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An Energy-Efficient Decentralized Clustering Protocol for Wireless Sensor Networks

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Abstract: - This paper presents a novel clustering protocol, the Decentralized Energy Efficient cluster Propagation (DEEP) protocol, that manages the communication of data while minimizing energy consumption across sensor networks. The paper also presents an Inter-Cluster Routing protocol (ICR) that is compatible with the proposed clustering technique. The proposed clustering protocol uses the unique technique of forming clusters using a pre-selected initial cluster head that initiates the advertisement process. The initial cluster head also identifies its cluster members as well as new cluster head candidates based on the relative distance between sensor nodes and their remaining energy levels. Because this model results in a balanced load among cluster heads, protocol overhead due to frequent re-clustering is eliminated. Simulation results demonstrate that the DEEP protocol distributes energy consumption approximately eight times better than the LEACH clustering scheme. In addition, the DEEP protocol substantially reduces total data communication and route setup energy consumption in the network compared to the LEACH protocol.

Key Words: - Sensor networks, Clustering algorithm, Network management, Routing protocols, Wireless networking, Network topology control, Wireless ad-Hoc networks.

1. Introduction

Decentralized clustering techniques attempt to force the sensor nodes to collaborate with each other and create clusters without the help of any centralized base station. The optimum number of cluster heads can be found using ωd^n as a substantial energy model for the transceiver power consumption. However, sometimes the wireless energy model could not follow the ωd^n rule due to the dominating distance independent term and *multi-rate* communication. On the other hand, hierarchical clustering is not practical because wireless technologies have a limited transmission range, and as level of hierarchy grows, cluster heads get further from each other and can not reach the upper layer leader. Max-Min d-Clustering [3], [4] creates d-hop clusters, but there is no energy optimization associated with the algorithm. Low Energy Adaptive Clustering Hierarchy (LEACH) is a decentralized clustering algorithm [5] that does not optimize energy consumption since there is no strategy in terms of cluster head's position and distribution.

For a cluster based sensor network, both inter-cluster and intra-cluster routing protocols have been developed to keep network connected. Centralized route selection algorithms aim to choose the appropriate next neighbor for each node using a central command node [6]. Wireless networks that perform distributed routing leave the route selection decision to the sensor nodes by themselves. SPIN [8] and directed diffusion [7] introduce a concept of "interest" propagation whenever a node wants to send data or a source needs to ask for it. Flooding the network with the interest signal will establish a path from the sink to every possible source (spanning tree). While directed diffusion reinforces the paths with higher data rate, SPIN concentrates exclusively on the path set up via negotiation.

2. Communication Energy Model

In general we can summarize all transceiver energy components as [3]:

$$E_{(Watt)} = \theta + \eta_{amp} \times \omega d^n$$

Where θ is a distance-independent term that accounts for overheads of the radio electronics and digital processing, and ωd^n models the attenuation of a transmission path. *n* could be a number between 2 and 4 based on the environmental conditions, and η_{amp} stands for the amplifier inefficiency factor. The effect of distance dependent term in the total energy consumption depends on the real world transceiver parameters, θ, η_{amp}, and the path attenuation ωd^n. If the value of θ is overshadowing $\eta_{amp} \times \omega d^n$, reduction in transmission distance through the use of multihop communication wouldn't be effective [3]. Atheros2004 tri-mode chipset [2] has been chosen to observe the real values for the radio hardware. In practical implementations, power amplifier efficiency is less than 40% [5]. Therefore θ is calculated using the assumption $\eta_{amp} = (1/0.4 = 2.5)$. While maximum output power and total power consumption is provided in the manufacturer data sheet, θ could be calculated based on the following formula (See [9] Table 1):

$$\theta = \theta_{TX} + P_{RX} = (P_{TX} - \eta_{amp} \times \omega d^n) + P_{RX}$$

Despite the fact that the path attenuation energy increases exponentially by the transmission distance, The static power consumption, θ, dominates the path loss and therefore causing the total power consumption to remain constant as transmission distance increases. While 802.11g wireless technologies technique has never been proposed for sensor networks, multi-rate communication can decrease the transmission energy for smaller distances by switching to the higher data rates and keeping the transceiver on for a shorter period of time. In this case, energy in terms of Joule/bit reduces discretely as the transmission distance increases.

$$E_{Joule/bit} = \frac{(\theta + \eta_{amp} \times \omega d^n)_{Joule/\sec}}{(Rate)_{bit/\sec}}$$

Due to the large value of θ compared to maximum output power, single rate communication energy remains constant as transmission distance increases while multi-rate communication energy decreases for shorter transmission ranges. Multi-rate communication would also necessitate the presence of a robust rate selection protocol. As seen, energy model for none of the mentioned methods follow the famous rule of ωd^n.

2.1. Multi-Hop vs Direct Communication

The traditional objective of multi-hop communication is to reduce the transmission distance into smaller ranges and conserve energy by means of $E = m \times (\theta + \eta_{amp} \times \omega (d/m)^n)$. Considering the real world radio parameters and multi-rate communication impacts, we should re-evaluate the effectiveness of multi-hop communication. Since multi-rate communication reduces energy consumption for smaller distances by switching to higher data rates, multi-hop can conserve energy. However, if division of transmission distance happens when maximum range is less than 18.75m for 802.11g, data rate remains constant and total energy consumption multiplies by the number of hops.

It is predicted that sensors should be placed, in average, no more than 10m away from each other. In order to compare the energy consumption of direct and multi-hop communication inside the cluster, we set up an environment representing one cluster. The dimension of the field is 50m$\times$50m, and 25 nodes are randomly dispersed in the field. Fig. 1 shows the energy consumption of direct, minimum 2-hop, and minimum 3-hop path based on the distance between every single node in the cluster and the cluster head for a chosen 802.11g technology. For this technology, direct transmission is the optimum choice for ranges less than 37m. Therefore, if cluster radius is limited to 37m, frequent control and extra power consumption associated with route set up be avoided. The best placement for a cluster head is the center of cluster while sensor nodes are positioned closer than 37m around it.

3. Proposed Energy-Efficient Protocol

A robust clustering technique is essential in order to configure clusters with almost the same radius and cluster heads that are positioned in the center of clusters. Since sensor nodes begin without any knowledge about their location relative to the base station, distributed clustering algorithm should be able to form clusters without the help of base station and knowledge of network member's position. Although location finder devices and protocols could be deployed, they are either costly or put too much overhead on the network.

DEEP is based on the idea of starting with an initial cluster head candidate and spreading the cluster heads gradually so that they are placed all at the same approximate distance from each other.

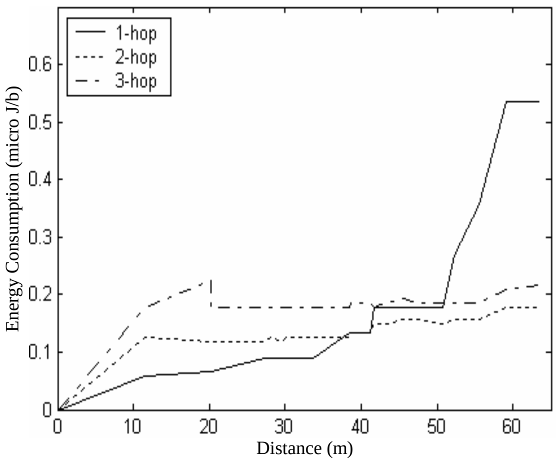

Fig. 1: Communication energy versus transmission distance between sensor nodes and cluster head.

Due to the balanced weight on each cluster head, periodic re-clustering is not necessary and therefore operational expenses caused by frequent re-clustering is eliminated. In order to explain the details of algorithm, first we introduce control signals and algorithm parameters:

- Control signals:
  1. Cluster Head (CH) declaration signal.
  2. Cluster Head (CH) exploration signal.
  3. Membership search signal.
- Control Parameters:
  1. Declaration range (d_r).
  2. Exploration range (e_{r1}, e_{r2}).
  3. Minimum number of members (*m*).
  4. Fixed output power of CH exploration signal (P_{out}).

Protocol control parameters are application specific choices and can be defined prior to the network deployment. Algorithm DEEP forms clusters by starting with an initial cluster head candidate that can be chosen prior to the network deployment. This initial cluster head candidate starts the cluster set up phase by propagating cluster head declaration signal within the range of d_r. This means that cluster head candidate chooses the appropriate data rate and signal output power so that it can reach nodes that are less than d_r away from the sender. At this point sensor nodes that receive the declaration signal accept the corresponding cluster head as a leader. They can estimate their relative distance to the candidate by looking at the received signal energy level. Once they know the relative distance to the cluster head candidate, they can conserve energy by adjusting the transmission speed to the appropriate value and switching to the sleep mode. Now initial CH candidate propagates the CH exploration signal within the range of e_{r2} (Fig. 2). All the sensor nodes that are in this range can listen to the exploration signal but only nodes that have never played the role of CH and can verify the following equality will be chosen as a new candidate:

$$E_{rc1} < E_r < E_{rc2}$$

E_r is the received signal energy and it should be bigger than E_{rc1} and smaller than E_{rc2} so that the node can consider itself as a candidate. E_{rc1} and E_{rc2} are fixed protocol parameters that can be determined using the following formula:

$$E_{rc1} = P_{out} - \omega(e_{r1})^n$$

$$E_{rc2} = P_{out} - \omega(e_{r2})^n$$

P_{out} is the invariable output power of the cluster head exploration signal, and ω and *n* are parameters that can be achieved based on the environmental conditions of the deployment area. This ensures nodes that are placed between e_{r1} and e_{r2} are the only newly chosen candidates. Now each candidate sends a declaration signal within the range of d_r. If two candidates could hear the declaration signal of each other, one of them will be eliminated through negotiation. Because it shows that these two cluster heads are too close to each other and the presence of both of them is unnecessary.

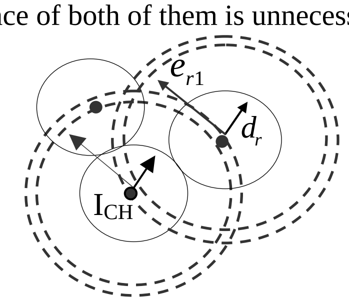

Fig. 2: New cluster head candidates send the exploration signal within the range of e_{r2} to continue the process of cluster establishment.

Now confirmed cluster heads propagate exploration signal and nodes that have been chosen as cluster head or member ignore the CH exploration or declaration signals. This process will continue until all the nodes in the field are belonging to a cluster. At this point if there is a cluster that its total number of members is smaller than “Minimum number of members” (*m)*, cluster will be dissolved and all the members including cluster head initiate a *Membership search signal.* Then they listen to the responds from the local cluster heads and choose the closest cluster head based on the received signal power. At the end, if $t = time_{out}$ and a sensor node hasn't received any control signal, it sends a *membership search signal* and chooses the closest cluster head as a leader. Algorithm execution can be summarized as follow:

1. All nodes calculate $E_{rc2} = P_{out} - \omega(e_{r1})^n$ & $E_{rc2} = P_{out} - \omega(e_{r2})^n$
2. Initial cluster head finds members by sending "CH declaration".
3. Initial cluster head finds new CH candidates by sending "CH exploration signal".
4. Nodes that are placed on the (e_{r1}, e_{r2}) ring find members (go to step 2).
5. Nodes that receive more than one CH declaration choose the closest CH based on the received signal energy.
6. Cluster head candidates that receive CH declaration signal negotiate with the sender, and one of them gets eliminated.
7. If number of members in a cluster is less than *m*, all the members find new clusters by sending *membership search signal.*
8. At the end, if a node has not received any control signal, it sends *membership search signal.*

4. Inter-Cluster Routing Protocol

After establishing well-distributed Cluster Heads (CH) and clusters in the network, energy conscious routing is very important to extend network lifetime. Due to the limited transmission range of low power wireless technologies, CHs' data packets can not reach to the far base station unless other CHs act as a relay node and forward the data to each other. In this section, we propose an Inter-Cluster Energy Conscious Routing (ICR) protocol that is compatible with the proposed clustering algorithm. ICR uses interest flooding similar to directed diffusion [13] and Energy Aware Routing (EAR) [10] to establish routes between the base station and sensor nodes, but it differs from EAR and directed diffusion in some aspects. First we describe the ICR scheme and then accentuate the differences from EAR.

Local Base Station (LBS) initiates the route discovery phase by propagating an *Interest* signal that includes the *type* and the *period* of the desirable signal. If LBS requires some periodic data collection phases, it can set the *period* in which nodes sends that specific *type* of information. If LBS require sensor nodes to detect some specific event, it can include the *type* of that specific event in the interest signal. Also *expiration* field is a counter that destroys the interest after timeout. We can explain the ICR execution in the following steps:

1. LBS sends an interest signal within the range of R_i .
2. Each Intermediate cluster head that receives the interest signal searches in the cash memory to find the same entry. If there is no entry, it saves the signal in the cash, updates the cost field of the outgoing interest signal and sends it within the range of R_i .
3. W define the cost function as:

   $$Cost = Hop\_Number + \sum_i \frac{1}{B_{ri}}$$

   B_r represents the remained energy in the battery of the node.
4. If a cluster head receives an interest that currently exists in the memory, it compares the cost field of the received signal with the cost field of the previously saved message. If it is smaller, the node replaces the old one, updates the cost field, and propagates the packet. If it's bigger, the node should destroy the packet. In case these two values are equal, the node creates another entry for the incoming interest as an option.
5. After a cluster head collects the requested information from sensor nodes, it compresses them into a packet with identical length, searches for the relay neighbor's address in the memory, and sends the packet to that neighbor.
6. In order to reduce the diffusion of spare data bits in to the network, relay nodes can receive the data packets, each of length *L*, from *N* nodes and aggregate them into one single packet of length *L*. See the details in [9].

After the execution of routing protocol a spanning tree is established that is rooted in the base station and connects all the cluster heads to the base station.

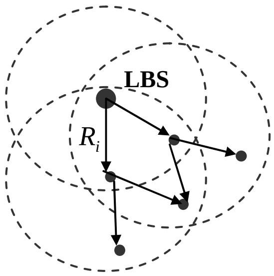

Fig. 4: Local Base Station starts the route discovery process by generating interest signal.

5. Simulation Results

We implemented the proposed DEEP protocol along with the ICR routing and simulated the algorithm using different protocol parameters d_r, e_{r1}, e_{r2} and *m* while initial cluster head candidate is placed at the center of the field. Fig. 5 shows the output of one of these simulations with parameters d_r=30m, e_{r2}=80m, e_{r1}= 78m, *m*= 14. Based on the results obtained from Section 2.1, 30m is an initial choice for d_r. In order to avoid overlapping between clusters, the value of e_{r1} and e_{r2} should be more than twice of the value of d_r. Since average distance between sensor nodes in this application is 10m, 80m is a fair choice for e_{r2}. The width of the (e_{r1}, e_{r2}) ring should be large enough to accommodate new cluster head candidates and small enough to avoid cluster head candidates that are too close to each other. We chose 2m as an initial value for the ring width. In order to balance the load, DEEP controls the cluster head distribution rather than the number of cluster members since shorter transmission distance indicates higher data rates and lower transmission time.

Fig. 6 shows the energy consumption in each cluster head in order to receive one bit of information from all the cluster members using 802.11g technology. Due to the inconsistent distribution of cluster heads, LEACH puts a lot of pressure on some of the cluster heads (CH) while DEEP share out the weight among all of them. The standard deviation (ESD) of CHs' communication energy for LEACH is 7.7013 μ Joule/bit, about 8 times larger than ESD of communication energy for DEEP while the average energy consumption per CH for LEACH is 5.476 μ J/b, about 2.3 times larger than the same parameter for DEEP.

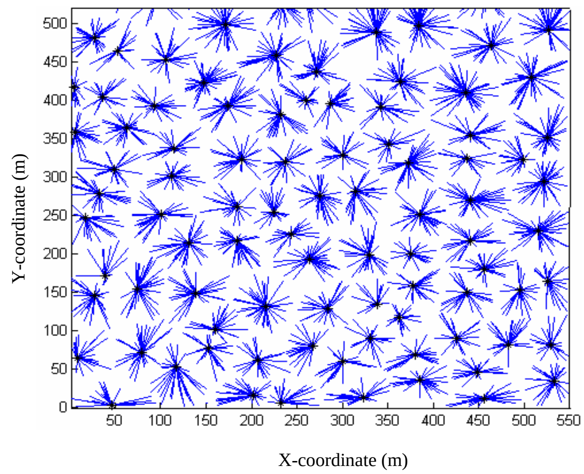

Fig. 5: Final generated clusters while nodes are directly connected to the associated cluster head.

In order to prevent over-utilization of some sensor nodes, clustering technique should ensure that the cluster head responsibility rotates among all the sensor nodes. To achieve this, in LEACH [5], re-clustering is performed periodically, but every round of re-clustering requires several control signal exchanges among self-elected CHs and sensor nodes. When the current period of cluster setting is finished, current CH candidate chooses the nearest node that has never been acted as an initial cluster head. This node starts the clustering process and creates a totally different cluster head constellation. We simulated the clustering process for 30 rounds.

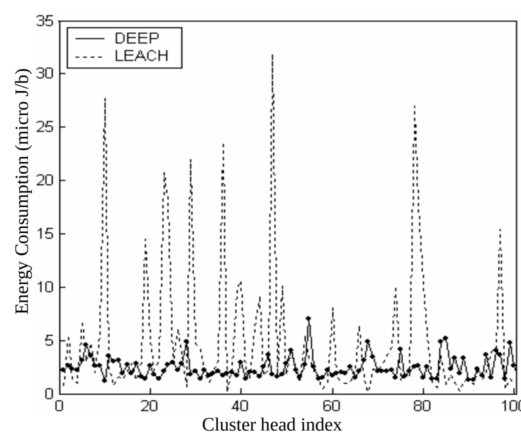

Fig. 6: Intra-cluster energy consumption (μ J) for each cluster head.

Our next experiment shown in Fig. 7 compares the total energy consumption in the network that has been clustered using DEEP and LEACH protocol and uses ICR to find the routes among cluster heads. To achieve different densities for cluster heads in LEACH protocol, we changed the value of the protocol parameter, p, from 0.04 to 0.09.

Fig. 7 shows the total energy consumption in the network to collect one bit of data from every sensor node. Network is clustered using both DEEP and LEACH algorithm and routes have been set up among cluster heads using ICR. As seen, DEEP has noticeably

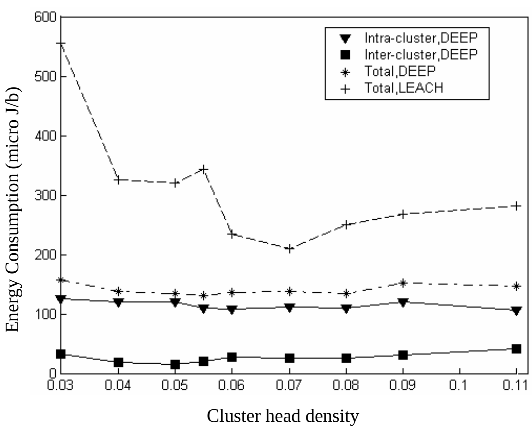

Fig. 7: Total energy consumption (μ J) versus cluster head density.

better energy efficiency compared to LEACH for any cluster head density. In order to set the routes, maximum range of the interest signal (R_i) should be chosen high enough to keep the cluster head network connected and low enough to prevent unnecessary energy consumption and interest generation. But as cluster head density increases and cluster heads get closer to each other, R_i can decrease. Since we adjust the maximum range of the output signal by changing the transmission data rate, R_i should follow the values provided in [9] (Table 2) for 802.11g. In this scenario, R_i has changed from 100m to 76.5m, for LEACH, when cluster head density reaches 0.055 point and from 76.5m to 57m, for DEEP, when cluster head density reaches 0.05 point. For a chosen cluster head density, R_i is higher for LEACH compared to DEEP since LEACH protocol distributes the cluster heads inconsistently. Higher values for R_i lead to extra route set up overheads and faster network degradation.

6. Conclusion

While wireless sensor networks introduce challenging energy limitations, clustering protocols can reduce the amount of energy consumption by dividing the network into well-distributed clusters. In this paper, we have proposed a new energy-efficient clustering algorithm (DEEP) that is based on the idea of controlling the geographical dimensions of clusters and distribution of cluster heads. Because of the balanced load among cluster heads, there is no need for frequent re-clustering, but after current cluster heads are out of energy, protocol can rotate the cluster head position among all the sensor nodes. Results from our experiments show that DEEP can reduce the energy consumption and prolong network lifetime.

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