A Density-based Energy-efficient Game-theoretic Routing Algorithm for Wireless Sensor Networks

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Abstract. Study on energy-efficient routing algorithms is one of the critical problems of wireless sensor networks. In this paper, we propose a Density-based Energy-efficient Game-theoretic Routing Algorithm (DEGRA). As a clustering algorithm, DEGRA adopts game theory and make cluster head determination based on nodes' density, residual energy and average energy consumption of its neighboring nodes. We also design an intra-cluster and multi-hop inter-cluster routing algorithm. Simulation results show that cluster heads are evenly distributed and our proposed routing algorithm do consume much less energy than both LEACH and DEER.
Keywords: wireless sensor networks, multi-sink, clustering, multi-hop

1 Introduction

Routing in Wireless Sensor Networks (WSNs) [1] has been the subject of intense research efforts for years. As the battery, capability of computing, storage and data processing of a sensor are limited, how to reduce the energy consumption while prolonging the network lifetime stays the key problem.

We often confront with the conflicts between the interests of one sensor and the entire network. For an individual sensor node, it prefer to send its data directly to the sink node. It is because having cooperation during the routing path not only stands for enjoying other nodes relaying its data, but also includes relaying data without its direct interest for others. It consumes its limited energy and in turn makes its own routing less efficient. On the contrary, taking the entire network into consideration, it is obvious that such direct communication between all sensor nodes and the sink would cause much traffic load, and it leads to anything but energy-efficiency. Moreover, energy consumption of certain sensors near the sink or on critical paths is much faster than other nodes even in some comparably energy-efficient algorithms. Such energy hole problem alleviates the network lifetime.

In this paper, we propose a Density-based Energy-efficient Game-theoretic Routing Algorithm (DEGRA) for WSNs. Game theory [2] studies the conflict and cooperation between intelligent rational decision-makers. Here it is adopted to balance the interests between the individual and overal. DEGRA is a hierarchical routing algorithm which adopts clustering and ensures even distribution of cluster heads due to the evaluation of nodes' density. Moreover, the residual energy and average energy consumption of one's neighboring nodes are under consideration. Via determining relatively powerful cluster heads, DEGRA alleviates the energy hole problem. An intra-cluster and multi-hop inter-cluster routing algorithm is also propped aiming at saving energy to some extent.

2 Related Work

Many energy-efficient routing algorithms have been proposed based on the hierarchical topology. Clustering divides the network into clusters and makes cluster heads responsible for data fusion. Clustering has the advantages of low energy consumption, simple routing scheme and good scalability, and it is especially suitable for WSNs. LEACH [3] is a classical clustering algorithm. In a periodical way, it randomly chooses the cluster heads. PEGASIS [4] is an improvement over LEACH. It's a chain-based protocol. Each node communicates only with a close neighbor and takes turns to transmit data to the sink. In HEED [5], cluster heads are decided based on the average minimum reachability power. Unequal clustering algorithms like [6] aim to solute the energy hole problem. For the clusters, the closer they are to the sink, the smaller size they are formed. It saves energy for the inter-cluster communications. However, too many clusters around the sink will produce a large number of summary packets that leads to heavy traffic load.

Appropriate cluster-head election is an essential consideration and nodes' location and connectivity have been primarily focused. NECHS [7] uses fuzzy logic technique considering two factors: neighbor nodes and remaining energy. Cluster heads elected in [8] are determined to have minimum composite distance of sensors to cluster head and cluster head to base station. In [9], the cluster-head selection depends on remaining energy level of sensor nodes for transmission. H.Munaga et al. [10] provide the first trajectory based clustering technique for selecting the cluster heads and meanwhile extenuate the energy hole problem. DBCP [11] improves LEACH on the basis of a metric of nodes' relative density.

Game theory have been used with great success in analyzing routing algorithms, most of which based on the planner network topology. Ad hoc-VCG [12] pays intermediate nodes a premium, which covers the incurred cost so as to achieve the cost-efficiency and truthfulness. However the message overhead is high. In TEAM [13] message complexity is reduced. Intermediate nodes bid to redirect the path by advertising the aggregate transmission power, the route may not be energy-efficient though. FDG [14] is a game theoretic approach with the probability of strategy selection based on the mixed strategy Nash equilibrium of the game. Comparing to AODV [15], it limits the number of redundant broadcasts in dense networks while still allowing connectivity. VGTR [16] judges the energy consumption of the paths and takes notice of nodes with low remaining energy or high information value. DEER [17] adopts a game-theoretic model with both remained energy and average energy loss on among neighboring nodes while evaluating the payoff function for determining cluster heads.

3 Our Proposed DEGRA

3.1 Energy model

We use the same energy model in [18]. Based on the distance between transmitter and receiver, a free space (d^2 power loss) or multi-path fading (d^4 power loss) channel models are used.

Each sensor node will consume the following E_{Tx} amount of energy to transmit a *l*-bits packet over distance *d,* where the E_{elec} is the energy dissipated per bit to run the transmitter or receiver circuit, ε_{fs} and ε_{mp} represent the transmitter amplifier's efficiency and channel conditions:

$$E_{Tx}(l,d)=\begin{cases} lE_{elec}+l\varepsilon_{fs}d^2, d<d_o \\ lE_{elec}+l\varepsilon_{mp}d^4, d\geq d_o \end{cases} \tag{1}$$

To receive a packet, radio consumes energy:

$$E_{Rx}(l)=lE_{elec} \tag{2}$$

3.2 Game-theoretic Model

We assume that the network consist of *N* uniformly dispersed intelligent sensor nodes that are denoted as $S=\{s_1,s_2,...,s_N\}$. In the game-theoretic model, they are regarded as players (participants in a game), and aim to transmit data to the sink node *BS* which is often far from the sensing field.

We have the following assumptions:

（1）All nodes are homogeneous and stationary after deployment.

（2）Nodes can adjust their transmission power according to the relative distance to receiver

（3）Links are symmetric.

As sensor nodes are intelligent and have rational tendency to pass data reliably to the sink as well as to survive long time, our proposed algorithm focuses on both energy consumption and network lifetime. We adopt a hierarchical network topology and players participate in a strategic situation of deciding whether to become a cluster head. The strategy set is denoted as $L=\{l_1,l_2,...,l_N\}$, where $l_i=1$ if node s_i becomes one cluster head, else $l_i=0$.

In this paper, we assume N sensor nodes in a $M\times M$ square region are divided into *k* clusters, with R representing the standard transmission radius for message exchange during the set-up stage of clusters. Thus we have:

$$M\times M=k\pi R^2\Rightarrow R=\frac{M}{\sqrt{\pi k}} \tag{3}$$

Basically, we determine the cluster heads according to the density (denoted as Den) of each node. Here, the metric of density represents the number of nodes located within a circle transmission region of neighboring nodes. With itself as the center and *R* as the radius, the density of node s_i can be calculated via searching the entire network as formula (4), where $d(s_i,s_x)$ represents the distance between s_i and another node s_x.

$$Den(s_i)=\sum_{0<x\leq N\ \&\ d(s_i,s_x)\leq R} 1 \tag{4}$$

Nodes' connectivity is under consideration by evaluating *Den*. Thus ensure the even distribution of cluster heads and alleviate energy hole problem. Despite nodes' connectivity, we also focus on the residual energy and average energy consumption of its neighboring nodes. It is because cluster heads have relative heavy responsibility due to data fusion. More residual energy and less energy consumption along the routing path make the determined cluster heads survive longer lifetime. The payoff function for cluster head determination is defined as follows:

$$p(s_i)=\frac{E_{residual}(s_i)}{E_{total\_cost}(s_i)/Den(s_i)} \tag{5}$$

Here, $E_{residual}$ denotes the residual energy for one node and E_{total_cost} denotes the total energy consumption of its *Den* neighboring nodes. In this way it represents that a sensor node with larger residual energy and relative smaller average energy consumption among its neighboring node has a better chance to become a cluster head.

3.3 Cluster Head Determination

Based on the game-theoretic model, the cluster head determination turns into a nodes' decision-making procedure which can be described as:

All sensor nodes calculate its payoff value *p* and broadcast a massage to announce it to others. Any received node that has larger payoff value becomes a new cluster head candidate and broadcasts a new message with its own information; otherwise, the received node with smaller payoff value broadcasts the original received message. Nodes with equal payoff value compare the ID and assume that node with a smaller ID wins. Once all sensor nodes have been compared, node with the largest payoff value is chosen as one cluster head.

As we aim to find *k* cluster head, the procedure performs in *k* rounds periodically. However, different from DEER, we notice that neighboring nodes of the determined cluster head often have similar density value which is large enough for disturbing the determinations in following rounds, so later such neighboring nodes are excluded. We focus on nodes outside the transmission range of the determined cluster heads. Recalculate nodes' density and its corresponding payoff function. The rest cluster heads are still determined for the maximum payoff value per round, following the procedure described above. It can be deduced that cluster heads are more evenly distributed.

Cluster head determination can be regarded as a *k*-stage dynamic game. Moreover, since every player knows the payoffs and strategies available to other players and each choose its strategy based on the observation of previous stages, it is a finite complete and perfect information game [19] for determining the cluster heads. With the maximum payoff value chosen, the finite game of complete and perfect information has a pure-strategic Nash Equilibrium for each stage. And all stages constitute a subgame-perfect Nash equilibrium of the dynamic game.

3.4 Routing Procedure

After determining all cluster heads, sensor nodes send data to one cluster head directly within one hop. The corresponding cluster head should be determined with the least energy consumption for the transmission cost along the path. According to formula (1) in the energy model, distance plays a significant role. The inter-cluster algorithm can be formulated as to find the node with smallest distance to the cluster head.

In LEACH, cluster heads send data to the base station directly within one hop. There is high chance that it consumes large energy due to the remote location of some cluster head. In our DEGRA, we perform inter-cluster routing in a multi-hop way. Suppose cluster head CH_i chooses another CH_j as its relay node and let CH_j

communicate directly with the sink node *BS*. In order to deliver a *l*-length packet to BS via CH_j, the energy consumed of CH_i is calculated as formula (6) where ε and α vary in different situations according to the energy model.

$$\begin{aligned} E_{CH_i} &= E_{Tx}(l, d(CH_i, CH_j)) + E_{Rx}(l) + E_{Tx}(l, d(CH_j, BS)) \\ &= 3lE_{elec} + \varepsilon d^{\alpha}(CH_i, CH_j) + \varepsilon d^{\alpha}(CH_j, BS) \end{aligned} \quad (6)$$

For each cluster head CH_i, we choose an optimal relay cluster head which maintains the least energy consumption E_{CH_i}. We compare it with the direct communication cost to *BS*, and determine the optimal inter-routing according to the smaller energy dissipation.

4. Performance Evaluation

4.1 Simulation Environment

We evaluate the performance of the DEGRA via simulations in Matlab. The simulation environment is set up with the parameters listed in Table.1.

Table.1 Network parameters

Parameter Name	Value
Network Scale ($Area$)	100×100
Number of the sensor nodes (N)	100
Length of the packet (l)	4000bits
Initial energy of the sensor nodes ($E_{initial}$)	0.25J
Energy consumption on circuit (E_{elec})	50nJ/bit
Channel parameter in free-space model (ε_{fs})	10pJ / bit / m^2
Channel parameter in multi-path model (ε_{mp})	$0.0013\text{pJ / bit / m}^4$
Channel parameter for data aggregation (ε_{DA})	5pJ/bit/signal

4.2 Simulation Results

Fig.1 denotes the initial network. Fig.2 shows the distribution of five cluster heads in LEACH. As it adopts randomization in the selection procedure, there is high chance that some cluster heads locate relatively close to each other. Thus it results in heavy traffic load for remote nodes to transmit data to any cluster head. Differently, with nodes' density under consideration in our DEGRA, cluster heads are distributed much more evenly as is shown in Fig.3.

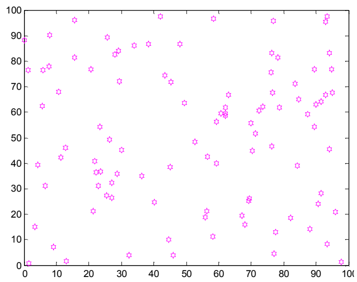
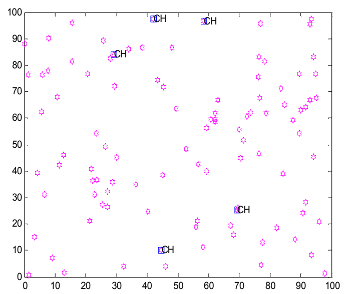


Fig.1 initial network



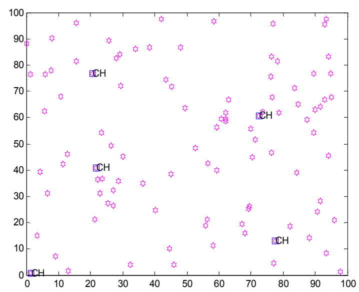


Fig.2 cluster head distribution in LEACH Fig.3 cluster head distribution in DEGRA

We compare the total energy consumption of LEACH, DEER and our DECA, as is shown in Fig.4. During 20 rounds, DEER outperforms LEACH as cluster heads have relative small average energy consumption along the path between itself and its neighboring nodes. In comparison, DEGRA shows much better performance than both LEACH and DEER with less energy consumption. This is mainly because of the energy-efficient cluster head determination and the multi-hop inter-cluster routing that might choose a better path in order to save energy.

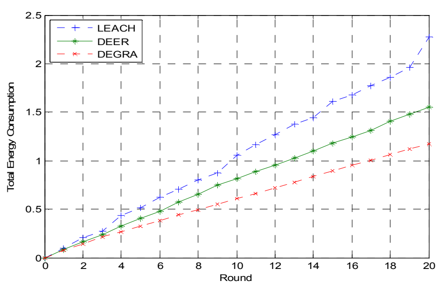


Fig.4 comparison of energy consumption

5. Conclusions

For wireless sensor networks, each sensor node prefers to transmit data directly o the sink node without any communication with other nodes, but the overall network would suffer from such individual benefit. In this paper we propose a Density-based Energy-efficient Game-theoretic Routing Algorithm (DEGRA) for WSNs. It adopts game theory and solves the above conflict. In our DEGRA, nodes' density, residual energy and average neighboring nodes' energy consumption all contribute to form the payoff function and implement the cluster head determination. An intra-cluster and multi-hop inter-cluster routing algorithm is proposed. Simulations show that cluster heads are more evenly distributed . Total energy consumption is reduced compared with algorithms LEACH and DEER.

6. Acknowledgements

This work was supported by Jiangsu Province Universities Natural Science Research Program (NO.11KJB510010) and Jiangsu Province Research and Innovation Project for College Graduates (NO.CXZZ12_0515). It was also supported by the Industrial Strategic Technology Development Program (10041740) funded by the Ministry of Knowledge Economy (MKE) Korea, and by the Natural Science Foundation of Jiangsu Province (No. BK2012461).

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