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Published in:
Wireless Personal Communications

DOI:
10.1007/s11277-021-08927-w

Published: 31/01/2022

This is a post-peer-review, pre-copyedit version of an article published in Wireless Personal Communications. The final authenticated version is available online at: http://dx.doi.org/10.1007/s11277-021-08927-w”

Adaptive cross-layer Routing Protocol for Optimizing Energy Harvesting Time in WSN

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***Abstract*— Trade-off between energy conservation and efficiency is one of the most important issues in designing Wireless Sensor Network (WSN) based applications. Network life time is primarily determined by the life time of battery. Recently, energy harvesting techniques that will recharge the battery in different non-conventional ways are being investigated by researchers. In this paper, an adaptive cross layer protocol is proposed which will provide trade off between energy harvesting time and active time for message transmission with the aim of increasing network lifetime. Depending on the value of various network parameters like, remaining energy of node, node density, message density in a particular region of the network, the cross-layer protocol will change its policy. The paper also proposes a cluster head selection method that ensures maximum network life time and higher quality of service. The result shows an overall increase in network lifetime as compared to other protocols.**

***Index Terms*— Energy Harvesting, Cross Layer, MAC protocol, Wireless Sensor Network.**

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1 Introduction

Routing protocols have become essential in WSN to gather sensing information in an energy efficient way. Once sensors are deployed in field, generally they remain unattended. They use up battery power in sensing and forwarding data. Routing algorithms find optimum path to send data to sink node in order to minimize usage of battery energy [1], [2]. However, most routing protocols use similar strategy for the entire network at any instant of time. However, adopting suitable strategy based on local network parameters for the application area seems to be more efficient approach. This paper proposes technique where message sending strategy will be tuned by the local level trade-off. The proposed technique has also considered that instead of switching to sleep mode, the sensor node will harvest energy if its energy falls below a certain threshold. Energy can be harvested from various ambient sources like solar, thermal, vibration and wireless RF energy [3], [4], [5], in clustered WSN. Clustering is an energy-efficient solution of data gathering in WSN [6]. WSN is organized into several clusters with one cluster head each [6].

Initially, distributed clustering was done by Low Energy Adaptive Clustering Hierarchy (LEACH) protocol [7]. It uses a probabilistic model to select cluster head. Cluster heads gather data from member nodes and forward data to sink after aggregation. Although it is simple to implement but it causes early death of nodes. Residual energy of nodes is not considered in the cluster head selection. Wang et al. [8] propose a routing algorithm with mobile sink utilizing particle swarm optimization (PSO). PSO is used to form clusters in the WSN. One cluster head is selected in each cluster based on position of nodes and residual energy. To avoid hotspot problem in traditional multi-hop WSN, the sink is moved from one region to another. Simulation results demonstrate that this increases lifetime, transmission delay, packet delivery.

In [9], authors devise a hierarchical clustering algorithm to reduce network traffic towards sink. In the proposed secure energy efficient data transmission (SEED), cluster heads forward data directly to sink. It divides the network into three regions based on energy. Sensors with same application form sub-clusters in which only one awaken node transmit data whereas others remain in sleep. Following a sleep-awake scheduling provides prolonged network lifetime. Distributed energy efficient clustering (DEEC) [10] is a routing protocol developed for heterogeneous WSNs. Nodes are considered different with respect to battery energy and hardware complexities. In DEEC, the selection of cluster head is based on the ratio of residual energy and the estimated average energy of network. There are many improvements to DEEC like EDDEEC and IDEEC. The authors in IDEEC [11], achieve better performance than DEEC and EDDEEC by improving cluster head selection probability and optimizing estimated average energy of network.

Fuzzy logic is being used to select cluster head in WSN routing [12]. In [13], the authors select cluster heads based on confidence factor of a node. The confidence factor is estimated utilizing Type-2 Fuzzy Logic (T2FL) on the basis of residual battery power, distance to sink, and concentration. It achieves higher throughput and lifetime of network than algorithms applying Type-1 Fuzzy Logic (T1FL) as T2FL can better handle uncertainties than T1FL. In [14], optimum path selection in WSN routing is proposed using Honey Bee Optimization technique. It consumes less energy and transmission time. It outperforms other algorithms using ant colony optimization and particle swarm optimization in terms of throughput, link quality, and energy consumption.

An uneven clustering algorithm for WSN in IoT-based applications is developed in [15]. It achieves energy efficiency through uneven clustering. Cluster head rotation is followed in order to balance energy dissipations among nodes in a cluster. To alleviate energy hole problem, a dynamic multi-hop routing algorithm is followed. This algorithm attains better throughput, lifetime, and energy efficiency. Authors in [16] provide a clustering algorithm for WSN used in IoT applications. For selecting cluster head a modified equation for threshold value calculation is used using initial energy and residual energy. This ensures electing a node with higher energy as cluster head. Optimum number of clusters in WSN is also estimated by an equation. This algorithm outperforms low energy adaptive clustering hierarchy protocol in terms of energy consumption, lifetime, and throughput.

A distributed clustering algorithm for multi-target WSN is demonstrated in [17]. Nodes with same target form cluster in the network. An effort is also made for topology optimization in view of minimizing limited sensor resources. Simulation results prove that this approach is well suitable in fusion and tracking. Network lifetime is also enhanced due to distributed clustering approach. In [18], an algorithm for energy efficient clustering in WSN using game theory and dual cluster head selection method is proposed. Reduction in energy consumption through rotation of cluster head is made possible by dual selection of cluster head. Energy consumption among cluster heads is balanced by a proposed non-cooperative game model. Simulation results demand energy efficiency of clustering approach.

Hybrid Energy-Efficient Distributed Clustering (HEED) [19] is an efficient algorithm in WSN routing. It follows multi-hop data communication to sink. Unlike low energy adaptive clustering hierarchy (LEACH) protocol, residual energy of nodes is considered as to select a cluster head. Tie breaking is done based on degree of node, distance to neighbor, and intra-cluster energy. But, due to more number of cluster heads hotspots problem remain in the WSN. Authors in [20] propose a routing protocol based on cross layer design along with energy harvesting. In the cross layer design in the research ensures energy efficient routing whereas energy harvesting method helps nodes gaining energy from non-conventional energy sources like thermal energy. This approach outperforms LEACH and HEED in terms of remaining energy, and lifetime of WSN.

This paper proposes an adaptive cross layer protocol with self-sufficient energy harvesting technique. As our protocol is capable to adapt to network parameters based on lower level parameters, it achieves energy efficiency. Table 1 describes different symbols used in this paper.

The remainder of the paper is organized as follows. Hierarchical nature of network parameters is illustrated in Section II. Parameters for optimizing MAC layer protocol are considered in Section III. Section IV gives the algorithmic outline of adaptive routing protocol while Section V provides calculation of different parameters. Energy harvesting schedule is mentioned in Section VI while the algorithm is given in Section VII. Performance evaluation is done in Section VIII and conclusion is made in Section IX.

TABLE 1
DESCRIPTION OF SYMBOLS

Parameters	Description
δ	Percentage of time a node will remain active for message transmission/reception
e_{rem}^{i}	Remaining energy of i^{th} node.
$e_{\max}$	Maximum energy storing capacity of battery
ξ	Percentage of communication synchronicity
m_i^d	Message density at the i^{th} node
n_i^d	Node density of a local region centering the i^{th} node
$n_{\max}$	Maximum possible node density(hypothetically assumed)
η_i	Regular occurrence of data in the surrounding region of i^{th} node
ρ	Reactiveness/Proactiveness of the network
τ_i	Parameter determining cluster head for i^{th} cluster
k_i	Different constants where i is natural number
RT_j	Routing table for j^{th} node
d_{avg}^{k}	Average distance of neighbor nodes from node k

2 HIERARCHICAL NATURE OF NETWORK PARAMETERS

There are different parameters that characterize the cross layer protocol at local level based on which decisions are made. The network will adapt itself locally that will lead it to the global optimization of parameters such as life time of the network, energy harvesting time and network coverage. Different intermediate parameters will be derived from lower level parameters. It is assumed that there will be m level of parameters. Intermediate level parameters that depend on other parameters are denoted by I_{ij} (j^{th} parameter at i^{th} level). Independent parameters for different levels are denoted by L_{ij} . The solution approach can be represented as a bottom up structure in Fig. 1.

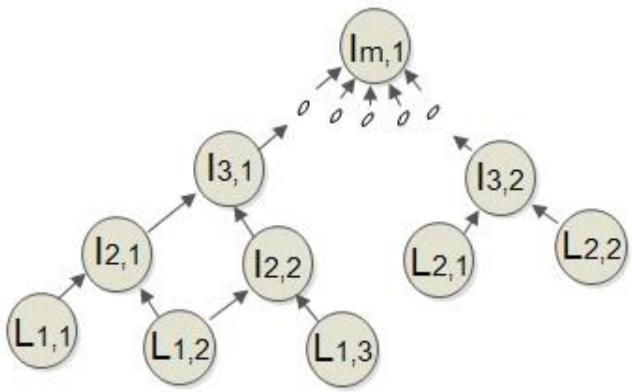

Fig. 1. Bottom up approach for finding network parameters

Fig. 1 shows the example of how to get upper level parameters by using lower level parameters. For eample, $I_{3,1}$ and $I_{2,1}$ are derived according to Equations (1) and (2):

$$I_{3,1} = I_{2,1} \otimes I_{2,2} \tag{1}$$

$$I_{2,1} = L_{1,1} \otimes L_{1,2} \tag{2}$$

In this way, we can get the expression for $I_{m,1}$

$$I_{m,1} = I_{m-1,1} \otimes I_{m-1,2} \ldots\ldots \otimes I_{m-1,n}$$
$$\otimes L_{m-1,1} \otimes L_{m-1,2} \ldots . \otimes L_{m-1,k} \tag{3}$$

Equations (1), (2) and (3) are sample equations for finding the final parameters $I_{m,1}$. This way we can find out the intermediate parameters based on local independent parameters, where $\otimes$ represents an operator.

3 PARAMETERS FOR OPTIMIZING MAC LAYER PROTOCOL

Design of the MAC layer protocol considers contention in the network, frequency of event occurrence, and remaining energy of sensor node among others [6], [21]. Based on these parameters the protocol can be designed to be either synchronous or asynchronous for message transmission. Also, these parameters will determine the time a node will spend on energy harvesting and the duration for which the node will remain active within certain period of time. To do so, we need to estimate some intermediate parameters like δ (percentage of time a node will remain active for message transmission/reception), ξ (percentage of communication synchronicity)and ρ (of the network) in order to tune various network parameters for obtaining optimum MAC layer protocol.

A. Percentage of time for a node to remain active (δ)

When remaining energy is low, energy harvesting time will be increased in comparison with the active time period. On the contrary, when remaining energy of a node becomes high, the node involves itself more in active mode.
Therefore, we can say

$$\delta \alpha \left(e_{rem}^{j} / e_{\max} \right) \tag{4}$$

Again, when node density increases then per node message sending responsibility will decrease. Thus, nodes get involved in energy harvesting. Therefore, we can say

$$\delta \alpha \left(n_i^d / n_{\max} \right)^{-1} \tag{5}$$

Combining Equations (4) and (5), we get the following:

$$\delta = k_1 \left(e_{rem}^{i} / e_{\max} \right) \left(n_i^d / n_{\max} \right)^{-1} \tag{6}$$

where, k_1 is a constant.

B. The percentage of synchronous communication (ξ)

With high node density, the network will be relatively with lower contention, because per node message transmission will be less. Message density decreases with increase in node density. Therefore, the percentage of synchronous communication will decrease with increase in the value of node density n_i^d in the local area centring i^{th} node. Thus, the relation between percentage of synchronous communication (ξ) parameter and node density n_i^d is:

$$\xi \alpha \left(n_i^d / n_{\max} \right)^{-1} \tag{7}$$

Intuitively, we can say that if the message density (m_i) becomes higher, then the value of synchronous communication parameter (ξ) will be higher. Therefore, the relation between ξ and m_i is as follows:

$$\xi \alpha \left(m_i / m_{\max} \right) \tag{8}$$

Higher value of the parameter representing the regular occurrence of data (η) means that message is coming in regular intervals. If the value of η is large, it can be claimed that the protocol is more synchronous. Thus, an increase in the value of η means percentage of synchronous communication will increase and therefore the value of ξ will increase.

Therefore, the relation between ξ and η can be expressed as directly proportional to each other:

$$\xi \alpha \left(\eta_i \big/ \eta_{\max} \right) \tag{9}$$

Combining Equations (7), (8) and (9), we get equation (10):

$$\xi = k_2 \left(\frac{n_i^d}{n_{\max}} \right)^{-1} \left(\frac{m_i}{m_{\max}} \right) \left(\frac{\eta_i}{\eta_{\max}} \right) \tag{10}$$

where k_2 is a constant.

C. Proactiveness of the network

Generally, in case of higher contention in message transmission, proactiveness of network proves to be beneficial. Conversely, in case of lower contention based application, reactiveness of the network is required. The value of ρ determines how the network will function: proactive or reactive. If the value of ρ is high, then it signifies that the network is more proactive and less reactive. Thus, we can say if the parameter *regular occurrence of data* increases, then proactiveness of the network should increase, conversely, the reactiveness of the network will decrease. From the above discussion we can say that the percentage of synchronous communication is related to the parameters n_i^d , m_i and η_i. Thus, percentage of synchronous communication (ξ) is a function of n_i^d , m_i and η_i. Therefore, the relation between reactiveness of the network (ρ) and (ξ) is:

$$r a \left(\frac{x}{x_{\max}} \right) \tag{11}$$

When energy is low, the nodes will be involved more in energy harvesting mode. Therefore, the network has less number of messages. In this circumstance, reactiveness of the network will increase. Therefore, the parameter 'percentage of time a node remains active' (δ) will be directly proportional to the parameter ρ .

$$r a \left(\frac{d}{d_{\max}} \right) \tag{12}$$

Combining Equations (11) and (12), we get,

$$\rho = k_3 \left(\frac{\xi}{\xi_{\max}} \right) \left(\frac{\delta}{\delta_{\max}} \right) \tag{13}$$

From (6) and (10) and (13) we can write

$$\rho = k_4 \left(\frac{e_{rem}^i m_i \eta_i}{\left(n_i^d \right)^2} \right) \tag{14}$$

where $k_4 = k_1 k_2 k_3 \left(\frac{1}{\delta_{\max} \xi_{\max}} \right) \left(\frac{\left(n_{\max}^2 \right)^2}{e_{\max} m_{\max} \eta_{\max}} \right)$ is a constant.

4 Algorithmic Structure of the Adaptive Routing Protocol

The proposed cross-layer protocol works in the following two phases.

D. Set up phase

The network is logically divided into several smaller regions, called clusters using LEACH protocol [7]. Excepting selection of cluster head, our protocol follows LEACH protocol in set up phase. Priority based cluster head selection approach is adopted in our protocol. Each region will have one cluster head node. Other nodes decide cluster head and join a cluster according to the signal strength of the cluster head node. During message transmission, every node will send priority value for selection of cluster head node along with the sensed data. Priority value signifies the measurement of relative of preference for cluster head node among all neighboring nodes. The preference of a node as a cluster head depends on remaining energy of that node and distance from the neighbor nodes. Priority is assigned by individual node. Total priority assigned by different nodes will evaluate the final priority of a node. The priority of node j to become a cluster head as assigned by node i is denoted as $p_{j,i}$ .Here, higher priority value confirms the network is more proactive rather than reactive. Therefore, $p_{j,i}$ is directly proportional to ρ_j^α (where ρ_j denotes the reactiveness of the network in the surrounding area of node j and α is the priority constant with respect to proactiveness). Since priority of a node to become cluster head will be higher if the node resides at a shorter geographical distance, we can say $p_{j,i}$ is inversely proportional to d_{ji}^β, where β is priority constant with respect to distance. Here, relatively greater value of α with respect to β determines the network to be more proactive. Therefore we can say α enforces priority over proactiveness of the network, and β enforces priority over the reactiveness of the protocol. Let, e_j be remaining energy of node j and d_{ji} is the distance between node j and node i. Equation (15) represents the relative priority of node j with respect to the neighbor node i .

$$p_{i,j} = \frac{\left(\rho_j \right)^\alpha}{\left(d_{j,i} \right)^\beta}$$

$$p_{i,j} = k_4^{\alpha} \frac{\left(e_{rem}^{j}\right)^{\alpha} m_j^{\alpha} \eta_j^{\alpha}}{\left(n_j^{d}\right)^{2\alpha} \left(d_{j,i}\right)^{\beta}} \quad (15)$$

At the end of a steady state, every node j will calculate the *overall priority* τ_j which will determine the cluster head. For a particular node j the parameter τ_j is calculated as

$$\tau_j = \sum_{i=1}^{N} p_{i,j} \quad (16)$$

If we keep other parameters constant and vary e_{rem}^{j}, then the Equation (16) can be rewritten as

$$\tau_j = k_5 \left(e_{rem}^{j}\right)^{\alpha} \quad (17)$$

where $k_5 = k_4^{\alpha} \frac{m_j^{\alpha} \eta_j^{\alpha}}{\left(n_j^{d}\right)^{2\alpha}} \sum_{i=1}^{N} \frac{1}{\left(d_{j,i}\right)^{\beta}}$

If the value of τ_j is greater than threshold value (τ_{th}), then that node will declare itself as a cluster head node.

Theorem I: If the value of τ_j is greater than the value of τ_k and other parameters remain same then the remaining energy of node j is greater than that of node k .

Proof: After simplifying the expression, $\tau_j - \tau_k$ becomes

$$\tau_j - \tau_k = k_5 \left\{ \left(e_{rem}^{j}\right)^{\alpha} - \left(e_{rem}^{k}\right)^{\alpha} \right\} \quad (18)$$

From Equation (18), it can be said that the chance of becoming cluster head is more for the node possessing more remaining energy than others. Now, if $\tau_j - \tau_k > 0$, three cases may arise with respect to threshold value (τ_{th}):

Case 1: $\tau_j > \tau_k > \tau_{th}$

According to case 1, the τ value of node j and node k are greater than the threshold value τ_{th}. The algorithm can, therefore choose any node as the cluster head. If node k is chosen, then unequal energy dissipation may occur. The previous assumption is true until a certain limit which will be discussed under case 2.

Case 2: $\tau_j > \tau_{th} > \tau_k$

In case 2, the value of τ for node j is greater than threshold value τ_{th} whereas the value of τ for node k is less than τ_{th}. In this circumstance, the algorithm will choose node j as the cluster head. Following case 1, choosing node k rather than node j increases energy difference between two nodes. Once the τ value falls under the threshold value then algorithm will not prefer node k any more over node j. Therefore, we can say that energy difference is generated in case 1 and that is overcome if case 2 arises. Therefore, a uniform energy distribution criterion has been satisfied.

Case 3: $\tau_{th} > \tau_j > \tau_k$

According to case 3, the threshold τ_{th} is greater than the values of τ for both nodes (τ_j and τ_k), and thus, no node will be selected as the cluster head node. Node j and node k will act as multi-hop relay nodes only. The nodes will remain reactive in nature. The node whose priority value is less than τ_{th} signifies that its remaining energy is reduced to threshold level and will be involved in energy harvesting. During the period messages coming from neighbour nodes will be forwarded in reactive mode. The node having more remaining energy will be chosen for sending a message to the next hop.

Therefore, from above discussion it can be said that the proposed routing protocol ensures uniform energy dissipation.

Theorem II: The value of τ_j is greater than the value of τ_k when the number of neighbour nodes of node j is greater than that of the node k while other parameters remain unchanged.

Proof: While other parameters remain constant and number of neighbour nodes varies for node j and node k then the expression for $\tau_j - \tau_k$ will be

$$\tau_j - \tau_k = \frac{k_4^{\alpha} \left(e_{rem}^{j}\right)^{\alpha} m_j^{\alpha} \eta_j^{\alpha}}{\left(n_j^{d}\right)^{2\alpha} d_j^{\beta}} \left\{ N_j - N_k \right\} \quad (19)$$

Here, N_j and N_k are number of neighbour node of node j and node k respectively. From the previous discussion and from Equation (17), it can be said that if $\tau_j > \tau_k$,then $N_j > N_k$. In other words, we can say a node with more number of neighbour nodes, when other parameters are the same, gets more priority to become the cluster head node.

Theorem III: The value of τ_j is greater than τ_k when average distance node j from the neighbour nodes is less than that of node k assuming other parameters are the same for both node.

Proof: From Equation (15), we can say that β mean square value of distance is inversely proportional to the value of τ .

Let us assume d_j^{avg} is the β mean square value for node j. Thus, τ_j will be

$$\tau_j = \frac{k_4^\alpha \left(e_{rem}^j\right)^\alpha m_j^\alpha \eta_j^\alpha N_j}{\left(n_j^d\right)^{2\alpha} \left(d_j^{avg}\right)^\beta} \tag{20}$$

Therefore, expression for $\tau_j - \tau_k$ will be

$$\tau_j - \tau_k = \frac{k_4^\alpha \left(e_{rem}^j\right)^\alpha m_j^\alpha \eta_j^\alpha N_j}{\left(n_j^d\right)^{2\alpha} \left(d_k^{avg} d_j^{avg}\right)^\beta} \left\{ \left(d_k^{avg}\right)^\beta - \left(d_j^{avg}\right)^\beta \right\} \tag{21}$$

From Equation (21), it can be said that a node obtains higher priority for becoming a cluster head node if follower nodes reside relatively closer to it. This fact signifies the positional importance of cluster head node.

E. Steady State Phase

In the steady state phase, sensor nodes are mainly involved in communication, energy harvesting and sleep schedule. Thecluster headnode gets network information from the member nodes. Using this information, the cluster head node calculates the network parameters ξ, δ and ρ. Thereafter, the cluster head sends the values of these parameters to the member nodes of that cluster along with the time schedule for each node. After getting the parameters, individual member node decides the mode of message transmission like synchronous transmission (TDMA), asynchronous transmission (CSMA) or combination of synchronous and asynchronous type of message transmission to follow. Even the duration of the steady state is also variable and it depends on different parameters.

5 Calculation of Different Parameters

If we can calculate parameters ($e_{rem}^j, m_j, n_j^d, \eta_j$ and $d_{j,i}$) and constant k_4 then we are able to calculate the parameter $p_{i,j}$ from which τ_j can be calculated. Knowing the value of τ_j, a node j can decide whether it will become a cluster head node or not.

F. Calculation of constant k_4

If we can assume the value of k_1, k_2 and k_3 as 1 then the value of k_4 becomes $\left(\frac{1}{\delta_{\max}\xi_{\max}}\right)\left(\frac{\left(n_{\max}^d\right)^2}{e_{\max} m_{\max} \eta_{\max}}\right)$, where every parameters are in absolute form and that can be assumed as the known parameters. Therefore, from the above discussion we can easily find out the value of constant k_4. The modified expression for $p_{i,j}$ will be

$$p_{i,j} = \left(\frac{1}{\delta_{\max}\xi_{\max}}\right)^\alpha \left(\frac{\left(n_{\max}^d\right)^2}{e_{\max} m_{\max} \eta_{\max}}\right)^\alpha \frac{\left(e_{rem}^j\right)^\alpha m_j^\alpha \eta_j^\alpha}{\left(n_j^d\right)^{2\alpha} \left(d_{j,i}\right)^\beta} \tag{22}$$

G. Calculation of node density of the region surrounding arbitrary node j

Here, n_j is the node density at the j^{th} node. At the time of communication j^{th} node receives message from its neighbour node. Suppose total number of neighbour node for node j is a_j and the communication range of the node is r. Therefore, within area of πr^2 total number of nodes present including j^{th} node is a_j. So, the node density is $a_j / \pi r^2$. Thus, the value of n_j^d is equal to $a_j / \pi r^2$. The modified expression for $p_{i,j}$ will be

$$p_{i,j} = \left(\frac{1}{\delta_{\max}\xi_{\max}}\right)^\alpha \left(\frac{\left(n_{\max}^d\right)^2}{e_{\max} m_{\max} \eta_{\max}}\right)^\alpha \frac{\left(e_{rem}^j\right)^\alpha \pi^{2\alpha} r^4 m_j^\alpha \eta_j^\alpha}{\left(a_j\right)^{2\alpha} \left(d_{j,i}\right)^\beta} \tag{23}$$

H. Calculation of message density of the region surrounding node j

Here, m_j is the message density of the region surrounded by node j. The node j will calculate the number of message came to it per unit time and that is b_j. Since the node number in the surrounded region of node j is a_j then message density (message sending per node) is b_j / a_j. Therefore the value of m_j is b_j / a_j and that is known value. Thus, the modified expression for $p_{i,j}$ will be

$$p_{i,j} = \left(\frac{1}{\delta_{\max}\xi_{\max}}\right)^{\alpha}\left(\frac{\left(n_{\max}^{d}\right)^{2}}{e_{\max}m_{\max}\eta_{\max}}\right)^{\alpha} \frac{\left(e_{rem}^{j}\right)^{\alpha}\pi^{2\alpha}r^{4}b_{j}^{\alpha}\eta_{j}^{\alpha}}{\left(a_{j}\right)^{3\alpha}\left(d_{j,i}\right)^{\beta}} \quad (24)$$

I. Calculation of distance between node i and j

The distance between node i and node j can be estimated by the signal strength indicators of receiver and sender using the equation below.

$$\frac{P_r}{P_t} = G_t . G_r \left(\frac{\lambda}{4\pi d}\right)^2 \quad (25)$$

where, P_r is received power, P_t is transmitted power, G_t and G_r are transmitter and receiver antenna gains respectively, and d denotes the distance between receiver and sender.

J. Calculation of regular occurrences of data of the region surrounding node j

Here, η_j denotes the regular occurrences of data at time instants t_1, $t_2, t_3 \ldots t_n$. Let us assume the mean value of t_1, $t_2, t_3 \ldots t_n$ be t_{mean}.

Theorem IV: When data occurs at regular interval then the standard deviation of time difference of data occurrence will be lower.

Proof: Let us assume, D is the difference matrix.

$$D = \{t_2 - t_1, t_3 - t_2, ..., t_n - t_{n-1}\}$$

or, $D = \{\Delta t_{2,1}, \Delta t_{3,2}, ..., \Delta t_{n,n-1}\}$

Let us assume, Δt_{mean} be the mean of set D

$$\Delta t_{mean} = \sum_{i=2,j=1}^{n,n-1} t_{i,j} /(n-1) \quad (26)$$

We are assuming s_j is the standard deviation of set D

$$s_j = \sqrt{\sum_{i=1}^{n}\left(\Delta t_{i,i-1} - \Delta t_{mean}\right)^2 / n}$$

$$s_j^2 = \sum_{i=1}^{n}\left(\Delta t_{i,i-1} - \Delta t_{mean}\right)^2 / n$$

$$s_j^2 = \frac{\left(\Delta t_{2,1} - \Delta t_{mean}\right)^2}{n} + \frac{\left(\Delta t_{3,2} - \Delta t_{mean}\right)^2}{n} + \ldots + \frac{\left(\Delta t_{n,n-1} - \Delta t_{mean}\right)^2}{n} \quad (27)$$

The minimum value of $\left(\Delta t_{2,1} - \Delta t_{mean}\right)^2$ is zero when $\Delta t_{2,1} = \Delta t_{mean}$. Therefore, the value of s^2 will be minimum when

$$\Delta t_{2,1} = \Delta t_{3,2} = .. = \Delta t_{n,n-1} = \Delta t_{mean} \quad (28)$$

Hence, it can be said that Equation (28) is the condition when s_j will be minimum. Alternatively, we can also write Equation (28) for any i, $1 < i < n$

$$\Delta t_{i,i-1} = \Delta t_{i+1,i}$$

$$t_i - t_{i-1} = t_{i+1} - t_i$$

$$t_i = \frac{\left(t_{i+1} + t_{i-1}\right)}{2} \quad (29)$$

Equation (29) expresses the condition that s_j be minimum. As Equation (29) is true for all i, we can say the message arriving times are sequential in nature. Therefore, from the above discussion it is obvious that if message comes in regular interval then the standard deviation of time difference of data occurrence will be low and in ideal case it will be zero. Now, η_j can be represented by s_j. Therefore, the modified equation of $p_{i,j}$ will be

$$p_{i,j} = \left(\frac{1}{\delta_{\max}\xi_{\max}}\right)^{\alpha}\left(\frac{\left(n_{\max}^{d}\right)^{2}}{e_{\max}m_{\max}\eta_{\max}}\right)^{\alpha} \frac{\left(e_{rem}^{j}\right)^{\alpha}\pi^{2\alpha}r^{4}b_{j}^{\alpha}s_{j}^{\alpha}}{\left(a_{j}\right)^{3\alpha}\left(d_{j,i}\right)^{\beta}} \quad (29)$$

In Equation (30), the parameters $\delta_{\max}$, $\xi_{\max}$, $e_{\max}$, $m_{\max}$, $n_{\max}$, $\eta_{\max}$, α, β, r will be predefined and the parameters a_j, b_j, s_j, $d_{i,j}$ can be measured very easily as discussed above. Therefore, the proposed algorithm can find out $p_{i,j}$ without any ambiguity. From $p_{i,j}$, the value of τ_j can be calculated easily. Knowing the value of τ_j the node can decide whether the current node will be the cluster head or not.

6 Energy Harvesting Schedule

Energy harvesting scheduling is made during the steady state phase. The scheduled time for energy harvesting of a particular node depends on the remaining energy of the node. As the remaining energy decreases the scheduled time of energy harvesting of a node increases which is depicted in Fig. 2. Initially in phase 1, there is no need of energy harvesting as nodes are fully charged. In steady state phase 2, nodes loose energy a bit. So, they need to harvest energy by decreasing active state. While in steady state phase 3, as nodes loose more energy, more time is scheduled for energy harvesting compared to active time. We can express scheduled time for energy harvesting of node j is as:

$$T_H^j = T_H^{\max}\left(1-\frac{e^j_{rem}}{e_{\max}}\right) \tag{31}$$

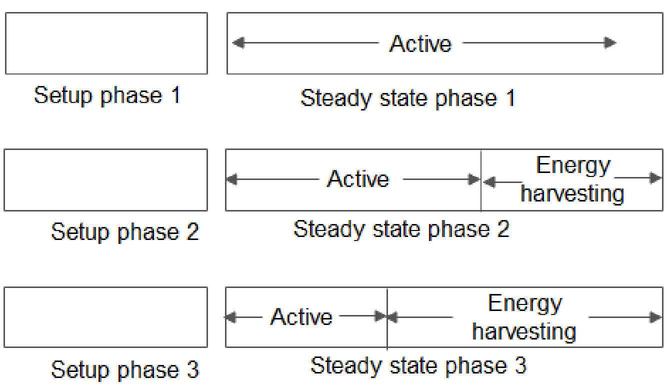

Fig. 2. Time schedule of active phase and energy harvesting phase

7 Algorithm Setup Phase

1. Deploy sensor nodes in application area.
2. Set the initial values of parameters: $\delta_{\max}, \xi_{\max}, n_{\max}, e_{\max}, m_{\max}, \eta_{\max}, \alpha, \beta, r$.
3. Initially, every node will send message to its neighbor node.
4. Each node i calculates the distance ($d_{i,j}$) from any arbitrary node j using Equation (25).
5. After receiving initial message, node j measures parameters a_j, b_j, s_j and $d_{i,j}$.
6. Each node calculates priority $P_{i,j}$ of node j with respect to other node i using Equation (23).

$$p_{i,j} = \left(\frac{1}{\delta_{\max}\xi_{\max}}\right)^{\alpha}\left(\frac{\left(n^d_{\max}\right)^2}{e_{\max}m_{\max}\eta_{\max}}\right)^{\alpha}\frac{\left(e^j_{rem}\right)^{\alpha}\pi^{2\alpha}r^4 m_j^{\alpha}\eta_j^{\alpha}}{\left(a_j\right)^{2\alpha}\left(d_{j,i}\right)^{\beta}}$$

7. Each node j calculates over all priority (τ_j)for all its neighbor nodes as:

$$\tau_j = \sum_{i=1}^{N} p_{i,j}$$

8. If τ_j is greater than τ_{th}, then node j declares itself as cluster head and sends message to its neighbor nodes.

Steady state phase

1. Non cluster head nodes sense data and send it to cluster head.
2. Cluster head node collects data from different source nodes or higher gradient cluster head node(s).
3. Data are aggregated by cluster head node and sent either to the next cluster head node with lower gradient or to sink.
4. Nodes follow energy harvesting and wakeup schedule (Fig2 explains the scenario).

8 Performance Evaluation

For evaluating the performance of our proposed protocol, a WSN with 400 nodes capable of harvesting environmental energy is simulated. Nodes are randomly deployed over an area of 100 m × 100 m. size of each data packet is considered 200 bytes in our experiment. The detail of simulation parameters is listed in Table 2. The calculation of energy consumed by transmitter and receiver is made as per the energy model in [7]. We compared our adaptive routing with low energy adaptive clustering hierarchy (LEACH), hybrid energy efficient distributed (HEED) cluster-based routing protocol, and secure routing protocol with energy harvesting by Alrajeh et al. [20]. Fig. 3 depicts the network lifetime of three protocols in terms of number of rounds. The ability of our proposed cross layer protocol to adapt network parameters hierarchically increases network lifetime with respect to the others.

In Fig. 4, the remaining network energy is shown in terms of number of rounds. Due to efficient balance between energy harvesting and active time, the proposed approach outperforms others. In LEACH, network energy reduces faster with increasing no. of rounds. As there is no concept of energy harvesting in HEED, network energy decreases gradually after 40 rounds. A comparison of routing overhead of algorithms is shown in Fig. 5. It reveals that proposed algorithm has higher overhead than LEACH but fewer than others. Fig. 6 depicts number of live nodes with respect to number of rounds in increased traffic scenario towards destination. Our protocol can support the WSN with more than 350 nodes even after 2000 rounds due to efficient cluster head selection and energy harvesting.

TABLE 2
DETAILSOFSIMULATIONPARAMETERS

Parameter	**Value**
Network size	100x100m^2
No. of nodes	400
Initial energy	1J
Packet size	200 bytes
E_{elec}	50 nJ/bit
ε_{fs}	100 pJ/bit/m^2
ε_{amp}	0.013pJ/bit/m^4

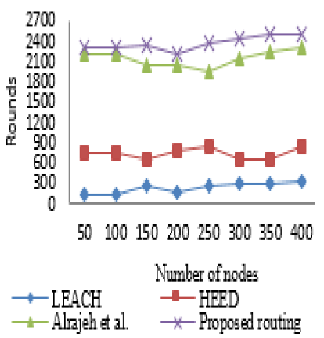

Fig. 3 Network lifetime in number of rounds.

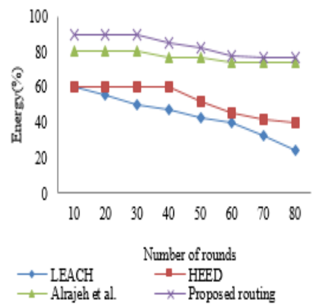

Fig. 4 Remaining network energy of a WSN with 400 nodes.

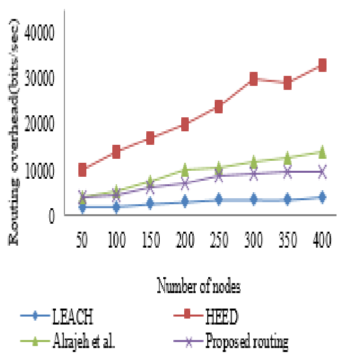

Fig. 5 Routing overhead comparison in bits/sec.

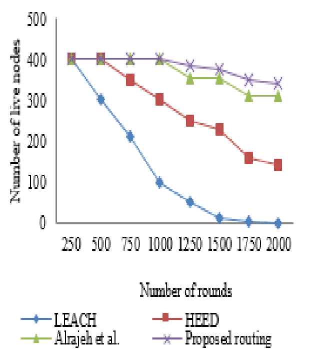

Fig. 6 Number of live nodes in increased traffic scenario.

In a nutshell, we give a comparison of our proposed algorithm with LEACH, HEED, and work of Alrajeh et al. [20] on the basis of balanced clustering, clustering stability, sleep-awake aware, and cross-layer design in Table 3.

TABLE 3
COMPARISON OF PROPOSED ALGORITHM WITH OTHER ALGORITHMS

Clustering approach	Balanced clustering	Clustering stability	Sleep-awake aware	Cross-layer design
LEACH	Not good	Moderate	No	No
HEED	Good	High	No	No
Alrajeh et al.	Good	Moderate	Yes	Yes
Proposed routing	Good	High	Yes	Yes

9 Conclusion

The paper proposes a run time optimization process of various network parameters based on cross layer protocol for energy harvesting in WSN. Depending on some parameters like node density, remaining energy and message density, the network adjusts its cross-layer protocol policies for certain duration of time. Every node sends the relative preference value for electing a cluster head node. The proposed scheme minimizes the active periods of sensor nodes by maintaining efficiency and reliability of the network and application. In terms of number of rounds and remaining energy, this algorithm performs better than other algorithm as it is able to balance clustering and sleep awake scheduling.

Declarations

Funding: Not applicable

Conflicts of interest/Competing interests: There are no conflicts of interests.

Availability of data and material: Data is generated during the study and may be available on request.

Code availability: Custom code may be available on request.

Authors' contributions: All authors contributed to this research.

References

[1] S. Dutt, S. Agrawal, and R. Vig, "Cluster-head restricted energy efficient protocol (CREEP) for routing in heterogeneous wireless sensor networks," Wirel. Pers. Commun., vol. 100, no. 4, pp. 1477–1497, 2018.

[2] V. Rahmati, "Near optimum random routing of uniformly load balanced nodes in wireless sensor networks using connectivity matrix," Wirel. Pers. Commun., pp. 1–17, 2020.

[3] H. Yoo, M. Shim, and D. Kim, "Dynamic duty-cycle scheduling schemes for energy-harvesting wireless sensor networks," IEEE Commun. Lett., vol. 16, no. 2, pp. 202–204, 2011.

[4] P. Kamalinejad, C. Mahapatra, Z. Sheng, S. Mirabbasi, V. C. M. Leung, and Y. L. Guan, "Wireless energy harvesting for the Internet of Things," IEEE Commun. Mag., vol. 53, no. 6, pp. 102–108, 2015.

[5] S. Ulukus et al., "Energy harvesting wireless communications: A review of recent advances," IEEE J. Sel. Areas Commun., vol. 33, no. 3, pp. 360–381, 2015.

[6] P. Sengottuvelan and N. Prasath, "BAFSA: Breeding artificial fish swarm algorithm for optimal cluster head selection in wireless sensor networks," Wirel. Pers. Commun., vol. 94, no. 4, pp. 1979–1991, 2017.

[7] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, “An application-specific protocol architecture for wireless microsensor networks,” IEEE Trans. Wirel. Commun., vol. 1, no. 4, pp. 660–670, 2002.

[8] J. Wang, Y. Cao, B. Li, H. Kim, and S. Lee, “Particle swarm optimization based clustering algorithm with mobile sink for WSNs,” Futur. Gener. Comput. Syst., vol. 76, pp. 452–457, 2017.

[9] G. Ahmed, J. Zou, M. M. S. Fareed, and M. Zeeshan, “Sleep-awake energy efficient distributed clustering algorithm for wireless sensor networks,” Comput. Electr. Eng., vol. 56, pp. 385–398, 2016.

[10] L. Qing, Q. Zhu, and M. Wang, “Design of a distributed energy-efficient clustering algorithm for heterogeneous wireless sensor networks,” Comput. Commun., vol. 29, no. 12, pp. 2230–2237, 2006.

[11] B. Xie and C. Wang, “An improved distributed energy efficient clustering algorithm for heterogeneous WSNs,” in 2017 IEEE Wireless Communications and Networking Conference (WCNC), 2017, pp. 1–6.

[12] T. Gao, R. C. Jin, J. Y. Song, T. B. Xu, and L. D. Wang, “Energy-efficient cluster head selection scheme based on multiple criteria decision making for wireless sensor networks,” Wirel. Pers. Commun., vol. 63, no. 4, pp. 871–894, 2012.

[13] P. Nayak and B. Vathasavai, “Energy Efficient Clustering Algorithm for Multi-Hop Wireless Sensor Network Using Type-2 Fuzzy Logic,” IEEE Sens. J., vol. 17, no. 14, pp. 4492–4499, 2017.

[14] M. Selvi, C. Nandhini, K. Thangaramya, K. Kulothungan, and A. Kannan, “HBO based clustering and energy optimized routing algorithm for WSN,” in 2016 Eighth International Conference on Advanced Computing (ICoAC), 2017, pp. 89–92.

[15] Z. Wang, X. Qin, and B. Liu, “An energy-efficient clustering routing algorithm for WSN-assisted IoT,” in 2018 IEEE Wireless Communications and Networking Conference (WCNC), 2018, pp. 1–6.

[16] T. M. Behera, S. K. Mohapatra, U. C. Samal, M. S. Khan, M. Daneshmand, and A. H. Gandomi, “Residual energy-based cluster-head selection in WSNs for IoT application,” IEEE Internet Things J., vol. 6, no. 3, pp. 5132–5139, 2019.

[17] S. Li, H. Fang, and J. Chen, “Energy efficient multi-target clustering algorithm for WSN-based distributed consensus filter,” in 2017 36th Chinese Control Conference (CCC), 2017, pp. 8201–8206.

[18] D. Lin and Q. Wang, “An energy-efficient clustering algorithm combined game theory and dual-cluster-head mechanism for WSNs,” IEEE Access, vol. 7, pp. 49894–49905, 2019.

[19] O. Younis and S. Fahmy, “HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks,” IEEE Trans. Mob. Comput., vol. 3, no. 4, pp. 366–379, 2004, doi: 10.1109/TMC.2004.41.

[20] N. A. Alrajeh, S. Khan, J. Lloret, and J. Loo, “Secure routing protocol using cross-layer design and energy harvesting in wireless sensor networks,” Int. J. Distrib. Sens. Networks, vol. 9, no. 1, p. 374796, 2013.

[21] R. R. Swain, S. Mishra, T. K. Samal, and M. R. Kabat, “An energy efficient advertisement based multichannel distributed MAC protocol for wireless sensor networks (Adv-MMAC),” Wirel. Pers. Commun., vol. 95, no. 2, pp. 655–682, 2017.