

Gradual Cluster Head Election for High Network Connectivity in Large-Scale Sensor Networks

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Abstract— The large-scale deployment of high density wireless sensor networks (WSNs) necessitates efficient organization of the networks for high network connectivity and low orphan node ratio. The multi-hop clustering technique has proven to be an efficient one for self-organizing thousands of randomly deployed sensors in a huge area. In this paper, we propose new clustering algorithms with a set of parameters for clustering nodes in static ad hoc sensor networks. First, we present a gradual cluster head election algorithm (GCA) that gradually elects cluster heads according to the proximity to neighbor nodes and the residual energy level (E_r) at each clustering phase. In addition, we propose a gradual cluster head election algorithm with one-hop neighbor information (GCA-ON), which elects cluster heads based on E_r and the relative location information of sensor nodes such as the number of cluster heads in one-hop neighbor (N_{CH-ON}). Ideal distributions or capabilities of the sensor nodes are not assumed in the proposed algorithms. We evaluate the performance of the proposed algorithms in large-scale high density WSN environments. In view of network connectivity, our algorithms outperform the typical existing cluster head election algorithms.

Keywords— wireless sensor networks; clustering; self-organization; cluster head election; network connectivity

I. INTRODUCTION

Recently wireless sensor networks (WSNs) have gained world-wide attention due to their various applications. In most of the WSN applications, such as the military detection and tracking [1], the golden gate bridge monitoring [2], the volcano monitoring [3], and the urban-scale data collection [4], the manual deployment of sensor nodes is commonly assumed. In these networks, the sensor nodes are deployed onto the predefined location by human. On the other hand, some applications require unmanned deployment scenarios. For example, the enemy detection in military scenarios or the forest fire detection should be applied to large-scale areas with hundreds or thousands of sensor nodes. In these cases, the manual installation of the sensor nodes is almost impossible and the target areas are usually dangerous and difficult to be accessed by human. As a result, sensor nodes should be deployed by unmanned methods such as helicopter or flight drop.

Considering WSNs for military or disaster monitoring applications mentioned above, because sensor nodes are distributed randomly and are on a critical mission, they should

self-organize the networks and reduce the number of orphan nodes and dead zones, which may result in mission failure. In addition, the sensor nodes should establish the shortest route to the sink node in order to reduce delay and to save energy consumption. In this paper, we investigate the network topology suitable for the randomly deployed large-scale sensor networks and propose self-organization algorithms which guarantee high network connectivity.

The remaining sections of this paper are composed as follows. Section II introduces related works which cover network topologies and existing self-organization algorithms with various parameters for WSNs. In Section III, we present proposed cluster head election schemes. Their simulation results including the network formation procedures with realistic assumptions are shown in Section IV. Finally, we conclude in Section V.

II. RELATED WORKS

A. WSNs Topologies

References [5] and [6] classified WSN topologies into four types of models as shown in Fig. 1. Among these types, the previous works show that the multi-hop clustering model reveals an ideal network topology in view of scalability, overhead, energy consumption, and resource management [7].

In the single-hop models (Fig. 1(a) and Fig. 1(b)), all sensor nodes transmit their data to the sink node directly. These architectures are infeasible in large-scale areas because transmission cost becomes expensive in terms of energy consumption and in the worst case, the sink node may be unreachable.

In the multi-hop models, we can consider the flat model (Fig. 1 (c)) and the clustering model (Fig. 1(d)). In the multi-hop flat model, because all nodes should share the same information such as routing tables, overhead and energy consumption can be increased. On the other hand, in the multi-hop clustering model, sensor nodes can maintain low overhead and energy consumption because particular cluster heads aggregate data and transmit them to the sink node. Additionally, wireless medium is shared and managed by individual nodes in the multi-hop flat model, which result in low efficiency in the resource usage. In the multi-hop clustering model, resources can be allocated orthogonally to each cluster to reduce collisions between clusters and be

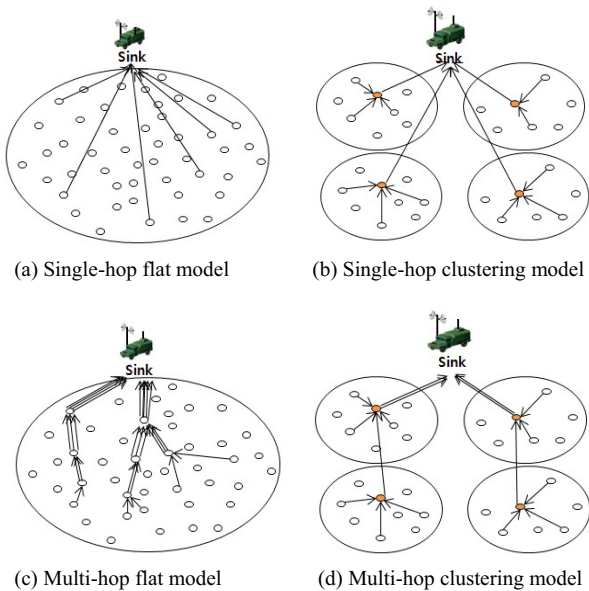


Figure 1. Classification of WSN topologies

reused cluster by cluster. As a result, the multi-hop clustering model is appropriate for the sensor network deployed in remote large-scale areas.

B. Clustering Algorithms

In the multi-hop clustering model, self-clustering schemes have been extensively studied so far. The multi-hop clustering can be done by a centralized way [8], [9] such that one node (e.g., a sink node) among sensor nodes forms the network, or by a distributed scheme ([10]–[13]), in which all nodes individually perform the clustering algorithm based on the pre-defined probability or residual energy.

While the centralized clustering scheme can establish an efficient network topology, the network results in low scalability and requires high overhead and energy consumption. Thus, the distributed clustering scheme is suitable for the large-scale and high density WSNs. However, the distributed scheme can lead to an asymmetric topology and low network connectivity with dead zones in which sensor nodes are not joined into the network.

C. Parameters for Clustering Algorithms

The clustering algorithms proposed in previous works used various decision parameters. In [14], nodes with the highest unique identifier in a group became cluster heads. In [10] and [15], a degree which is the number of neighbor nodes within a transmitter range was a key criterion for the election. In [11] and [16], nodes with maximum residual energy could be cluster heads. In [13], cluster heads are randomly selected by themselves based on comparison between their own random numbers and the pre-defined probability. The location information of cluster heads is also an important parameter to enhance network connectivity and network lifetime. The location-based algorithm such as GAF [17], assumes that all sensor nodes know their location information.

However, all these works only consider the aspect of energy consumption. Not only the energy consumption, but also the network connectivity is one of the most important factors in large-scale dense WSNs. To guarantee high network connectivity, we propose new cluster head election algorithms in next section.

III. PROPOSED CLUSTER HEAD ELECTION ALGORITHMS

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The main purpose of this paper is to present cluster head election schemes to enhance network connectivity in large-scale and dense sensor networks. Before starting to show the algorithms, assumptions for realistic sensor network environments should be given in this paper.

- Unattended WSNs.
- Fixed sensor nodes after random distribution.
- Sensor nodes with the same capabilities such as transmission range and power
- No location information support (e.g., global positioning system (GPS))

In this section, we describe our proposed algorithms in detail, the gradual cluster head election algorithm (GCA) and the GCA based on the one-hop neighbor information (GCA-ON).

A. GCA

In the multi-hop clustering model, a cluster head election is important as the network structure of the multi-hop clustering model strongly depends on the cluster head election algorithm. As mentioned in Section II, the centralized and the distributed cluster head election schemes have restrictions to apply to the hierarchical cluster structure. To overcome these restrictions, we propose GCA utilizing the advantages of both the centralized and the distributed schemes. The GCA described in Fig. 2 has several key features. First of all, cluster heads are elected by the level of sensor nodes at each cluster tree level. Secondly, the number of cluster heads depends on the number of join requests from non-joined sensor nodes so that the cluster heads could be elected adaptively based on the density of the network. The last feature is that the number of cluster heads which is needed to be elected (N_{CH}) is maintained in all clusters and at least one cluster head could be guaranteed in the next level when N_{CH} is lower than one. In GCA, cluster heads are elected based on the information from non-joined sensor nodes in order to reduce the overhead compared to the centralized scheme.

GCA is gradually performed by cluster heads in each level (e.g., sink node and nodes A, B, G, H, and I) as shown in Fig. 3. After sensor nodes being distributed, the sensor nodes should self-organize a network and form a cluster tree structure. A sink node (or a cluster head) sends a beacon with the information of its own level (e.g. level i) to neighbor nodes within its transmission range. After receiving the beacon, the nodes of the level i send join requests to the sink node to join the network. After receiving and confirming all join requests, the cluster head election algorithm is performed by the sink

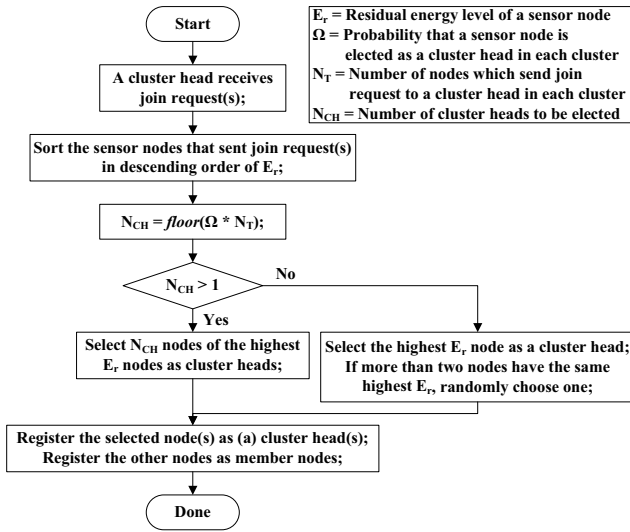


Figure 2. Flowchart of GCA

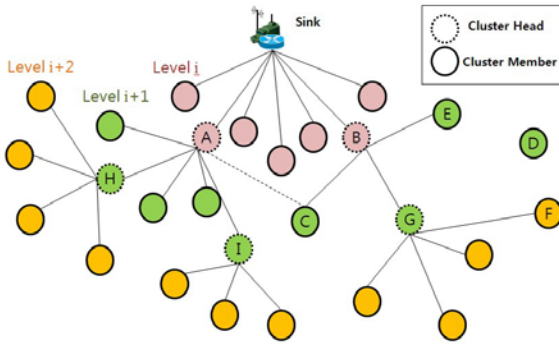


Figure 3. Topology and formation of WSN

node. The sensor nodes A and B which were elected as cluster heads in the level i send beacon messages to their non-joined neighbor nodes within their transmission ranges with the increase of the level to $i+1$. This procedure continues to be performed by cluster heads at each level. In Fig. 3, node C which received more than two beacons from different cluster heads (node A and B) choose the lower level and higher received strength signal indicator as a criteria to select its cluster head for making the shortest path from a sensor node to the sink node and saving energy.

B. GCA-ON

Although GCA improves the network connectivity, it could not make a well-organized network topology without the location information of sensor nodes. To mitigate the asymmetric cluster tree topology and reduce orphan node ratio, we propose GCA-ON.

In GCA-ON, the cluster head which received join requests elects cluster heads of its next level with the residual energy level (E_r) of sensor nodes and the number of cluster heads in one-hop neighbor (N_{CH-ON}). A cluster head elects cluster heads at next level among the non-joined nodes with the lowest N_{CH-ON} and the highest E_r .

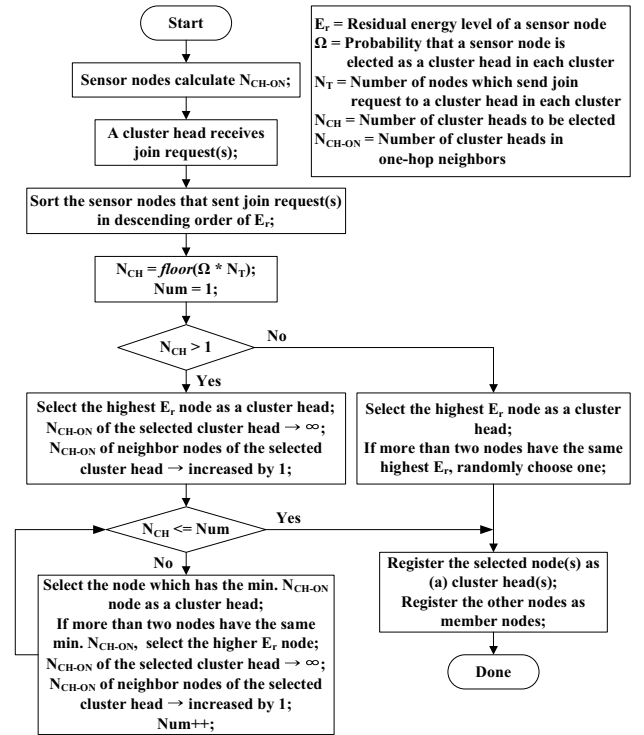
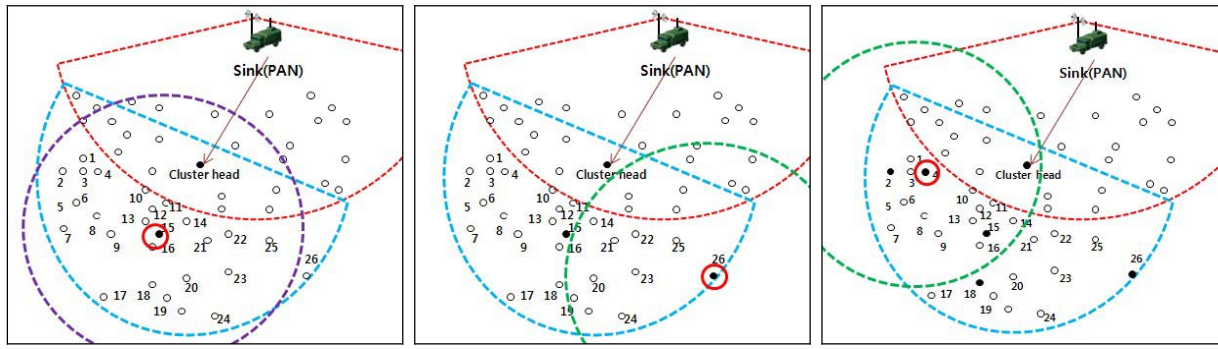


Figure 4. Flowchart of GCA-ON

The GCA-ON procedure can be explained with Fig. 4 and Fig. 5.

- All non-joined sensor nodes (e.g., from node 1 to node 26) which receives a beacon from a cluster head send join requests including their information (e.g. N_{CH-ON} and E_r) to the cluster head. These nodes are cluster head candidates. The cluster head sorts the cluster head candidates in descending order of E_r . Then, the cluster head elects a node with the highest E_r as the first cluster head. In Fig. 5(a), node 15 is elected as the cluster head of the next level because it has highest E_r (Fig. 5(e)). N_{CH-ON} of node 15 is changed to ∞ because it should not be elected as a cluster head at the remaining steps. Then, the sensor nodes within the transmission range of node 15 increases N_{CH-ON} by one. Because node 26 is not a one-hop neighbor of node 15, N_{CH-ON} of node 26 is not increased. If N_{CH} is smaller than two, this algorithm stops.
- If N_{CH} is greater than one, the cluster head should continue to elect the remaining cluster heads of the next level. Because node 26 has the lowest N_{CH-ON} as we can see in Figs. 5(b) and 5(d), the cluster head elects node 26 as a cluster head of the next level. Then, the cluster head increases N_{CH-ON} of the other candidates within the transmission range of node 26.
- The cluster head checks whether the number of elected cluster heads is less than N_{CH} . If so, it continues the election procedure as shown in Fig. 5(c). When more than two cluster head candidates have the same N_{CH-ON} , the candidate with higher E_r is elected. In our example,



(a) First step of cluster head election

(b) Second step of cluster head election

(c) Remaining steps of cluster head election

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Step1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	∞	1	1	1	1	1	1	1	1	1	1	0
Step2	1	1	1	1	1	1	1	1	1	1	1	1	1	2	∞	2	2	2	2	2	2	2	2	2	2	∞
Step3	2	∞	2	2	2	2	2	2	2	2	2	2	2	3	∞	2	2	2	2	2	2	2	2	2	2	∞
Step4	2	∞	2	2	2	3	3	3	3	3	3	3	3	3	∞	3	2	∞	3	3	3	3	3	3	3	∞
Step5	3	∞	3	∞	3	4	4	4	4	4	4	4	4	4	∞	4	2	∞	3	3	3	3	3	3	3	∞
Step6	3	∞	4	∞	4	5	5	5	5	5	5	5	5	5	∞	5	∞	∞	4	4	4	4	4	4	3	∞

(d) N_{CH-ON} of sensor nodes from step one to step six

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Step1	87	89	85	75	91	86	77	71	89	81	83	93	87	92	96	84	78	89	84	81	94	92	88	86	78	93

(e) E_r of sensor nodes (initial value = 100)

Figure 5. GCA-ON procedure (Ω : 0.25, N_T : 26, N_{CH} : $\text{floor}(0.25 \times 26) = 6$)

finally, nodes 2, 18, 4, and 17 become cluster heads through step three to six.

IV. PERFORMANCE EVALUATION

To evaluate the performance of GCA and GCA-ON, we simulate the proposed algorithms with the distributed cluster head election algorithm [13] using MATLAB. We assume that sensor nodes are randomly distributed in an area of 1000m by 1000m. Table I shows the simulation parameters used in this paper.

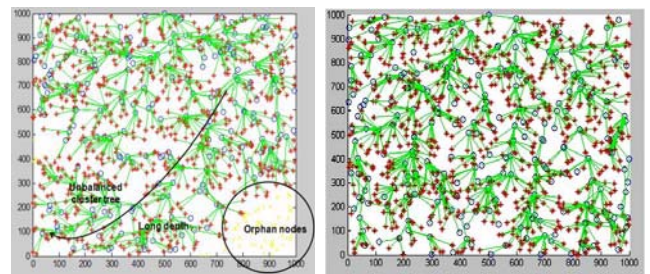
The first simulation (*Simulation I*) is performed to show the orphan node ratio of GCA and the distributed cluster head election algorithm. 1000 sensor nodes are randomly distributed with fixed cluster head probability (20%) and fixed transmission range (100m). The simulation is repeated 30 times. Fig. 6 shows the snapshots of the distributed algorithm and GCA. At each simulation round, the distributed scheme leads to an asymmetric topology and low network connectivity with dead zones in which sensor nodes are not joined into the network. On the other hand, GCA makes the network well-organized, which means that no dead zones exist. The orphan node ratio of the distributed algorithm and GCA at each simulation round is shown in Fig. 7. The orphan node ratio of GCA is close to zero at each round but the distributed algorithm shows inconsistent and large orphan node ratio.

The second simulation (*Simulation II*) is performed to present the orphan node ratio of GCA, GCA-ON, and the distributed cluster head election algorithm with 500 simulation times. To evaluate the performance of the algorithms in more dense environments, 4000 sensor nodes are randomly

distributed in the same size of area. Fig. 8 shows the orphan node ratio with various cluster head probability from 5% to 45%. The result shows that the orphan node ratio of GCA and GCA-ON is lower than that of the distributed election scheme. The decrease of probability leads to the increase of the orphan node ratio, especially in the distributed election algorithm. GCA-ON shows the lowest orphan node ratio in comparison

TABLE 1. SIMULATION PARAMETERS

Parameters	Simulation I	Simulation II
Number of nodes	1000	4000
Position of sink node	(500, 1000)	
Network size	1000m x 1000m	
Cluster head probability	20%	5% ~ 45%
Transmission range	100m	50m
Simulation times	30	500



(a) Snapshot of distributed algorithm

(b) Snapshot of GCA

Figure 6. Snapshots of the distributed algorithm and GCA

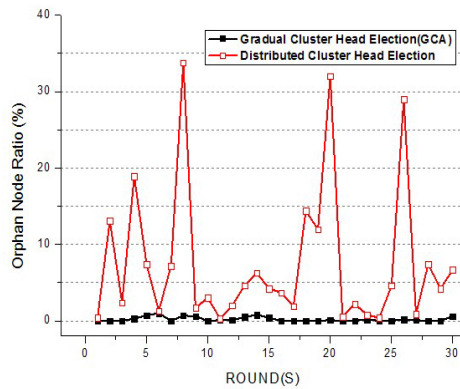


Figure 7. Orphan node ratio of GCA and distributed cluster head election algorithm at each round of simulation I

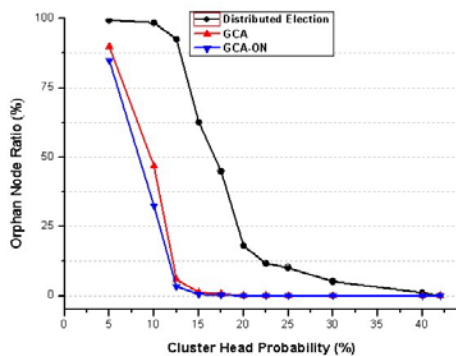


Figure 8. Orphan node ratio with various cluster head probability (transmission range = 50m)

with GCA and the distributed election algorithm. Maximum 14% (560 nodes) of the orphan node ratio of GCA-ON at the 10% cluster head probability is lower than that of the distributed election algorithm. This implies that GCA-ON can achieve higher network connectivity than the others without location-awareness. From the performance results mentioned above, we can see that GCA and GCA-ON can obtain network connectivity with low orphan node ratio.

V. CONCLUSIONS

A cluster head election scheme is an important one to establish an energy efficient WSN in large-scale environments. In this paper, we propose two cluster head election algorithms, GCA and GCA-ON. This paper focuses on centralized cluster head election which is gradually performed by cluster heads at each level. These algorithms can enhance the network connectivity with lower orphan node ratio as GCA and GCA-ON can elect the well-distributed cluster heads without any biased head distribution.

Our approach can be applied to several static and randomly distributed environments that require high network connectivity, scalability, and energy efficiency. We are currently studying more enhanced cluster head election algorithms which can be applied to more realistic environments (e.g. large-scale high density wireless sensor networks with unpredictable obstacles) for higher network connectivity.

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