A Self-Organized Localization-Free Clustering Approach for Redundancy Exploitation in Large Wireless Sensor Networks

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Abstract: This paper investigates organization problems of large wireless sensor networks. In spite of their random deployment, nodes have to organize themselves as energy efficient as possible to avoid redundant sensor and transceiver tasks. In addition to energy awareness, the network has to guarantee complete sensor coverage and connectivity as long as possible. This paper presents a novel clustering algorithm, which allows building up clusters without knowledge about their position. Next to the advantage that only one node per cluster has to be active at each time, also no node has to localize itself. We compared our developed algorithm with former clustering and redundancy detection approaches in terms of nodes per cluster and coverage abilities.

1 Introduction

The recent development of small wireless communication and computing systems makes it feasible to construct wireless sensor network (WSN) systems for environment surveillance. Such WSNs consist of hundreds of tiny sensor nodes, each equipped with sensor and wireless communication system, battery and microcontroller. Sensor nodes are deployed randomly over an area to observe it. In scenarios like forest fire surveillance, precision farming or the measurement of volcanic activity, a network of simple sensor nodes is much more powerful than some single complex sensors in terms of detecting phenomena. However, sensor nodes have to act self-sustained and independently from the environment they observe. Hence, they have only limited energy resources for detection, computation and transmission and ‘die’ when their resources are exhausted. In order to achieve a maximum network lifetime, the whole network has to act as energy-efficiently as possible.

Current researches try to increase network lifetime by different, mostly self-organized approaches like efficient routing [BV07] or load balanced communication [HGW02]. In this paper, we develop a clustering algorithm based on the XGAF (Extended Geographical Adaptive Fidelity) algorithm [Sa07]. Without a fixed grid, nodes do not have to localize their own position before the clustering. Furthermore, the algorithm increases the size of a cluster autonomously, which leads to few active nodes and therefore further energy saving. The remainder of the paper is organized as follows: Section 2 describes related work and the idea of the already existing XGAF algorithm, Section 3 presents our new clustering approach, Section 4 compares characteristic parameters of the presented and the former XGAF algorithm by simulations with PROWLER [SVM03]. Section 5 gives a conclusion and an outlook.

2 Related Work

The central problem in wireless sensor networks is power consumption. A major research goal is to increase the total lifetime of a network by temporary deactivating a subset of nodes. Today, there exist two different strategies, which search for redundant nodes inside a wireless sensor network and are still able to guarantee complete network functionality. In the context of the paper, complete network functionality means the availability of following two properties:
1.) Complete coverage: A network achieves complete coverage if every point in the area to observe is in the sensing range of at least one active node.
2.) Complete connectivity: A network achieves complete connectivity if every node can establish a connection to every other node. This connection can be achieved by using any number of hops to other nodes.

2.1 Node Redundancy

Node redundancy methodologies are characterized by the fact that each node of a sensor network tries to find out whether it is necessary or not for complete network functionality or special network tasks, e.g. message broadcasting [SPD07].
In [TG02], Tian et al. developed a redundancy detection algorithm. The task of the algorithm is that redundant nodes detect their redundancy autonomously by evaluating angles and distances to adjacent nodes.
In the first step, all nodes are activated. Then, a starting node uses its sensing range as radius for a circle, using the node’s position as center. The circle is called sensing disk. If there are enough active neighbor nodes available to cover the whole sensing disk with their own sensing disks, the starting node declares itself as redundant and is allowed to switch-off.
In [SPD07], the nodes starts form the opposite point of view. As basic setting, a node is of no importance for the network functionality. If a data message should be broadcasted through the network, a node shall only react if its distance is far away from the node that sends that message. To achieve this, all nodes in transmission range of the starting node answer with control messages and listen to other answer messages. Afterwards, the starting node sends an additional control message, containing the number of received control message.
The relative distance estimation from a node to the starting node occurs by enumerating the control messages of all nodes in its transmission range and compares the number to the number of received control messages of the starting node. The further away from a sending node, the shorter is the waiting time of the node for further broadcasting the data message.

In spite of their efficient redundancy detection methodologies, these algorithms have two major disadvantages.
The first one is that each single node failure may lead to a partial network breakdown or coverage holes. This behavior has to be compensated by formerly switched-off nodes.
Algorithms which find the optimal nodes which can repair such emerging network holes are still complex and expensive in terms of energy, normally the whole redundancy algorithm has to run again in a certain area.
The second one is the missing awareness of a node's importance for network functionality. If a node in a sparse populated region is able to get knowledge about its importance, it might me able to avoid complex routing tasks, which would lead to a faster node breakdown and therefore a hole in the network.

2.1 Cluster-Based Redundancy

In cluster-based redundancy methodologies the whole network area is divided into cells. Nodes inside a cell organize themselves into a cluster. The main idea is that the cell size is chosen in such a way that one active node per cell (the clusterhead) is sufficient for complete network coverage.
The XGAF algorithm clusters the WSN into a regular grid, based on the position of each node. Not only the transmission range but also the sensing ranges of the nodes are used for calculating the geographical cluster size.
In contrast to other clustering approaches like GAF (Geographical Adaptive Fidelity) [XHE01] and (E)HGAF (Enhanced Hierarchical Geographical Adaptive Fidelity) [II07], it is guaranteed that each member of a cluster is able to sense the whole cluster and not only serves as connector between neighboring clusters. To calculate the maximum cell size for an XGAF cell, we introduce the working range R_W,

$$R_W = \min(R_S ; R_T / 2) \tag{1}$$

whereby R_S is the maximum sensing range and R_T the maximum transmission range of a node. The geometric estimation of the working range and the XGAF idea are also shown in Figure 1 A). The resulting grid and cluster structure is shown in Figure 1 B).
Next to the advantage of cluster based redundancy algorithms, that only one active node per cell is necessary for complete network functionality, it is now possible to substitute a clusterhead which runs out of energy. By a role changing protocol, e.g. [Re06], a cluster node is able to become clusterhead before the previous clusterhead dies. Hence, there is no need for a rerun of the algorithm after a breakdown of a node.
The characteristic of exchangeable nodes leads to another advantage. In contradiction to node redundancy algorithms it is now possible to calculate the cluster strength by simply enumerating the nodes per cluster. A strong cluster with a lot of nodes is able to fulfill more routing, computing or broadcasting tasks before the cluster breaks down than a weak cluster could do. The cluster strength can be used to achieve an energy balanced network or graceful degradation. However, the cluster based redundancy algorithms have one major disadvantage.

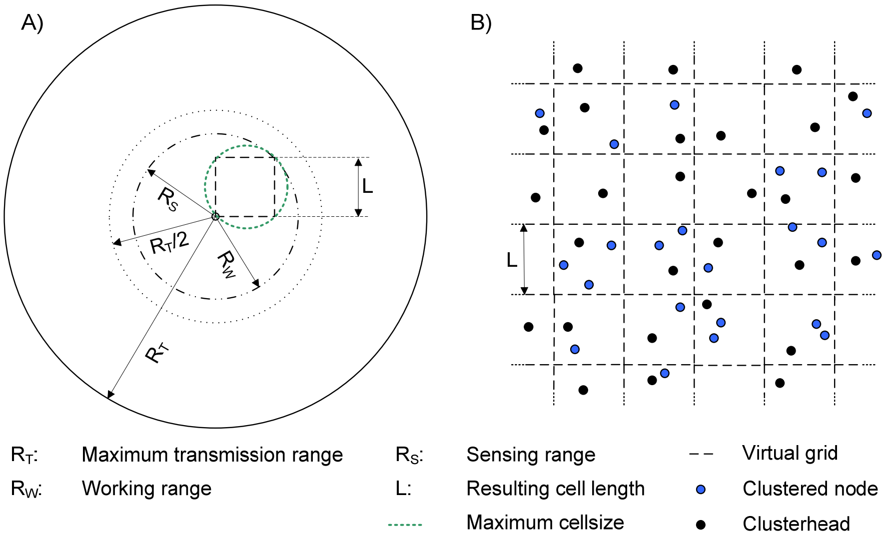

Figure 1: XGAF approach A) Estimation of maximum square cell sizes B) Appliance to a WSN with random distributed nodes

All nodes have to know their exact position in the area to join the right cluster. But, localization algorithms are associated with a lot of transmissions, possibly complex and therefore have a high energy cost per node [Re08]. Our presented algorithm avoids these high energy cost per node, but is still able to detect reasonable XGAF clusters.

3 Position Independent Clustering Approach

In this section we propose our self-organized clustering approach. The design goal of the clustering approach is the emergence of clusters of adjacent neighbors. The cluster density has to be similar to XGAF, so that one active node per cluster is sufficient for complete network functionality. The following assumptions were applied to reduce the complexity of the WSN:

1. The network is a homogeneous network, all nodes have same transmission and sensing range
2. Nodes are able to reduce their transmission power to following transmission ranges: R_W, $R_W/2$
3. There are no obstacles in the area and the transmission of every message is guaranteed until a selected transmission range is reached
4. The medium access policy is synchronous TDMA, there exist no synchronization problems between the nodes
5. The nodes are distributed randomly in the area to observe.

The basic concept of our algorithm is illustrated in Figure 2. The algorithm works for a starting node in 3 phases which are repeated on nodes chosen by the algorithm. It is furthermore imaginable that there exists more than one starting node in a WSN to reduce the operation time of the algorithm. The 3 phases are explained in detail as follows.

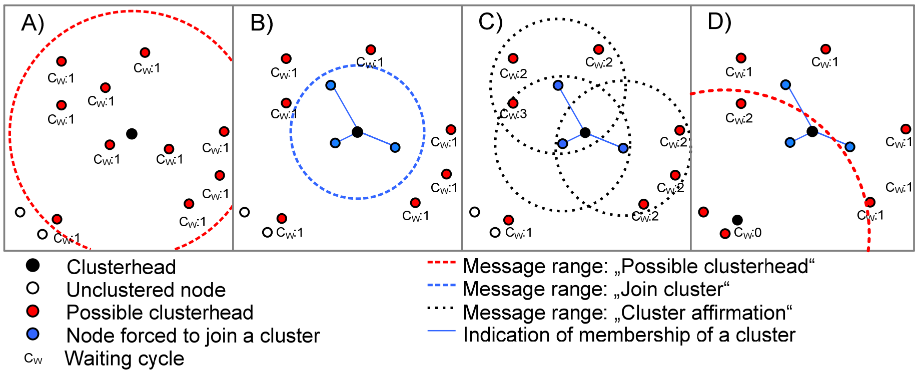

Figure 2: Emergence of the clusters in the network A) Clusterhead informs nearby nodes B) Clusterhead forces nearby nodes to join his cluster C) Nodes confirm and increase Waiting cycles of near remaining nodes D) Node with shortest waiting cycle becomes new clusterhead

1.) Information Phase: In this phase, the starting node (the first clusterhead) has the task to inform all nearby nodes about its existence and that they have to listen whether they have to join the cluster or are allowed to become the next starting node. To achieve this, the starting node broadcasts a "Possible clusterhead" message with transmission range R_W. All nodes which receive this message change to the mode "Possible clusterhead" and initialize a counter, called waiting cycle C_W. The counter describes the remaining time cycles until they become clusterheads themselves. C_W is set to the value '1'. The Information Phase is illustrated in figure 2 A).

2.) Clustering Phase: In this phase, the starting node has to inform the nearest nodes to join its cluster. The maximum cell size is reasoned by the 'one active node per cluster' idea, i.e. the diameter of the cell is R_W, as shown in Figure 1 A).

To achieve this, the starting node sends a message with transmission range $R_W/2$. All nodes which receive this message are forced to change to the mode "Join cluster". The Clustering Phase is illustrated in Figure 2 B).

3.) Affirmation Phase: In this phase, all "Join cluster" nodes shall affirm their membership to the clusterhead. Simultaneously, their messages have the task to avoid that nearby "Possible clusterhead" nodes, which are too close to the just emerged cluster, become new clusterheads. To achieve this, all "Join cluster" nodes broadcasts a "Cluster affirmation" message in their time slot with transmission range $R_W/2$. All "Possible clusterhead" nodes, which receive "Cluster affirmation" messages, have to increase their waiting cycle C_W by '1' for each received "Cluster affirmation" message. The behavior of the "Affirmation Phase" is illustrated in Figure 2 C).

The clustering process for one starting node is now completed and nodes of the cluster don't react furthermore of messages of type "Possible clusterhead" or "Join cluster". After each complete time cycle, C_W of each "Possible clusterhead" node is reduced by one. If a counter has reached the value '0', the according node becomes new clusterhead and the algorithm starts with the according node as clusterhead. The behavior of the "possible clusterhead" nodes in the Affirmation Phase is now obviously:

The farer the “possible clusterhead” node is away from the first starting node, the fewer “Cluster affirmation” messages will receive by this node.
Hence, the node has earlier the chance to become new clusterhead, the cluster density is reduced to a minimum and the cluster distribution tries autonomously to reach the maximum cell size, which is illustrated in Figure 1A. After the clustering algorithm is applied, the network is able to fulfill its work similar to a network clustered by XGAF.

4 Simulation environment and results

We extended the MATLAB based simulator PROWLER [SVM03] by a Time Division Medium Access protocol to simulate our developed clustering approach and to compare it with former algorithms. To avoid edge effects, we deployed nodes not only inside the simulation area, but also outside in the distance R_W of the observing area. For estimation of simulation results, we regarded only the interior area.
We compared our algorithm with the cluster-based XGAF algorithm in terms of achieved coverage. The results, illustrated in Figure 3, show that the new algorithm performs in terms of network functionality similar to XGAF, and additionally without a former energy intensive localization.
It has to be regarded that the simulation results in Figure 3 show only the assured network functionality, i.e. a node of an XGAF cell is only counted as covering its own cell, and a clusterhead of the new approach is only covering a circle with a radius of $R_W/2$. Of course, the real coverage is quite larger for each node. To compare the algorithm with other redundancy algorithms, e.g. the node-based redundancy algorithm developed by Tian et al. in [TG02], we have to consider the real coverage. The real coverage of Tian, XGAF and our new approach is compared in Figure 4. Next to the achieved coverage, the algorithm’s efficiency is defined by the network’s lifetime, which we can derived from the remaining active nodes after the appliance of the algorithm.

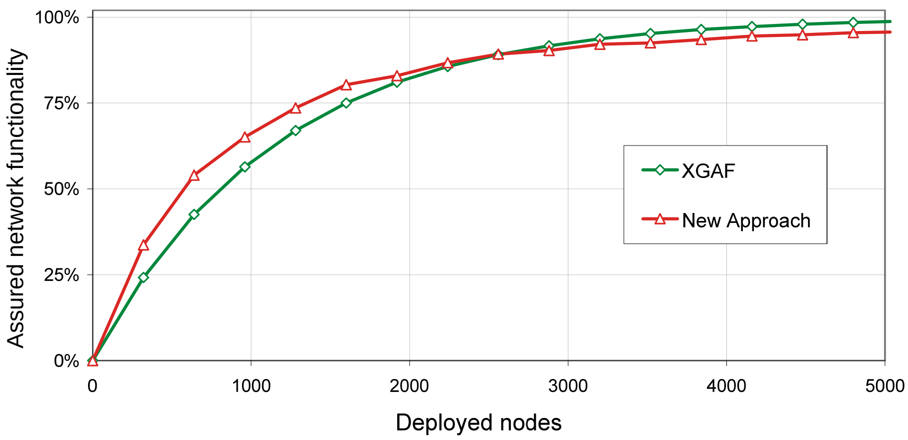

Figure 3: Average assured network functionality versus random deployed nodes. Observed area size: 646m*646m, Working range: 26,87m, Simulations: 200

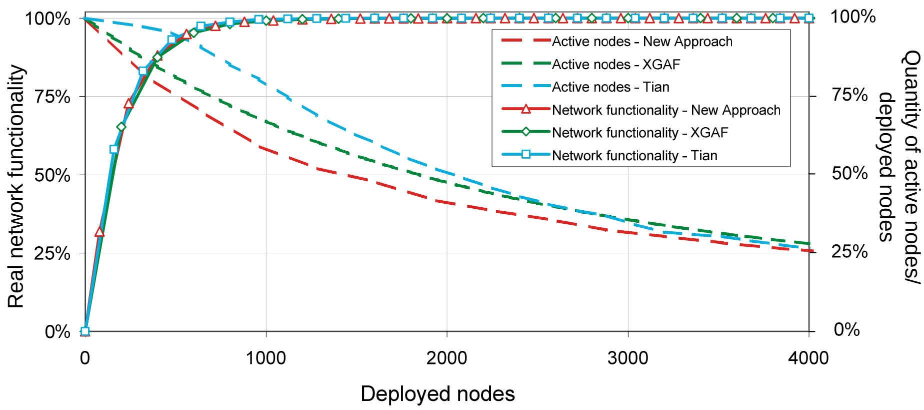

Figure 4: Average real network functionality and Quantity of active nodes versus random deployed nodes. Observed area size: 646m*646m, Working range: 26,87m, Simulations: 200

The number of active nodes compared to the number of deployed nodes of all three algorithms is also pictured in Figure 4. It becomes obviously that our new approach achieves nearly similar results in achieved coverage like Tian. This result shows that only unimportant nodes are switched off by our algorithm.
Additionally, our algorithm performs better in terms of active nodes. In the interval between 500 and 2000 nodes, our approach needs 20% less nodes than Tian. This leads to higher energy savings and therefore an increased network lifetime.

5 Conclusion and Outlook

In our present work we introduced a new self-organized clustering approach as an enhancement of the existing XGAF algorithm. Although our algorithm works without the barrier of costly pre-clustering localization, we achieved similar results in terms of coverage than XGAF. In terms of detecting redundant nodes, we achieved even better results than previous approaches
In future works, we will improve the algorithm for less egoistic clusterhead estimation. More neighborhood relationships could be utilized to achieve this behavior. Furthermore, it is imaginable to include a self-healing algorithm for broken clusters.

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