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Balancing Energy Loads in Wireless Sensor Networks through Uniformly Quantized Energy Levels-Based Clustering

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***Abstract*—Clustering is considered a common and an effective method to prolong the lifetime of a wireless sensor network. This paper provides a new insight into the cluster formation process based on uniformly quantizing the residual energy of the sensor nodes. The unified simulation framework provided herein, not only aids to reveal an optimum number of clusters but also the required number of quantization levels to maximize the network's lifetime by improving energy load balancing for both homogeneous and heterogeneous sensor networks. The provided simulation results clearly show that the uniformly quantized energy level-based clustering provides improved load balancing and hence, a longer network lifetime than existing methods.**

***Keywords*-Clustering, energy load balancing, network lifetime, uniform quantization, wireless sensor network.**

I. Introduction

Wireless sensor networks (WSNs) are mainly composed of devices with moderate processing, storage capabilities and scarce energy resources. These constrained resources formulate a complex and challenging task in terms of data collection and communication among sensor nodes. Since, sensor nodes are usually battery operated, this makes the lifetime analysis in such a network of vital importance as it needs to be maximized. Efficient clustering is considered a viable solution to extend the lifetime of a sensor network as it limits the energy depletion problem by largely curtailing the transmission distance among nodes, which is often the main energy starving process.

The Low-Energy Adaptive Clustering Hierarchy (LEACH) [1], [2] protocol introduces a simple but elegant distributed algorithm for choosing cluster heads by assigning a probabilistic indicator function to each node for a homogeneous network. The work in [2] also provides a derivation for an approximate expression to determine the optimum number of clusters in a given network. Stable Election Protocol (SEP) [3] extends the idea of LEACH to a heterogenous network where high and low energy nodes are assigned different probabilistic indicator functions with the aim to elect high energy nodes more frequently as cluster heads. In [2], a simulated annealing based centralized algorithm LEACH-C is described to improve the lifetime of a network by ensuring that the network has a certain number of clusters, as the standard LEACH algorithm does not guarantee to have the same number of cluster heads in each round due to its probabilistic nature. The Hybrid Energy-Efficient Distributed (HEED) [4] algorithm considers quasi-stationary sensor network and chooses cluster heads based on a probabilistically scaled residual energy model. In [5], a multi-hop routing protocol employing equal area grids to form clusters to extend the network lifetime is proposed with improved results. Similarly, authors in [6] have proposed an energy-balancing unequal clustering protocol by forming smaller sized clusters near the sink as compared to the ones that are farther away from the sink to increase the network lifetime with effective results. Recently, authors in [7] have stressed again on the importance of number of clusters to improve the lifespan of a WSN by considering the cases when the base station (BS) is located inside and outside the sensing field. Although, all of the above mentioned algorithms have their pros and cons they generally do not highlight explicitly how to handle energy load balancing problem in WSNs so that the lifetime of the network is extended and also the gap between the death of the first and the last node is minimized.

This paper focuses on the formation of optimum number of fixed clusters in a randomly deployed WSN consisting of stationary nodes for either a homogeneous case (i.e., a network with all nodes having identical initial energy) or a heterogeneous case (i.e., a network with nodes having different initial energy) in order to maximize the network lifetime. The novelty of this work is that it introduces a new centralized cluster formation scheme which uses a few number of bits to represent the residual energy by employing uniformly quantized energy levels clustering (UQEC) to share their residual energy information as part of their transmitted packets. This sharing of quantized energy information enables us to apply a near optimum energy load balancing scheme with extended system lifetime.

The remaining sections of this paper are organized in the following order: Section II provides details about the

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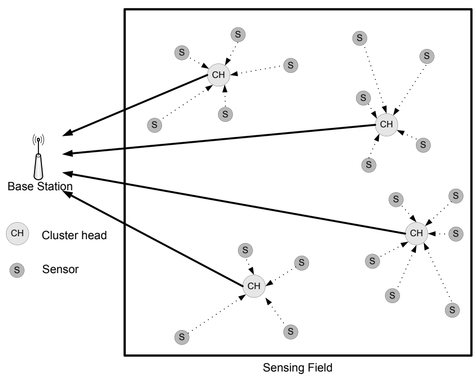

Figure 1. Wireless sensor network model.

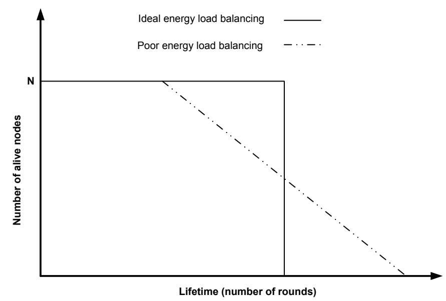

Figure 2. Heuristic lifetime curves.

used network model. Section III defines the lifetime of the WSN and provide two different heuristic lifetime curves to highlight the problem at hand. Section IV provides a brief summary about the working logic of LEACH and its variants. In Section V, the proposed uniformly quantized energy levels based algorithm is explained in detail. Section VI focuses on the performance analysis and depicts lifetime curves for both homogenous and heterogenous sensor networks. Finally, Section VII concludes the paper by summarizing the findings of the work.

II. Network Model

The sensor network model used in this paper is illustrated graphically in Fig. 1. We consider a randomly deployed WSN consisting of two distinct roles of nodes: cluster heads and regular sensor nodes. Each node is aware of its position and is equipped with a limited initial energy supply and has moderate processing power and data transmission capabilities. There exist a fixed number of clusters in the network for each round and only one cluster head in each cluster. A sensor can only transmit its data to an associated cluster head which forwards the aggregated data to the BS. In the case of having fewer than required cluster heads in the network, the remaining nodes will directly transmit the data to the BS. The association between the sensors and their corresponding cluster heads is determined by using the shortest Euclidean distance approach.

III. Heuristic Lifetime Curves

In a WSN, the lifetime of the network can be defined as either the amount of time elapsed until the first node completely depletes its energy or the last node in the network dies. In our work, we assume that once a node dies, the network will become unstable and will not provide the necessary coverage. The behavior of the lifetime curve of a WSN is mainly determined by how evenly the load is balanced in terms of used energy among nodes. It is obvious that cluster heads spend more energy than the regular sensor nodes as they not only spend energy in the sensing process but also in collecting data from the associated nodes and forwarding it to the BS. Therefore, it is important that cluster heads must be rotated in a wisely fashion so that some node's energy is not overly utilized than others.

Fig. 2 heuristically shows two different lifetime performance curves with different energy load balancing characteristics. In an ideal energy load balancing case, the workload is evenly distributed such that the energy dissipated by each node is balanced and the entire network dies at the same time. Although, it is an ideal model and is difficult to achieve in practical scenarios but it will serve as a good reference point to judge the performance of the proposed and existing models. The poor energy load balancing case shows that some nodes are overly utilized as compared to others and thus, the time elapsed between the exhaustion of the first and the last node is moderately high, i.e., a curve with a longer tail.

IV. LEACH and Variants

LEACH [1], [2] is a well-know TDMA cluster-based protocol (or data dissemination technique) for WSN applications. The intention of this protocol is to simply transmit its gathered data through sensor nodes to the sink node. In LEACH, all nodes are assumed to be identical. However, for a period of time, a set of nodes may be elected as cluster head while others remain as ordinary nodes. LEACH follows a probabilistic approach for cluster head election by devising a mechanism that the cluster head role is rotated randomly among all the nodes in the network. This random rotation enables sensor nodes consume energy in a balanced fashion which in turn prolongs the lifetime of the WSN application. The operation of LEACH is organized in rounds. Each round consists of two phases, namely, the setup phase and the transmission phase.

A. Setup phase

Within the setup phase, the nodes organize themselves into clusters with one node playing the cluster head role in each cluster. The cluster head decision is made locally and randomly within each node. However, the authors gave the average value of the nodes to serve as local cluster heads in each round.

B. Transmission phase

During the transmission phase, the cluster heads collect data from its cluster members and apply data aggregation before forwarding it directly to the sink. Effective data aggregation techniques can be utilized at the cluster heads to fuse the correlated data signals from the cluster members into one smaller frame and thus save additional energy. Upon transmitting the aggregated data to the sink, the transmission phase and similarly, the round are said to be completed. At the end of each round, a new set of nodes become cluster heads for the subsequent round. Furthermore, the duration or repetition of the transmission phase is set much larger than that of the setup phase in order to compensate the overhead due to cluster formation phase. Thus, LEACH could provide an effective model where localized algorithms and data aggregation can be performed within randomly self-elected cluster heads, which help reduce information overload and provide a reliable set of data to the end user. The lifetime of a WSN application is highly dependent on the number of nodes and number of clusters. However, the probabilistic nature of LEACH leads to having more or less clusters than the optimum value. In other words, LEACH cannot assure to provide the optimum number of clusters in each round.

C. SEP

SEP [3], which is a variant of LEACH, extends the idea to heterogenous networks where high and low energy nodes are assigned different probabilistic indicator functions with the aim to elect high energy nodes more frequently as cluster heads so that better energy load balancing can be achieved in order to prolong the network lifetime.

D. LEACH-C

As its name implies, LEACH-C uses a centralized algorithm during the setup phase. Unlike LEACH, in LEACH-C, the sink receives information regarding the location and energy level of each sensor node in the WSN. Upon receiving this information, the sink computes the number of required clusters and the members of each cluster by making use of simulated annealing based algorithm [8] to achieve a near-optimal number of clusters. Sink decides on the clusters to minimize the energy required for sensor nodes to transmit their data to their associated cluster heads. Before running the algorithm that determines and selects the clusters, the sink makes sure that only those nodes that have enough energy are participating in the cluster head selection process (i.e., set-up phase). The transmission phase of LEACH-C is the same as that of LEACH. LEACH-C is superior than LEACH in two key aspects:

1) The sink utilizes its entire topology of the WSN to produce better clusters that require less energy for data transmission.
2) The number of cluster heads in each round of LEACH-C equals a predetermined optimal value, whereas, for LEACH the number of cluster heads varies from round to round due to the lack of global coordination.

V. Uniformly Quantized Energy Levels Clustering

For UQEC, we propose a new cluster formation algorithm after the random deployment of sensor nodes over a sensing field using the following steps:

1) All nodes send their location and n bit quantized residual energy level information to the BS.
2) The BS elects k desired number of cluster heads among the nodes based on the largest energy as determined by nodes' quantized energy level (QEL) information and associates each sensor node to a cluster head by using the minimum Euclidean distance criteria. In the case of a tie i.e., multiple nodes having the same energy level, the candidate nodes that are closet to the previous cluster heads are chosen as new cluster heads.
3) The BS broadcasts the IDs and location of each cluster head along with the IDs of associated nodes in the network.
4) All nodes in the network start the sensing process.
5) Associated nodes send a packet containing sensed data and estimated QEL to their cluster head. After each transmission, all associated nodes update their QEL.
6) Upon receiving all sensed data from the associated nodes, the cluster head aggregates the data and send a packet containing the aggregated sensed data together with a list of candidate cluster heads and their estimated QEL to the BS. Then, all cluster heads update their QEL.
7) Go to Step 2.

In order to create quantization levels, the maximum initial energy node having an energy of E_{max} is used to partition the energy of each node into disjoint regions denoted by R_i, where, $1 \leq i \leq K$ and K is the required number of quantization levels. The E_{max} and the spacing between equal sized intervals Δ can be written as

$$E_{max} = K\Delta + E_{th}, \quad \Delta = a_{i+1} - a_i. \tag{1}$$

where, E_{th} is the minimum threshold energy required to transmit directly from the furthest node in the network to the BS. The partitioned regions can be expressed as $R_1 = [E_{th},\ a_1]$, $R_2 = (a_1,\ a_2]$,....., $R_K = (a_{K-1},\ E_{max}]$. Hence, the number of bits required to represent the discretized residual energy of each node becomes $n = \log(K)$.

VI. Simulation Parameters And Results

In our simulations, the channel model and the related parameters are chosen according to the ones used in [2]. It is assumed that 100 sensor nodes each having an initial energy of 0.5J are deployed over a sensing field with dimensions 100m×100m. The BS is located at the point (50,175). The energy consumption per bit for both transmission and reception is 50nJ, the energy consumed by data aggregation per bit is 5nJ, the amplified transmitting energy for free space and multipath models is $\epsilon_{fs} = 10\text{pJ}/\text{bit}/\text{m}^2$ and $\epsilon_{mp} = 1.3\ \text{fJ}/\text{bit}/\text{m}^4$ respectively. Moreover, a fixed packet size of 512 bytes is assumed for all sensed and aggregated data transmission in the simulations.

Fig. 3 exhibits lifetime curves for the homogeneous network for direct communication, LEACH, LEACH-C and UQEC schemes. It is evident from the plots that direct communication provides the worse performance as each node needs to dissipate energy heavily in the transmission process and the nodes located far from the BS are exhausted quickly. A large set of simulations were carried out for LEACH and only the prominent ones are shown in the plot. It is clear as the number of clusters determined by the probability p — one of the parameters in probabilistic indicator functions as described in [1] and [2] — is increased, the performance of the network degrades. Interestingly, the optimal value of clusters is found to be 3 which is converse to the theoretical result derived in [2] (an optimum value of 5). The discrepancy makes sense as the expression for optimum number of cluster was derived by using approximations but it is consistent with the derived result that the optimum number of clusters is indeed between 3 and 5. Intensive simulations for LEACH-C showed that under chosen parameters the optimal result was obtained by forming 3 clusters. Likewise, rigorous simulation studies were carried out for UQEC and we found that 64 quantization levels (i.e., $n = 6$ bits) having 3 to 6 clusters provide the optimum results with 5 and 6 clusters slightly superseding the performance than others. We also found that 32 quantization levels show similar behavior but perform slightly worse than the case of 64 quantization levels. Moreover, increasing the number of quantization levels beyond 64 do not provide further gains as the performance saturates at 64 quantization levels.

Similarly, Fig. 4 provides lifetime curves for heterogeneous case where 10% of the sensor nodes were equipped with twice as much initial energy (i.e., 1J) as regular sensor nodes. Again, direct communication gives the worse lifetime and only the time required for the whole network to die is prolonged due to the existence of some high energy nodes. An extensive set of simulations were also carried out for SEP (heterogeneous variant of LEACH) and LEACH-C and only the prominent ones are shown in the plot. It is clear that as the number of clusters are increased the performance of the network degrades. Once again the optimal value of clusters for prolonged lifetime is found to be 3 for both SEP and LEACH-C. Similarly, the simulation studies were carried out for the proposed system and we found that 64 quantization levels having 3 to 7 clusters provide optimum results with 5 and 6 clusters proving to be slightly better than others.

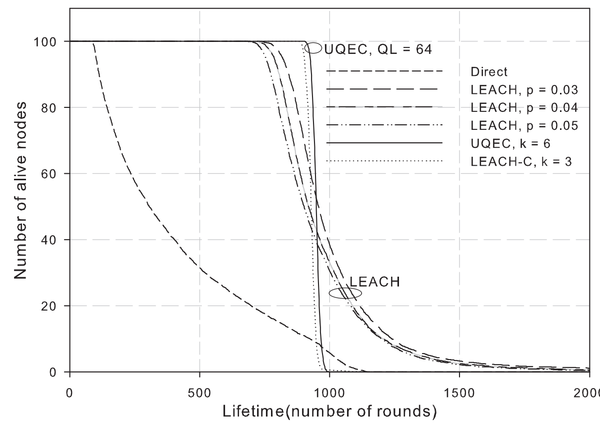

Figure 3. Lifetime curves for homogeneous WSN.

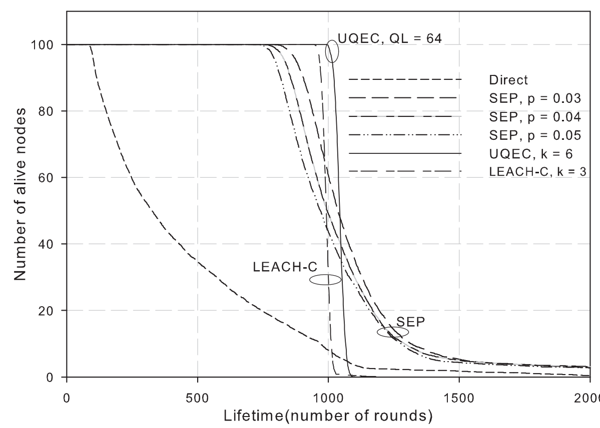

Figure 4. Lifetime curves for heterogeneous WSN with 10% nodes having higher energy.

The simulation results provided in Fig. 3 and Fig. 4 clearly show that the proposed clustering algorithm outperforms the best attained results for both LEACH, LEACH-C and SEP by approximately 22%, 5% and 30% respectively, with the minor penalty of transmitting a few number of additional bits to represent the quantization level in each packet. Additionally, UQEC exhibits behavior substantially close to the ideal heuristic energy load balancing case with a prolonged lifetime and a short time span between the death of first and last node in the network.

VII. Conclusion and Remarks

This paper introduces a new centralized clustering algorithm that is based on transmitting the uniformly quantized residual energy of the sensor nodes to the base station to form desired number of clusters that can perform improved energy load balancing. The proposed algorithm uses only a few number of bits to share the quantized residual energy with the base station to obtain clusters capable of performing improved energy load balancing in order to prolong the lifetime of the deployed sensor network. The proposed algorithm is capable of equally performing well in both homogeneous and heterogeneous networks without requiring any modifications. Simulation results are in accord with the heuristic lifetime curve and hence show improved performance.

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