Enhancing Clustering in Wireless Sensor Networks with Energy Heterogeneity

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ABSTRACT

While wireless sensor networks (WSN) are increasingly equipped to handle more complex functions, in-network processing still requires the battery-powered sensors to judiciously use their constrained energy so as to prolong the elective network life time. There are a few protocols using sensor clusters to coordinate the energy consumption in a WSN, but how to deal with energy heterogeneity remains a research question. The authors propose a modified clustering algorithm with a three-tier energy setting, where energy consumption among sensor nodes is adaptive to their energy levels. A theoretical analysis shows that the proposed modifications result in an extended network stability period. Simulation has been conducted to evaluate the new clustering algorithm against some existing algorithms under different energy heterogeneity settings, and favourable results are obtained especially when the energy levels are significantly imbalanced.

Keywords: *Clustering, Energy Heterogeneity, Life-Time, Three-Tier Energy Setting, Wireless Sensor Networks*

1. INTRODUCTION

Wireless communication technologies continue to grow in diverse areas to provide new opportunities for business data 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 production systems, and natural or social environments. There is a growing need for the nodes to handle more complex functions in data acquisition and processing, and energy saving solutions remains a major requirement for these battery-powered sensor nodes.

A sensor node consists of three sensor subsystems (Qing et al., 2006): the environment sensor; the data processor that performs local computations on the data sensed, and the communicator that performs information exchange between neighbouring nodes. Each

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sensor is usually limited in their energy capacity, processing power, memory capacity and sensing capabilities. However, a network of these sensors gives rise to a robust, reliable and accurate network.

Many studies on WSNs have been carried out (Akyildiz et al., 2002a, 2002b; Baronti et al., 2007; Younis & Fahmy, 2004). WSN technologies are continuously finding new applications 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 the 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 (Heinzelman et al., 2002). It is noted that, to maintain a reliable information delivery, data aggregation and information fusion are 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. More in-depth discussions on the design issues of in-network processing and data aggregation can be found in Karl and Wilig (2007).

However, one of the key issues that merit attention is the energy heterogeneity in sensor networks (Mhatre & Rosenberg, 2004). To some extent energy heterogeneity among WSN nodes is inevitable. It occurs when there is significant energy difference between an individual sensor and its neighbours, 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, e.g., different nodes having different sensor functions and hence different batteries. An inefficient use of the available albeit heterogeneous energy among the nodes will lead to poor performance and short lifecycle of the network. Despite some progress made in solving this problem, energy heterogeneity remains a challenge to WSNs. We present a modified algorithm for properly distributing sensor energy and ensuring prolonged network life time. Our algorithmic approach operates in a WSN under a modelling of three-level energy heterogeneity that controls the probability of conducting data transmission. 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 the cluster formation mechanism are presented in details in Section 3 and the pattern of energy consumption within the clusters is examined. We then present our proposed clustering protocol in Section 4. The simulation results are presented in Section 5. Finally, we conclude the paper and highlight some future directions for further research.

2 RELATED WORK

Clustering techniques have been employed to deal with energy management in WSNs. Low Energy Adaptive Clustering Hierarchy (LEACH) (Heinzelman et al., 2002) 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 the network. The rotation of cluster heads can also be a means of fault tolerance (Abbasi & Younis, 2007). However, the LEACH protocol is not heterogeneity-aware, in the sense that when there is an energy difference to some extent between sensor nodes in the network, the sensors die out faster than a more uniform energy setting (Smaragdakis & Bestavros, 2004). In real life situation it is difficult for the sensors to maintain their energy uniformly, which 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) (Shepard, 1996) do not assure a balanced and uniform use of the sensors' residual energy as the network evolves. In Distributed Energy-Efficient Clustering algorithm (DEEC) (Qing et al., 2006), 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. It however requires additional energy consumption to share the information among the sensor nodes. The Stable Election Protocol (SEP) (Smaragdakis & Bestavros, 2004) is another heterogeneity-aware protocol. It does not require energy knowledge sharing, but is based on assigning weighted probabilities for cluster head election according to each node's respective energy. This approach improves the random selection of cluster heads, 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.

For a wider range of discussions, a survey of clustering algorithm was presented in (Abbasi & Younis, 2007); the proper distribution of sensors in clusters so that load balancing can be achieved is another objective of clustering when designing a robust protocol for WSNs (Al-karaki & Kamal, 2004; Younis & Fahmy, 2004). The clustering issue was also discussed in a review on wireless multimedia sensor networks (Akyildiz et al., 2007).

We focus on the clustering optimisation in heterogeneous energy settings. The contribution of this work is a SEP extension that considers 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. We analyse the energy consumption pattern of sensor nodes and reveal the importance of customised control on sensor cluster head election for heterogeneous energy settings. Our goal is to achieve a robust self-configured WSN that maximizes its lifetime.

3. THE NETWORK MODEL

Hereafter we introduce the network model with its radio and energy settings, the energy dissipation model, and the cluster head election mechanism.

3.1. Radio Channel and Energy Dissipation

Let us consider a radio energy dissipation model used in a number of previous studies (Heinzelman et al., 2002; Qing et al., 2006; Smaragdakis & Bestavros, 2004) as shown in Figure 1. Assume that for each bit energy dissipation is $E_{elec} = 50nJ$ 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.

To transmit k bits, the energy to be expended is:

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d) = \quad (1)$$

Here d_0 is the distance threshold for swapping amplification models. It can be calculated as $d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}$.

To receive a k -bit message, the radio will consume:

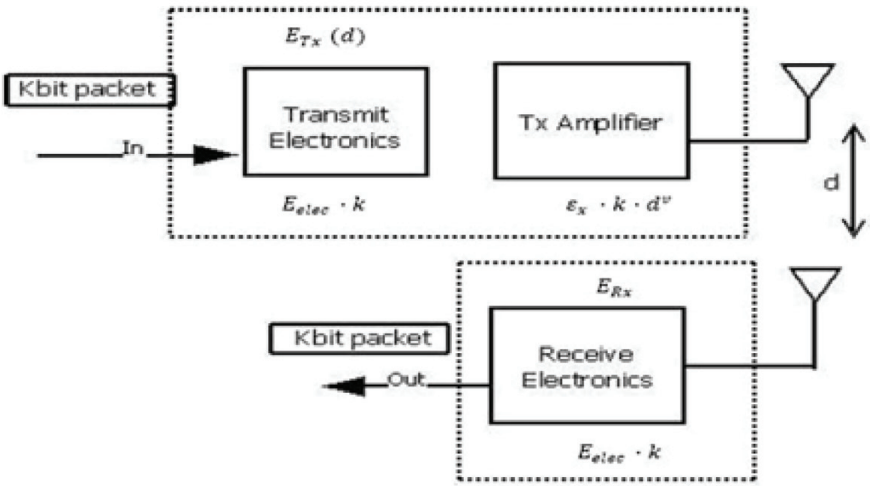
$$E_{Rx}(k) = E_{elec}k. \quad (2)$$

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 and Data Aggregation

To form clusters, a distributed algorithm is used similarly to Heinzelman et al. (2002) and Smaragdakis and Bestavros (2004). The main

Figure 1. Network model diagram



idea is for the sensor nodes to elect themselves with respect to their energy levels autonomously. By clustering, sensor nodes save on communication cost as the transmission distance is reduced and much lower energy consumption is needed. Each node transmits its data to the closest cluster head, and the cluster heads performs data aggregation (Heinzelman et al., 2002; Smaragdakis & Bestavros, 2004), further reducing data transmission.

Now we proceed to our indicator function of choosing 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 form a set G in the past $\frac{1}{P_{opt}}$ round.

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

$$T(i) = \begin{cases} \dfrac{P_{opt}}{1 - P_{opt}\left[r \bmod \left(\dfrac{1}{P_{opt}}\right)\right]} & if \quad i \epsilon G; \\ 0 & Otherwise. \end{cases} \tag{3}$$

Assume nodes are uniformly and randomly distributed in a square area of M m^2. On average there would be $\frac{n}{c}$ nodes per cluster, one cluster head (CH) and $\frac{n}{c} - 1$ non-CH nodes. 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:

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

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

For a non-CH node, the energy expended will be to transmit k bits to the respective CHs, while a free space power loss d^2 is adopted since normally $d_{toCH} < d_0$ in Eqn.(1):

$$E_{non-CH} = kE_{elec} + k\epsilon_{fs} d_{to\,CH}^2 , \quad (5)$$

where d_{toCH} is the distance from each node to their respective cluster heads.

The average value of d_{toCH} can be estimated as $M / \sqrt{2\pi c}$ (Heinzelman et al., 2002). The energy dissipated in a cluster per round can be estimated as

$$E_{cluster} \approx E_{CH} + \frac{n}{c} E_{non-CH} \quad (6)$$

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

$$E_{total} = cE_{cluster} \quad (7)$$

If the average of d_{toSink} is greater than d_0, the total energy can be calculated as:

$$E_{total} = c[kE_{elec}(\frac{n}{c} - 1) + kE_{DA}\frac{n}{c} + kE_{elec} + k\epsilon_{mp} d_{to\ Sink}^4] + (kE_{elec} + k\epsilon_{fs} M^2 / 2\pi c). \quad (8)$$

Otherwise, when $d_{toSink} < d_0$ applies, the total energy dissipation becomes

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

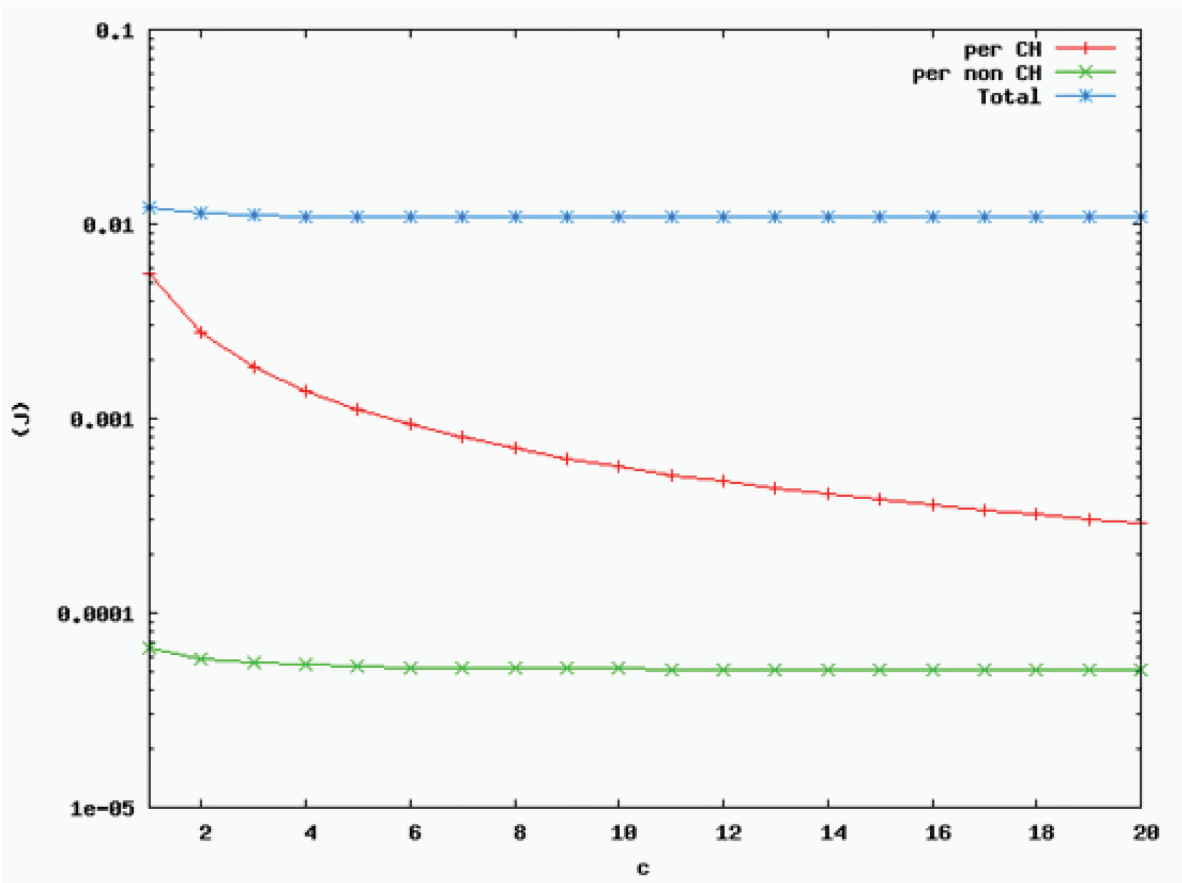
Here the number of clusters (c) is an important parameter that controls the level of data aggregation (within clusters) and communication within and without clusters. The bigger c is, the smaller is the cluster sizes, hence lesser is energy consumption for data aggregation and within-cluster transmission; however, more CH nodes will be doing longer-distance transmission to the sink. As discussed in Heinzelman et al. (2002) and Smaragdakis and Bestavros (2004), 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 solutions. We consider the situation when the sink is located at the centre of the monitoring area and $d_{toSink} < d_0$ applies. It is shown $c_{opt} = 2.614\sqrt{\frac{n}{2}}$ (Smaragdakis & Bestavros, 2004). In a typical setting (details given later in Section 5), the energy consumption on average by each individual non-CH sensor and CH sensor, and the total energy consumed in each round, are plotted out in Figure 2 against varying numbers of clusters (c). While the total energy hits the bottom with $c_{opt} = 10$, it is not too sensitive to the setting of c as shown on the log-scale plot. However, it is clearly shown that for each node the energy consumption as a CH is much more significant than a non-CH node – more than 10 times as much over a wide range of c values.

The energy consumption pattern given in Figure 2 has a clear implication. For the network to operate over a long lifetime, the election of cluster heads hence is crucial, as inadequate control of the election process may lead to unduly over-consumption of energy, resulting in early death of nodes especially when a node with very low energy is chosen to be a CH. When energy heterogeneity exists, this issue becomes even more serious.

3.3. Energy Heterogeneity

Here we briefly discuss the intuition behind SEP and its improvement on LEACH. SEP improves the stable region of the system using a clustering hierarchy, making an efficient use of the extra energy introduced into the system that serves as a source of heterogeneity. Two energy levels are considered. SEP deals with the heterogeneous setting by extending the epoch of the sensor network to the LEACH protocol in proportion to the energy increment.

Figure 2. Energy consumption pattern when the number of clusters (c) changes. Energy values in log-scale are in the unit of Joules



For optimization of the stable region, SEP proposed a new epoch equal to $\frac{1}{P_{opt}}(1+m\alpha)$ (Smaragdakis & Bestavros, 2004).

SEP uses 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 are chosen to reflect the extra energy introduced into the network system. These probabilities and the total initial energy are given below respectively:

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

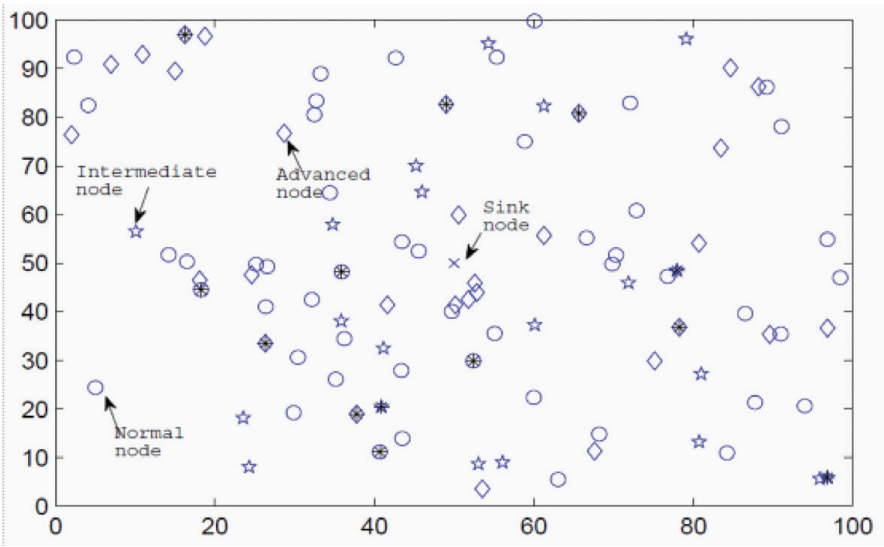
where P_{nrm} is the election probability for normal nodes, P_{adv} is the probability for the advanced nodes, m is the proportion of advanced nodes (with α times more energy than the normal nodes), and finally E_{Init} is the total initial energy of the network.

4. EXTENDING SEP

4.1. The New Model

In this section we present our proposed solution as an extension to the SEP protocol, called 'SEP-E', by considering three energy levels in two hierarchy settings as an intended improvement to SEP and LEACH. We intend to optimize the stable region of the network system by further increasing the epoch to accommodate the additional energy introduced to the system. In our

Figure 3. A WSN with a 3-tier energy heterogeneity among sensor nodes



approach we introduce an additional type of nodes 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 continuous re-energization of nodes throughout the data retrieval process, by deploying new nodes to replace dead ones.

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 3 demonstrates the heterogeneous settings we used. The new heterogeneous setting with the 3-tier node energy has no effect on the spatial density of the network. We keep P_{opt} the same. The total initial energy of the system is increased by the introduction of intermediate nodes:

$$E_{Init} = nE_o(1-m-b) + nmE_o(1+\alpha) + nbE_o(1+\mu) = nE_o(1+m\alpha+b\mu), \quad (11)$$

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 Smaragdakis and Bestavros (2004), the following conditions must be satisfied:

C1: The advanced nodes must be cluster head exactly $(1+\alpha)$ times within an epoch;
C2: The intermediate nodes must be cluster head exactly $(1+\mu)$ times within an epoch;
C3: Every normal node must also become cluster head once every epoch;
C4: The average number of cluster in the network should be nP_{opt}.

This translates into a probability problem that we can solve mathematically, giving a new set of election probabilities, with P_{int} introduced for intermediate nodes:

$$P_{nrm} \quad (12)$$

$$P_{int} = (P\_opt\ (1+\mu)) / (1+m\alpha+b\mu), \quad (13)$$

and:

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

To guarantee that the sensor nodes become cluster heads according to these probabilities as given above, we must define new thresholds for the election processes, modifying Eqn.(3). The threshold $T(n_{nrm})$, $T(n_{int})$, $T(n_{adv})$ for normal, intermediate and advanced nodes respectively, becomes:

$$T_{nrm}(n) = \begin{cases} \dfrac{P_{nrm}}{1 - P_{nrm}\left[r \bmod \left(\dfrac{1}{P_{nrm}}\right)\right]} & if\ n_{nrm} \epsilon G'; \\ 0 & Otherwise, \end{cases} \quad (15)$$

where G' is the set of normal nodes that has not become cluster head in the past $1/P_{opt}$ rounds. Hence we have $n(1-m-b)$ normal node, meeting exactly Condition C3. The same applies to the conditions C2 and C1 for intermediate and advanced nodes, controlled by the following thresholds respectively:

$$T(n_{int}) = \begin{cases} \dfrac{P_{int}}{1 - P_{int}\left[r \bmod \left(\dfrac{1}{P_{int}}\right)\right]} & if\ n_{int} \epsilon G''; \\ 0 & Otherwise, \end{cases} \quad (16)$$

where G'' is the set of intermediate nodes that have not become cluster head in the past $1/P_{int}$ rounds, and

$$T(n_{adv}) = \begin{cases} \dfrac{P_{adv}}{1 - P_{adv}\left[r \bmod \left(\dfrac{1}{P_{adv}}\right)\right]} & if\ n_{adv} \epsilon G'''; \\ 0 & Otherwise, \end{cases} \quad (17)$$

with G''' being the set of advanced nodes that has not become cluster head in the past $1/Padv$ rounds.

From Eq. (12) - (14), the average total number of cluster heads per round will be:

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

This gives us the same number of cluster heads compared with the original LEACH setting. Therefore, while using new thresholds to ensure that conditions C1-C3 hold, C4 is also satisfied. On the other hand, energy dissipation is better adapted to energy heterogeneity in our approach, as we will illustrate as follows by examining the theoretical average lifetime of the sensor nodes.

4.2. Lifetime Analysis

Here we provide a mathematical analysis of the lifetime of SEP-E and show that compared with LEACH, SEP-E extends the lifespan of its all three types of nodes.

First, we concentrate on the normal nodes as they are the energy bottleneck of the network. It can be safely assumed that energy consumption at each node is largely caused by being elected as cluster head and having to conduct data aggregation and transmission. The lifetime of a normal node, in a LEACH setting, can then be roughly estimated as:

$$L = \frac{E_0}{E_{CH} P_{opt}} \quad (19)$$

In SEP-E, the nodes' election probabilities are modified, hence, according to Eq. (12) - Eq. (14), their lifetime is also changed. For normal nodes, we have

$$L' = \frac{E_0}{E_{CH} P_{nrm}} = (1 + m\alpha + b\mu)L, \quad (20)$$

which indicates an extended lifetime compared with LEACH.

For intermediate and advanced nodes (note that they have elevated initial energy), similarly we can work out the relevant lifetimes for SEP-E:

$$L'_i = \frac{(1+\ \mu)E_0}{E_{CH} P_{int}} = (1 + ma + b\mu)L, \quad (21)$$

$$L'_a = \frac{(1+\ a)E_0}{E_{CH}P_{adv}} = (1+ma+b\mu)L,$$

suggesting both $L'_i = L'_a = L' > L$. Clearly the advanced nodes and intermediate nodes enjoy the same prolonged average lifetime. The stability period in SEP-E is therefore extended.

5. SIMULATION

5.1. Simulation Settings

For simulation 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 the 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 energy heterogeneity.

By changing the parameter values such as α, μ, m and b, we can simulate different scenarios of energy heterogeneity among the sensor nodes. Specifically, suppose we 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 epoch for the heterogeneous setting becomes $\frac{1}{P_{opt}}(1+m\alpha\ +b\mu)$. 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 $nbPint=4$ intermediate nodes as cluster heads per round and $nmPadv = 4$ advanced nodes as cluster heads per round. Other parameters used in our simulation are shown in Table 1.

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.

As explained in Smaragdakis and Bestavros (2004), the larger the stability period and the smaller the instability period are, the better the reliability of the clustering process of the network system is. However, we need to note the trade-off between the reliability and lifetime of the network system. In some cases the last alive node can still provide feedback, but this could in most cases be unreliable. Therefore when assessing the performance of the three protocols we look for a good balance between the stability and instability periods.

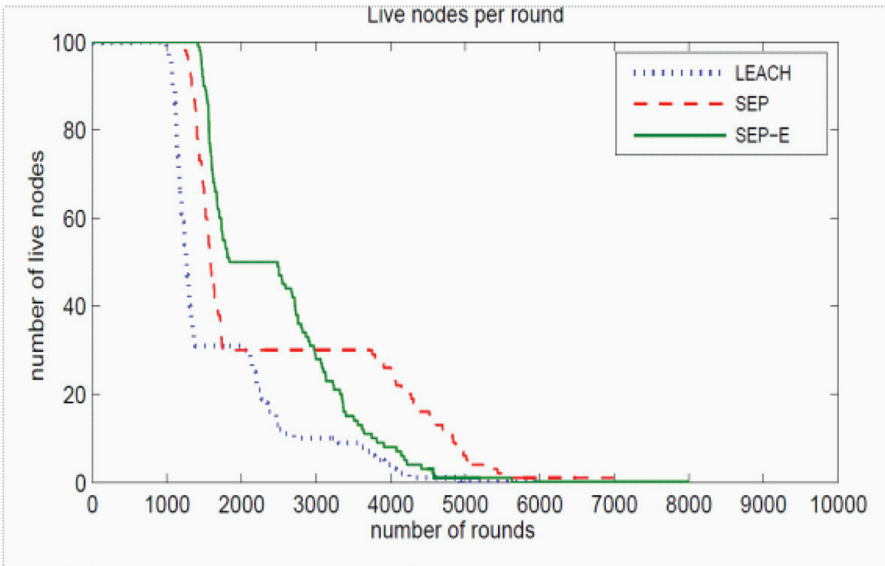
5.3. Simulation Results

We compare the result of our simulation with both LEACH and SEP in dealing with different levels of energy heterogeneity: high, moderate, and low. Figure 4 shows the number of live nodes over time when using SEP-E, LEACH and SEP respectively in the presence of energy heterogeneity. The stability of SEP-E compared with LEACH increases from 995 rounds to 1450 rounds, and the instability is 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 intermediate nodes to SEP-E, which acts as a bridge between the advanced nodes and the normal nodes, thus lowering the instability region. For an application with loose reliability requirements, for instance, it

Table 1. Parameter settings

Parameter	Values
$Eelec$	50nJ/bit
EDA	5nJ/bit/message
Eo	0.5J
k	4000
$Popt$	0.1
$\grave{o}_{fs}$	10pJ/bit/m^2
$\grave{o}_{mp}$	0.0013pJ/bit/m^4
n	100

Figure 4. Performance comparison under high energy heterogeneity: SEP-E (m=0.2, b=0.3, α=3 and μ=1.5), LEACH (m=0.2, b=0.3,α=3 and μ=1.5) and SEP (m=0.3, b=0, α=3.5 and μ=0); E_{Init} *=102.5J*



allows node death up to 50%, SEP-E will still outperform both SEP and LEACH, maintaining operation up till around Round 2500, compared with Round 1800 and 1500 respectively.

In scenarios with moderate or low level of energy heterogeneity as shown in Figure 5 and Figure 6, the stability region of SEP-E gain is reduced, yet SEP-E maintains the same stability period as SEP. In general, LEACH performs very poorly in the presence of energy heterogeneity compared with SEP-E. While the heterogeneity setting gives extra energy for LEACH to extend its stability period, the effect is negated by the lack of adaptiveness in LEACH, i.e., there is no mechanism in allowing normal nodes (with lower energy levels) get less chance

Figure 5. Performance comparison under moderate energy heterogeneity: SEP-E (m=0.1, b=0.2, α=2 and μ=1), LEACH (m=0.1, b=0.2, α=2 and μ=1) and SEP (m=0.3, b=0, α=1.3 and μ=0); E_{Init} *=70J*

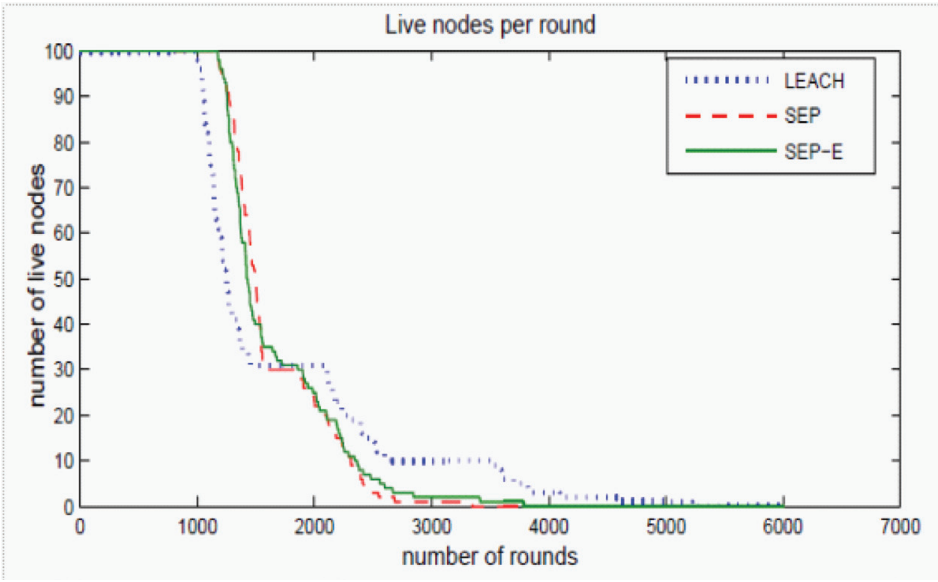
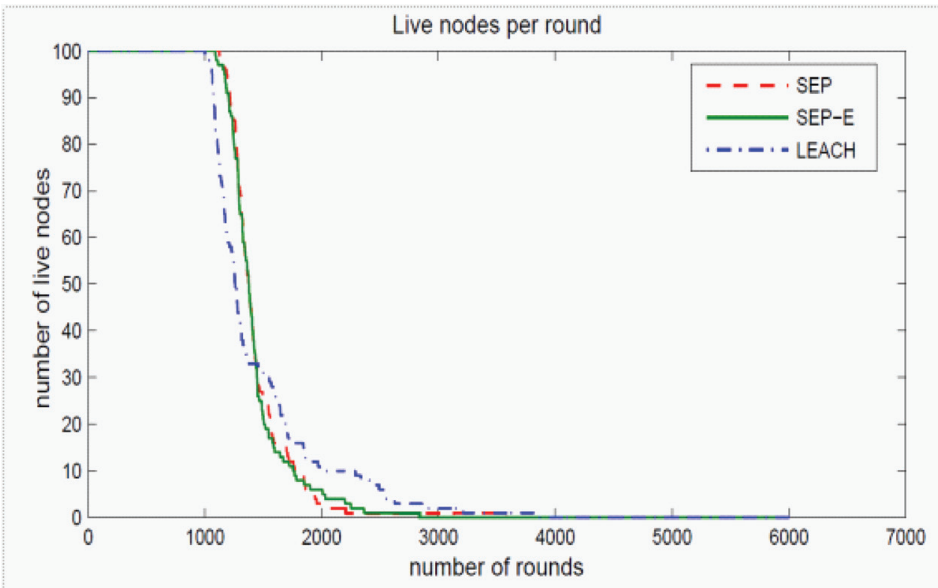


Figure 6. The performance of SEP-E (m=0.1, b=0.2, α=1 and μ=0.5), LEACH (m =0.1, b=0.2, α=1 and μ=0.5) and SEP (m=0.3, b=0, α=0.7 and μ=0); E_{Init} *= 60J in the presence of low energy heterogeneity*



of being elected as cluster heads. This results in unnecessary early death of normal nodes, leading to a prolonged instability period.

Figure 7 summarizes the spread of SEP-E, SEP and LEACH stability data in the presence of high energy heterogeneity. The box plots were generated by running each protocol under the same randomized setting for 10 runs. The stability period length of the three protocols is very distinct from each other. It is observed that

SEP-E achieved a clear advantage over both SEP and LEACH.

The superiority of SEP-E compared with LEACH can also be observed from the aspect of energy dissipation rates. Figure 8 compares the average energy dissipation pattern for three types of nodes under LEACH and SEP-E. For normal nodes, clearly SEP-E's energy dissipation slope is flatter than that of LEACH, therefore achieving a prolonged stability period approaching 2000 rounds. Interestingly, energy dissipation for intermediate nodes and advanced nodes are more aggressive in SEP-E than in LEACH, which suggests that these nodes take more turns in serving as cluster heads and reduces the potentially hazardous energy consumption on low-end normal nodes. LEACH on the other hand have rather similar energy dissipation pattern across three types of nodes the three corresponding curves are almost parallel to each other. Clearly, SEP-E achieves better utilization of energy heterogeneity introduced into the system compared with LEACH, confirming our design objective for the new protocol.

To sum up, in our simulation we have 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

We present an enhanced clustering 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, therefore retaining more uniformly distributed energy among sensor nodes. Our result shows that the enhanced protocol, SEP-E, is more robust in terms of network life time. The stability period produced by SEP-E is especially significantly improved from previous protocols such as LEACH and SEP when energy heterogeneity is high within the network. Further than the stability period, the number of live nodes can still remain relatively higher before the network becomes too unreliable to use.

The same as in other related work based on sensor clustering in either homogeneous or heterogeneous settings, we have only examined the constant-bit-rate (CBR) traffic model for the sensor nodes. In our future work we intend to consider variable bit rate (VBR) traffic pattern which is necessary for some specific applications, for example to deal with compressed video streams that are bursty in nature. Sensoring modality can also be extended into a multi-modal scenario where information fusing can contribute to better local decision-making, which implies potentially more energy consumption for storage and computation. Nevertheless, this is worth of consideration. 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 so as to effectively manage the available resources in a large network.

Another potential approach that we intend to explore for improving the overall network life cycle is to employ some kind of protocol switching mechanism between homogeneous and heterogeneous settings. The parameter might be an energy variance among neighbour sensor nodes, so that when a threshold is exceeded, the system triggers a protocol that is robust in heterogeneous settings and vice versa.

Finally, we are investigating how we can best control the number of associated cluster members in every cluster. The idea is to create a load balancing capability that ensures a balanced number of nodes in each cluster to be formed. This would give a better uniformity in their respective energy usage, eventually leading to further prolonged network life time. Another potential advantage resulted from this may be a more uniform distribution of live nodes, which then allows the network to maintain full or large coverage of the monitored area for a longer period.

Figure 7. The behaviour of SEP-E and LEACH for 10 trials in the presence of heterogeneity. We have m = 0.2, b = 0.3, α = 3 and ¼ = 1.5

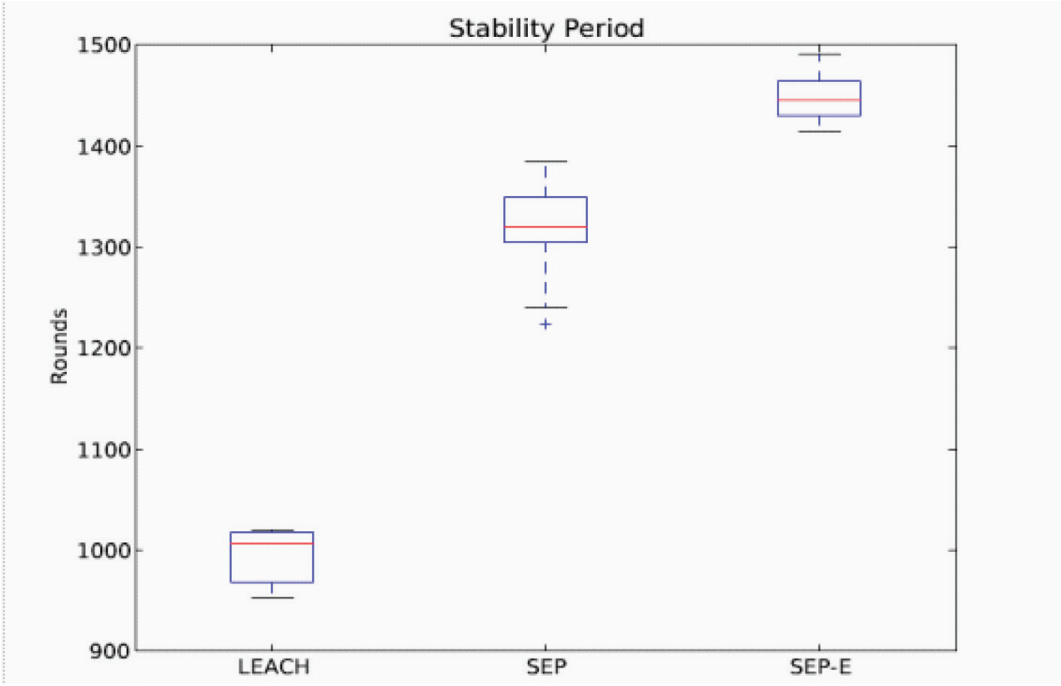
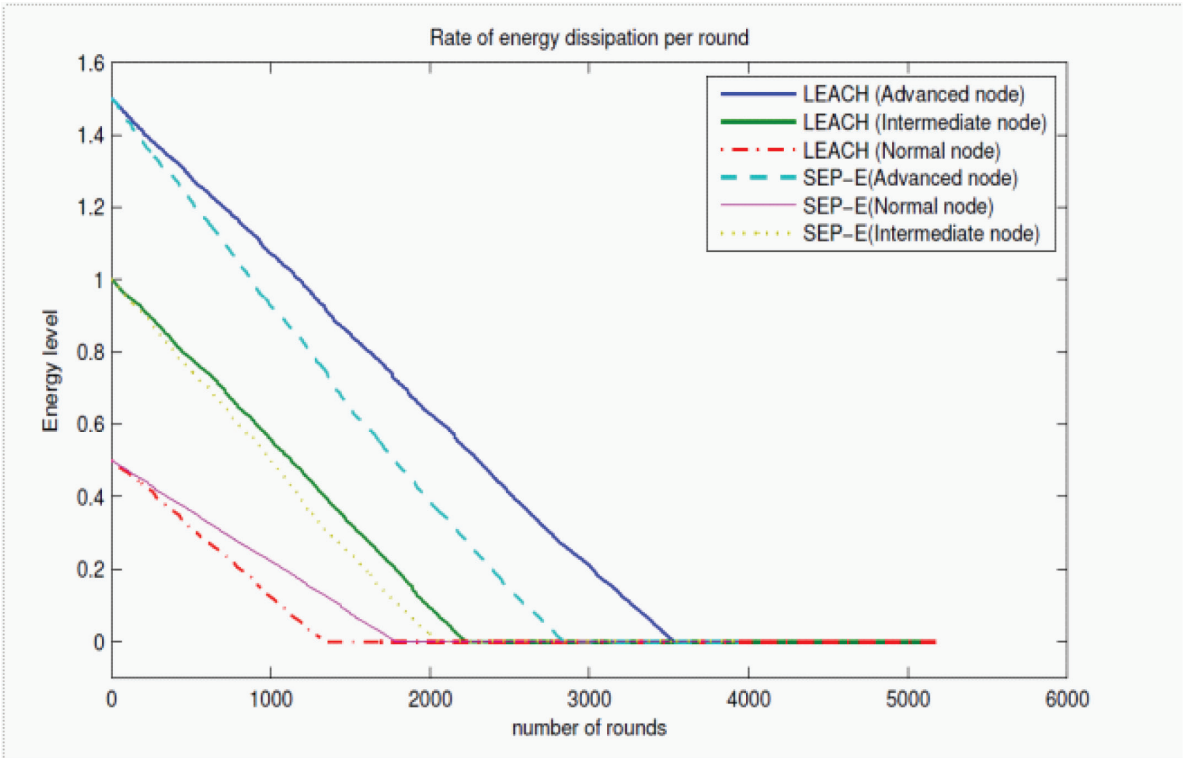


Figure 8. Shows the rate of energy dissipation of SEP-E and LEACH nodes the presence of energy heterogeneity. We have $m = 0.2$, $b = 0.3$, α = 2 and ¼= 1



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