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An Energy-Efficient Threshold-Based Clustering Protocol for Wireless Sensor Networks

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Abstract Energy-constrained wireless sensor networks (WSNs) have been deployed widely for monitoring and surveillance purposes. Since sensor nodes (SNs) have significant power constraints (battery life), energy-efficient protocols must be employed to prolong the network lifetime. In this paper, we propose an energy-efficient protocol which provides a new way of creating distributed clusters. This protocol is a modified version of Low Energy Adaptive Clustering Hierarchy (LEACH) protocol. The experimental results show that our protocol that takes into account both the residual energy at each SN and the distance between the SNs outperforms LEACH protocol in terms of first node death time and average residual energy.

Keywords Wireless sensor network · Energy-efficient · Threshold-based · Clustering · LEACH · Simulation

1 Introduction

WSNs are ad hoc networks that consist of SNs and one or more base stations (BSs), which are much more powerful than the SNs. For WSNs, the goal is to collect sensed data from all SNs to certain BSs and then perform further analysis at these BSs. WSNs are used for monitoring purposes, such as monitoring the temperature in a geographical area [3,4,6,23,24,35]. The SNs of WSN have limited battery energies.

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Cluster-based algorithms [1,6,8,9,13,15,18,20,21,24,25,27,32–34] have been proposed for WSN for various reasons including scalability and energy efficiency. In the networks that employ cluster-based algorithms, SNs are organized into clusters, with cluster heads (CHs) relaying messages from the cluster nodes (CNs) in their clusters to the BS(s). In this kind of algorithms, the selection of CHs is considered one of the main issues, since a proper selection of CHs leads to reducing the energy consumption and prolonging the network lifetime [7,11,14,16].

One of the well-known cluster-based communication protocols is LEACH [2,10,12,19,25,30] with advantages such as energy efficiency, simplicity, load balancing, and data aggregation abilities [6,22]. In LEACH, every SN in the network will be selected as a CH with a probability p at each round. After the CHs are selected, each SN not selected as a CH chooses the CH it wants to join according to the distance between them. The CH collects data from the CNs in its cluster and forwards them to the BS directly. LEACH reduces the loads on SNs by preventing them from becoming CHs again within $\frac{1}{p}$ rounds. Though LEACH provides a good solution for data collection operation, it suffers from a number of drawbacks. The first drawback is that the CHs are selected randomly, without any consideration to the residual energy at different SNs. Additionally, CHs are not uniformly distributed; so CHs might be located at the edges of the WSN or concentrated in one part of it. In these cases, some SNs will be located far from any CH. As a result, these SNs need to increase their power, thereby spending much more energy to transmit to the CH [17].

Since SNs have limited battery life, they need to consume their energy efficiently in order to prolong their life. This is achieved by two things. Firstly, the CHs need to be selected based on three factors: their residual energy, their distance to other SNs, and the residual energy of the other SNs. Secondly, the CHs need to be properly distrubued over the WSN so any SN can find a close CH to send to. Having a close CH means reducing the transmission distance and as a result reducing the energy consumption. The new proposed protocol named enhanced centralized LEACH (ECLEACH) takes these two things into account and selects the CHs based on the above mentioned three factors and at the same time distributes the CHs in a proper way by having a minimum distance between every CH and the next (MDBECHAN). This MDBECHAN ensures that the CHs are not concetrated in one place.

The rest of this paper is organized as follows. Section 2 describes the underlying network structure. Section 3 shows the energy consumption model. Section 4 presents the new proposed protocol. Section 5 describes the metrics for measuring the performance of the protocols. Section 6 explains how the simulation is configured. Section 7 discusses the simulation results. Section 8 concludes the paper and describes future directions.

2 Network Structure

The network structure consists of a BS and a number of SNs that interact with each other as shown in Fig. 1. The SNs are divided into a number of clusters with one SN assigned as a CH for each cluster. Every CH forwards the messages received from its CNs to the BS. Each SN periodically produces information by sensing a geographical area, and send it via its CH to the BS. The user then can retrieve information of interest from a WSN by injecting queries and gathering results from the BS, which behaves as an interface between the user and the WSN. Additionally, the BS collects sensor readings, performs costly operations on behalf of the SNs, and manage the WSN.

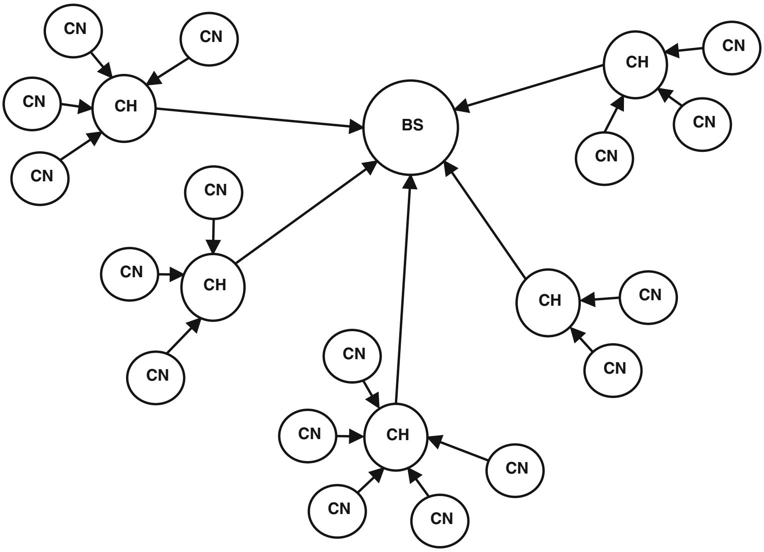

Fig. 1 Network structure

3 Energy Consumption Model

In WSN, the main energy consumption consists of two parts: message sending and receiving [3,5,8,13,24,28,35].

$$E_{tx}(k,d) = E_{\text{elec}} \times k + \varepsilon_{\text{amp}} \times k \times d^2 \tag{1}$$

$$E_{rx}(k) = E_{\text{elec}} \times k \tag{2}$$

Where $E_{tx}(k,d)$ is the energy spent sending a k-bit message a distance d assuming that d is always less than the crossover distance, $E_{rx}(k)$ is the energy spent in reception of a k-bit message, E_{elec} is the base energy required to run the transmitter or receiver circuitry, ε_{amp} is the unit energy required for the transmitter amplifier, and k is the message length in bits.

Therefore, the total energy consumption for transmitting a k-bit message from a source node i to a destination node j a distance d ($E_{i,j}(k,d)$) is:

$$\begin{aligned} E_{i,j}(k,d) &= E_{tx}(k,d) + E_{rx}(k) \\ &= E_{\text{elec}} \times k + \varepsilon_{\text{amp}} \times k \times d^2 + E_{\text{elec}} \times k \\ &= 2 \times E_{\text{elec}} \times k + \varepsilon_{\text{amp}} \times k \times d^2 \\ &= k \times (2 \times E_{\text{elec}} + \varepsilon_{\text{amp}} \times d^2) \end{aligned}$$

4 ECLEACH Protocol

As mentioned in the introduction section, LEACH is a cluster-based communication protocol and organizes SNs into clusters, each with one SN selected to be a CH. LEACH divides the time into rounds. At each round, there are two main phases: setup phase and steady-state phase. The setup phase consists of two steps that are CH selection and cluster formation. In the first step, CH selection, each SN generates a random number RN between 0 and 1 and compares it to a threshold named $T(n)$ where n is the SN number. If RN is less than the threshold, then the SN becomes a CH. The threshold ensures that nodes which were CHs in the last $\frac{1}{P}$ rounds are not selected in the current round.

The threshold, $T(n)$, is calculated as follows:

$$T(n) = \begin{cases} \frac{P}{1-P(r \bmod \left(\left(\frac{1}{P}\right)\right)} & \forall n \in G \\ 0 & \text{if } n \notin G \end{cases}$$

Where G is the set of nodes that have not been selected to become CHs in the last $\frac{1}{P}$ rounds, r denotes the current round number, and P is a predefined parameter that represents the CH probability and is equal to the required number of CHs divided by total number of SNs in the WSN.

At the end of the CH selection process, every SN that was selected to be a CH announces this to the rest of the network. Upon receiving the CH advertisements, each SN not selected as a CH decides which CH to join based on the received signal strength. Then, each SN informs its selected CH of its desire to become part of the cluster. In the second step, cluster formation, each CH creates a time division multiple access (TDMA) schedule for the CNs in its cluster and sends it to every member of the cluster. The TDMA schedule determines the time slot allocated for each member of the cluster. Moreover, each CH selects a code division multiple access (CDMA) code, which is then distributed to all members of its cluster. The aim of using CDMA is to reduce intercluster interference.

In the steady-state phase, the CNs collect information and use their allocated TDMA slots to transmit their collected data to the CH which in turn tramsits them to the BS. This data collection is performed periodically [30].

LEACH has a number of advantages such as energy efficiency, simplicity, load balancing, and data aggregation abilities. However, LEACH has some gaps such as random selection of CHs and in some cases bad distribution of CHs over the WSN. To fill these gaps, an enhanced version of LEACH (ECLEACH) has been proposed. ECLEACH follows a centralized approach in which the BS is responsible for the selection of CHs based on some criteria. A centralized approach is employed, because the BS has unlimited resources such as power supply, storage, and computation. ECLEACH only differs from LEACH in how the CHs are selected. The BS starts the selection process at the begining of each round with caclulating a threshold for every SN n in the network as in (3). After the BS calculates the thresholds for all SNs, it selects the SN with the highest threshold to be the first CH. Then, it checks if the distance between the SN with the highest threshold and the SN with second highest threshold is greater than or equal to MDBECHAN. If it is, then the SN with the second highest threshold is going to be the second CH. Otherwise, it checks the distance between the SN with the highest threshold and the SN with third highest threshold in the same way. The BS is not going to select two consecutive CHs if the distance between them is less than MDBECHAN. This is important to ensure that the CHs are properly distributed over the network. If the BS cannot meet the condition of MDBECHAN, then it needs to decrease the MDBECHAN value. When all CHs are selected, the BS broadcasts the list that contains the CHs in the current round to all SNs. It is important to mention that each CN sends its residual energy together with its sensed data to its CH which it turn forwards it together with the aggregated data from its CNs to the BS.

Obviously, the new proposed protocol adds extra overhead (e.g. additional data and communications) and which is considered in our simulation results presented in Sect. 7. However, the new proposed protocol has a better performance than LEACH protocol. This is because it selects the CHs in a better way, and therefore reducing the energy consumption and prolonging the network lifetime.

$$T(n) = \frac{\mathrm{RE}(n)}{\sum_{i=1}^{m} \frac{D(i,n)}{\mathrm{RE}(i)}} \tag{3}$$

Where $\mathrm{RE}(n)$ is the residual energy of the SN n, m is the number of SNs in the network, $D(i, n)$ is the distance between SN i and SN n and is equal to 0 if $i = n$, and $\mathrm{RE}(i)$ is the residual energy of SN i.

The residual energy of the SN is important to avoid selecting the SNs with low energy power so their batteries do not get depleted. It is known that the CH energy consumption rate is high because it receives sensed data from all the CNs in its cluster [27]. The distance is divided by the residual energy to give higher priority in the selection process to SNs that are close to low energy SNs. As a result, these low energy SNs will transmit over a short-distance because of having close CHs and therefore reducing their energy consumption. By reducing their energy consumption, their lifetime will be longer.

Pseudocode 1 shows the CH selection in this protocol. For definitions of variables used in the pseudocode, refer to Table 1.

Pseudocode 1: CH selection in ECLEACH protocol

```
for $n = 1$ to $NOSN$ do
    Initialize $Sum$ to 0;
    for $i = 1$ to $NOSN$ do
        $Sum = Sum + \frac{DList(i,n)}{RE(i)}$;
    end
    $TList(n) = \frac{RE(n)}{Sum}$;
end
$Sort(Tlist)$;
for $n = 1$ to $NOSN$ do
    if $n \geq 2$ and $DList(NNlist(n), NLSNSCH) \geq MDBECHAN$ then
        $CHlist.add(NNlist(n))$;
        $NLSNSCH = NNlist(n)$;
    else
        $CHlist.add(NNlist(n))$;
        $NLSNSCH = NNlist(n)$;
    end
end
```

5 Comparison Metrics

In the current work, there are n SNs $\mathrm{SN}_1, \mathrm{SN}_2, \ldots, \mathrm{SN}_n$ in the WSN, m CHs $\mathrm{CH}_1, \mathrm{CH}_2, \ldots, \mathrm{CH}_m$ in each round, and one BS.

In order to determine the best performing protocol, a suitable set of metrics need to be defined. Two metrics are used to measure the performance of different protocols: first node death time and average residual energy. The first metric needs to be maximized, while the second metric needs to be minimized. First node death time is the time when the battery of the first SN is depleted. Our concern in this paper is only the depletion of the first SN's battery. This is because each SN covers an important part of the sensed area and losing it means losing the data from that important part. Therefore, it is required to extend the lifetime

Table 1 Definitions of pseudocode variables of CH selection in ECLEACH protocol

Variable	Definition
NOSN	Number of SNs
IE(i)	Initial energy of SN *i*
RE(i)	Residual energy of SN *i*
Sort(Tlist)	The function that sorts the values in Tlist in decreasing order
MDBECHAN	Minimum distance between every CH and the next
NLSNSCH	The number of the last SN selected as CH
DList	The list that contains the distances between the SNs in the WSN
Tlist	The list that contains the thresholds of SNs
NNlist	The list that contains SN numbers of the corresponding thresholds in $Tlist$
CHlist	The list that contains the numbers of SNs that were selected as CHs

Table 2 Metrics of protocols

M_1 = FNDT	FNDT = First node death time
M_2 = ARE	ARE = Average residual energy

of all SNs as long as possible. Average residual energy is the sum of residual energies of all SNs divided by the total number of SNs in the WSN. This metric is calculated when the first SN lifetime ends. The protocol that achieves smaller value for this metric will have a better way to balance the energy consumption among all the SNs in the WSN. In other words, if this metric is small, then the residual energy of the SNs will be closer to zero which is the residual energy of one of the SNs because as mentioned this metric is calculated when the first SN lifetime ends (its residual energy is zero). Thus, energy consumption will be divided more evenly between the SNs. On the other hand, if this metric is large, then this means that the protocol is not good in balancing the load among the SNs and therefore leaving some SNs with high residual energy and one SN with zero residual energy.

Table 2 shows the metrics used to measure the performance of protocols.

6 Simulation Setup

In this paper, an event-driven simulator written in Java is used for evaluating two cluster-based protocols which are LEACH, and our new proposed protocol named ECLEACH. A performance comparison between LEACH and ECLEACH is made under 2 different scenarios. In the first scenario, the number of SNs is fixed to 100, while the number of CHs is varied between 5 and 40 (5, 10, 20, 30, and 40). In the second scenario, the percentage of CHs is fixed to 10 % of the number of SNs, while the number of SNs is varied between 50 and 400 (50, 100, 200, 300, and 400). The MDBECHAN in ECLEACH is set to 50 m in the first scenario, while it is set to 60 m in the second scenario. The first scenario shows the effect of varying the number of CHs on the performance of these protocols, while the second scenario shows the effect of varying the number of SNs on that performance. In order to see the impact of changing the value of MDBECHAN in ECLEACH on its performance, another scenario is used. In this third scenario, the number of SNs and CHs are fixed to 100, 10 respectively, while the value of MDBECHAN is varied between 0 and 60 m (0, 20, 40, and 60). In all scenarios, the extra overhead that is added by ECLEACH such as additional data and communications is taken into account.

Table 3 Simulation scenarios

Scenario number	Number of SNs	Number of CHs	Value of MDBECHAN in ECLEACH
1	100	Varied between 5 and 40	50 m
2	Varied between 50 and 400	10 % of the number of SNs	60 m
3	100	10	Varied between 0 and 60 m

Table 4 Simulation parameters

Parameter	Value
E_{elec}	50×10^{-9} J
ε_{amp}	100×10^{-12} J
Size of messages that carry sensed data	500 bytes
Size of broadcast messages	100 bytes
Round length	100 min
Initial energy at each SN	5 J
Radio range of every SN	150 m
Area of WSN	100 m × 100 m

Table 3 shows the simulation scenarios.

In each simulation, all the SNs are set to employ one of the protocols under a set of parameters. In all simulations, the used network topology is a complete graph. The nodes in each simulation are distributed in a 100×100 m^2 region, and one of the nodes is the BS, which has unlimited energy supply and can receive data from multiple SNs at the same time by using multi-packet reception capability [29]. The coordination of points that represent the location of SNs are selected randomly in that region taking into consideration that no two points have the same coordination. The BS is given a fixed location at (0,0). All the SNs are homogeneous and have the same capability. The initial energy assigned to each SN is identical and is equal to 5 J. The radio range of every SN is 150 m. The size of the messages that carry sensed data is identical and is equal to 500 bytes, and the size of the broadcast messages is also identical and is equal to 100 bytes. In ECLEACH, the broadcast message contains the list of CHs in the current round and which is sent from the BS to all SNs. The length of each round is set to 100 min. The costs of computation, aggregation, signaling, and retransmission are not taken into account.

It is assumed that all CHs employ perfect aggregation [10,26,31]. In perfect aggregation, a CH aggregates the received data in one unit of data and then sends it to the BS, where average, maximum, and count operations are examples of perfect aggregation functions.

Table 4 shows the simulation parameters and their values.

7 Simulation Results and Discussion

In this section, a performance comparison between LEACH and our ECLEACH is made under two scenarios (scenarios one and two). Additionally, another scenario (scenario three) is used to show the effect of varying the value of MDBECHAN in ECLEACH on its performance.

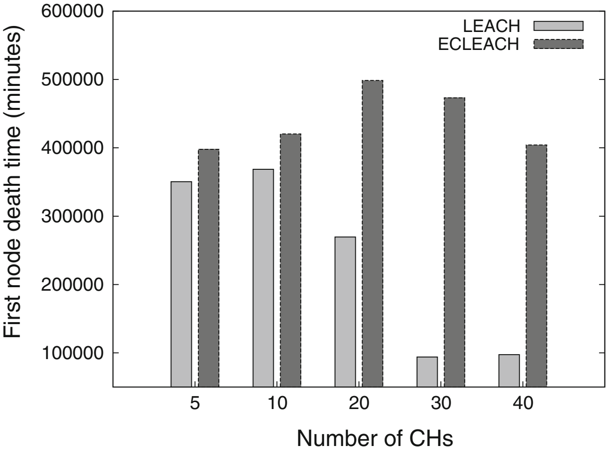

Fig. 2 First node death time achieved by LEACH and ECLEACH protocols under different number of CHs

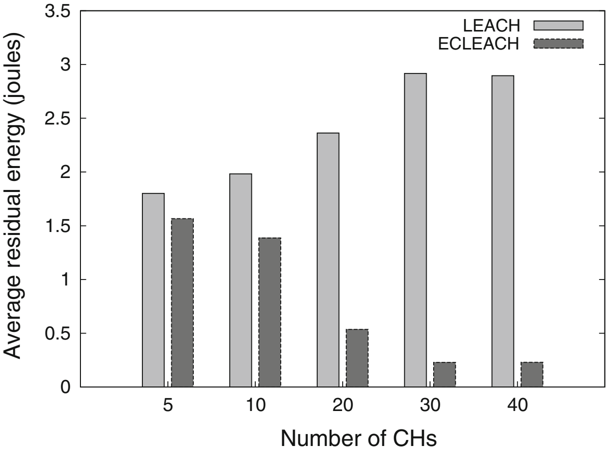

Fig. 3 Average residual energy achieved by LEACH and ECLEACH protocols under different number of CHs

7.1 Scenario One

In this scenario, the performance of LEACH and ECLEACH is evaluated under different number of CHs. From Figs. 2 and 3 it can be seen that ECLEACH protocol is the superior one. This is because of two reasons. Firstly, in ECLEACH, the CHs are not selected randomly but selected based on their residual energy, their distance to other SNs, and the residual energy of the other SNs. Secondly, ECLEACH gives better distribution of CHs by having a minimum distance between consecutive CHs. As a result, each SN can allocate a close CH to send its data to it and thus reducing the energy consumption. By reducing the energy consumption, the batteries of SNs will last longer.

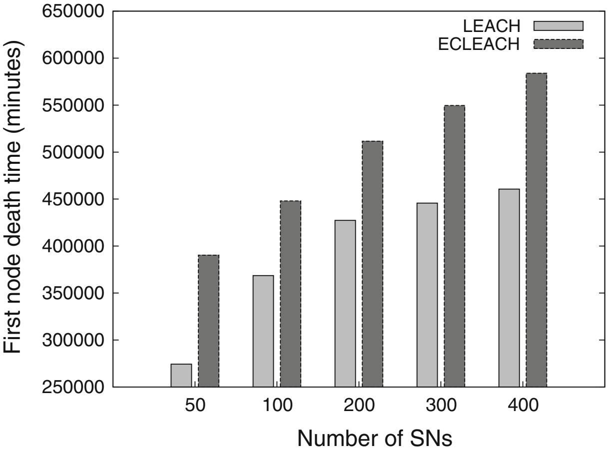

Fig. 4 First node death time achieved by LEACH and ECLEACH protocols under different number of SNs

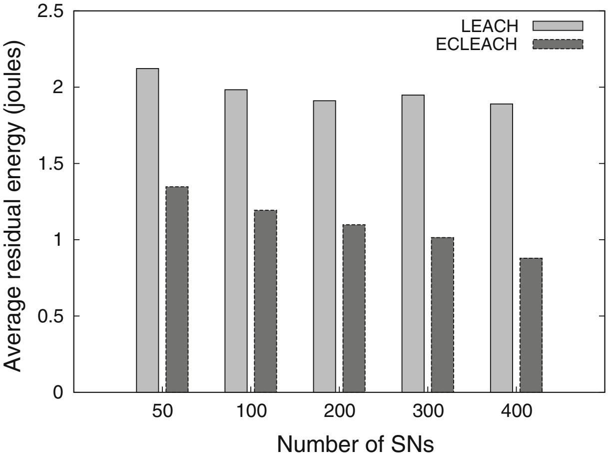

Fig. 5 Average residual energy achieved by LEACH and ECLEACH protocols under different number of SNs

7.2 Scenario Two

In this scenario, the performance of LEACH and ECLEACH is is evaluated under different number of SNs. From Figs. 4 and 5, it appears that the performance of the two protocols is usually better than their performance in the previous scenario. The reason is that increasing the number of SNs in the same network size will result in increasing the number of CHs in that network as well since the percentage of CHs is fixed to 10 % of the number of SNs. Increasing the number of SNs and CHs in the same network size usually results in reducing the transmission distance and therefore reducing the energy consumption. ECLEACH achieved the best performance in this scenario too because of the same reasons mentioned in scenario one.

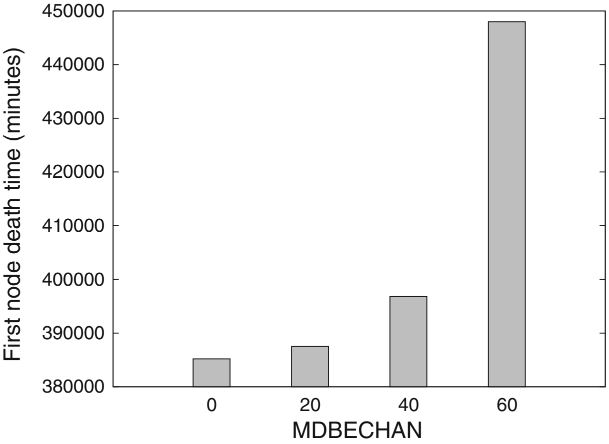

Fig. 6 First node death time achieved by ECLEACH protocol under different values of MDBECHAN

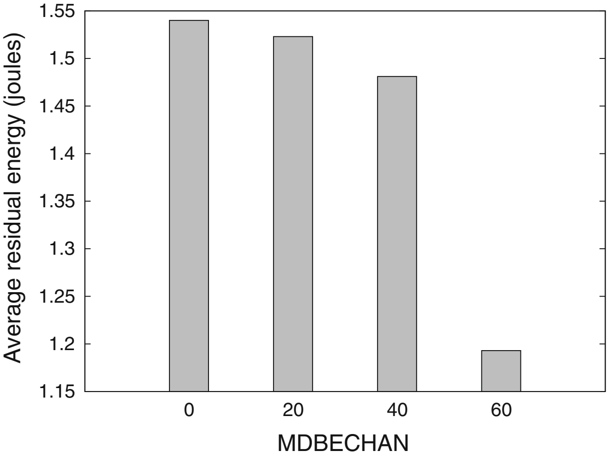

Fig. 7 Average residual energy achieved by ECLEACH protocol under different values of MDBECHAN

7.3 Scenario Three

In this scenario, the performance of ECLEACH is evaluated under different values of MDBECHAN. Figures 6 and 7 show that increasing the value of MDBECHAN has a positive effect on the performance of ECLEACH. This is because of having a better distribution of CHs over the network when MDBECHAN is increased.

8 Conclusion

In this paper, a new cluster-based protocol for WSN named ECLEACH has been presented. ECLEACH is a threshold-based protocol that selects the CHs based on their residual energy, their distance to other SNs, and the residual energy of the other SNs. ECLEACH also keeps a minimum distance between every CH and the next in order to have a better distribution of CHs over the network. The performance of this protocol has been compared with LEACH protocol by event-driven simulations with 2 different scenarios. The evaluation shows that ECLEACH outperforms LEACH in the 2 scenarios in terms of first node death time and average residual energy. Additionally, it has been shown that increasing the value of MDBECHAN improves the performance of ECLEACH, because of having a proper distribution of CHs over the network when MDBECHAN is increased.

In future work, there are two main areas of consideration: considering more factors to select CHs, and undertaking further experimental investigations.

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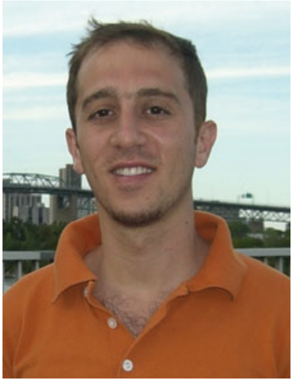

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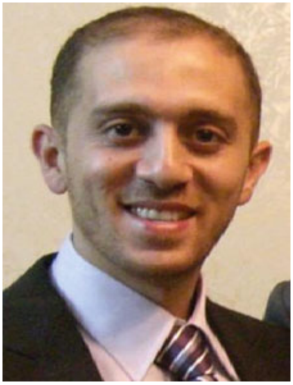

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