A Project Report

On

Analysis of a Density-based Clustering Algorithm In WSNs Using Game Theory

BY

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Birla Institute of Technology and Science - Pilani,

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Certificate

This is to certify that the project report entitled 'Analysis of a Density-based Clustering Algorithm in WSNs using Game Theory' submitted by the team of Preksha Rastogi, Sonakshi Mishra, Arundhati Ghose, Rudraksh Tiwari, Uppala Keerthana, Arihant Garg and Ankit Ashok, in partial fulfillment of the requirements of the course MATH F242 - Operations Research, embodies the work done by them under my supervision and guidance.

Date: 04/04/2021 **(DR. DIPAK K SATPATHI)**

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Abstract

Improving energy efficiency is one of the key challenges facing Wireless sensor networks (WSNs), which are becoming more ubiquitous by the day. Since the nodes (sensors) often have to rely upon limited energy stores to execute their job of data collection as relaying of data from other nodes, optimization of data transfer path becomes important to enhance the network lifetime. Grouping of nodes into a cluster with a cluster head (CH) is a common way of achieving this.

However, the two roles of nodes as data collectors and data relays are in conflict with each other with respect to energy consumption; as the data relay operation (necessary for the proper functioning of the network as a whole) digs into the limited energy stores, it may reduce the node's lifetime, hindering its data collection. This inherent conflict, between self-survival and contribution to the network, opens up interesting avenues for the use of Game Theory in modelling sensor networks. One such model, DEGRA, has been presented in this study along with comparison to other models, namely LEACH and DEER. The algorithm accomplishes this by taking into account the residual energy of the node in question as well that of the surrounding nodes.

Keywords: wireless sensor networks; energy efficiency; clustering; game theory; network lifetime; DEGRA

Contents

Introduction

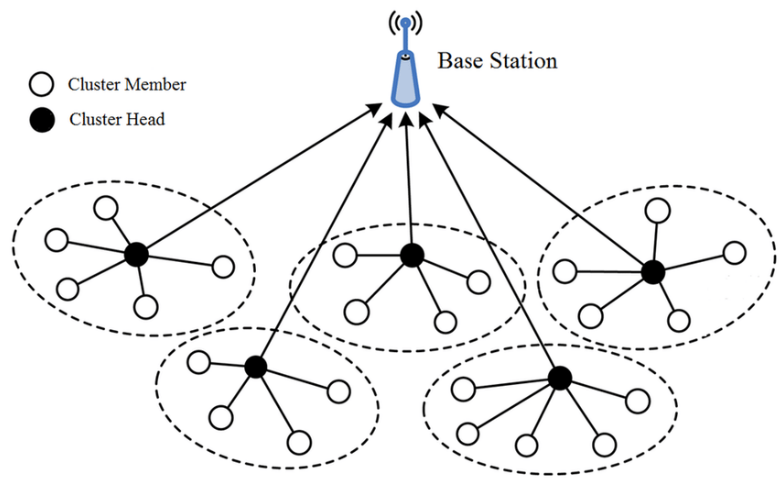
From smart cities to self-driving cars, there is a lot of excitement around the Internet of Things (IoT) these days. And at the heart of it all is data, Big Data. Until recently, we didn't have the technology required for collection and analysis of data, but that changed with the advent of fast, reliable and widespread internet connectivity, coupled with more powerful computers and the reducing costs of it all.

While some of this data is a byproduct of our digital life, other has to be deliberately collected. Enter sensors. In hundreds, thousands, millions. While sometimes it might be feasible to connect them to the grid, it may turn out to be not so economically viable or it may be downright impossible, as is the case with GPS sensors being implanted in the horns of rhinos in South Africa for conservation purposes (Wired, 2017). Meaning, the sensors have to make do with limited energy and constrained communication, while sensing and relaying data to the base station. In this light, it becomes clear that the sensors need to optimize their energy consumption for longer network lifetime, while finding a way around the limited transmission range and low bandwidth available.

Sensor Clustering

Clustering is a technique used in Wireless Sensor Networks (WSNs) in which the network is divided into clusters where each has a cluster head (CH) which forwards aggregated data to the basic station. It is a very efficient technique when it comes to energy efficiency and extending life nodes. It is a routing method.

The CHs manage the network in the cluster, aggregate the required data from the member nodes and send the processed data to the sink through the CHs/sensor nodes. Each CH belongs to only one cluster (Esmaeeli & Ghahroudi, 2016). Adopting the clustering protocol is beneficial as energy is consumed efficiently, traffic load is reduced, it conserves communication bandwidth and improves the overall scalability of the network.



The selection of CHs is very important as if it is not done properly, it is counterproductive and creates conflicts between the interests of a sensor node and the rest of the network. Individual sensor nodes prefer to send its data directly to the sink node i.e. the basic station as cooperation during the routing path includes relaying data without its direct interest. This makes the protocol less efficient and the network will consume excess energy. Therefore, such direct communication between all sensor nodes and the sink would cause much traffic load and thus, decreases efficiency. This will create an energy hole problem reducing network lifetime and therefore in clustering, the selection of cluster heads is of vital importance. (Xu, Yin & Wang, 2012).

Applying Game Theory models the network in such a way that the nodes are game players in a given situation. A balance can be found between the interests of individual nodes and the whole network. In classical game theory the assumption is made that all the players are perfectly rational. Then the prediction about the game is consistent with the actual results (Lin, Xiong, Vasilakos, Chen & Guo, 2011). But this is not practical as then every node should be aware of other nodes' action as well as their characteristics. In this project, CHs are determined according to the density of each node. Each node calculates its utility value and transmits messages. Thus, a game theoretic model is built around this and CH selection takes place.

Introduction to Game Theory

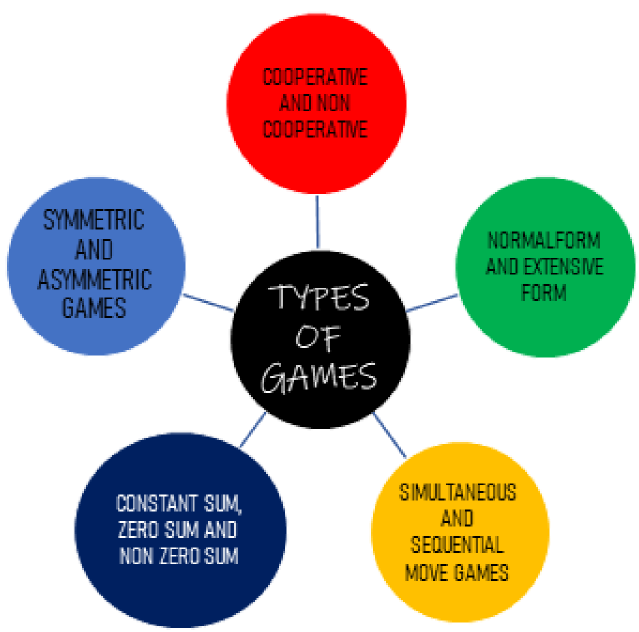
Game theory - The science of decision making.

The pioneers of game theory were Hungarian-conceived American mathematician John von Neumann and his Princeton University partner Oskar Morgenstern, a German-conceived American economist, proposed game theory to tackle the issues in economics . According to them economics was much like a game where players predict or expect the others moves and hence requires another sort of mathematics which they called it as game theory.

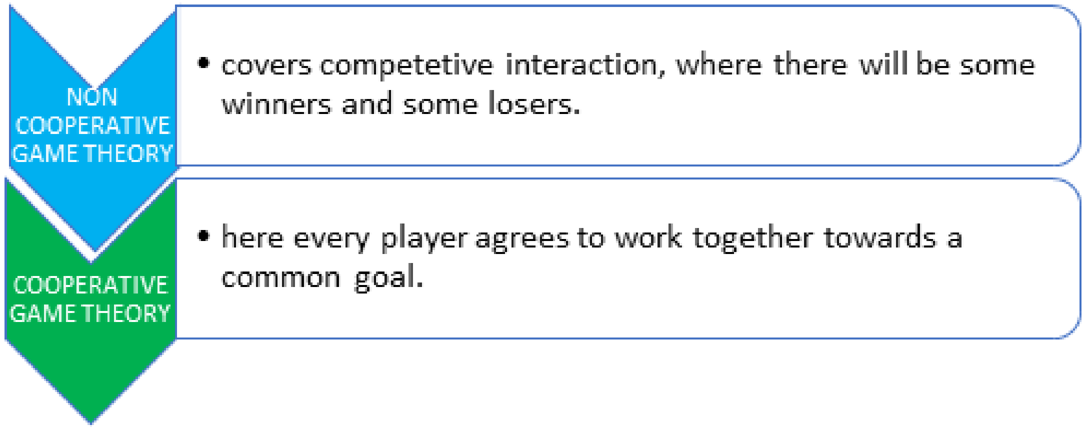
Games in Game theory have the following:

- ❏ Rules : oversee the behaviour of the players
- ❏ Strategies : these impact the procedure of decision-making.
- ❏ Pay-offs : for instance to draw, win or lose.

Game theory has an expansive scope of utilizations, including psychology, military,biology, experimental economics, politics, economics business, technology,bargaining,auctions etc.Indeed there is no single theory . Different theories have been proposed, each relevant to various circumstances and each with its own ideas of what comprises an answer.



Though there are various number of game theories cooperative and noncooperative theories are used widely.



Nash Equilibrium: It was proposed by Nobel winning economist **John Nash**. A player in a game has discovered Nash equilibrium when it settles on a decision that leaves them better off regardless of what their opponents choose to do.

Game theory is used to model the interaction among rational players with differing interests. These interests might be competitive, cooperative or a combination of both. The nodes in WSNs not only have to collect and transmit data themselves (selfish or competitive), but also have to relay information from other nodes (cooperative). This competitive-cooperative nature can be understood from the lens of game theory.

The desirable features of a WSN are flexibility, inexpensive, fault tolerance, rapid deployment, high sensing fidelity and high energy efficiency, with uses in automation, optimal resource utilization, remote sensing, machine learning, artificial intelligence and so on.

Nevertheless, it is not an easy task and there's a lot going into designing an optimal WSN to fulfill performance objectives such as extended operation periods and maximum sensing coverage. So, to achieve a feasible and a practical WSN and because of the operative nature of the network, game theory is viewed as an appealing and reasonable premise to achieve the plan objective . It can be utilised to analyse system operations in self-organizing and decentralized networks. Game Theory describes the conduct of players in a game. Players might be either cooperative or non-cooperative while attempting to maximize their outcomes from the game. Therefore, here sensors run their operations in terms of power resources dedicated to sensing and inter-communication with a global controller to such an extent that the assigned task could be finished successfully as desired.

Modelling and Simulation

We now give an overview of the proposed DEGRA algorithm.

Energy Model

So for a free area, d*d power loss is used, and for multi-path fading, d^4 power loss channel models are used, depending on the distance between transmitter and receiver. Each sensor node would expend energy to send a l-bit packet over a distance d, as well as the energy dissipated per bit to run the transmitter or receiver circuit. The Cluster heads then combine the m l-bit data packets with some data fusion cost of a per bit signal. E_{DA} is the data fusion cost of a bit per signal and hence the energy consumption is calculated as $E_{agg}(m,l)=mlE_{DA}$

Game theoretic Model

The network consists of n uniformly distributed intelligent sensor nodes, denoted by {s1, s2,..., sn} .They are regarded as players in the game-theoretic model, with their goal being transmission of data to the sink node BS, which is often far from the sensing area.

We make the following suppositions:

1. After deployment, all nodes are homogeneous and stationary;
2. Nodes can change their transmitting power based on the distance between them and the receiver.
3. There are symmetrical links, i.e. once the transmitting power is given, a node will calculate the approximate distance to another node based on the received signal intensity.

Sensor nodes have a logical instinct to efficiently transfer data to the basic station in their own interests. It is more concerned with its own personal gain, so it is always unable to cooperate with others in transmission, even though doing so might save energy for the entire network. Thus making it a non cooperative game. Cluster heads, on the other hand, play a critical role in a hierarchical topology. Cluster heads provide service to others while lowering the overall network's energy usage. However, in addition to its network contribution, a cluster head requires a considerable amount of energy and is more likely to run out of resources. As a result, a sensor node is unlikely to be the cluster head on its own.

We formally describe cluster head determination as a game in which players participate in a strategic situation in which they must determine whether or not to become a cluster head. Essentially, the cluster heads are calculated by the density of each node. The number of nodes inside the circular propagation area of neighbouring nodes is defined as the density metric.

When determining density, the connectivity of the nodes is taken into account. As a result, an even distribution of cluster heads is ensured, as well as the elimination of energy hole issues. Despite the connectivity of the nodes, we still look at the residual energy and average energy consumption of the nodes nearby. Because of data fusion, cluster heads bear a disproportionate amount of liability. The determined cluster heads have a longer lifespan because they have more residual energy and use less energy along the routing route. We have a proper payout in exchange for a sensor node's contribution to the entire network in order to allow it to become a cluster.

Cluster Head Selection

Based on this model, the n nodes' decision-making procedure determines cluster head selection.

Steps in the procedure:

- Each node calculates a utility value u, and broadcasts it to the other nodes.
- There are 3 cases, the node receiving the broadcast can have a utility value less than or equal to or greater than u. Value broadcasted is as follows:

- **Less than:** Broadcast originally received utility value, u.
- **Equal to:** As utility is same, to obtain a single potential cluster head candidate, compare IDs (as IDs are unique). The Node with a smaller ID wins as a potential candidate.
- **Greater than:** Receiving node broadcasts a message with its own details and is now a new cluster head candidate.

➢ After all nodes are done being compared, the chosen cluster head is the node with the largest utility value.

Requirement: k cluster heads => procedure is repeated k times.

If the selected cluster head's neighbouring nodes have similar density values, cluster head selection in successive rounds can be disturbed.

To exclude such neighbouring nodes, a cluster head broadcasts a NEIGHBOR_MSG containing its ID, $R_{communication\_radius}$ and other factors such as residual energy.

All nodes within $R_{communication\_radius}$ are considered neighbor nodes and exit the ongoing round of selection.

To ensure all nodes have been studied, flags are used.

The selection ends when k cluster heads are selected.

For nodes beyond the range of transmission of selected cluster heads, the nodes' density and utility function are recalculated. The remaining cluster heads continue to be determined following the described procedure for maximum utility value per round.

The cluster heads have an even distribution.

Lemma 1:
There is no chance that two nodes are both cluster heads if one is in the other's communication range.

Proof:

Assume sensor nodes s_i and s_j are possible cluster heads.

Node s_j is in the communication range of s_i=> it is a neighbor of s_i.

If s_i becomes a cluster head before s_j, s_i will notify its neighboring nodes of its current state, and these neighboring nodes leave the competition until the next cluster head selection round and vice versa when s_j becomes a cluster head before s_i.

The selection of a cluster head is a k-stage dynamic game which is a finite, complete and perfect information game; as every player is aware of the strategies and utilities available to other players and will base its choice of strategy by observing previous stages.

Every stage constitutes a subgame.

As utility value is chosen as maximum, this game has a pure-strategy Nash equilibrium at every stage as each player plays their best response to the possible choices in the strategy of their opponents.

Pseudocode:

$\mu \leftarrow 0$
$Flag_\alpha \leftarrow 0,\ \alpha = 1, 2, ..., n$
while $\mu < k$ **do**
    if $u_i = mac\{u_\alpha\},\ Flag_\alpha = 0$ then
        $beClusterHead \leftarrow TRUE$
        $Flag_i = 1$
        $broadcast\ a\ NEIGHBOR\_MSG(s_i.ID)$
    end if
    on receiving a $NEIGHBOR\_MSG(s_i.ID)$ for node s_j
    if $d(s_i, s_j) \leq R_{comm\_radius}$ **then**
        $Flag_j = 1$
        broadcast a $QUIT\_SELECTION\_MSG(s_j.ID)$ and then EXIT
    end if
    $\mu \leftarrow \mu + 1$
end while

Routing Procedure

Once the Cluster head is determined,nodes belonging to the same cluster using single hop transmission, transfer their data to the Cluster head & it then has to transmit the information to the sink node.According to the energy model described, distance between the nodes can be used to determine the energy cost of transmission along a certain path.Keeping the primary focus on energy Efficiency DEGRA makes use of a inter-cluster forwarding algorithm.

In this algorithm the cost of direct transmission from a cluster head say CH_i to the sink node BS is compared with the cost of transmission using a relay cluster head say CH_j which is chosen in such a way so as to minimise the sum of the distance squared between the initial cluster head and relaying cluster head and the distance squared between relaying cluster head and the sink node.

For simplicity assume that CHi has to send an l-length packet to the sink node.For this it chooses CH_j as the relay node which then transmits directly to the sink node.This is a case of 2-hop transmission and the energy cost of this process is given by

$$E_{2\text{-}hop}(CH_i,CH_j)=E_{Tx}(l,d(CH_i,CH_j)) + E_{Rx}(l) + E_{Tx}(l,d(CH_j,BS))$$
$$=l(E_{elec}+ \varepsilon_{fs}d^2(CH_i,CH_j))+ lE_{elec} + l(E_{elec}+\varepsilon_{fs}d^2(CH_j,BS))$$
$$=3lE_{elec} + l\varepsilon_{fs} (d^2(CH_i,CH_j) + d^2(CH_j,BS))$$

Now let,

$E_{relay}(CH_i,CH_j)=d^2(CH_i,CH_j)+d^2(CH_j,BS)$

We note that as E_{relay} increases, transmission cost also increases.So the algorithm proceeds to find a CH_j if it exists such that E_{relay} is minimum and less than $E_{direct}(CH_i,BS)$.
The pseudocode for this algorithm is given as follows:

while $\forall CH_x \neq CH_i$ *is not null* **do**
  compute $E_{relay}(CH_i, CH_x)$
end while
find out s_j that satisfies
$E_{relay}(CH_i, CH_j) = \min\{E_{relay}(CH_i, CH_x)$
if $E_{relay}(CH_i, CH_j) < E_{direct}$ **then**
  the route is $CH_i \rightarrow CH_j \rightarrow BS$
else
  the route is $CH_i \rightarrow BS$
end if

A MATLAB-based Simulation of DEGRA

We used MATLAB environment to evaluate the performance of Density based Energy efficient Game theoretic Routing Algorithm) using simulations.Setting up an initial environment with fixed variables such as field dimension ,number of nodes,Optimal Election Probability of a node to become cluster head and the maximum number of rounds for simulation.

Initiating Simulation: Applying the DEGRA Approach

All the nodes in the field are prompted every round to calculate their utility value & broadcast it to the others in the system. Any node that is in the range of the broadcast,receives the message and has greater value than this utility then proceeds on to becoming the new candidate for cluster head & proceeds to broadcast a different message ,one generated by itself. The receiving nodes with a lesser utility than that of the node broadcasting the information broadcasts the aboriginal message without performing any alteration from its side. The node with the largest utility becomes the new cluster head.

DEGRA finds the k-cluster head, the same process is performed periodically throughout the rounds of simulation. The algorithm simulation focuses on nodes that are beyond the transmission range, recalculating the density of the nodes in the field and their corresponding utility, so there can be a more even distribution after every round. The other CHs,that are in the transmission range, are still decided by the same familiar algorithm of the greatest utility value per round.With highest utility value in the transmission range selected, the simulation’s finite game of complete & perfect information fulfils its aim of achieving strategic equilibrium each round.

Simulation Environment

We input the following values in the environment in MATLAB:

PARAMETER NAME	VALUE
Field Dimensions (xn*yn(sink length*sink breadth))	10,000 m square
Number of Nodes in the field(n)	100
Optimal Election Probability of a node to become cluster head	0.05
Initial Energy(Eo)	0.25 J
Maximum Number of rounds(in simulation)	3000
Energy consumption on circuit (Eelec)	50n J
Energy consumption for data aggregation (EDA)	5pJ/bit/signal

Simulation Results

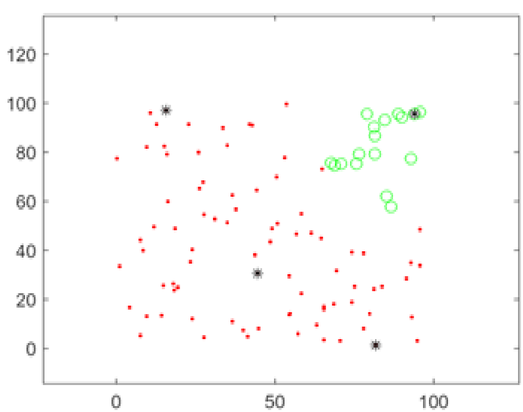
We see that our results mimic the three graphs in the report under review,we get similar results as those mentioned in our principle report on DEGRA,the key difference being we have about 3000 rounds of simulations as opposed to the 1000 rounds of simulation process used in the parent report.

Location of Cluster Heads in DEGRA

The data displayed in the report(right) shows the cluster heads generated in 1000 simulations,there are about 5 cluster heads spread in a more even fashion than the other methods of choosing cluster heads due to the density based allocation of cluster heads.

We simulated the results with all parameters similar to that of the parent report,with 3000 simulations ,therefore we have 4 cluster heads in our simulation.But the distribution of the remaining cluster heads is identical to that of the study,and we see that the node that is likely eliminated is the one closest to the origin,due to lesser density of nodes in that region.

But since the data of our simulation follows a similar pattern to that of the data reported in the study,we see the working of the report to be validated.



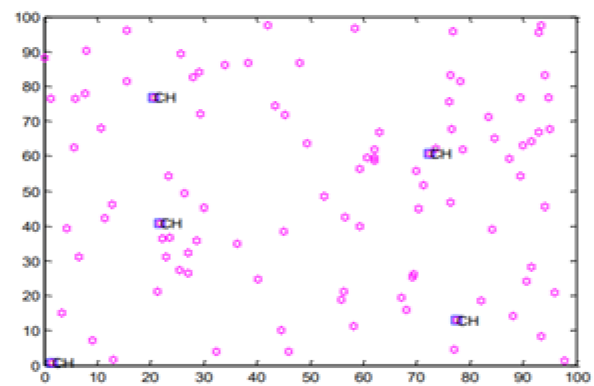
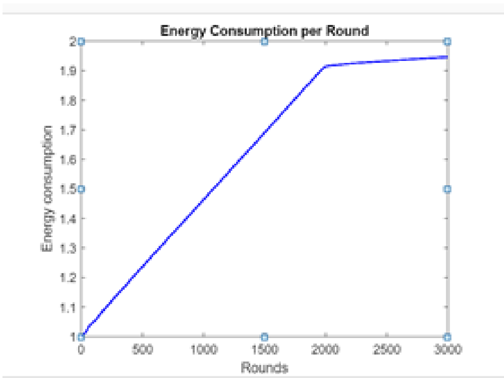


Figure 5. Location of Cluster Heads in DEGRA

Energy Consumption per round vs Rounds For DEGRA

It is visible in our simulation(left) that the energy consumption is linearly increasing but stagnates to a very small slope after about 66.67 percent of the simulation rounds.Since the rounds in the report data are minimised,we have a better estimate of what happens after two thirds of the rounds are complete. But the results show majorly how the data reported in context with DEGRA is accurate and thus DEGRA indeed consumes least amount of energy in the three protocols compared in the parent report.



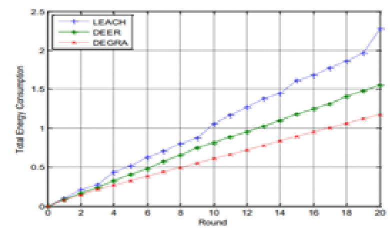
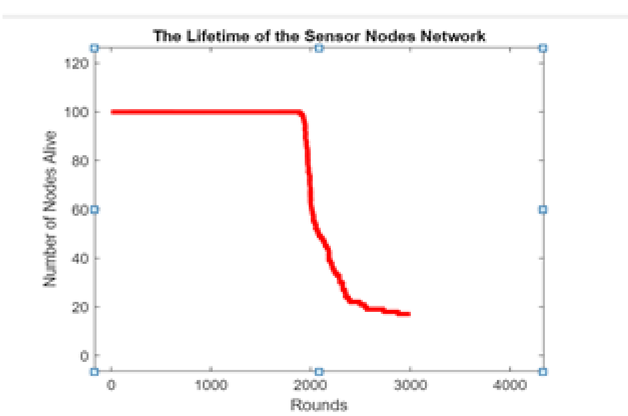
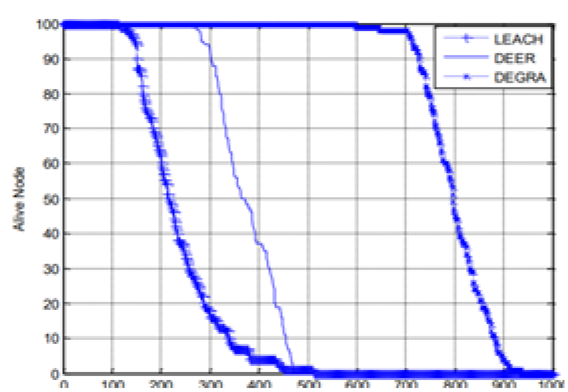


Figure 6. Comparison of Energy Consumption

Lifetime of Sensor Nodes vs. Rounds for DEGRA

Comparing our lifetime of sensor nodes vs number of nodes alive(left) with that of DEGRA results in the report(right),we see our results retain the same shape but they are dispersed over 3000 simulations instead of the 1000 simulations of the initial report,so we have increased the accuracy of the model through an extra 2000 simulations. But since the shape of the graph is retained,it is clear that the same result can be inferred from our graph as well,ie. DEGRA shows





and gives more efficient results as compared to the other two methods mentioned . Therefore our results second the results of the parent report.

DEGRA vs. Other Algorithms

In the domain of clustering in WSN's efficiency can be increased by tackling the problem of selecting cluster heads,size of a cluster and intracluster transmission. DEGRA focuses on the issue of selecting a cluster head. Becoming a cluster head is an added load and nodes primarily tend to act in their own interest (transmit directly to the sink node) instead of the interest of the entire network so game theory is employed in this situation. Each node calculates its own utility which is proportional to the residual energy of the node as well as inversely proportional to the average energy consumption of nodes which are in its transmission radius. This enables the algorithm to choose relatively powerful nodes which are more equipped to be the Cluster Heads hence attenuating the energy hole problem and aiding in maximising the network lifetime(vs LEACH(Low Energy Adaptive Clustering Hierarchy) where cluster heads are periodically and randomly chosen).Since density is also a factor in the decision of choosing the Cluster Heads DEGRA ensures that Cluster Heads are evenly distributed.(Vs LEACH where random distribution can mean uneven distribution of cluster heads).When it comes to to transmission, cluster heads can directly send data to the base station (single hop transmission) which is efficient when a cluster head is in close proximity to the base station but otherwise as the distance between a Cluster Head and base station increases single hop transmission proves to be inefficient.This issue is dealt by DEGRA using an inter-cluster forwarding algorithm that aims to find an intermediate relay Cluster Head if possible, and hence determining a path with least transmission cost.

In Game Theoretical Computation based Energy Efficient Routing for Wireless Sensor Networks (2014) the authors compare GERA(Game theory based Energy efficient Routing Algorithm) and DEGRA using NS2 simulations using the parameters

i) Total energy consumed by a node

(ii) Packet Delivery Ratio

(iii) Probability that a node will become a cluster head

and conclude that GERA outperforms DEGRA.This can be credited to the fact that GERA makes a much more extensive use of Game theory to ascertain Cluster heads and even uses a cost function to aid in Cluster formation.

A Comprehensive Review of Distance and Density Based Cluster Head Selection Schemes (2014) compared DDCHS (Distance and density based cluster head selection), DECA (Density-based Energy-efficient Clustering Algorithm) and DEGRA and concluded that DEGRA performs better than the others. This can be explained by the use of game theory in DEGRA to determine Cluster heads, as the other two algorithms simply relied on density and distance to select cluster heads.

Conclusion

Wireless sensor networks use clustering algorithms to a great degree. The choice of cluster heads is integral to improving Efficiency. Each sensor node is likely to send data directly to the sink node without having any additional correspondence with other nodes.

Nevertheless , it brings about focus on the conflict between its selfish tendency and the efficiency of the entire whole network. Game theory is used to overcome such a conflict between individuals and the network. Routing algorithm DEGRA for WSN that adopts game theory has density,nodes, average neighboring nodes, residual energy and energy consumption all come up with the utility function. In which cluster head selection is executed iteratively.A multi-hop inter-cluster and an intra-cluster routing algorithm are proposed. Simulations convey that, both the network lifetime and energy consumption get improved compared with algorithms such as LEACH .

DEGRA (Xuetal.) takes both the residual energy of a node and the average energy consumption of its neighbors in consideration. However, it is observed that DEGRA loses efficiency when the size of clusters increases.

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