A Bio-Inspired Algorithm for Performance Optimization in Wireless Sensor Networks

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Abstract—A wireless sensor network typically comprises a number of inexpensive power constrained sensors which collect data from the sensing environment and transmit them towards the base station in a coordinated way. Employing techniques of clustering and election of cluster heads can increase the transmission efficiency and prolong the network lifetime. This paper proposes a bio-inspired de-centralized clustering algorithm for wireless sensor networks. The clustering algorithm is evaluated assuming a first-order radio model. Simulation results show that the proposed algorithm brings a 16 % to 161 % improvement over other de-centralized clustering algorithms in terms of network lifetime. Simulation results also show that the proposed de-centralized clustering algorithm has a similar performance as the centralized clustering algorithm.

Keywords—bio-inspired algorithm, clustering, de-centralized control, wireless sensor networks.

1. Introduction

Advanced electronic technologies allow the production of light-weight and low-power wireless sensors at low-cost. A wireless sensor network consists of a large number of sensors which collect data from a sensing area which is possibly inaccessible. Since sensor nodes are power-constrained devices, frequent and long-distance transmissions should be kept to minimum in order to prolong the network lifetime [1, 2]. Thus, direct communications between nodes and the base station are not encouraged.

One effective approach is to divide the network into several clusters, each electing one node as its cluster head [3]. The cluster head collects data from sensors in the cluster, directly or via other sensors in the cluster that form a routing path. Several data will be fused at the cluster head and transmitted towards the base station. Thus, only some nodes are required to transmit data over a long distance. The rest of the nodes in the network will need to do only short-distance transmission. The overall network lifetime can thus be prolonged.

In this paper, a bio-inspired clustering algorithm is proposed. This new clustering algorithm will be evaluated and compared with other existing algorithms [3, 4, 5].

2. Review of Existing Clustering Algorithms

Basically any clustering algorithm is concerned with the management of clusters, which includes forming a suitable number of clusters, selecting a cluster head for each cluster, and controlling the data transmission within clusters and from cluster heads to the base station [1].

In Low-Energy Adaptive Clustering Hierarchy (LEACH) algorithm [3], one single node will be elected as the cluster head in each cluster randomly. As the root of the cluster, the cluster head collects data from its cluster members and may combine several related data into one single unit. With the fusion of data, fewer transmissions are required and therefore the network lifetime can be prolonged.

The Low-Energy Adaptive Clustering Hierarchy with Deterministic Cluster Head Selection (LEACH w/DCHS) modifies the original LEACH algorithm by taking the residual energy level in each node into consideration [4].

One widely used centralized clustering scheme is the Power-Efficient Gathering in Sensor Information Scheme (PEGASIS) [5]. In this scheme, sensor nodes are sorted and connected to form a chain. Each node on the chain receives data from its neighbors, fuses the data with its own and transmits it to a neighbor closer to the cluster head.

3. Biological Decentralized Systems

By evolution and natural selection, living organisms have become the most optimized or nearly optimized systems. In constructing practical engineering systems, biological phenomena represent good sources of inspiration for achieving high efficiency and performance.

Among many organizational structures in living organisms, the social structure of honeybees or ants is chosen as the source of inspiration in our study because of its massive number of simple individuals and de-centralized control mechanisms which show the greatest similarity to wireless sensor networks [6, 7, 8].

4. Bio-Inspired Clustering Algorithm

Each sensor node in a wireless sensor network is analogous to an individual in the social insect colony. The cluster head is the queen and the pheromone is represented by a ranking packet. The pheromone concentration corresponds to the ranking. The available power of a cluster head is mapped to the reciprocal of the age of the queen in the social insect colony. The operation of bio-inspired clustering algorithm can be described in two phases.

In a network of N nodes, each node is labeled with a unique node number n, where $n = 1, 2, 3, \cdots, N$. A cluster is organized in concentric layers with the cluster head located at the center. A node in a cluster will be assigned with a ranking L_n. Nodes in an inner layer (closer to the center) will have a higher ranking (smaller value of L_n) while nodes at a outer layer will have a lower ranking (bigger value of L_n). The cluster head will be the only node in a cluster with $L_n = 0$ (highest). For a cluster head with node number $n = j$, its ruling cluster will be named as "cluster j".

4.1. Phase 1

The algorithm begins with an arbitrary choice of a node to be a cluster head. To recruit its cluster members, this cluster head will broadcast a ranking packet toward its neighbor sensor nodes within a distance of r_n, where r_n is a function proportional to the residual energy in a node, i.e.,

$$r_n = \left(k_1 + k_2 \frac{\epsilon_{n\_\mathrm{residual}}}{\epsilon_{n\_\mathrm{initial}}}\right) \tag{1}$$

where $\epsilon_{n\_\mathrm{residual}}$ is the residual energy of a sensor node, $\epsilon_{n\_\mathrm{initial}}$ is the initial energy of a sensor node, and k_1, k_2 are constants.

The ranking packet contains (i) the name of the cluster, (ii) the ranking of the sender, and (iii) a threshold β_j. The threshold β_j is a function proportional to the residual energy of a cluster head with $n = j$ which is used to control the number of layers in a cluster, i.e.,

$$\beta_j = \mathrm{round}\left(k_3 \frac{\epsilon_{j\_\mathrm{residual}}}{\epsilon_{j\_\mathrm{initial}}}\right) \tag{2}$$

where $\epsilon_{j\_\mathrm{residual}}$ is the residual energy of a cluster head with $n = j$, $\epsilon_{j\_\mathrm{initial}}$ is the initial energy of a cluster head with $n = j$, and k_3 is a constant.

Case 1

If sensor node q does not belong to any cluster at the moment of receiving the packet and the "ranking of the sender" does not go beyond the threshold β_j in the packet, sensor node q will make itself belong to the cluster issuing the packet and rank itself with ranking of the sender plus one. Afterwards, sensor node q will modify the the ranking of the sender in the packet with its own ranking L_q and forward it toward its neighbors within a distance of r_q.

Case 2

If a sensor node already belongs to a cluster, a sensor node will compare its own ranking with the ranking of the sender in the ranking packet. If the ranking of the sender does not go beyond the threshold β_j in the packet and the sender can offer it with a higher ranking, a neighbor sensor node will resign from its original cluster and join the new cluster. The newly joined sensor node will modify and forward the ranking packet toward its neighbors. If the ranking of the sender goes beyond the threshold β_j, the ranking packet will be considered invalid. All invalid ranking packets will be ignored.

Once started, all nodes (except those cluster heads) in the network will start their own timers and generate their own random time delays T_1 and T_2. Both T_1 and T_2 start at the same reference point with T_2 longer than T_1. If node p cannot offer its neighbor sensor node q with ranking higher than node q's original ranking, the ranking packet from node p will be backed up in the memory of node q. If no valid ranking packet with higher ranking is received by the sensor node q within the period T_1, the stored packet will be retrieved, and node q will resign from the original cluster and join the cluster contained in the retrieved packet. Its ranking will become the ranking contained in the stored packet plus one. The timer will reset itself once a sensor node has made a decision on joining a cluster. If a sensor node cannot receive any valid ranking packet throughout T_2, it will emerge as a new cluster head and start up a new cluster.

A cluster head will retire when its energy level is below a threshold α. Once retired, the node will act as a normal senor node and may join another cluster when a valid ranking packet is received. When the energy level of a node is below the threshold α and can no longer receive any valid ranking packet, the node will enter phase 2.

4.2. Phase 2

Sensor nodes in phase 2 will exchange their energy information with their neighbors. Assuming that the size of the energy information is much smaller than the data, the energy consumed in broadcasting the energy information is negligible. A sensor node will only send data to its nearest neighbor with available energy higher than its own. Any node having no such neighbor will become a 'false queen'. A 'false queen' will fuse its own data with data received from others and transmit it toward the base station.

5. Simulation Study

We assume that the radio channel is symmetric. All sensors are assumed to sense the environment periodically and always have data to send to the base station. We adopt a simple radio model [5], where the radio dissipates $E_{\mathrm{elec}} = 50$ nJ/bit to run the transmitter or receiver electronics and dissipates $\epsilon_{\mathrm{amp}} = 100$ pJ/bit/m^2 in the transmit amplifier to achieve an acceptable signal-to-noise ratio at the receiver. The cost for data fusion is assumed to be $E_{\mathrm{fus}} = 5$ nJ/bit.

The simulation was carried out in MATLAB with 50 to 100 sensor nodes randomly distributed in an area of 50×50 m^2. All sensor nodes are kept stationary throughout each simulation. The user, i.e., the base station, is located 100 m from the sensing area, at $(x, y) = (25$ m, -100 m$)$. The base station is assumed to be a power unlimited device. Each message is 2000 bits in length. Each node is initially given 0.5 J of energy. When the energy drops to 0 J, the node is considered as "dead". The simulation does not consider the setup time and the energy for configuring the dynamic clusters.

The simulations are run in rounds. In each round, each sensor nodes will send a message toward the base station through different routes. When all nodes in the network have finished sending their data to the base station, a round is completed. The simulation continues until all sensor nodes in the network are running out of energy. The number of nodes remain alive in each round is used to evaluate the performance of the clustering algorithm.

6. Results and Evaluations

6.1. Network Lifetime

There is no single definition of network lifetime. For network consists of sensors with small sensing range, the coverage of the network is highly correlated with its number of nodes that remain alive. The network quality will be greatly reduced with the death of the first node. In such cases, the time at which the *first node dies* (FND) gives a good indication of the network lifetime. If the sensing range of each sensor is allowed to extend a bit further, their sensing ranges will start overlapping and the same event may be sensed by several sensors simultaneously. The loss of several nodes will not degrade the performance of the network to a great extent. The time at which *half of the nodes alive* (HNA) will then be used instead of FND to estimate the network lifetime. For network filled with sensors of large sensing ranges, a single sensor node will be enough to cover the whole area. In this case, the time elapsed until the *last node dies* (LND) will be the best representation of the network lifetime. Therefore, we will use these three lifetime definitions to evaluate the performance of different clustering algorithms. The results are shown in Figs. 1 and 2.

As shown in Fig. 1 and Fig. 2, the bio-inspired clustering algorithm is 16% to 161% better than LEACH and LEACH with DCHS in terms of the three lifetime definitions. Simulation results also show that the bio-inspired clustering algorithm can give similar FND, HNA and LND as PEGASIS in prolonging network lifetime.

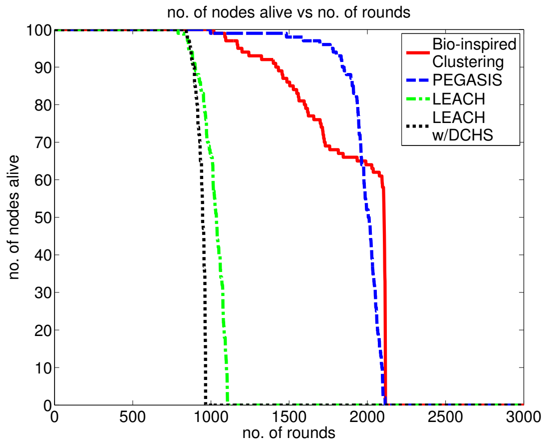

Figure 1: Network lifetime evaluation (100 nodes) for different clustering algorithms.

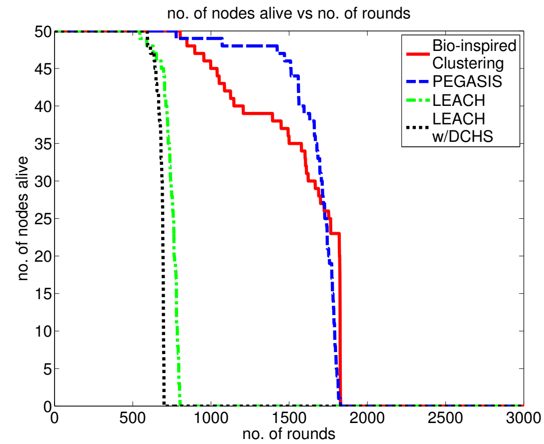

Figure 2: Network lifetime evaluation (50 nodes) for different clustering algorithms.

6.2. Network Robustness

A network has better robustness if its LND remains unaffected or only mildly affected when a significant portion of the network is destroyed. We consider the same network of 100 nodes, as evaluated earlier. Here, 50 operating nodes are randomly destroyed at the 500th round. The aim of the simulation is to evaluate the impact of losing half of the nodes during operation on the lifetime of the network.

As shown in Fig. 3, losing half of the nodes will lead to only 14.27% reduction in the lifetime of the network when the bio-inspired clustering algorithm is employed. However, for LEACH and LEACH with DCHS, the lifetime reduction can be as big as 15.86% and 21.84%, respectively. For PEGASIS, the impact of losing 50 nodes is also significant, with 18.16% reduction in lifetime.

6.3. Network Coverage

An important aspect of network performance is the coverage. If dead nodes are more evenly distributed over the sensing area, a wider coverage can be maintained. We assume a fixed radius of 10 m for each working sensor, and evaluate the percentage of coverage over the sensing field. As shown in Figs. 5, 6 and 4, our bio-inspired algorithm gives a better coverage than other algorithms.

7. Conclusions

In this paper, a novel bio-inspired clustering algorithm has been proposed. Inspired by the structural organization of social insect colonies, an algorithm has been derived for forming and maintaining clusters in a wireless sensor network. It has been shown that our proposed de-centralized algorithm can improve network lifetime significantly over

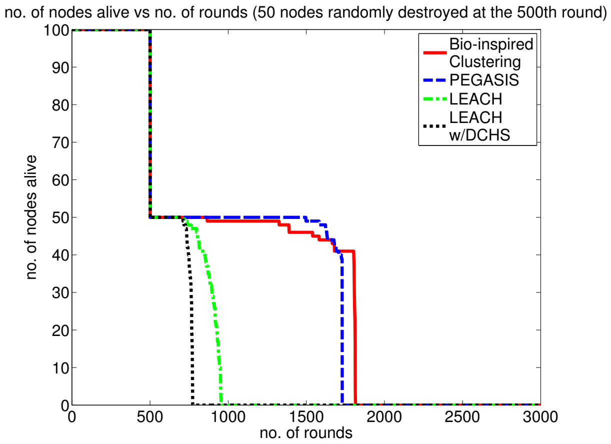

Figure 3: Network robustness evaluation for different clustering algorithms (50 nodes destroyed at the 500th round).

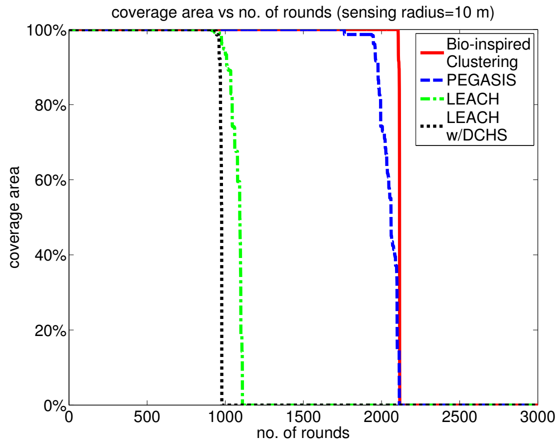

Figure 5: Network coverage evaluation (100 nodes) for different clustering algorithms (sensing radius = 10 m).

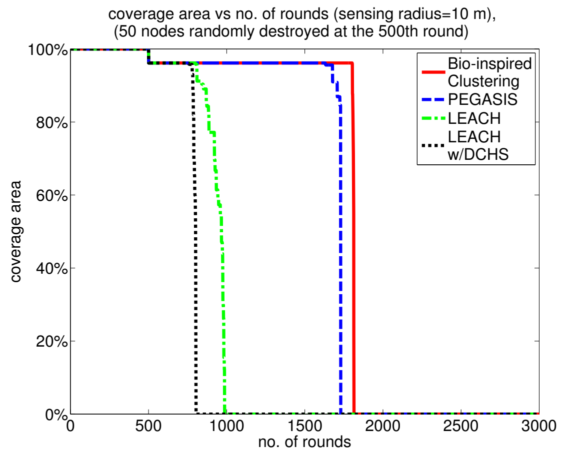

Figure 4: Network coverage evaluation (100 nodes) for different clustering algorithms (50 nodes destroyed at the 500th round, sensing radius = 10 m).

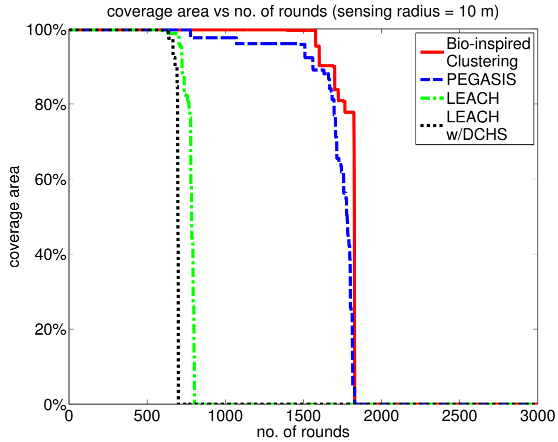

Figure 6: Network coverage evaluation (50 nodes) for different clustering algorithms (sensing radius = 10 m).

other de-centralized clustering algorithms, and that it can give similar performance as centralized systems. Our proposed clustering algorithm also obtains a significant improvement among other clustering algorithms in terms of system robustness and network coverage.

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