Prolonging the Lifetime of Wireless Sensor Networks via Unequal Clustering

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Abstract—Organizing wireless sensor networks into clusters enables the efficient utilization of the limited energy resources of the deployed sensor nodes. However, the problem of unbalanced energy consumption exists, and it is tightly bound to the role and to the location of a particular node in the network. If the network is organized into heterogeneous clusters, where some more powerful nodes take on the cluster head role to control network operation, it is important to ensure that energy dissipation of these cluster head nodes is balanced. Oftentimes the network is organized into clusters of equal size, but such equal clustering results in an unequal load on the cluster head nodes. Instead, we propose an Unequal Clustering Size (UCS) model for network organization, which can lead to more uniform energy dissipation among the cluster head nodes, thus increasing network lifetime. Also, we expand this approach to homogeneous sensor networks and show that UCS can lead to more uniform energy dissipation in a homogeneous network as well.

I INTRODUCTION

One of the most restrictive factors on the lifetime of wireless sensor networks is the limited energy resources of the deployed sensor nodes. In order to achieve high energy efficiency and assure long network lifetime, sensor nodes can be organized hierarchically by grouping them into clusters, where data is collected and processed locally at the cluster head nodes before being sent to a base station. In many sensor network applications where data collection and processing can be done "in place", this hierarchical approach is a promising method for efficiently organizing the network. Also, many signal processing algorithms used for extraction of final information from the data gathered by the sensors are well-suited for local processing of data within the clusters.

Communication within a cluster as well as communication between different clusters can be organized as a combination of one-hop and multi-hop communication. In one-hop communication, every sensor node can directly reach the destination, while in multi-hop communication, nodes have limited transmission range and therefore are forced to route their data over several hops until the data reach the final destination. In both models, there is an unavoidable problem of unbalanced energy dissipation among different nodes, leading to the situation where some nodes lose energy at a higher rate and die much faster than others, possibly reducing sensing coverage and leading to network partitioning. For single-hop communication, the nodes furthest away from the base station are the most critical nodes, while in multi-hop communication, the nodes closest to the base station are burdened with a heavy relay traffic load and die first (i.e., the "hot spot" problem).

Clustered sensor networks can be broadly classified as heterogeneous and homogeneous with respect to the type and functionality of the nodes in the network. In homogeneous networks, all nodes have the same hardware and processing capabilities. The cluster head role is usually periodically rotated among the nodes to balance the load. Although rotating the cluster head role ensures that sensors consume energy more uniformly, the hot spot problem described above cannot be completely avoided. In heterogeneous networks, a certain number of nodes with much higher processing capabilities and complex hardware are deployed over the field together with numerous sensor nodes. As cluster head nodes, the more powerful nodes need to encompass several functions, serving as data collectors and processing centers for data gathered by sensor nodes. Because heterogeneous networks assume static cluster head assignment, the network lifetime is determined by the cluster heads' functioning time, which is directly related to cluster head activity and energy consumption. The cluster heads can form a backbone network and use multi-hop routing to route the data to the base station. This leads to "hot spots" in the network, where cluster heads in the hot spot use their energy at a much higher rate and die much faster than the other cluster heads. Managing the load becomes necessary in order to prevent the problem of premature battery drainage for particular cluster head nodes.

The positions of cluster heads in a network affect the total energy consumption of all nodes. Cluster heads can be dispersed in the sensor field randomly, or they can be deployed in a deterministic fashion. In the latter case, for example, these nodes can have the ability to move, and therefore change their positions until they reach some locations determined a priori. Although a randomly deployed heterogeneous sensor network is more common and easier to deploy, it is much harder to control the actual sizes of clusters and to effectively balance the traffic among the cluster head nodes. Therefore, the hot spot problem can easily appear as a result of excessive energy consumption of particular cluster head nodes.

We are interested in exploring a deterministic approach, where the cluster head nodes have the ability to move and to adjust their locations, managing at the same time the size of their clusters and the expected load from other clusters further away. We are dealing with the problem of unbalanced energy consumption, particularly among the cluster head nodes, assuming that this type of node is much more expensive than the simple sensor nodes, and that the loss of one cluster head node means the loss of data from an entire part of the network. As one way to overcome this problem, we develop a network clustering scheme where the clusters' sizes (and therefore the number of nodes in every cluster, assuming a uniform deployment of nodes), are determined in a way such that more balanced energy consumption among the cluster head nodes is achieved. We show that for both homogeneous and heterogeneous networks, our approach can prolong network lifetime.

II RELATED WORK

During the last few years, many clustering algorithms have been proposed as an efficient way to organize communication and data processing in a sensor network. The problem of hierarchical (clustering) network organization consists of several aspects that depend on the structure of the sensor network and the particular application's demands. We mention some of the most relevant papers related to clustering.

In [1] the authors propose a distributed clustering algorithm where communication between the nodes is organized in a multi-hop manner. Every node has a probability p of becoming a cluster head. Clusters form Voronoi tessellations of the sensor field. Using the results of stochastic geometry, the authors formulate a network energy dissipation function and find the probability of becoming a cluster head that minimizes energy dissipation. They further extend this work, generating a multi-level hierarchical network, and they show that the energy savings increase with the number of levels.

The authors in [2] propose LEACH, a distributed, single-hop clustering algorithm for a sensor network. The cluster head role is periodically rotated among the sensor nodes to balance energy dissipation. It is assumed that all nodes have the necessary processing capabilities and that they all have the ability to coordinate intra-cluster transmissions, support different MAC protocols, and perform long distance transmissions to the base station. The authors analytically determine the optimum number of cluster heads by taking into account the energy spent by all clusters.

Mhatre et al. [3] present a comparative study of homogeneous and heterogeneous networks in terms of overall cost of the network, defined as the sum of the energy cost and the hardware cost. They analyze both single-hop and multi-hop networks. They use LEACH [2] as a representative of a homogeneous, single-hop network, and they compare LEACH with a heterogeneous single-hop network. The authors conclude that using single-hop communication between sensor nodes and the cluster head may not be the best choice when the propagation loss index k for intra-cluster communication is large (k>2). They propose a multi-hop version of the LEACH protocol (M-LEACH) and show the cases in which M-LEACH outperforms the single-hop version of the protocol.

The authors in [4] analyze the problem of prolonging the lifetime of a network by determining the optimal cluster size. For a general clustering model, they find the optimal sizes of the cells by which maximum lifetime or minimum energy consumption can be achieved. Based on this result, they propose a location aware hybrid transmission scheme that can further prolong network lifetime.

Although much of the literature on organizing the network into clusters deals with the problem of unbalanced load in sensor networks, to the best of our knowledge, this is the first time that this problem is treated by utilizing clusters of unequal sizes.

III PROBLEM FORMULATION

We consider a sensor network of N nodes randomly deployed over a circular area of radius R_a. In addition to simple sensor nodes that collect data, a smaller number of more powerful nodes are deployed to serve as cluster head nodes with pre-determined locations. The base station is located in the center of the observed area, and it collects data from the network. The data from all sensors in the cluster are collected at the cluster head, which aggregates the data and forwards the aggregated data toward the base station. The forwarding of aggregated packets is done through multiple hops, where every cluster head chooses to forward its data to the closest cluster head in the direction of the base station.

Depending on how often cluster heads need to forward incoming packets from other clusters, there is a significant difference in energy dissipation among the cluster head nodes. In this case, cluster heads closer to the base station are more active, serving as relay stations for packets coming from upper parts of the network, which creates unbalanced energy consumption among the cluster head nodes.

As one possible solution to this problem, we analyze an approach where the network is organized into clusters of different sizes. In general, every cluster head spends its energy on inter-cluster and intra-cluster communication. The energy consumed on intra-cluster communication changes proportionally with the number of nodes within a cluster, while the energy spent on inter-cluster communication (i.e., forwarding data from other clusters) is a function of the expected load from the clusters further away. Therefore, by changing the number of nodes in every cluster with respect to the expected relay load, we can maintain more uniform energy consumption among the cluster heads, so that the total energy dissipated for every cluster head is similar.

IV NETWORK MODEL

As stated previously, the positions of the cluster head nodes are determined a priori, with all cluster head nodes arranged symmetrically in concentric circles around the base station. Every cluster is composed of nodes in the Voronoi region around the cluster head. This represents a layered network, as shown in Figure 1 for a two layer network, where every layer contains a particular number of clusters. We assume that the inner layer has m_1 clusters and the outer layer has m_2 clusters. Furthermore, in order to simplify the theoretical analysis of this model, we approximate the Voronoi regions as pie shaped regions (Figure 2). Due to the symmetrically circular organization of cluster head nodes, all clusters in one layer have the same size and shape, but the sizes and shapes of clusters in the two layers are different. We introduce the parameter R_1, which is the radius of the first layer around the base station. By varying the radius R_1, while assuming a constant number of clusters in every layer, the area covered by clusters in each layer can be changed, and therefore the number of nodes contained in a particular cluster is changed.

Many authors in the literature assume that cluster heads have the ability to perfectly aggregate multiple incoming packets into one outgoing packet. Although this scenario is highly desirable, it is limited to cases when the data are all highly correlated. When this is not the case, or in cases when higher reliability of collected data is desired, the base station can simply demand more than one packet from every cluster head. In such a case, every cluster head will send more than one packet of aggregated data in each round. Therefore, we consider two cases of data aggregation: *perfect aggregation*, when every cluster head compresses all the data received from its cluster into one outgoing packet, and *nonperfect aggregation*, when every cluster head sends more than one packet toward the base station. We do not deal with the particular data aggregation algorithm, but only with the amount of data generated in the aggregation process. We assume that all cluster heads can equally successfully compress the data, where this efficiency is expressed by the aggregation coefficient α.

Time is divided into communication rounds, where one round comprises the time for inter-cluster and intra-cluster communication. The final amount of data forwarded from every cluster head to the base station in one round is $\alpha * N_c$, where N_c is the number of nodes in the cluster and α is in the range $[1/N_c, 1]$. Thus $\alpha = 1/N_c$ represents the case of perfect aggregation, while $\alpha = 1$ represents the case when the cluster head does not perform any aggregation of the packets. The model for energy dissipation is taken from [2], where, for our multi-hop forwarding scheme we assume a free space propagation channel model. The energy spent for transmission of a *p*-bit packet over distance *d* is:

$$e_t = p(e_1 + e_2 \cdot d^2) \tag{1}$$

and the energy spent on receiving a *p*-bit packet is:

$$e_r = pe_1 \tag{2}$$

Here, e_1 and e_2 are parameters of the transmission/reception circuitry, given as $e_1 = 50nJ/bit$ and $e_2 = 10pJ/bit/m^2$. Also, we assume that energy for data aggregation is $e_3 = 5nJ/bit/signal$. We assume that the medium is contention free and error free and we do not consider the control mess ages exchanged between the nodes, assuming that they are very short and do not introduce large overhead.

The position of a cluster head within the cluster boundaries determines the overall energy consumption of nodes that belong to the cluster. To keep the total energy dissipation within the cluster as small as possible, every cluster head should be positioned at the centroid of the cluster. In this case, the distances of cluster heads in layer 1 and layer 2 to the base station are given as:

$$d_{ch1} = \frac{\int_0^{R_1} r 2r \sin(\beta_1) dr}{R_1{}^2 \beta_1} = \frac{2}{3} R_1 \frac{\sin(\beta_1)}{\beta_1} \tag{3}$$

$$d_{ch2} = \frac{\int_{R_1}^{R_a} r 2r \sin(\beta_2) dr}{(R_a^2 - R_1{}^2)\beta_2} = \frac{2}{3} \frac{(R_a{}^3 - R_1^3)}{(R_a{}^2 - R_1^2)} \frac{\sin(\beta_2)}{\beta_2} \tag{4}$$

where β_1 and β_2 are the angles determined by the number of clusters each layer contains, as $\beta_i = 2\pi / m_i$, $i \in \{1,2\}$.

In this scenario the network has been divided into clusters during an initial set-up phase, and these clusters remain unchanged during the network lifetime. It is desirable that all cluster heads last as long as possible and die at approximately the same time to avoid network partitioning and loss of sensing coverage. Therefore, we define *network lifetime* as the time when the first cluster head exhausts its energy supply.

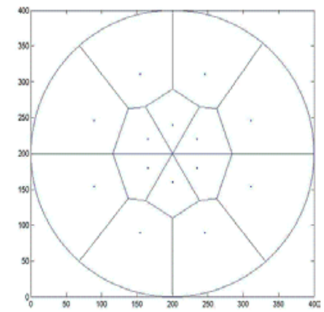


Fig. 1) The Voronoi tessellation of a network where cluster heads are arranged circularly around the base station.

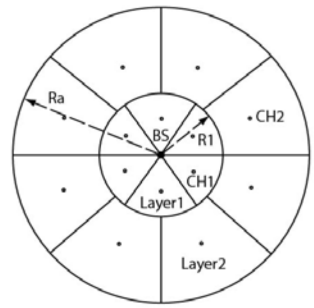


Fig. 2) Pie shaped clusters arranged in two layers around the base station. Note that this model, used for analytic simplicity, approximates the Voronoi tessellation of the network.

The energy consumed by cluster head nodes in layer 1 and layer 2 in one round is described by the following equations:

$$E_{ch2} = pe_1(N_{cl2} - 1) + pe_3 N_{cl2} + \alpha p N_{cl2}(e_1 + e_2 d_{ch21}^2) \tag{5}$$

$$E_{ch1} = pe_1(N_{cl1} - 1) + pe_3 N_{cl1} + \alpha p N_{cl2} \frac{m_2}{m_1} e_1 + p \cdot \alpha (N_{cl2} \frac{m_2}{m_1} + N_{cl1})(e_1 + e_2 d_{ch1}^2) \tag{6}$$

where d_{ch21} is the distance from a cluster head in layer 2 to a cluster head in layer 1, d_{ch1} is the distance from a cluster head in layer 1 to the base station, N_{cl2} is the number of nodes for clusters in layer 2, and N_{cl1} is the number of nodes for clusters in layer 1, which is proportional to the area covered by the cluster:

$$N_{cl1} = N \frac{R_1^2}{R_a^2 m_1} \tag{7}$$

$$N_{cl2} = N \frac{R_a^2 - R_1^2}{R_a^2 m_2}. \tag{8}$$

The factor of m_2 / m_1 in equation (6) comes from the fact that all packets from the second layer are equally split on m_1 cluster heads in the first layer.

V THEORETICAL ANALYSIS

Here we present the evaluation of the energy consumption for two hierarchical (clustered) network models. The first model is one commonly used in the literature, where the network is divided into clusters of approximately the same size. We call this model Equal Clustering Size (ECS). For the second model, we use the two-layered network model described previously, where the cluster sizes in each layer are different. We want to find, based on the amount of energy every cluster head spends during one round of communication, how many nodes each cluster should contain so that the total amount of energy spent by all cluster head nodes is balanced. We call our approach *Unequal Clustering Size* (UCS).

The variable that directly determines the sizes of clusters in every layer is the radius of the first layer R_1, shown in Figure 2. For ECS, the radius of the first layer R_1 is obtained from the fact that the area covered by a cluster in layer 1 is approximately equal to the area of a cluster in layer 2.

$$\frac{R_1^2 \cdot \pi}{m_1} = \frac{\left(R_a^2 - R_1^2\right) \cdot \pi}{m_2} \tag{9}$$

From this, we can obtain the radius of the first layer, R_{eq}:

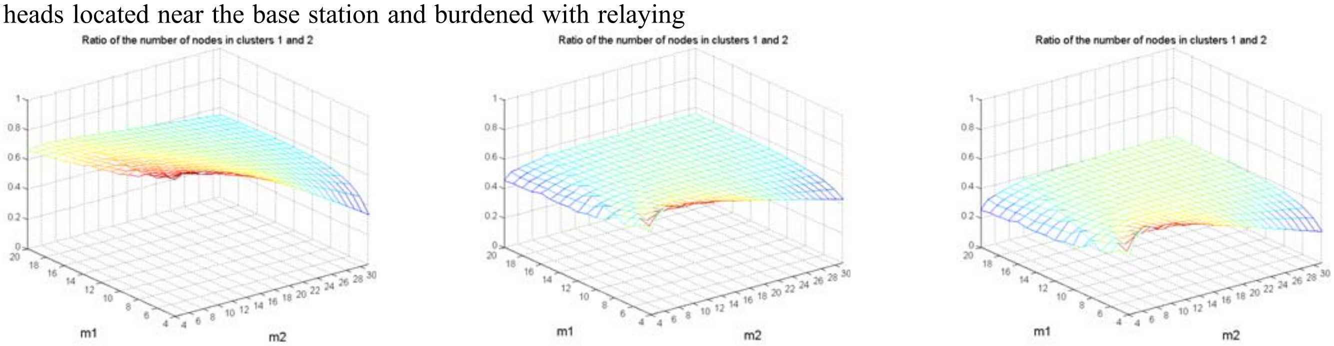
$$R_{eq} = R_a \sqrt{\frac{m_1}{m_1 + m_2}} \tag{10}$$

For UCS, the constraint of equal energy consumption for all cluster heads ($E_{ch1} = E_{ch2}$) has to be satisfied, so the value for R_1 is determined from equations (5) and (6) for different values of the parameters m_1, m_2 and aggregation coefficient α. For each value of R_1 we calculate the number of nodes that clusters in layer 1 and layer 2 should contain using equations (7) and (8). This result shows that clusters in layer 1 should contain fewer nodes than the clusters in layer 2. The ratio of the number of nodes for a cluster in layer 1 and a cluster in layer 2 for UCS is shown in Figure 3. This ratio varies with the number of clusters in each layer, as well as with the aggregation coefficient. The difference in cluster sizes increases as the network less efficiently aggregates the data. We note that this ratio is always less then one, which is the characteristic for ECS. This confirms our intuition, that cluster heads located near the base station and burdened with relaying traffic from the rest of the network, should support fewer cluster members.

When cluster heads compress data more efficiently, the difference between R_1 obtained for UCS with R_{eq} for ECS gets smaller. This leads to the conclusion that when the aggregation is close to "perfect aggregation," the cluster sizes for UCS should converge to the same size, as in ECS. However, even in the case when cluster heads send only one packet (i.e., perfect aggregation), we find that there should be a difference in cluster sizes in layer 1 and layer 2. Therefore, the amount of load that burdens every relaying cluster head strongly influences the actual number of nodes that should be supported in the cluster in order to energy-balance the network.

We compare the amount of energy spent by cluster head nodes in both models. Let the amount of energy that one cluster head in UCS spends in one round be E_{ch}. In ECS, the cluster heads in both layers do not spend the same amount of energy during one round. Let the energy spent in one round by a cluster head in layer 1 and layer 2 for ECS be E_{qch1} and E_{qch2}. Then, if the network is dimensioned to last at least T rounds, the cluster head nodes in ECS should be equipped with enough energy to satisfy $E_{qbch} = T \cdot \max\{E_{qch1}, E_{qch2}\}$ Joules, assuming that all cluster head nodes have the same characteristics. For UCS, cluster head nodes should have batteries with $E_{bch} = T \cdot E_{ch}$ Joules. We note that cluster head nodes in UCS need smaller capacity batteries than cluster head nodes in ECS.

The more balanced energy consumption among the cluster head nodes in UCS comes at a price of more unbalanced energy consumption for simple sensor nodes. In the simplest case, where the network consists of one-hop clusters, the nodes furthest from the cluster head will drain their energy much faster than those closer to the cluster head.

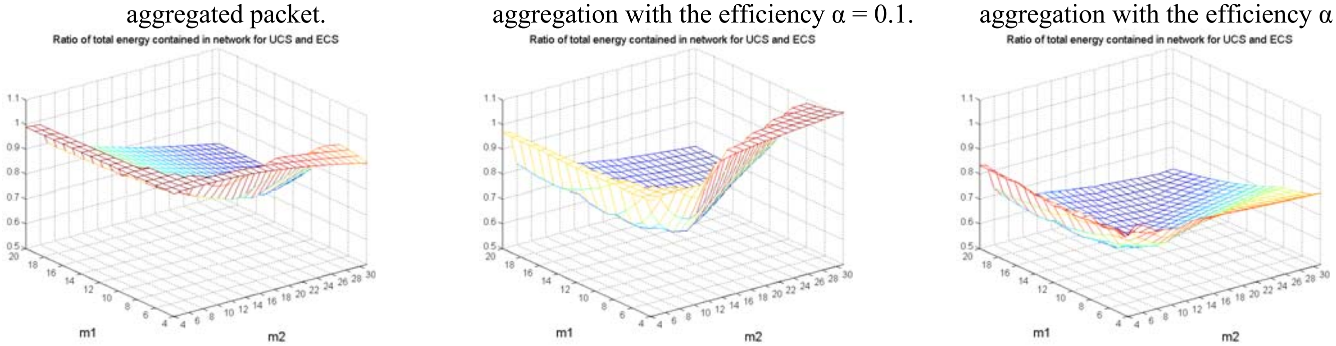


Ratio of the number of nodes in clusters of layer 1 and 2.

Fig. 3a) Every cluster head sends 1 aggregated packet.

Fig. 3b) The cluster heads perform aggregation with the efficiency α = 0.1.

Fig. 3c) The cluster heads perform aggregation with the efficiency α = 1.



Ratio of the total energy spent on batteries for the entire network for UCS and ECS.

Fig. 4a) Every cluster head sends 1 aggregated packet.

Fig. 4b) The cluster heads perform aggregation with efficiency α = 0.1.

Fig. 4c) The cluster heads perform aggregation with efficiency α = 1.

All deployed sensor nodes are of the same type, regardless of the layer to which they belong, and they are equipped with batteries of the same capacity. So, in order that all sensor nodes last during the network lifetime *T*, with the constraint of equal batteries for all sensors, the battery of sensor nodes has to be dimensioned as: $E_{bsn} = T \cdot E_{fn}$, where E_{fn} is the energy spent in one round by the node in the network that is furthest from its cluster head. Sensor nodes spend energy only to transmit their data to the cluster head, which is equal to: $E_{fni} = c_1 + c_2 \cdot d_{fni}^2$, $i \in \{1,2\}$ where d_{fni} is the distance of the furthest point to the cluster head in a cluster for both layers. In order to assure the lifetime *T* for all sensor nodes, every node has to be equipped with a battery of size $E_{bsn} = T \cdot \max\{E_{fn1}, E_{fn2}\}$. The batteries obtained in this way, for both UCS and ECS, are labeled as: E_{bsn} and E_{qbsn}.

We compare the overall energy required for batteries of all nodes in the network, for both UCS and ECS. The total energy needed to assure a lifetime *T* for all nodes is:

$$E_t = (m_1 + m_2) \cdot E_{bch} + (N - m_1 - m_2) \cdot E_{bsn} \quad (11)$$

$$E_{qt} = (m_1 + m_2) \cdot E_{qbch} + (N - m_1 - m_2) \cdot E_{qbsn} \quad (12)$$

for UCS and ECS, respectively. The ratio of E_t and E_{qt} for different aggregation efficiency parameters is shown in Figure 4. On average, the UCS network spends less energy than the ECS network. Again, when the network aggregates the data less efficiently, the difference in total energy for ECS and UCS is larger.

VI SIMULATIONS

To validate the analysis from the previous section, we simulate the performances of the proposed UCS for organization of sensor nodes in a network. The simulations were performed in Matlab and utilized a network with 400 nodes randomly deployed over a circular area of radius R_a = 200 m. We perform simulations for two cases: pie shaped clusters, for which the theoretical analysis was performed in the previous section, and the more realistic case of Voronoi clusters, where cluster heads are placed in two layers around the base station. The energy that every node spends to transmit a *p*-bit packet is:

$$e_t = \begin{cases} p \cdot \left(e_1 + e_2 \cdot d^2\right) & d \le d_o \\ p \cdot \left(e_1 + e_5 \cdot d^4\right) & d > d_o \end{cases} \quad (13)$$

where d_o is determined based on the given energy model as $d_o = \sqrt{e_2 / e_5}$, with $e_5 = 0.0013 pJ / bit / m^2$ (see [5]).

VI.A Heterogeneous Networks

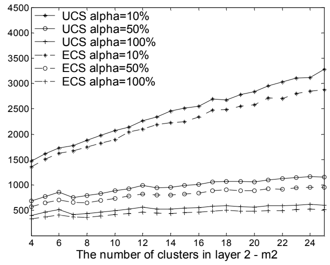
In the first set of simulations we simulate UCS and ECS in a heterogeneous network. As there are too many parameters to simulate all possible scenarios, for these simulations, we keep the number of cluster heads in layer 1 (m_1) constant while changing the number of clusters in layer 2 (m_2) and varying the radius of the first layer (R_1) in small values from the range [0.2, 0.9]*R_a. The cluster heads are positioned at the centroids of the clusters, as determined by equations (3) and (4). The goal is to find, for every pair (m_1, m_2) the maximum number of rounds before the first cluster head in the network dies, and we measure the radius R_1 in that case. This value of R_1 determines the ratio of clusters' sizes in layers 1 and 2 that assures the longest lifetime for a particular pair (m_1, m_2). The same set of simulations is repeated for different in-network aggregation coefficients. The final results are obtained by averaging the results of simulations for ten different random scenarios. The results of these simulations are then compared with the simulations of ECS, where the clusters cover approximately the same area and have approximately the same number of nodes.

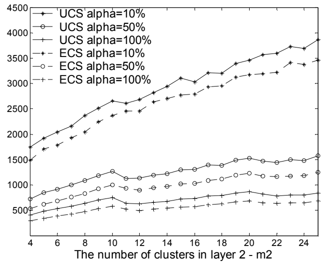
Figure 5 shows the maximum number of rounds the network can last until the first cluster head node in the network dies, for UCS and ECS, when cluster heads forward 10%, 50% and 100% of the cluster load (α = 0.1, 0.5, 1). The number of cluster head nodes in the first layer (m_1) is 6 (Figures 5a and 5c) and 10 (Figures 5b and 5d). Using UCS, the sensor network always achieves longer lifetime than with ECS. In most cases, when the maximum number of rounds is reached, the cluster heads spend the energy uniformly over the network. With more clusters closer to the base station, the lifetime of the network improves, as can be seen from Figures 5a and 5b. For example, when the number of clusters in the first layer is 6, the improvement in lifetime for UCS with the pie shaped scenario is about 10-20%, while when the number of clusters in the first layer increases to 10, the improvement in lifetime is 15-30%, depending on the aggregation efficiency. The improvement with the Voronoi clusters is even better: 17-35% for m_1 = 6, and 15-45% for m_1=10. Also, the improvement in lifetime increases as the cluster heads perform less aggregation, which confirms that UCS can be useful for heterogeneous networks that perform nonperfect aggregation.

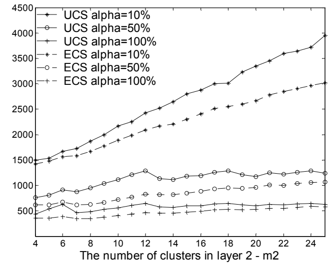
The ratio of the average number of nodes for clusters in layer 1 and layer 2 in UCS, for the parameters where a maximum number of rounds is obtained, is shown in Figure 6. When the number of cluster head nodes in layer 2 increases, it is observed that the ratio of the number of nodes in the clusters in layer 1 and 2 is slightly smaller. The cluster heads in layer 1 forward more load from the upper layer, so they can support a relatively smaller number of nodes in the cluster.

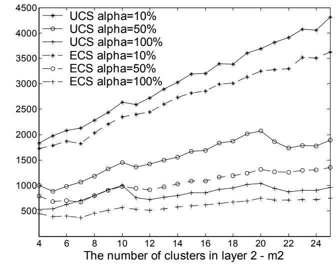
In general, by comparing the results obtained with pie shape clusters and with Voronoi shaped clusters, we observe similar behaviors. Both scenarios show that UCS can provide the benefit of more uniform energy dissipation for the cluster heads. Also, these results justify our approximation of Voronoi–shaped clusters used in the previous section to ease the analysis.

However, as stated previously, the unequal cluster sizes lead to unequal energy consumption of sensor nodes in a cluster. The average energy consumed by a sensor node per one round in ECS is less than in UCS. Although it is favorable to have less energy consumption of sensor nodes, their ability to send useful data to the base station is determined by the functionality of cluster heads. To assure that no sensor node runs out of energy before the first cluster head in the network dies, the battery of all sensor nodes should be of size *T***E*(spent in one round by the furthest node from cluster head). Also, for cluster head nodes, the battery should be dimensioned as: *T**max (E (spent by cluster head nodes in one round)), where *T* is the desired network lifetime.









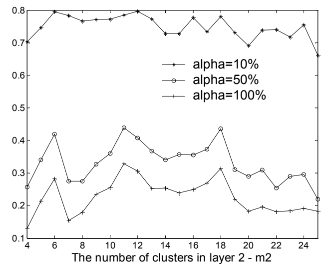
Maximum number of rounds for UCS and ECS.

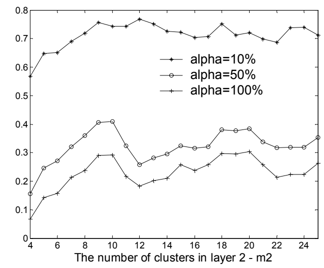
Fig. 5a) Pie shape clusters $m_1 = 6$

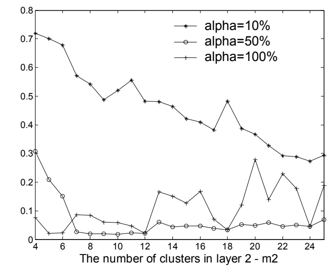
Fig. 5b) Pie shape clusters $m_1 = 10$

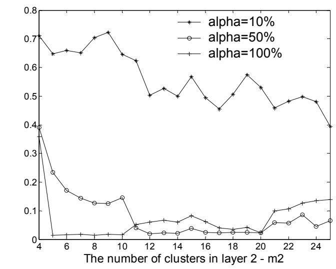
Fig. 5c) Voronoi clusters $m_1 = 6$

Fig. 5d) Voronoi clusters $m_1 = 10$









The ratio of average number of nodes in clusters in layer 1 and 2.

Fig. 6a) Pie shape clusters $m_1 = 6$

Fig.6b) Pie shape clusters $m_1 = 10$

Fig. 6c) Voronoi clusters $m_1 = 6$

Fig. 6d) Voronoi clusters $m_1 = 10$

Using the results from simulations, we dimensioned the batteries of sensor nodes and cluster head nodes, for both ECS and UCS. To achieve the same lifetime in both clustering schemes, the cluster head nodes in UCS should store about 20% less energy than the cluster head nodes in ECS, while the sensor nodes should be equipped with batteries that are about 10-15% larger. Overall, the total energy the network should contain is always smaller for UCS than ECS for the same network lifetime.

These results provide intuition about the use of UCS in a network where all nodes (sensors and cluster heads) have fixed transmission ranges and hence fixed energy dissipation for transmitting data. In this case, the energy consumption of all sensors is the same during one communication round, regardless of their position in the cluster, and thus UCS will always outperform ECS.

As a final result for heterogeneous networks, we simulate the same network but now divided into 3 layers of clusters around the base station. We perform the same type of simulations, where we keep the number of cluster heads in the first layer constant while we change the number of clusters in the second and third layer. Also, we vary the radius of the first and second layers, R_1 and R_2, changing by this the actual cluster sizes in every layer. For every triple (m_1, m_2, m_3) we find the maximum lifetime of the network and the sizes of clusters in that case. Also, we measure the number of rounds the network can last for the cases when the ratio of the number of nodes in clusters of layer 1 and 2, and the ratio of the number of nodes in clusters of layer 2 and 3 is approximately equal to 1. We repeat several simulations on different scenarios, and for different values of aggregation coefficient α. On average, the improvement in network lifetime when α = 0.1 is about 15%, and when α = 0.5 and α = 1, the improvement is about 26% over ECS.

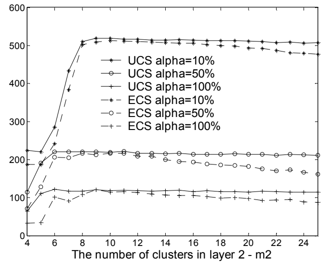
VI.B Homogeneous Networks

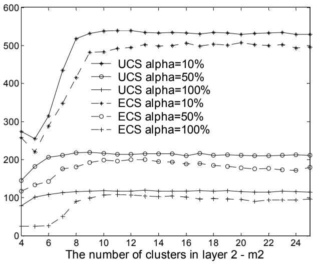
We evaluate UCS in a network where a certain number of cluster head nodes are periodically elected among a number of equivalent sensor nodes. The cluster heads route the data over shortest hop paths to the cluster heads closer to the base station. We perform simulations on two scenarios: first, when the network is divided into *static* clusters, where the nodes are grouped into the same cluster during the network lifetime, and second, when the clustering is *dynamic*, such that clusters are formed around the elected cluster heads.

VI.B.1 Static Clustering

In the first set of simulations, static clusters are formed initially in the early phase of the network, so that every node belongs to one cluster during its lifetime. In every cluster, the role of cluster head is rotated among the nodes, and the cluster head is elected based on maximum remaining energy. Here, we assume that in the initial phase the network is divided into Voronoi-shape clusters, formed around the selected cluster heads and aligned in two layers around the base station. These static clusters with cluster heads that rotate among the cluster nodes can actually be seen as a hybrid solution between the heterogeneous and homogeneous networks. In static clustering, the large overhead that occurs every time clusters are re-formed can be avoided, which is similar to heterogeneous networks. On the other hand, as in homogeneous networks, the rotation of the cluster head role among the nodes within every cluster contributes to more uniform energy dissipation in the network.

Again, as in the case of heterogeneous networks, we vary the number of clusters in layer 2 (m_2) and the radius of the first layer (R_1) while keeping the number of clusters in layer 1 (m_1) constant. For every set of parameters (m_1,m_2), we measure the maximum network lifetime until 10% of the nodes die, and we determine for which sizes of clusters in both layers this

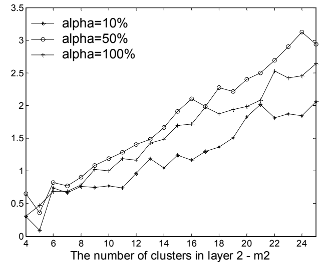


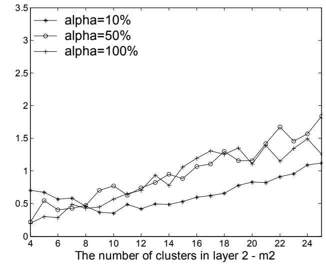


Maximum number of rounds for UCS and ECS, for a network with static clusters.

Fig. 7a) Voronoi clusters $m_1 = 6$

Fig. 7b) Voronoi clusters $m_1 = 10$





Ratio of average number of nodes in clusters in layer 1 and 2 in UCS, for a network with static clusters.

Fig. 7c) Voronoi clusters $m_1 = 6$

Fig.7d) Voronoi clusters $m_1 = 10$

maximum network lifetime is achieved. This network lifetime is compared with the case when all clusters are of approximately the same size (ECS). The results for maximum network lifetime for UCS and ECS are shown in Figure 7.

UCS achieves, on average, an 8-28% improvement in network lifetime over ECS, depending on the aggregation efficiency. The improvement is slightly lower than in the case of a heterogeneous network, which is the result of utilizing a static clustering scheme. Although the nodes balance energy better among themselves, all nodes on average perform longer transmissions to the cluster head than in the case when the cluster head is in the middle of the cluster. It is interesting to observe that for homogeneous networks with static clustering, as the number of clusters in the outer layer increases, the ratio of sizes of clusters of both layers dramatically changes, with clusters in layer 1 *larger* than clusters in layer 2 (Figures 7c and 7d). Because cluster heads in layer 1 receive more packets, they drain their energy faster. Thus, larger clusters in layer 1 assures that there is enough energy "accumulated" by the larger number of nodes in those clusters, so that one node is not frequently elected for the cluster head position and it does not drain its energy on cluster head activities.

VI.B.2 Dynamic Clustering

Finally, we discuss the use of UCS for homogeneous networks utilizing cluster head rotation and dynamic clustering. For these simulations, clusters are formed as Voronoi regions around the elected cluster head nodes. We compare two clustering models, as the representatives of ECS and UCS. In the first model, all nodes have an equal probability p_o to become cluster head in the next round, where p_o is in the range (0, 0.5]. The sizes of the clusters formed in this manner are not fixed, but the expected number of nodes in every cluster is $1/p_o$. We call this model *Equal Probability Election Model* (EPEM). For the second case, we again assume that, because of higher energy consumption due to extensive relay activity, the cluster head nodes closer to the base station should support smaller clusters. To obtain smaller clusters in the region around the base station, the nodes in this region have a higher probability of being elected as a cluster head. We call this the *Unequal Probability Election Model* (UPEM), where the probability of becoming a cluster head for every node depends on the distance *d* between the node and the base station as:

$$p_i(d) = C \cdot \frac{R_a - d}{R_a} \tag{14}$$

where *C* is a positive constant.

We compare EPEM and UPEM when the average number of cluster heads elected in every round is the same. In EPEM, the average number of cluster heads elected in every round is simply $k_o = p_o \cdot N$, so the average number of cluster heads in UPEM must be set as:

$$\frac{N}{R_a^2 \pi} \int_0^{R_a} C \frac{(R_a - r)}{R_a} \cdot 2\pi r dr = \frac{N \cdot C}{3} = k_0 \tag{15}$$

From equation (15), the constant *C* can be found:

$$C = 3 \cdot p_0 . \tag{16}$$

The probability of node election as a cluster head should satisfy the basic probability condition: $0 \le p_i \le 1$, from which we can find a condition for the distance *d*:

$$d \ge R_a \cdot (1 - \frac{1}{3p_0}) \tag{17}$$

Since *d* is in the range $0 \le d \le R_a$, p_o is bounded as:

$$0 \le p_0 \le \frac{1}{3} \tag{18}$$

When this is not the case, then some nodes closest to the base station should have a probability of being elected as a cluster head equal to 1. This does not, however, mean that they will necessarily serve as a relay station in every round to cluster head nodes further away, because now the nodes further away will have the possibility to choose among more nodes as their next relay station.

The radius R_s, within which all the nodes will have to be chosen as cluster heads with the probability 1, can be determined from the condition that the total number of nodes elected as cluster heads has to be equal to k_o, or:

$$\frac{N}{R_a^2 \pi} \left(\int_0^{R_s} 2\pi r dr + \int_{R_s}^{R_a} 3 p_0 \frac{(R_a - r)}{R_a} 2\pi r dr \right) = k_0 \tag{19}$$

which gives us:

$$R_s = R_a \frac{(3 \cdot p_0 - 1)}{2 \cdot p_0} \tag{20}$$

Therefore, the probability of cluster head election in UPEM should change as:

$$p_i(d) = 3 \cdot p_0 \frac{(R_a - d)}{R_a} \quad 0 \le d \le R_a \quad p_o \le \frac{1}{3}$$

$$p_i(d) = \begin{cases} 1 & 0 \le d \le R_s \quad \frac{1}{3} < p_o \le 1 \\ 3 \cdot p_0 \frac{(R_a - d)}{R_a} & R_s < d \le R_a \quad \frac{1}{3} < p_o \le 1 \end{cases} \tag{21}$$

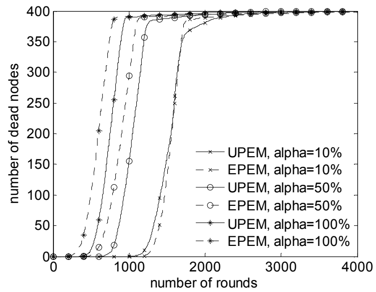


Fig. 8a) Comparison of the number of dead nodes over time for UPEM and EPEM, for $p_o = 0.1$

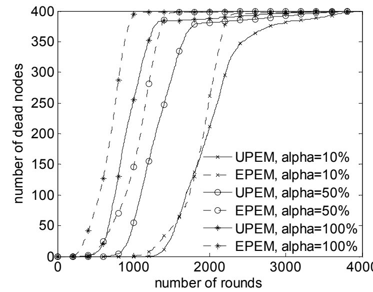


Fig. 8b) Comparison of the number of dead nodes over time for UPEM and EPEM, for $p_o = 0.3$

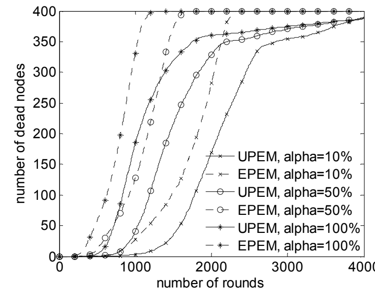


Fig. 8c) Comparison of the number of dead nodes over time for UPEM and EPEM, for $p_o = 0.5$

We compare EPEM and UPEM for several scenarios, changing the probability of cluster head election for EPEM (p_o) and adjusting the probability of cluster head election for UPEM accordingly, for different aggregation coefficients α. Figure 8 shows the number of dead nodes during the simulation time.

For the case when p_o is small (Figure 8a) and when data is more efficiently aggregated, there is no noticeable difference between EPEM and UPEM. The network has large clusters, and the relay load is not dominant in energy consumption over the energy spent for serving the nodes within the cluster. However, with an increase in relay traffic (α = 0.5 and α = 1) UPEM performs better than EPEM in terms of the number of nodes that die over the simulation time. The improvement in time until the first node dies in UPEM over EPEM is 23% when α = 0.5 and 32% when α = 1. The energy spent on load relaying is now dominant, and smaller clusters around the base station can contribute to more uniform energy dissipation. With an increase in p_o (Figure 8b) we can see a difference in the results compared with the case when $p_o = 0.1$. The time until the first node dies is increased with UPEM by 35% for α = 0.1, and by 75% for α = 0.5 and α = 1. With a further increase in p_o, the network is overloaded with clusters, and with so many data flows the network looses energy quickly. Therefore, the nodes start to die sooner than in the previous cases, but still UPEM achieves drastically better results than EPEM.

VII CONCLUSIONS

In this paper, we analyze an approach for the hierarchical organization of wireless sensor networks where, in order to balance the energy consumption of cluster head nodes, unequal size clusters are formed. Our proposed scheme is compared with a classical clustering approach, where all clusters contain approximately the same number of nodes. Through analysis and extensive simulations of different scenarios for both homogeneous and heterogeneous networks, we show that our Unequal Clustering Size (UCS) scheme achieves an improvement of about 10-30% over the Equal Clustering Size (ECS) scheme, depending on the aggregation efficiency of the cluster head nodes. We show that unequal clustering can be beneficial, especially for networks that must collect large amounts of data from the network. Also, we show that this approach can yield longer lifetimes in homogeneous networks, as well as heterogeneous networks with static clusters. Our results show that this direction has the potential to improve performance in terms of network lifetime.

To ease the analysis of UCS and ECS, we have made several simplifying assumptions that we will address in our future research. For example, we will study the effect of errors and collisions on both UCS and ECS. By considering multiple concentric layers around the base station, we will extend our clustering model, and we will try to find a closed form solution that will determine the optimal number of cluster heads in every layer. Finally, we will look at the effects of event-based networks where the data generation rate at each node is a function of phenomena in the environment rather than constant at each node.

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