Centroidal Voronoi Tessellation Based Energy Efficient Clustering Protocol for Heterogeneous Wireless Sensor and Robot Networks

Md. Enamul Haque*, Md. Muntasir Rahman†, Aminur Rahman‡ and K.M Imtiaz- Ud-Din§

*Department of Computer Engineering
King Fahd University of Petroleum and Minerals, Dhahran-31261, Kingdom of Saudi Arabia
Email: enamul_cse@yahoo.com
†Department of Computer Science and Engineering
Islamic University of Technology, Gazipur-1704, Bangladesh
‡Department of Computer Science and Engineering
East West University, Dhaka-1219, Bangladesh

Abstract—In this paper, we propose a novel clustering protocol for wireless sensor and robot networks (WSRN) to ensure efficient energy usage and maintain maximum connectivity among the sensors. Our algorithm mainly works in two phases: (i) creates optimal number of clusters in the region of interest via three-point centroidal voronoi diagram. (ii) aggregates data from the members of each cluster and transfers to base station. This protocol is designed using double layered adaptive clustering and unknown region exploration which can be changed when needed for specific application. Additionally, this protocol works without the prior knowledge of the deployment region. We compared the results with LEACH and LEACH-C as a proof of concept. Specifically, simulation results exploit higher level of performance improvement in terms of energy dissipation, node failure, transmission overhead, and data aggregation among large number of mobile sensors. Finally, we analyzed the protocol with different settings which manifest the viability of our design.

Index Terms—clustering, energy efficiency, region exploration, voronoi diagram, wireless sensor network

I. INTRODUCTION

Wireless sensor networks (WSNs) have acquired great deal of popularity over the past years in different areas of applications, i.e. military, disaster management, agriculture, communication etc. A WSN is generally composed of sensor devices which are responsible for monitoring, processing, and transmitting sensed data back to a base station (BS). In this particular network, the sensing devices must communicate among them to establish efficient collaboration and election mechanism. Election mechanism is required for deciding some specific nodes from the whole group to work as coordinator/relay for base station. This grouping is termed as clustering in sensor network research. There are different levels of clustering available to facilitate the efficient energy consumption, guaranteed data transmission, and proper management. In this research, we have used two-layered clustering, lower layer consists of the neighboring nodes and the upper layer consists of the cluster heads. Cluster heads are responsible for relaying data back to base station after certain predefined interval. If the clusters are kept unchanged then the cluster heads will run out of energy pretty soon and the network outage will occur frequently. So, the easiest way is to rotate the cluster heads among each cluster or formulate new set of clusters after certain time. We employ the latter approach in this research using centroidal voronoi tessellation method. This scheme provides randomness and independence of exploring unknown geographical region with obstacles.

In addition, we use mobile sensors or actuators (i.e. robots) instead of static sensors. The network formation is random based on the residual energy of the actuators which exploits heterogeneity within the network. The actuators have homogeneous architecture and anyone have the option to be elected as cluster-head. Actuators (both neighbors and cluster-heads) can recharge its battery from docking station when residual energy becomes lower than some predefined threshold value. When at least two neighboring cluster-heads run out of energy, new voronoi tessellation is formed among the corresponding neighbors to select the cluster heads at the centroids. On the other hand, base station selects certain voronoi cluster to put the recharged actuators back to the network and keeps the sensing operation uninterrupted for the whole network.

Large number of sensor nodes with limited energy builds up a wireless sensor network. Wireless sensor networks are deployed into remote area to gather raw data about the surroundings and to transmit to remote base stations. Our proposed clustering algorithm (VEECP) can be adjusted to both small-scale network and in hierarchical clustering protocols. Research on wireless sensor and robot networks (WSRN) is in a pretty nascent stage in term of implementation for real life problem solving. We can employ VEECP protocol to use in military operation, agricultural field monitoring, weather monitoring etc. Our main focus is to remove the dependency of using static sensors and having known geographic area for the deployment. Furthermore, we compared the performance with most renowned LEACH [1] and LEACH-C [2] algorithms which shows significant improvement.

The remainder of this paper is organized as follows. In
section II, we mentioned a concise overview of the related work done in this area. Section III describes the motivation behind this research. Section IV represents general introduction about Centroidal Voronoi Tessellation (CVT). In section V, we describe the proposed model with algorithms. Section VI provides brief information about the energy model used in our experiment. In section VII, we discuss the simulation results and analysis. Finally in section VIII, we conclude and suggest future direction of our work.

II. RELATED WORK

Several techniques have been proposed for energy efficient sensor deployment and clustering protocol till date and most of them are based on the prior knowledge of the region of deployment i.e. through GPS and many others are not efficient enough to cover the region completely. This section is dedicated to discuss more about the recent trend in solving the energy efficiency issue of clustering in wireless sensor networks, which can be extended to WSRN as well.

In Randomized Scheduling Algorithm in Wireless Sensor Networks, the whole sets of Sensors does not work simultaneously, instead only a subset of them are scheduled to work at a time and other sets are scheduled to sleep, hence there is a tradeoff between network lifetime and Quality of Service. Xiao et al. [3] proved that the optimal solution exists considering the tradeoffs and provided conditions of the existence of that solution.

An experimental methodology has been developed to show the feasibility of low-cost, COTS sensor nodes in a distributed multi-modal system for surveillance and tracking of ground targets in conditions with high noise and clutter in [4]. With the use of low cost radar transceivers, supplemented by acoustic, vibration, magnetic, and infrared sensors, this method provides efficient solutions for detecting, tracking and classifying different types of targets.

Unlike always awake sensor network, Low-Duty-Cycle Wireless Sensor Networks has a trade-off between energy efficiency and minimum latency since every node has its own working schedules to wake-up periodically. A novel broadcasting algorithm has been designed in this paper [5] where, some early wake-up nodes postpone their wake-up slots which results increased latency but as these nodes are carefully selected not to be in latency-critical paths therefore, it does not affect the minimal broadcasting latency, hence gives an Energy-efficient Broadcast Scheduling with Minimum Latency.

Clustering of nodes in WSN is one of the techniques used to increase the energy efficiency through data aggregation at the cluster head. This paper [6] proposed a Particle Swarm Optimization (PSO) algorithm implementation at the base station of a centralized energy aware clustering network. Unlike other similar solution which uses the PSO algorithm, this one makes use of a high-energy node as a cluster head and produces clusters that are evenly positioned throughout the network, thus minimize the intra cluster distance between itself and other nodes and results optimized energy management of the network.

Saleem et al. [7] studied different swarm intelligence (SI) based routing protocol developed in WSN over time. They discussed the general principles of SI and its application towards routing and pointed out a number of methodological flaws in the way algorithms are commonly presented in different proposal. They also suggested future integration between mathematical modeling and real-world implementations.

Wang et al. [8] studied 15 energy-efficient scheduling mechanisms for sensor networks. To design such mechanism different researchers made different assumptions about the sensor parameters like detection model, area, range, network structure etc. based on their application target.

Angelopoulos et al. [9] mentioned efficient energy recharging of wireless sensor nodes in a wireless Rechargeable Sensor Networks (WRSNs), where the network comprises of two types of nodes, the normal sensor nodes and the special mobile charger node which recharges the energy of those sensor nodes. The key issues for recharging between mobile charger and sensor nodes have been addressed and three new alternative protocols have been proposed there. Simulation results exploited better performance compared to other schemes.

A bio-inspired patrolling algorithm has been proposed in [10], where the key players are the sensors, sinks and robots. In the network, an event can happen at any time and they have different priorities. By using the proposed patrolling algorithm, robots can efficiently handle many high priority events [11] by following the most efficient path towards the event occurrence [12].

To have efficient multi-robot team coordination, the participating robots should carefully choose to broadcast useful information as limited bandwidth is a key constraint of scaled up team. Taking the proper decision of communicating with neighboring robots is known as multi-agent decision problem. To solve this problem, Xu et al. [13] proposed a context-free decision model using complex network effects. This proposed model have key advantages of being incorporated in already existing information sharing algorithm.

III. MOTIVATION

In a wireless sensor network, the main challenges faced by cluster-based routing techniques are efficient energy consumption and improving lifetime of the network. Well known clustering techniques focuses mainly on FND (First Node Dies) and LND (Last Node Dies) which sometimes compromises stability and network lifetime [14]. Our research is motivated by three major improvement over several contemporary research to overcome these challenges.

Firstly, most of the research on monitoring some region using sensor network assumes that sensors are static. So, we used mobile sensors in the form of actuators which provides additional scope for reducing the network outage. It also introduces self-recharging [15] from the charging dock without any external help, avoiding dependency.
Secondly, mobile sensors do not need to have prior geographical knowledge about the deployment region. Centroidal voronoi diagram based algorithm helps the mobile actuators explore unknown and obstacle prone regions. So, traditional assumption about ideal area, where there is no obstacles are assumed, is avoided in this scheme.

Thirdly, the deployment of the sensors are in most cases implicit in the research or manual placement is mentioned. But, what if the region is not easily accessible or hazardous to human? To solve this, Voronoi based Energy Efficient Clustering Protocol (VEECP) is introduced. We can completely avoid human intervention while node deployment if VEECP is employed.

Furthermore, we can easily avoid using GPS (Global Positioning System) to localize each actuators as the centroids are known to the base station. Base station can calculate the sensors location from each cluster-head using the centroid location. This scheme also avoids broadcasting of hello message among all the mobile sensors within the network to formulate new clusters. Thus, this protocol provides reduced message overhead too. Finally, node failure is properly taken cared by updating the cluster formation and periodical recharging of nodes.

VEECP protocol have covered the above issues in detail with efficient data structure with less number of sensor devices compared to grid structure. It also demonstrably provides efficient centralized scheduling mechanism from base station to maximize total network lifetime.

IV. CENTROIDAL VORONOI TESSELLATION

Centroidal Voronoi Tessellation (CVT) is similar to voronoi diagram [16] except it defines the region-generating point as mean or center of mass. Voronoi cells are constructed with some predefined set of points, called generator or seed. If there is a set of finite initial points \( \{p_1, p_2, \ldots, p_n\} \) then seed \( p_i \) refers to a point from all other voronoi cell points \( v_{cell} \) within the each cell in such a way that the distance to \( v_{cell} \) from \( p_i \) is less or equal to any other cell. For example, two neighboring voronoi cells have centroids \( A \) and \( B \) respectively. Furthermore, A and B has \( p_a \) and \( p_b \) as the neighbor set. Now, C is another node within some random distribution and its neighbors are defined as \( p_c \). So, C can be the cluster head only if the distance from C to \( p_c \) is lower than the distance from C to A and B. As we used minimum three points to construct voronoi tessellation, there will be at least one meetpoint of three edges which is further used as prospective centroidal locations, meaning this meet point will be one of the cluster-head position in the next network topology formation. Following the previous rules, \( C_1, C_2, C_3 \) are elected as cluster-heads and \( p_1, p_2, p_3 \) are slave nodes under \( C_1 \); \( d \) is less than \( D \) thus \( C_1 \) was elected as cluster-head at the beginning (see Figure 1.). Same applies for other cluster-head selection as well.

To be more specific, if cluster-head \( C_1 \) has set \( p \) as slave nodes and \( C_n \) as neighboring cluster heads, then \( C_1 \) was selected using Equation 1.

\[
d(C_1, \{p\}) \leq d(C_1, C_n)
\]

Where \( n = 2,3 \) and \( d(a, b) \) measures the Euclidean distance between points \( a \) and \( b \). The slave nodes of each cluster are considered to be in layer one and the cluster-heads which forms Delaunay triangulation among them are in layer two.

V. VORONOI BASED ENERGY EFFICIENT CLUSTERING PROTOCOL (VEECP)

VEECP protocol is composed of three phases, i.e., initial state, stable state, and data aggregation and relay state. This section provides brief description about these three states with algorithm.

**Algorithm 1 Initial State**

1: select random 3 nodes
2: create voronoi cells
3: for \( i = 1 \rightarrow 3 \) do
4:     for \( j = 1 \rightarrow n - 2 \) do
5:         if range \( \leq \) th_range then
6:             next_node \( \leftarrow \) random\((j)\)
7:         end if
8:     end for
9: if boundary \( \neq 1 \) then
10:    go to step 1
11: else
12:    break
13: end if
14: end for

Initial state algorithm (see Algorithm 1.) ensures the coverage of the deployment region with sufficient voronoi clusters. At the beginning, three mobile robots start to explore the intended region after forming centroidal tessellation among them. Then each of these nodes selects other remaining nodes as slave nodes who lies within its sensing range (except the two other heads). Mobile sensors know the boundary of the deployment region that helps to cover only the intended area.

Stable state (see Algorithm 2.) algorithm starts to affect after initial clustering. Every clusterhead then communicates with its slave nodes using TDMA (Time Division Multiple
Algorithm 2 Stable State
1: ch ← total_heads
2: n ← ch_neighbors
3: for i = 1 → ch do
4:     for j = 1 → n do
5:         if residual_energy(j) ≤ th_energy then
6:             group[i] ← group[i] − node[j]
7:         end if
8:     end for
9:     ch[i] ← max(group[i])
10: end for

Algorithm 3 Data Aggregation and Relay State
1: n ← voronoi regions
2: quota ← current_nodes
3: for region = 1 → n do
4:     for node = 1 → quota do
5:         ch[region] ← data[node]
6:     end for
7:     ch[region].data ← unique(ch[region])
8:     if BS ∈ range then
9:         direct ← true
10:     else
11:         direct ← false
12:         find nearest ch
13:         send data to ch
14:     end if
15: end for

Data aggregation and relay state (see Algorithm 3.) ensures unique data delivery from different sources to the sink base station. Aggregation and relay task is solely provided by all the cluster-heads. Every slave node sends sensed data using TDMA to its corresponding cluster-head whenever any information need to be transferred to the base station. If the slave node is closer to the base station than from its cluster-head, the node can bypass the communication with cluster-head and send directly to BS. For example, cluster-head, A, of some region has filtered out 16 unique messages from its 20 slave nodes. Among these 20 nodes, only 18 nodes sent data to A and other 2 nodes were closer to BS, thus sent directly. Every cluster-head has unique identification numbers which is proportional to the distance from base station, further cluster-heads have greater ID’s than the closer ones. So, cluster-heads relay data to another head which has much lower ID than its own to ensure the delivery to the base station.

VI. ENERGY MODEL

We adopted the most typical and reliable energy model used in wireless ad hoc networks [17] [18], namely, End-to-End Retransmission (EER) and Hop-by-Hop Retransmission (HHR). In EER model, the intermediate nodes along the data transmission do not support with link layer retransmission. The source node has to retransmit the data if it is not received at the receiver end. On the other hand, HHR model provides link layer retransmission [19] [20].

The energy consumption while data transmission from slave node to its cluster-head is defined after calculating both energy required for sending and receiving. The relationship is shown in Equation 1.

\[ E_{TX} = n \times E_E + n \times E_A \times d^2 \]  
\[ E_{RX} = n \times E_E \]  

where \( E_{TX} \) and \( E_{RX} \) means transmission, receiving energy. \( n, E_E, E_A \) in Equations (2) and (3) refers to number of packets, electronic circuit energy dissipation, and free space energy respectively. \( \alpha \) refers to the propagation model constraint which depends on the environment. We used \( \alpha=2 \) for free space model. Equation (4) explains the data aggregation required for the cluster-heads.

\[ E_{Agg} = n_{data} \times E_E + n_{data} \times E_A \times d^2 \]  

VII. SIMULATION RESULTS AND ANALYSIS

In this section, we first introduce the experimental settings used for the simulation, then we show the results, evaluation and analysis. We simulate our proposed process using Matlab. Table I provides detail simulation setup parameters for this particular experiment.

TABLE I. Simulation parameters

<table>
<thead>
<tr>
<th>System parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of nodes in the network</td>
<td>100 (Min.), 300 (Max.)</td>
</tr>
<tr>
<td>Area considered</td>
<td>100×100 (m²)</td>
</tr>
<tr>
<td>Location of base station</td>
<td>(100,50)</td>
</tr>
<tr>
<td>Location of charging dock</td>
<td>(0,100) and (100,0)</td>
</tr>
<tr>
<td>Maximum cluster count</td>
<td>18</td>
</tr>
<tr>
<td>Sensor battery charging capacity</td>
<td>10 Joulle</td>
</tr>
<tr>
<td>Energy consumption in free space</td>
<td>0.1 nJoulle/bit/m²</td>
</tr>
</tbody>
</table>

Figure 2. shows the voronoi cells created using the initial state algorithm. Base station and recharge dock is not shown in the diagram. Plain and tiny circles are slave nodes, plus signs are slave nodes which are lacking energy, and filled circles are the cluster-heads. We simulated LEACH, LEACHC along with VEECP using the parameters from Table I and
measured the performance comparison in terms of number of packet received, energy consumption, residual energy, end-to-end delay, packet delivery ratio etc. The simulation was run 10 times at each round and average values were considered.

LEACH and LEACH-C both uses probabilistic approach to select cluster-head and the slave nodes who can transmit data. Experimental data shows that the total data transmission becomes steady after approximately 300 seconds (see Fig. 3) for all these three protocols.

Some nodes become short of energy and takes itself out from the cluster to the charging dock after every round. As LEACH and LEACH-C uses some probability to select cluster-head, some nodes may be selected as cluster-head for consecutive rounds which can create unbalanced energy status. In the long run this will produce some nodes not participating in the network which are called dead nodes. If cluster-heads need to be changed, VEECP makes proper balance after each round. So, VEECP have more alive nodes after longer rounds than LEACH and LEACH-C (see Fig. 4).

Energy consumption on the overall network increases after each round. VEECP uses TDMA for data transmission from slaves to cluster-head. Then, cluster-heads relay the data received from slaves to another cluster-head which have the minimum ID among its neighbor cluster-heads. Energy consumption is measured using free space model with $\alpha = 2$. VEECP shows less energy consumption when compared to LEACH and LEACH-C (see Fig. 5).

VEECP has recharging modality which helps to keep the residual energy constant over the rounds. LEACH and LEACH-C wanes all the energy from all the nodes after longer rounds (see Fig. 6(a)).

End-to-end delay is measured from the difference between source sending time and the receiving time at sink. In LEACH and LEACH-C, group of nodes can form a cluster far from the base station, but VEECP does not allow this as the coverage is
performed in an exploratory manner. Thus the average distance from source to sink becomes less than the others, which eventually benefits in achieving reduced end-to-end delay. (see Fig 6(b))

Base station has connection with the cluster-heads only for receiving aggregated data and sending control data. VEECP cluster-heads are selected using greedy approach as the method solely depends on the residual energy. Thus, the information exchange between sender and receiver remains almost constant, while the ratio drops significantly in LEACH and LEACH-C (see Fig. 6(c)).

VIII. CONCLUSION

In this paper, VEECP is described as a clustering protocol to ensure energy minimization, usage of mobile sensors, dynamic recharging, and hazardous region exploration with the concept of Centroidal Voronoi diagram. We have compared the results with two of the most well known clustering protocols as well and found significant improvement.

REFERENCES


