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EEACE: Energy Efficient ACE Algorithm for Wireless Sensor Networks

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Abstract

The ultimate goal of researches on Wireless Sensor Networks (WSNs) is how to improve network energy efficiency as possible as can. Certainly, there are many researches concerned to energy efficient scheme in wireless sensor networks. Dividing geographically distributed sensor nodes into different clusters in order to decrease transmission range and transmission quantity is one of traditional energy efficient strategies for WSNs. In this paper, an energy efficient ACE clustering algorithm named EEACE in short is presented to improve the performance of ACE scheme. The EEACE algorithm is derived from ACE scheme but overcomes many shortcomings of ACE and other clustering algorithms such as famous LEACH and DCHS. By dividing sensor nodes into uniform clusters with minimum communication cost, EEACE algorithm improves the network's performance at aspect of lifetime and energy efficiency significantly. The simulation results verified that EEACE algorithm prolongs the lifetime of WSNs by more than 15% comparing with ACE and DCHS algorithm.

Index Terms: Wireless Sensor Networks (WSNs); Clustering Algorithm; Energy Efficiency; Algorithm for Cluster Establishment (ACE)

1. Introduction

The researches on Wireless Sensor Networks (WSNs) [1] have been gaining momentum in recent years due to its great potential in pollution monitoring, critical infrastructure surveillance, emergency response and battlefield operation. Typical WSNs consists of thousands of sensor nodes scattered around one or several base stations (BS). Information collected by the sensor nodes is transmitted to the base station for further analysis. Sensor nodes are powered with batteries of very limited capacity, and usually have limited computing and memory resources. Limited power requests WSNs to be energy efficient in particular; as a result, most of researches on WSNs are dedicated to this topic.

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Clustering algorithm is a fundamental mechanism in WSN design. By merging sensory data, clustering algorithms reduce both the quantity of data to be transmitted and the average transmission distance, therefore, reduce energy consumption and prolong network lifetime [2]. Symmetric propagation means the energy needed to transmit one bit of data from node *u* to node *v*, is the same as transmitting one bit from node *v* to node *u*. Cluster heads collect N k-bit messages from N adjacent one-hop sensor nodes and compress the data to $c \cdot N$ k-bit messages, where $c \leq 1$ denotes the compression coefficient, and transmit them to the base station finally.

Clustering algorithms in WSNs can be divided into two categories based on the way that cluster heads are elected, namely centralized algorithms and localized algorithms. Centralized algorithms have inherent difficulties in the properties of scalability and robustness, which are two important design goals in WSNs [3]. Localized algorithms only require each sensor node to interact with its one-hop neighbors. Clusters are established without too much information exchange with the base station.

The remainder of this paper is organized as follows. Section 2 analyses popular clustering algorithms and their shortcomings in detail. In Section 3, EEACE algorithm is proposed in detail. Simulation results and comparison between algorithms are provided in Section 4. Finally, section 5 concludes the paper and discusses possible future researches.

2. Related Works

There are a lot of clustering algorithms proposed in the literal to address energy efficiency problem of WSNs.

LEACH (Low Energy Adaptive Clustering Hierarchy) [4] is the most notable clustering algorithm for wireless sensor networks. LEACH combines the ideas of energy-efficient cluster with application-specific data aggregation to achieve good performance, conserves limited amount of energy by selecting a few cluster heads with randomized rotation selection method. LEACH distributes the energy load among sensor nodes in the network and prolongs network lifetime. PEGASIS (Power Efficient Gathering in Sensor Information Systems) [5] is a chain-based clustering scheme to improve LEACH. In PEGASIS, only one sensor node will be chosen to be cluster head randomly in each round, and then each sensor node will form a chain using minimum distance method. PEGASIS outperforms LEACH because PEGASIS performs data fusion at each chain node except the end node in the chain. HEED [6] extends LEACH by incorporating communication range limits and cost information. Different with LEACH, the probability of HEED for each sensor to become cluster head is dependent on its residual energy. Later on, sensor nodes that are not covered by any cluster heads double their probability of becoming a cluster head until all sensors are covered by at least one cluster head. At last, sensor nodes join in certain cluster heads of lowest cost. DCHS (Deterministic Cluster-head Selection) [7] prolongs network lifetime by adding energy adaptive mechanism to the cluster-head selection process, achieving much better performance on energy efficiency compared with other algorithms derived from LEACH. Haowen et al proposed ACE (Algorithm for Cluster Establishment) [8], which is an emergent algorithm. By forming clusters through interactions between one-hop sensor nodes, ACE scheme greatly reduces overlap between clusters and minimizes the number of cluster to assure network coverage, thus an efficient and balanced clustering result is obtained. The ACE scheme concerns only on cluster establishing phase, but doesn't take care of sensor node energy changes in the working phase. Unbalanced energy consumption may lead to early death of some sensor nodes and the lifetime of WSNs is thus cut short enormously.

In order to reduce energy consumption so as to prolong network lifetime, a clustering algorithm ought to divide sensor nodes into most balanced clusters. ACE scheme outperforms many other popular clustering algorithms because it adopts mechanisms to reduce energy consumption during cluster formation and data transfer. By restricting cluster size and migrating to better cluster heads, ACE reduces overlap between different clusters. However, ACE algorithm concerns only about the cluster formation period and ignores residual energy levels of sensor nodes. The cluster heads elected by ACE will remain unchanged unless sensor nodes undergo some major changes. Because cluster heads are responsible for merging and transmitting aggregated data to the base station, it consumes more energy than cluster members. The disadvantage of ACE is described as below:

- The cluster heads elected by ACE scheme die early due to higher energy consumption. They are the best cluster heads in the clusters region and selecting other nodes as cluster heads will increase communication cost.
- When certain cluster head is lost, its cluster members have to rebuild a new cluster, therefore, part of coverage of the network will be lost before new cluster is established.
- Choosing the best cluster head in the ACE model is too simple to describe the communication cost within clusters.

On the other hand, DCHS algorithm achieves energy-efficiency by choosing those sensor nodes that have more energy to be cluster heads in each round of interaction. This approach solves the problem of uninformed energy consumption while reducing the stability of clusters significantly. However, frequent cluster changes are not preferred because energy is wasted in cluster establishment and it would bring great difficulties for upper layer protocol design. The requirement of a synchronized clock in DCHS algorithm also introduces difficulty in its implementation.

3. EEACE Algorithm

3.1. Energy-consumption Model

Before discussing EEACE algorithm, we first investigate how energy is consumed in WSNs. In [9, 10], Handy et al established a model where a d^2 energy loss due to channel transmission is assumed. Thus, to transmit and receive an m-bit message over distance d under this model, the sensor node consumes energy:

$$E_i^{tx} = (e_i^t + \varepsilon_{amp} \times d^2) \times m \qquad E_i^{rx} = e_i^r \times m \tag{1}$$

where E_i^{tx} denotes the energy to send m bits and E_i^{rx} denotes the energy consumed to receive m bits, $\varepsilon_{\mathrm{amp}}$ denotes the transmitter amplifier's energy consumption, e_i^t and e_i^r denote the transmission energy required by sensor node i to transmit or receive an information unit (bit) respectively. In the simulation setting of this paper, these parameters are set as follows:

$$e_i^t = e_i^r = 50 \text{ nJ/bit} \quad \varepsilon_{amp} = 100 \text{ pJ/(bit} \cdot \text{m}^2\text{)} \tag{2}$$

With these parameter values, transmitting and receiving a message is not a low cost operation. Energy efficient algorithms should thus try to minimize not only the transmission distance but also the number of transmission and receiving operations for each message.

In this paper, an emergent clustering algorithm named energy efficient improved ACE clustering algorithm (EEACE in short) is proposed. The proposed EEACE algorithm is based on following assumptions [8]:

- The base station is static.
- Sensor nodes are homogenous and energy-constrained.
- Sensor nodes are able to communicate directly with the base station.
- Sensor nodes have no geographical location information.
- The wireless channels are symmetric propagation channels.
- Cluster heads are provided with data compression ability.

In EEACE algorithm, each sensor node in the network runs clustering algorithm independently, according to their different states. By adding energy adaptive mechanism, EEACE algorithm ensures that energy consumed among different sensor nodes more balanced. Compared with ACE algorithm, EEACE algorithm consumes less energy for exchanging information between sensor nodes.

3.2. Detailed description of EEACE Algorithm

Inspired by ACE algorithm, EEACE algorithm adopts a cluster head migration mechanism to yield the near-optimal clustering results. A migration is an action initiated by a cluster head, which will periodically POLL the sensor nodes in its cluster. Among all the neighbor nodes (two nodes are neighbors if and only if the distance between them is smaller than the maximal communication radius) of the polling cluster head, the sensor node with highest energy level and lowest communication cost will be voted as the best cluster head. On finding the optimal cluster head, the old cluster head will transfer qualification of cluster head to the best one. Migrations occur during the whole lifetime of the WSNs, ensuring that at any moment the cluster head of a cluster is always the one that can deliver the service with the lowest cost.

EEACE algorithm dose not require all sensor nodes in WSNs with a synchronized clock. Each sensor node just needs to maintain its own clock to decide when to start its interaction. Interaction is the action initiated by sensor nodes to decide whether there is a necessity for a state change. Interactions are separated by random intervals to prevent broadcast storms in WSNs. A sensor node will only initiate exchanges with other nodes during its interaction, but will respond to messages immediately. When sensor nodes start interaction, they execute following different rules according to their independent states.

Sensor nodes may be in one of the following states before they exhaust all their energy [8]: unclustered, without joining in any of the existing clusters; clustered, choosing a cluster head that lies within its communication radius; cluster head, merging data from cluster members in its cluster then delivery these data to the remote base station.

If a node m is unclustered, it will first check whether there is a cluster that it could join in by checking its potential cluster head list. If the list is not empty, it will choose the cluster with cluster head closest to itself. If the list is empty, this node will POLL its neighbors for its priority factor p, if all the neighbors with a priority factor higher than its own have become clustered, this node will declare itself as cluster head and then broadcast a RECRUIT message to its neighbors.

If a node m is clustered, it will check its potential cluster head list to check whether there is a cluster with cluster head closer than the current cluster head. If yes, it will join in the nearest cluster.

If a node m is cluster head, it will POLL nodes within its communication radius that are unclustered or in its own cluster or being a cluster head. If the node n with the highest priority factor p is not itself, node m will send node n a PROMOTE message, then node m will wait until it receives RECRUIT message from node n. On receiving that, node m will broadcast an ABDICATE message, then turn into clustered state and choose a cluster to join in.

After interaction, sensor nodes will wait for an interval before next interaction is initiated. To achieve full coverage (when all nodes become clustered or cluster head, the network is fully covered) in a shorter time, unclustered nodes will have a relatively shorter interval. On the other hand, to avoid cluster adjustment occurs too frequently, clustered and cluster head nodes should wait for a longer time between interactions. At the end of each interaction, for an unclustered node, it will generate a random waiting interval between 0 and T_s; clustered nodes or cluster heads will pick a random value between 0 and T_l, where $T_s << T_l$.

- On receiving messages, sensor nodes will respond according to its state immediately.
- On receiving RECRUIT message, all sensor nodes will add cluster head ID of this message into its potential cluster head list, along with the distance to that cluster head. Distance information can be obtained by detecting the signal strength.
- On receiving ABDICATE message, all sensor nodes will delete cluster head ID of this message from its potential cluster head list. If the node is clustered and belongs to the cluster of the abdicated cluster head, it will become unclustered and broadcast this state change to inform its one-hop neighbors.

- On receiving PROMOTE message, sensor node will change its state into cluster head and broad a RECRUIT message to its one-hop neighbors.
- On receiving message from one-hop neighbors indicating state changes, sensor node will simply update the recorded state of that node and don't respond.

The priority factor p is defined as the probability of sensor node to be a cluster head. The larger p a node has, the better it will perform when it becomes cluster head. The priority factor p of a node m is calculated as follows:

$$p(m) = \frac{E \cdot n}{D(m)/n} \tag{3}$$

where E denotes the residual energy of the node, n denotes the number of followers (the followers of a node m are those nodes that are unclustered or have node m's cluster head in their potential cluster head lists). D denotes the total distance, it is calculated as follows:

$$D(m) = d_{BS}(m) + \sum_{i=1}^{NB_m} d(m,i) \tag{4}$$

where $D(m)$ denotes the total distance factor of a node m, $d_{BS}(m)$ denotes the square of the distance between node m and the base station, NB_m denotes the number of node m's neighbors and $d(m,i)$ denotes the square of the distance between node m and its i^{th} neighbor.

4. Simulations

In the simulations of this paper, 1000 homogenous sensor nodes are randomly scattered in a plain area of 1000×1000 meters. The base station locates at (500, 500), which is the geographical center of the plain area. Each sensor node is assumed to have 1J energy at the beginning. Energy consumption is modeled as descriptions in section Ⅲ(A). In the simulations, we set the communication radius of EEACE and ACE to be 100 meters, and use 10% as the initial percentage of cluster head in DCHS [7].

In this session, we present simulation results of EEACE as well as ACE and DCHS for comparison. The network topology derived from EEACE is demonstrated in Fig.1. From the comparison of simulation result it can find that the distribution of cluster heads of EEACE algorithm is more symmetrical than DCHS algorithm but similar to ACE algorithm.

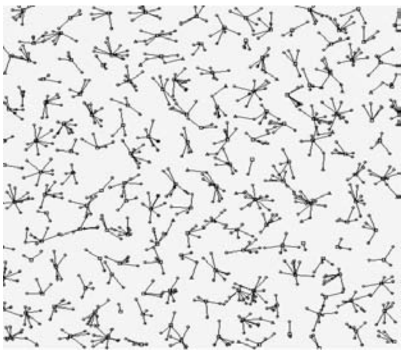

Fig 1. The topology derived from EEACE

One of the most important criterions distinguishing the performance of clustering algorithm is its capability to prolong network lifetime. To make a sensor node work longer, its energy consumption must be decreased by reducing the communication cost between clustered nodes and the cluster heads and that between cluster heads and the base station as possible as can. Fig.2 reveals energy consumption per node at different stages of WSNs. As we can see in Fig.3, at any stage, EEACE algorithm has a lower energy consumption level comparing with the other two algorithms. EEACE algorithm tends to choose those nodes that are most energy efficient to be cluster heads using an energy aware strategy in cluster head selection.

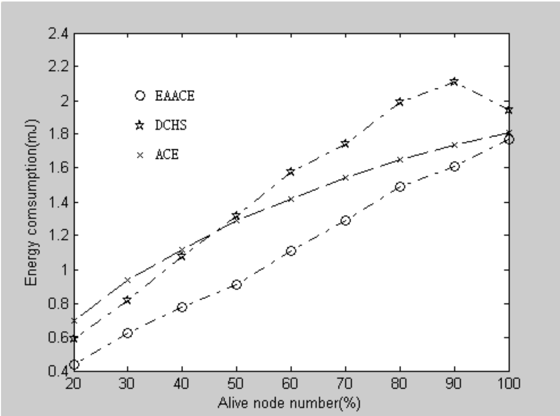

Fig 2. Comparison of energy-consumption per node

Lower energy consumption results in obviously longer network lifetime. EEACE algorithm has a significant advantage over ACE and DCHS at most stages. For HNA (Half Node Alive) time [7], which is the time when half sensor nodes are dead due to energy exhaustion, EEACE algorithm prolongs it by 15% compare with ACE scheme.

Finally, we investigate the relationship between communication radius and network lifetime. Larger radius means more nodes in one cluster and it would be easier to find the cluster head that is most energy efficient, which is why the average energy consumption is lower. However, larger radius will also increase the cost of communication within the cluster. In the long run, larger radius has significant negative effect on network lifetime. On the other hand, smaller radius will prevent the algorithm from finding the best cluster heads. Therefore, choosing a proper communication radius is also very important.

5. Conclusions

In this paper, we present an emergent clustering algorithm EEACE which is robust against node failure and efficient in communication without requiring any geographical location information. With its energy efficient cluster head selection mechanism, EEACE algorithm significant reduces energy consumption in communication, prolongs the lifetime of the network by 15% compare with ACE. Besides its practical usefulness, the algorithm's flexibility and emergent characteristic endow its capability in the implementation of large scale WSNs.

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