Distributive Energy Efficient Adaptive Clustering Protocol for Wireless Sensor Networks

Udit Sajjanhar
Indian Institute of Technology, Kharagpur, India
udit.sajjanhar@iitkgp.ac.in

Pabitra Mitra
Indian Institute of Technology, Kharagpur, India
pabitra@cse.iitkgp.ernet.in

Abstract

Clustering sensors into groups, so that sensors communicate information only to cluster-heads and then the cluster-heads communicate the aggregated information to the base station, saves energy and thus prolongs network lifetime. Adapting this approach, we propose a Distributive Energy Efficient Adaptive Clustering (DEEAC) protocol. This protocol is adaptive in terms of data reporting rates and residual energy of each node within the network. Motivated by the LEACH protocol [1], we extend its stochastic cluster selection algorithm for networks having spatio-temporal variations in data reporting rates across different regions. Simulation results demonstrate that DEEAC is able to distribute energy consumption more effectively among the sensors, thereby prolonging the network lifetime by as much as 50% compared to LEACH.

1. Introduction

Sensor nodes are often left unattended e.g., in hostile environments, which makes it difficult or impossible to re-charge or replace their batteries. This necessitates devising novel energy-efficient solutions to some of the conventional wireless networking problems, such as medium access control, routing, self-organization, so as to prolong the network lifetime.

In most of the applications sensors are required to detect events and then communicate the collected information to a distant base station (BS) where parameters characterizing these events are estimated. The cost of transmitting information is higher than computation and hence it is be advantageous to organize the sensors into clusters [1] [2], where the data gathered by the sensors is communicated to the BS through a hierarchy of cluster-heads.

LEACH [1] is perhaps the first cluster based routing protocol for wireless sensor networks, which uses a stochastic model for cluster head selection. LEACH has motivated the design of several other protocols [3] [4] which try to improve upon the cluster-head selection process by considering the residual energy of the nodes. TL-LEACH [8] uses two levels of cluster heads instead of one in LEACH. EDAC [7] enables cluster heads to change status asynchronously and co-ordinate energy consumption. HEED [6] uses a hybrid approach based on residual energy and communication cost to select cluster heads. ANTICLUST [9] uses a two level cluster-head selection process involving local communication between neighboring nodes. Protocols like APTEEN [5], and EDC [10] optimize energy by responding to events in the network but are not suited for applications which require continuous data delivery.

However none of the above approaches exploits both of the spatial and temporal correlation present in the data transmitted by the sensor nodes. In many applications due to high density of sensor nodes in network topology, spatially proximal sensor observations are highly correlated. Also the nature of the energy radiating physical process constitutes the temporal correlation between consecutive observations of a sensor node [11]. CAG [12] exploits spatial correlation by clustering the nodes sensing similar values. ELECTION [13] is an event based clustering system which also exploits spatial and temporal correlation by controlling sleep schedules of the sensor nodes.

In all the above approaches either the data is collected from the network periodically or on an occurrence of an event. Hence, none of them adapts to the temporal variations in data delivered by the sensor network. This necessitates the use of a hybrid approach for data collection that readily adapts to the changes in the data delivery rate. The proposed DEEAC protocol is well suited for such applications.

The regions in the network having high data generation rate are considered to be “hot regions”. “Hotness” value of a node is a parameter indicating the data generation rate at that node relative to the whole network. DEEAC tries to optimize the energy consumption of the network by ensuring that nodes belonging to hot regions have a high probability of becoming a cluster heads. Thus nodes belonging to hot regions, which are expected to transmit data more frequently, now do it over shorter distances, thereby leading to balanced energy consumption over the network. DEEAC selects a node to be a cluster head depending upon its hotness value and residual energy. This is an improvement over stochastic approach used in LEACH in terms of energy efficiency.

The DEEAC approach considers two additional parameters for cluster-head selection. These are the residual energy of a node and the hotness of the region sensed by the node. These two factors are used in a fashion which leads to Spatio-temporal adaptation for optimum energy usage.

2. Leach Protocol

In LEACH, nodes organize themselves into clusters and all non-cluster head nodes transmit to the cluster-head. The cluster head performs data aggregation and transmits the data to the remote base station. Therefore, being a cluster-head node is much more energy intensive than being a non-cluster head node.

During the setup phase in LEACH [2] the cluster heads are selected based on the suggested percentage of them for the network and the number of times the node has been a cluster-head so far. This decision is made by each node *n* choosing a random number between 0 and 1. If the number is less than a threshold *T*(*n*), the node becomes a cluster-head for the current round. The threshold is set as follows:

$$T(n) = \begin{cases} \dfrac{P}{1 - P(r \bmod \frac{1}{P})} & \text{if } \quad n \in G \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where *P* is the desired cluster-head probability, *r* is the number of the current round and *G* is the set of nodes that have not been cluster-heads in the last 1/*P* rounds.

Once the nodes have elected themselves to be cluster heads they broadcast an advertisement message (ADV). Each non cluster-head node decides its cluster for this round by choosing the cluster head that requires minimum communication energy, based on the received signal strength of the advertisement from each cluster head. After each node decides to which cluster it belongs, it informs the cluster head by transmitting a join request message (Join-REQ) back to the cluster head. The cluster head node sets up a TDMA schedule and transmits this schedule to all the nodes in its cluster, completing the setup phase, which is then followed by a steady-state operation. This steady state operation is broken into frames, where nodes send their data to the cluster head at most once per frame during their allocated slot.

3. Motivation for Spatio-Temporal Adaptation

In LEACH, a node becomes a cluster-head by a stochastic mechanism of tossing biased coins. This stochastic approach doesn't consider hotness of a region while selecting cluster-heads. Hence non cluster-head nodes belonging to the hot regions, which are expected to transmit frequently, dissipate more energy in transmitting data to a remote cluster-head located far. This leads to uneven energy dissipation over the network thereby reducing the network lifetime. Secondly, LEACH assumes that every time a node becomes a cluster-head, it dissipates an equal amount of energy. This is incorrect, as cluster-heads located far from the base station spend more energy in transmitting data those located near the base station.

4. DEEAC Protocol Architecture

LEACH's stochastic cluster-head selection is prone to producing unbalanced energy level reserves in nodes and thus increase the total energy dissipated in network. To ensure an even energy load distribution over the whole network, additional parameters including the residual energy level of candidates relative to the network and their hotness value should be considered to optimize the process of cluster-head selection. The main principle in our algorithm is to choose nodes with high residual energy and greater hotness values as cluster heads. This can be achieved by making some beneficial adjustments to the threshold T(n) proposed in LEACH. Modified T(n) is denoted in Eq. (2). Using this equation each node decides whether or not to be a cluster-head for the current round, where *K* is the optimal number of cluster-head nodes per round, E_{res} is the residual energy of the node and E_{est_net} is the estimate of the residual energy of the network. *Hotness_factor* is the relative hotness of the node with respect to the network.

$$T(n) = \left\{ k \times \frac{E_{res}}{E_{est\_net}} \times Hotness\_factor \right. \quad (2)$$

4.1. Distributive Energy Model

The *T(n)* in Eq. (2) requires an estimate of the residual energy of the network at each node. LEACH-C [1] achieves this estimate by making each node send its current energy to the base station during the setup phase.

However this approach is energy inefficient as it involves transmissions from every node to base station. DEEAC uses a novel distributed approach to estimate the residual energy of the network. During the setup phase, each node sends its residual energy to the cluster-head along with the Join-REQ. Thus at the end of the setup phase each cluster-head has the aggregate energy of its cluster. During the steady phase when the cluster-head transmits to the base station, it also transmits the average residual energy of the cluster along with the aggregated data. The base station aggregates the residual energy values received from different cluster heads to estimate the residual energy (E_{est_net}) of the whole network. The base station periodically broadcasts the E_{est_net} value updating the nodes in the network.

DEEAC's distributive approach is more energy efficient than the centralized approach used in LEACH-C as non cluster-head nodes transmit their residual energy value over much smaller distances. Also the distributive approach doesn't necessitate separate transmissions for sending the residual values from the non cluster-head nodes to the cluster-heads or from the cluster-heads to the BS.

4.2. Adaptive Hotness Model

A cluster-head assigns a TDMA schedule to the non cluster-head nodes in its cluster. Nodes sense a physical phenomenon and report to the cluster-head during their allocated TDMA slot. LEACH assumes that sensors *always* transmit data to the cluster head during their allocated TDMA slot. However this assumption might not hold for the phenomenon being observed. The phenomenon under observation might have different data generation rates over different periods of time. The data generation rate may also vary across different regions at the same time instant. DEEAC uses a novel *hotness* approach to adapt to the temporal variations in data generation rate.

The *Hotness_factor* for a node is its relative data generation rate to that of the network. We define the ratio R as follows:

$$R = \frac{N_{used}}{N_{alloc}} \quad (3)$$

where N_{used} is number of TDMA slots used for transmission and N_{alloc} is the number of TDMA slots allocated over a time period T_o. We define $H_{last\_5\_avg}$ as the aggregate of the last 5 vales of ratio R and H_{avg_node} as the aggregate of all the values of R calculated. Each node in the network calculates the ratio R, $H_{last\_5\_avg}$ and H_{avg_node}. The cluster-head calculates ratio R for each node in its cluster and aggregates it to R'. During the steady phase when the cluster-head transmits to the base station, it also transmits R' along with the aggregated data. The base station aggregates the R' values received from different cluster heads to estimate the hotness value ($H_{avg\_network}$) of the whole network. The base station periodically broadcasts the $H_{avg\_network}$ value updating the nodes in the network.

Hotness_factor defined in Eq. (4) has been designed to adapt to both dynamic changes ($H_{last\_5\_avg} >> H_{avg\_node}$) and passive ($H_{avg\_node} >> H_{avg\_network}$) changes in the data delivery rate of the network. Hence DEAAC is able to adapt to the

$$Hotness\_factor = \left(\frac{H_{avg\_node}}{H_{avg\_network}} + \frac{H_{last\_5\_avg}}{H_{avg\_node}} \right) \div 2 \quad (4)$$

temporal variations in data. Also according to Eq. (2), a node having high value to *Hotness_factor* has a better chance of becoming a cluster-head. A hot node belongs to a hot region. Thus nodes from hot regions are better placed to become cluster-heads. This enables DEEAC to adapt to the variations in data generation rate over different regions at the same instant.

5. Analysis and Simulation of DEEAC

We used network simulator ns-2 for evaluating DEEAC and compare it to LEACH. For our experiments, we used a 100-node network where nodes are randomly distributed between (*x=0, y=0*) and (*x=100, y=100*) with a single BS at location (*x=50, y=175*). The bandwidth for the channel was set to 1Mb/s, each message 500 bytes long, and the packet header for each type was 25 bytes long.

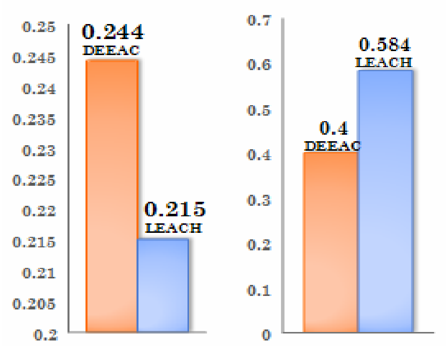
We use the same radio model as discussed in [1]. In this model, a radio dissipates E_{elec} = 50 nJ/bit in the transmitter or receiver circuitry and ε_{amp} = 100 pJ/bit/m^2 for the transmitter amplifier to achieve an acceptable E_b/N_o. The radios have power control and can expend the minimum required energy to reach the intended recipients. The radios can be turned off to avoid receiving unintended transmissions. An r^2 energy loss is used due to channel transmission. Thus, to transmit a l-bit message a distance D, the radio expends:

$$E_{tx}(l, D) = lE_{elec} + l\varepsilon_{amp}D^c \quad (5)$$

where c is path loss exponent (usually $2 \leq c \leq 4$). To receive this message, the radio expands:

$$E_{rx}(l, D) = lE_{elec} \quad (6)$$

We use k, the optimal number of cluster heads per round, equal to 5 as in LEACH. LEACH [1] derives the value of k by minimizing the total energy consumption for cluster-head and non cluster-head nodes. Since we use the same energy model, using the same value of k is justified.



(a) (b)

Fig. 1(a) Fraction of cluster heads from hot regions. Fig. 1(b) Fraction of Energy dissipated by the nodes belonging to hot regions

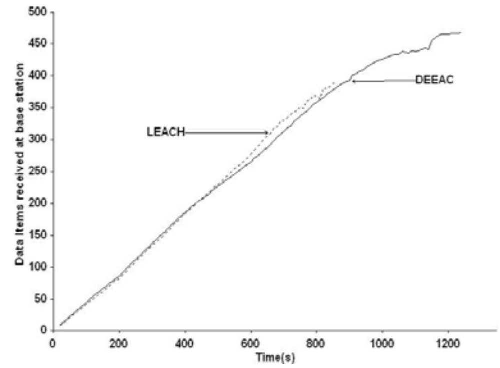


Fig. 2 Total amount of Data received at BS over time

5.1 Simulation Model

In order to emulate spatio-temporal variations in data reporting rates over the network, we stochastically generate synthetic data-sets. At the start of experiment the network is divided into smaller *hot* regions. The area and location of these *hot* regions is decided randomly and the number of such regions varies randomly from 1 to 4. This process is repeated after every 200 seconds. Nodes belonging to a *hot* region report data with a higher probability i.e. ($P_o + \Delta P$) while other nodes report data with a probability P_o. The values for P_o and ΔP are chosen as 0.3 and 0.4 respectively.

The above model is able to achieve temporal variations in data rate over the same region and also spatial variation in data reporting rate across the network at the same time instant. The results reported in the next section are an aggregate of 100 simulations.

5.2 Results and Discussion

Results are derived from limited energy simulations where each node begins with 2J of energy. Fig. 1(a) shows a 14% increase in the fraction of cluster heads selected from hot regions and Fig. 1(b) shows 32% decrease in the fraction of energy dissipated by the nodes of a hot region. According to Fig. 2 the amount data transmitted over time remains the almost the same in LEACH and DEEAC. While in LEACH the cluster heads are chosen randomly, DEEAC has cluster heads from *hot* regions. This reduces the energy loss due to transmission for the nodes expected to transmit frequently, thereby delivering the same amount of data with less energy dissipation as shown by Fig 3. Fig. 5 verifies that DEEAC is more energy efficient than LEACH. Fig. 4 shows the number of nodes alive over time. DEEAC outperforms LEACH with this regard, extending the lifetime of the network by 50%.

Although the first node dies earlier in DEEAC, both have almost the same death rate up to 80% nodes alive, after which LEACH has an abrupt fall. LEACH selects cluster-heads assuming that each time a node becomes a cluster-head it dissipates the same amount of energy. This leads to inefficient selection of heads towards the end of simulation thereby depleting the network fast. DEEAC selects cluster-heads based on the residual energy of a node with respect to the residual energy of the network, thereby prolonging the network lifetime.

Although DEEAC appears to be a promising protocol there is an area of improvement. In the current implementation of DEEAC, the nodes transmit data only during their allocated TDMA slot. Since all the nodes do not transmit all the time, the intra-cluster communication scheme needs to be changed to efficiently utilize bandwidth.

6. Conclusions

In this paper, we describe a modification of the LEACH's stochastic cluster-head selection algorithm by considering two additional parameters, the residual energy of a node relative to the residual energy of the network and the spatio-temporal variations in the data reporting rates of a node relative to the network. Since DEEAC evenly distributes energy-usage among the nodes in the network by efficiently adapting to the variations in the network, our optimal cluster-head selection saves a large amount of communication energy of sensor nodes. This increases the lifetime of the system. Simulation results on synthetic data show that DEEAC is able to prolong the network lifetime by 50% as compared to that of LEACH, while delivering more data for the same amount of energy consumption.

7. References

[1]. W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "An Application-Specific Protocol Architecture for Wireless

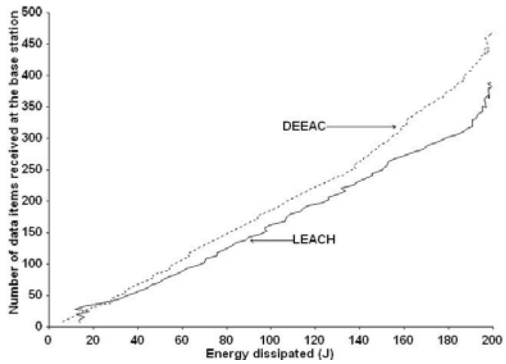


Fig. 3 Total amount of data received at BS per given amount of energy

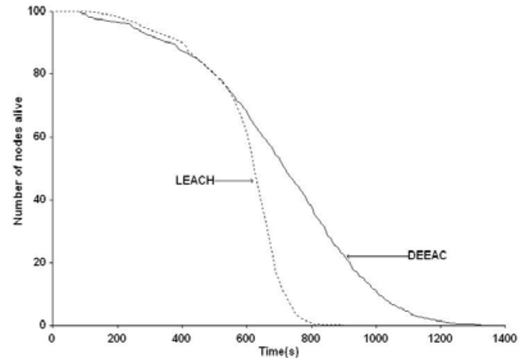


Fig. 4 Number of Nodes alive over time

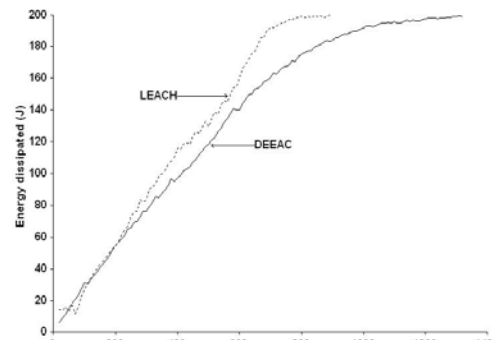


Fig. 5 Total Amount of Energy dissipated Vs Time

Microsensor Networks," IEEE Transactions on Wireless Communications, vol. 1, no. 4, pp. 660–670, October 2002.

[2] Wendi Heinzelman, Anantha Chandrakasan, and Hari Balakrishnan. Energy- Efficient Communicat ion Protocol for Wireless Microsensor Networks. Proceedings of the Hawaii International Conference on System Sciences, January 4-7, 2000 © 2000 IEEE.

[3] M. J. Handy, M. Haase, and D. Timmermann, "Low energy adaptive clustering hierarchy with deterministic cluster-head selection," in Proc. 4th IEEE International Workshop on Mobile and Wireless Communications Network (MWCN '02), pp. 368-372, Stockholm, Sweden, September 2002.

[4] I. Saha Misra, S. Dolui and A. Das, "Enhanced-Efficient Adaptive Clustering Protocol for distributed sensor networks", ICON 2005

[5] A. Manjeshwar and D. P. Agrawal, "An Efficient Sensor Network Routing Protocol (APTEEN) with Comprehensive Information Retrieval," Proc. Second Int'l Workshop Parallel and Distributed Computing Issues in Wireless Networks and Mobile Computing, Apr. 2002.

[6] Ossama Younis, Sonia Fahmy, "HEED: A Hybrid, Energy-Efficient, Distributed Clustering Approach for Ad Hoc Sensor Networks," *IEEE Transactions on Mobile Computing*, vol. 03, no. 4, pp. 366-379, Oct., 2004.

[7] Yongcai Wang, Qianchuan Zhao and Dazhong Zheng, "Energy-Driven Adaptive Clustering Data Collection Protocol in Wireless Sensor Networks", Proceedings of the 2004 International Conference on Intelligent Mechatronics and Automation , Chengdu, China August 2004

[8] Loscri' V. , Marano S. , Morabito G. , " A Two-Levels Hierarchy for Low-Energy Adaptative Clustering Hierarchy (TL-LEACH).". Proceedings "VTC2005", Dallas (USA), pp. 1809-1813, Sept, 2005

[9] Junpei Kamimura and Naoki Wakamiya and Masayuki Murata, "Energy-efficient clustering method for data gathering in sensor networks," in Proceedings of First Workshop ON Broad-band Advanced Sensor Networks and October 2004

[10] Zengwei Zheng, Zhaohui Wu, and Huaizhong Lin. An Event-Driven Clustering Routing Algorithm for Wireless Sensor Networks. Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems. Sendai, Japan, Sep. 28 - Oct. 2, 2004.

[11] M. C. Vuran, O. B. Akan, I. F. Akyildiz, "Spatio-Temporal Correlation: Theory and Applications in Wireless Sensor Networks," *Computer Networks Journal (Elsevier)*, vol. 45, no 3, pp. 245 -259, June 2004

[12] SunHee Yoon and Cyrus Shahabi, "Exploiting Spatial Correlation Towards an Energy Efficient Clustered AGgregation Technique (CAG)", IEEE International Conference on Communications (ICC), 16-20 May 2005, Seoul, Korea

[13] Shamim Begum, Shaocheng Wang, Bhaskar Krishnamachari, Ahmed Helmy, "ELECTION: Energy-efficient and Low-latEncy sCheduling Technique for wIreless sensOr Networks," *The 29th Annual IEEE Conference on Local Computer Networks (LCN)*, Tampa, FL, November 2004.