Stochastic and Balanced Distributed Energy-Efficient Clustering (SBDEEC) for heterogeneous wireless sensor networks

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Abstract. Typically, a wireless sensor network contains an important number of inexpensive power constrained sensors which collect data from the environment and transmit them towards the base station in a cooperative way. Saving energy and therefore, extending the wireless sensor networks lifetime, imposes a great challenge. Many new protocols are specifically designed for these raisons where energy awareness is an essential consideration. The clustering techniques are largely used for these purposes. In this paper, we present and evaluate a Stochastic and Balanced Developed Distributed Energy-Efficient Clustering (SBDEEC) scheme for heterogeneous wireless sensor networks. This protocol is based on dividing the network into dynamic clusters. The cluster's nodes communicate with an elected node called cluster head, and then the cluster heads communicate the information to the base station. SBDEEC introduces a balanced and dynamic method where the cluster head election probability is more efficient. Moreover, it uses a stochastic scheme detection to extend the network lifetime. Simulation results show that our protocol performs better than the Stable Election Protocol (SEP) and than the Distributed Energy-Efficient Clustering (DEEC) in terms of network lifetime. In the proposed protocol the first node death occurs over 90% times longer than the first node death in DEEC protocol and by about 130% than SEP.

Keywords: Energy Consumption, DEEC, Clustering, Wireless Sensor Networks, Heterogeneous environment.

(Received July 07, 2009 / Accepted September 23, 2009)

1 Introduction

With the faster growing in electronics industry, small inexpensive battery-powered wireless sensors have already started to make an impact on the communications with the physical world.
Wireless sensor network (WSN) consists of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants, at different locations [1]. The development of wireless sensor networks was originally motivated by military applications for battlefield surveillance. Thereafter, wireless sensor networks are used in many civilian application areas, including environment and habitat monitoring, health care applications, home automation, and traffic control. This network contains a large number of nodes which sense data from an impossibly inaccessible area and send their reports towards a processing center which is called "sink". Since, sensor nodes are power-constrained devices, frequent and

long-distance transmissions should be kept to minimum in order to prolong the network lifetime [2, 3]. Thus, direct communications between nodes and the base station are not encouraged. Because the large part of energy in the network is consumed in wireless communication in a WSN [4], several communication protocols have been proposed to realize power-efficient communication in these networks. One effective approach is to divide the network into several clusters, each electing one node as its cluster head [5]. The cluster head collects data from sensors in the cluster which will be fused and transmitted to the base station. Thus, only some nodes are required to transmit data over a long distance and the rest of the nodes will need to do only short-distance transmission. Then, more energy is saved and overall network lifetime can thus be prolonged. Many energy-efficient routing protocols are designed based on the clustering structure where cluster-heads are elected periodically [6, 7]. These techniques can be extremely effective in broadcast and data query [8, 9]. DEEC is a distributed energy-efficient clustering algorithm for heterogeneous wireless sensor networks which is based on clustering, when the cluster-heads are elected by a probability based on the ratio between residual energy of each node and the average energy of the network. The round number of the rotating epoch for each node is different according to its initial and residual energy. DEEC adapts the rotating epoch of each node to its energy. The nodes with high initial and residual energy will have more chances to be the cluster-heads than the low-energy ones. Thus DEEC can prolong the network lifetime, especially the stability period, by heterogeneous-aware clustering algorithm [10]. This choice penalizes always the advanced nodes, specially when their residual energy deplete and become in the range of the normal nodes. In this situation, the advanced nodes die quickly than the others. The Stochastic and Balanced Distributed Energy-Efficient Clustering (SBDEEC), permits to balance the cluster head selection over all network nodes following their residual energy. So, the advanced nodes are largely solicited to be selected as cluster heads for the first transmission rounds, and when their energy decreases sensibly, these nodes will have the same cluster head election probability like the normal nodes. Moreover, an other key idea of this algorithm is to better reduce the intra-clusters transmission when the objective is to collect the maximum or minimum data values in a region (like temperature, humidity...). With this second idea our protocol will be stochastic.
The outline of this paper is as follows. Section II describes a review related work. In section III, we present the details of SBDEEC algorithm. Additionally, section IV gives the simulation results. Finally, a conclusion is presented.

2 Related work

Because the large part of energy in a WSN is consumed when the wireless communications are established [4], several communication protocols have been proposed to realize power-efficient communication in these networks. Moreover, many techniques were proposed to allow transmission in WSN providing energy efficiency multi-hop communication in ad hoc networks. Currently, there are several energy efficient communication models and protocols that are designed for specific applications, queries, and topologies.
The Directed Diffusion protocol proposed in [4] is data centric in that, all nodes transmit informations directly to the base station.

M. Ettus [11] and T. Shepard [12] proposed the so-called MTE (Minimum Transmission Energy) routing scheme which selects the route that uses the least amount of energy to transport a packet from the source to the destination. Assuming that the energy consumption is proportional to square distance between nodes, the intermediate nodes, which operate as routers, are chosen for minimizing the sum of squared distances over the path. For example, assume that a network is formed by nodes A, B, and C. The node A would transmit to node C. In the MTE, the node B participates to the route only if:

$$d_{AC}^2 > d_{AB}^2 + d_{BC}^2 \quad (1)$$

Heinzelman and al. proposed LEACH [13] a protocol based on network clustering. Basically any clustering algorithm is concerned with the management of clusters, which includes: forming a suitable number of clusters, selecting a cluster head for each cluster and controlling the data transmission within clusters and from cluster heads to the base station [2]. There are two kinds of clustering schemes. The clustering algorithms applied in homogeneous networks which are called homogeneous schemes, where all nodes have the same initial energy, like the Low-Energy Adaptive Clustering Hierarchy (LEACH) [13], Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [14], and Hybrid, Energy-Efficient Distributed clustering (HEED) [15].

- LEACH chooses cluster heads periodically and distributes energy consumed uniformly by role rotation. Under the heterogeneous network this protocol will become poor and not efficient.

- The LEACH-C is a centralized LEACH where the base station first, receives all the information about each node regarding their location and energy level. The base station then runs this algorithm for the formation of cluster heads and clusters. Here the number of cluster heads is limited and the selection of the cluster heads is also random but the base station makes sure that a node with less energy does not become a cluster head. However, LEACH-C is not feasible for larger networks because nodes far away from the base station will have problem sending their states to the base station and as the role of cluster heads rotates so every time the far nodes will not reach the base station in quick time increasing the latency and delay.

- In the PEGASIS protocol all network become like a one chain which is calculated by nodes or by the base station. Only one node of the chain aggregates all data and sends it to the Sink. The difficulty of this protocol is based on the requirement of the global knowledge of the network topology.

- The HEED protocol is another distributed cluster based protocol in which the election of cluster head is dependent upon the residual energy of the nodes and also selects these cluster heads stochastically. In heterogeneous WSNs, there is a probability that the lower energy nodes could own larger election probability than the higher energy nodes.

The heterogeneity of nodes in terms of their initial energy defines the second type of clustering algorithms which are applied in heterogeneous networks. There are plenty of heterogeneous clustering algorithms, such as LEACH-E [16], Stable Election Protocol (SEP) [17], M-LEACH [18], Energy Efficient Clustering Scheme (EECS) [19], LEACH-B [20] and Equitable Distributed Energy-Efficient Clustering (EDEEC)[21].

- The SEP protocol is a two-level heterogeneous network, these tow levels are defined by the initial energy of each nodes. It is based only on the initial energy but not on the residual one.

- M. Ye et al, develop the EECS which chooses the cluster- heads with more residual energy through local radio communication. In cluster formation phase, EECS considers the trade-off of energy expenditure between nodes to the cluster-heads and the cluster heads to the base station. But on the other hand, it increases the requirement of global knowledge about the distances between the cluster heads and the base station.

- In the EDEEC B. elbhiri et al, develop a clustering algorithm for heterogeneous network, using an intermediate cluster-based hierarchical solution. However, this protocol is suitable only if the Base Station is far away from the network.

Moreover, in [10], Li Qing et al propose and validate the Distributed Energy Efficiency Clustering (DEEC) protocol which uses a new conception based on the ratio between residual energy of each node and the average energy of the network. The simulation results of DEEC show clearly its performances than the others. Certainly, our SBDEEC protocol is based on DEEC but with a new proposal strategies. These last ones, develop more the performance of all nodes and increase more the network lifetime. The SBDEEC is a Stochastic and balanced DEEC. Stochastic because the number of transmission intra-clusters is reduced when the objective is to collect the maximum or minimum data values in a region (like temperature, humidity ...) and balanced because the clustering is more fair and equitable.

3 Radio energy dissipation model

At the beginning, for the purpose of this study we use similar energy model and analysis as proposed in [13]. According to [13],[16] the radio energy dissipation model

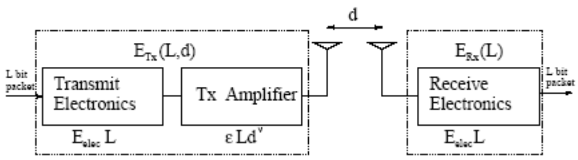

Figure 1: Radio Energy Dissipation Model

illustrated in figure 1. In order to achieve an acceptable Signal-to-Noise Ratio (SNR) in transmitting an L-bit message over a distance d, the energy expended by the radio is given by

$$E_{tx}(L,d) = \begin{cases} LE_{elec} + LEfsd^2 & \text{if} \quad d < do \\ LE_{elec} + LEmpd^4 & \text{if} \quad d \geq do \end{cases} \tag{2}$$

where E_{elec} is the energy dissipated per bit to run the transmitter(E_{TX}) or the receiver circuit(E_{RX}). The E_{elec} depends on many factors such as the digital coding, the modulation, the filtering, and the spreading of the signal [16]. *Efs* and *Emp* depend on the transmitter amplifier used model, and d is the distance between the sender and the receiver. For the experiments described here, both the free space (d^2 power loss) and the multi path fading (d^4 power loss) channel models were used, depending on the distance between the transmitter and the receiver. If the distance is less than a threshold, the free space (**fs**) model is used; otherwise, the multi path (**mp**) model is used.

we have fixed the value of do like on DEEC [10] at $do = 70$.

4 The SBDEEC

The Stochastic and Balanced Distributed Energy Efficient Clustering protocol (SBDEEC) is based on DEEC scheme, where all nodes use the initial and residual energy level to define the cluster heads. To evade that, each node needs to have the global knowledge of the networks, DEEC and SBDEEC estimate the ideal value of network lifetime, which is used to compute the reference energy that each node should expend during each round. In this paper, we consider a network with N nodes, which are uniformly dispersed within a $M \times M$ square region. The network is organized into a clustering hierarchy, and the cluster heads collect measurements information from cluster nodes and transmit the aggregated data to the base station directly. Moreover, we suppose that the network topology is fixed and no-varying on time. We assume that the base station is located at the center 2.

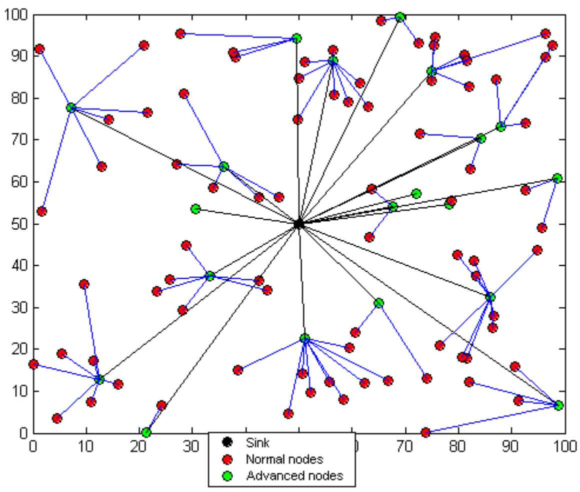

Figure 2: Heterogeneous random network with 100-nodes

Furthermore, the figure 2 shows a two-level heterogenous network, where we have two categories of nodes, $m.N$ $advanced$ nodes with initial energy equal to $Eo.(1+a)$ and $(1-m).N$ $normal$ nodes, where the initial energy is equal to Eo. Where a and m are tow variable which control the nodes percentage types (advanced or normal) and the total initial energy in the network E_{total}. So, this last value is given by:

$$Etotal = N.(1-m).Eo + N.m.Eo.(1+a) = N.Eo.(1+am) \tag{3}$$

4.1 Balanced DEEC

SBDEEC implements the same strategy such as DEEC in terms of estimating average energy of networks and the cluster head selection algorithm. This strategy is based on the initial and the residual energy where:

- The average energy of rth round is set as follows

$$\overline{E}(r) = \frac{1}{N} E_{total}(1 - \frac{r}{R}) \tag{4}$$

  R denote the total rounds of the network lifetime and is defined as

$$R = \frac{E_{total}}{E_{Round}} \tag{5}$$

- E_{Round} is the total energy dissipated in the network during a round, is equal to:

$$E_{Round} = L(2NE_{elec} + NE_{DA} + kEmpd^4_{toBS} + NEfsd^2_{toCH}) \tag{6}$$

  where k is the number of clusters, E_{DA} is the data aggregation cost expended in the cluster heads, d_{toBS} is the average distance between the cluster head and the base station, and d_{toCH} is the average distance between the cluster members and the cluster head.

- Because we are assuming that the nodes are uniformly distributed [10], we can get:

$$d_{toCH} = \frac{M}{\sqrt{2k\pi}}, \qquad d_{toBS} = 0.765\frac{M}{2} \tag{7}$$

- The optimal number of clusters is defined as:

$$k_{opt} = \frac{M}{d^2_{toBS}} \frac{\sqrt{N}}{\sqrt{2\pi}} \frac{\sqrt{Efs}}{\sqrt{Emp}} \tag{8}$$

The difference between SBDEEC and DEEC is localized in the expression which defines the probability to be a cluster head for normal and advanced nodes:

$$p_i = \begin{cases} \frac{p_{opt} E_i(r)}{(1+am)\overline{E}(r)} & \text{for normal nodes} \\ \frac{(1+a) p_{opt} E_i(r)}{(1+am)\overline{E}(r)} & \text{for advanced nodes} \end{cases} \quad (9)$$

In this expression we observe that nodes with more residual energy (Advanced nodes) - $\overline{E}_r$ at round r- are more probable to be a clusters head. Certainly, the objective of this strategy is to distribute correctly the energy consumption on the network and to increase more the lifetime of the low-energy nodes which is not the case on LEACH. However, it is possible on one moment some of advanced nodes will have the same residual energy like normal ones. Although, DEEC continues to penalize just the advanced ones. This case is not the optimal way, because these nodes will be continuously a clusters head, then they will die quickly than the others. Let us explain why? Because the advanced probability is higher, it is possible that an advanced node will be a cluster head through all rounds of simulations. Then, at each iteration the residual energy is decreased by:

$$E_{disAN} = L[E_{TX} + Emp(DoptBS^4) + (E_{RX} + E_{DA})n/Kopt] \quad (10)$$

Where E_{disAN} is the Energy dissipated by an Advanced Node by round.

Then, the number of iterations possible for a CH Nb_{CH} with a initial energy equal to $(1+a)Eo$ is

$$Nb_{CH} = (1+a)Eo/E_{disAN} \quad (11)$$

In the same way we can define the Energy dissipated by a Normal Nodes E_{disNN} in each round:

$$E_{disNN} = L(E_{TX} + Efs(DtoCH^2)) \quad (12)$$

We can define the number of iterations possible for a normal node Nb_{NN} with Eo initial energy by:

$$Nb_{NN} = Eo/E_{disNN} \quad (13)$$

In figure 3, we observe that, for critical round, the advanced and normal nodes will have the same residual energy. Although and according to Li Qing and all [9], the advanced nodes probability to be a cluster head is greater than the normal one. In this way, we continue to punish more just these nodes, so they spend more energy and they will die quickly 3.

To avoid this unbalanced case, our protocol SBDEEC introduces some changes on the equation 9. These changes are based on using a threshold residual energy value Th_{REV}, which is equal to:

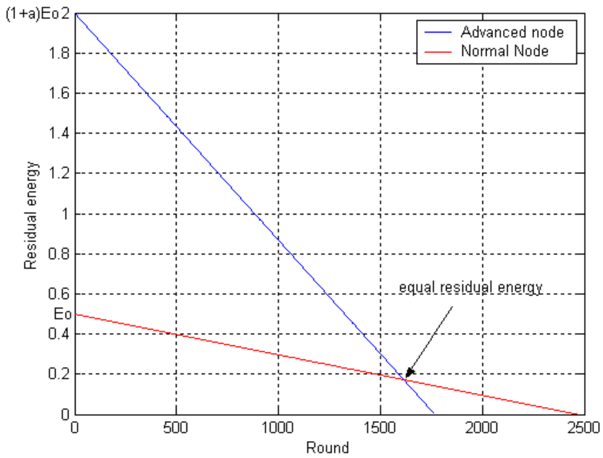

Figure 3: variation of residual energy for an advanced and normal nodes

$$Th_{REV} = Eo(1 + \frac{aE_{disNN}}{E_{disNN} - E_{disAN}}) \quad (14)$$

It represents the theoretical value where normal and advanced nodes have a equal residual energy. This value is represented by the intersection lines on the figure 3. The key idea is that, under this Th_{REV} all nodes, the advanced an normal ones, must have the same probability to be cluster head. Therefor, the cluster head election will be balanced and more equitable. So, equation 9 which represents the nodes average probability p_i to be a cluster head will changed as fellow:

$$p_i = \begin{cases} \frac{p_{opt} E_i(r)}{(1+am)\overline{E}(r)} & \text{Nml node, } E_i(r) > Th_{REV} \\ \frac{(1+a) p_{opt} E_i(r)}{(1+am)\overline{E}(r)} & \text{Adv node, } E_i(r) > Th_{REV} \\ c\frac{(1+a) p_{opt} E_i(r)}{(1+am)\overline{E}(r)} & \text{Adv, Nml node, } E_i(r) \leq Th_{REV} \end{cases} \quad (15)$$

The value of Th_{REV} is written as $Th_{REV} = bEo$ where

$$b = (1 + \frac{aE_{disNN}}{E_{disNN} - E_{disAN}}) \quad (16)$$

Where $b \in [0, 1[$ and if $b = 0$, we will have the traditional DEEC.

Nevertheless, in the reality and during simulation, all advanced nodes can not be even a cluster heads. It is due certainly to the randomness of selection. The same case for normal nodes will be applied, where it is probable that some of them will be a cluster heads. So, this last theoretical value of b is not exact. Then, through a lot of simulations with a random topology, we tried to find the nearest value of b which improves the performances of the network. We use the parameters described in table 1 which are presented by Li. Qing in [10]. In figure 4, we represent the first node dies variation in function of b through 100 simulations. This figure presents the perfect value of b and which is equal to $b = 0.7$, So:

$$Th_{REV} \simeq (7/10)Eo \tag{17}$$

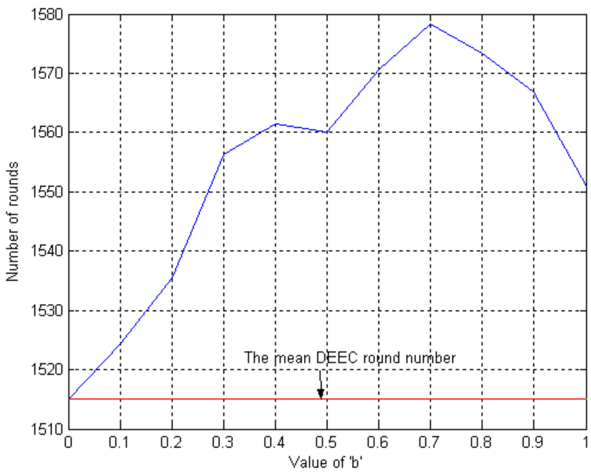

Figure 4: Round first node dies when b is varying

In addition, c is a reel positive variable which controls directly the clusters head number. On one hand, if c is higher, the number of cluster heads will increase. Then, the network scheme will be like a direct communication because all nodes will be a cluster head and transmit directly their information to the base station, in this case the network performances will increase considerably. On the other hand, if $c = 0$, the probability to be a cluster heads will be equal to zero for all nodes. So, they go to transmit directly their measurement to the base station, thus, they die quickly which we want to avoid certainly.
To solve this compromise and find the correct value of c which gives an important result, we have run 100 random simulations and in each one, we compute the first node dies (FND). Figure 5 shows how c affects the round value of the FND. We observe that if c is nearest to 0.02 we have more network performances.

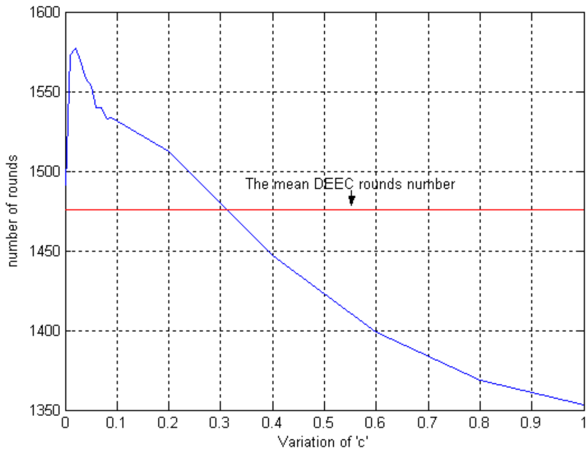

Figure 5: Round first node dies when b is varying

Moreover, 6 and 7 illustrate the residual energy variation for advanced nodes on the DEEC and our protocol. The comparison between these figures shows that the SBDEEC advanced nodes will alive more and the DEEC ones will die quickly. These figures explain that the first Advanced node on the DEEC, figure 6, dies at the round 1800, but on the SBDEEC, figure 7, is done at 2100. Thus, In our proposed protocol the first Advanced node death occurs over 16% times longer than the first Advanced node death in DEEC protocol. With this results, we prove the efficiency of our suggestions and the performance of our SBDEEC protocol.

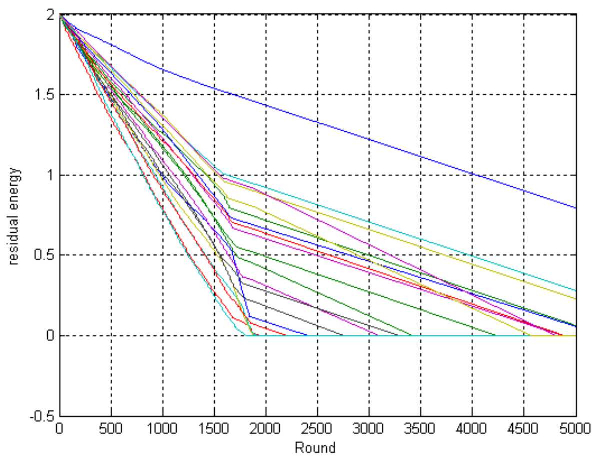

Figure 6: Variation of residual energy for advanced nodes on the DEEC protocol

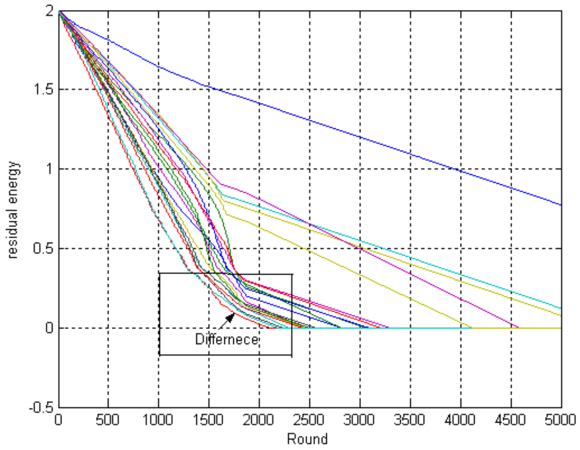

Figure 7: Variation of residual energy for advanced nodes on the SBDEEC protocol

4.2 Stochastic DEEC

In DEEC the network nodes are subdivided into clusters. Moreover, special nodes, referred to as cluster heads, are elected in order to aggregate data locally and transmit the result of such aggregation to the sink. In many applications, the collected data are used to determine the maximal or minimal value of observed phenomena in the region [21]. Thus, the cluster head selects the pertinent information (the minimum or the maximum) between those received and send it to the base station. In this case, if the clusters head receive only from nodes with significant information and the other nodes must be in sleep mode, the total number of transmission and reception will be largely reduced. Therefore, the energy consumption strategy will be more efficient and the overall network lifetime can thus be prolonged. The cluster head broadcasts its sensed information assuming it the searched data, only nodes with significant data send its message to the cluster head which updates its data and send it towards the base station. Let suppose that each node i on the network has a probability S_i to have the searched value in the considered cluster. The total energy consumed E_{total} in the network to transmit the significants data to the sink is:

$$E_{total} = K_{opt}(E_{CHtoBS} + \sum S_i E_{itoCH}) \qquad (18)$$

where E_{CHtoBS} is the energy consumed when the cluster head transmits data to the base station.
E_{itoCH} is the energy consumed to transmit data from node i to the cluster head.
K_{opt} as is defined on 8 is the cluster heads optimal number.

Table 1: Radio characteristics used in our simulations

Parameters	Value
Eelec	5 nJ/bit
efs	10 pJ/bit/m2
emp	0.0013 pJ/bit/m4
E0	0.5 J
E_{DA}	5 nJ/bit/message
do	70 m
Message size	4000 bits
Popt	0.1

The equation 18 will be :

$$E_{total} = LK_{opt}[Empd^4_{toBS} + E_{elec} + (E_{elec} + E_{DA} + Efsd^2_{toCH}) \sum S_i] \qquad (19)$$

This equation shows clearly that the total energy consumed by round is largely reduced. In this situation, the network life time will be more prolonged.

5 Simulation Results

In this section, we evaluate the performance of SBDEEC protocol using MATLAB. We simulated this, DEEC and SEP using a wireless sensor network with $N = 100$ nodes randomly distributed in a $100m \times 100m$ field. The sink is located in the center of the sensing area. As on DEEC protocol, we ignore the effect caused by signal collision and interference in the wireless channel and the radio parameters used are shown in 1. In our simulations we fixed both c and b values which give more performances. where $c = 0.02$ and $b = 0.7$.

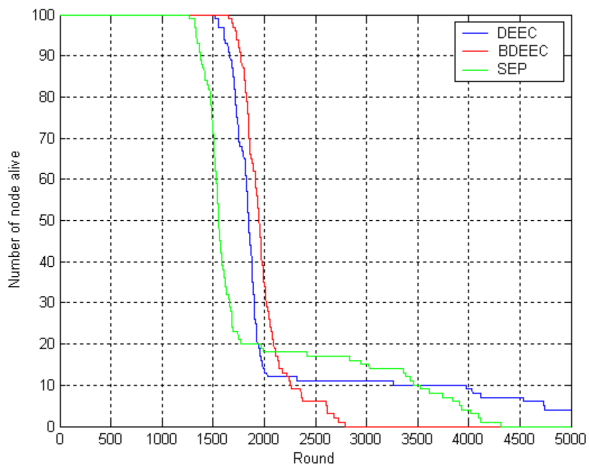

Figure 8: Number of nodes alive over time of SEP, DEEC, and BDEEC under two-level heterogeneous networks

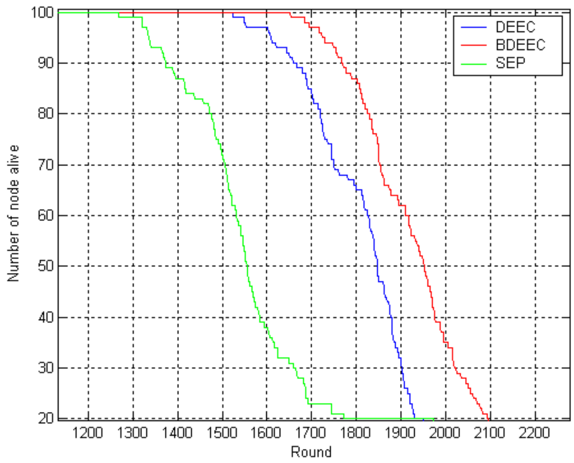

Figure 9: Number of nodes alive over time of SEP, DEEC, and BDEEC under two-level heterogeneous networks over 20 simulations: with Zoom

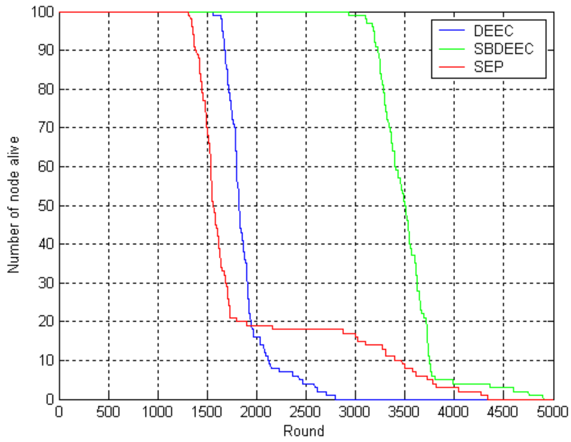

Figure 10: Number of nodes alive over time of SEP, DEEC, and SBDEEC under two-level heterogeneous networks

In figures 8 and 9, we introduced just the balanced characteristic of our protocol. we observe that the unstable region of SEP is also larger than DEEC and than our protocol. It is because the advanced nodes die more slowly than normal nodes in SEP. For the reason that, DEEC take into account both the initial and residual energy, the stability period of DEEC is much longer than that of SEP. Moreover, we observe that BDEEC takes some advantage than DEEC in terms of first node dies and the prolongment of the stable time. It is due to the fusion between DEEC techniques and the balanced cluster head election introduced by the BDEEC. The simulation results on 8 and 9 show that BDEEC is better than DEEC with 10% in terms of First Node Died. Certainly, this performance is due to our modifications and because the protocol introduces a balanced way through all simulations steps.

Now, we run simulation for our proposed protocol SBDEEC introducing both, the balanced cluster heads election and the stochastic technique. In figure 10, the first node death happens in SEP protocol. In the first 1600 transmissions rounds, the nodes death rate is important in SEP compared to DEEC and SBDEEC. The network nodes die randomly in the supervised area, and the network monitoring is better while the number of nodes still alive is important and the stability period is long. So, SBDEEC grants a maximal network lifetime compared to SEP and DEEC. This extension of the network service duration is made by the balanced cluster heads election. Moreover, it is due to the reduction of the number of messages transmitted intra-cluster. Consequently to this reduction, the transmissions and reception nodes energy is economized, and, therefore, the network lifetime is extended.

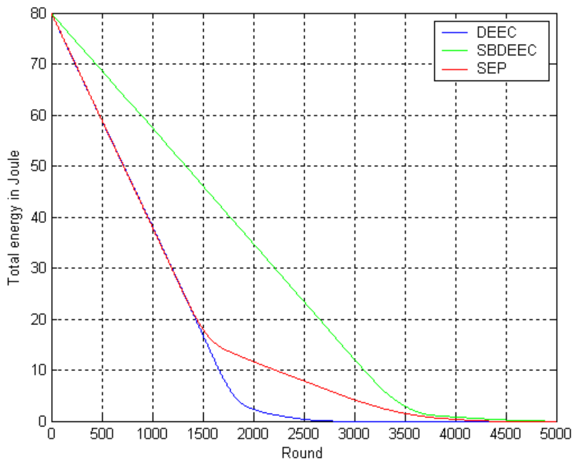

Figure 11: Evolution of the remaining energy in the network when the transmission rounds succeed

Figure 11 gives the total network remaining energy in every transmission round. The network remaining energy decreases rapidly in the SEP and DEEC protocols. So, it presents a slope approximately -0.04J/Round, compared to -0.02J/Round in SBDEEC. Then, the network energy depletion is fast in SEP and DEEC. In addition, we can see that, in the 2000 first transmissions rounds, approximately 96% and 85% of the total network energy is consumed in DEEC and SEP respectively. Whereas, the SBDEEC consumed only 47% of this total energy of the network.

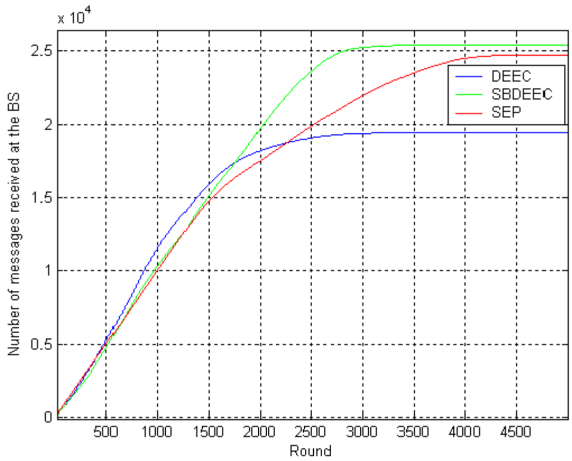

Figure 12: Number of message received at base station over time

As shown in figure 12, we represent the number of data messages received at the base station. We observe that this number of messages received at the base station varies linearly for all protocols, SEP, DEEC and SBDEEC, for the first 1500 transmissions rounds. After that, we observe a stagnation of this number for DEEC. The raison is that the number of death nodes increases quickly, and consequently, the number of messages to transmit towards the base station decreases. Moreover, we can notice that, when the entire network nodes are dead, the total number of messages transmitted to the base station is substantial for the SBDEEC protocol. This means that SBDEEC is more efficient than SEP and DEEC.

6 Conclusion

We have explained SBDEEC protocol which is a Stochastic and Balanced Distributed Energy-Efficient Clustering for heterogeneous wireless sensor. It is an energy-aware adaptive clustering protocol and with an adaptive approach which employ the average energy of the network as the reference energy like in DEEC. When every sensor node independently elects itself as a cluster head based on its initial and residual energy and without any global knowledge of energy at every election round. To further increase the DEEC protocol performances, the SBDEEC implements and introduces a balanced and dynamic way to distribute the spent energy more equitably between nodes. Moreover, our protocol is adapted in situations where we have to monitor the whole area, and then, the data aggregation consists of selecting the important information in the cluster. These modifications introduced enlarges better the performances of our SBDEEC protocol than the others. We can note that, in the proposed protocol the first node death occurs over 90% times longer than the first node death in DEEC protocol and by about 130% than SEP.

Acknowledgment

This work is supported by The ***Académie Hassan II des Sciences et Techniques***. $(Morocco)$

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