Wireless Networks (2019) 25:2603–2620
https://doi.org/10.1007/s11276-018-1689-0

CAMP: cluster aided multi-path routing protocol for wireless sensor networks

Mohit Sajwan[1] · **Devashish Gosain**[2] · **Ajay K. Sharma**[1]

Abstract

In this article, we propose a novel routing algorithm for wireless sensor network, which achieves uniform energy depletion across all the nodes and thus leading to prolonged network lifetime. The proposed algorithm, divides the Region of Interest into virtual zones, each having some designated cluster head nodes. In the entire process, a node can either be a part of a cluster or it may remain as an independent entity. A non-cluster member transmits its data to next hop node using *IRP-Intelligent Routing Process* (based on the trade-off between the residual energy of itself as well as its neighbor, and the required energy to transmit packets to its neighbor). If on the transmission path, some *cluster member* is elected as a next hop, it rejects *IRP* and transmits the packets to cluster head, which later forwards them to sink (adopting multihop communication among cluster heads). Routing is not solely performed using clusters, rather they aid the overall routing process, hence this protocol is named as Cluster Aided Multipath Routing (*CAMP*). *CAMP* has been compared with various sensor network routing protocols, viz., LEACH, PEGASIS, DIRECT TRANSMISSION, CEED, and CBMR. It is found that the proposed algorithm outperformed them in network lifetime, energy consumption and coverage ratio.

Keywords Routing · Clustering · Network lifetime · WSN

1 Introduction

A wireless sensor network (WSN) consists of tiny, low powered sensors communicating with each other possibly through multi-hop wireless links and collaborating to accomplish a common task [1]. They have naturally emerged as enabling infrastructures for cyber-physical applications that closely interact with external stimulus. Homeland security, physical infrastructures monitoring, health care, building or factory automation are just a few elucidative examples of how these emerging technologies will impact our daily life and society at large [2, 3]. Sensor nodes are small micro-electromechanical systems (MEMS) devices [4, 5], which operate on limited power supplies for pervasive computing [6] and Internet of Things [7] which globally interconnect smart devices and sensor networks. Thus, it becomes essential to keep them functional as long as possible [8]. Conventional, single shortest path routing algorithms like Bellmanford [9] are not well suited in this context as they will cause significant energy depletion of nodes constituting a single shortest path, leading to shorter network lifetime [10]. Moreover, they will cause either significant degradation in the perceived quality at the sink nodes or large queuing delays due to insufficient bandwidth [12]. Traditional routing protocols of computer networks are not apt for energy constrained wireless sensor networks. All these protocols do not consider the limited memory and energy capacity of the sensor nodes.

Thus, many routing protocols [11] have been proposed and specifically tailored to minimize the energy consumption of sensor nodes. They can be broadly classified into flat and hierarchical algorithms [13].

The former approach includes DD [14], SPIN [15] etc. and latter includes LEACH [16], PEGASIS [17], TEEN [18], HEED [19] etc. In flat routing, a node generally transmits its packets to neighboring nodes within its transmission range. Whereas in hierarchical routing a node transmits its data to its nearest cluster head (*CH*) which in

---

✉ Mohit Sajwan
mohitsajwan@nitdelhi.ac.in

[1] National Institute of Technology Delhi, New Delhi, India

[2] Indraprastha Institute of Information Technology Delhi, New Delhi, India

turn sends it to the sink. Both the approaches have their own advantages and drawbacks. The founding principle of flat routing is cooperative multi-hop forwarding, but in doing so, a large volume of traffic is generated [in simplistic case a packet from each node is generated and forwarded to the Base Station (BS) or sink[1]] and it results in energy depletion of many nodes. Whereas, in hierarchical routing scheme, there are some designated cluster head nodes which are responsible for data aggregation from their cluster members and finally sending the aggregated information to the sink themselves. This conserves the energy of cluster members but puts a heavy toll on *CH*s [20, 21]. Also, since all the sensor nodes are bound to latch themselves to some *CH*, they may do so by communicating out of normal radio range. This further results in poor QoS [22] and degraded performance.

CAMP attempt to provide a solution to the aforementioned problems by incorporating both hierarchical and flat routing strategies. It primarily divides the ROI into equal sized zones, each having a unique *CH*. In *CAMP*, only those nodes which lie in the communication range of *CH*s become the part of the cluster, and adopts hierarchical routing. Remaining nodes act as independent entities, and adopts multi-hop routing for communication with BS. The major contributions of this research are:

- We propose a novel routing protocol CAMP, which aims at *increasing the network lifetime*, by intelligently routing the sensed data towards the sink.
- Important tasks like CH selection, are carried out by sink itself; thereby reducing the load on sensor nodes.
- Under its operation no node communicates more than d_0 distance (discussed in detail in Sect. 3.4) resulting in tremendous energy conservation.
- CAMP ensures that CHs do not communicate directly with sink. We developed an intelligent routing process (IRP) and CHs adopt IRP to avoid long links (discussed in Sect. 4).
- CAMP inherits the merits of both flat and clustered routing scheme. A non-cluster member can transmit its data using both the aforementioned schemes.[2]
- We compared CAMP with other established routing protocols under various simulation settings (varying area, number of sensor nodes and sink locations) and found that it outperformed all. We observed the 910% performance gain against LEACH [16], 213% against PEGASIS [17], 671% against CEED [23] and 108% against CBMR [24].

The rest of the paper is organized as follows. In Sects. 2 and 3, we present our related research and formulate our system model and the data aggregation schemes. The *CAMP* protocol is described in detail in Sect. 4. Next, in Sect. 5, we describe comparative analysis and simulation results of CAMP protocol compared with other known algorithms. Later, we describe concluding remarks in Sect. 6. Finally, in Sect. 7 we present future work.

2 Related research

In WSN, after sensors are deployed the main task of each sensor is to transmit its sensed data periodically to the base station (BS) or sink[3]). The simplistic approach to achieve this is Direct Transmission [shown in Fig. 1(a)], which allows nodes to directly communicate with BS [16]. However, it leads to uneven energy depletion among the sensor nodes.Therefore, the nodes which are placed far from the BS, would drain out faster in comparison to the nodes which are placed closer to the BS. The high disparity in energy consumption of nodes, ultimately shortens the overall network lifetime, violating the basic criteria of WSN (viz., energy conservation of sensor nodes). To overcome such issues, Heinzelman et al. [16] proposed a Low Energy Adaptive Clustering Hierarchy (LEACH) protocol [shown in Fig. 1(b)], where network is divided into various clusters, while network operation is divided into various rounds. Each round is further divided into two phases: the setup and the steady state phase. In the setup phase, each node computes a threshold value followed by a random number. If this random number has a lesser value than the threshold, it will elect itself as a cluster head. Each node latches itself to the nearest cluster head, leading to a cluster formation. During steady state phase, cluster head aggregates the data packets received from its cluster members and by adopting single hop communication it send data packets to BS. LEACH, improved the network lifetime, eight times more than the direct transmission. Similarly, M-LEACH [25] is the multihop version of LEACH, where a CH transmit data packets to the sink using other CHs as intermediate hops (discarding the direct communication of each CH with sink as proposed in LEACH). Centralized LEACH (C-LEACH) [26] is another variant of LEACH, where BS is solely responsible for cluster formation. TL-LEACH [27] is an extension of M-LEACH where two level hierarchical tree structure (primary and secondary) of CHs is formed. Primary CHs receive data packets from sensor nodes, and secondary CHs, higher up in the hierarchy, receive data packets from primary CHs (creating a cluster of CHs) resulting in

---

[1] In this article, sink and BS are interchangeably used.

[2] Among the two schemes, it greedily selects that approach which results in less energy consumption.

[3] In this article, sink and BS are interchangeably used.

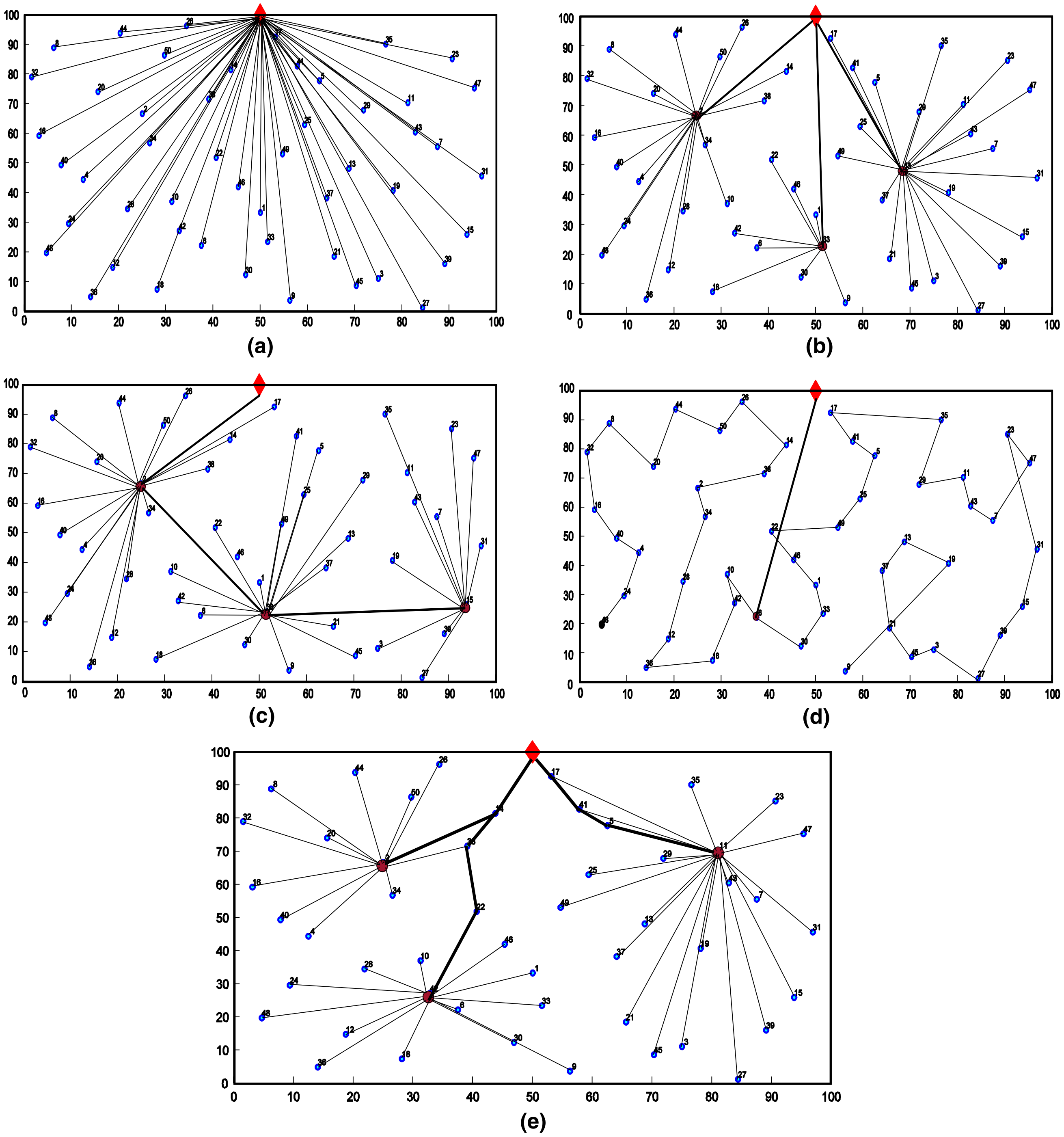

Fig. 1 Communication paths under various routing protocols. **a** Direct transmission, **b** LEACH, **c** CEED, **d** PEGASIS, **e** CBMR

increased network lifetime. Successively, in Hybrid Energy Efficient Distributed Clustering (HEED) [19] authors introduce a new technique for cluster head selection which is the hybridization of residual energy and communication cost (incorporating node degree).

In order to improve the existing clustering protocols, Ahmad et al. [28] proposed $(ACH)^2$; an adaptive clustering scheme, which regulates the CH election in such a way that uniform load on CHs is ensured. In this approach each round is divided into five phases. When predefined number of CHs are elected, the round is completed, otherwise the process gets repeated. This incurs an additional delay in the network as round completion takes prolonged time. The other issue with this approach is the random selection of CHs, which sometimes may exclude the desired node (e.g. high energy node) for not participating in the cluster head election process.

In [29] authors propose Hamilton Energy-Efficient Routing Protocol (HEER), where CH selection is similar to LEACH, but instead of forming the clusters in each round, they are created only once, viz., at the commencement of the routing protocol. This decreases delay and energy consumption of the network. After the one-time cluster formation, a Hamiltonian path (constituting of nodes) is constructed in each cluster leading to multiple virtual chains in the network. For each Hamiltonian path, node having the highest residual energy will be elected as a CH for that round. In all subsequent rounds, virtual chains remain same but CHs vary. This approach has one shortcoming; since cluster formation happens once for entire protocol operation, the success of this approach depends on how well and balanced the clusters are formed. If for instance, all the initial CHs elected are very close to each other, it will lead to non-uniform cluster density, with many nodes communicating along long links, eventually degrading the overall performance of the network.

Later, Huynh et al. [30] propose a new CH selection scheme where each node competes to become a CH. The nodes having the high residual energy are given preference over low residual energy nodes. Once the CHs are elected and clusters are formed, again the CH having the high residual energy and in close proximity to the sink are elected as parent CHs for all other remaining CHs. It is a two-step process; first clusters are formed and later among all CHs their parent CHs are elected. The parent CH collects data of all the CHs (viz., the entire networks sensed data) and transmits it to the sink using multi-hop forwarding.

In [31] sabet et al. propose a distributed energy efficient multi-level route-aware clustering algorithm for WSNs (MLRC). It has three phases; CH election, route construction (among CHs) and cluster formation. All those nodes whose residual energy is greater than the average energy of the network, compete for CH selection. CHs are elected using min-max normalization technique by considering two factors, residual energy, and distance from the base station of each node. Once the CHs are elected they form a route among themselves to transmit packets in a multi-hop manner to the sink. Later, in cluster formation phase, every non-CH node latches to some CH node based on the trade off between closeness to the CH and number of existing cluster members of the CH.

In all aforementioned approaches, authors focus on evenly distributed cluster density but in [32] Xia et al. propose UCCGRA protocol, which is an improved unequal clustering algorithm for WSNs. The main idea of this approach is that the cluster heads closer to the sink should support smaller cluster size as they will consume less energy during the intra-cluster data processing, and preserve more energy for the inter-cluster relay traffic. Once the CHs are elected (based on the aforementioned goal), using connected graph theory inter CH communication takes place.

All routing protocols, in the family of hierarchical routing schemes, suffer the problem of the early death of CHs (due to high load of cluster members), thus to overcome this, Lindsey et al. [17] proposed Power Efficient Gathering in Sensor Information Systems (PEGASIS). Similar to the aforementioned algorithms, PEGASIS also operates in rounds. At the beginning of each round, all the nodes virtually align themselves in one single chain, with any one node being a leader [shown in Fig. 1(c)]. Each node communicates only with a close neighbor and takes turns transmitting to the BS, thus reducing the amount of energy spent per round. Though it outperforms LEACH by 100–300% (for FND_Statistics[4]), but its practical deployability is not a trivial task. PEGASIS relies on a far fetched assumption that nodes have global knowledge of the network, viz., every node knows the location of all other nodes in the network, which makes it poorly scalable. Also, it can not opt for delay sensitive applications because whenever a node dies, the entire chain is reconstructed, which incurs, large delays. Similar to PEGASIS, Chatterjee and Kumar proposes [33] 'green' and 'udreen' algorithms for Gaussian and uniform distributed sensor networks respectively.

Recently, Sivraj et al. merged chain based and tree-based routing in [34]. They propose a novel multi-branch tree-based clustering approach to extend the lifetime of the WSNs. This protocol incorporates the concept of independent node set (INS)[5] and dominant set in the construction of routing tree. The main idea of this approach is to create 'n' levels and then for each level designate an independent node set which leads to the formation of the backbone of the tree. The levels start from sink and end at leaf nodes. Sink acts as a parent for INS of level 1, and level 1 INS nodes act as parents for INS nodes of level 2 and so on. This leads to the tree construction in the network. The remaining nodes at each level create virtual chains terminating at some INS of the same level. These

---

[4] The time from the start of the network operation to the death of the first node in the network.

[5] Set of nodes in which no node is the immediate neighbor any other node.

chains can be visualized as sub-branches to the main routing tree.

In GSTEB [35] authors proposed to make a single node as the root node (node having maximum residual energy) rather than electing multiple CHs. On the beginning of each round, sink broadcasts the node ID of the elected root node. Each node in the field has only two alternatives; if there is some node present in between the transmitting node and the root node, transmitting node elects the intermediate node as next hop otherwise it assumes root node to be its next hop directly [depicted in Fig. 1(d)].

Tree Based Clustering (TBC) [36] is also an improvement of LEACH. Initially, $p\%$ of nodes are elected as CH followed by cluster formation phase. In LEACH each cluster member communicates directly to its CH, which leads to high energy dissipation of those sensor nodes which resides far from the CH. To avoid long link communication inside each cluster, TBC divides each cluster into α levels, where α is a design parameter. Node residing in Lth level elects the closest node belonging to $(L-1)$th level. Eventually, a tree like structure is created inside the cluster rooted at CH which is assigned the 0 level [shown in Fig. 1(e)].

Very recently, in [23], Gawde et al., proposed a Centralized Energy Efficient Distance (CEED) based routing protocol [depicted in Fig. 1(c)], which is an enhancement of LEACH, primarily improving the cluster head selection and cluster formation. In CEED, *CH* selection is based on residual energy and distance of each node from the sink. In cluster formation also, each node chooses its *CH* on the basis of residual energy and distance parameter. Later, it constructs a chain between cluster heads for transmitting data packets to the sink (in a multihop manner).

In [32] and [24] authors argue that, rather than CHs transmitting data directly to BS, they must adopt multihop paths towards the BS. Cluster Based Multipath Routing (CBMR) [24] works in three phases (1) neighbor discovery, (2) topology construction, (3) cluster head selection and formation [illustrated in Fig. 1(e)]. Initially, each node sends its neighbor information to the sink. On reception of neighbor information from all the nodes, sink creates the topology and selects the *CH* on the basis of residual energy and node degree. Later, *CH* aggregate data from cluster members[6] and forwards data packets to the sink using multihop communication along the path specified by the sink itself.

3 System model

3.1 Network model

A wireless sensor network can be represented as an undirected graph $G=(V,E)$, where V is the set of sensor nodes and E describe the adjacency relation (set of links) between the nodes. E is dependent upon transmission range of a sensor. In our model, we have assumed that N number of nodes are randomly deployed in the terrain, and each node has an *ID* (unique identity) associated with it. A node is represented as i (its ID), and $N(i)$ is a set of alive neighbors of node i.[7]

3.2 Assumptions

1. Sensor nodes are stationary and are randomly deployed in the terrain.
2. The sensor nodes are aware of their locations through some localization techniques [38].
3. Sensor node's circuitry consumes same energy in transmission and reception of packets.
4. Once the nodes are deployed their battery is irreplaceable.
5. Nodes can adjust their transmission level based upon the distance from the receiver.
6. Each node is capable of aggregating data, received from its neighbors.
7. Communication channel is reliable and error free.
8. There is only one Base Station (or Sink) which is fixed and can be placed at the center, corner, or at far from the terrain.

3.3 Aggregation model

In *CAMP*, each node is capable of doing data aggregation, as it significantly decreases the energy consumption of the network. Figure 2 depicts the simplistic scenario, where nodes are placed in linear order. Each node has data packets to be transmitted to the sink. In the first case, since each node transmits (without data aggregation), a total of $N(N+1)/2$ data packets are observed in the network. While for the other case (using data aggregation), a total of N data packets are observed in the network (each node aggregate its sensed data with the data received from the preceding node). Hence using data aggregation, $(N+1)/2$ data packets would be reduced in the network.

---

[6] Nodes latch themselves to *CH* based on RSSI value of the *CH* or on the basis of distance to *CH* [37].

[7] Nomenclature of all the symbols are tabulated in Table 1.

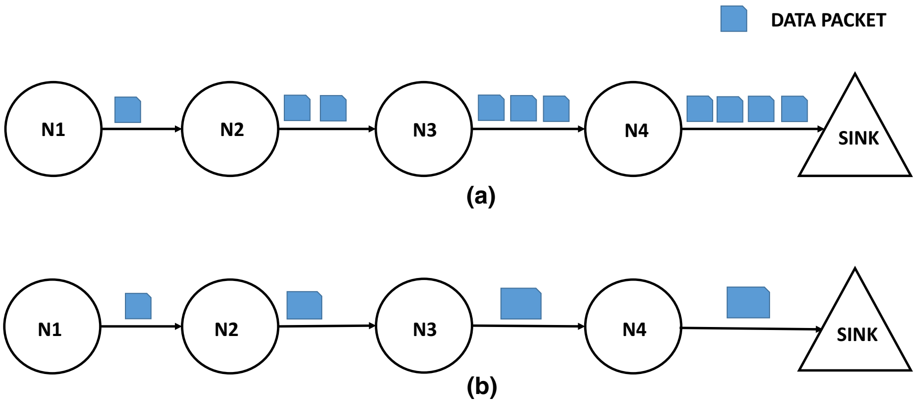

Fig. 2 Data transmission with **a** no data aggregation **b** data aggregation

Table 1 Nomenclature table

Symbol	Description
FND	First Node Dead
LND	Last Node Dead
BS	Base Station
CH	Cluster Head
E_{elec}	Energy consumed by transmitter and receiver circuitry
E_{fs}	Energy consumed in free space model
E_{mp}	Energy consumed in multi path model
k	Data packet size
NCM	Non cluster member node
CM	Cluster member node
N	Total number of nodes
P	No. of Cluster member nodes in a zone
Q	No. of direct set nodes in a zone
R	No. of non cluster member nodes in a zone
S	Number of cluster heads
T	Number of non cluster heads
D_{agg}	Set of nodes performing data aggregation
ID	Identity of a node
ROI	Region of Interest
IRP	Intelligent Routing Process
$\lvert A \rvert$	Cardinality of set *A*
NS	Neighbor set
PNS	Progressive neighbor set

3.4 Energy model

In wireless sensor networks, energy scavenging is of utmost importance as each sensor node has a limited battery supply. WSN once deployed is left undisturbed with an intention of periodic (or event driven) data collection. A sensor node consists of many functional units constituting sensor, processor, memory, battery and transceiver unit. It is an established fact that among all, transmitter consumes maximum energy [39]. The first order radio model suggests that if a node i has to transmit k bit data to node j, which are d distance apart, then energy consumed by node i is given as

$$E_{Tx}(k,d) = \begin{cases} E_{elec} * k + E_{fs} * k * d^2 & \text{if } (d < d_0) \\ E_{elec} * k + E_{mp} * k * d^4 & \text{if } (d \geq d_0) \end{cases} \quad (1)$$

And energy consumed by node j is given as

$$E_{Rx}(k,d) = E_{elec} * k \quad (2)$$

In the above equations, E_{elec} represents the energy that is consumed by transmitter or receiver circuitry. E_{fs} and E_{mp} indicate the energy consumed by the transmitter amplifier for free space and multipath model respectively. And d_0 is the threshold value equals to $\sqrt{\frac{E_{fs}}{E_{mp}}}$.

3.5 Network life time

In this work, we adopt *First Node Dead Statistics (FND_Stats)* as a metric for network lifetime. It is defined as the interval between the rounds where the first node start transmitting data and the round where the first node gets dead [35, 40].

4 CAMP algorithm

CAMP is a self-sustained pro-active routing protocol in which at any instance of time, each node stores the information about its neighbors[8] only, thereby reducing the memory requirements. The neighbor table (*Nbr_Table*) of each node has only three fields:

---

[8] Neighbors are those nodes which lie in the communication range of a given node.

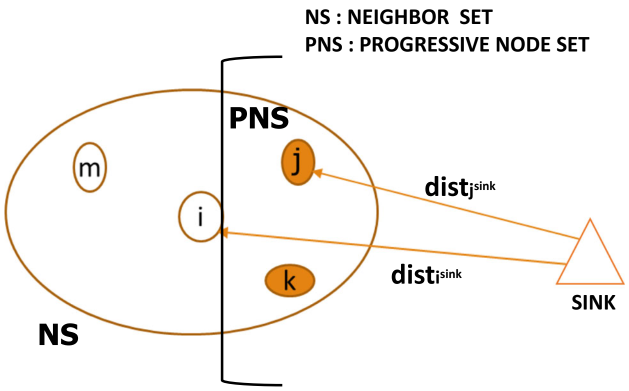

Fig. 3 Progressive node set

1. Neighbor ID (*Nbr_ID*).
2. Location of neighbor (*Nbr_Loc*).
3. Residual energy of the neighbor (*Nbr_Residual_Energy*).

The fundamental idea of *CAMP* is to have balanced *CH* density in ROI. Thus, it divides the ROI into η equal sized *zones*, such that each *zone* is assigned at least one *CH* (or multiple *CH*s depending on the node density of the *zone*), which makes *CH* density uniform across the field. Also, in existing clustering algorithms each node is bound to latch to some *CH*, whereas in *CAMP* nodes are not forced to join any *CH*. If *CH* and sensor node both are in communication range, then only, peering will occur else sensor node performs multihop (or flat) routing. In CAMP, network management task (such as *CH* selection) has been taken away from nodes and are given to BS, to reduce the overall complexity of the network. This algorithm is generic in nature and has not been designed to meet the specific requirements of any application. It also performs well with BS located at different locations. We placed BS at three locations (i) center of the field (ii) corner of the field (iii) far away from the field, and found that, in all scenarios, it outperformed other protocols such as DIRECT TRANSMISSION, LEACH [16], PEGASIS [17], CEED [23], and CBMR [24] with respect to various network parameters.

CAMP works in two phases: *Setup Phase* and *Routing Phase (divided into rounds)*. In *Setup Phase*, each node exchanges its information with their neighbors and update their *Nbr_Table*. Those nodes for which BS is a direct neighbor constitutes *Direct_Set* and throughout their lifetime, they transmit their data directly to BS only. Later, BS virtually divides the ROI into equal sized *zones* and designates a *CH* to each *zone*. In each *zone*, all those nodes which are one hop away with *CH* (in communication range) constitute the cluster and are termed as cluster members (*CM*). Rest of the nodes are designated as non-cluster-member (*NCM*). *Direct_Set* nodes are excluded from this grouping process. If total cluster heads are more than number of regions, then those regions which have maximum remaining *NCM*s are assigned additional *CH*s. Formally, it can be represented as,

$$\sum_{\forall zones} |NCM| + |CM| + |Direct\_Set| = N \tag{3}$$

In *Routing Phase*, a node after sensing the environment, transmit its packets towards BS either in multihop or in a hierarchical manner. If a node is not a part of any cluster, the former approach is used otherwise latter approach is adopted. To adopt multihop communication, a node undergoes *IRP*. For this, it constructs a *ProgressiveNodeSet* (*PNS*) depicted in Fig. 3. Nodes m, j, and k constitute the Neighbor Set (*NS*) of node i. Any node which belongs to *NS*, and is also present in between Node i and sink, constitutes the *PNS* (nodes j and k). For instance, node j must satisfy the following two conditions, to become the member of *PNS* of node i,

1. node $j \in NS$.
2. $dist_i^{sink} - dist_j^{sink} > 0$.

The operation of CAMP protocol is explained with the help of flow diagram in Fig. 4. [For successful *CAMP* operation, total *CH*s must be greater than or equal to total virtual zones viz., four.[9]]

4.1 Energy consumption in a virtual zone

Let us assume there are total N_{zone} nodes in the zone. Since a zone has cluster members (*CM*), non-cluster members (*NCM*) and direct set nodes (*Direct_Set*).

$$N_{zone} = P + Q + R$$

where

$$P = |CM|_{zone};\ Q = |Direct\_Set|_{zone};\ R = |NCM|_{zone}$$

where *CM* includes cluster head (*CH*) and non cluster head (*NCH*).

$$P = S + T$$

where

$$S = |CH|; T = |NCH|$$

Energy consumed in a round,

$$E_{Round} = E_{DT} + E_{NCM} + E_{CM}$$

Energy consumed by the nodes constituting the *Direct_Set* (*Q*)

---

[9] Ideally 5–6% of the total nodes must be designated as *Total_CH*s [26].

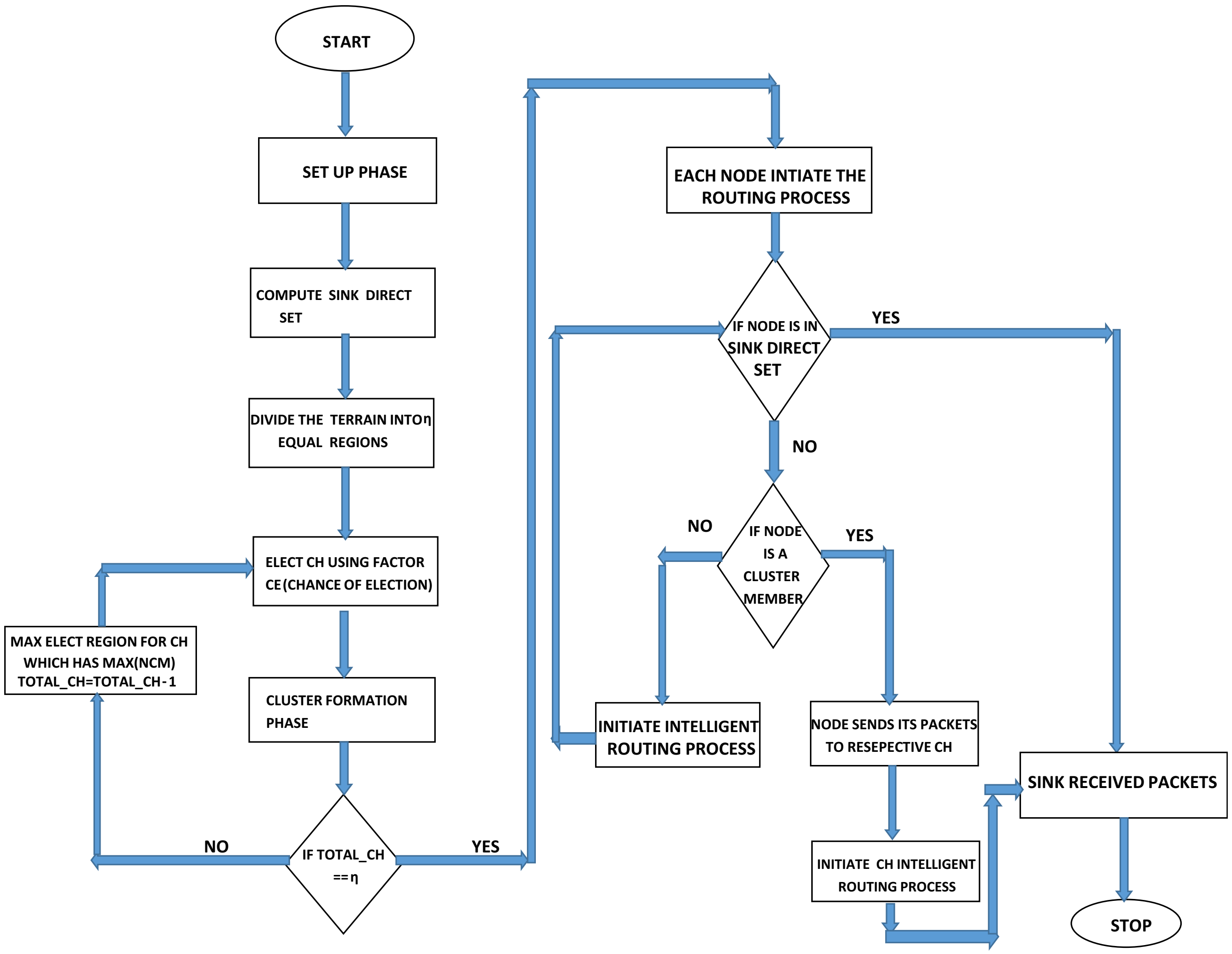

Fig. 4 Flow chart depicting the control flow (value of *Total_CH* must be at least four)

$$E_{DT}(ID,k,d)=\begin{cases} E_{elec}*k+E_{fs}*k*d^{2} & \text{if } ID\notin D_{agg} \\ E_{elec}*k+E_{elec}*k*R & \\ \quad +E_{D_{agg}}*k*(R+1)+E_{fs}*k*d^{2} & \text{if } ID\in D_{agg} \end{cases} \tag{4}$$

Energy consumed by the nodes constituting the *NCM set (R)*

$$E_{NCM}(ID,k,d)=\begin{cases} E_{elec}*k+E_{fs}*k*d_{neighbor}^{2} & \text{if } ID\notin D_{agg} \text{ and } d<d_{0} \\ E_{elec}*k+E_{mp}*k*d_{neighbor}^{4} & \text{if } ID\notin D_{agg} \text{ and } d\geq d_{0} \end{cases} \tag{5}$$

$$E_{NCM}(ID,k,d)=\begin{cases} E_{elec}*k+E_{elec}*k*(R-1) & \\ \quad +E_{D_{agg}}*k*(R)+E_{fs}*k*d_{neighbor}^{2} & \text{if } ID\in D_{agg} \text{ and } d<d_{0} \\ E_{elec}*k+E_{elec}*k*(R-1) & \\ \quad +E_{D_{agg}}*k*(R)+E_{mp}*k*d_{neighbor}^{4} & \text{if } ID\in D_{agg} \text{ and } d\geq d_{0} \end{cases} \tag{6}$$

Cluster member nodes (P) consist of two types of nodes *CH* and *NCH*.

$$E_{CM}=E_{CH}+E_{NCH} \tag{7}$$

$$E_{CH}(ID,k,d)=\begin{cases} E_{elec}*k+E_{elec}*k*((P/S)-1) & \\ \quad +E_{D_{agg}}*k*(P/S)+E_{fs}*k*d_{sink}^{2} & \text{if } d<d_{0} \\ E_{elec}*k+E_{elec}*k*((P/S)-1) & \\ \quad +E_{D_{agg}}*k*(P/S)+E_{mp}*k*d_{sink}^{4} & \text{if } d\geq d_{0} \end{cases} \tag{8}$$

$$E_{NCH}(ID,k,d)=\begin{cases} E_{elec}*k+E_{fs}*k*d_{CH}^{2} & \text{if } ID\notin D_{agg} \\ E_{elec}*k+E_{elec}*k*R & \\ +E_{D_{agg}}*k*(R+1)+E_{CH}*k*d_{sink}^{2} & \text{if } ID\in D_{agg} \end{cases} \tag{9}$$

Each *zone* consists of three mutually disjoint set of sensor nodes, *CM*, *NCM* and *Direct_Set*. Energy consumption of each type of node can be estimated using the first order radio energy model.[10]

---

[10] This model incorporates both reception and transmission energy expended by the sensor node for communication. Nodes which performs data aggregation constitutes the D_{agg} set.

Table 2 $|NCM|$ of each zone after assigning single CH to each of the four zones respectively

Zone	No. of NCM
NW	40
NE	30
SW	20
SE	10

Equation (4), calculates energy consumed by *Direct_Set* nodes. Some of those nodes may perform data aggregation (if received packets from neighbors) and some may not. Since, *CM* will transmit their packets to *CHs*, only *NCM* can transmit their data to *Direct_Set* nodes for further transmission towards the sink. Thus, *Direct_Set* nodes can receive packets from the maximum of R sensor nodes.

Equation (5), represents the scenario for those *NCM* nodes which have not received data packets from other neighboring nodes and does not incur data aggregation cost. Whereas, Eq. 6, represents the case, where an *NCM* node has received data from other *NCM* nodes (maximum $R-1$; excluding itself) and performs data aggregation.

For *CM* (divided into *CH* and *NCH*), Eq. (8), represents the energy consumed by a *CH*. Initially, it receives packets from its $P/S-1$ (average number of cluster members assigned to each *CH*, excluding itself) cluster members, and later it performs data aggregation on the received data packets. Equation (9), represents the case, where an *NCH* (member of *NCM*) receives data packets from *NCM* nodes (maximum of *R* nodes) and then performs data aggregation.

4.2 Setup phase

In the beginning, the network is in the gestation period. Each node sends *hello_packet* to all other nodes (in its communication range) and complete the entries in their *Nbr_Table*. BS, after obtaining this information from all the nodes divides the field (and nodes[11]) into η equal sized *zones*.

For e.g., with $\eta = 4$, we divide the field into 4 zones namely North West (NW), North East (NE), South West (SW) and South East (SE). To each of these zones, a unique *CH* is assigned. For this, BS calculates a parameter, *chance of election* (*CE*) for each of the node based on three factors:

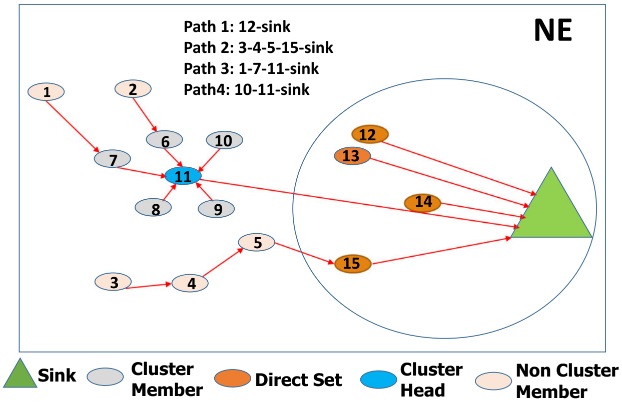

Fig. 5 Camp routing process in zone NE

1. *Node degree* and its tuning factor alpha (α): the number of direct neighbors of the node.
2. *Residual Energy* and its tuning factor beta (β): the total remaining energy of the node.
3. *Dist_to_Sink* and its tuning factor gamma (γ): the euclidean distance of the node from the sink.

For a node to be elected as *CH*, all the aforementioned parameters must be high and $\alpha+\beta+\gamma=1$ must hold good. In this algorithm, biasing can be done for any parameter by increasing the weight of its tuning factor. For e.g., $\alpha=0.6$, $\beta=0.2$, and $\gamma=0.2$ will favor that node which has the highest node degree.

If total cluster heads are more than four, then those *zones* which have maximum remaining *NCMs*, are assigned additional *CHs*. For instance, in the scenario depicted in Table 2, *zone* NW will be allocated the fifth *CH*. This process is repeated till the ROI has *CHs* equal to *Total_CH*. The process is formally described in Algorithm 1.

4.3 Routing phase

At this stage, ROI has been divided into η equal sized virtual *zones* and each node uniquely belong to a particular *zone*. Before the commencement of routing operation, each node is expected to have its *Nbr_Table* instantiated (viz., it is aware of all its neighbors *Nbr_ID*, *Nbr_Loc* and *Nbr_Residual_Energy*). Also, each node knows whether it is *NCM*, *CM* or member of *Direct_Set* as shown in Fig. 5. In each zone, a node can opt following routing policies,

---

[11] Each node is assigned to a single *zone* only.

Algorithm 1 CAMP: Setup Phase

```
procedure SETUP PHASE(Number of nodes $N$, Number of Cluster Heads $Total\_CH$, Number of zones $\eta$)
                                                ▷ $N$ nodes are randomly distributed in ROI
    declare alpha $\alpha$                      ▷ Tuning parameter for Node degree
    declare beta $\beta$                        ▷ Tuning parameter for Residual Energy
    declare gamma $\gamma$                      ▷ Tuning parameter for Distance from sink
    declare $Direct\_Set$ = (empty set)         ▷ To store those node ID's for which BS is a direct neighbor
    for every node $n \in N$ do
        if $BS$ is in $T_x$ then
            Add node $n$ to $Direct\_Set$
        end if
    end for
    Divide the ROI (virtually) in $\eta$ equal zones
                                                ▷ Each node belongs to one unique region
marker:
    for every zone $z$ do
        declare Cluster Members (CM) = (empty set)       ▷ to store node IDs which constitutes a cluster
        declare Non Cluster Members (NCM) = (empty set)  ▷ to store node IDs which does not constitute a cluster
        for every node $n \notin Direct\_Set$ and $n \in z$ do
            Calculate chance of election $CE$
            $CE = \alpha * \left(\frac{NodeDegree}{max(nodedegree)}\right) + \beta * \left(\frac{ResidualEnergy}{InitialEnergy}\right) + \gamma * \left(\frac{dist\_from\_sink}{max(dist\_from\_sink)}\right)$
        end for
        Designate cluster head (CH) : a node which has max(CE)
        Assign CM: all nodes which are under $T_x$ of $CH$
    end for                                     ▷ All $\eta$ zones have designated $CHs$
    if $Total\_CH > \eta$ then                  ▷ Some zones will be assigned more than one $CHs$
        Sort zones based on $|NCM|$ (of each zone)   ▷ the zone with maximum number of non-cluster members will be given preference
        go to marker
    end if
end procedure
```

Case 1 Node is a member of *Direct_Set*.

The node for which BS is in communication range, transmit messages directly to BS. In Fig. 5, node 12 sends data to BS using *Path1*.

Case 2 Node is *CM*.

If the node belongs to some cluster, it send packets to its *CH*, which aggregate it with its own sensed data packet and packets received from other *CM*s. Finally, *CH* sends the data to sink (shown as *Path4,* Fig. 5).

Case 3 Node is *NCM*.

If the node is not a part of any cluster, it will opt for multi-hop communication [using intelligent routing process as explained in procedure IRP(n)]. IRP is a greedy selection approach which selects the next hop node based on the trade-off between the remaining energy of itself (and its corresponding forwarding neighbor) to the energy required to transmit packets to its neighbor. The aim is to maximize the residual energies of the nodes and minimize

Algorithm 2 CAMP: Routing Phase

```
declare $Next\_Hop\_ID = Start\_node\_ID$   ▷ Initially, ID of the starting node is stored in variable $Next\_Hop\_ID$
while $Next\_Hop\_ID \neq Sink\_ID$ do
    if $n \in Direct\_Set$ then
        Send packets directly to BS
        $Next\_Hop\_ID = Sink\_ID$
    else if $n \in CM$ of any $CH$ then
        Send packets to CH
        $CH$ sends packets to BS   ▷ $CH$ calls IRP with other $CH$s as potential Next_hop (Multihop communication to BS with only $CH$s as intermediate hops)
        $Next\_Hop\_ID = Sink\_ID$
    else if $n \in NCM$ of any zone then
        $Next\_Hop\_ID = IRP(Next\_Hop\_ID)$
    end if
end while
```

```
procedure IRP($n$)
    declare $LS = NULL$   ▷ set containing local selection parameters for all the nbrs of node $n$
    declare $Next\_Nbr\_ID = NULL$
    declare $ResidualEnergy_n$   ▷ remaining energy of the node $n$ initiating IRP
    declare $ResidualEnergy_i$   ▷ remaining energy of neighbor $i$ of node $n$
    declare $TransmissionEnergy_i^n$   ▷ Energy required by node $n$ to transmit its data to neighbor $i$
    declare $ProgressiveNodeSet$   ▷ Neighboring nodes which are present in between node $n$ and the sink. It provides gradient to the data packets towards the sink, avoiding loops and delays.
    for every node $i \in ProgressiveNodeSet$ do
        Calculate $LS_i =$
            $$\frac{ResidualEnergy_n}{TransmissionEnergy_i^n} * ResidualEnergy_i$$
            ▷ Local Selection ($LS_i$) parameter of each element $i$ of $ProgressiveNodeset$, is calculated by node $n$. It provides a trade-off between the residual energy of itself (and its neighbor) and the required energy to transmit packets to its neighbor
        $LS = LS \cup LS_i$
    end for
    Calculate $LS_{sink} =$
        $$\frac{ResidualEnergy_n}{TransmissionEnergy_{sink}^n}$$
    $LS = LS \cup LS_{sink}$
    $Next\_Nbr\_ID = Id\_of(max(LS))$   ▷ Neighbor whose LS factor is maximum is selected as next hop node
    Return $Next\_Nbr\_ID$
end procedure
```

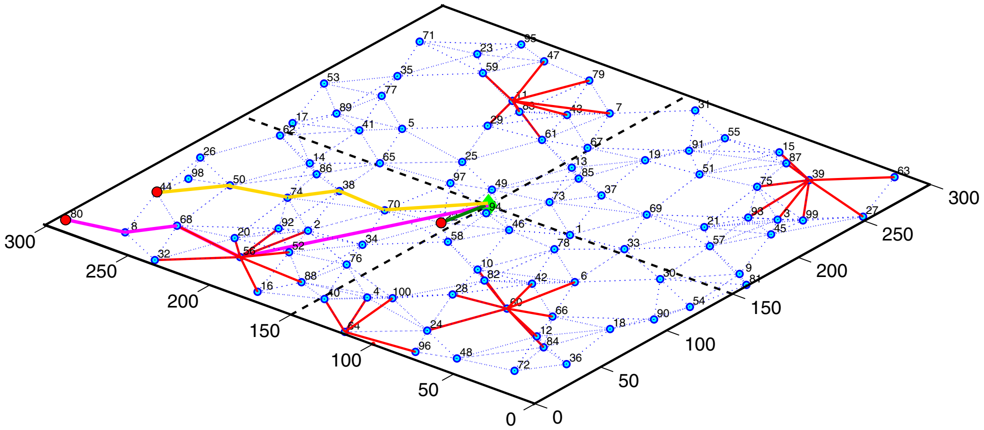

Fig. 6 MATLAB simulation of *CAMP* routing process

Table 3 Simulation parameters

Parameters	Values
Free space energy Dissipation (E_{fs})	10 pJ/bit/m^2
Multi path energy Dissipation (E_{mp})	0.0013 pJ/bit/m^4
Transmitter electronics energy Dissipation ($E_{Tx-elec}$)	50 nJ/bit
Receiver electronics energy Dissipation ($E_{Rx-elec}$)	50 nJ/bit
Energy for data aggregation (E_{DA})	5 nJ/bit/signal
Data packet size	2000 bits
Control packet size	200 bits
Initial energy	.5 J
Communication range	30 m
Number of zones (η)	4

the transmission energy for communication. The neighbor which has the maximum value, is chosen as next hop.

If the next hop node is also *NCM*, the same process is repeated (shown as *Path2*, Fig. 5). On the contrary, if the next node is a *CM*, it aggregates its data with received data and transmits it to *CH*. *CH*, later transmits this data to BS (shown as *Path3*, Fig. 5). When node 7 (*CM*) receives packets from node 1, it performs data aggregation and sends it to node 11 (*CH*), which eventually transmit the packets to the sink.

This represents the possibility that a *CH* can also directly transmit data to BS (contrary to normal control flow of CAMP, where *CH* communicates with sink using other *CH*'s as intermediate hops).

Any node which calls *IRP* (only *CH* and *NCM* can adopt *IRP*), obtains the flexibility to choose between direct or multihop communication towards the sink. Node calculates a local selection parameter for all its neighbors and sink.

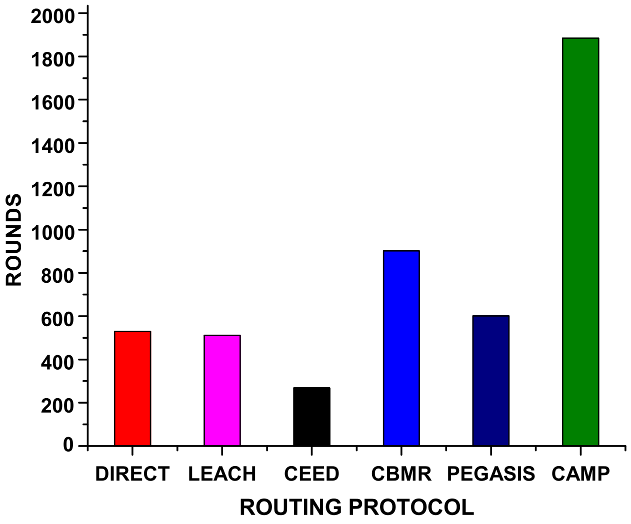

Fig. 7 FND_Stats (sink at center)

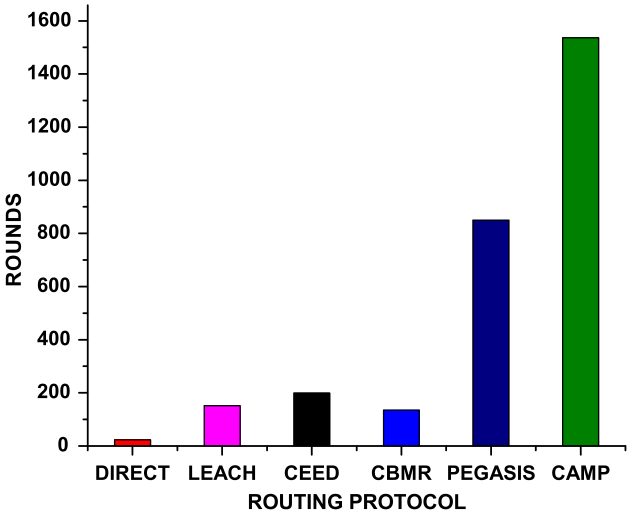

Fig. 8 FND_Stats (sink at far)

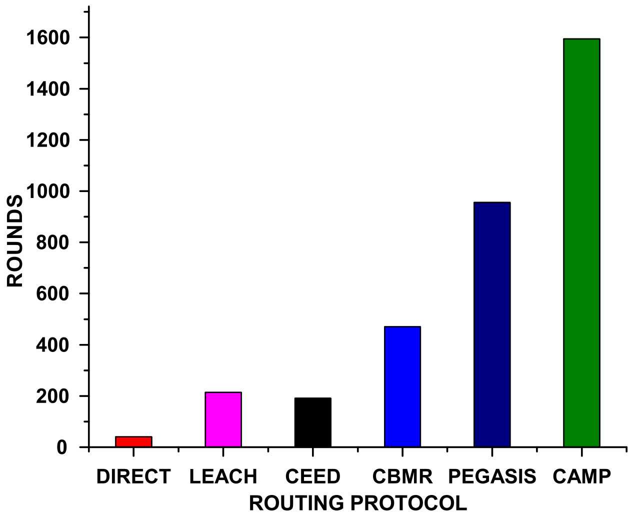

Fig. 9 FND_Stats (sink at corner)

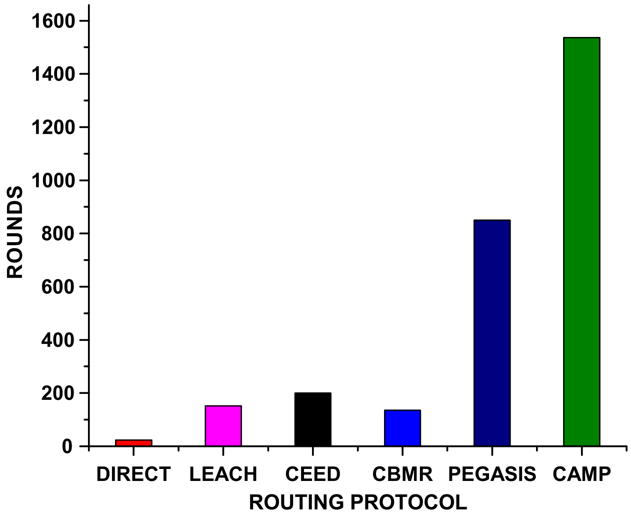

Fig. 10 Alive node statistics (sink at far)

Table 4 Performance gain of CAMP

Protocols	Sink location		
	Far (%)	Center (%)	Corner (%)
LEACH [16]	910	602	734
CEED [23]	671	267	644
CBMR [24]	1037	108	239
PEGASIS [17]	155	213	86

The node corresponding to the highest parameter value is selected as next hop. If the sink has the highest parameter value, direct transmission is adopted else multihop communication takes place.

Formally, routing process is represented in Algorithm 2.

5 Comparative analysis and simulation results

In this section, we validate our claims by extensive MATLAB simulations and compared *CAMP*'s performance with other established routing protocols in the existing literature. Figure 6, represents the different communication paths adopted by data packets under *CAMP* routing protocol. Pink path denotes the communication links, which consist of *NCM* and *CM* together. Communication starts at *NCM* node 80 and when the *CM* node 68 is reached, IRP is rejected, and hierarchical communication takes place. CH node 56 directly transmits to the sink. Yellow path denotes communication links consisting of *NCM* nodes only, thus adopting IRP throughout. Green link denotes direct transmission by the *Direct_Set* node to the sink.

For our experiments, performance is measured by quantitative metrics like network lifetime, total energy consumption and network coverage. Throughout our simulations, we follow the same network parameters used for evaluations, described in Table 3.

5.1 Network life time

In this work, we adopt *First Node Dead Statistics (FND_Statistics)* as a metric for network lifetime. It is defined as the interval between the rounds where the first node start transmitting data and the round where the first node gets dead [35, 40]. Here, network was created, by randomly deploying 150 nodes in the terrain size of $200 \times 200\,\mathrm{m}^2$, under the following scenarios:

1. Scenario 1: sink at center
2. Scenario 2: sink at far[12]
3. Scenario 3: sink at corner

Analysis of the three aforementioned scenarios are described in Figs. 7, 8, and 9. Figures plot the **FND_Statistics** for different routing protocols including *CAMP*.

It can be observed from the figures, that *CAMP* very well outperformed other protocols (for *FND_Statistics*), for all the three simulated scenarios. Figure 10 establishes the robustness and completeness of *CAMP*. It can be visualized, that for any *network lifetime* definition (*FND*, 10, 25, 50, 75% of node dead and *LND* statistics), *CAMP* performs better than others.

The performance gain [41] as per FND_Statistics has been tabulated in Table 4 and is calculated by Eq. (10).

---

[12] The nearest node to the sink is more than d_0 distance apart.

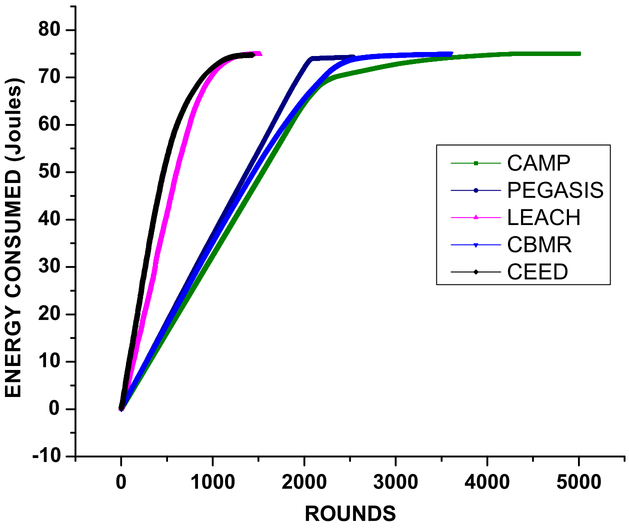

Fig. 11 Total energy consumption of network

Table 5 Variation

Case	Condition
1	$\alpha(.33) = \beta(.33) = \gamma(.33)$
2	$\beta(.7) > \alpha(.15) = \gamma(.15)$
3	$\beta(.6) > \alpha(.3) > \gamma(.1)$
4	$\beta(.6) > \gamma(.3) > \alpha(.1)$
5	$\beta(.4) = \gamma(.4) > \alpha(.2)$
6	$\beta(.4) = \alpha(.4) > \gamma(.2)$

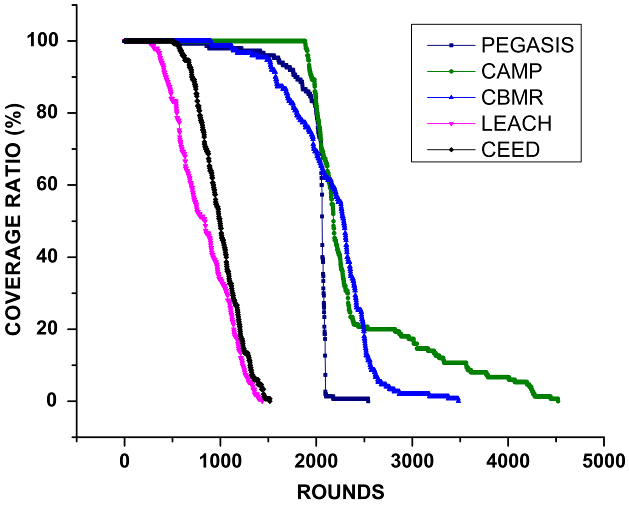

Fig. 12 Coverage ratio

$$Performance\ gain = \frac{CAMP_{Rounds} - Protocol_{Rounds}}{Protocol_{Rounds}} * 100\% \tag{10}$$

Table 4, summarizes the *performance gain* of *CAMP* compared to other protocols, based on network lifetime.

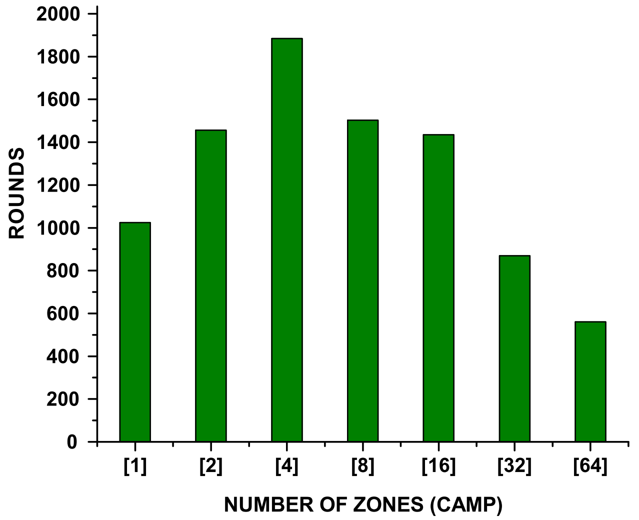

Fig. 13 FND_Stats (sink at center)

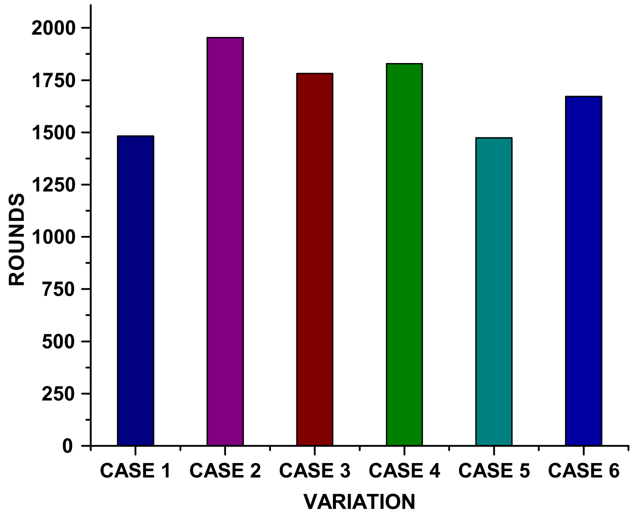

Fig. 14 FND_Stats (variation of tuning factors α, β, and γ)

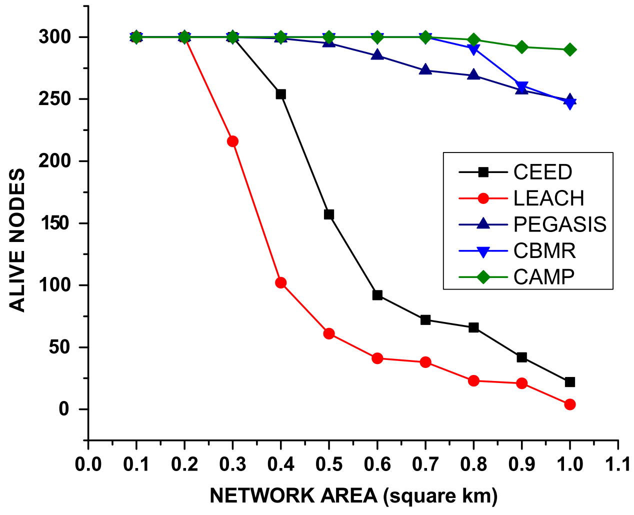

Fig. 15 Number of nodes alive as a function of network area

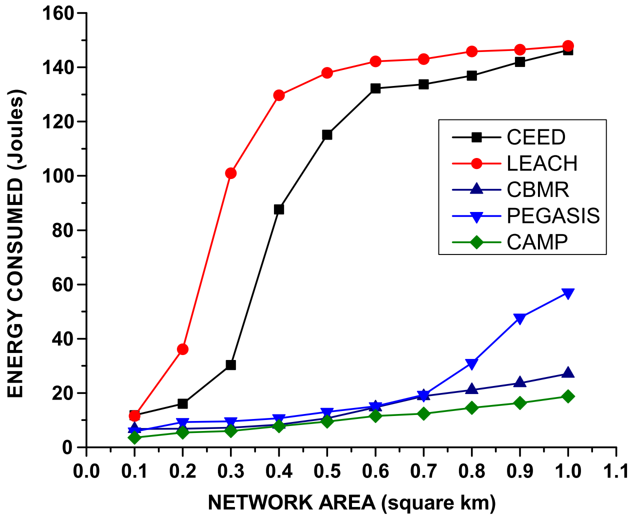

Fig. 16 Total energy consumption over varying network areas

For different set of experiments (placing sink at different locations), with different routing protocols, *CAMP* remarkably outperformed all its existing counterparts. For PEGASIS, it achieves a minimum of 86% improvement, whereas for LEACH it achieves a maximum of 910% improvement.

5.2 Total energy consumption

It is defined as the sum of energy consumed by all nodes in each rounds. Total Energy consumption (TEC) is expressed as:

$$TEC = \sum_{Rounds} \sum_{Nodes} (E_{Tx(Nodes)} + E_{Rx(Nodes)}) \tag{11}$$

Figure 11[13] shows the total ***energy consumption*** of the protocols against number of rounds. The plot depicts that *CAMP* has a desirable energy expenditure curve against other existing protocols. The total energy exhaustion occurs at 4500 rounds for *CAMP*, whereas for others, it is as low as 1500 rounds.

5.3 Coverage ratio

Coverage ratio [42] is defined as the ratio of coverage area when all nodes alive to the coverage area of alive nodes in that round. In coverage ratio as a performance parameter, *CAMP* maintains a high network coverage in comparison to its other existing counterparts. From Fig. 12 it can be inferred that around 2000 rounds coverage ratio of *CAMP* is still 100% whereas, for all other algorithms, it is between 60–90%. Coverage ratio of *CAMP* reduces to zero at round 4500, whereas for all others it is in the range of 1500–3500 rounds. Hence, our experimental results confirm that for all those applications where coverage is of prime concern, *CAMP* is the best choice among different routing protocols.

5.4 Zone selection

As mentioned earlier in Sect. 4, zone selection is the initial step of *CAMP* routing protocol. The success of the protocol depends on the optimal number of zones selected. Figure 13 depicts that for simulation setting of area: $200 \times 200\,\mathrm{m}^2$, nodes: 150 maximal FND_Statistics is observed for 4 virtual zones. It can be well understood from the fact that very few zones (≤ 2) result in imbalanced cluster density which leads to long multi-hop paths.

On the contrary, if there are large number of zones (> 4), it would lead to multiple small size clusters, eventually leading to multi-hop forwarding completely ignoring the clustered routing. We repeated this experiment for different terrain size and different number of nodes and we found that for all tested cases, 4 zones result in maximum FND_Statistics.[14]

5.5 Impact of tuning factor

In order to verify whether *CAMP* is a *generic algorithm*, (viz., it is not suited for some specific application), we carried out different experiments, by varying the values of tuning factors α, β and γ. Figure 14 shows *FND_Statistics* against different cases tabulated in Table 5. For all different cases, *CAMP* maintains a high *FND_Statistics*. In applications where throughput is of major concern, tuning factor α (controls node degree of potential CH) can be made biased. For applications, where delay is of prime concern, tuning factor γ, can be given high preference. In general, any WSN application, aims at minimizing the energy consumption, thus in all cases, tuning factor β, is given the highest priority.

5.6 Impact of network area variation

In order to test the suitability of *CAMP* for large network areas, we evaluate the performance of *CAMP* by increasing the ROI.We tested the performance of *CAMP* by varying the terrain size. For these experiments, we fixed the number of nodes to 300 and increased the terrain size from 100 to 1000 m^2. The simulation was carried out for 100 rounds. Figures 15 and 16, represents the variation of the number of alive nodes and energy consumed (by all the nodes) with

---

[13] For simulations corresponding to Figs. 11, 12, 13, 14, 15, and 16 sink is placed at the center of the field.

[14] Indeed the test cases are not exhaustive, but for our simulated scenarios, 4 zones suffice. We will further look into the formulation of the optimal number of zones in our future work.

increasing area. Again, *CAMP* outperformed other protocols, with remarkable improvements.

5.7 Discussion

Our proposed approach CAMP, overcomes important limitations of the existing routing protocols of WSN. Established hierarchical approaches [16], compel sensors to latch to at least one cluster head, which results in tremendous energy exhaustion of the nodes due to the large distance between cluster nodes and the cluster head. Also, cluster heads are elected either randomly [16] or based on residual energies of the node [23]. This may lead to uneven cluster distribution across the ROI, eventually reducing the network lifetime. *CAMP* addresses these issues and provides a robust routing mechanism, specifically tailored to meet the stringent energy requirements of the wireless sensor network. The salient features of *CAMP* are enumerated as:

1. Uniform Cluster Density: ROI is divided into zones each having multiple clusters (depending upon node density). Each zone has a mix of cluster and non-cluster members resulting in uniform energy consumption. Each node intelligently selects the next hop neighbor based on the trade off between the remaining energy of the neighbor and the energy required to transmit to the next node.
2. Nodes are not forced to latch to any cluster head: In existing hierarchical approaches, there is a constraint on all the sensors to latch themselves to some cluster head (based on distance or RSSI value). In *CAMP*, if cluster head is in the transmission range of the node, then only it joins the cluster else it acts as an independent entity (in that round).
3. Adjustable tuning factors: Node degree (α), Remaining Energy (β) and *Dist_to_Sink* (γ) can be changed according to the application. In those applications where throughput is of major concern, high preference can be given to α, and cases where delay needs to be minimized, preference can be given to γ. Since, energy capacity of the sensor node is always limited, the highest priority has been assigned to β.

6 Conclusion

Conservation of energy is the main challenge in the development of wireless sensor networks. We have presented in this paper CAMP, a novel energy balanced routing protocol, which can adapt itself, under the centralized control of the sink. The algorithm consists of clustering and routing phases. We have developed an efficient strategy with which *sink* partition the network into various regions (and their corresponding clusters). A node belonging to some cluster, transmits its sensed data to its CH, and CH in turn will send it to sink. For non cluster members we have devised a simple but elegant scheme with which they can route their data using both flat and clustered scheme depending upon which scheme requires less energy consumption. Finally, CAMP ensures *that no node transmits greater than* d_0 *distance* as opposed to existing hierarchical approaches like LEACH [16], which compel sensors to latch to at least one cluster head, which results in tremendous energy exhaustion of the nodes due to the large distance between cluster nodes and the cluster head.

In order to test the robustness of CAMP, we simulated it with different parameters and settings viz., varying the terrain size, number of nodes and location of the sink. Simulation results confirm that CAMP yields improved *network lifetime* and reduced *energy consumption* compared to its existing counterparts.

7 Future work

1. Our simulation results confirm that *CAMP* provides significant improvement in network lifetime for different sink locations, terrain size and number of nodes. We would further like to analyze its performance by incorporating mobility to sink.
2. The proposed algorithm could be modified to take into account some aspects that have not been addressed in this work. For instance, incorporating the concept of heterogeneity [43, 44], security [45] and reliability [46] etc. could be considered in future studies. Hence we aim to simulate it on NS2 [47] in future.
3. In this work, we have assumed the first order radio model for energy consumption. In future, the proposed approach CAMP can be evaluated on other established energy models like [48, 49].
4. Present work assumes, zones to be of fixed size and shape (viz. rectangular). In future, *CAMP* can be tested with varying zone shapes and sizes.

References

1. Ammari, H. M., & Das, S. K. (2009). Fault tolerance measures for large-scale wireless sensor networks. *ACM Transactions on Autonomous and Adaptive Systems (TAAS)*, *4*(1), 2.
2. Jurcik, P., Kouba, A., Severino, R., Alves, M., & Tovar, E. (2010). Dimensioning and worst-case analysis of cluster-tree sensor networks. *ACM Transactions on Sensor Networks (TOSN)*, *7*(2), 14.

3. Rashid, B., & Rehmani, M. H. (2016). Applications of wireless sensor networks for urban areas: A survey. *Journal of Network and Computer Applications*, *60*, 192–219.
4. Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., & Cayirci, E. (2002). Wireless sensor networks: A survey. *Computer Networks*, *38*(4), 393–422.
5. Amjad, M., Sharif, M., Afzal, M. K., & Kim, S. W. (2016). TinyOS-new trends, comparative views, and supported sensing applications: A review. *IEEE Sensors Journal*, *16*(9), 2865–2889.
6. Marinagi, C., Belsis, P., & Skourlas, C. (2013). New directions for pervasive computing in logistics. *Procedia-Social and Behavioral Sciences*, *73*, 495–502.
7. Atzori, L., Iera, A., & Morabito, G. (2010). The internet of things: A survey. *Computer Networks*, *54*(15), 2787–2805.
8. Akhtar, F., & Rehmani, M. H. (2015). Energy replenishment using renewable and traditional energy resources for sustainable wireless sensor networks: A review. *Renewable and Sustainable Energy Reviews*, *45*, 769–784.
9. Bellman, R. (1958). On a routing problem. *Quarterly of Applied Mathematics*, *16*(1), 87–90.
10. Chen, Y., & Zhao, Q. (2005). On the lifetime of wireless sensor networks. *IEEE Communications Letters*, *9*(11), 976–978.
11. Pantazis, N. A., Nikolidakis, S. A., & Vergados, D. D. (2013). Energy-efficient routing protocols in wireless sensor networks: A survey. *IEEE Communications Surveys and Tutorials*, *15*(2), 551–591.
12. Jin, R. C., Gao, T., Song, J. Y., Zou, J. Y., & Wang, L. D. (2013). Passive cluster-based multipath routing protocol for wireless sensor networks. *Wireless Networks*, *19*(8), 1851–1866.
13. Akkaya, K., & Younis, M. (2005). A survey on routing protocols for wireless sensor networks. *Ad Hoc Networks*, *3*(3), 325–349.
14. Intanagonwiwat, C., Govindan, R., & Estrin, D. (2000). Directed diffusion: A scalable and robust communication paradigm for sensor networks. In *Proceedings of the 6th Annual International Conference on Mobile Computing and Networking* (pp. 56–67).
15. Heinzelman, W. R., Kulik, J., & Balakrishnan, H. (1999). Adaptive protocols for information dissemination in wireless sensor networks. In *Proceedings of the 5th annual ACM/IEEE International Conference on Mobile Computing and Networking* (pp. 174–185).
16. Heinzelman, W. R., Chandrakasan, A., & Balakrishnan, H. (2000). Energy-efficient communication protocol for wireless microsensor networks. In *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences, 2000* (pp. 1–10).
17. Lindsey, S., & Raghavendra, C. S. (2002). PEGASIS: Power-efficient gathering in sensor information systems. In *Aerospace Conference Proceedings IEEE* (pp. 1125–1130).
18. Manjeshwar, A., & Agrawal, D. P. (2001). TEEN: A routing protocol for enhanced efficiency in wireless sensor networks. In *Proceedings of the 15th International Parallel and Distributed Processing Symposium (IPDPS)* (Vol. 1, pp. 189–195).
19. Younis, O., & Fahmy, S. (2004). HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. *IEEE Transactions on Mobile Computing*, *3*(4), 366–379.
20. Meng, X., Shi, X., Wang, Z., Wu, S., & Li, C. (2016). A grid-based reliable routing protocol for wireless sensor networks with randomly distributed clusters. *Ad Hoc Networks*, *51*, 47–61.
21. Kim, H. Y. (2016). An energy-efficient load balancing scheme to extend lifetime in wireless sensor networks. *Cluster Computing*, *19*(1), 279–283.
22. Snigdh, I., & Gupta, N. (2016). Quality of service metrics in wireless sensor networks: A survey. *Journal of The Institution of Engineers (India)*, *97*(1), 91–96.
23. Gawade, R. D., & Nalbalwar, S. L. (2016). A centralized energy efficient distance based routing protocol for wireless sensor networks. *Journal of Sensors*, *2016*, 1–8.
24. Sharma, S., & Jena, S. K. (2015). Cluster based multipath routing protocol for wireless sensor networks. *ACM SIGCOMM Computer Communication Review*, *45*(2), 14–20.
25. Mhatre, V., & Rosenberg, C. (2004). Homogeneous vs heterogeneous clustered sensor networks: A comparative study. In *Communications IEEE International Conference* (Vol. 6, pp. 3646–3651).
26. Heinzelman, W. B., Chandrakasan, A. P., & Balakrishnan, H. (2002). An application-specific protocol architecture for wireless microsensor networks. *IEEE Transactions on Wireless Communications*, *1*(4), 660–670.
27. Loscri, V., Morabito, G., & Marano, S. (2005). A two-levels hierarchy for low-energy adaptive clustering hierarchy (TL-LEACH). *IEEE Vehicular Technology Conference*, *62*(3), 1809–1813.
28. Ahmad, A., Javaid, N., Khan, Z. A., Qasim, U., & Alghamdi, T. A. (2014). $(ACH)^2$: Routing scheme to maximize lifetime and throughput of wireless sensor networks. *IEEE Sensors Journal*, *14*(10), 3516–3532.
29. Yi, D., & Yang, H. (2016). HEERA delay-aware and energy-efficient routing protocol for wireless sensor networks. *Computer Networks*, *104*, 155–173.
30. Huynh, T. T., Dinh-Duc, A. V., & Tran, C. H. (2016). Delay-constrained energy-efficient cluster-based multi-hop routing in wireless sensor networks. *Journal of Communications and Networks*, *18*(4), 580–588.
31. Sabet, M., & Naji, H. (2016). An energy efficient multi-level route-aware clustering algorithm for wireless sensor networks: A self-organized approach. *Computers and Electrical Engineering*, *56*, 399–417.
32. Xia, H., Zhang, R. H., Yu, J., & Pan, Z. K. (2016). Energy-efficient routing algorithm based on unequal clustering and connected graph in wireless sensor networks. *International Journal of Wireless Information Networks*, *23*(2), 141–150.
33. Anand Chatterjee, R., & Kumar, V. (2017). Energy-efficient routing protocol via chain formation in Gaussian distributed wireless sensor networks. *International Journal of Electronics Letters*, *5*(4), 449–462.
34. Sivaraj, C., Alphonse, P. J. A., & Janakiraman, T. N. (2017). Independent neighbour set based clustering algorithm for routing in wireless sensor networks. *Wireless Personal Communications*, *96*(4), 1–23.
35. Han, Z., Wu, J., Zhang, J., Liu, L., & Tian, K. (2014). A general self-organized tree-based energy-balance routing protocol for wireless sensor network. *IEEE Transactions on Nuclear Science*, *61*(2), 732–740.
36. Kim, K. T., Lyu, C. H., Moon, S. S., & Youn, H. Y. (2010). Tree-base clustering (TBC) for energy efficient wireless sensor networks. In *IEEE 24th International Conference on Advanced Information Networking and Applications Workshops (WAINA), 2010* (pp. 680–685).
37. Zhu, H., & Alsharari, T. (2015). An improved RSSI-based positioning method using sector transmission model and distance optimization technique. *International Journal of Distributed Sensor Networks*, *11*(9), 1–11.
38. Niculescu, D., & Nath, B. (2001). Ad hoc positioning system (APS). In *Global Telecommunications Conference GLOBECOM'01 IEEE* (Vol. 5, pp. 2926–2931).
39. Sohraby, K., Minoli, D., & Znati, T. (2007). *Wireless sensor networks: Technology, protocols, and applications*. New York: Wiley.
40. Chang J. H., & Tassiulas, L. (2000). Energy conserving routing in wireless ad-hoc networks. In *INFOCOM Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies Proceedings* (Vol. 1, pp. 22–31).

41. Solaiman, B. (2016). Energy optimization in wireless sensor networks using a hybrid k-means pso clustering algorithm. *Turkish Journal of Electrical Engineering & Computer Sciences*, *24*(4), 2679–2695.
42. Hacioglu, G., Kand, V. F. A., & Sesli, E. (2016). Multi objective clustering for wireless sensor networks. *Expert Systems with Applications*, *59*, 86–100.
43. Kumar, D., Aseri, T. C., & Patel, R. B. (2009). EEHC: Energy efficient heterogeneous clustered scheme for wireless sensor networks. *Computer Communications*, *32*(4), 662–667.
44. Deniz, F., Bagci, H., Korpeoglu, I., & Yazc, A. (2016). An adaptive, energy-aware and distributed fault-tolerant topology-control algorithm for heterogeneous wireless sensor networks. *Ad Hoc Networks*, *44*, 104–117.
45. Mittal, V., Gupta, S., & Choudhury, T. (2018). Comparative analysis of authentication and access control protocols against malicious attacks in wireless sensor networks. In *Smart Computing and Informatics* (pp. 255–262). Springer, Singapore.
46. Islam, K., Shen, W., & Wang, X. (2012). Wireless sensor network reliability and security in factory automation: A survey. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, *42*(6), 1243–1256.
47. Bukhari, S. H. R., Siraj, S., & Rehmani, M. H. (2016). NS-2 based simulation framework for cognitive radio sensor networks. *Wireless Networks*. https://doi.org/10.1007/s11276-016-1418-5.
48. Yildiz, H. U., Temiz, M., & Tavli, B. (2015). Impact of limiting hop count on the lifetime of wireless sensor networks. *IEEE Communications Letters*, *19*(4), 569–572.
49. Amjad, M., Afzal, M. K., Umer, T., & Kim, B. S. (2017). QoS-aware and heterogeneously clustered routing protocol for wireless sensor networks. *IEEE Access*, *5*, 10250–10262.

Mohit Sajwan received his B.Tech. degree in Computer Science Engineering from Amrapali Institute of Technology, Uttrakhand Technical University, Dehradun and M.E. (software engineering) from Birla Institute of Technology, Mesra, Ranchi. Presently, he is pursuing his Ph.D. in wireless sensor networks from National Institute of Technology, Delhi.

Devashish Gosain received his B.Tech. degree in Computer Science Engineering from Guru Gobind Singh Indraprastha University, Delhi and M.Tech. (Computer Science) degree from Birla Institute of Technology, Mesra, Ranchi. Presently he is pursuing his Ph.D. in network anonymity privacy and anti-censorship from Indraprastha Institute of Information Technology, Delhi.

Ajay K. Sharma is working as Director National Institute of Technology, Delhi since October 2013. He received his B.E. in Electronics and Electrical Communication Engineering from Punjab University Chandigarh, India in 1986, M.S. in Electronics and Control from Birla Institute of Technology (BITS), Pilani in the year 1994 and Ph.D. in Electronics Communication and Computer Engineering in the year 1999. His Ph.D. thesis was on “Studies on Broadband Optical Communication Systems and Networks”. After serving various organizations from 1986 to 1995, he has joined National Institute of Technology (Erstwhile Regional Engineering College) Jalandhar as Assistant Professor in the Department of Electronics and Communication Engineering in the year 1996. From November 2001, he has worked as Professor in the ECE Department and thereafter he has worked as Professor in Computer Science and Engineering from 2007 to 2013 in the same institute. His major areas of interest are broadband optical wireless communication systems and networks, dispersion compensation, fiber nonlinearities, optical soliton transmission, WDM systems and networks, Radio-over-Fiber (RoF) and wireless sensor networks and computer communication. He has published 280 research papers in the International/National Journals/Conferences and 12 books. He has supervised 23 Ph.D. and 52 M.Tech. theses. He has completed two R&D projects funded by Government of India and one project is ongoing. He was associated to implement the World Bank project of 209 Million for TEQIP-I programme of the institute. He has been appointed as member of technical Committee on Telecom under International Association of Science and Technology Development (IASTD) Canada for the term 2004-2007 and he is Life Member of Optical Society of America, USA, (LM ID-361253), Computer Society of India, Mumbai, India, (LM-Associate: 01099298), Advanced Computing and Communications Society, Indian Institute of Science, Bangalore, India, (L284M1100306), SPIE, USA, (ID: 619838), Indian Society for Technical Education (I.S.T.E.), New Delhi, India, (LM-11724), Fellow The Institution of Electronics and Telecommunication Engineers (IETE), (F-224647).