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RESEARCH ARTICLE - COMPUTER ENGINEERING AND COMPUTER SCIENCE

ECS: An Energy-Efficient Approach to Select Cluster-Head in Wireless Sensor Networks

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Abstract In Wireless Sensor Networks, usually sensor nodes suffer from limited battery power. It is a difficult task to work with sensor nodes in an energy-efficient way. To work with this claim, in this work authors propose a Cluster-Head (CH) selection approach named as Energy-Efficient Approach to select Cluster Head (ECS) which works with two algorithms: ECHSA-1 and ECHSA-2. The ECHSA-1 algorithm works with Nash Equilibrium (NE) decision of the game theory. Here, each player in a game is considered as a cluster for both ECHSA-1 and ECHSA-2. The players select their best strategy according to the node's residual energy. But, ECHSA-1 algorithm suffers from multiple NEs. So, ECHSA-2 algorithm is proposed based on the Sub-game Perfect Nash Equilibrium (SPNE). Based on the SPNE decision, CHs are selected. The simulation results show that the network lifetime is longer in case of ECS as compared to the baseline algorithms such as UCR, DEEC, and BEEG.

Keywords WSNs · Game theory · Energy consumption · Residual energy

1 Introduction

To support large data rate, the nodes in WSNs must have sufficient battery power. But, one of the main problems in case of WSNs is that the battery power of nodes is limited which affects the overall network lifetime [1,2]. To minimize the consumption of energy is one of the important tasks in WSNs because the sensor nodes are deployed in such locations where it is very difficult to replace their battery [3,4]. Sensor nodes consume energy for replying query request as well as for sending or receiving data [6]. In WSNs, there may be more than one cluster. The nodes in a cluster send their information to their corresponding Cluster Heads (CHs). The CHs may change from round to round [7]. A CH aggregates the data and sends it to the base station. For sending information to the CH from various nodes, there may be support for single or multihop. In single hop, the sensor nodes spend more battery power when their distance from the CH is more whereas, because of relying in multihop, nodes spend more battery power when their distance from CH is less [6].

In this work, authors propose ECS which takes the decision for selection of CH from each cluster in WSNs. ECS mainly works with two algorithms named as ECHSA-1 and ECHSA-2. ECHSA-1 is based on the Nash Equilibrium (NE) [8] decision and ECHSA-2 is based on the SPNE decision. In ECHSA-2, each cluster acts as a player, and according to backward induction, NE is selected. In ECHSA-1, it selects optimum CH in each round, but suffers from multiple NEs. ECHSA-2 overcomes the problem of ECHSA-1.

The rest of the paper is organized as follows: Sect. 2 describes the related work. Sections 3 and 4 present the energy consumption model and our proposed approach, respectively. Section 5 presents the performance evaluation of ECS. Finally, the paper is concluded in Sect. 6.

2 Related Work

In WSNs, sensor nodes play a vital role for sending and receiving of data unit. In [18], authors proposed a CH selec-

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tion approach for WSNs based on the QoS by limiting the degree of nodes which can minimize energy consumption as well as load. For increasing network lifetime, a couple of work have been proposed [1–3,6,7]. For selecting CH, in [6] authors proposed an approach called Deterministic Stable Election Protocol (D-SEP) which was basically developed for distributed environment. Balanced Energy-Efficient Grouping (BEEG) protocol as proposed in [9] works well for heterogeneous environment where various nodes fall under different groups, with one CH. But, for answering user requests a node spends its energy which may affect the entire network [9].

In [10], authors proposed an approach based on the Markov chain model which considers a node having two states: *sleep* and *active* state. The authors proposed that the nodes spend more energy in case of *active* state in comparison with *sleep* state. Cluster-Head Relay (CHR) routing protocol as proposed in [11] uses low- and high-end sensors. The high-end sensors forward information to the base station after aggregating information from different sensor nodes. Adaptive Fidelity Energy-Conserving Algorithm (AFECA) as proposed in [12] is typically based on the sleep-scheduling technique for improving energy efficiency. A node may go back to the awake mode from the sleep mode once it receives Route REQuest (RREQ) packets and starts to listen to the channel [12].

In case of Distributed Energy-Efficient Clustering (DEEC) algorithm, the sensor nodes consume their energy by changing the CH [13]. According to DEEC, it selects CH based on the ratio of node's residual energy and network energy (average) [13]. Unequal Cluster-based Routing (UCR) protocol [14] works with network-wide announcements for formation of cluster. But, the major drawback in case of UCR is that a large number of clusters are formed in the network which may increase the traffic as well as the latency.

3 Energy Consumption Model

There are various reasons for which sensor nodes consume energy. In this section, the factors that play major role for consumption of energy are considered. To compute residual energy of a node, it is required to compute the total energy consumption for processing data unit. ECS mainly works based on the current residual energy of a sensor node. The notations used in the energy consumption model and their definitions are given in Table 1. The factors causing energy consumption by a sensor node are described as follows.

3.1 Energy Consumption for Sensing

Before performing any operation by a sensor node, it should sense the environment first so that it can collect the data from the environment [15]. However, sensing is one of the major characteristics of sensor nodes and for that a node consumes its energy denoted by $E^s\ (n_i)$ and is computed by using Eq. (1).

Table 1 Different Notation Definitions

Symbol	Definition
n_i	A sensor node where $i = \{1, 2, ..., p\}$
$E^s(n_i)$	Energy consumption for sensing
$E^l(n_i)$	Energy consumption for logging
$E^t(n_i)$	Energy consumption for sending
$E^r(n_i)$	Energy consumption for receiving
E_{sa} or e_s	Energy consumption for moving from sleep to active mode
$E_{total}(n_i)$	Total energy consumption of sensor nodes
$E_{residual}(n_i)$	Residual energy of a sensor node n_i
E_{tr}	Consumption of energy levels for transmitter radios
E_{rcv}	Consumption of energy levels for receiver radios
α	System parameter
V_{supp}	Supply voltage

$$E^s\ (n_i) = l_{msg} V_{supp} I_{se} t_{se} \tag{1}$$

Here, authors assume that the duration of time for sensing l_{msg} bit packet is t_{se} and for that I_{se} be the amount of current needed for that and V_{supp} be the supply voltage.

3.2 Energy Consumption for Logging

A sensor node also consumes energy for reading l_{msg} bit packet and writing it into the memory [15]. Therefore, the consumption of energy for logging denoted by $E^l\ (n_i)$ is computed by using Eq. (2).

$$E^l(n_i) = \frac{l_{msg} V_{supp}}{8} \left(I_{wrt} t_{wrt} + I_{read} t_{read}\right) \tag{2}$$

Here, t_{wrt} and t_{read} be the time duration for the amount of current needed for writing as well as reading one byte of data and are denoted as I_{wrt} and I_{read}, respectively.

3.3 Energy Consumption for Sending and Receiving Data Unit by a Sensor Node

A sensor node consumes energy when it sends data unit denoted as $E^t(n_i)$ and is computed by using Eq. (3).

$$E^t(n_i) = l_{msg}(E_{tr} + l_{amp}.d_2);\ When\ d \le d_0 \tag{3}$$

$$\text{and } l_{msg}(E_{tr} + l_f.d^4);\ When\ d_i > d_0$$

A sensor node also consumes energy for receiving data unit denoted as $E^r(n_i)$ and is computed by using Eq. (4).

$$E^r(n_i) = E_{rcv}.l_{msg} \tag{4}$$

where two nodes are placed at a distance d_i and d_o denotes the threshold distance between them. In Eqs. (3) and (4), E_{tr} and E_{rcv} are the consumption of energy levels for transmitter and receiver radios. In Eq. (3), l_{amp} and l_f are the amplifier parameters of transmission corresponding to the multipath fading model and free-space model, respectively.

3.4 Energy Consumption for Sleep to Active Mode

A sensor node also consumes its energy when it moves from sleep to active mode. But, the consumption of energy is negligible when a sensor node moves from active to sleep mode [10]. Let us assume that there are n number of nodes placed in WSNs. So, the total energy consumption due to transition from sleep to active mode is computed by using Eq. (5).

$$E_{sa} = ne_s \tag{5}$$

For $n = 1$, Eq. (5) can be rewritten as

$$E_{sa}(n_i) = e_s \tag{6}$$

Now, using Eq. (1)–(5) the total energy consumption of a sensor node (n_i) can be computed and is computed by using Eq. (7).

$$E_{total}(n_i) = E_s(n_i) + E_l(n_i) + E_t(n_i) + E_r(n_i) + E_{sa}(n_i) \tag{7}$$

Let $E_{initial}$ be the initial energy of a sensor node. Therefore, the residual energy of a sensor node is computed by using Eq. (8).

$$E_{residual}(n_i) = E_{initial}(n_i) - E_{total}(n_i) \tag{8}$$

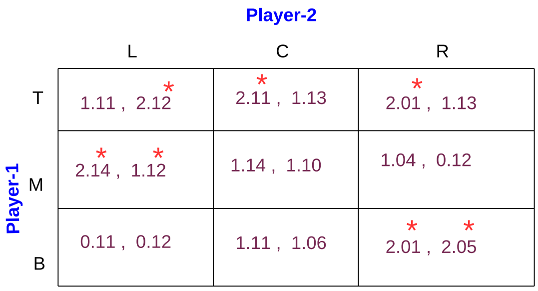
4 NE Using Best Response Function (BRF)

There are mainly two features of NE:

A. Initially, a player believes in other player's actions and the action should be taken by a player from model of rational choices.

B. The action taken by another player should be correct.

To determine NE, authors used Best Response Function (BRF) [16] and is described using Eq. (9)



	L	C	R
T	1.11 , 2.12*	2.11* , 1.13	2.01* , 1.13
M	2.14* , 1.12*	1.14 , 1.10	1.04 , 0.12
B	0.11 , 0.12	1.11 , 1.06	2.01* , 2.05*

Fig. 1 NE for 2-player game

An action profile (AP) denoted as Q^* is said to be a NE if there exists a BRF .

$$Q^*_p \in K_p \;\in K_p(Q^*_{-p})\ \forall\ player\ p \tag{9}$$

where K_p denotes the BRF of player p. The other player's action list or action profile is denoted as Q_{-p} and B_p is the BRF where, from each Q_{-p}, $\forall$ player $\in P$ has one best response and the single member of $K_p(Q_{-p})$ by $B_p\ (Q_{-p})$ $(that\ is, K_p(Q_{-p}) = \{B_p(Q_{-p}\})$; then, from Eq. (9).

$$K^*_p = B_p(K^*_{-p})\ \forall\ player\ p, \tag{10}$$

In case of WSNs, it consists of large number of sensor nodes and they form a cluster. In case of WSNs, the strategy of a player that is a cluster in WSNs indicates as node's residual energy. For example, if it is a two-player game, there are two players that are player 1 (P_1) and player 2 (P_2) as shown in Fig. 1. Let both P_1 and P_2 have three strategies denoted by (B, M, T) and (L, C, R), respectively. The strategy of each player may be different. If there are three nodes, their residual energy is B, M, and T, respectively, which are considered as the strategies of these players. According to the game, if P_1 selects T in such situation, P_2 has three strategies (L,C,R). But, during the game, P_2 selects his best strategy. So, P_2 will select L. On the other hand, when P_1 selects M or B, in such situation P_2 selects L and R, respectively. During the game, there may be the scenario where P_2 selects R; then, P_1 selects T and B. The reason behind this is that both having similar payoffs. The best payoff is denoted by star symbol (*). So, the result of game is both (M,L) and (B,R) and is selected as NEs.

Figure 2 shows the game for n number of players, and the best strategy is indicated by a circle. When P_1 has single strategy, then P_2 has more than one strategy.

A game G is formed by three tuples $T = \{P, N, S\}$ [8] where n number of player $(p_1, p_2, p_3, ..., p_n) \in P$, $(n_1, n_2, n_3, ..., n_k) \in N$, q number of strategies $(s_1, s_2, s_3, ..., s_q) \in S$.

It is assumed that initially there are no CHs in WSNs and all are the normal nodes. Now, as ECHSA-1 works based on

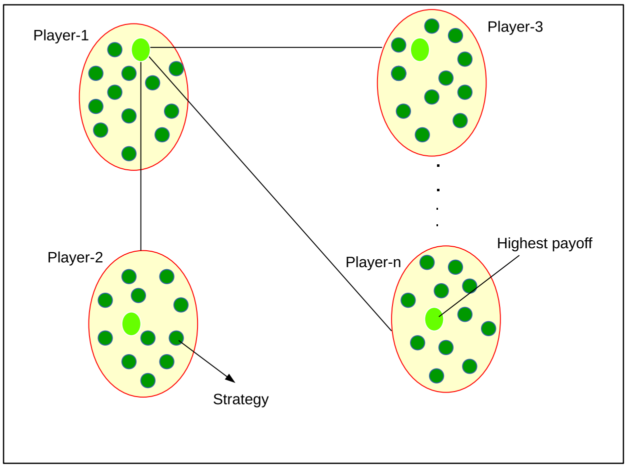


Fig. 2 NE for n-player game

the game theory, each player acts as a cluster, and in case of WSNs each cluster consists of different number of nodes. The steps to select a CH in WSNs using NE of game theory are given in Algorithm 1. During the processing of information, nodes consume their energy and $E_{residual}$ of each node is computed and is treated as a strategy of game G (steps 1-9 of ECHSA-1). Now, according to the definition of NE as described in Sect. 4, each player follows other players action from action profile Q_{-i}. One player selects his best payoff based on the comparison with other player's action (step 12-13 of ECHSA-1). A game consists of different players, and during a game, selecting NE is the optimal strategy and the nodes which are selected as a NE are chosen as a CH (step 14–15 of ECHSA-1).

Algorithm 1: ECHSA-1

```
$P \leftarrow \{p_1, p_2, p_3, ..., p_n\}$
$N \leftarrow \{n_1, n_2, n_3, ..., n_k\}$
$S \leftarrow \{s_1, s_2, s_3, ..., s_q\}$
$NE \leftarrow false$
$CH \leftarrow \emptyset$ ;Initially there are no CHs
for each $p_i \in P$
    for each $n_k \in N$
    $Find\ E_{residual}$
    $s \leftarrow E_{residual}(n_k)$
    end for
end for
for$\forall\ p_i \in P\ and\ \forall\ s_i \in S$
    if$(s_i(Q_i, Q_{-i}) \geq s_i(Q'_i, Q_{-i}))$
    $NE \leftarrow true$
    $CH \leftarrow NE$
    end if
    else $NE \leftarrow false$
end for
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In ECHSA-1, one of the main problems is that there may be the existence of multiple NEs. To work with multiple

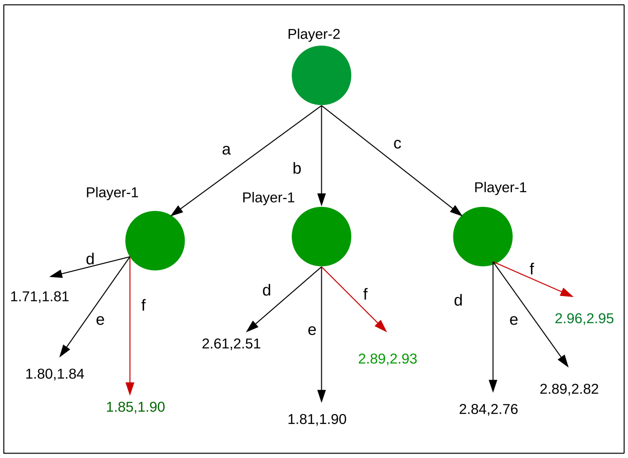

Fig. 3 Extension form of game tree

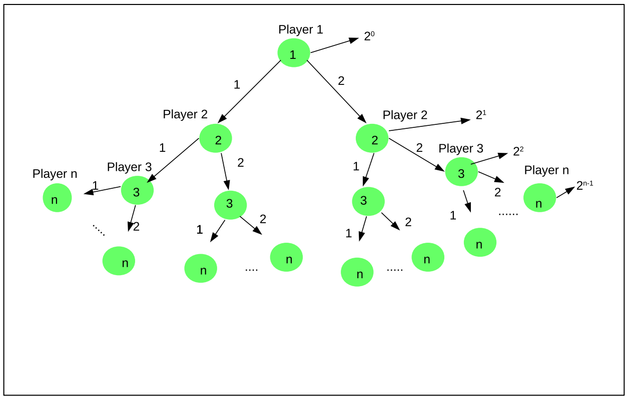

Fig. 4 Extension form of game tree for n-player game

NEs, the concept of Sub-game Perfect Nash Equilibrium (SPNE) [17,18] is used. Basically, SPNE is used to find NE for each sub-game of an original game. Backward induction is used for finding the way of playing game. That means by using backward induction one can move from one player to another because it works in each node of the tree. The backward induction is used in ECS for finding SPNE. An example of SPNE is shown in Fig. 3 which is called the extensive form of game tree. According to Fig. 2, it indicates that there are two players named as player 1 and player 2 and both the players act as a cluster in case of WSNs. The residual energy of each node is considered as the strategy of each player. When P_2 starts an action, the same action is followed by P_1. During game, if P_2 selects a strategy a, then the same strategy is followed by P_1 and suppose P_1 has three options d, e, f, respectively. So, in such situation P_1 only selects those strategy which have the highest payoffs and it chooses f. On the next sub-game, P_1 chooses strategy f and f is followed by P_2's strategies b and c. But, during a game, P_1 has the knowledge about P_2 and P_1 and hence chooses the third combination that is (c,f).

In ECHSA-2, the residual energy of each node (steps 5-8) is computed, and then, SPNE is determined and is selected as a CH (steps 11-13).

Theorem 4.1 *According to ECHSA-2, for a n-strategic game there are* n^{n-1} *number of nodes.*

Proof Let $(p_1, p_2, p_3, \ldots, p_n)$ be a set of n players in case of WSNS. From Fig. 2, it is clear that for a two strategic game there are 2^0 number of nodes, and hence, for p_n there are 2^{n-1} number of nodes in a tree. So, according to ECHSA-2, for a n-strategic game there are n^{n-1} number of nodes. □

Theorem 4.2 *During game, if there is imperfect strategy found by one player followed by other player's action, then the player can move from one strategy to another strategy in case of SPNE.*

Proof Let us consider that two strategies (s_1, s_2) be a NE and payoffs of these two are $(\alpha_1, \alpha_2) \in \alpha_i$. Now, suppose strategies (s_1^*, s_2^*) have payoffs $(\alpha_1^*, \alpha_2^*) \in \alpha_i^*$. If payoff $\alpha_i < \alpha_i^*$, but α_i^* is not a SPNE. Now, if the player moves from one strategy to another, then the player may achieve payoff β_i so that

$$\beta_i > \alpha_i^* > \alpha_1.$$

Now, the following calculation is necessary when a player does not deviate from his strategy. Assume that o_i is the lower bound when a player does not deviate from his strategy. Suppose in stage x, a player can deviate from his strategy and $y > x$ is the player switches from one strategy to another then

$(1 - o_i) \sum_{y=0}^{\infty} o_i^y.\alpha_i^* \geq (1 - o_i)(\sum_{y=1}^{x-1} o_i^y.\alpha_i^* + o_i^y.\beta_i + \sum_{y=x+1}^{\infty} o_i^y.\alpha_i$

$\iff \sum_{y=x}^{\infty} o_i^y.\alpha_i^* \geq o_i^y.\beta_i + \sum_{y=x+1}^{\infty} o_i^y.\alpha_i$

$\iff \sum_{y=0}^{\infty} o_i^y.\alpha_i^* \geq \beta_i + \sum_{y=1}^{\infty} o_i^y.\alpha_i$ (cancel first x terms and cancel o_i^x)

$\iff \frac{\alpha_i^*}{1-o_i} \geq \beta_i + \frac{o_i}{1-o_i}\alpha_i$

$\iff \alpha_i^* \geq \beta_i(1 - o_i) + o_i.\alpha_i$

$\iff \alpha_i^* - \beta_i \geq o_i(\alpha_i - \beta_i)$

$\iff o_i \geq \frac{\beta_i - \alpha_i^*}{\beta_i - \alpha_i}$

During a game, a player will not deviate from his strategy at this o_i bounds. □

Theorem 4.3 *In case of ECHSA-2, there exists one pure strategy NE.*

Proof According to Zermelo's theorem [19], in case of a finite game there always exists a pure strategy NE when complete knowledge is available, but there exists SPNE for finite extensive game. □

Algorithm 2: ECHSA-2

```
$P \leftarrow \{p_1, p_2, p_3, \ldots, p_n\}$
$N \leftarrow \{n_1, n_2, n_3, \ldots, n_k\}$
$S \leftarrow \{s_1, s_2, s_3, \ldots, s_q\}$
$CH \leftarrow \emptyset$; Initially there are no CHs
for each $p_i \in P$
  for each $n_k \in N$
    Find $E_{residual}$
    $s_i \leftarrow E_{residual}$
  end for
end for
for $\forall\, p_i \in P$ and $\forall\, s_i \in S$
  Find SPNE; Find SPNE from extensive form of game tree
  $CH \leftarrow$ SPNE
end for
```

5 Performance Evaluation of ECS

In case of DEEC, one of the main problems is that the performance of advanced node is decreased when $E_{residual}$ is decreased that means the advanced node dies very fast in case of DEEC. In case of UCR [14], a large number of clusters are formed in the network and result in the high latency as well as traffic overload. But, the performance of DEEC is less as compared to the performance of UCR. This is because of the high advance nodes. Another problem with UCR is that it considers the network-wide broadcasting which causes high energy consumption and also selects CH based on the distance between nodes and the sink node. BEEG does not support the hot spot of the network. ECS is a distributed approach to form CH and is basically works by forming suitable cluster based on the hop distance to the sink node [21]. That is because in case of UCR, it increases the intra-cluster communication cost because of large number of clusters, but on the other hand less number of clusters also increase the inter-cluster communication cost. So that it works well as compared to the DEEC and UCR. In case of ECHSA-1, it selects optimal CH in each round.

5.1 Simulation Parameters

The proposed algorithms are implemented in MATLAB version R2013a. During simulation, the network range of $200 \times 200\ \mathrm{m}^2$ was considered and nodes were deployed ranging from 10 to 90 in a cluster. Initially, energy of each sensor node was taken as 3.8J. For sending and receiving, energy consumed by a node was taken as 0.0151 and 0.0586 mJ, respectively. To find $E_{residual}$ of each node, the different values in each round were taken which are given in Table 2. To calculate $E_{residual}$, energy consumption model as described in Sect. 3 was used. After finding the best $E_{residual}$ of each round, the concepts as described in [21] were used to select the cluster.

Table 2 Parameters used for proposed approach

Parameters	Values
Network size	$200 \times 200\,\mathrm{m}^2$
Number of nodes	100
$E_{initial}$	3.8 J
E_{tr}	0.0151 mJ
E_{rcv}	0.0586 mJ
l_{msg}	2000 bit/s
l_{amp}	0.1 pJ/bi /m^2
l_{fs}	0.2 pJ /bit/m^4
d	≤ 10 m
e_s	0.31 nJ/bit

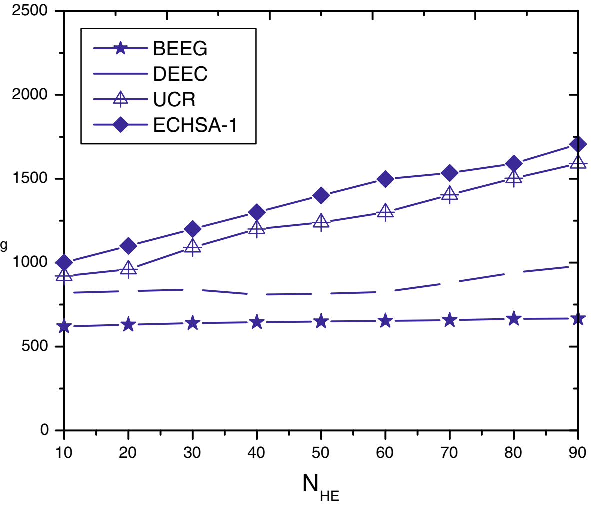

Fig. 5 Average number of rounds with respect to number of varying high energy nodes when first node dies

5.2 Simulation Results

For analysis of the results obtained after simulation, three popular baselines algorithms named as DEEC [13], UCR [14], and BEEG [9] were used. Figure 5 shows the comparison of ECHSA-1 with respect to the baseline algorithms. Figure 5 indicates that the ECHSA-1 performs better as compared to the baseline approaches. In Fig. 5, X-axis represents the number of varying high energy nodes (N_{HE})and Y-axis represents the average number of rounds (R_{avg}). From Figs. 5 and 6, it is clear that the network lifetime of ECHSA-1 is more with respect to baseline algorithms. During our simulation, we considered the network lifetime when the first node dies. In Fig. 6, N_a indicates the number of average nodes alive over round. From Fig. 7, it is clear that the $E_{residual}$ of nodes in ECHSA-1 is more as compared to the baseline algorithms. From Fig. 7, we can see that in case of UCR, average $E_{residual}$ is 1.0 after 3500 rounds, but $E_{residual}$ is 2.1 in case of ECHSA-1.

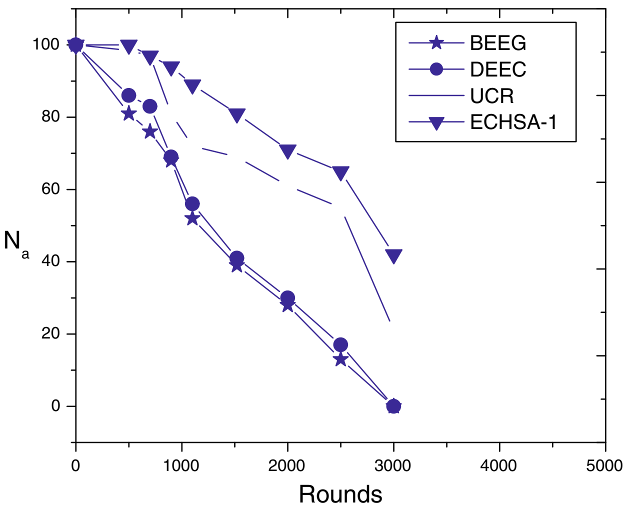

Fig. 6 Average number of nodes alive over round

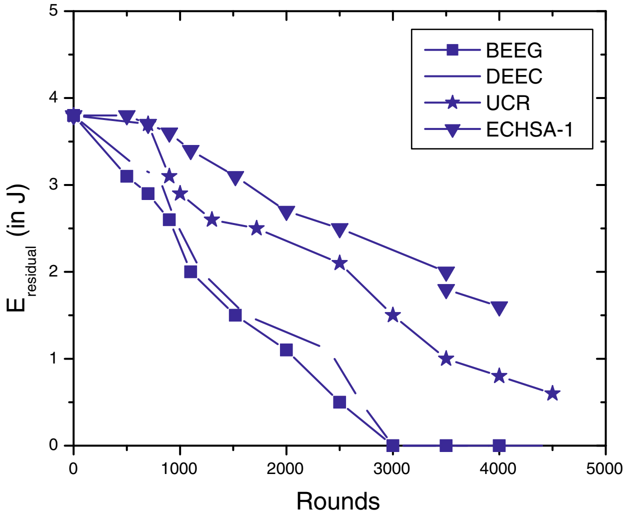

Fig. 7 Average residual energy labels for ECHSA-1 and existing approaches

From Fig. 8, it is clear that the performance of ECHSA-2 is more as compared with baseline algorithms. Figure 9 shows the average residual energy labels of both ECHSA-1 and ECHSA-2. Figure 9 indicates that ECHSA-2 performs better as compared to ECHSA-1. This is because in case of ECHSA-1, it mainly works with NE. But, in one round if there are multiple NEs, then sometimes CHs are formed which are having less energy. This is because more than one CH candidate is selected. In such situation, ECHSA-2 works well which can overcome the problem of multiple NEs. That means in each round it selects optimum CHs. Thus, ECHSA-2 works well as compared to ECHSA-1.

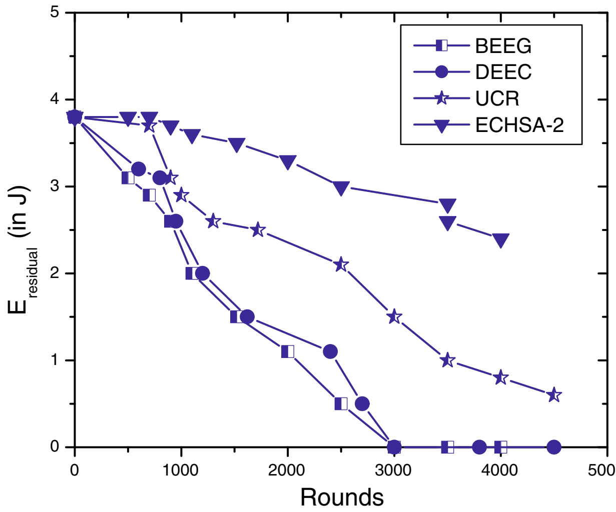

Fig. 8 Average residual energy labels for ECHSA-2 and existing approaches

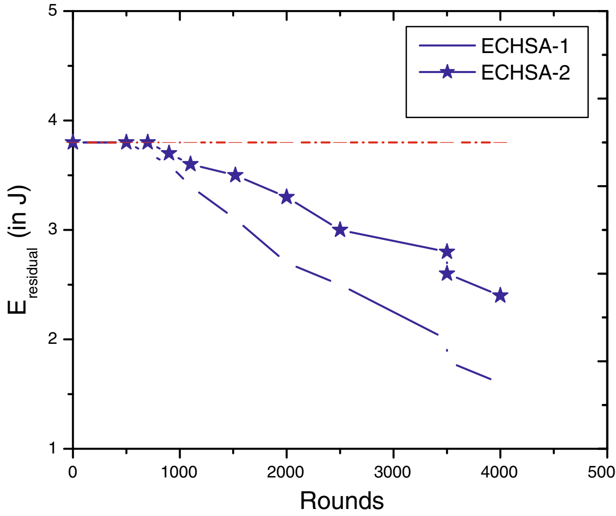

Fig. 9 Average residual energy labels for both ECHSA-1 and ECHSA-2

6 Conclusion

In this work, authors propose a CH selection algorithm based on the NE decision of the game theory where in each round ECS determines an optimal CH using NE. ECS works with two algorithms: ECHSA-1 and ECHSA-2. ECHSA-1 suffers from multiple NEs, but ECHSA-2 overcomes this problem. The results of both ECHSA-1 and ECHSA-2 indicate that the network lifetime is longer in case of ECS as compared with the baseline algorithms BEEG, DEEC, and UCR. In future, we will try to use these concepts in case of heterogeneous environment where some of the nodes in the network suffer from less battery power.

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