Adaptive Clustering with Dynamic Cluster Radius for Wireless Sensor Network

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Abstract

Topology control in Wireless Sensor Network (WSN) has recently been an area of intense investigation, especially the cluster-based topology control algorithms. In this study, we propose Adaptive Clustering with Dynamic Cluster Radius (ACDCR), a cluster-based topology control algorithm. This protocol proves to have several salient features, such as higher energy efficiency, and better QoS (Quality of Service). The design is accomplished by employing the hop-adaptive cluster radius, cluster head selection criteria with left energy threshold, and several other mechanisms. In ACDCR, only nodes with higher residual energy level than their neighbors are identified as cluster head candidates. Each cluster is assigned with a hop related radius for load balancing. In addition, nodes are allowed to setup direct links with the base station, rather than only their cluster heads. Simulation study shows that ACDCR outperforms HEED (Hybrid Energy-Efficient Distributed Clustering) in terms of network lifetime and QoS with fairly reasonable tradeoffs.

Keywords: *wireless sensor network; topology control; clustering; quality of service; adaptive cluster radius*

1. Introduction

After decades of research, Wireless Sensor Network (WSN) [1-2] has already been put into practices in different areas, including battle field surveillance [3], wild animal protection [4], and volcano monitoring [5]. Although extensive work has been done in this area, some problems have yet to be addressed and investigated [6]. One of the problems is how to deal with the frequent changes of underlying network structure, and provide high quality service to the end user (Here high quality service refers to longer network lifetime and better coverage.).

Due to frequent node failures, unstable wireless channel, and other reasons, the underlying network structure of WSN is more volatile than those of other networks. Such problem can be alleviated by topology control [7], which has already become one of the most important supporting techniques for WSN. Moreover, topology control also helps balancing load, saving energy, and reducing interference [8].

According to the overall network architecture, topology control algorithms can be categorized into two different types, hierarchical [9] and non-hierarchical [10]. In this study, we concentrate on the hierarchical algorithms with emphasis on cluster-based algorithms in the context of routing environment, and propose a clustering algorithm called Adaptive Clustering with Dynamic Cluster Radius (ACDCR).

The rest of the paper is organized as follows. First of all, the taxonomy of clustering algorithms and the most typical approaches of each category is given. Secondly, the network model, including assumptions and notations, and the clustering problem are addressed. And then the operation of ACDCR is presented. Following is the analysis and simulation of ACDCR. At last, the conclusion is made and possible future work is listed.

2. Related Works

Topology control methods can be classified into different categories by using different criteria. Below are some most common criteria, followed by a brief introduction of the most typical ones.

✓ Methodology

The protocol can be executed in either centralized or distributed manner. It is preferred that the algorithm can be executed for each sensor node separately, which is helpful in large scale scenarios. However, centralized algorithms can be found in some early studies, for example LEACH-C [11].

✓ Assumption

Topology control approaches are based on very different assumptions. For example, sensors are required to equip the location-aware module [12]; Nodes are assumed to have long-haul communication capability [13]. The topology control problem is studied with the existence of mobile agents [14].

✓ Design Goals

Algorithms are developed to achieve different design goals by applying different mechanisms. The earlier work focuses on energy efficiency [12]. Later, more factors are taken into account, such as the percentage of cluster head, the scale of each cluster, and other cluster characteristics [15].

A multi-criteria clustering method considering the number of cluster members and the total cost for all cluster members to communicate with their cluster head is proposed in [16]. A coverage and connectivity guaranteed clustering approach is presented in [17]. Intermediate mode, which uses cluster members for message relay, is introduced to increase the robustness and efficiency of the network in [18]. Overlapping clusters are formed instead of non-overlapping clusters for the consideration of fault-tolerance in [19]. More examples can be found in [9].

✓ Inter-cluster and Intra-cluster Topology

The inter-cluster communication, *i.e.* the communication between the base station and cluster heads, can be arranged into single-hop [12] or multi-hop manner. In most cases, nodes are not capable of long-distance communication, so that it is well accepted that a multi-hop link should be setup between the base station and cluster heads. Moreover, generally speaking, the multi-hop mode can be more energy-efficient than the single-hop mode.

In contrast to inter-cluster communication, to avoid adding too much complexity, the most common solution for intra-cluster communication is to let cluster members communicate with their cluster head directly. However, in DWECH (Distributed Weight-based Energy-efficient Hierarchical clustering protocol) [20], lower energy consumption is achieved by generating a multi-hop intra-cluster topology.

✓ Algorithm Complexity

The complexity of clustering approaches is different in terms of convergence time. For example, among the above mentioned algorithms, [12] terminates after constant rounds, while [11] has a time complexity of $O(n)$.

There are still more attributes, such as the cluster count in the network is variable or fixed, can be used to classify clustering algorithms. However, due to space limitation, we will not explore them in detail here.

By summing up the favored features for clustering algorithm, we here propose a distributed algorithm with constant convergence time called ACDCCR. In ACDCCR, mechanisms, like adaptive cluster radius and lower bound of residual energy for cluster head, are introduced to balance the load among nodes and achieve better coverage quality.

3. Preliminary

3.1. Network Model

The study is carried out under following assumptions, although all of them are widely accepted ones, for completeness, we still include them here. Moreover, for ease of illustration, some abbreviations and notations will be introduced.

- 1) All nodes and the *BS* (Base Station) are stationary once deployed.
- 2) Sensor nodes are driven by batteries, while the *BS* has sustainable energy supply.
- 3) All nodes are homogeneous, in terms of initial battery level and maximum transmission range.
- 4) All nodes are assigned with a unique *ID*, for example i for the i th node.
- 5) All nodes can adjust its transmission range between 0 and its maximum transmission range according to the requirement.
- 6) The approximate distance between node i and j , denoted as $dist(i, j)$, can be estimated by RSSI (Received Signal Strength Index), and thus GPS equipment is not required.

3.2. The Clustering Problem and Proposed Solution

In cluster-based algorithms, nodes are arranged into clusters. There is a *CH* (Cluster Head) in each cluster, and other nodes are called *CMs* (Cluster Members), where a directly link is setup between the *CH* and each *CM*. Thereafter, in the allocated TDMA slots, *CMs* can transmit the sensed data to their *CHs*, where the data can be further processed and then relayed to the *BS*.

The information needed for cluster formation is acquired through the exchanged information among one-hop neighbors. By the localized neighboring information, nodes decide whether to be *Tentative_CHs* or *CMs*, common criteria for such decision include residual energy, node degrees, and so forth. Then a bunch of *Final_CHs*, which will be in charge of intra-cluster and inter-cluster communication, are selected from *Tentative_CHs*, while the rest nodes will step back to be *CMs*.

In ACDCCR, *CMs* are further divided into the *FLCMs* (First Level Cluster Members) and the *SLCMs* (Second Level Cluster Member). For *FLCM*, it has a direct link to its *CH*, while *SLCM* communicates with *CH* by using *FLCM* as intermediate. Moreover, clusters have different cluster radius called *ClusterRange* to balance energy consumption. Note that, we

focus on the process of clustering, so existed methods for inter-cluster communication will be put into use directly.

4. The ACDCCR Algorithm

Step I. Hop Initialization

With the help of the *BS*, every node initializes its hops to *BS*. The *BS* broadcasts a beacon message, and every node can sets its hops to *BS* according to the received beacon message. Additionally, every node relays the beacon message with the hop information updated. Besides the hop information, other global settings like $Intra_0$ and $Intra_{max}$ can be spread simultaneously in this step. The $Intra_0$ and $Intra_{max}$ here denote the lower bound and upper bound for *ClusterRange*, respectively.

Hop Initialization is treated as a separate step, because unlike other steps, it only needs to be executed once during the network lifetime.

Step II. Neighbor Discovery

$$Range_i = (1 + \alpha \times \frac{(Hop_i + 1)}{\max hop}) \times Intra_0 \quad (1)$$

$$ClusterRange_i = \min(Range_i, Intra_{max}) \quad (2)$$

In this step, for each node i , it first computes its own $ClusterRange_i$ by (1) and (2), which are designed as a countermeasure to the ‘funneling effect’ [21].

It is known that nodes closer to the *BS* drain out their battery more quickly because of the ‘funneling effect’. Furthermore, the ‘funneling effect’ does not only lead to unbalanced energy consumption, it also results in network disconnection. Based on such observation, it is reasonable to let nodes, which have farther distance to the *BS*, have a larger cluster radius.

Figure 1. Node State Transition Diagram

A neighbor discovery message, including node *ID*, hop and residual energy, will be broadcasted by each node after the decision of cluster radius. And then every node within the distance of *ClusterRange*, will receive and reply for the message. It is worth noticing that nodes will reply the neighbor discovery message, regardless of its own *ClusterRange*. At the end of this step, nodes are considered Initialized (transition 1 in Fig. 1).

Step III. CH Election

If node i cannot find any neighbor inside its $ClusterRange_i$, it will become a CH directly (transition 2 in Figure 1). Otherwise it needs to decide whether to be a $Tentative_CH$ or a CM according to its residual energy level. As the average energy level of i 's one-hop neighbors can be calculated, it will nominate itself as a $Tentative_CH$ (transition 3 in Figure 1) if the condition described in (3) can be satisfied, else it chooses to be a CM (transition 4 in Figure 1). Such setting will guarantee that nodes with rather low energy level will not be eligible candidates for CH .

$$E_r(i) \geq Avg(i), \text{ where } Avg(i) = \frac{\sum_{j=1}^{neighborcount} E_r(j)}{neighborcount} \quad (3)$$

For $Tentative_CH$ i , it will determine to become a CH (transition 5 in Fig. 1) if $CH_Prob(i)$, which can be computed by (4), reaches 1. Otherwise, the $CH_Prob(i)$ will be doubled in next iteration. Moreover, the probability is not allowed to fall below P_{min} [15-16]. Such constraint is introduced to ensure that the CH election ends after constant iterations, which will be further illustrated in section IV.

$$CH_Prob(i) = \max(2^{iteration} \times (\frac{E_r(i)}{Avg(i)}), 2^{iteration} \times P_{min}) \quad (4)$$

A CH announcement will be broadcasted by CH i within the radius of $ClusterRange_i$, if $CH_Prob(i)$ reaches 1. Nodes, which receive such announcement, will take actions according to their own states. For CM s, they will include i in their neighbor CH list for parent CH selection. As for $Tentative_CH$ s, in addition, they will step back to CM state (transition 6 in Fig. 1). For CH s, CH i will be stored in its CH list for inter-cluster link setup.

This step ends while there is no $Tentative_CH$ node.

Step IV. Cluster Joining

Figure 2. Cluster Joining Choice

Figure 3. Topology Sample for ACDCR

CMs have to choose a cluster to join, *i.e.*, choose a parent *CH* (transition 7 in Figure 1). Here, the distance between a *CM* and its potential parent *CHs* is used as a primary parameter for parent *CH* selection, and the potential parent *CH's* hop to *BS* is used as the second parameter. And those nodes, which have a direct link to *CHs*, are called *FLCMs*.

Moreover, there might be such situation as depicted in Figure 2. For *CM o*, which is covered only by *CH i*, it will become the child of *CH i*. For *CM n* and *CM m*, which are covered by the *BS* only, they will become the *BS's* children. As for *CM k*, the situation is a little complicated, it will become the child of the *BS*, if $dist(BS, k)$ is smaller than or equals to $dist(i, k)$. On the other hand, if $dist(BS, k)$ is bigger than $dist(i, k)$, it will choose *CH i* to be its parent.

To round up, *CMs* are allowed to setup direct link with the *BS* in ACDCCR. Such setting can further alleviate the ‘funneling effect’, because a message can be delivered to the *BS* with less intermediate nodes.

One last question is how to deal with the ‘orphaned’ nodes, which are neither covered by any *CH* nor the *BS*. For such node, it will become a child of the nearest *FLCM* (transition 8 in Figure 1), *i.e.* the *SLCM*.

Step V. Backbone Network Setup

This step deals with the problem of inter-cluster communication by setup a backbone network among *CHs*. The main purpose of this step is to make sure that messages can be properly delivered to the *BS*, *i.e.*, the network connectivity. So *CH i* selects the nearest *CH j* with a smaller hop than itself to be its parent *CH*. In addition, the research result about how to preserve the network connectivity in [17] is applied here directly.

Step VI. Data Collection

Table 1. Pseudo code of ACDCCR

<p>Step I. Initialization The <i>BS</i> broadcasts a beacon message, and the message is relayed with the hop information updated by nodes.</p> <p>Step II. Neighbor Discovery FOR each pair of node <i>i</i> and nod <i>j</i>, where $dist(i, j) \leq ClusterRange_i$ <i>i, j</i> exchange <i>hop</i> and E_r information</p> <p>Step III. CH Election FOR each node <i>i</i>, where $E_r(i) \geq Avg(i)$ <i>Tentative_CH</i> $\leftarrow i$ WHILE <i>Tentative_CH</i> $\neq \phi$ FOR each <i>Tentative_CH i</i> IF <i>CH_Prob</i> (<i>i</i>) ≥ 1 <i>Final_CH</i> $\leftarrow i$ <i>Tentative_CH</i> = <i>Tentative_CH</i> – { <i>i</i> } <i>i</i> broadcasts a <i>CH</i> announcement FOR each <i>Tentative_CH j</i> IF $dist(i, j) \leq ClusterRange(i)$ <i>CM</i> $\leftarrow j$ FOR each <i>CM j</i> <i>j</i> includes <i>i</i> in its <i>CH</i> list ELSE <i>CH_Prob</i> (<i>i</i>) doubles</p>	<p>END WHILE</p> <p>Step IV. Cluster Joining FOR each <i>CM i</i> IF $dist(i, BS) \leq dist(i, any\ CH)$ direct link to the <i>BS</i> ELSE IF <i>i</i> is covered by any <i>CH</i> <i>FLCM</i> $\leftarrow i$ ELSE <i>SLCM</i> $\leftarrow i$</p> <p>Step V. Backbone Network Setup FOR each <i>CH i</i> FOR each neighbor <i>CH j</i>, where $hop(i) > hop(j)$ and $i \neq j$ IF $dist(i, j)$ is the minimum among all neighbor <i>CHs</i> <i>i's</i> parent <i>CH</i> is <i>j</i></p> <p>Step VI. Sensed Data Collection FOR each <i>CM i</i> transmits sensed data to its parent <i>CH</i> FOR each <i>CH i</i> fuses the received data from its cluster members transmits fused data to the <i>BS</i></p>
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After the network topology is formed, *CMs* transmit sensed data to their parent *CHs* in the allocated time frame. Thereafter, *CHs* can do further processes like data fusion, then the data will be relayed to the *BS* through the backbone network.

This step will be executed for R rounds without any adjustment. And the R , referred as Stable Interval in following sections, is an application-specific parameter. Once data collection is executed for R rounds, a *CH* rotation or topology reformation is processed by executing Step II. ~ Step V.

The pseudo code of ACDCR is shown in Table 1. And a sample topology generated by executing ACDCR is shown in Figure 3, in which 200 nodes with random initial energy are dispersed randomly in a 200*200 area. And “*” denotes the *BS*, “×” denotes nodes run out of energy, “◇” denotes *CHs*, “●” denotes *FLCMs*, and ‘+’ denotes *SLCMs*.

5. Analysis and Simulations

5.1. Complexity Analysis

Lemma 1: ACDCR terminates in $N_{iter} = O(1)$ iterations.

Proof. The worst case happens when the residual energy level is rather low. Under such situations, the initial value of $CH_Prob(i)$ will be set to P_{min} , and then doubles after every repetition. Then

$$2^{N_{iter}} \times P_{min} \geq 1 \quad (5)$$

and hence

$$N_{iter} \leq \left\lceil \log_2 \frac{1}{P_{min}} \right\rceil \quad (6)$$

Therefore, $N_{iter} \approx O(1)$. The proof is similar to the proof in [15].

5.2. Simulation Settings

Parameters used in the simulation are listed in Table 2. Moreover, to exclude the possibility that the results are outcomes of specific cases, experiments are conducted in two different scenarios and all results are average of 20 experiments. In scenario 1, there are 200 nodes equipped with 0.5J batteries, while 400 nodes are deployed with 1J initial energy in scenario 2. Besides the above, the widely accepted energy model is assumed in our simulation, the detail of which can be referred in [12, 15-16] and many other articles in this area. And the HEED (AMRP), AMRP refers to Average Minimum Reachability Power, is used as the benchmark algorithm in the simulation. Last of all, all simulation is performed via Matlab 7.1.

Table 2. Simulation Parameters

Parameter	Value	Parameter	Value
Number of Nodes	200/400	Threshold distance	$\sqrt{\epsilon_{mp}/\epsilon_{fs}}$
Network Grid	(0,0)~(200,200)	$Intra_0$	25
Base Station	(100,100)	$Intra_{max}$	0.15
Initial Energy	0.5J/1J	α	0.15
E_{elec}	50 nJ/bit	Control Packet Size	25 bytes
ϵ_{fs}	10 pJ/bit/m ²	Data Packet Size	100 bytes
ϵ_{mp}	0.0013 pJ/bit/m ⁴	Stable Interval	10
E_{fusion}	5 nJ/bit/signal		

5.3. Performance Evaluation

- ✓ Network Lifetime

Table 3. Comparison of lifespan

Number of Nodes	Initial Energy	Algorithm	Round First Node Dies	Round Last Node Dies
200	0.5J	ACDCR	2422	18678
		HEED	1954	11987
400	1J	ACDCR	4328	37228
		HEED	3872	17677

Energy conservation has always been the first priority for protocol design in WSNs. The comparison of lifespan between ACDCR and HEED is shown in Table 3. Furthermore, the life curves in the assumed scenarios for both ACDCR and HEED are given in Figure 4 and Figure 5. It can be inferred from the results that ACDCR achieves a longer network lifespan than HEED.

Figure 4. Lifetime Curve under Senario1

Figure 5. Lifetime Curve under Senario2

✓ QoS

Figure 6. QoS under Senario1

Figure 7. QoS under Senario2

Given the same node distribution, there is no doubt that more active nodes will lead to a better chance for successful event detection. And for simplicity, the problem of coverage overlapping will not be addressed in this study. Based on the above assumption, the number of active nodes can be used as a QoS (Quality of Service) index. Furthermore, the terms for different QoS level are defined as follows.

1. *High Quality*, all nodes are alive.
2. *Medium Quality*, node failure begins, but more than 80 percent nodes are alive.
3. *Low Quality*, less than 80 percent but more than 50 percent nodes are alive.
4. *Poor Quality*, less than 50 percent but more than 30 percent nodes are alive.

Based on the above definition, the QoS of ACDCR and HEED is compared. The results are illustrated as Figure 6 and Figure 7, and it is safe to say besides longer longevity that ACDCR also has a better QoS as compared to HEED.

✓ Percentage of CH

It is favored for clustering algorithm to have a small amount of *CHs*, and the percentage of *CH* keeps stable in the lifecycle. The comparison illustrated in Figure 8 and Figure 9, implicates that ACDCR has less *CHs* and smaller fluctuation in the *CH* ratio as compared to HEED.

Such outcomes are gained by the different handling of the ‘orphaned’ nodes. In HEED, the ‘orphaned’ nodes, which have no neighbor in their neighborhood area, will become *CH*. Such setting will inevitably lead to more *CH* nodes. Instead of letting ‘orphaned’ nodes become *CH*, in ACDCR, they join clusters as *SLCMs*.

Figure 8. CH Raito under Senario1

Figure 9. CH Raito under Senario2

✓ Anti-Funneling Effect

Not unexpectedly, shown by Figure 10 and Figure 11, as nodes die, the network coverage area shrinks while the connectivity is preserved, which is compounded by the cluster radius setting, and allowing the sensor nodes to setup direct link with the *BS*.

Figure 10. Topology after 4000 rounds

Figure 11. Topology after 8000 rounds

✓ Side Effects

It should be noticed that it is possible that nodes can neither be covered by the *BS* and *CHs*, nor *FLCMs*. However, such situation occurs with very small probability, which is convinced by over 100 experiments (random initial energy level range from 0 to 1, 10 rounds each experiment), illustrated in Table 4.

Table 4. Uncovered nodes

Number of Nodes	Isolation Occurred Times	Average Uncovered Nodes Per Round
200	3	0.3
400	1	0.1

6. Conclusions

A distributed clustering algorithm called ACDCR is proposed in this paper, which is designed for quasi-stationary networks. And no special assumption, such as location-aware, is made. Moreover, with the strategy for *CH* selection and the setting of adaptive cluster radius, it terminates in constant iterations and achieves better performance with ignorable side effect.

For future study, efforts can be made in the node deployment pattern's influence on topology control. Moreover, fault-tolerant mechanisms for inter-cluster communication can be further discussed to achieve better robustness.

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