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An Efficient Distributed Clustering and Gradient based Routing Protocol for Wireless Sensor Networks

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This paper proposes an Efficient Distributed Clustering and Gradient based Routing Protocol (EDCGRP) to support the Wireless Sensor Networks (WSNs) in (i) prolonging the network lifetime (ii) utilizing the battery energy efficiently (iii) reducing the overhead of the network (iv) ensuring high Packet Delivery Ratio (PDR) with minimal delay. To achieve this goal, the delay time based Cluster Head (CH) selection is presented based on the node's residual energy, node degree, and Received Signal Strength (RSS). And also, the RSS based network partitioning is introduced to establish the gradient based on-demand routing between the source and the Base Station (BS). The proposed protocol performs the clustering process whenever the residual energy of the current CH goes below the threshold level, thus minimizing the exchange of control packets. In addition, the BS collects the data from each CH periodically which helps in reducing the collision and Medium Access Control (MAC) layer contention. From the simulation results, it is evinced that the performance of the proposed protocol is better than the well-known existing protocols in terms of PDR, Average End-to-End Delay (AEED), Average Energy Consumption (AEC), and control overhead.

Keywords: cluster head, energy efficiency, gradient, residual energy, wireless sensor networks

1. INTRODUCTION

In recent decades, Wireless Sensor Network (WSN) plays a key role in providing the most promising solutions to several challenging real time applications [1-5]. The sensor node generally consists of the sensing elements, processor, memory, transceiver, and battery. However, the sensor nodes have got the constraints in memory, processing capability, bandwidth, and battery power. This is due to the tiny nature of the sensor nodes [6]. In WSNs, the sensor nodes are densely deployed in highly hazardous environments (*e.g.*, atomic radiation monitoring, chemical factories, mines, *etc.*) for sensing the events and forwarding it to the Base Station (BS). After being installed, the replacement or recharge of the sensor battery is not possible [7]. Thus, the energy efficiency is found to be an important design consideration of WSNs to enhance the lifetime of the networks and to ensure the node connectivity and coverage [8, 9]. The Received Signal Strength (RSS) plays a vital role in WSNs to achieve its characteristics of the self configuration, in which each node finds itself the neighbor nodes. And it also computes the link quality and distance to the neighbors, so that it efficiently constructs the stable network with high quality link avoiding the packet retransmission, collision, overhearing, and interference [10-12]. Thus, it significantly conserves the battery energy and extends

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the network lifespan. And it also greatly reduces the complexity of hardware and the number of men involved in the network setup. Moreover, the performance of the routing protocols in WSNs depends on the size of the targeted area and density of the sensor nodes. In the reactive protocol, the routing path is obtained in an on-demand manner resulting in high delay, whereas the proactive protocol suffered due to the extra communication overhead since the routing information is periodically updated and stored [13]. In [14], a reliable route was achieved by sending the redundant source packets through alternate paths, but it increases the energy consumption of sensor nodes. The gradient based routing in WSNs [15] was utilized to search for a next hop node to the BS with a reduced control overhead and delay.

The cluster formation is an efficient data collection technique in WSNs, in which the sensor nodes are typically separated into different groups. Each group has got a head node, called Cluster Head (CH) which is responsible for coordinating the operations and collecting the data from the sensor nodes. One important task of the CH is data aggregation, in which the CH removes the redundant and unwanted data packets, thereby reducing the overhead and delay. The clustering reduces the routing complexity by minimizing the size and number of nodes in the routing, thereby enhancing the effective utilization of the bandwidth and memory. It also provides the contention free channel access between the Cluster Member (CM) and CH by using the Time Division Multiple Access (TDMA) schedule efficiently. Thus, it enhances the stability and scalability of the sensor networks. The benefits of the unequal clustering were discussed in [16, 17], in which the CH selection and size of the cluster were determined based on the distance to the BS. Also, it addressed the bottleneck problem and early depletion of the battery energy nearer to the BS. In [18], the authors deliberated the mechanism of adjusting the transmission power capability between the nodes which plays a major part in reducing the energy consumption, interference, and collision. This power adjustment mechanism can effectively enhance the link quality of the nodes. Hence, the transmission delay, data retransmissions, network congestion, and battery energy consumption are reduced considerably. The CH selection using a distributed mechanism was discussed in [19-22], in which each node has got the responsibility to organize and control the network operations. And each node also performs the cluster formation and CH selection based on the local information. Thus, it avoids the extra communication overhead for updating the global knowledge to the BS. Heinzelman *et al.* [23] presented Low Energy Adaptive Clustering Hierarchy (LEACH) protocol, in which CHs were elected based on the probability value. However, all the CHs may be elected nearer to the boundary of the network area leading to the isolated node problem. Hybrid Energy Efficient Distributed (HEED) clustering protocol was proposed in [24], in which the communication cost and residual energy were used to select the best CHs. Hybrid Unequal Clustering with Layering (HUCL) presented in [25], in which the CH candidate nodes could wait a time before broadcasting the CH awareness message based on the node's residual energy, distance to the BS and number of neighbor nodes. Gu *et al.* [26] presented a distributed clustering algorithm in which the waiting time was determined to broadcast the CH awareness message based on the remaining energy and coverage. Barati *et al.* [27] considered the residual energy, distance from the BS, distance from the neighbor nodes and the number of neighbor nodes as the input parameters to find the delay time to broadcast the CH awareness message. The Cluster Tap Root based Data Collection (CTRDC) proposed in [28] was utilized the waiting time-based CH selection to distribute the CH uniformly to the whole network area. Srivastava *et al.* [29] proposed Optimized Zone based Energy Efficient routing Protocol (OZEEP), in which the node mobility, node density, distance, and residual energy were given as input parameters to the fuzzy inference system to find the CH. However, all the operations and controls of the network were stipulated by the BS resulting in poor scalability. Sasirekha *et al.* [30] proposed a Cluster-Chain Mobile Agent Routing (CCMAR) Algorithm, in which each node calculated the CH selection value based on the node's residual energy, distance from the neighbor node, the number of bits transmitted and the amount of energy required for transmitting one bit. However, the CCMAR resulted in isolated node problem, because it was unaware of the CH selection value of the neighbor's neighbor.

The problems found in the literature are: (i) There is no guarantee for uniform distribution of the CHs to the entire networks; (ii) The presence of multiple CHs located in the same cluster causes high interference, collision, and energy consumption; (iii) The quick depletion of the battery energy is due to the selection of the same node as a CH repeatedly; (iv) The node may be left out by the CH leading to the isolated node problem which causes the uneven distribution of work load and energy consumption resulting in poor network performance.

In order to overcome these problems, the EDCGRP is proposed in this paper which consists of clustering and routing. The main contributions are: (i) Introducing a delay time based distributed CH selection method to avoid multiple CHs located within each other's transmission range ensuring the even distribution of CH and workload; (ii) Focusing the periodical data collection without any collision and interference; (iii) Introducing a cost value based IRN selection to ensure the shortest path to reach the BS in an energy efficient manner.

The rest of the paper is planned as follows: Section 2 is used to describe the network model, Section 3 gives the design of EDCGRP, and Section 4 shows the simulation results and performance evaluations. Finally, the conclusion is presented in Section 5.

2. NETWORK MODEL

In EDCGRP, there are (N_a) number of sensor nodes deployed over the sensing area of $M \times M$ meter^2. The operation of the EDCGRP consists of the setup and steady state phases. The delay time-based CH selection is performed during the setup phase. In the steady state phase, the CH collects the data from the CM during the allotted time period by using the TDMA schedule. The CH sends the combined data to the BS at the end frame of the TDMA schedule using gradient based on-demand routing.

2.1 Network Model Assumption

The following assumptions are made in the proposed design:

(i) All the sensor nodes are static after the deployment and location unaware.
(ii) The links between the sensor nodes are assumed to be symmetric.
(iii) Nodes can adjust their transmission power according to the distance between them.
(iv) The BS is located at the top of the sensing area and it can cover the entire networks since it has a sufficient transmission power.

2.2 Energy Consumption Model

The communication energy consumption model utilized in this paper is similar to that of [31]. The energy required for transmitting and receiving the data packets over a distance d is given in Eqs. (1)-(3).

$$E_t(l, d) = l \times (E_{ele} + \varepsilon d^{\alpha}) \tag{1}$$

$$E_r(l) = l \times E_{ele} \tag{2}$$

E_{ele} is the energy dissipation due to the electronic circuits, l is the size of the data packets, ε is the amplifier energy consumption, α is the amplifying factor, for free space model $\alpha = 2$, when $d \leq d_0$ and multi-path fading model, $\alpha = 4$ when $d > d_0$

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \tag{3}$$

where ε_{fs} and ε_{mp} are the amplifier energy for free space (fs) and multipath (mp) model.

3. EDCGRP DESIGN

3.1 Cluster Formation Phase

At the begin of CH selection, the sensor nodes broadcast the HELLO message with its residual energy information to the neighbors by using Carrier Sense Multiple Access and Collision Avoidance (CSMA/CA). This message is used to find the neighbor's energy level, distance between them and number of neighbors. The proposed clustering method is described in Algorithm 1, in which all the deployed nodes are eligible to participate in the CH selection at every round. Each sensor node calculates the delay time for broadcasting the CH awareness message to its neighbors based on the distance, node degree, and residual energy. Once the CH is selected, it does the service and maintains the same cluster structure for a few rounds. It means that the selected CH set continues their operations until anyone CH in the CH set losses its residual energy below its threshold level. If the energy level is low, then it sends the 0 bit along with the data packet to the BS for reorganizing the cluster formation. Upon receiving this message, the BS broadcasts the new cluster formation message and initiates the CH selection process.

(i) Residual Energy

The normalized value of the battery energy (ζ_{RE}) is obtained based on the maximum residual energy of the neighbors instead of the maximum energy of the sensor node at the time of deployment, so that sensor node efficiently utilizes the duration of cluster formation for broadcasting the CH awareness message and reduces the MAC layer level contention and collision. ζ_{RE} is calculated based on Eq. (4).

$$\zeta_{RE} = \frac{E_r}{E_{N_m}} \tag{4}$$

E_r denotes the residual energy of the sensor node, E_{Nm} is the maximum residual energy of the neighbor.

(ii) Number of neighbor nodes

The least number of sensor node (N_l) required to cover the targeted network area is obtained by using Eq. (5).

$$N_l = \frac{A_{ta}}{A_c} \tag{5}$$

where A_{ta} is the area of the targeted network area, A_c is the coverage of sensor node in regular hexagon. The maximum number of cluster members (N_m) in each cluster is found based on Eq. (6).

$$N_m = \frac{N_a}{N_l} \tag{6}$$

The normalized value of the number of neighbors (ζ_{NN}) is obtained by using Eq. (7) and it reduces the workload and ensures the uniform energy consumption of the CH.

$$\zeta_{NN} = \frac{N_c \bmod(N_m + 1)}{N_m} \tag{7}$$

N_c is the number of current neighbors.

(iii) Average Received Signal Strength

The RSS is found to be a vital parameter for determining the cluster size. And it also reduces the energy dissipation of the sensor node by reducing the transmission distance between the CH and CM. The normalized value of the average RSS between the nodes (ζ_{RSS}) is obtained by using Eq. (8)

$$\zeta_{RSS} = \frac{\sum_{i=1}^{N_c} RSS(i)}{N_c \times RSS_M(i)} \tag{8}$$

where $RSS(i)$ is the RSS value of i^{th} node, $RSS_M(i)$ is the maximum RSS of i^{th} neighbor.

In EDCGRP, the weighted sum method [32] is utilized to obtain the optimal value (η_{CF}) and it is calculated based on Eq. (9).

$$\eta_{CF} = \alpha\zeta_{RE} + \beta\zeta_{NN} + \gamma\zeta_{RSS} \tag{9}$$

Here $\alpha + \beta + \gamma = 1$, where α, β, γ are the tuning parameters which depend on the selection of the application. This η_{CF} is used to find the fitness value of the sensor node to act as a CH, *i.e.*, it ensures that the selected CH has high residual energy, high RSS, and optimum number of neighbor nodes in its cluster region as compared to its neighbors.

Each sensor node calculates the delay time for broadcasting the final CH awareness message (B_{dt}) with respect to η_{CF} based on Eq. (10). In the proposed method, B_{dt} is inversely proportional to the η_{CF}. This means that the low fitness value of the sensor node waits for a long time to broadcast the final CH awareness message, *i.e.*, it has less chance to act as a CH.

$$B_{dt} = (1 - \eta_{CF}) \times t_{tcf} + \delta_{rt} \quad (10)$$

where t_{tcf} is the time taken for cluster formation, δ_{rt} is the random time which is very small ($\delta_{rt} \ll t_{tcf}$) to reduce the MAC layer contention.

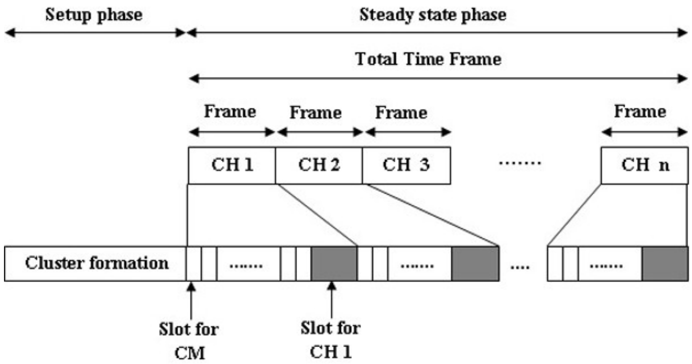

Fig. 1. Time slot structure of EDCGRP.

Once the delay time of the sensor node is expired, it broadcasts the final CH message within its transmission range. If any sensor node receives the CH awareness message before its delay time is expired, then it gives up its CH competition and joins as a CM to the nearest CH by sending the join request message to the concerned CH based on the RSS. The orphan CH means that it does not receive any join request message from the neighbors. At the end of the cluster formation, the selected CHs send the approval message to the BS in multihop fashion and get the time frame (periodical data transmission) for preparing the TDMA schedule. Then, the BS broadcasts the time frame to reach the registered CHs directly. The time slot structure of EDCGRP is mentioned in Fig. 1. During the steady state phase, CH divides the time frame into mini-slot and broadcasts to its member node for collecting the data. At the end of the time frame, CH sends the collected data to the BS by using the gradient based on-demand routing.

Algorithm 1: Cluster Formation of EDCGRP

```
initialization:
node[i].broadcast "HELLO message"
node[i].Calculate "ζ_RE, ζ_NN, ζ_RSS"
node[i].Calculate "B_dt"
while Check the status do
    if node[i].B_dt == "expired" then
        node[i].Status "final CH"
        node[i].Broadcast "final CH awareness message"

    else
        node[j].WaitToReceive == "awareness CH message (OR) node[j].WaitTo
        expire == B_dt"
    end
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    if node[j].Receive == "awareness CH message && node[j].B_dt != Expire" then
        node[j].Status "CM"
        node[j].Send "join request message"

    else
        node[j].WaitToReceive=="awareness CH message (OR) node[j].WaitTo
        expire==B_dt"
    end
    if node[i].Receive== "join request message" then
        node[i].Calculate "Number of CM registration"

    else
        "Orphan CH"
    end
end
Final stage: the CH and Orphan CH send the CH approval registration message to the BS
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3.2 Gradient based On-demand Routing

The general network architecture of the EDCGRP is described in Fig. 2. At the very beginning of the node deployment, the nodes in the sensing area are horizontally divided into the layers based on the transmission range (R_m) of the sensor node. Initially, the BS broadcasts the INITIALIZATION MESSAGE with a layer ID using the transmission power to reach up to R_m, the sensor nodes that receive this INITIALIZATION MESSAGE form the layer-1. Then, BS increases the signal power level in the rate of nR_m, where n is the index number of the layer and broadcasts the INITIALIZATION MESSAGE again. This process is continued till the entire network area is covered. Moreover, the RSS is used by the sensor nodes to find the distance from the BS. The CH in the n^{th} layer collects the data from its CMs and forwards the gathered data to the BS through the intermediate layers. In this method, the source CH initiates the route discovery process by sending the QUERY PACKETS which contains the CH-ID, Layer-ID, Hop Count (HC), and distance between the CH and BS ($d_{CH\text{-}BS}$).

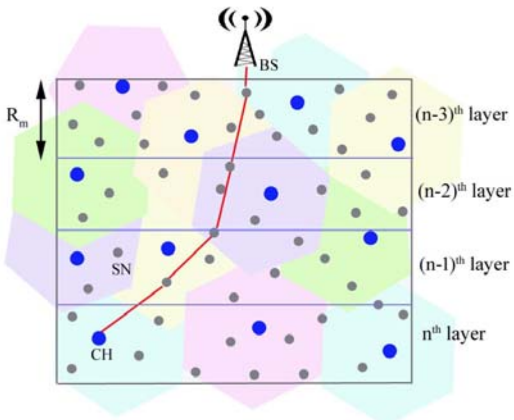


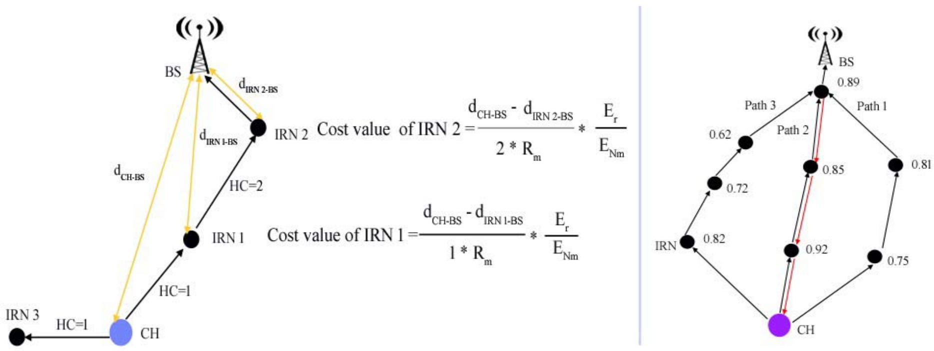
Fig. 2. Architecture of EDCGRP.

A gradient value for each sensor node is computed with respect to the Layer-ID for finding the shortest path to reach the BS. The HC value is updated for every hop which is used to maintain the minimum hop count to the BS. However, the overlapped cluster formation is unavoidable in the distributed algorithm based CH selection because it makes the decision depending on the local information. Thus, the architecture of EDCGRP is shown in Fig. 2 based on the node's connection with CH, *i.e.*, the cluster member which belongs to its corresponding CH. The cost value of the Intermediate Routing Node (IRN) is calculated in Eq. (11) based on the residual energy and distance to the BS.

$$Cost\ value = \frac{d_{CH-BS} - d_{IRN-BS}}{HC \times R_m} \times \frac{E_r}{E_{Nm}} \tag{11}$$

where HC is the hop count, $d_{CH\text{-}BS}$ is the distance between CH and BS, $d_{IRN\text{-}BS}$ is the distance between IRN and BS.

In Eq. (11), $d_{CH\text{-}BS} - d_{IRN\text{-}BS}$ is normalized by $HC \times R_m$ which ensures the shortest path to reach the BS and the searching of IRN in the direction of BS efficiently. This is because the effective utilization of its transmission range ensures the minimum number of nodes and hop count. Here, the node's residual energy is normalized by E_{Nm} which reduces the chance value of low energy node to become an IRN. It is clear from Fig. 3 (a) that HC is used to determine the normalized value between 0 and 1. And the consideration of distance minimizes the chance value of IRN 3 by reducing the cost value of IRN 3 (*i.e.*, almost negative). The CH in n^{th} layer relays the QUERY PACKET to the nodes in the $(n-1)^{th}$ layer and continues to relay hop by hop till the BS is reached.



(a) (b)

Fig. 3. (a) Selection of IRN; (b) Example for gradient based on-demand routing.

This QUERY PACKET updates the cost value of all the visited intermediate routing nodes in the direction of the BS. Finally, the QUERY PACKET traverses with the highest cost value in the path to the source CH. Then, the source CH forwards the combined data through the traversed reverse path which ensures to reach the BS with a minimum hop count and achieves a load balance and uniform energy consumption of the sensor nodes.

It is clear from Fig. 3 (b) that the CH initiates to send a QUERY PACKET in the direction of the BS. This QUERY PACKET updates all possible cost value of IRN in the routing to the BS. The BS selects the highest cost value path and traverses the QUERY PACKET to the CH (*i.e.*, it selects Path 2). Moreover, the use of Layer ID, CH_ID and HC avoids the loop formation and redundant packets.

The features of the EDCGRP are: (i) The delay time based CH selection helps in providing a well distributed CHs over the entire network area and avoids the isolated node; (ii) The consideration of residual energy in CH selection avoids the low energy node to be selected as a CH; (iii) The RSS based CH selection conserves the significant amount of sensor's battery energy and prolongs the network lifetime considerably; (iv) The optimal number of CMs in each cluster helps in providing better load-balancing of the CH and reduces the work burden, thereby avoiding the premature death of the sensor node; (v) The proposed protocol does not select CH frequently unlike LEACH protocol, so that, it avoids the extra control overhead and makes the system design easy; (vi) The IRN selection process ensures that the selected path utilizes the minimum number hop count and the shortest path to reach the BS in an energy efficient manner.

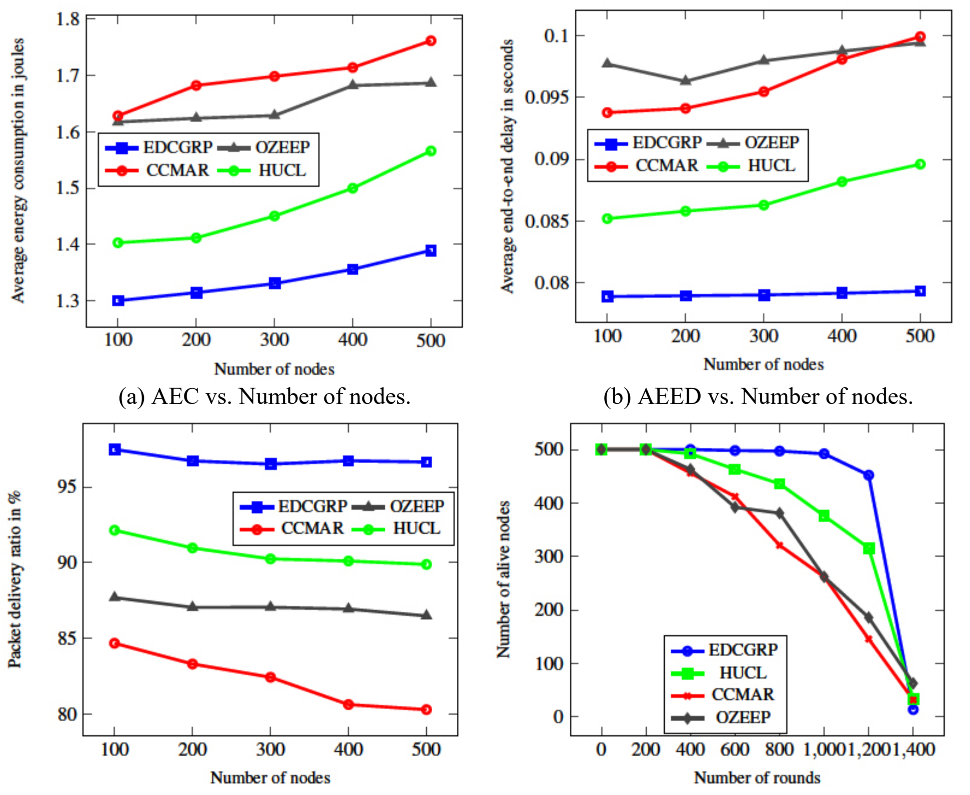
4. RESULTS AND DISCUSSION

The Network Simulator version-2 (NS-2) is used to carry out the simulation and analyze the performance efficacy of the proposed EDCGRP by comparing with HUCL, OZEEP, and CCMAR. Table 1 provides the simulation setup of the proposed EDCGRP.

Table 1. Simulation setup.

Simulation parameters	Values
Targeted sensing network area	800×800 meter^2
Number of sensor nodes	100−500
Transmission range of antenna	90 m
Data packet size	512 bytes
Control packet size	25 bytes
Initial energy of sensor nodes	100 joules
E_{ele}	50 nJ/bits
E_{amp}	1.3 fJ/bits/m^4
E_{aggr}	5 nJ/bits/signal

Fig. 4 (a) shows that the EDCGRP is capable of achieving a significant reduction in AEC, *i.e.*, 11.27%, 17.61%, and 21.13% in comparison with HUCL, OZEEP, and CCMAR respectively. In EDCGRP, the selected CHs depend on the number of neighbor nodes, so that it ensures the balanced work burden of the CHs. And also, it utilizes a periodical data collection from the CMs by using TDMA schedules which avoids the data collision and interference, thereby reducing the data retransmission. Moreover, the consideration of the RSS in the CH selection conserves the battery energy significantly by reducing the transmission distance since the sensor node having the power adjustment capability depends on the distance between them. Fig. 4 (b) shows that the proposed protocol achieves low AEED, *i.e.*, 11.49%, 20.233%, and 20.65% in comparison with HUCL, OZEEP, and CCMAR respectively. This is due to the gradient based routing of the EDCGRP which uses a minimum number of hops to reach the destination. In this routing, the selection of IRN depends on the distance from the BS and layer-ID, therefore it ensures the minimum number of sensor nodes utilized in the routing and the shortest path to reach the destination. In addition, the CH uses a QUERY PACKETS for selecting the best path based on the cost value, so that it avoids the link failure and provides a stable path between the CH and BS. Fig. 4 (c) shows that the PDR of the EDCGRP is higher, *i.e.*, 7%, 10.52%, and 16.92% than HUCL, OZEEP, and CCMAR respectively. This is because of the delay time-based CH selection ensuring well distribution of the CHs and makes link availability to the entire networks so that it avoids the isolated nodes in the sensing area. It is observed in Fig. 4 (d) that the proposed EDCGRP is maintaining consistent longevity of the sensor nodes because the proposed clustering mechanism ensures a well distributed CHs to the whole networks and provides a load balancing among the CHs. Moreover, the selection of the CH and IRN depends on the residual energy of sensor nodes which avoids the early depletion of the battery energy. And the normalization of the residual energy is also performed by using the maximum residual energy of the neighbors, so that it ensures the uniform energy consumption of the sensor nodes. It is observed from the simulation result that the maximum number of sensor nodes are alive till the end of the battery lifetime.



(a) AEC vs. Number of nodes. (b) AEED vs. Number of nodes.

(c) PDR vs. Number of nodes. (d) Number of alive nodes vs. Number of rounds.

Fig. 4. Performance comparison of EDCGRP.

At the beginning of each round, there are (N_a) number of HELLO messages which are broadcasted to find its neighbor nodes and their status. The total number of final CH awareness message broadcast is N_{CH} and ($N_a - N_{CH}$) number of the cluster join messages are sent by the sensor to join as a CM. (N_{CH}) number of the CH approval registration messages are sent by CH to the BS. The CH utilizes (N_{CH}) number of control packets for TDMA schedule. Therefore, the total number of control packets utilized in each round for cluster formation $O(T)$ is calculated by using Eq. (12).

$$O(T) = 2(N_a + N_{CH}) \approxeq O(2N_a) \qquad (12)$$

where N_{CH} is the number of CHs.

Table 2. Overhead analysis with respect to number of nodes.

Protocols	100 Nodes	200 Nodes	300 Nodes	400 Nodes	500 Nodes
EDCGRP	4466	9222	13292	17191	21999
HUCL [25]	5541	10386	14533	18271	22122
OZEEP [29]	5759	10587	14700	18684	22408
CCMAR [30]	5618	10649	14741	18735	22552

From Table 2, the number of control packets used in the EDCGRP is low as compared with HUCL, OZEEP, and CCMAR respectively because of it performs CHs selection whenever the residual energy of the CH goes below the threshold level. And also, a delay time based CH selection avoids the isolated nodes and it blocks the unnecessary CH searching by the isolated node reducing the control overhead of the network efficiently. Further, the gradient based routing avoids the flooding of QUERY PACKET in all the directions.

5. CONCLUSION

It is observed that energy efficiency is an important task in battery operated WSNs. In this paper, the EDCGRP is proposed which performs the data gathering from the targeted sensing area by using the clustering mechanism and gradient based on-demand routing. From the simulation results, it is reflected that the efficacy of the proposed protocol is better than HUCL, OZEEP, and CCMAR. The proposed protocol is well adapted to the periodical data collection based applications such as machine preventive maintenance, water irrigation management, smart farming, and structural health monitoring *etc.*, since EDCGRP provides a consistent performance in average end-to-end delay, packet delivery ratio, average energy consumption, and control overhead when the deployed nodes are increasing.

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