Improving Energy Efficiency of Wireless Sensor Network through Optimum Selection of Cluster Heads

Akhtar Saeed, Irfan Ahmed, Muhammad Imran Aslam, and Tahir Malik

***Abstract* — In this paper we propose that the energy efficiency of wireless sensor networks can be enhanced by optimally selecting number of cluster head in a hierarchical-based routing protocol in a hexagonal topology. The proposed protocol is a variant of famous "Low Energy Adaptive Clustering Hierarchy (LEACH)" protocol and uses probabilistic model in a hexagonal topology to calculate optimum number of cluster heads. In addition to the improvement in energy efficiency, the hexagonal topology gives a better approximation of the realistic propagation environment as the circular coverage region of an omnidirectional antenna is well-approximated by a hexagonal topology. We compare the performance of our proposed protocol through numerical simulations with relevant variant of the LEACH protocol. Results of our numerical simulation results show that the proposed protocol significantly reduces the total energy consumption thereby improving life time of the network.**

***Index Terms* — Cluster-head, LEACH, Random node deployment, Residual Energy, Wireless Sensor Networks, WSNs**

I. INTRODUCTION

The advent of Wireless Sensor Networks (WSNs) has secured the attention of researchers and engineers in a very short time. Due to their key factors, such as miniature size, portability, energy efficiency and being autonomous, they are being preferred over traditional sensing and actuating systems especially in environments where recurrent maintenance is not feasible [1]. A WSN is primarily composed of miniaturized sensors, commonly known as nodes capable of transmitting data to a central location through the network. In contrast, to the long-range conventional wireless communication systems, WSNs are especially designed for shorter ranges, with limited information processing and data payload capabilities. The WSN comprises of four basic sections: 1) Sensor nodes which are used to collect data for the specific application through relevant transducers, 2) inter-linked Wireless transceivers which are used to wirelessly communicate to other sensor nodes and the base station for data transfer, 3) A Base-Station (BS); responsible for all the centralized data handling-related activities and 4) Embedded data-processing systems at both the BS and individual node's level. Various sub-bocks of a typical WSN node are shown in Fig. 1.

Critical issues pertaining to the performance of WSNs are primarily energy-concentric, as major overlay of such networks rely on available residual energies. Several approaches have been presented to optimize the WSN's energy performance, such as flat-based routing, location-based routing, hierarchical-based routing, etc. [2]. In this work we focused on the hierarchical-based routing as this technique provides a better networking overlay by cluster formations [3]. In hierarchical-based routing, a WSN is segregated into smaller chunks signified as clusters, resulting in better routing and consequently optimized energy consumption. Each cluster has a head referred to as a Cluster Head (CH) and all other nodes of the cluster are called as the nodes of the respective CH. Communication between the BS and nodes is routed through the respective CHs, as shown in Fig. 2.

Various routing protocols follow this clustering approach; among them, "Low Energy Adaptive Clustering Hierarchy (LEACH)" [4] and its variants [5-7] are the most prominent ones. LEACH protocol uses probabilistic methods for the selection of CHs resulting in improved energy consumption across the WSN. The deficiency of LEACH protocol in providing mathematical basis for the selection of number of CHs in WSNs is addressed by various researchers [5, 8, 9] to optimally select number of cluster heads.

In this paper we further optimize an improved variant of LEACH protocol commonly known as LEACH-E [5]. In LEACH-E, the coverage area is distributed in a square topology and the number of cluster heads of the WSN is mathematically calculated by assuming square topological coverage area of WSN. However, square topology does not approximate the circular coverage area of the omnidirectional antenna. A better approach is to use the hexagonal topology which reasonably approximates the circular coverage area [10] for omnidirectional antennas which are commonly used in WSNs. Our simulations show that distribution of clusters in the hexagonal topology improves the energy efficiency of the network as compared to the LEACH-E protocol. Therefore the proposed protocol named as LEACH-S (Saeed), results in better performance than LEACH-E by consuming the network's residual energy more efficiently and increasing the overall network lifetime.

Rest of the paper is organized as follows. The radio propagation model used in the paper is described in section II. The proposed LEACH-S protocol is defined in section III with the mathematical foundation for the optimization of number of CHs, followed by the discussion on the selection of the CH in each cluster. In section IV, simulated performance of both LEACH-S and LEACH-E are compared. The work is concluded in section V. In order to facilitate the reader, all symbols used in the paper are defined

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in APPENDIX I. In APPENDIX II, detailed evaluation of an integral used in the paper is presented.

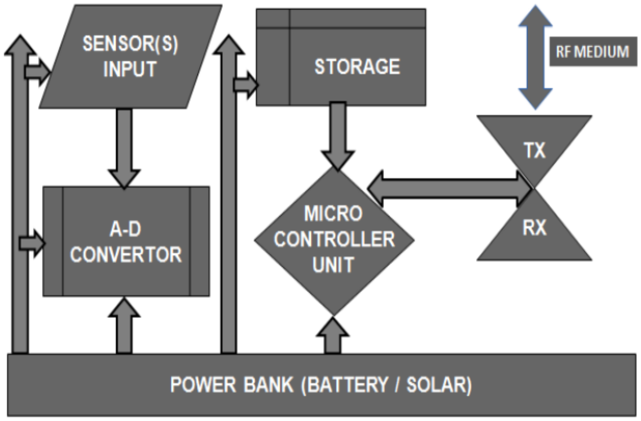

Fig. 1 Block diagram of a typical WSN node. Major components of a WSN node are indicated.

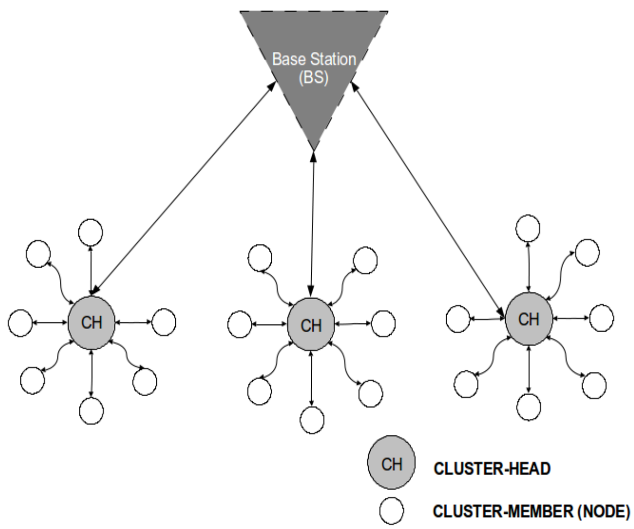

Fig. 2 Schematic diagram of clustering in a WSN. All nodes communicate to respective cluster heads which is linked to the base station.

II. RADIO PROPAGATION MODEL

In wireless systems the received power at a node depends on the link propagation distance and the path loss index which depends on the radio propagation environment. The path loss index itself is dependent on the physical separation between the communicating nodes. In most WSNs, the received power is generally modelled using two-slope path loss model [11] where the path loss exponent is small for shorter distances and a relatively larger path loss exponent for longer distances. For shorter distances, the propagation environment can be conveniently modeled as free space propagation environment with path loss index is close to 2. For longer distance, the propagation environment is better described by the ground reflection model with path loss index 4. We therefore, assume a first order radio propagation model commonly used to model the WSN propagation environment [5, 12], as shown in Fig. 3. In this model, energy needed for transmitting a data depends on the propagation distance between the communicating nodes and the number of bits that are being transmitted. Therefore the energy needed for transmitting a data consisting of b-bits over a distance d is given by

$$\boldsymbol{E_{TX}(b,d) = E_{TX-ELECT}(b) + E_{TX-AMP}(b,d)} \quad (1)$$
$$= \begin{cases} \boldsymbol{bE_{ELECT} + bE_{FS}d^2} & \boldsymbol{, d < d_0} \\ \boldsymbol{bE_{ELECT} + bE_{MP}d^4} & \boldsymbol{, d \geq d_0} \end{cases}$$

Where the threshold distance (d_0) can be evaluated by equating both square law and fourth power law scenarios given in equation (1). Comparing both the scenarios the threshold distance is found to be

$$d_o = \sqrt{\frac{E_{FS}}{E_{MP}}} \quad (2)$$

Furthermore, as the radio channel is deemed to be symmetric, therefore,

$$\boldsymbol{E_{RX}(b) = E_{TX}(b) = E_{ELECT}b} \quad (3)$$

It must be noted that our assumption of the radio propagation channel is in line with the assumptions used in LEACH-E [5] protocol so that both the protocols can be fairly compared without having effect of wireless propagation environment.

Considering the clustering scenario, the radio propagation environment between CH and the respective node need to be dealt differently as compared to the radio propagation environment between the CH and the BS. As the CH is physically closer to the nodes present in the respective cluster, the path loss follows square law i.e. the energy consumed as a function of the square of the distance. By virtue of the longer distance, the path loss in the propagation environment between CH and the BS follows fourth power law i.e. the energy consumed as a function of the fourth power of the distance.

The subsequent analysis in this work is based on the following assumptions

- All the nodes in the network are homogeneous
- BS is far away from the CHs. Therefore, we should use the fourth power law to calculate the energy consumption to establish communication between the BS and a CH.
- All CHs can communicate directly to the BS
- The distance of all the member nodes in a cluster is shorter than the threshold distance given in equation (3). Therefore, we should use the square law to calculate the energy consumption to establish communication between nodes with respective CH.
- All members (nodes) in a cluster can communicate directly to the corresponding CH.

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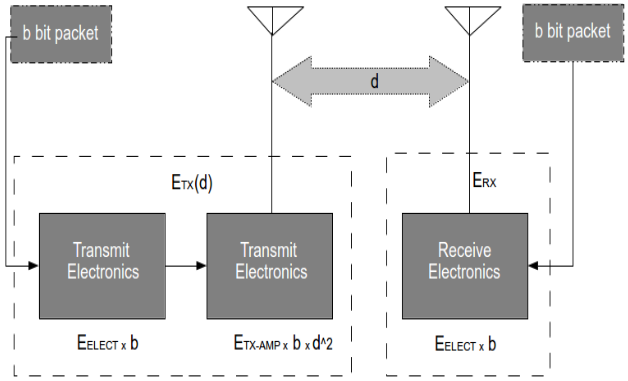

Fig. 3 The first order radio propagation model used in the study

III. PROPOSED LEACH-S PROTOCOL

A. Optimization of number of cluster-heads

We follow similar approach as in LEACH-E [5] to calculate the optimum number of CH except that the clusters are distributed in a hexagonal topology. We begin with calculating energy consumption of a CH that can be segregated into three segments: 1) energy required for receiving data, 2) energy required for data aggregation and 3) energy needed to relay the aggregated data to BS. Therefore, total energy consumed in the CH by a particular data packet would be:

$$E_{C-HEAD} = bE_{ELECT}\eta_1 + bE_{D-AGG}(\eta_1 + 1) + bE_{ELECT} + bE_{\mathrm{MP}}d^4{}_{\mathrm{BASE-ST}} \quad (4)$$

Where η_1 denotes the number of node in a cluster which is assumed to follow Poisson distribution. The mean constituent member of every cluster is given by [13]:

$$E\{\eta_1|\eta = n\} = E\{\eta_1\} = \frac{\gamma_0}{\gamma_1} \quad (5)$$

Where,

$$\gamma_0 = (1 - P_{C-HEAD})\,\gamma \quad (6)$$

$$\boldsymbol{\gamma_1 = P_{C-HEAD}\,\gamma} \quad (7)$$

$$P_{C-HEAD} = \frac{\beta}{n} \quad (8)$$

$$n = \gamma\,\alpha \quad (9)$$

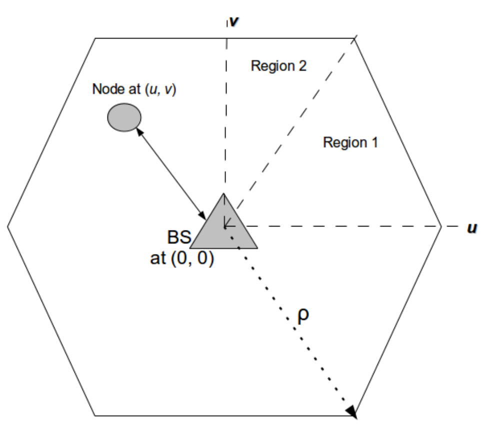

Fig. 4 Regular hexagonal coverage area of WSN

Contrasting to the area assumption of a square region in LEACH-E, we considered a more practical approach of hexagonal topology for the coverage area selection. As most WSNs use omnidirectional antennas with circular radiation pattern, they can be approximated best by a regular hexagon [14]. There are numerous additional motives and benefits of considering hexagonal topology for network coverage [15], such as:

1. There will be no overlapping of coverage areas between two neighboring CHs, thereby reducing interference among two neighboring clusters.
2. There will be no blind regions in WSN. Furthermore, two or more sensor nodes could provide connectivity required for each communication, thus increasing reliability.
3. Overall network's lifetime would be enhanced by setting a single node in each hexagonal coverage area awake while other nodes in sleep mode.
4. Usually, node degree in hexagonal-based coverage in WSNs is reduced up to 3, thereby decreasing overall data interruption and bottlenecking.
5. In contrast to any other coverage area, hexagonal topology offers minimum nodes requirement.

The BS is assumed to be located at the center of a regular hexagon, having each side of ρ units, as shown in Fig. 4. CHs are assumed to be uniformly distributed in the hexagonal coverage area of the base station. Therefore, the mean distance $E\{\Delta_1|n\}$ from the BS to every CH is:

$$E\{\Delta_1|\eta = n\} = \iint \Delta_1 \mu_\alpha \, du\, dv \quad (10)$$

Whereas μ_α represents the probability density function of CH's in the area which are assumed to follow uniformly distribution in the hexagon with area α. Therefore,

$$\mu_\alpha = \begin{cases} \dfrac{1}{\alpha} = \dfrac{2}{3\sqrt{3}\rho^2} & \text{Inside Hexagon} \\ 0 & \text{Outside Hexagon} \end{cases} \quad (11)$$

Therefore, equation (10) becomes:

$$E\{\Delta_1|\eta = n\} \quad (12)$$

$$= \iint_{Area\ of\ Hexagon} \sqrt{u^2 + v^2}\ \frac{2}{3\sqrt{3}\rho^2} du\ dv$$

$$= 0.60798\rho\ units$$

The detailed evaluation of integral in equation (12) is provided in APPENDIX II.

Using values from equations (5) and (12), equation (4) can be written as:

$$E_{C-HEAD} = \frac{n-\beta}{\beta} bE_{ELECT} + \frac{n}{\beta} bE_{D-AGG} + bE_{ELECT} + 0.1366\rho^4 bE_{MP} \quad (13)$$

Second we evaluate the energy consumption of a non-CH node. In contrast to the CH, a non-CH node does not spend any energy for data reception or data aggregation. The energy consumption in the non-CH node is only due to

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transmitting the data to the CH. As the relative distance between a CH and its member node (non-CH) is short, the square-law path loss model is used to find energy consumed in the node being non-CH. Therefore:

$$E_{NON-C-HEAD} = bE_{ELECT} + bE_{FS}d^2_{C-HEAD} \tag{14}$$

As per the mathematical foundation laid in [13], average of the sum of the distance from cluster member node to the CH is given by

$$E\{\delta_1|\eta = n\} = E\{\delta_1\} = \frac{\gamma_0}{2\,\gamma^{\frac{3}{2}}} \tag{15}$$

The mean distance between a CH and its linked node is given by

$$E\{\delta_2|\eta = n\} = \frac{1}{2}\,(\frac{\beta\,\gamma}{n})^{-\frac{1}{2}} \tag{16}$$

Substituting the value of the average distance between CH and cluster members given in equation (16) in equation (14), the avaerage energy expenditure for non-CH nodes is found to be

$$E_{NON-C-HEAD} = bE_{ELECT} + \frac{n}{4\beta\gamma}bE_{FS} \tag{17}$$

As each cluster comprises of one CH and (on an average) η_1 non-CH nodes. Therefore the energy exhausted by a cluster per unit of data packet is

$$E_{CLUSTER} = E_{C-HEAD} + \eta_1 E_{NON-C-HEAD} \tag{18}$$

Hence, the total energy expenditure of the entire network would be

$$E_{\Sigma} = \beta\, E_{CLUSTER} \tag{19}$$

Using values from equations (13), (17) and (18), equation (19) becomes.

$$E_{\Sigma} = b\left[(2n-\beta)E_{ELECT} + nE_{D-AGG} + 0.1366\rho^4\beta E_{MP} + \frac{n(n-\beta)}{4\beta\gamma}E_{FS}\right] \tag{20}$$

Equation (20) gives total energy expenditure of the network as function of the number of CHs (β). We intend to calculate the optimum number of CHs that result in minimum energy consumption of the network. In order to do that, derivative of E_{Σ} with respect to β is equated to zero

$$\frac{d}{d\beta}E_{\Sigma} = -E_{ELECT} + 0.1366\rho^4 E_{MP} - \frac{n^2}{4\beta^2\gamma}E_{FS} = 0 \tag{21}$$

From equation (9)

$$\gamma = \frac{n}{\alpha} = \frac{2}{3\sqrt{3}}\frac{n}{\rho^2} \tag{22}$$

Substituting equation (22) in equation (21), the optimum value of β is found to be

$$\beta_{OPT} = \sqrt{\frac{0.6495n\rho^2E_{FS}}{0.1366\rho^4E_{MP} - E_{ELECT}}} \tag{23}$$

One important parameter is the probability of selection of a node as the CH which is dependent on the optimum number of CH required to be selected in each round of the selection. Therefore, the optimized probability of a node to be selected as a CH corresponding to the optimum number of CHs is given by

$$P_{OPT} = \frac{\beta_{OPT}}{n} \tag{24}$$

Using equation (23) The optimum probability to become a CH can be written as

$$P_{OPT} = \sqrt{\frac{0.6495\rho^2E_{FS}}{n(0.1366\rho^4E_{MP} - E_{ELECT})}} \tag{25}$$

B. Selection of cluster heads

The selection of CH can be made on the basis of available energy resources at each node. A CH is expected to spend more energy as compared to other non-CH nodes in the network. Therefore, in each cycle of selection, nodes with higher residual energy should be considered as potential CH. An important parameter in this regard is the ratio of the residual energy available at each node to the initial energy ($E_{RESIDUAL}/E_{INITIAL}$). Nodes having higher value of the energy ratio $E_{RESIDUAL}/E_{INITIAL}$ should have higher probability of being selected as the CH. Second important parameter in selection of CH is the optimum number of CH (β_{OPT}) calculated in equation (23) which determines the probability of node to become CH as given in equation (24). Higher value of β_{OPT} depicts that more nodes should be selected as CH thereby increasing the probability for a node to be selected as CH. Utilizing abovementioned parameters a threshold ($T(n)$) can be defined as [5]

$$T(n) = \begin{cases} \dfrac{P_{OPT}}{1 - P_{OPT}\cdot\left(r \bmod \frac{1}{P_{OPT}}\right)}\dfrac{E_{RESIDUAL}}{E_{INITIAL}} & n \in G \\ 0 & \text{otherwise} \end{cases} \tag{26}$$

It is evident from equation (26) that the subsequent reduction of threshold $T(n)$ by introducing an extra factor of the energy ratio ($E_{RESIDUAL}/E_{INITIAL}$) help increasing the probability of the nodes having higher residual energy to become the CHs in the selection process.

The proposed protocol is based on three-stage operation in each round of the selection of the CH. These stages can be designated as (i) CH selection stage, (ii) cluster configuration stage, and (iii) data dissemination stage. In first stage of the each round / selection cycle, all those nodes which were not selected as CHs in the previous $1/P_{OPT}$ rounds generate a random number (RN) between 0 and 1. The RN generated by each node is compared with the threshold ($T(n)$) for the node calculated using equation (26). The node is selected as CH if RN > $T(n)$, otherwise the node continue to serve as the cluster member. After being selected as CH, all newly selected CHs relay their status message to other WSN nodes to update their status. In reply, all the WSN nodes connect themselves to the nearby CHs. In this stage the network is

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configured so that each member node is connected to the respective CH and prepare themselves for data dissemination. Once the connection is established among cluster members and CH, nodes start disseminating data in their designated time division multiple access (TDMA) slot. A node selected as CH continue to work as CH for a pre-defined time duration after that the entire procedure is repeated to select new CHs. This three-stage proposed protocol is represented in the flowchart shown in Fig. 5.

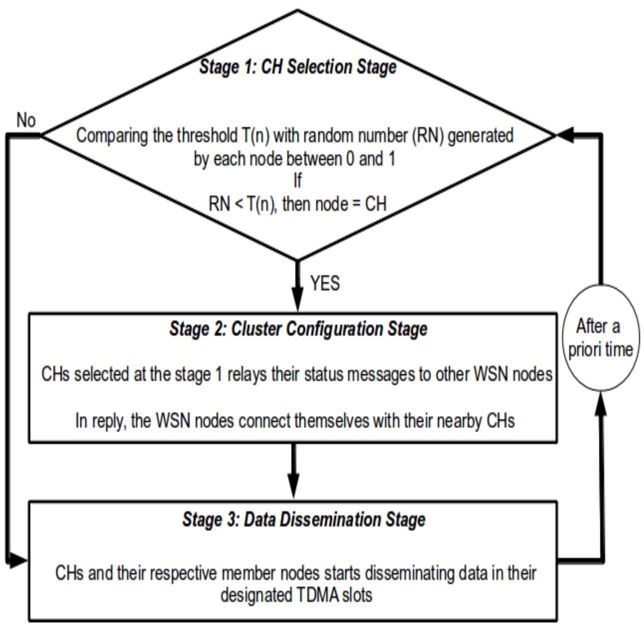

Fig. 5 Flow chart of proposed protocol

IV. RESULTS AND DISCUSSION

The proposed protocol presented in section III is analyzed using MATLAB simulations and the energy consumption by the network is computed and compared with that of LEACH-E protocol [10]. The BS is assumed to the in the center of the area where WSN is deployed. For each iteration of the simulation, location of all the sensor nodes was generated randomly in the WSN area using Poisson Process. Numerical values of the parameters used in the simulation for both LEACH-E and LEACH-S are summarized in Table 1.

TABLE 1. NUMERICAL VALUES OF THE PARAMETERS USED IN THE SIMULATION

Parameter	Value
$E_{INITIAL}$	0.5J
E_{ELECT}	50nJ/bit
E_{MP}	0.0013pJ/bit/m^4
E_{FS}	10pJ/bit/m^2
$E_{D\text{-}AGG}$	5nJ/bit/signal
b	4000bits

First we analyze the total energy consumption (E_{Σ}) for the network as a function of the number of clusters in a round (β). Fig. 6 shows the comparison results of the proposed LEACH-S protocol with that of LEACH-E protocol for different values of size of the monitored region (ρ) and the number of nodes (n). It is evident that the total energy consumption for the proposed LEACH-S protocol is considerably smaller than LEACH-E for same values of n and ρ. Moreover, it can be observed in both cases that the energy consumption is larger for small values of n and ρ as well as for larger values of n and ρ creating a "knee-region" at intermediate values for both n and ρ. This knee region corresponds to the optimum value of number of clusters that result in the minimum energy consumption of the network. Therefore, for given values of n and ρ, one can easily find optimum number of clusters required to minimize the total energy consumption as derived in the equation (23).

In Fig. 6(a), The optimal number of clusters in each turn is opted as the independent variable, whereas the total (or the sum) of the energy consumptions of the network is taken as the dependent variable, for both the protocols under consideration. Both of the parameters are observed for three different values of ρ (i.e. 150, 170 and 200). Further, Fig. 6(a) shows that energy consumption in LEACH-S protocol is slightly better than LEACH-E for medium size of coverage area. However, as the coverage area size increases, the proposed LEACH-S protocol uses significantly low energy as compared to LEACH-E. Therefore, the proposed protocol performs better for relatively larger coverage areas.

In Fig. 6(b), the total energy consumption of the network is plotted as a function of number of cluster for three different values of n (i.e. 100, 150, and 200). It is observed from Fig. 6(b) that energy consumption in the proposed technique remains low and pretty much constant for different number of nodes. Whereas in the case of LEACH-E protocol, total energy consumption increases rapidly as n increases. Therefore the energy performance of the network based on the proposed LEACH-S protocol does not degrade significantly with increase in the number of nodes deployed in the network.

The selection of optimum number of clusters in the network depends on the values of n and ρ. As shown in Fig. 7, the proposed protocol deploys more clusters as compared to LEACH-E at a fixed side length of the monitored region (ρ) and the number of nodes (n), thereby decreasing the average distance between the CH and the member nodes. Therefore, the member nodes require lesser amount of energy to communicate with the CH, resulting in better energy efficiency of the network.

In Fig. 7(a), the size of the area under consideration (i.e. ρ) is taken as the independent variable, while the optimal number of clusters in each turn is opted as the dependent variable. The parameters are observed for both the LEACH-E and LEACH-S protocols. Fig. 7(a) shows that the optimum number of CHs (β_{OPT}) of LEACH-S decreases more steeply than of LEACH-E as the side length of the monitored area is increased. However, the optimum number of CHs remains larger than what is required for the LEACH-E.

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In Fig. 7(b), the optimal cluster count is plotted as function of total number of nodes for both LEACH-E and LEACH-S protocols. The result in Fig. 7(b) depicts that the β_{OPT} of LEACH-S increases with the number of nodes. The prime reason behind the fact is that as the node density boosts in an area under consideration, the relative distance between a CH to its member node decreases, causing an increment in the number of clusters. However, it can be observed that the number of the clusters required for the proposed LEACH-S is larger than that for LEACH-E which is consistent with all other observations.

Finally, the proposed LEACH-S protocol is compared with LEACH-E in terms of the number of rounds versus the number of nodes alive, as shown in Fig. 8. The result shows the superiority of our proposed protocol as nodes remain alive for almost twice of the time (number of rounds) as compared to that in LEACH-E. Secondly, the death rate of nodes in LEACH-E is noticeably higher as compared to the proposed LEACH-S. Moreover, it can be observed that the LEACH-E protocol lost its lifetime abruptly as soon as it reached the 1000th round. While LEACH-S gave a better response and provide an enhanced network life time of the WSN, i.e. up to the 2500th round. The results concluded that the proposed LEACH-S protocol is more efficient as compared to the LEACH-E protocol in terms of energy utilization and enhanced network lifetime resulting in almost doubling of the network lifetime.

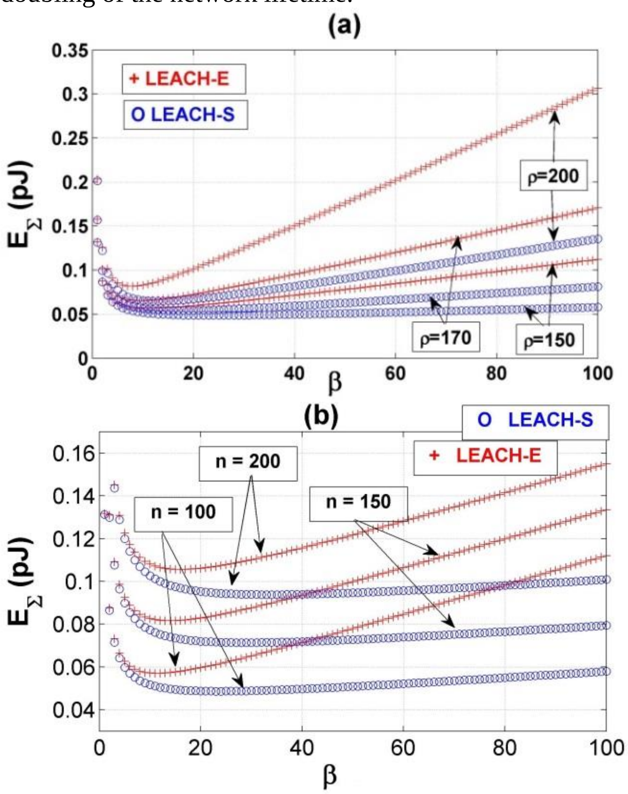

Fig. 6 The total energy consumption with respect to optimum number of cluster in a turn (a) for ρ = {150m, 170m, 200m} and n=200; (b) for n = {100, 150, 200} and ρ=150m.

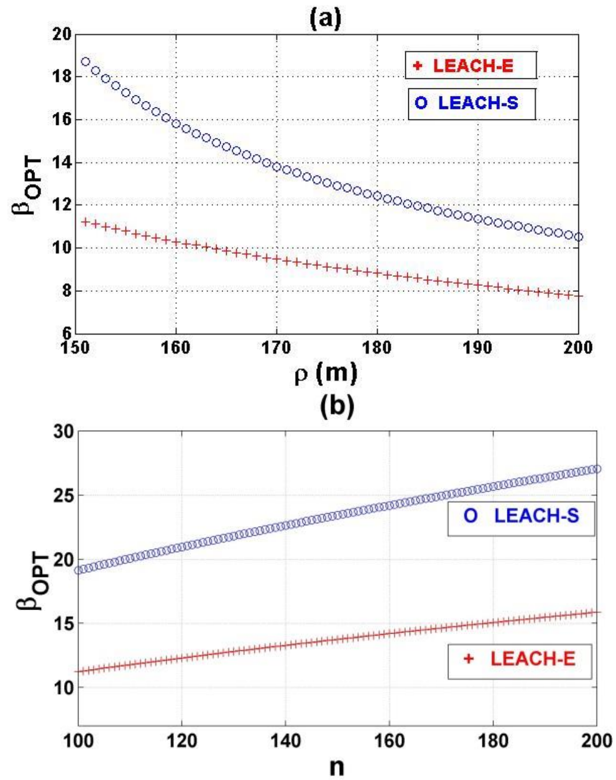

Fig. 7 The optimum number of clusters (β_{opt}) as a function of (a) side length of the area under consideration (b) number of nodes

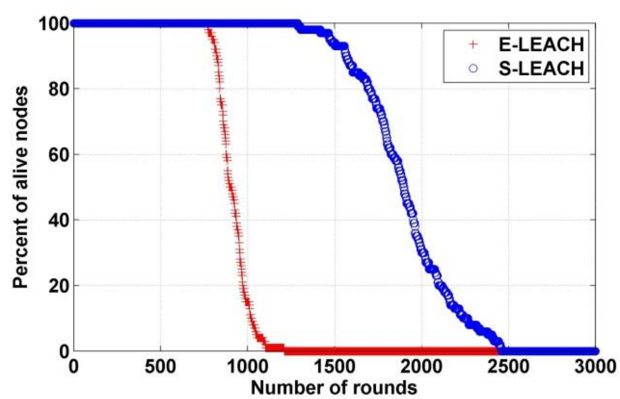

Fig. 8 Comparison of LEACH-S and LEACH-E on the basis of percentage of nodes alive after certain number of selection rounds to depict the network lifetime.

V. CONCLUSION

In this paper we addressed the issue of increasing energy efficiency of a WSN using Hierarchal-based routing. We propose an improved version LEACH-E protocol by considering hexagonal area topology of the network. We calculated optimum number of cluster heads by using probability model. The number of nodes is assumed to follow Poisson distribution whereas clusters are assumed to be uniformly distributed over the monitored area. In each round, the cluster head is selected by comparing random number generated by a node with its threshold which depends on its residual energy and optimized probability of cluster-heads. This procedure selects high-energy nodes as cluster heads thereby optimizing energy utilization of overall network. Simulation results show that our proposed protocol significantly reduces the overall energy consumption of the network as compared to LEACH-E resulting in increase in overall lifetime of the network.

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APPENDIX I

Table 2 provides the description of each of the variable used in the paper. The numerical values for each variables used in simulation are summarized in Table 1.

Table 2. Nomenclature of variables used in the paper

Parameter	Description
$E_{TX}(b, d)$/ $E_{RX}(b, d)$	RF energy expenditure by transmitter/ receiver circuitry for a single bit
$E_{TX-ELECT}$	Energy consumed by transmitter electronic circuitry
E_{TX-AMP}	Energy consumed by the transmitter amplifier circuitry
E_{TX} / E_{RX}	Energy consumed by transmitter/receiver
E_{ELECT}	$E_{ELECT} = E_{TX} = E_{RX}$
E_{FS}	Rate of energy consumed by transmitting / receiving a single bit using Square Law Path loss Model
E_{MP}	Rate of Energy consumed by transmitting / receiving a single bit using fourth Power Path loss Model
E_{D-AGG}	Energy consumed for Data Aggregation
d_0	Threshold Distance
d	Distance considered
b	Number of Bits transmitted or received
E_{C-HEAD}	Energy consumed by CH in one packet/frame
η_1	Random Variable to represent cluster member number (Poisson distributed)
b_{MP}	Bits Tx/Rx/aggregated using fourth Power Path loss Model
$d_{BASE-ST.}$	Distance to the BS
γ	Density of the all nodes (Poisson Distribution)
γ_0	Density of the None CH nodes
γ_1	Density of the CH nodes
P_{C-HEAD}	Probability of a node to be CH
n	Number of nodes
α	Area of the hexagonal region where WSN nodes are deployed
β	Number of Clusters
Δ_1	Random Variable representing distance from CH to BS (Poisson Distributed)
μ_α	CH's probability density in the area α
$E_{NON\ C-HEAD}$	Energy consumed by non-CH node in one packet/frame
δ_1	Aleatory variable signifies the sum of the distance from cluster member to CH (Poisson Distributed)
δ_2	Aleatory variable signifies distance from cluster member to CH (Poisson Distributed)
$E_{CLUSTER}$	Energy consumed by a Cluster during the packet
E_Σ	Overall Energy expenditure
β_{OPT}	Optimum Number of Clusters
P_{OPT}	Optimized Probability of Number of CHs
T(n)	Threshold for Selection of CHs
$E_{RESIDUAL}$	Node's residual energy
$E_{INITIAL}$	Node's initial energy
G	Collection of nodes; never been CH in previous $1/P_{OPT}$ rounds

APPENDIX II

In Appendix II, we evaluate the integral given in equation (12). From equation (12)

$$I = \iint_{Area\ of\ Hexagon} \sqrt{u^2+v^2}\,\frac{2}{3\sqrt{3}\rho^2}\,du\,dv \tag{27}$$

As we are working on a regular hexagonal geometry having symmetry in all quadrants, the integral can be written as:

$$I = 4 \times \iint_{\substack{Area\ of\ Hexagon\\ in\ the\ first\ quadrant}} \sqrt{u^2+v^2}\,\frac{2}{3\sqrt{3}\rho^2}\,du\,dv \tag{28}$$

which can be written as

$$I = \frac{8}{3\sqrt{3}\rho^2} \iint_{\substack{Area\ of\ Hexagon\\ in\ the\ first\ quadrant}} \sqrt{u^2+v^2}\,du\,dv \tag{29}$$

In order to evaluate the integral we divide the area of the hexagon in the first quadrant in two regions 1 & 2 as shown in Fig. 9. Therefore, the integral can be written as

$$I = \frac{8}{3\sqrt{3}\rho^2}\left[\iint_{Region\ 1} \sqrt{u^2+v^2}dudv + \iint_{Region\ 2} \sqrt{u^2+v^2}dudv\right] \tag{30}$$

The integral can easily be evaluated in polar coordinates by defining $u = r\cos\theta$ and $v = r\sin\theta$ as:

$$I = \frac{8}{3\sqrt{3}\rho^2}\left[\iint_{Region\ 1} r^2\,dr\,d\theta + \iint_{Region\ 2} r^2\,dr\,d\theta\right] \tag{31}$$

In order to calculate the limits for the both the region, it may be observed that the variable θ is characterized by constant limits i.e. $0 \le \theta \le \pi/3$ for region 1 and $\pi/3 \le \theta \le \pi/2$ for region 2. To find limits for variable r, we observe that lower limit for r is always zero whereas upper limit is bounded by line A for region 1 and line B for region 2 as shown in Fig. 9. We therefore, calculate equations of both the lines in polar coordinates to find limit of r which are given as

$$r = \begin{cases} \dfrac{\sqrt{3}\rho}{sin\theta + \sqrt{3}cos\theta} & \text{Line A} \\ \dfrac{\sqrt{3}\rho}{2sin\theta} & \text{Line B} \end{cases} \tag{32}$$

Combining these results, equation (30) can be written as

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$$I = \frac{8}{3\sqrt{3}\rho^2}\left[\int_{\theta=0}^{\frac{\pi}{3}}\int_{r=0}^{\sqrt{3}\rho/(sin\theta+\sqrt{3}cos\theta)} r^2\,dr\,d\theta + \int_{\theta=\frac{\pi}{3}}^{\frac{\pi}{2}}\int_{r=0}^{\sqrt{3}\rho/(2sin\theta)} r^2\,dr\,d\theta\right] \quad (33)$$

These integrals can easily be evaluated to give

$$I = 0.60798\rho \quad (34)$$

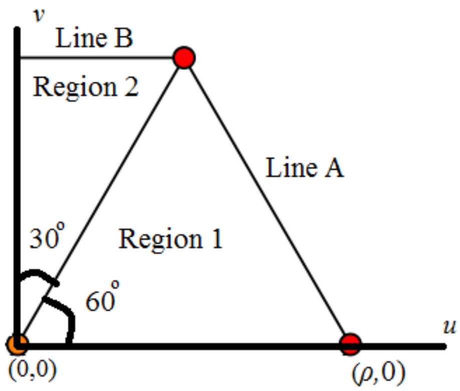

Fig. 9 First quadrant of the hexagonal area under study