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LEACH-MAC: a new cluster head selection algorithm for Wireless Sensor Networks

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Abstract Battery power is a critical resource of Wireless Sensor Networks (WSNs). Therefore, an effective operation of WSNs depend upon the efficient use of its battery resource. Cluster based routing protocols are proven to be more energy efficient as compared to other routing protocols. Most of the cluster based routing protocols, especially Low Energy Adaptive Clustering Hierarchy (LEACH) protocol, follows Dynamic, Distributed and Randomized (DDR) algorithm for clustering. Due to the randomness present in clustering algorithms, number of cluster heads generated varies highly from the optimal count. In this paper, we present an approach which attempts to control the randomness present in LEACH's clustering algorithm. This approach makes the cluster head count stable. NS-2 simulation results show that proposed approach improved the First Node Death (FND) time and Last Node Death (LND) time by 21 and 24 % over LEACH, 10 and 20 % as compared to Advance LEACH (ALEACH) and 5 and 35 % over LEACH with Deterministic Cluster Head Selection (LEACH-DCHS) respectively.

Keywords Clustering · Energy efficiency · Network lifetime · Routing protocol · Wireless Sensor Networks

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1 Introduction

Nowadays, Wireless Sensor Networks (WSNs) are playing an essential role in the effective operation of many applications such as smart transportation, health monitoring, battlefield surveillance, smart grids, weather forecasting, satellite communication, IoT etc. [1–6]. WSN's attractive features such as low cost, low power radios and sensing capability have increased its use in day to day life. WSN consists of a large collection of resource constrained (especially battery power) sensor nodes. These sensor nodes sense analog data (e.g., temperature, humidity) from the environment and convert into digital form for processing. This processed data is aggregated and reported back to the sink or Base Station (BS) [7].

WSNs suffer from many issues such as coverage, security, energy-efficiency, localization, etc. [8–13]. Among these issues energy-efficiency is the critical issue, as sensor nodes are battery operated. Depending upon the application requirements, sometimes, WSN is deployed in the unattended region or harsh environment where human intervention is not possible. In such environments, efficient use of battery power plays a critical role in the effective operation of WSN as they are equipped with non-replaceable battery resource. A number of efforts have been made to make WSN energy efficient by saving energy from the physical level to routing level, by improving data acquisition strategies and by incorporating mobility into the nodes [14–23]. However, it is established that most of the energy is consumed in data transmission and reception [24]. Therefore, energy saving routing protocols are required.

Cluster based routing protocols, a cross layer solution, have attracted great attention of the researchers in this regard. A cluster based routing protocol works in two phases: setup phase and steady state phase. In the setup phase, the network is divided into various groups of nodes called clusters. In these clusters, one node acts as a leader node called cluster head. In the steady state phase, cluster members periodically sense and send data to the cluster head, according to the Time Divison Multiple Access (TDMA) schedule sent by the cluster head. Cluster head weeds out the redundant data, minimizes the data size via aggregation and sends it to the BS. A clustering technique transforms the global communication into the local communication for saving energy.

LEACH (Low Energy Adaptive Clustering Hierarchy) [25] is the first attempt towards cluster based routing protocols. In the setup phase of the LEACH protocol, cluster heads are selected using a dynamic, distributed and randomized algorithm. Each node generates a random number in [0, 1]. Those nodes, which generate random number less than the threshold $T(n)$ (Eq. 1), will elect themselves as cluster head.

$$T(n) = \begin{cases} \dfrac{P}{1 - P \times (r \bmod 1/P)} & if \quad n \in G \\ 0 & otherwise \end{cases} \tag{1}$$

where, P is the initial percentage of cluster heads, which is usually 5% of total nodes, r is the round number, G is the set of nodes, which are not cluster heads in previous rounds and n is the node number. Therefore, there is no control on the generation of cluster heads, i.e., as many as nodes generate random number less than the threshold, will become cluster heads. Hence, number of cluster heads vary from the optimal count as expected [26, 27]. Cluster head count affects energy efficiency of a cluster based routing protocol. If the cluster head count will be more then more aggregation energy will be consumed. In the converse case, more energy will be consumed by the cluster members in communication with cluster head and aggregation load on the cluster heads will also get increased. To control the inherent randomness present in LEACH, this paper presents an approach to control the number of cluster heads formed. For carrying out the approach, Medium Access Control (MAC) layer information is used. Simulation results in the Sect. 7 show the improved results.

The remainder of the paper is organized as follows. Section 2 briefs the related work in this area. Network model and assumptions are discussed in Sect. 3. In Sect. 4, the proposed approach is presented. The proposed approach is mathematically analyzed in Sect. 5. Results showing the efficacy of the approach has been presented in Sect. 6. Finally, paper is concluded along with future scope in Sect. 7.

2 Related work

Cluster based routing protocols, due to their energy efficiency feature, attracted significant attention among different categories of routing protocols such as data-centric, location based, QoS aware and hierarchical routing protocols. LEACH [24] is a baseline cluster based routing protocol. In this protocol, dynamic cluster heads are formed using a randomized algorithm. In order to balance the energy among sensor nodes, the role of the cluster heads is rotated. Two Level hierarchy-LEACH (TL-LEACH) [28] balances the load among the sensor nodes by creating two levels of hierarchy, i.e., primary cluster heads and secondary cluster heads. Energy efficient hierarchical clustering algorithm [29] increased the energy efficiency by developing multiple levels of cluster heads.

In LEACH protocol, low energy nodes can also become cluster heads. Thus to select nodes with higher residual energy as cluster heads, LEACH with Deterministic Cluster Head Selection (LEACH-DCHS) and Advance LEACH (ALEACH) protocols are proposed in [30, 31]. Along with higher energy nodes as cluster heads, Hybrid Energy Efficient Distributed (HEED) [32], Energy Efficient Clustering Schme (EECS) [33] and Enhanced Centralized LEACH (ECLEACH) [34] made the cluster head distribution uniform.

To increase life time of the network, authors in [35] improved the cluster formation strategy. Ashfaq et al. [36] proposed $(ACH)^2$ for adaptive cluster head selection and cluster association. In $(ACH)^2$, free association technique is used to eliminate back transmissions. To improve life span of the network, distance (hop count) based algorithm for cluster head selection and cluster formation are used in [37, 38].

LEACH also suffers from the cluster head variability problem [26, 27]. To mitigate this problem, Stepwise Adaptive Clustering Hierarchy (SWATCH) [39] protocol is proposed. SWATCH protocol divides setup phase into two stages (Initial selection stage and add-on selection stage) for keeping cluster head count in the optimal range. Huafeng et al. [40] modified probability of cluster head selection to keep cluster head count stable. LEACH with sliding window and Dynamic Number of Nodes (LEACH-SWDN) [41] modified threshold function and also made use of dynamically changing random interval of cluster head selection for stabilizing the cluster head count.

However, authors [39–41] did not solve the root cause of the cluster head variability problem, i.e., inherent randomness present in the cluster head selection process. In this paper, we propose an approach to control the randomness present in setup phase. Proposed approach also gives priority to higher energy node in the cluster head selection.

3 Network model and assumptions

Consider a WSN comprises of N randomly and uniformly distributed sensor nodes in $M \times M$ m^2 region. These sensor nodes continuously monitor the region of interest. Network model and assumptions are as follows:

Table 1 Table of notations

Notation	Description
N	Total number of nodes
$M \times M$	Network size
l	Number of bits
E_{elec}	Energy consumed per bit to run electronic circuitry
ε_{fs}	Amplification factor for free space model
$\varepsilon_{two-ray}$	Amplification factor for multi-path model
d	Distance between nodes
d_c	Cross-over distance
k	Optimal number of cluster heads
E_{CH}	Energy consumed by the cluster head
E_{non-CH}	Energy consumed by the nodes that are not cluster heads
E_{DA}	Aggregation energy
$E_{cluster}$	Energy consumed by a cluster
E_{total}	Total consumed energy
P	Initial percentage of cluster heads
G	Nodes eligible for cluster head selection
r	Number of rounds
E_{SAL}	Energy consumed by LEACH in sending advertisement
E_{SALMAC}	Energy consumed by LEACH-MAC in sending advertisement
E_{RAL}	Energy consumed by LEACH in receiving advertisement
E_{RALMAC}	Energy consumed by LEACH-MAC in receiving advertisement
E_{SJL}	Energy consumed by LEACH in sending join request
E_{SJLMAC}	Energy consumed by LEACH-MAC in sending join request
E_{RJL}	Energy consumed by LEACH in receiving join request
E_{RJLMAC}	Energy consumed by LEACH-MAC in receiving join request
E_{STL}	Energy consumed by LEACH in sending TDMA schedule
E_{STLMAC}	Energy consumed by LEACH-MAC in sending TDMA schedule
E_{RTL}	Energy consumed by LEACH in receiving TDMA schedule
E_{RTLMAC}	Energy consumed by LEACH-MAC in receiving TDMA schedule
E_{TEL}	Total energy consumed by LEACH in cluster configuration
E_{TELMAC}	Total energy consumed by LEACH-MAC in cluster configuration
$E_{non-CHL}$	Energy consumed by non cluster head in LEACH protocol
$E_{non-CHLMAC}$	Energy consumed y non cluster head in LEACH-MAC protocol.
E_{totL}	Total energy consumed by LEACH in steady state phase
$E_{totLMAC}$	Total energy consumed by LEACH-MAC in steady state phase

- BS is located outside the sensor field and nodes can communicate with the BS directly.
- Nodes are stationary, location unaware and of same hardware configuration.
- Nodes can change the power levels depending upon the Receive Signal Strength (RSS).
- For saving energy, the node's transceivers can go into sleep mode.
- Links are symmetric, i.e., equal amount of energy is dissipated in the communication on either side.
- Each node can aggregate the data and the energy consumed in aggregation is $E_{DA}(nJ/bit)$.

List of symbols used in the paper is shown in Table 1.

3.1 Radio model

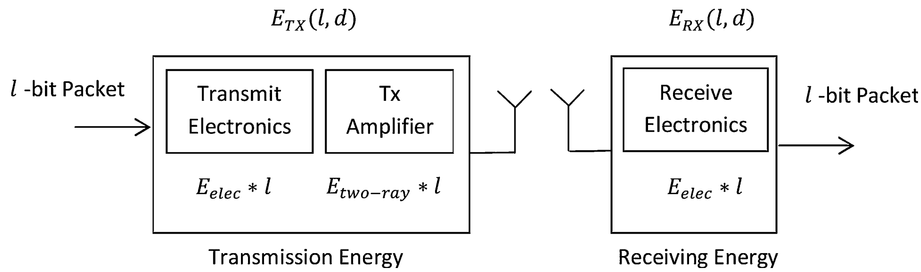
In this paper, the first order radio model [25] has been used for energy consumption analysis. The energy consumption model is shown in Fig. 1.

Energy consumed in transmitting l-bit data at distance d is given as:

$$E_{TX}(l,d) = \begin{cases} l * E_{elec} + l * \varepsilon_{fs} * d^2 & , d < d_c \\ l * E_{elec} + l * \varepsilon_{two-ray} * d^4 & , d \geq d_c \end{cases} \quad (2)$$

where, E_{elec} is energy dissipated due to electronic circuitry, which depends upon the coding, modulation, filtering and

Fig. 1 Energy consumption model



spreading of the signal. $d_c = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{two-ray}}}$, is the cross-over distance. ε_{fs} and $\varepsilon_{two-ray}$ are the amplification factor for free-space and two-ray ground model respectively. Energy consumed in receiving the l-bit message is: $E_{RX} = l * E_{elec}$.

4 Preliminaries and proposed approach

For effective clustering, the number of cluster heads should lie in the optimal range. Following section calculates the optimal count [42] in LEACH protocol.

4.1 Optimal cluster head count

Assume that the optimal number of cluster heads are k. Average number of nodes per cluster are $\frac{N}{k}$. The total energy consumed by a cluster in a single frame of TDMA schedule is given as:

$$E_{cluster} = E_{CH} + \frac{N}{k} E_{non-CH} \tag{3}$$

where, E_{CH}, energy dissipated by the cluster head in reception, aggregation (E_{DA}) and transmission of data to the BS is given as:

$$E_{CH} = lE_{elec}N/k + lE_{DA}N/k + l\varepsilon_{two-ray}d^4_{toBS} \tag{4}$$

and E_{non-CH}, energy consumed by the cluster member in transmitting data to the cluster head is given by Eq. (5).

$$E_{non-CH} = lE_{elec} + l\varepsilon_{fs}d^2_{toCH} \tag{5}$$

were, $E(d^2_{toCH}) = \frac{1}{2\pi}\frac{M^2}{k}$, assuming the area occupied by the cluster is circular with radius R and density of nodes $\rho(r,\theta) = \frac{k}{M^2}$, which is a constant for r and θ.

Total energy consumed in a frame is given as:

$$E_{total} = kE_{cluster} \tag{6}$$

Optimal cluster heads, k, can be found by differentiating E_{total} with respect to k and equating to 0 (Eq. 7).

$$k = \frac{\sqrt{N}}{\sqrt{2\pi}}\sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{two-ray}}}\frac{M}{d^2_{toBS}} \tag{7}$$

For the simulation, we considered (see Sect. 5), $N = 100$, $M = 100$, $\varepsilon_{fs} = 10\,\text{pJ/bit/m}^4$, $\varepsilon_{two-ray} = 0.0013\,\text{pJ/bit/m}^4$ and $75 < d_{toBS} < 185$. With these parameters, the expected number of cluster heads lie in the range $1 < k < 6$. Through the verification of analytical results using simulations, the optimal number of cluster heads are found to be in the range 3–5. Therefore, in this paper, value of $k = 5$ has been taken.

4.2 Proposed approach

The proposed approach attempts to restrict the number of cluster head advertisements. At the time of cluster head advertisement reception, a variable CHheard_ initialized as 0 and is incremented by 1 as soon as node receives the advertisement. The steps of the proposed approach are as follows:

- After passing through the threshold function, nodes select a uniform random time in the interval [0 *total_adv_time*], where *total_adv_time* is the total time required for cluster head transmission and reception [43] and it is calculated as:

$$\begin{aligned} Transmission\,Time &= \frac{(Number\ of\ bytes * 8)}{Bandwidth} \\ adv\_time &= Transmission\,Time\ of \\ &\quad (Control\_Packet\_Size * 4) \\ total\_adv\_time &= adv\_time \\ &\quad * (Num\_of\_Clusters) * 4 + 1) \end{aligned}$$

Let the selected time be R_t.

- Now the selected time R_t is divided by the current (residual) energy so that higher energy nodes can send the advertisement earlier than low energy nodes. Time of sending CH advertisement: $t_{adv\_CH} = \frac{R_t}{Current\ Energy}$
- At the time t_{adv_CH}, node checks the number of advertisements heard by itself through the CHheard_ variable. If the value of CHheard_ variable is less than optimal value, i.e., 5 then it will send the cluster head advertisement otherwise declare itself as normal node.

This entire process as a flow graph is shown in the Fig. 2.

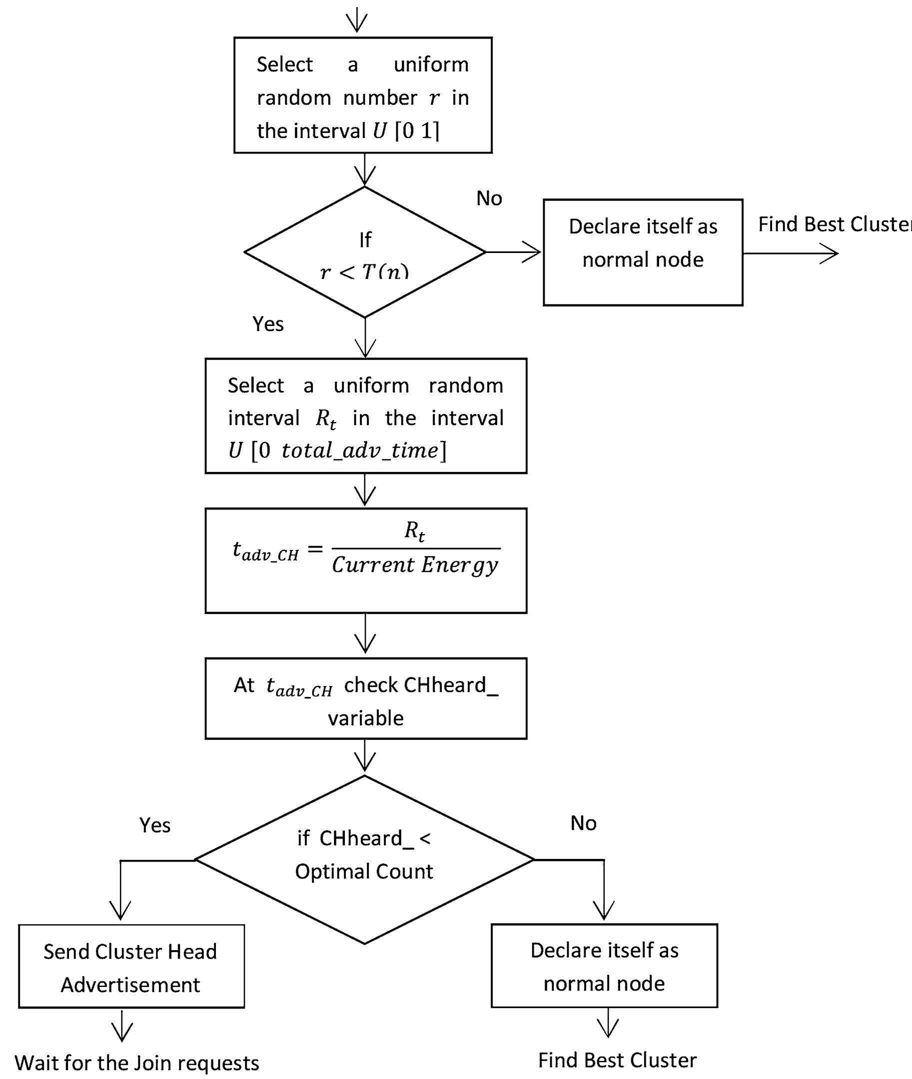


Fig. 2 Flow graph of proposed approach

5 Mathematical analysis

Assume G is the number of eligible nodes out of N nodes for cluster head (CH) selection. $T(n)$ is the initial probability p with which node elects itself as cluster head. Number of cluster heads k can be modelled as binomial distribution [4], i.e.,

$$k = \binom{N}{G} p^G (1-p)^{N-G}$$

Time R_t at which CH advertisement is to be sent is given as:

$$R_t = U[0 \quad total\_adv\_time]$$

Since generated uniform random time R_t is directly proportional to number of sent CH advertisements. Thus, the probability, P of sending CH advertisements is given as:

$$P(Sending\ CH\ advertisements) = \frac{1}{total\_adv\_time}$$

CH advertisement is received by the remaining nodes in the interval [0 adv_recv], assuming that advertisement is sent immediately. Therefore, the probability, P of receiving CH advertisements is given as:

$$P(Receiving\ CH\ Advertisements) = \frac{1}{adv\_recv}$$

In this case, $adv\_recv < total\_adv\_time$ Therefore,

$$P(Receiving\ CH\ Advertisements) > P(Sending\ CH\ advertisements)$$

Thus, some nodes will definitely receive some CH advertisements before declaring themselves as cluster head.

Let 1st CH advertisement is sent at time t, and consecutive advertisements are sent at $t + \delta_i$ such that

$\delta_i < \delta_{i+1}$, where δ_i is very small fraction of a $total\_adv\_time$ and i varies from 1 to 4.

Therefore, random interval can be divided into

$$[0 \quad (adv\_recv + \sum \delta_i) \quad total\_adv\_time], i = 1, 2, 3, \text{and } 4.$$

So some nodes will send advertisement at time generated in the interval

$$[(adv\_recv + \sum \delta_i) \;\; total\_adv\_time]$$

Such nodes will definitely listen ≥ 5 CH advertisements and will not declare themselves as cluster head.

The number of CH advertisements (m) sent in the interval $[(adv\_recv + \sum \delta_i) \quad total\_adv\_time]$ is given as:

$$\frac{k * (total\_adv\_time - (adv\_recv + \sum \delta_i))}{total\_adv\_time} \tag{8}$$

where, i =1, 2, 3, and 4. From Eqs. (7) and (8), the number of CH advertisements in the proposed approach is

$$k^{'} = k - m. \tag{9}$$

Hence, number of CH advertisements in the proposed approach will be less than original approach.

5.1 Analysis of proposed method

Let k be the number of cluster heads in LEACH protocol.

$k^{'}$ be the number of cluster heads in LEACH-MAC protocol.

From Eq. (9) $k > k^{'}$. Therefore,

Number of non-CH nodes in LEACH protocol = $N - k$.

Number of non-CH nodes in LEACH-MAC protocol = $N - k^{'}$.

5.1.1 Cluster configuration analysis

5.1.2 Steps for cluster configuration

The Network is divided into clusters by the following steps:

- Nodes passing through the threshold function broadcast the cluster head advertisement.
- Nodes receive the cluster head advertisements and send the join request to the cluster head with smallest distance.
- After receiving the cluster head advertisement, cluster heads build and send the TDMA schedule to the cluster members.
- Cluster members receive the TDMA schedule and send data according to the schedule to the concerned cluster head in the steady state phase.

5.1.3 Energy consumption analysis

Energy consumed in sending CH advertisement:

$$E_{SAL} = k * (lE_{elec} + l\varepsilon_{two-ray} d^4_{tonodes}) \tag{10}$$

$$E_{SALMAC} = k^{'} * (lE_{elec} + l\varepsilon_{two-ray} d^4_{tonodes}) \tag{11}$$

where, E_{SAL} and E_{SALMAC} denote the energy consumed in sending cluster head advertisements by the cluster heads in LEACH and LEACH-MAC protocol respectively.

Energy consumed in receiving CH advertisement:

Since each node receives CH advertisement from all cluster heads for choosing best cluster head for further communication. Therefore,

$$E_{RAL} = k * ((N - k) lE_{elec}) \tag{12}$$

$$E_{RALMAC} = k^{'} * ((N - k^{'}) lE_{elec}) \tag{13}$$

where, E_{RAL} and E_{RALMAC} represent the energy consumed in receiving cluster head advertisements by the nodes in LEACH and LEACH-MAC protocol respectively.

Energy consumed in sending join message to the best cluster head:

Join request will be sent only to the nearest cluster head based on receive signal strength. Therefore,

$$E_{SJL} = (N - k) * (lE_{elec} + l\varepsilon_{fs} d^2_{toCH}) \tag{14}$$

$$E_{SJLMAC} = (N - k^{'}) * (lE_{elec} + l\varepsilon_{fs} d^2_{toCH}) \tag{15}$$

where, $E_{SJL}$and E_{SJLMAC} denote the energy consumed in sending join requests by the nodes in LEACH and LEACH-MAC protocol respectively.

Energy consumed in receiving join message:

Assuming that for the uniform distribution, average number nodes per cluster are $\frac{N}{k} (\frac{N}{k^{'}})$. Energy consumed in receiving join message is given as:

$$E_{RJL} = k * \left(lE_{elec} * \frac{N}{k} \right) \tag{16}$$

$$E_{RJMAC} = k^{'} * \left(lE_{elec} * \frac{N}{k^{'}} \right) \tag{17}$$

where, $E_{RJL}$and E_{RJLMAC} represent the energy consumed in receiving join requests by the cluster heads in LEACH and LEACH-MAC protocol respectively.

Energy consumed in sending TDMA schedule by the cluster heads:

Since TDMA schedule is broadcast by the CHs at the maximum distance. Therefore,

$$E_{STL} = k * (lE_{elec} + l\varepsilon_{two-ray} d^4_{tonodes}) \tag{18}$$

$$E_{STLMAC} = k^{'} * (lE_{elec} + l\varepsilon_{two-ray} d^4_{tonodes}) \tag{19}$$

where, E_{STL} and E_{STLMAC} denote the energy consumed in sending TDMA schedule by the cluster heads in LEACH and LEACH-MAC protocol respectively.

Energy consumed by the nodes in receiving TDMA schedule:

$$E_{RTL} = (N - k) * lE_{elec} \tag{20}$$

$$E_{RTLMAC} = (N - k^{'})lE_{elec} \tag{21}$$

where, $E_{RTL}$and E_{RTLMAC} represent the energy consumed in receiving TDMA schedule by the nodes in LEACH and LEACH-MAC protocol respectively.

Total energy consumed in cluster configuration:

$$E_{TEL} = E_{SAL} + E_{RAL} + E_{SJL} + E_{RJL} + E_{STL} + E_{RTL} \tag{22}$$

$$\begin{aligned} E_{TELMAC} = {} & E_{SALMAC} + E_{RALMAC} + E_{SJLMAC} + E_{RJLMAC} \\ & + E_{STLMAC} + E_{RTLMAC} \end{aligned} \tag{23}$$

where, $E_{TEL}$and E_{TELMAC} denote the total energy consumed in cluster configuration in LEACH and LEACH-MAC protocol respectively.

After solving Eqs . (22) and (23) We get,

$$\begin{aligned} E_{TEL} = {} & (k+3)NlE_{elec} + (N-k)l\varepsilon_{fs}d^2_{toCH} \\ & + 2lk\varepsilon_{two-ray}d^4_{tonodes} - k^2lE_{elec} \\ E_{TELMAC} = {} & (k^{'}+3)NlE_{elec} + (N-k^{'})l\varepsilon_{fs}d^2_{toCH} \\ & + 2lk^{'}\varepsilon_{two-ray}d^4_{tonodes} - k^{'2}lE_{elec} \end{aligned}$$

Since, $E(d^2_{toCH}) = \frac{1}{2\pi}\frac{M^2}{k}$. Therefore,

$$\begin{aligned} E_{TEL} = {} & (k+3)NlE_{elec} + (N-k)l\varepsilon_{fs}\frac{1}{2\pi}\frac{M^2}{k} \\ & + 2lk\varepsilon_{two-ray}d^4_{tonodes} - k^2lE_{elec} \end{aligned} \tag{24}$$

$$\begin{aligned} E_{TELMAC} = {} & (k^{'}+3)NlE_{elec} + (N-k^{'})l\varepsilon_{fs}\frac{1}{2\pi}\frac{M^2}{k^{'}} \\ & + 2lk^{'}\varepsilon_{two-ray}d^4_{tonodes} - k^{'2}lE_{elec} \end{aligned} \tag{25}$$

By subtracting (25) from (24), we get the amount of energy saved in the proposed LEACH-MAC protocol. i.e.,

$$E_{TEL} - E_{TELMAC} = \frac{l(k-k^{'})}{kk^{'}} * (A * kk^{'} - B * kk^{'}(k+k^{'}) + C) \tag{26}$$

where, $A = lE_{elec} + 2\varepsilon_{two-ray}d^4_{tonodes}$, $B = E_{elec}$, $C = \frac{M^2}{2\pi} * N\varepsilon_{fs}$. After putting values $E_{elec} = 50nJ/bit$, $M = 100$, $N = 100$, $\varepsilon_{fs} = 10pJ/bit/m^2$, $\varepsilon_{two-ray} = 0.0013pJ/bit/m^4$ and $d_{tonodes} = 141.42$ we get, $A = 6.039X10^{-6}$, $B = 5X10^{-8}$, and $C = 1.592X10^{-6}$. By this Eq. (26) becomes

$$\begin{aligned} E_{TEL} - E_{TELMAC} = {} & \frac{l(k-k^{'})}{kk^{'}} * (6.039X10^{-6} \\ & * kk^{'} - 5X10^{-8} * kk^{'}(k+k^{'}) + 1.592X10^{-6}) \end{aligned} \tag{27}$$

For any value of k and $k^{'}$ such that $1 < k^{'} < k < 6$, $E_{TEL} - E_{TELMAC} > 0$. Thus, it can be concluded that energy is saved in our approach.

5.2 Steady state phase analysis

In the steady state phase, nodes send data to the cluster heads according to their respective slots assigned in TDMA schedule. In turn, cluster heads receive, aggregate and send data to the BS.

5.2.1 Energy consumption analysis

Energy consumed by the cluster heads is given as:

$$E_{CHL} = lE_{elec}\frac{N}{k} + lE_{DA}\frac{N}{k} + l\varepsilon_{two-ray}d^4_{toBS} \tag{28}$$

$$E_{CHLMAC} = lE_{elec}\frac{N}{k^{'}} + lE_{DA}\frac{N}{k^{,}} + l\varepsilon_{two-ray}d^4_{toBS} \tag{29}$$

where E_{CHL} and E_{CHLMAC} are the energy consumed by the cluster head in receiving, aggregating and transmitting data to the BS in LEACH and LEACH-MAC protocol respectively.

Energy consumed by non-cluster head is given as:

$$E_{non-CHL} = lE_{elec} + l\varepsilon_{fs}\frac{1}{2\pi}\frac{M^2}{k} \tag{30}$$

$$E_{non-CHLMAC} = lE_{elec} + l\varepsilon_{fs}\frac{1}{2\pi}\frac{M^2}{k^{,}} \tag{31}$$

where, $E_{non-CHL}$ and $E_{non-CHLMAC}$ denote the energy spent by the non-cluster heads in sending data to the cluster heads in LEACH and LEACH-MAC protocol respectively.

Since, $E_{cluster} = E_{CH} + \frac{N}{k}E_{non-CH}$ (See Sect. 4.1). Therefore, total energy consumed in a frame of TDMA schedule is given as: $E_{tot} = k * E_{cluster}$

$$\begin{aligned} E_{totL} = {} & l\Big(E_{elec}N + E_{DA}N + k\varepsilon_{two-ray}d^4_{toBS} \\ & + NE_{elec} + N\varepsilon_{fs}\frac{1}{2\pi}\frac{M^2}{k}\Big) \end{aligned} \tag{32}$$

$$\begin{aligned} E_{totLMAC} = {} & l\Big(E_{elec}N + E_{DA}N + k^{'}\varepsilon_{two-ray}d^4_{toBS} \\ & + NE_{elec} + N\varepsilon_{fs}\frac{1}{2\pi}\frac{M^2}{k^{'}}\Big) \end{aligned} \tag{33}$$

where, E_{totL} and $E_{totLMAC}$ represent the total energy consumed by the cluster in LEACH and LEACH-MAC protocol respectively.

By subtracting (33) from (32) we get,

$$E_{totL} - E_{totLMAC} = l(k - k^{'})(0.519kk^{'} - 1.592)X10^{-6} \quad (34)$$

From the analysis in Sect. 4, the value of k lies between 1 and 6. Thus for any value of k, Eqn. (34) gives positive non-zero result.

Energy saved in a single frame= $(E_{totL} - E_{totLMAC})$

Energy saved in one round = $(E_{totL} - E_{totLMAC})*$ *Number of frames per round*

Total energy saved per round = Energy saved in setup phase + Energy saved in steady state phase i.e.,

$$((E_{TEL} - E_{TELMAC}) + (E_{totL} - E_{totLMAC}) * Number\ of\ frames\ per\ round)$$

Since total number of rounds are r, therefore,

Total saved energy = $r *$ Total energy saved per round. This saved energy is used in increasing the first node death time as well as number of rounds.

6 Simulation results and analysis

For simulation, legacy code of LEACH protocol, mit.tar.gz [43], has been ported to NS-2.35 [44]. LEACH-MAC protocol is compared against the protocols LEACH, ALEACH (Advance LEACH) and LEACH-DCHS (LEACH with Deterministic Cluster Head Selection) protocols. Metrics of comparison consists network lifetime, total energy consumption, number of packets received per unit energy at the BS and number of cluster heads per round.

In the network, 100 nodes are randomly and uniformly deployed in 100 × 100 m^2 square region. Nodes are assigned with the initial energy of 5 J. The BS is located at position (50,175). For achieving 95 % confidence interval, average of 10 simulations has been shown in the results. The rest of the simulation parameters are shown in Table 2.

Table 2 Simulation parameters

Parameter	Value
E_{elec}	50 nJ/bit
E_{fs}	10 pJ/bit/m^4
$E_{two-ray}$	0.013 pJ/bit/m^4
E_{DA}	5 nJ/bit
Control packet size	25 bytes
Data packet size	500 bytes
Round time	10*Initial energy[42]

6.1 Results

6.1.1 Network lifetime

This parameter measures that how long a network region can be monitored. It is made up of two parts as a stability period, i.e., when the first node death occurs and in-stability period, i.e, time between the First Node Death (FND) and the Last Node Death (LND) time. For some applications longer stability period is a prime requirement as loss of single node's data affects the final result. Whereas for other applications time until the last node death occurs matters.

Figure 3 shows the lifetime comparison of LEACH, LEACH-MAC, ALEACH and LEACH-DCHS protocols. From the figure it is observed that, LEACH-MAC improves FND by 180 s as compared to LEACH, 90 s against ALEACH, 50 s over LEACH-DCHS respectively. Similarly, Half Nodes Alive (HNA) time is increased by 240 s over both LEACH and LEACH-DCHS and 150 s as compared to ALEACH. LND shows an improvement of 169 s against LEACH, 269 s as compared to ALEACH and 419 s over LEACH-DCHS respectively. Thus, there is a significant improvement in both stability as well as instability period.

The reason behind this improvement is optimal cluster head generation. LEACH, ALEACH and LEACH-DCHS show large cluster head variations, especially when the first node death occurs and the next epoch (i.e., $\frac{N}{k}$) begins. In ALEACH and LEACH-DCHS, modified threshold function results into high cluster head fluctuations during the entire cycle as analyzed in [19]. LEACH-MAC protocol reduces these fluctuations by controlling the randomness present in the cluster head selection algorithm. Thus, during cluster configuration phase, less control packets, i.e.,

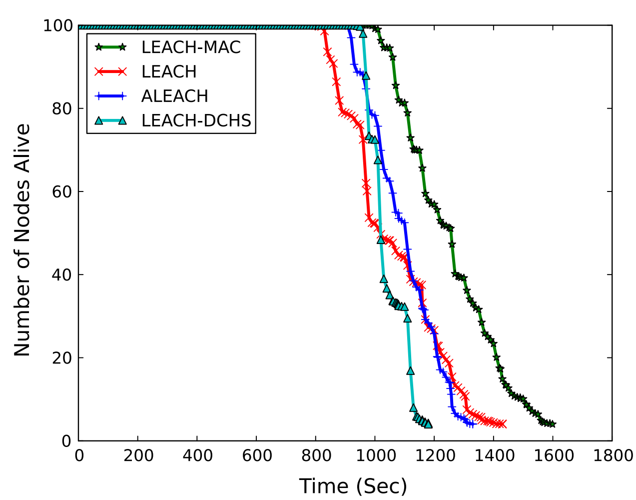


Fig. 3 Time versus number of nodes alive

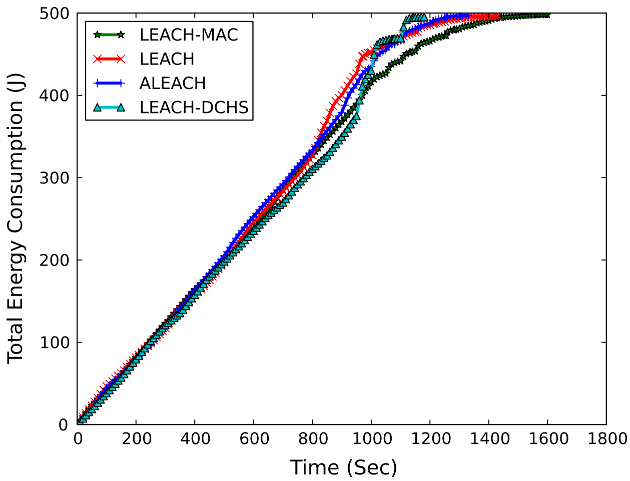


Fig. 4 Time versus energy consumption

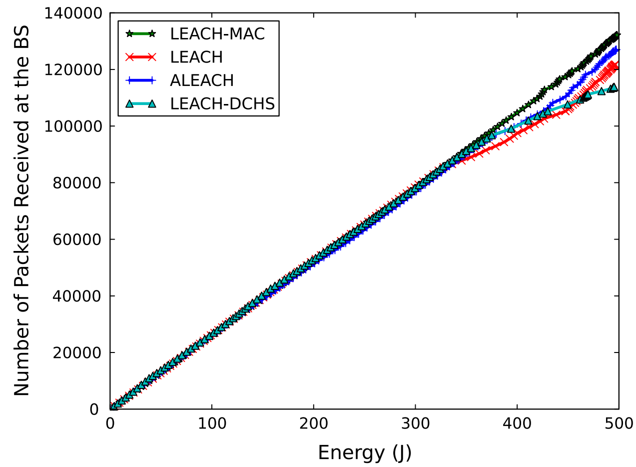


Fig. 5 Energy versus number of packets received at the BS

sending and receiving CH advertisements, join requests and TDMA schedules, are communicated. This results into saving of energy as analyzed mathematically. Since the cluster head count affects directly the aggregation energy, therefore, in steady state phase also energy is saved as shown in Sect. 5. Hence energy saved in earlier rounds results into increased network lifetime in terms of FND, HNA and LND.

6.2 Total energy consumption

Energy is consumed in transmission, reception, aggregation and due to electronics circuitry. Balanced energy consumption leads to longer network lifetime. For uniform energy consumption, load should be uniformly distributed among the nodes.

From the Fig. 4 it is observed that LEACH-MAC protocol consumes energy more uniformly as compared to LEACH, ALEACH and LEACH-DCHS protocols. Along with randomness, change in the threshold function value also causes variation in the cluster head count. The main cause of energy consumption in LEACH is production of high number of cluster heads as new epoch begins. This is due to increase in probability of selection of cluster head after the first node death and also all nodes become eligible for cluster head selection as the new epoch begins. ALEACH protocol threshold function causes variation in cluster head count from low to high in each epoch [19] which leads to more energy consumption. LEACH-DCHS protocol consumes energy uniformly in earlier rounds but in later rounds it shows the wavy nature. This is due to the high fluctuation in cluster head count [19] during the entire protocol operation.

Proposed approach not only keeps the cluster head count in the optimal range but also selects the higher energy node as cluster head. Therefore, the load will be properly balanced among the nodes. Balanced load leads to more uniformity in energy consumption of LEACH-MAC as compared to others as shown in the Fig. 4. Energy consumption analysis in Sect. 5 shows saving in energy both in setup phase and steady state phase. This saved energy leads to increased network lifetime.

6.3 Number of packets received at the BS

Packets are received at the BS at the expense of energy. Therefore, the quality of a protocol is estimated by the number of packets received at the BS. More is the uniformity in energy consumption, more is the number of packets received at the BS. Figure 5 shows the number of packets received at the BS per unit energy for LEACH-MAC, ALEACH and LEACH-DCHS. The number of packets received in proposed approach is more as compared to other protocols.

This improvement is due to stable cluster head generation method used for cluster head selection. Stable cluster head selection leads to uniform energy consumption and increased number of rounds. Reduced cluster head fluctuations and energy consideration while cluster head selection increased the energy efficiency and number of packets received at the BS.

6.4 Number of cluster heads

Cluster head count greatly impacts energy efficiency of the protocol. If the cluster head count is more, a large chunk of energy will be dissipated in aggregation as more number of cluster heads have to consume aggregation energy. If this count will be less then there will be more aggregation load on the cluster heads as a few numbers of cluster heads are

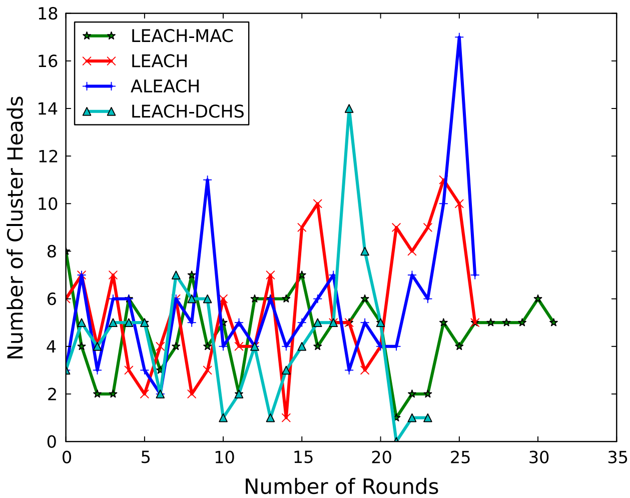


Fig. 6 Number of rounds versus number of cluster heads

responsible for communicating with the BS. Also, if cluster head count is less, the cluster members have to communicate with cluster heads at long distances which causes more energy consumption. Therefore, cluster head count should be stable for increasing the energy -efficiency of the protocol.

Comparison of cluster head count generated by the LEACH, LEACH-MAC, ALEACH and LEACH-DCHS protocol in each round is shown in Fig. 6. From the figure, it is observed that cluster head fluctuations are less in proposed LEACH-MAC protocol as compared to LEACH, ALEACH and LEACH-DCHS protocols. In LEACH protocol, cluster head variations are more as the next epoch begins. This is due to the inherent randomness present in the cluster head selection algorithm, increased probability of selection as the first node dies and also due to increased number of nodes eligible for cluster head selection. Modified threshold function and randomness of the cluster head selection algorithm are responsible for large variations in cluster head count for ALEACH and LEACH-DCHS in the entire protocol operation.

An additional check on the cluster head advertisements made the cluster head count stable in LEACH-MAC. Proposed approach controls the inherent randomness present in the cluster head selection algorithm and it is effective throughout the protocol operation. In this way, LEACH-MAC protocol has brought down the variations in cluster head count to a stable value.

7 Conclusion and future scope

Cluster head count affects the network lifetime greatly. If the cluster head count is more then, aggregation advantage cannot be taken fully. If this count is less, there will be more load on the cluster members as they have to communicate with the cluster heads at longer distances. In this paper, we have discussed an approach which attempts to control the inherent randomness of the cluster head selection algorithm by using MAC layer information. Proposed approach also gives priority to the higher energy node for becoming cluster head. Simulation results show that LEACH-MAC improves the overall network lifetime (FND, HNA and LND) than the LEACH, ALEACH and LEACH-DCHS protocols. The proposed approach has brought down the cluster head variations in the optimal range. As a future work, we will attempt to apply the LEACH-MAC protocol to the heterogeneous networks and also on the real time environment.

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