On Autonomous Clustering in Wireless Sensor Networks With Directional Antennas

Ying-Chih Chen, Pei-Lun Chung, and Chih-Yu Wen
Department of Electrical Engineering/GICE
National Chung Hsing University
Taichung 402, Taiwan, R.O.C.
{cwen@dragon.nchu.edu.tw}

Abstract—This paper proposes a decentralized algorithm for organizing an ad-hoc sensor network into clusters with directional antennas. The proposed autonomous clustering scheme aims to reduce the sensing redundancy and maintain sufficient sensing coverage and network connectivity in sensor networks. With directional antennas, random waiting timers, and local criteria, cluster performance may be substantially improved and sensing redundancy and communication interference can be drastically suppressed. The simulation results show that the proposed scheme achieves connected coverage and provides efficient network topology management.

Keywords – wireless sensor networks; clustering; directional antenna.

I. INTRODUCTION

Unlike wireless cellular systems with a robust infrastructure, sensors in an ad hoc network may be deployed without infrastructure, which requires them to be able to self-organize. Such sensor networks are self-configuring distributed systems and, for reliability, should also operate without centralized control. In addition, because of hardware restrictions such as limited power, direct transmission may not be established across the complete network. In order to share information between sensors which cannot communicate directly, communication may occur via intermediaries in a multi-hop fashion. Scalability and the need to conserve energy lead to the idea of organizing the sensors hierarchically, which can be accomplished by gathering collections of sensors into clusters. Clustering sensors is advantageous because it improves energy efficiency, aggregates information from individual sensors, abstracts the characteristics of network topology, and provides scalability and robustness for the network.

With sensors placed close to an event, wireless sensor networks can observe the phenomenon and receive data. However, having too few active sensors or excessive ones may result in reduced sensing coverage or severe interference, which will have a great influence on network performance features such as energy and bandwidth efficiency, and sensing quality. Hence, reducing the sensing redundancy and maintaining sufficient sensing coverage and network connectivity are critical requirements in sensor networks [1],[2]. In addition, the two issues of energy constraint and communication interference have to be considered together with both the network connectivity and data collection. Recently there has been great interest in using directional antennas on sensor nodes to improve the general performance of wireless sensor networks (WSNs) [3]-[9]. Directional antennas may actually promote communication quality by focusing transmission energy in one direction and reducing interference and fading. Compared with the traditional disc communication model, the asymmetrical feature of directional antennas causes much trouble for communication and has a large impact on network topology and node deployment [10].

In this work, a randomized distributed algorithm, Autonomous Clustering via Directional Antenna (ACDA), is proposed to govern network topology. The solution combines the advantages of clustering and the strength of directional antennas to achieve both connectivity and sufficient coverage in wireless sensor networks. For improving energy efficiency and suppressing communication interference, each sector of a sensor operates independently, monitoring communication among others, and uses a random waiting timer and local criteria to decide whether to be an active communication sector. Those sensors which have many neighbors that are not already part of a cluster are likely candidates for creating a new cluster by declaring themselves to be a new ‘clusterhead’. The proposed ACDA provides a protocol whereby this can be achieved and the process continues until all sensors are part of a cluster. The performance of the algorithm is investigated both by simulation and analysis.

The organization of this paper is as follows: Section II reviews the current literature on clustering and direction antennas. Section III describes the system model and derives an autonomous clustering solution that relies on a distributed self-configuring protocol [11]. Section IV considers the energy consumption of the ACDA assuming homogenous sensors. Section V summarizes the performance of the proposed clustering methodology. Finally, Section VI draws conclusions and shows future research directions.

II. LITERATURE REVIEW

There are two primary related research areas: (1) directional antenna research in wireless sensor networks and (2) the network topology control problem. Current research interests in sensor node antennas mainly focus on miniaturization of omnidirectional antennas [12]-[14]. However, due to the enhanced communication quality and networking performance in wireless sensor networks with directional antennas, the
prototypes of sensor nodes have been successfully developed [7],[8],[15]-[17].

Several clustering algorithms have been proposed in recent years [11],[18]-[26]. Many of the algorithms are heuristics intended to minimize the number of clusters. Perhaps the earliest of the clustering methods is the identifier-based heuristic called the Linked Cluster Algorithm (LCA) [18], which elects sensor to be a clusterhead if the sensor has the highest identification number among all sensors within one hop of its neighbors. The connectivity-based heuristic of [19],[20] selects the sensors with the maximum number of 1-hop neighbors (i.e. highest degree) to be clusterheads. The Weighted Clustering Algorithm (WCA) [21] considers the number of neighbors, transmission power, mobility, and battery usage in choosing clusters. It limits the number of sensors in a cluster so that clusterheads can handle the load without degradation in performance. The Max-Min D-cluster Algorithm [22] generates d-hop clusters with a complexity of $O(d)$ without time synchronization. It provides load balancing among clusterheads in the network. Simulation results suggest that this heuristic is superior to the LCA and connectivity-based solutions. The Low-Energy Adaptive Clustering Hierarchy (LEACH) of [23] utilizes randomized rotation of clusterheads to balance the energy load among the sensors and uses localized coordination to enable scalability and robustness for cluster set-up and operation. Although the above algorithms carefully consider the energy required for clustering, they are not extensively analyzed (due to their complexity) and there is no way of estimating how many clusters will form in a given network.

Most of these design approaches are deterministic protocols in which each sensor must identify a subset of sensors with a clusterhead to partition the network into clusters in heuristic ways [20]-[22]. The algorithms proposed in [23]-[26] focus on reducing the energy consumption without exploring the number of clusters generated by the protocols, though [21] and [22] demonstrate the average number of clusterheads via simulations. For most of the algorithms, no analysis of the number of clusters is available. Moreover, all these clustering approaches are based on the assumption of omnidirectional antennas. A comprehensive survey of clustering algorithms for wireless sensor networks with omnidirectional antennas can be found in [27].

Though many clustering schemes have been developed, very few papers address the problem of forming clusters in wireless sensor networks with directional antennas. In contrast, the proposed ACDA method considers coverage, connectivity, and sensing spatial redundancy simultaneously in order to improve energy efficiency in a hierarchical network structure.

III. AUTONOMOUS CLUSTERING ALGORITHM

This section describes a randomized distributed algorithm, Autonomous Clustering via Directional Antenna (ACDA), that forms clusters automatically in three phases: Phase I: Determining the Active Sensing Sectors; Phase II: Choosing the Communication Sectors and Clusterheads, and Phase III: Selecting the Gateways. The main assumptions are: (1) All sensors are homogeneous with the same transmission range; (2) The sensors are in fixed but unknown locations; (3) The network topology does not change; (4) The sensors have directional sensing and communication capability. Note that there are no base stations to coordinate or supervise activities among sensors.

A. Phase I: Determining Active Sensing Sectors

In Phase I, each sector of a sensor broadcasts a Hello message at a random sector waiting time (SWT), which allows each sector to estimate how many neighboring sectors it has. A Hello message consists of: (1) the sensor ID of the sending sensor, (2) the sector ID of the sending sensor, and (3) the cluster ID of the sending sensor. At the beginning, the cluster ID of each sensor is zero. Sectors update their neighbor information (i.e. a counter specifying how many neighbors it has detected) and decrease the random SWT based on each ‘new’ Hello message received. The updating formula for the random SWT of sector $j$ of sensor $i$ is

$$W_{T_{i}^{j,q+1}} = \beta \cdot W_{T_{i}^{j,q}}, \quad (1)$$

where $W_{T_{i}^{j,q}}$ is the SWT of sector $j$ of sensor $i$ at time step $q$, and $0 < \beta < 1$. When $W_{T_{i}^{j}} = 0$, sector $j$ of sensor $i$ broadcasts a message proclaiming that it is an active sensing sector; this also serves to notify its neighboring sectors that they are assigned to turn off their sensing radios and stop their waiting timers. The purpose of this phase is to reduce the sensing redundancy in the dense sensing field. Figure 1 shows an example of determining the active sectors. Observe that the sensing coverage of Figure 1 (top) and that of Figure 1 (bottom) are close, which may serve as a basis for scheduling management with directional sensing. The complete procedure of determining active sensing sectors is outlined in Table I.
TABLE I
ACTIVE SECTOR FORMATION
1. Each sector of a sensor initializes a random waiting timer SWT with a value $WT_j^{(i,0)}$ for sector $j$ of sensor $i$.
2. Each sensor transmits the Hello message at random times.
3. Establish and update the neighbor identification:
   if (a sensor receives a message of proclaiming of an active sensing sector at time step $q$)
     (a) turn off its sensing radio.
     (b) stop the waiting timer. (Stop!)
   else
     collect neighboring information.
   end
4. Decrease the random waiting time according to equation (1).
5. Active sector check:
   if ($WT_i = 0$ and the neighboring sectors are not proclaiming of active sectors)
     broadcast itself to be an active sensing sector.
   else
     go to Step 3.
   end

B. Phase II: Choosing Communication Sectors and Cluster-Heads
When completing the operation of Phase I, each sensor initiates a cluster waiting timer (CWT) for being a clusterhead. Note that in Phase I, random SWTs are used to decide the active sectors. In Phase II, each sensor sets a random CWT and update the timer based on the total number of message receptions and transmissions in its sectors during the operation in Phase I. The sensors that hear many neighbors are good candidates for initiating new clusters; those with few neighbors should choose to wait. The updating formula for the random CWT of sensor $i$ yields
\[
WT_i^{(CH)} = \alpha N_T \cdot WT_i^{(CH,0)} \quad \alpha > 1,
\]
where $WT_i^{(CH,0)}$ is the initial CWT of sensor $i$ for being a clusterhead, $N_T$ is the number of message transmissions. The rationale for the setting of parameter $\alpha$ is that a sensor with a higher number of transmissions in Phase I will make a higher portion of neighboring sectors turn off their radios, which may not make the sensor a good clusterhead candidate.

If both of the following conditions apply, then sensor $i$ declares itself a clusterhead:
- The random CWT expires. That is, $WT_i^{(CH)} = 0$.
- None of the neighboring sensors are already members of a cluster.

If sensor $i$ satisfies the above conditions, its each active sector broadcasts a message proclaiming that it is beginning a new cluster; this also serves to notify its neighbors that they are assigned to join the new cluster with ID $i$. When a sensor joins the cluster, it sends an updated Hello message and stops its waiting timer. Accordingly, the sensors are grouped into clusters and the communication sectors in each cluster are determined. Figure 2 depicts the communication sectors in each cluster (from cluster members to the clusterhead) and the cluster formation.

Therefore, by adjusting randomized CWTs, the sensors can coordinate themselves into sensible clusters, which can then be used as a basis for further communication and data processing.

The complete procedure of the clustering phase is outlined in the ACDA of Figure 3.

Fig. 2. The communication sectors in each cluster (from cluster members to the clusterhead) (top); an example of choosing the clusterheads (bottom).

Fig. 3. The procedure of the clustering phase.

C. Phase III: Selecting the Gateways
Observe that Phase II induces nonoverlapping clusters. Accordingly, to interconnect two adjacent nonoverlapping clusters, a sensor from each cluster must become a gateway. Denote the sensor which can communicate with more than one cluster as a border sensor. This subsection presents a method of choosing distributed gateways from border sensors for adjacent
nonoverlapping clusters. The operation of gateway selection can be either triggered by clusterheads or initialized by border sensors. As in Phases I and II, random waiting times and local information are applied to select gateways and further achieve communication between clusters. According to the operations in Phase II, sensors can obtain local information and know the number of neighboring active communication sectors in adjacent clusters. Therefore, given the local information, sensors may initialize their counters for gateway selection. The random gateway waiting time (GWT) of sensor $i$ yields

$$WT_i^{(G)} = \gamma \cdot N_R \cdot WT_i^{(CH,0)},$$

where $WT_i^{(CH,0)}$ is the initial CWT of sensor $i$ for being a clusterhead in Phase I, $N_R$ is the number of message receptions, and $0 < \gamma < 1$.

Figure 4 shows an example for gateway selection. Considering cluster 16 at the bottom left corner of the topology, if the GWT of sensor 8 expires, then sensor 8 broadcasts the inter-cluster connectivity information (e.g. the existence of link connection between sensor 8 and sensor 3) to its neighboring sensors. After receiving the broadcast message, the border sensors in cluster 16 will update their inter-cluster connection information and delete the redundant inter-cluster link connections. On the other hand, the border sensors in the neighboring clusters (e.g. sensors 3 and 8), may consider sensor 8 as a gateway candidate with respect to cluster 16. Consequently, when the GWT of sensor 3 expires, sensor 3 may select the earliest broadcasting gateway candidate (e.g. sensor 8) to establish a pair of distributed gateways for cluster 4 and cluster 16. Accordingly, the results of Phase III processing are that each cluster $i$ assigns a single member to communicate with each nearby cluster $j$ and the waiting timers help to ensure that the chosen member is one of the appropriate members for inter-cluster communication even though the topology of the system is unknown. If the clusters are too far apart (outside the communication range $R$), no gateway sensors will be assigned. The complete procedure of the gateway selection phase is outlined in the ACDA of Figure 5. Note that $C_i^{(m)}$ is the set of connected sectors of sector $m$ in sensor $i$ and $S_{id}$ is the set of distributed gateways from neighboring clusters.

After applying the ACDA, there are three different kinds of sensors: (1) the clusterheads (2) on-duty sensors with active communication sectors and an assigned cluster ID (3) off-duty sensors without active communication sectors which are on stand-by. These on stand-by sensors may join the nearest cluster later depending on the neighboring information or the demand of specific applications, such as sensor location estimation problem. Thus, the topology of the ad hoc network is now represented by a hierarchical collection of clusters.

**IV. ANALYSIS OF ENERGY CONSUMPTION**

This section considers the energy consumption of the ACDA assuming homogeneous sensors. The total power requirements include both the power required to transmit messages and the power required to receive (or process) messages. Suppose that the energy needed to transmit for sensors with omnidirectional
antennas is $E_T$, which depends on the transmitting range $R$, and the energy needed to receive is $E_R$. Hence, the energy consumption for transmission in sensors with $k$ sectors may be described by $E_T/k$.

A. Phase I

In the initialization phase, each sectors of a sensor broadcasts a Hello message to its neighboring sectors. Therefore, the number of transmissions $N_{T_r}$ is equal to the number of sectors in the network, $kN_S$, and the number of receptions $N_{R_r}$ is the sum of the neighboring sectors of each sensor. That is, $N_{T_r} = kN_S$ and $N_{R_r} = \sum_{i=1}^{N_S} \sum_{j=1}^{k} N_{r_{ij}}$, where $N_{r_{ij}}$ is the number of neighboring sectors of sector $j$ of sensor $i$. Now let $N_{T_r}$ and $N_{R_r}$ denote the number of transmissions and receptions for determining the active sectors, respectively. Hence, we obtain $N_{T_r} = [IAS]$ and $N_{R_r} = \sum_{s_{ij} \in IAS} N_{r_{ij}}$, where $s_{ij}$ denotes active sector $j$ of sensor $i$ and $IAS$ is a index set of active sectors. Thus, the total energy consumption, $E_{total}$, in Phase I is $E_{total} = \frac{1}{k} \cdot N_T \cdot E_T + N_R \cdot E_R$, where $N_T = kN_S + [IAS]$ and $N_R = \sum_{i=1}^{N_S} \sum_{j=1}^{k} N_{r_{ij}} + \sum_{s_{ij} \in IAS} N_{r_{ij}}$.

B. Phase II

As a sensor, say sensor $i$, meets the conditions of being a clusterhead, it broadcasts this and assigns cluster ID $i$ to its neighboring sensors. Its neighboring sensors then transmit a signal to their neighbors to update cluster ID information. During this clustering phase, $(1 + N_i)$ transmissions and $(N_i + \sum_{j \in C_i} N_{j})$ receptions are executed, where $C_i$ is the index set of neighboring sensors of sensor $i$ and $N_i$ is the number of neighboring sensors of sensor $i$. This procedure is applied to all clusterheads and their cluster members. Now let $N_{T_r}^c$ and $N_{R_r}^c$ denote the number of transmissions and receptions for all clusters, respectively. Hence, $N_{T_r}^c = \sum_{i \in \mathcal{I}} (1 + N_i)$ and $N_{R_r}^c = \sum_{i \in \mathcal{I}} \left( \sum_{j \in C_i} N_{j} + N_{i} \right)$, where $\mathcal{I}$ is a index set of clusterheads. Therefore, the total energy consumption, $E_{total}^c$, for cluster formation in the wireless sensor network is $E_{total} = \frac{1}{k} \cdot N_{T_r}^c \cdot E_T + N_{R_r}^c \cdot E_R$.

Observe that the above analysis is suitable for any transmitting range. However, overly small transmission ranges may result in isolated clusters whereas overly large transmission ranges may result in a single cluster. Therefore, in order to optimize energy consumption and encourage linking between clusters, it is sensible to consider the minimum transmission power (or range $R$) which will result in a fully connected network. This range assignment problem is investigated in [28], which proposes lower bounds on the magnitude of $R^dN_S$ (with respect to $l$), $R^dN_S \in O(l^d)$, and shows that $R^dN_S \approx l^d \ln(l)$ may be a good initial value for the search of optimized range assignment strategies to provide a high probability of connectivity. Note that $N_S$ is the number of sensors and $l$ is the length of sides of a $d$-dimensional cube. The performance of the total energy consumption of the ACDA with different selections of $R$ is examined via simulation.

V. Simulation Results

The simulations of this section examine the performance of the ACDA. Assume that $N_S$ sensors are uniformly distributed over a square region in two-dimensional space. Parameters for the random waiting timer, number of sensors, and ratio of transmitting range $R$ to the side length $l$ of the square, $R/l$, are investigated to provide a simulation-based study of the ACDA. Note that the entire experiments are conducted in a square region with side length $l = 100$ unit length.

A. Parameter Settings

Given a random network of $N_S = 100$ sensors with $R/l = 0.141$, the first set of experiment studies the impact of parameter settings on cluster formation. With varying the number of sectors $k$ in a sensor and the initial value of waiting times $WT(0)$, Figure 6 shows the portion of clusterheads, and the portion of gateway nodes in the network and Figure 7 shows the portion of off-duty nodes and the average sensing coverage in the network. As depicted in Figures 6 and 7, given the values of waiting timers, an acceptable network performance may be achievable with values of parameters $\alpha = 7.5$, $\beta = 0.4$, and $\gamma = 0.1$. Observe that for the number of sectors $k = 2$, about 78% of the network nodes are selected as clusterheads, 0% of the network nodes are marked as off-duty nodes, and 86% of the network nodes act as gateways. In contrast, for $k = 3$, about 26% of the network nodes play the role of clusterheads, up to 10% of the network nodes are determined as off-duty nodes, and 37% of the network nodes act as gateways. Moreover, compared with the network performances with $k = 4$ and $k = 5$, the network with $k = 3$ has a higher portion of network nodes to become off-duty nodes.

B. Cluster Formation

The second set of experiments examines the cluster-based network topology with respect to the number of sectors in a sensor and the ratio $R/l$. Given the number of sectors $k$, Figure 8 shows the cluster formation with different number of sectors in a sensor. With random waiting time parameters $WT(0)$ ($1 \sim 1.9$), $\alpha = 7.5$, $\beta = 0.4$ and $\gamma = 0.1$, Figure 9 depicts typical runs of the algorithm based on the same sensor deployment but with $k = 3$ and different $R/l$ ratios. Notice that in order to minimize energy use and keep strong connectivity in the network, an appropriate selection of the transmission range $R$ is essential. In [28], the authors suggest that $R \approx l^{\frac{\log l}{N_S}}$ may be a good choice for the initial range assignment for sensors in the $d$-dimensional space. The results show that each cluster is a collection of sensors which are up to 2 hops away from a clusterhead.

C. Energy Consumption

The third set of experiments considers the total energy consumption of the ACDA. Assume that the communication channel is error-free. Based on the analysis in Section IV and given $\alpha = 7.5$, $\beta = 0.4$, and $\gamma = 0.1$, Figures 10 shows the average number of transmissions and receptions of random
networks after applying the proposed algorithm. Figure 10 also shows that the number of receptions tends to increase as the ratio $R/l$ increases. This implies that energy consumption is higher for the network with larger transmission power. This can be attributed to the fact that larger transmission power allows sensors to detect more neighbors, which increases the number of receptions when assigning cluster ID or updating cluster ID information.

D. Impact of Antenna Types

The forth set of experiments investigates the impact of antenna types on network performance. Figure 11 (top) shows the relationship between the average number of clusterheads and the $R/l$ ratio with varying the number of sensors and the number of sectors in a sensor. For $k = 2$, the average number of clusterheads increases as the ratio $R/l$ increases. This is due to the property of directional antenna and the operations of the ACDA. It may lead to a larger percentage of isolated sensors which eventually become clusterheads in their own right. In contrast, for $k = 3 \sim 5$, the average number of clusterheads decreases as the ratio $R/l$ increases (i.e. the transmission power increases), which has similar network performance with omnidirectional antennas. Figures 11 (middle) and 11 (bottom) demonstrate the portion of off-duty nodes and the portion of gateway nodes in the network, which coincides with the network behaviors as described in Figure 6. Therefore, considering the trade-off between performance and implementation cost, $k = 3$ may be a good choice for clustering sensors with directional antennas.

E. Omnidirectional Antennas vs. Directional Antennas

The final set of experiments compares the cluster formation when using the clustering schemes with omnidirectional antennas (e.g. Max-Min D-Cluster Formation Algorithm [22] and Clustering Algorithm via Waiting Timer (CAWT) [11]) and the new decentralized clustering algorithm with directional antennas. The Max-Min heuristic generalizes the clustering heuristics so that a sensor is either a clusterhead or at most D hops away from a clusterhead. This heuristic has complexity of
Fig. 9. Clusters are formed in a random network of 20 sensors with $k = 3$ and (a) $R/l = 0.146$, (b) $R/l = 0.292$, and (c) $R/l = 0.283$.

Fig. 10. (a) The number of transmissions and (b) the number of receptions in random networks as a function of the number of sensors and $R/l$ ratio.

Fig. 11. The portion of clusterheads (top), the portion of off-duty nodes (middle), and the portion of gateway nodes (bottom) in the network with varying the $R/l$ ratio, the number of sensors, and the number of sectors in a sensor.

$O(D)$ rounds which is better than most clustering algorithms in the literature ([18],[20]) with time complexity of $O(N_S)$, where $N_S$ is the number of sensors in the network. In the CAWT approach, each sensor initiates 2 rounds of local flooding to its 1-hop neighboring sensors, one for broadcasting sensor ID and the other for broadcasting cluster ID, to select clusterheads and form 2-hop clusters. Similarly, 2 rounds of local flooding are initiated in the proposed ACDA scheme, one for determining the active sensing sectors and the other for choosing communication sectors and clusterheads. Hence, the time complexity is $O(2)$ rounds. This implies that the ACDA, the CAWT and the Max-Min heuristic with $D = 2$ have the same time complexity $O(2)$. Thus the CAWT and the Max-Min heuristic with $D = 2$ provide good ways to benchmark the performance of the ACDA with varying the number of sectors.

As shown in Figure 11 (top), for $k = 3 \sim 5$, load balancing may not be achieved without an appropriate transmission range since this may lead to either too large or too small cluster sizes. Hence, the cluster formation is examined with respect to the $R/l$ ratio and network density when using the ACDA, the CAWT and the Max-Min heuristic, respectively. Figures 12 shows that the average number of clusterheads increases approximately linearly with increased network density though the ACDA approach has more cluster-heads and smaller cluster sizes than the CAWT and the Max-Min heuristic. Figure 12 also demonstrates that a good selection of transmission range may lead to a minimal variation of the cluster size with increased network density. This may help to achieve
balance the load among the clusterheads. Thus, the above set of experiments implies that the ACDA is competitive with the CAWT and the Max-Min heuristic in terms of time complexity and cluster formation.

VI. CONCLUSION

This paper has presented a randomized, decentralized algorithm for organizing the sensors of an ad hoc network into clusters. Directional antennas, random waiting timers, and a neighbor-based criterion are used to form clusters automatically. The solution combines the advantages of clustering and the strength of directional antennas to achieve both connectivity and sufficient coverage in wireless sensor networks.

Although the proposed strategy achieves effective network topology control, further experimental and theoretical extensions are possible. In our future work, we plan to involve more mechanisms to make the protocol faultless and practical, such as developing a new algorithm for sensor scheduling and power management, comparing the network lifetimes resulting from omnidirectional antennas (e.g. the strategies in [29]) and directional antennas, searching for an appropriate transmission range for sensors with directional antennas, and proposing efficient mechanisms to make protocol suitable for adaptive topology management.

REFERENCES