

After cluster formation in each round, each SN senses the environmental surroundings, collects the data and transmits it to its respective CH in single hop. On reception of the data packets sent by the cluster members, each CH fuses its own data with received packets and transmits it to the BS directly in single hop.

4.2 Energy consumption model

For proposed protocol, we apply the radio-energy dissipation model to run transmitter or receiver circuitry (Heinzelman et al. 2000; Heinzelman et al. 2002).

The energy dissipated to send L-bit data message for a distance d between sender and receiver is given as,

$$E_{Tx}(L, d) = \begin{cases} L \times E_{elec} + L \times \epsilon_{fs} \times d^2, & if \;\; d \leq d_0 \\ L \times E_{elec} + L \times \epsilon_{mp} \times d^4, & if \;\; d > d_0 \end{cases} \tag{8}$$

The energy dissipated to receive L-bit data message by receiver is given as,

$$E_{Rx}(L) = L \times E_{elec} \tag{9}$$

where, E_{elec} shows the energy dissipated by transmitter or receiver during data sending or receiving. ϵ_{fs} and ϵ_{mp} are amplifying indexes used during data transmission procedures, determined by the distance d, between the circuitry of transmitter and receiver. The distance d can be calculated with reference to threshold distance d_0,

$$d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}} \tag{10}$$

The energy dissipated by a SN in data fusion is given as,

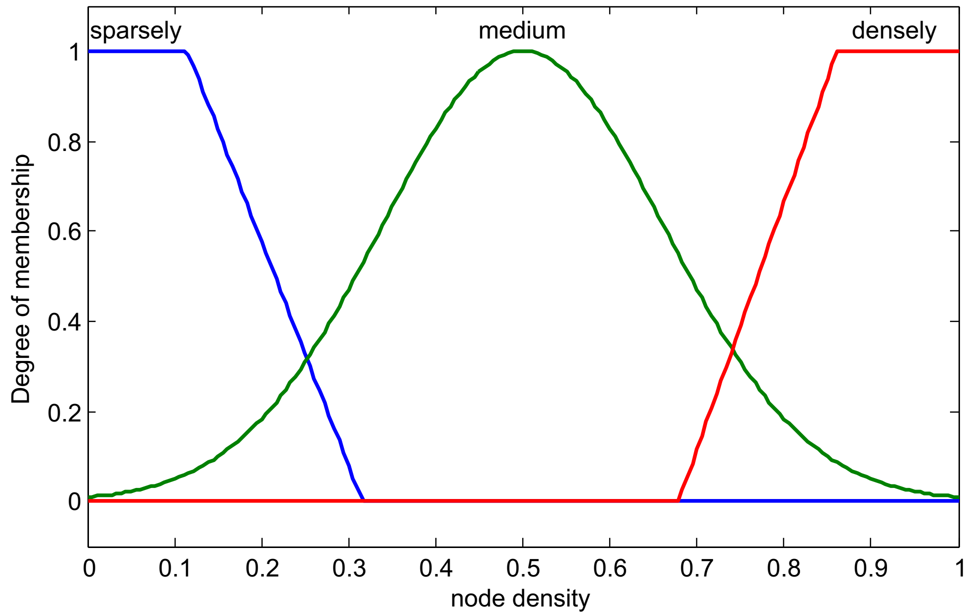


Fig. 3 Fuzzy rule set for input parameter "Node density" for ICFL-HEED protocol

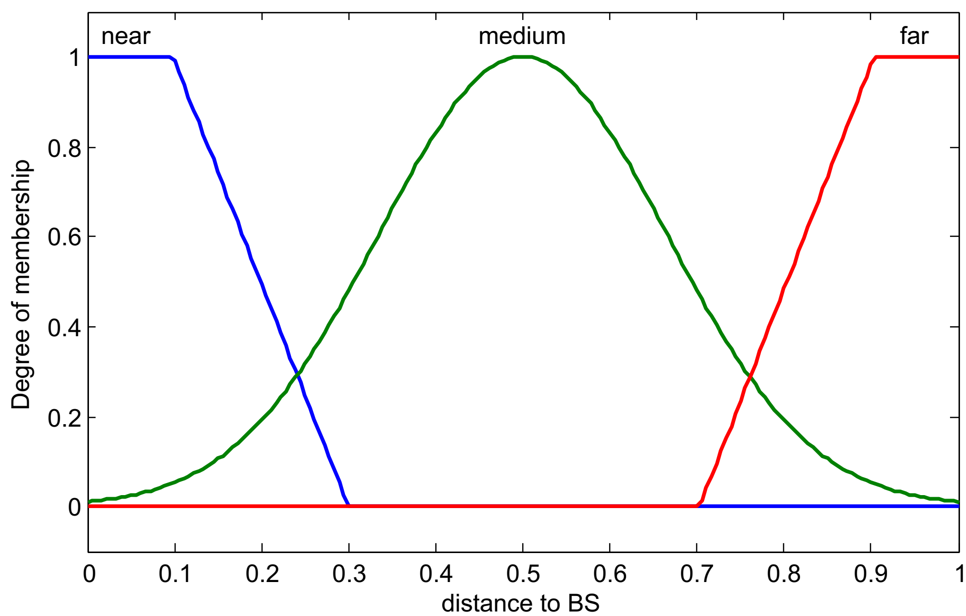


Fig. 4 Fuzzy rule set for input parameter "Distance to BS" for ICFL-HEED protocol

$$E_{fuse} = 5\ nJ/bit/message \tag{11}$$

Here, we partition N_{sn} number of SNs into M_{clus} number of clusters to provide the uniformity in the WSN. Each cluster includes N_{sn}/M_{clus} number of SNs with one CH. In a round, network includes specific tasks that consumes energy i.e., data sensing by each SN, data transmission by SNs to its CH, data reception by CHs, data fusion by CHs and forwarding of fused data packets by CHs to the BS.

The energy consumption by a SN (i.e., cluster member) in a round is given as,

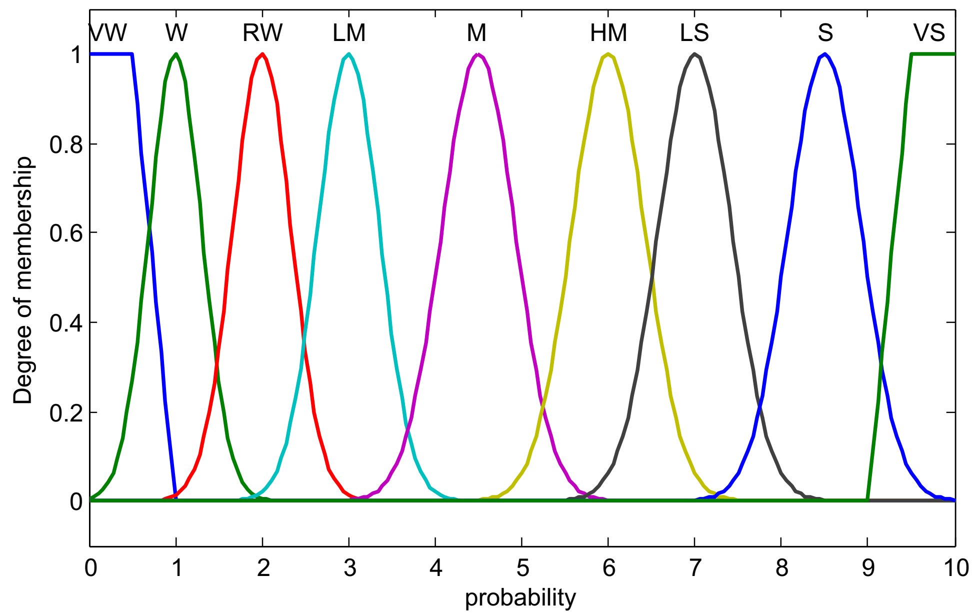
$$E_{SN} = E_{Tx}(L, d) \tag{12}$$

The energy consumption by a CH in a round is given as,

$$\begin{aligned} E_{CH} = {} & \left(\frac{N_{sn}}{M_{clus}} - 1 \right) \times E_{Rx}(L) \\ & + \left(\frac{N_{sn}}{M_{clus}} - 1 \right) \times E_{fuse} \times L + E_{Tx}(L, d) \end{aligned} \tag{13}$$

Here, the first term represents the energy dissipation occurred during data reception by the CH node from its different cluster members. The second term denotes the energy dissipation in data fusion by CH node. Moreover, the last

Fig. 5 Fuzzy rule set for output parameter “Probability” for ICFL-HEED protocol



term shows the energy dissipation by the CH, during data transmission of fused packet to the BS.

The total energy consumption by a cluster for a round is given as,

$$E_{clus} = \left(\frac{N_{sn}}{M_{clus}} - 1 \right) \times E_{SN} + E_{CH} \tag{14}$$

The total energy consumption by the network in a round is given as,

$$E_{round} = M_{clus} \times E_{clus} \tag{15}$$

5 Simulation results and discussion

Here, we evaluate the performance of proposed ICFL-HEED protocol with ICHB-HEED (Gupta 2017) and HEED (Younis and Fahmy 2004) using MATLAB framework. We consider the random deployment of the SNs with BS situated at center of the network field as shown in Fig. 6. Figure 7 shows an instance of cluster formation in a specific round for ICFL-HEED in homogeneous WSNs, where different CHs with their cluster members have been described by varying colors. All input parameters required for simulation environment of proposed work are described in the Table 2. Results have been averaged over 20 different random deployment strategies for each protocol.

5.1 Performance analysis in homogeneous WSNs

This section describes the performance of proposed protocol in homogeneous WSNs. The parametric requirements for homogeneous case are described in Table 3. Fig. 8 indicates the comparative analysis on HEED, ICHB-HEED and proposed ICFL-HEED protocol for number of alive nodes after each round in the network. Table 4 depicts first node dead (FND), half node dead (HND) and last node dead (LND) in the network run and Fig. 9 shows the residual energy of the network after each round. On applying ICHB algorithm in HEED results ICHB-HEED protocol, where lifetime of the network is increased by 30.22% in comparison to HEED. This is because of participation of only higher residual energy nodes for CH selection process using ICHB algorithm. In ICFL-HEED, the combination of ICHB algorithm and FLS is employed in HEED during clustering procedures, where ICHB algorithm is applied on residual energy parameter and FLS is used for secondary parameters i.e., node density and distance to BS. Here, simulation results show that last SN remains alive till 4368 number of rounds. This confirms that WSN’s lifetime is notably improved by 186.99% and 120.38% in comparison to HEED and ICHB-HEED respectively. This is due to the use of distance to BS parameter which allows to elect better CH in the network. For example: (1) Suppose, there arises a competitive condition between two SNs that may behave as tentative CHs with same residual energy and node density. However, one is far and another is near to BS. Based on distance to BS parameter, ICFL-HEED will select the nearer SN for the position of CH, because it will consume less energy for data transmission to the BS. (2) Suppose, another competitive condition arises between two tentative CHs, where CH_1 has higher residual energy than CH_2, however CH_2 is nearer to the BS in comparison to CH_1. In this case, ICFL-HEED will choose CH_1 as final CH even being farther from the BS. This is because ICHB algorithm always elects higher residual nodes in the network. These efficient practices of CH

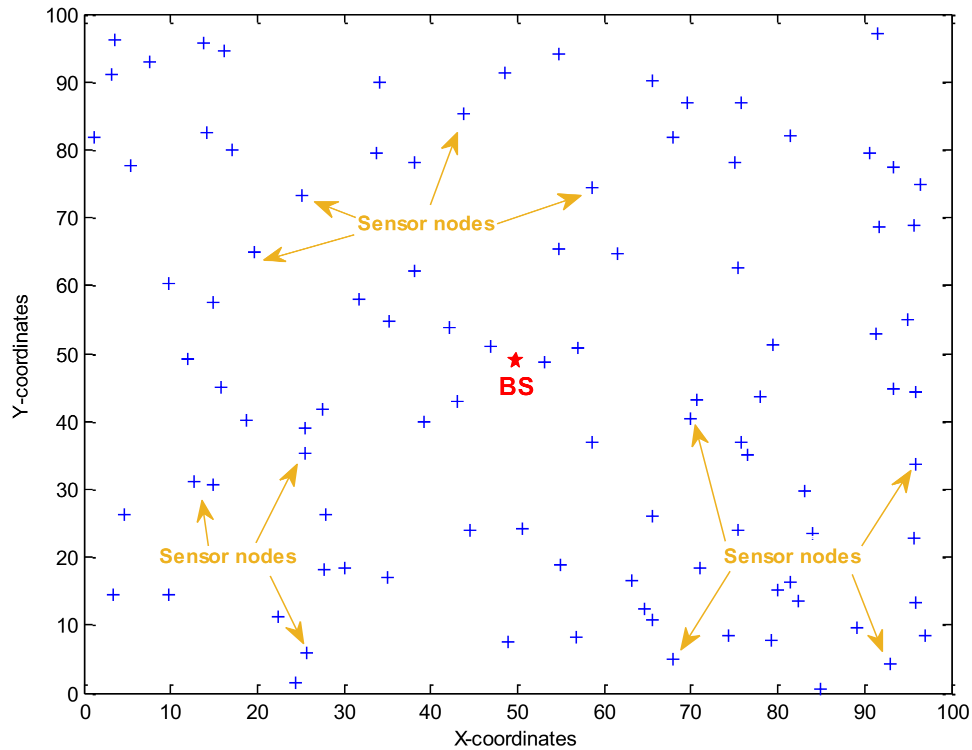


Fig. 6 Initial deployment of sensor nodes in WSN

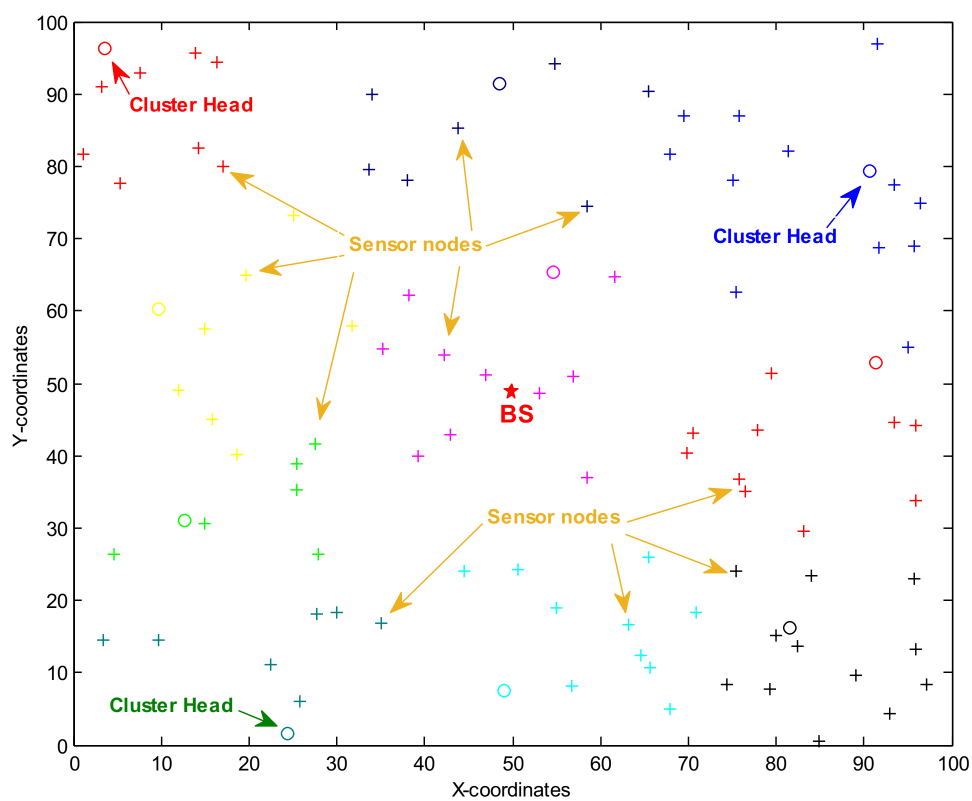


Fig. 7 Cluster formation model for ICFL-HEED protocol

Table 2 Parametric requirement for simulation

Parameters	Values
Size of WSN field ($K \times K$)	100×100 m^2
BS location	(50, 50)
Number of SNs (N_{sn})	100
Message Size (L)	4000 bits
Cluster radius (R)	25 m
Threshold distance (d_0)	75 m
Energy required to run trans-receiver circuitry (E_{elec})	50nJ/bit
Energy required by amplifier for signal transmission at shorter distance (ϵ_{fs})	10 pJ/bit/m^2
Energy required by amplifier for signal transmission at longer distance (ϵ_{mp})	0.0013 pJ/bit/m^4
Energy required for data fusion (E_{fuse})	5 nJ/bit/message

Table 3 Parameters required for homogeneous ICFL-HEED protocol

Variable	Value
Total number of SNs (N_{sn})	100
Initial energy of each SN (E_0)	0.5 J
Total energy of network (E_{hom})	50 J

Table 4 Comparative analysis for HEED, ICHB-HEED and ICFL-HEED protocols in terms of FND, HND, LND in homogeneous WSNs

Protocol	FND	HND	LND	Network lifetime	
				In rounds	Improvement in %
HEED	394	908	1522	1522	0.0
ICHB-HEED	163	885	1982	1982	30.22
ICFL-HEED	282	2291	4368	4368	186.99

selection delay the death of SNs in the network which helps in alleviation of holes and hot-spots problem, minimize & efficient energy consumption of SNs and provide extended network lifetime of WSNs.

Figure 10 depicts the energy consumption variation for consecutive rounds. First, the energy consumption is highest in HEED because of more CHs formation as compared to proposed one. Second, ICHB-HEED and ICFL-HEED form constant CHs in consecutive rounds, whereas HEED does not satisfy this condition. Moreover, ICFL-HEED depicts minimum energy consumption among all, because it uses distance to BS parameter additionally for CH selection. With this reason, it selects nearby SNs as CHs, which require less energy for data transmission to BS in comparison to ICHB-HEED protocol. This proves that ICFL-HEED is more efficient in terms of energy consumption with respect to HEED and ICHB-HEED protocols.

Figure 11 indicates the number of CHs formed per round. HEED utilizes the random election scheme on alive nodes during selection of tentative CHs, which creates higher number of CHs in each round. On the other hand, ICHB-HEED and ICFL-HEED protocols work on higher residual energy SNs without random election scheme. It helps to maintain persistent CHs in the network.

Figure 12 depicts the number of packets sent to the BS for each round. As long as SNs are alive in the network, packets to the BS will be delivered. With this fact, HEED and ICHB-HEED send total 1.26×10^4 and 1.59×10^4 number of packets respectively to the BS till the network runs. Similarly, ICFL-HEED sends 3×10^4 number of packets to the BS during network lifetime.

5.2 Performance analysis in two-level heterogeneous WSNs

This section describes the performance of proposed protocol in two-level heterogeneous WSNs. The parametric requirements for two-level heterogeneous case are described in Table 5. Figure 13 indicates the comparative analysis on HEED, ICHB-HEED and ICFL-HEED protocol for number of alive nodes after each round in the network. Table 6 depicts FND, HND and LND in the network run and Fig. 14 shows the residual energy of the network after each round. Here, the number of alive nodes of ICFL-HEED is increased by 117.20% and 98.64% in comparison to HEED and ICHB-HEED protocols. The reason for providing better results are same as discussed in homogeneous case.

Figure 15 depicts the number of packets sent to the BS for each round in two-level heterogeneous case. As long as SNs are alive in the network, packets to the BS will be delivered. With this fact, HEED and ICHB-HEED send total 1.76×10^4 and 1.87×10^4 number of packets respectively to the BS till the network runs. Similarly, ICFL-HEED sends 3.23×10^4 number of packets to the BS during network lifetime.

The energy consumption variation and number of CHs per round graphs for two-level heterogeneous case are similar as homogeneous WSNs. Due to this, these graphs are not represented here.

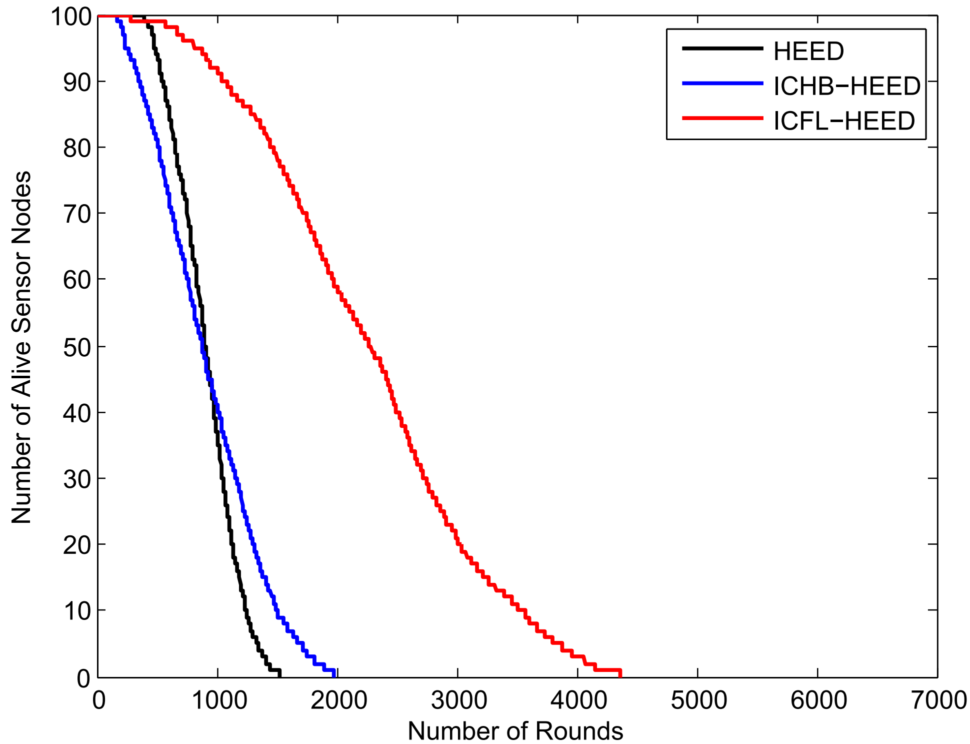


Fig. 8 Number of alive sensor nodes after each round in homogeneous WSNs

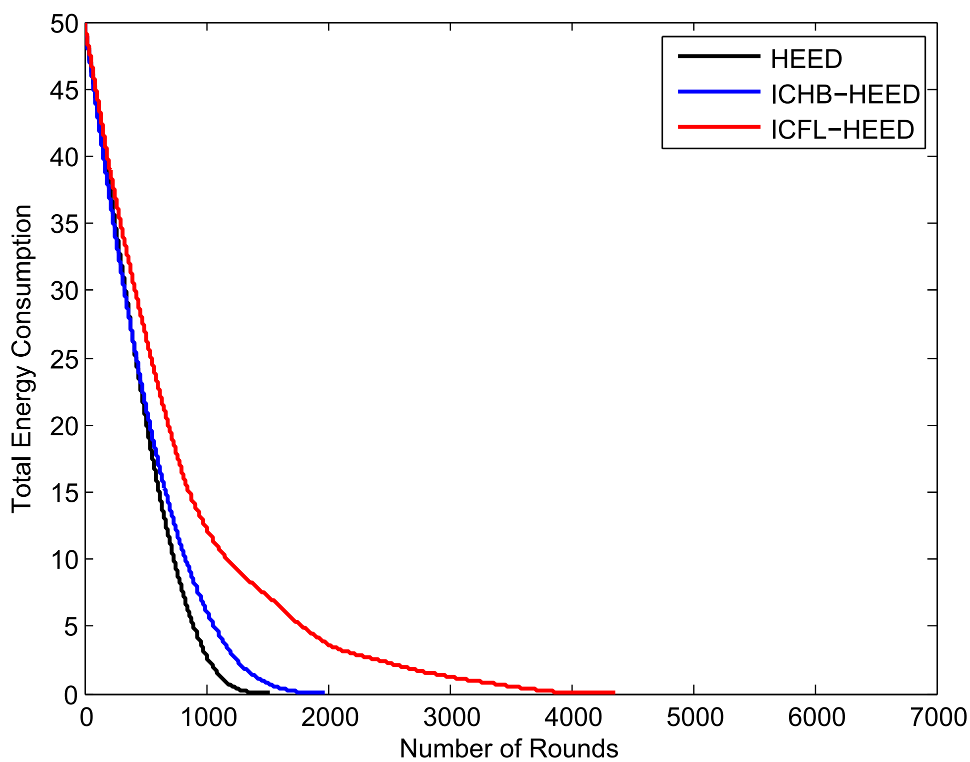


Fig. 9 Remaining energy of the network after each round in homogeneous WSNs

5.3 Performance analysis in three-level heterogeneous WSNs

This section describes the performance of proposed protocol in three-level heterogeneous WSNs. The parametric requirements for three-level heterogeneous case are described in Table 7. Figure 16 indicates the comparative analysis on HEED, ICHB-HEED and ICFL-HEED protocol for number of alive nodes after each round in the network. Table 8 depicts FND, HND and LND in the

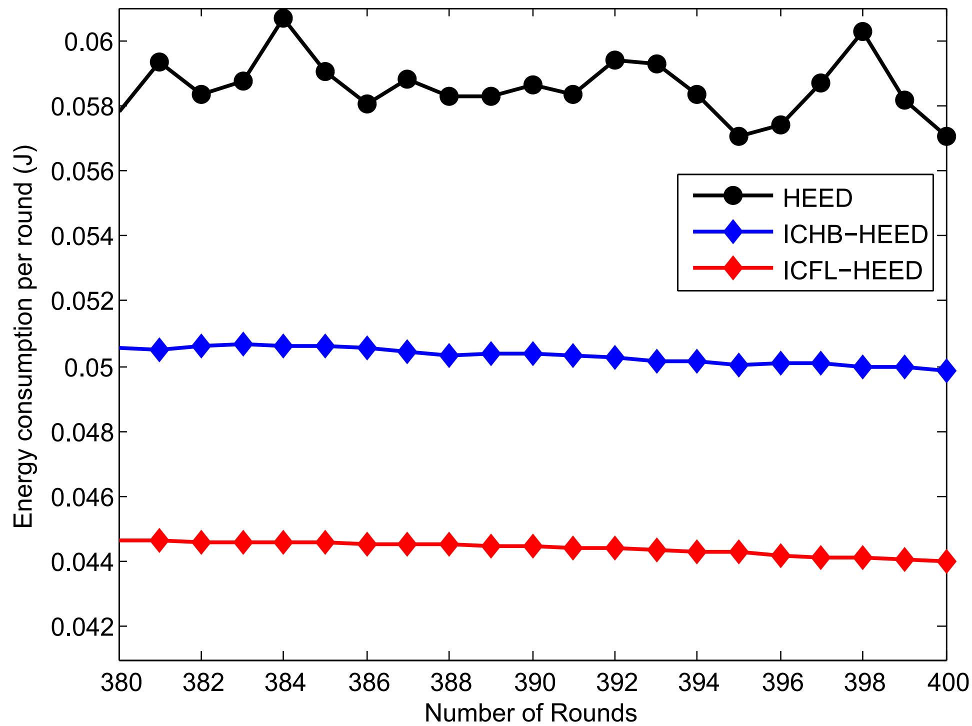


Fig. 10 Energy consumption variation per round in homogeneous WSNs

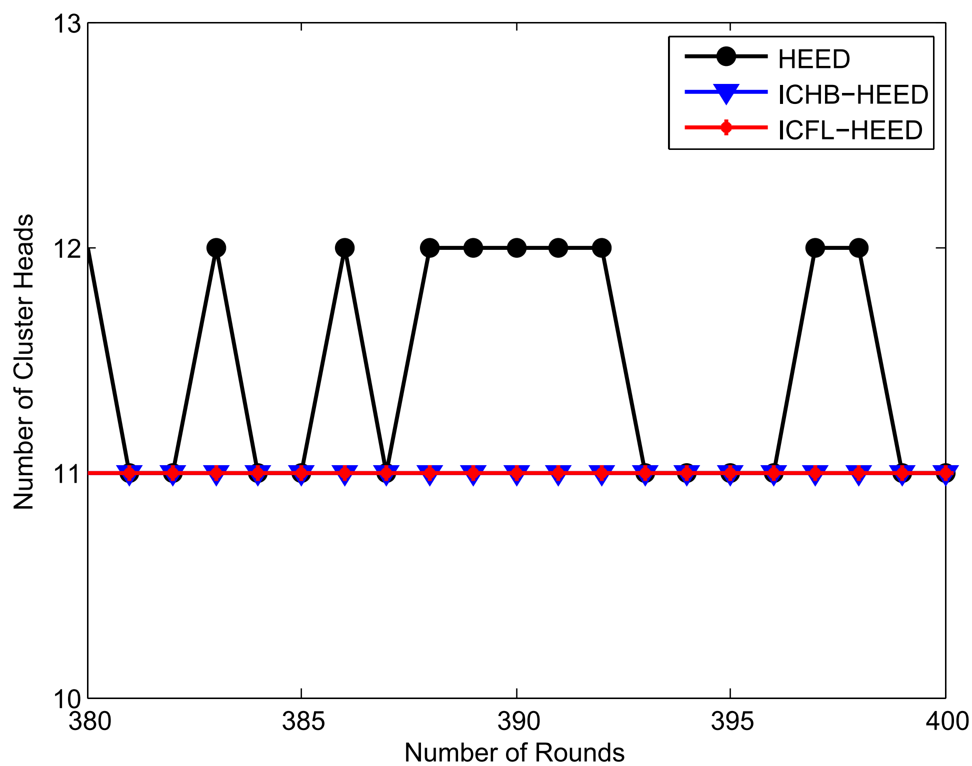


Fig. 11 Number of CHs formed per round in homogeneous WSNs

network run and Fig. 17 shows the residual energy of the network after each round. Here, the number of alive nodes of ICFL-HEED is increased by 58.10% and 35.59% in comparison to HEED and ICHB-HEED protocols. The reason for providing better results are same as discussed in homogeneous case.

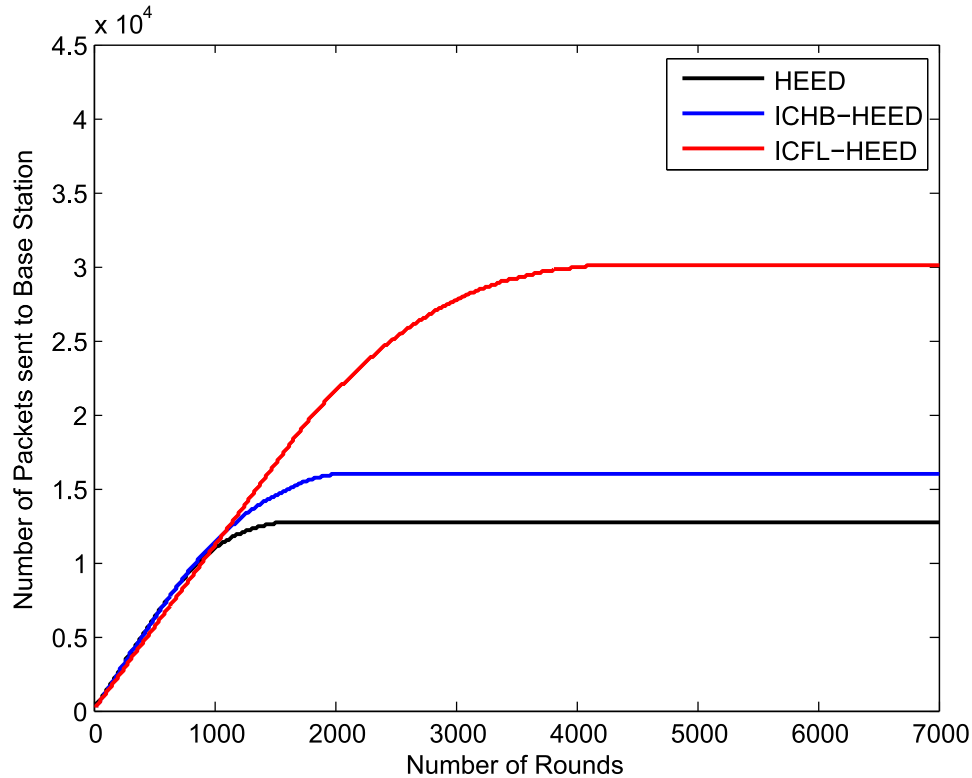


Fig. 12 Number of data packets sent to BS in each round in homogeneous WSNs

Table 5 Parameters required for two-level heterogeneous ICFL-HEED protocol

Variable	Value
Total number of SNs (N_{sn})	100
Fractional value for advanced SNs (μ)	0.39
Fractional value for normal SNs ($1-\mu$)	0.61
Total number of advanced SNs ($\mu \times N_{sn}$)	39
Total number of normal SNs ($(1-\mu) \times N_{sn}$)	61
Energy of an advanced SN ($E_0(1+\Psi)$)	0.8 J
Energy of a normal SN (E_0)	0.5 J
Total energy of network ($E_{two-lev}$)	61.7 J

Table 6 Comparative analysis for HEED, ICHB-HEED and ICFL-HEED protocols in terms of FND, HND, LND in two-level heterogeneous WSNs

Protocol	FND	HND	LND	Network lifetime	
				In rounds	Improvement in %
HEED	404	1067	2354	2354	0.0
ICHB-HEED	238	1092	2574	2574	9.35
ICFL-HEED	330	2112	5113	5113	117.20

Figure 18 depicts the number of packets sent to the BS for each round in two-level heterogeneous case. As long as SNs are alive in the network, packets to the BS will be delivered. With this fact, HEED and ICHB-HEED send total 4.28×10^4 and 4.21×10^4 number of packets respectively to the BS till the network runs. Similarly, ICFL-HEED sends 5.07×10^4 number of packets to the BS during network lifetime.

Further, we have compared the ICFL-HEED protocol with other existing similar kind of protocols under varying level of heterogeneity in Table 9, and results show that proposed protocol is better than these existing ones in terms of network lifetime.

6 Conclusion

This paper confirms the capabilities of proposed ICFL-HEED protocol based on efficient utilization of combination of ICHB algorithm and FLS relying on residual energy, node density and distance to BS parameters for CH selection procedure in HEED protocol. ICFL-HEED protocol proficiently utilizes the capabilities of ICHB algorithm for searching higher residual energy nodes in the network and formation of constant CHs in consecutive rounds. Furthermore, add-ons its capabilities by employing FLS module based on node density and distance to BS parameters; delays the death of SNs, minimizes the energy consumption of SNs, alleviates the holes and hotspots problem in the network effectively which in turn enhances the network lifetime by 186.99% & 120.38%

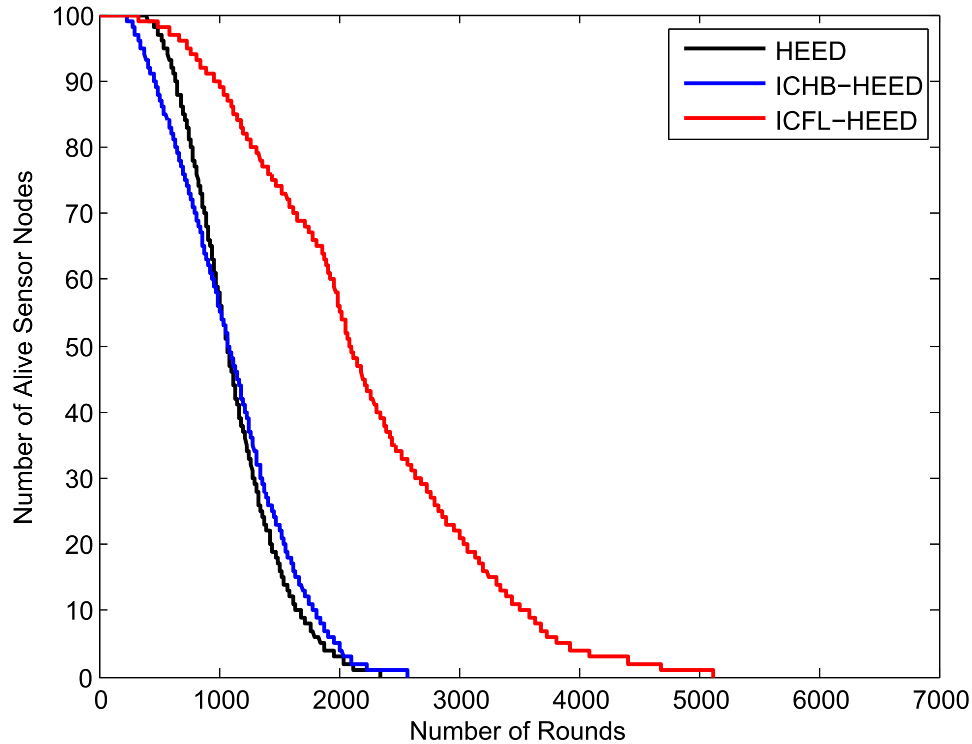


Fig. 13 Number of alive sensor nodes after each round in two-level heterogeneous WSNs

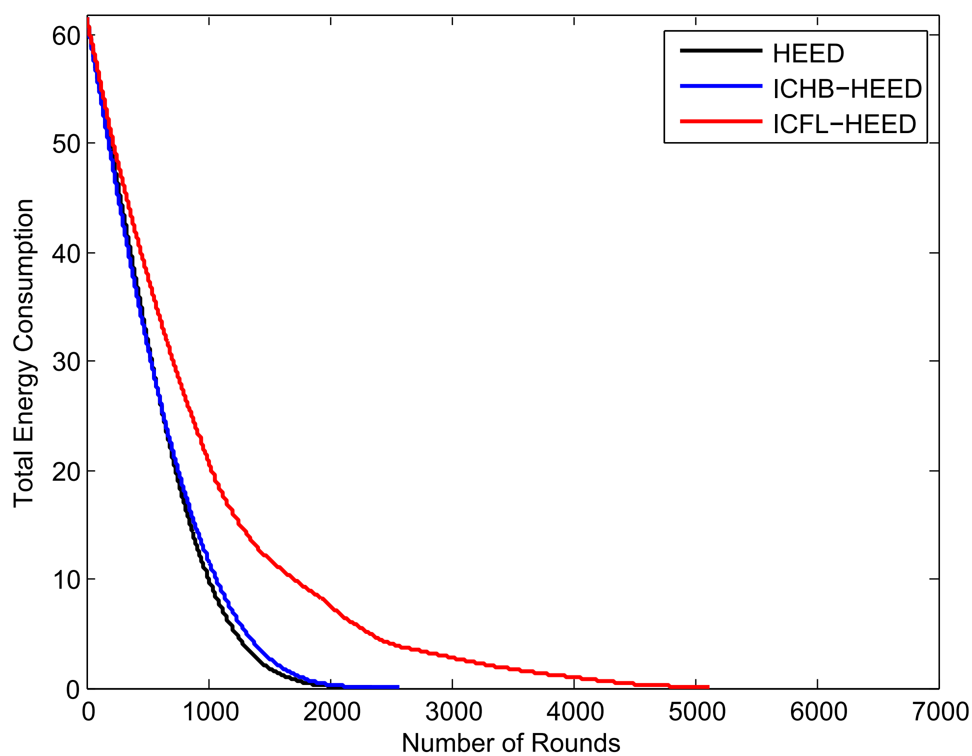


Fig. 14 Remaining energy of the network after each round in two-level heterogeneous WSNs

(in homogeneous case), 117.20% & 98.64% (in two-level heterogeneous case) and 58.10% & 35.59% (in three-level heterogeneous case) in comparison to HEED and ICHB-HEED protocols respectively. Moreover, proposed protocol improves the number of packets sent to BS by 239.68% & 143.18% (in homogeneous case), 164.78% & 125.13% (in two-level heterogeneous case) and 69% & 56.96% (in three-level heterogeneous case) in comparison to HEED and ICHB-HEED protocols respectively. These analyses

Fig. 15 Number of data packets sent to BS in each round in two-level heterogeneous WSNs

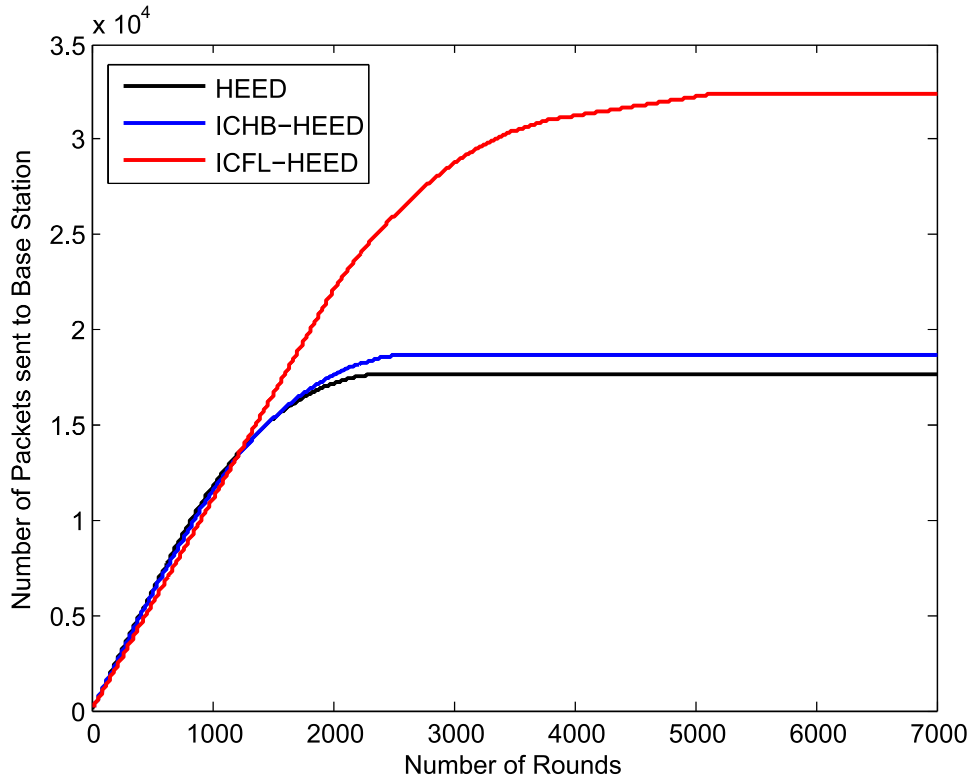


Table 7 Parameters required for three-level heterogeneous ICFL-HEED protocol

Variable	Value
Total number of SNs (N_{sn})	100
Fractional value for super SNs (μ_0)	0.47
Fractional value for advanced SNs (μ)	0.49
Fractional value for normal SNs ($1 - \mu$)	0.51
Total number of super SNs ($\mu \times \mu_0 \times N_{sn}$)	23
Total number of advanced SNs ($\mu \times (1 - \mu_0) \times N_{sn}$)	26
Total number of normal SNs ($(1 - \mu) \times N_{sn}$)	51
Energy of a super SN ($E_0(1 + \Theta)$)	2 J
Energy of an advanced SN ($E_0(1 + \Psi)$)	0.8 J
Energy of a normal SN (E_0)	0.5 J
Total energy of network ($E_{three-lev}$)	92.3 J

Table 8 Comparative analysis for HEED, ICHB-HEED and ICFL-HEED protocols in terms of FND, HND, LND in three-level heterogeneous WSNs

Protocol	FND	HND	LND	Network lifetime	
				In rounds	Improvement in %
HEED	407	1266	5790	5790	0.0
ICHB-HEED	265	1386	6751	6751	16.60
ICFL-HEED	381	1989	9154	9154	58.10

confirm that proposed protocol provide improved results for both homogeneous as well as heterogeneous WSNs.

This work shows its effectiveness in the development of clustering protocols based on the combination of bio-inspired and fuzzy logic system in the direction to achieve optimal results.

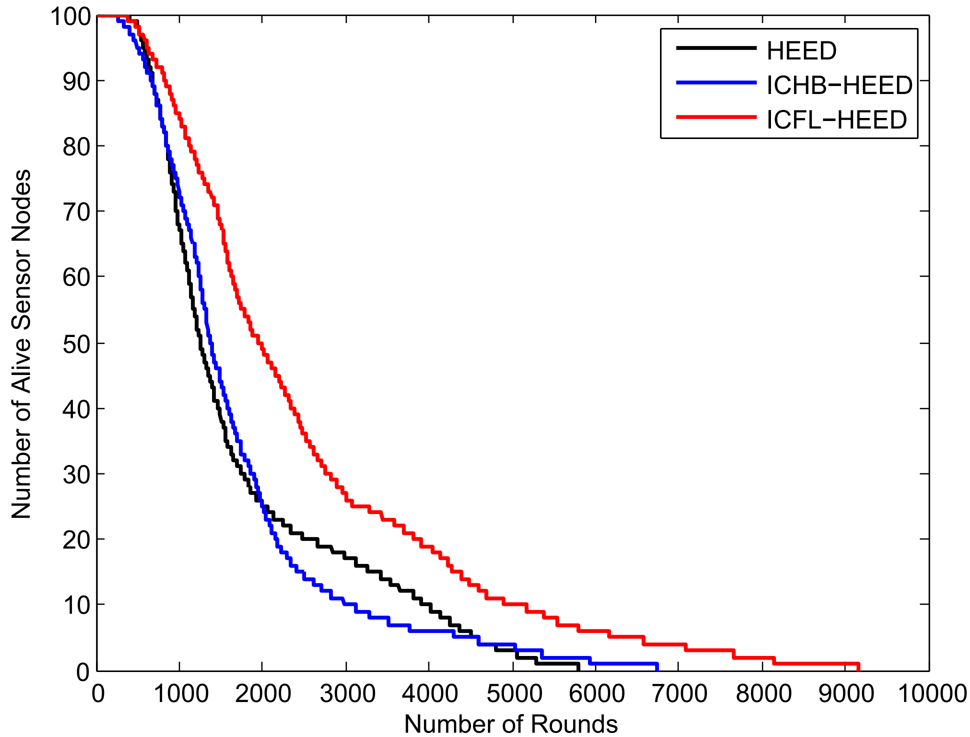


Fig. 16 Number of alive sensor nodes after each round in three-level heterogeneous WSNs

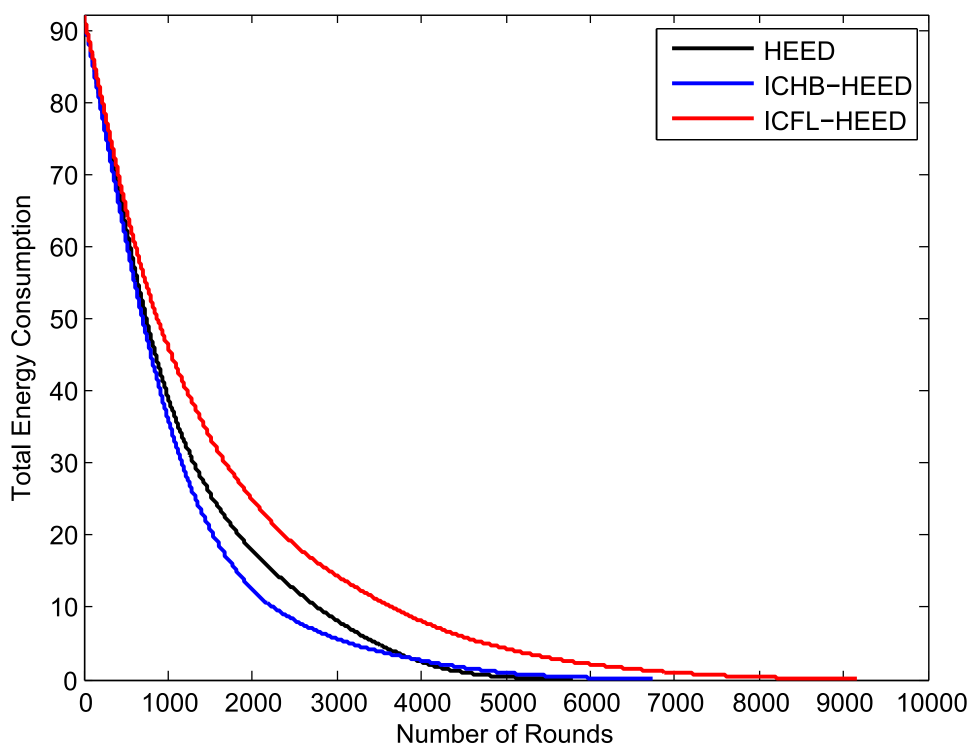


Fig. 17 Remaining energy of the network after each round in three-level heterogeneous WSNs

Fig. 18 Number of data packets sent to BS in each round in three-level heterogeneous WSNs

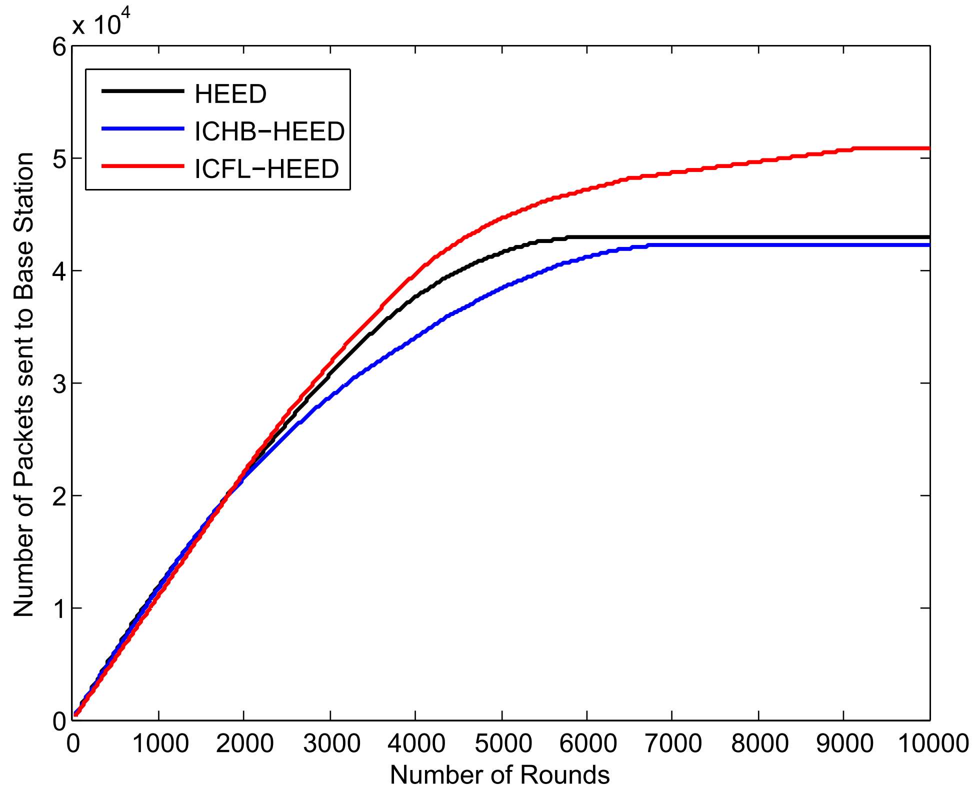


Table 9 Comparative analysis of ICFL-HEED protocol under different level of heterogeneity in terms of FND, HND, LND, and network lifetime

Level of heterogeneity	Total amount of energy (J)	Protocol	FND	HND	LND	Network lifetime (in rounds)
Homogeneous case	50	HEED (Younis and Fahmy 2004)	394	908	1522	1522
		IBLEACH (Salim et al. 2014)	426	1350	1938	1938
		ICHB-HEED (Gupta 2017)	163	885	1982	1982
		ICFL-HEED	282	2291	4368	4368
Two-level heterogeneous case	54.6	DEEC (Qing et al. 2006)	1317	1468	1665	1665
		SEARCH (Wang et al. 2015)	1021	1436	1674	1674
		HEED (Kour and Sharma 2010)	419	979	1730	1730
		ICHB-HEED (Gupta 2017)	201	969	2005	2005
		ICFL-HEED	299	2202	4869	4869
Three-level heterogeneous case	58.7	DEEC (Qing et al. 2006)	1413	1583	1940	1940
		SEARCH (Wang et al. 2015)	1087	1537	1817	1817
		HEED (Kour and Sharma 2010)	417	1070	1952	1952
		ICHB-HEED (Gupta 2017)	229	1038	2214	2214
		ICFL-HEED	303	2305	5628	5628

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