Enhancing Clustering in Wireless Sensor Networks with Energy Heterogeneity

Femi A. Aderohunmu, Jeremiah D. Deng, Martin K. Purvis

Abstract

While wireless sensor networks (WSN) are increasingly equipped to handle more complex functions, in-network processing still require the battery powered sensors to judiciously use their constrained energy so as to prolong the effective network life time.There are a few protocols using sensor clusters to coordinate the energy consumption in a WSN. To cope with energy heterogeneity among sensor nodes, a modified clustering algorithm is proposed with a three-tier sensor node setting. Simulation has been conducted to evaluate the new clustering algorithm and favorable results are obtained especially in heterogeneous energy settings.

Keywords: Wireless sensor network; heterogeneous settings; clustering.

1 Introduction

Wireless communication technologies continue to grow in diverse areas to provide new opportunities for networking and services. One fast-moving area, is wireless sensor networks (WSN). With the advances in micro-electro mechanical systems, sensor devices can be built as small as lightweight wireless nodes. Wireless sensor networks (WSN) are highly distributed networks of such kind of sensor nodes, and have been deployed in large numbers to monitor the environment or production systems. There is a growing need for the nodes to handle more complex functions in data acquisition and processing, and energy saving solutions remain a major requirement for these battery-powered sensor nodes.

Three major functions are performed by three sensor subsystems [10]: the environment sensor; the data processor that performs local computations on the data sensed, and the communicator that performs information exchange between neighboring nodes. Each sensor is usually limited in their energy level, processing power and sensing ability. However, a network of these sensors give rise to a robust, reliable and accurate network.

Many studies on WSNs have been carried out [3, 4, 13, 6]. WSN technology is continuously finding new application in various areas, such as in battle field surveillance, patient monitoring in hospital wards, and environmental monitoring in disaster prone areas. Although these sensors are not as reliable or as accurate as their expensive macro-sensors, their small size and low cost have enabled applications to network hundreds and thousands of these micro-sensors to achieve greater performance [8]. It is noted that, to maintain a reliable information delivery, data aggregation and information fusion that is necessary for efficient and effective communication between these sensor nodes. Only processed and concise information should be delivered to the sinks or ‘ actuators’ to reduce communications energy and to prolong the effective network lifetime.

However, one of the key issues that merits attention is the energy heterogeneity [9] in sensor networks. This occurs when there is energy difference to some threshold between an individual sensor and its neighbors, either caused by the introduction of new sensors or re-energization of sensor nodes, or by network settings which may be necessary for some applications. An inefficient use of the available energy will lead to poor performance and short life cycle of the network. To this end, energy in these sensors is a scarce resource and must be managed in an efficient manner. We present a modified algorithm for properly distributing sensor energy and ensuring the maximal network life time. Our algorithmic approach operates in a WSN under three-level energy heterogeneity. Simulation results show an improvement in the effective network life time, and increased robustness of performance in the presence of energy heterogeneity.

The remainder of this paper is organized as follows. We briefly review related work in Section 2. The network model and cluster formation are presented in details in Section 3. We present the protocol architecture in Section 3.3. We then discuss our proposed clustering technique in section 4. Our simulation result is presented in section 5. Finally, in section 6, we conclude the paper and highlights future directions for other aspects of improvement in WSN.

2 Related work

Clustering techniques have been employed to deal with energy management in WSNs. Low Energy Adaptive Clustering Hierarchy (LEACH) [8] is a pioneering work in this respect. LEACH is a clustering-based protocol, using randomized election and rotation of local cluster base station (so-called ‘cluster-heads’ for transferring data to the sink node) to evenly preserve the energy among the sensors in network. The rotation of cluster head can also be a means of fault tolerance [1]. The sensors organize themselves into clusters using a probabilistic approach to randomly elect themselves as heads in an epoch. However, the LEACH protocol is not heterogeneity-aware, in the sense that when there is an energy difference to some threshold between these nodes in the network, the sensors die out faster than a more uniform energy setting [12]. In real life situation it is difficult for the sensors to maintain their energy uniformly, this makes energy imbalance between nodes to occur easily. LEACH assumes that the energy usage of each node with respect to the overall energy of the system or network is homogeneous. Conventional protocols such as Minimum Transmission Energy (MTE) and Direct Transmission (DT) [11] do not also assure a balanced and uniformly use of the sensor's respective energy as the network evolves. In Distributed Energy-Efficient Clustering algorithm (DEEC) [10], a probability based clustering algorithm was proposed. DEEC elects cluster heads based on the knowledge of the ratio between residual energy of each nodes and the average energy of the network. This knowledge however requires additional energy consumption to share the information among the sensor nodes. Stable Election Protocol (SEP) [12] is another heterogeneity-aware protocol. It does not require energy knowledge sharing but is based on assigning weighted election probabilities of each node to be elected cluster head according to their respective energy. This approach ensures that the cluster head election is randomly selected and distributed based on the fraction of energy of each node therefore assuring a uniform use of the nodes energy.

In SEP, two types of nodes (two tier in-clustering) and two level hierarchies were considered. SEP is based on weighted election probabilities of each node to become cluster head according to the remaining energy in each node. A survey of clustering algorithm was presented in Ref. [1]; the even distribution of sensors in clusters is another primary objective of clustering called load balancing that needs to be considered when designing a robust protocol for WSNs [13, 5]. The clustering issue was also discussed in a review on wireless multimedia sensor networks [2].

The contribution of this work is a SEP extension called SEP-E, by considering a three-tier node classification in a two-level hierarchical network. The new node type for the purpose of this study is referred to as "intermediate nodes", which serves as a bridge between the advanced nodes and the normal nodes. The intermediate nodes can take on the role of information fusion and filtering depending on the application settings, which we intend to study further. Our goal is to achieve a robust self-configured WSN that maximizes its lifetime.

3 The Network Model

3.1 Radio channel and energy dissipation

Let us consider the radio energy dissipation model as used in a number of previous studies [8, 12, 10], shown in Figure 1. Assume for each bit our radio model dissipates the energy $E_{elec} = 50nJ/$bit to run the transmitter or receiver circuit. To transmit the data bits over a distance (d) with an acceptable SNR, amplification energy is expended to overcome either the free space (fs) or multipath (mp) loss, depending on the transmission distances (d).

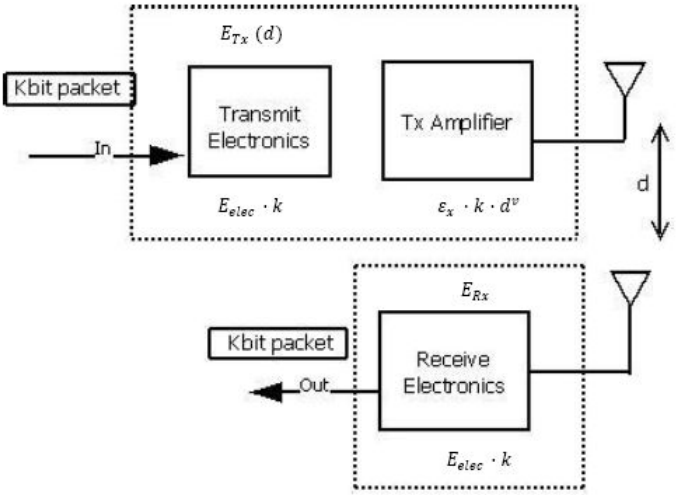

Figure 1: Network Model diagram

Therefore, to transmit k bits, the energy expended is:

$$\begin{aligned} E_{Tx}(k,d) &= E_{Tx-elec}(k) + E_{Tx-amp}(k,d) \\ &= \begin{cases} kE_{elect} + k\epsilon_{fs}\ d^2 & \text{if } d < d_o; \\ kE_{elect} + k\epsilon_{mp}\ d^4 & \text{if } d \geq d_o. \end{cases} \end{aligned} \tag{1}$$

where d_o is the distance threshold for swapping amplification models, which can be calculated as $d_o = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}}$.

To receive a k-bit message, the radio will expend

$$E_{Rx}(k) = E_{elec}k. \tag{2}$$

We further assume a symmetric radio channel i.e., the same amount of energy is required to transmit a k-bit message from node A to B and vice versa.

3.2 Cluster Formation

We form clusters using a distributed algorithm as in Ref. [8, 12]. The main idea is for the sensor nodes to elect themselves with respect to their energy levels autonomously. The goal is to minimize communication cost and maximizing network resources in other to ensure concise information is sent to the sink. Each node transmits data to the closest cluster head and the cluster heads performs data aggregation. We proceed to our indicator function of chosen a cluster head. Assume an optimal number of clusters c in each round. It is expected that as a cluster head, more energy will be expended than being a cluster member. Each node can become cluster head with a probability P_{opt} and every node must become cluster head once every $\frac{1}{P_{opt}}$ rounds. Intuitively, it means we have nP_{opt} clusters and cluster heads per round. Let the non-elected nodes be a member of set G in the past $\frac{1}{P_{opt}}$ rounds.

for each round sensor node chooses a random number between 0 and 1. If this is lower than the threshold for node $n, T(n)$, the sensor node becomes a cluster head. The threshold $T(n)$ is given by:

$$T(n) = \begin{cases} \frac{P_{opt}}{1-P_{opt}[r \ mod(1/P_{opt})]} & \text{if } n \in G; \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

Assume nodes are uniformly and randomly distributed in an area of m^2. On average there would be $\frac{n}{c}$ nodes per cluster, one cluster head and $\frac{n}{c} - 1$ non-cluster head. Each cluster head must dissipate energy receiving k bits of data packet from associated cluster members and transmitting to the sink. Also, data aggregation prior to transmission will also cost energy, which per bit is denoted as E_{DA}. In total, the energy dissipated by each cluster head is:

$$E_{CH} = kE_{elec}(\frac{n}{c} - 1) + kE_{DA}\frac{n}{c} + E_{Tx}(k, d_{toSink}), \tag{4}$$

where d_{toSink} is the distance from cluster head node to the sink.

For non-cluster head, the energy expended will be to transmit k bits of data to the respective cluster heads, while a free space power loss d^2 is adopted since normally $d_{toCH} < d_o$ in Eqn.(1):

$$E_{non-CH} = kE_{elec} + k\epsilon_{fs}d_{toCH}^2, \tag{5}$$

where d_{toCH} is the distance from each node to their respective cluster heads. The average value of d_{toCH} can be estimated as $M/\sqrt{2\pi c}$ [8].

The energy dissipated in a cluster per round can be estimated as

$$E_{cluster} \approx E_{CH} + \frac{n}{c}E_{nonCH} \tag{6}$$

And the total energy dissipation in the network per round will be the sum of the energy dissipated by all clusters, i.e.,

$$E_{total} = cE_{cluster} \tag{7}$$

If the average of d_{toSink} is greater than d_o, the total energy can be calculated as:

$$\begin{aligned} E_{total} = \ & (kE_{elec}(\tfrac{n}{c} - 1) + kE_{DA}\tfrac{n}{c} + kE_{elec} + k\epsilon_{mp}d_{toSink}^4) \\ & +(kE_{elec} + k\epsilon_{fs}M^2/2\pi c). \end{aligned} \tag{8}$$

Otherwise, when $d_{toSink} < d_o$ applies, the total energy becomes

$$E_{total} = k\left(2nE_{elec} + nE_{DA} + \epsilon_{fs}(cd_{toSink}^2 + nd_{toCH}^2)\right). \tag{9}$$

As discussed in Ref. [8, 12], the optimal number of clusters can be found by letting $\frac{\delta E_{total}}{\delta c} = 0$. The different forms of the E_{total} calculation will lead to different optimal c settings.

3.3 Energy heterogeneity

In this section we briefly discuss the intuition behind SEP and its improvement on LEACH. SEP improved the stable region of the system using clustering hierarchy technique by making an efficient use of the extra energy introduced into the system that serves as a source of heterogeneity. In SEP two energy levels were considered in two hierarchy settings, which is the first improvement of SEP to LEACH protocol which assumes the sensor nodes are equipped with same amount of energy (homogeneous settings). SEP considered a heterogeneous setting by extending the epoch of the sensor network to the existing LEACH protocol in proportion to the energy increment. For optimization of the stable region [12], SEP proposed a new epoch equal to $\frac{1}{P_{opt}}(1 + m\alpha)$.

SEP used an election probability based on the initial energy of each node to elect the cluster heads by assigning a weight equal to the initial energy of each node divided by initial energy of the normal nodes. The weighted probabilities for normal and advanced nodes in SEP were chosen to reflect the extra energy introduced into the network system. The probabilities and the total initial energy are given below respectively:

$$\begin{array}{ll} P_{nrm} & = P_{opt}/(1 + m\alpha), \\ P_{adv} & = (P_{opt})(1 + \alpha)/(1 + m\alpha), \\ E_{total} & = nE_o(1 + m\alpha), \end{array} \tag{10}$$

where P_{nrm} is the weighted probability for normal nodes and P_{adv} is the weighted probability for the advanced nodes and m is the proportion of advanced nodes with α times more energy than the normal nodes and finally, E_{Total} is the total initial energy of the network.

4 Extending SEP

In this section we discuss our proposed solution as an extension to the SEP protocol by considering three energy levels in two hierarchy settings, which is our first improvement to SEP and LEACH. We optimized the stable region of the network system by further increasing the epoch to accommodate the additional energy introduced to the system. In our approach we introduced an additional node called the 'intermediate nodes', with an intention to accommodate and cater for multi-nodes diversity. This can be very important for some application specific settings such as the continuous re-energization of nodes throughout the data retrieval process, by deploying new nodes to replace dead ones. The intermediate nodes take an initial energy level between that of the advanced nodes and the normal nodes.

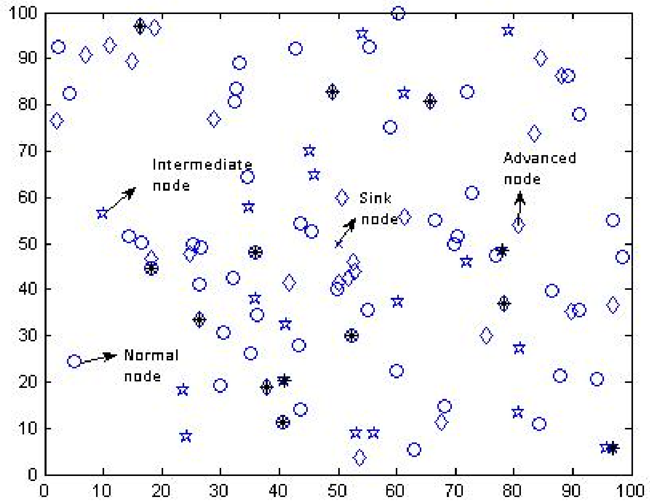

Figure 2: Wireless Sensor Network in clusters.

The intermediate node is chosen as fraction of energy between the limits of both the fractions of energy of advanced node as the upper bound and the normal node as the lower bound. As in SEP, the initial energy for normal nodes is E_o, and for advanced nodes, $E_{adv} = (1+\alpha)E_o$. Assuming for intermediate nodes, $E_{int} = (1+\mu)E_o$. For simplicity we set $\mu = \alpha/2$.

Figure 2 demonstrates the heterogeneous settings we used.
The new heterogeneous setting with the three-tier node energy has no effect on the spatial density of the network [12]. We keep P_{opt} the same. The total initial energy of the system is increased by the introduction of intermediate nodes:

$$\begin{aligned} E_{total} &= nE_o(1-m-b) + nmE_o(1+\alpha) + nbE_o(1+\mu) \\ &= nE_o(1+m\alpha+b\mu), \end{aligned} \tag{11}$$

Where n is the number of nodes, m is the proportion of advanced nodes to the total number of nodes n and b is the proportion of intermediate nodes. Proceeding from similar analysis in Ref.[12], the following conditions must be satisfied:

1. The advanced nodes must be cluster head exactly $(1+\alpha)$ times every $\frac{1}{P_{opt}}(1+m\alpha+b\mu)$.

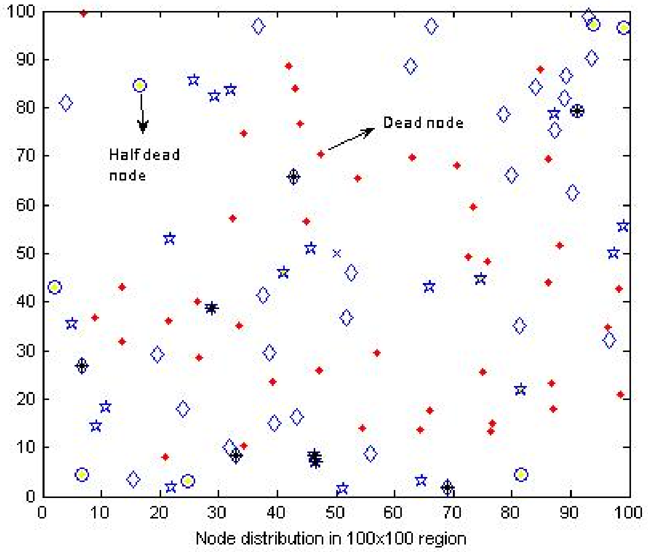

Figure 3: Wireless Sensor Network when some nodes are half dead and dead.

2. The Intermediate nodes must be cluster head exactly $(1+\mu)$ times every $\frac{1}{P_{opt}}(1+m\alpha+b\mu)$.
3. Every normal nodes must also become cluster head once every $\frac{1}{P_{opt}}(1+m\alpha+b\mu)$.
4. The average number of cluster in the network should be nP_{opt}.

This translates into a probability problem which we can solve mathematically. If we choose P_{nrm}, P_{int} and P_{adv} for probabilities of becoming normal, intermediate and advanced nodes respectively, we have:

$$P_{nrm} = P_{opt}/(1+m\alpha+b\mu). \tag{12}$$

$$P_{int} = P_{opt}(1+\mu)/(1+m\alpha+b\mu). \tag{13}$$

$$P_{adv} = P_{opt}(1+\alpha)/(1+m\alpha+b\mu). \tag{14}$$

To guarantee that the sensor nodes must become cluster heads as we have assumed above, we must define a new threshold for the election processes, Ref. 3. The threshold $T(n_{nrm}), T(n_{int}), T(n_{adv})$ for normal, intermediate and advanced respectively becomes:

$$T(n) = \begin{cases} \frac{P_{nrm}}{1-P_{nrm}[r \ mod(1/P_{nrm})]} & \text{if } n_{nrm} \in G'; \\ 0 & Otherwise, \end{cases} \tag{15}$$

From above we have $n(1 - m - b)$ normal node, which ensures that our assumption (1) is exact, where G' is the set of normal nodes that has not become cluster head in the past $1/P_{nrm}$ round r. The same analogy follows for the intermediate and advanced nodes,

$$T(n_{int}) = \begin{cases} \frac{P_{int}}{1-P_{int}[r \ mod(1/P_{int})]} & \text{if } n_{int} \in G''; \\ 0 & Otherwise, \end{cases} \tag{16}$$

We have nb intermediate nodes; with G'' the set of intermediate nodes that has not become cluster head in the past $1/P_{int}$ round r .

$$T(n_{adv}) = \begin{cases} \frac{P_{adv}}{1-P_{adv}[r \ mod(1/P_{adv})]} & \text{if } n_{adv} \in G'''; \\ 0 & Otherwise, \end{cases} \tag{17}$$

Similarly, we havenm advanced nodes; withG''' as the set of advanced nodes that has not become cluster head in the past$1/P_{adv}$ round r. From Eq. (11), (12), and (13), the average total number of cluster heads per round will be:

$$n(1 - m - b)P_{nrm} + nbP_{int} + nmP_{adv} = nP_{opt}. \tag{18}$$

This gives us the same number of cluster heads compared with the original LEACH setting. However, because of the energy heterogeneity setting, energy dissipation is better controlled in our approach, yielding more desirable results as shown in our simulation.

5 Simulation

5.1 Simulation settings

We used a $100m \times 100m$ region of 100 sensor nodes scattered randomly. MATLAB is used to implement the simulation. To have a fair comparison with LEACH, we introduced advanced and intermediate nodes with different energy levels as in our SEP-E protocol. Likewise, to have a fair comparison with SEP in two node scenario, we introduced additional energy so that the total initial energy of the network system becomes same as in SEP-E and LEACH in three node settings.The notion is for us to be able to assess the performance of these protocols in the presence of heterogeneity. Specifically, we have the following settings:
Let 20% and 30% of the nodes be advanced nodes and intermediate nodes with additional energy levels: $\alpha = 3$ and $\mu = 1.5$ respectively. The new heterogeneous epoch is $\frac{1}{P_{opt}}(1 + m\alpha + b\mu)$. Since $P_{opt} = 0.1$ on average we should have 10 nodes becoming cluster head per round. This means by our new heterogeneous epoch we should have, on average $n(1-m-b)P_{nrm} = 2$ normal nodes becoming cluster head per round. Similarly, we should have $nbP_{int} = 4$ intermediate nodes as cluster heads per round and $nmP_{adv} = 4$

advanced nodes as cluster heads per round. Other parameters used in our simulation are shown in table 1.

Parameter	**Values**
E_{elec}	50nJ/bit
E_{DA}	5nJ/bit/message
E_o	0.5J
k	4000
P_{opt}	0.1
ϵ_{fs}	10pJ/bit/m^2
ϵ_{mp}	0.0013pJ/bit/m^4
n	100

Table 1: Parameter settings

5.2 Performance metrics

The following metrics are adopted to access the performance of all clustering protocols involved:

1. Stability period, the period from the start of the network operation and the first dead node.
2. Instability period, the period between the first dead node and last dead node.
3. Number of alive and dead nodes per round.
4. Spatial distribution and uniformity of alive and dead nodes per round in the network region under consideration.

5.3 Simulation results

We compare the result of our simulation with both LEACH and SEP in three nodes and two nodes heterogeneous settings respectively. From Figure 4 above we show SEP-E, LEACH and SEP in the presence of energy heterogeneity, the stability of SEP-E compared with LEACH increased from 995 rounds to 1450 rounds and the instability reduced from 4585 rounds to 3751 rounds. Also the stability in SEP-E is slightly better than SEP, and the instability is much lower than SEP, this is due to the introduction of the intermediate nodes to SEP-E, which act as a bridge between the advanced nodes and the normal nodes in SEP-E, thus lowering the instability region.

With lower values of energy heterogeneity as seen in Figure 5 and Figure 6, the stability region of SEP-E is reduced relative to the energy levels. We can deduce from Figure 4 and Figure 6 that SEP-E takes advantage of the

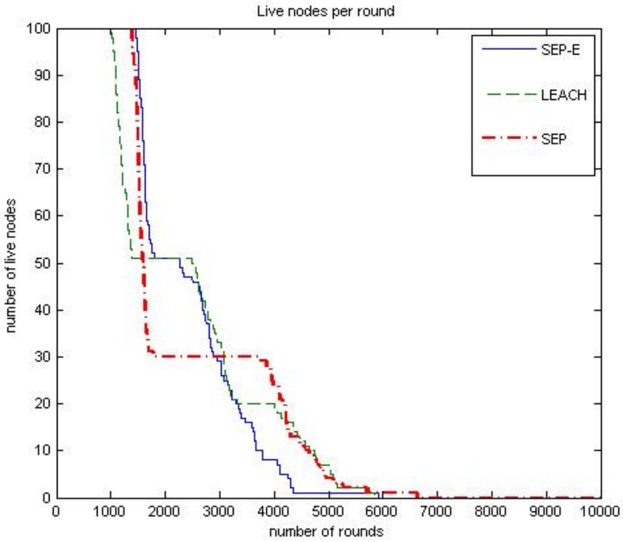

Figure 4: The performance of SEP-E ($m = 0.2, b = 0.3$, $\alpha = 3$ and $\mu = 1.5$), LEACH ($m = 0.2, b = 0.3$, $\alpha = 3$ and $\mu = 1.5$) and SEP ($m = 0.3, b = 0$, $\alpha = 3.5$ and $\mu = 0$), $E_{total} = 102.5J$ in the presence of high energy heterogeneity.

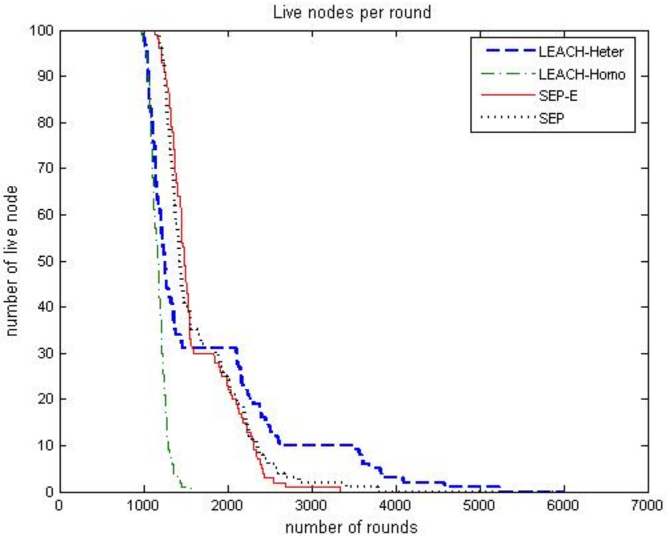

Figure 5: The performance of SEP-E ($m = 0.1, b = 0.2$, $\alpha = 2$ and $\mu = 1$), LEACH (Homogeneity,$m = 0, b = 0$, $\alpha = 0$ and $\mu = 0$), LEACH (Heterogeneity,$m = 0.1, b = 0.2$, $\alpha = 2$ and $\mu = 1$) and SEP ($m = 0.3, b = 0$, $\alpha = 1.3$ and $\mu = 0$), $E_{total} = 70J$.

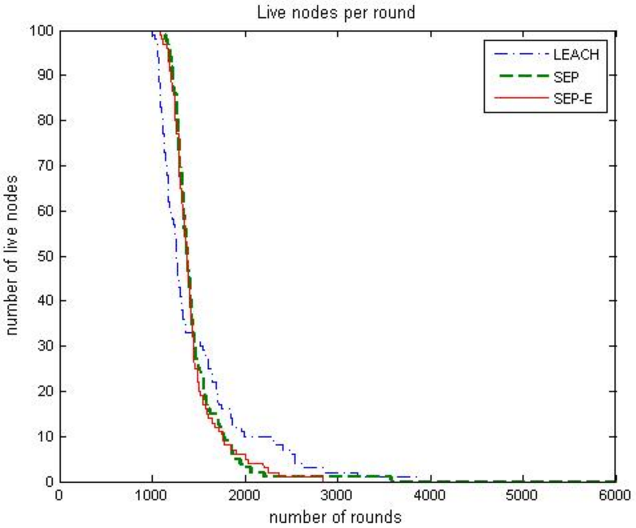

Figure 6: The performance of SEP-E ($m = 0.1, b = 0.2$, $\alpha = 1$ and $\mu = 0.5$), LEACH($m = 0.1, b = 0.2$, $\alpha = 1$ and $\mu = 0.5$) and SEP ($m = 0.3, b = 0$, $\alpha = 0.7$ and $\mu = 0$),$E_{total} = 60J$ in the presence of low energy heterogeneity.

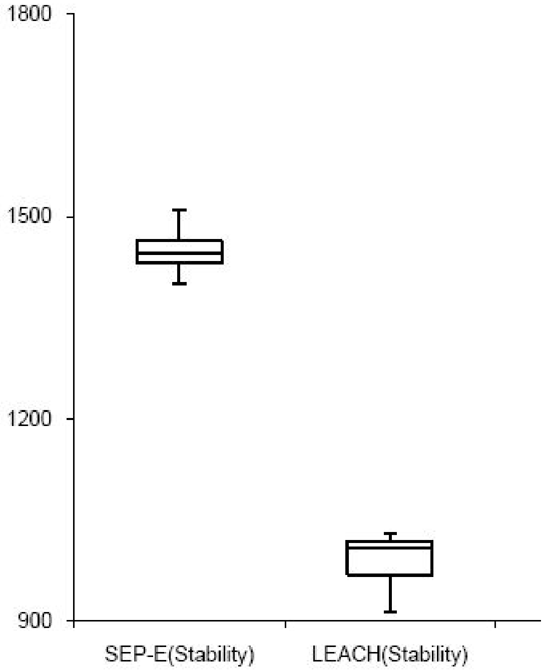

Figure 7: The behavior of SEP-E and LEACH for 10 trials in the presence of heterogeneity. We have $m = 0.2, b = 0.3$, $\alpha = 3$ and $\mu = 1.5$.

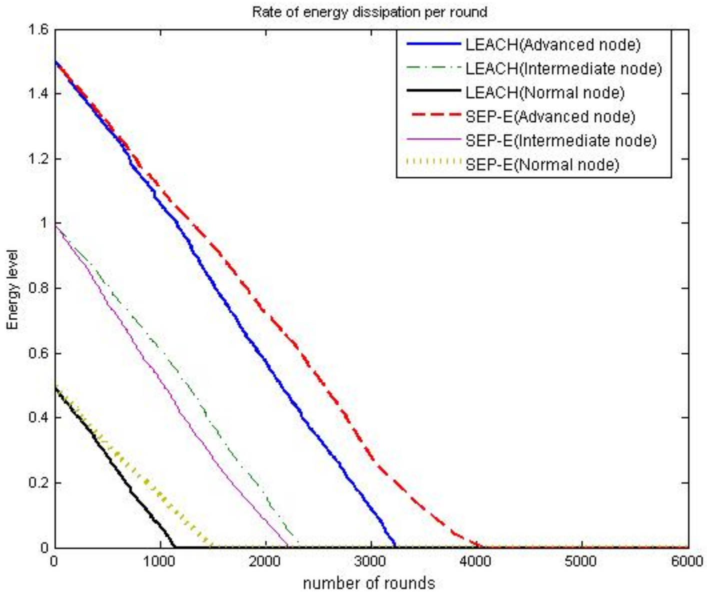

Figure 8: Shows the rate of energy dissipation of SEP-E and LEACH nodes the presence of energy heterogeneity. We have $m = 0.2, b = 0.3$, $\alpha = 2$ and $\mu = 1$.

extra energy introduced into the system. Figure 5 shows the performance of LEACH in the presence of energy heterogeneity and homogeneity, it is worth noting that LEACH performs well in the presence of energy homogeneity which is expected since that was the objective of the authors [7]. However, LEACH performs very poorly in the presence of energy heterogeneity compared with SEP-E. Even though the LEACH(heterogeneity) takes advantage of the extra energy compared to LEACH in the presence of homogeneity by extending the stability region, but, the instability in LEACH heterogeneity is also extended significantly, which negates the overall performance. This is because, 1) After the death of the first node LEACH (heterogeneity) becomes very unstable as there is no guarantee that the highly energized nodes become cluster heads more often than the normal nodes and 2) There is no guarantee that optimal number of cluster head would be selected in some rounds.

The rate of energy dissipation for all the nodes in SEP-E is much better than in LEACH (heterogeneity) (see Figure 8). This means SEP-E achieves better utilization of the extra energy introduced into the system compared with LEACH, which is the intended objective for our protocol design. Figure7 summarizes the spread of SEP-E and LEACH stability data in the presence of energy heterogeneity. The stability of SEP-E and LEACH was observed for 10 runs, the above graph revealed the skewness of SEP-E compared with the LEACH performance over same number of trials. Majority of our experimental data for SEP-E falls within some expected range and are better when compared with LEACH. We observed that the nodes in SEP-E use up half of its energy at an average of 704 rounds compared with LEACH at an average of 478 rounds. Also SEP-E's stability region is more flattened when studied over a number of trials compared with LEACH.

To sum up, in our simulation we obtained a prolonged stability period and a reduction in the instability region in all trials. Ideally the advanced nodes become cluster heads more than both the intermediate and normal nodes. The intermediate nodes take up the role of cluster head more frequently than the normal nodes, also as expected according to our model design.

6 Conclusion and Future Direction

We present an enhanced SEP algorithm for WSNs in the presence of energy heterogeneity. Using a heterogeneous three-tier node setting in a clustering algorithmic approach, nodes elect themselves as cluster heads based on their energy levels, retaining more uniformly distributed energy among sensor nodes. Our result shows that the enhanced SEP is more robust with respect to network life time and resource sharing. The traffic pattern in our work and related works that use clustering in heterogeneous scenario is constant bit rate (CBR).In our future work we intend to explore the variable bit rate (VBR) traffic pattern for application specific system in which we might be dealing with compressed video streams that are bursty in nature. We also intend to extend our work to a multi-hierarchy scenario, by making use of multi-level clustering techniques where some of the cluster heads might take up different roles to effectively manage the available resources in the network.

Another potential approach that we intend to explore for improving the overall network life cycle is to employ some kind of protocol switching between homogeneous and heterogeneous settings; here the parameter might be an energy variance such that when this is exceeded between neighboring nodes, the system triggers a protocol that is robust in heterogeneous settings and vice versa.

Finally, we are currently investigating how we can best control the number of associated cluster members in every cluster, the idea is to create a relative load balancing capability that ensures a balanced number of nodes in each clusters formed. This would give better uniformity in their respective energy usage, eventually leading to further prolonged effective network life time.

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