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Energy-efficient Harvested-Aware clustering and cooperative Routing Protocol for WBAN (E-HARP)

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ABSTRACT Wireless Body Area Network (WBAN) is an interconnection of small bio-sensor nodes that are deployed in/on different parts of human body. It is used to sense health-related data such as rate of heart beat, blood pressure, blood glucose level, Electro-cardiogram (ECG), Electro-myography (EMG) etc. of human body and pass these readings to real-time health monitoring systems. WBANs is an important research area and is used in different applications such as medical field, sports, entertainment, social welfare etc. Bio-Sensor Nodes (BSNs) or simply called as Sensor Nodes (SNs) are the main backbone of WBANs. SNs normally have very limited resources due to its smaller size. Therefore, minimum consumption of energy is an essential design requirement of WBAN schemes. In the proposed work, Energy-efficient Harvested-Aware clustering and cooperative Routing Protocol for WBAN (E-HARP) are presented. The presented protocol mainly proposes a novel multi-attribute-based technique for dynamic Cluster Head (CH) selection and cooperative routing. In the first phase of this two-phased technique, optimum CH is selected among the cluster members, based on calculated Cost Factor (CF). The parameters used for calculation of CF are; residual energy of SN, required transmission power, communication link Signal-to-Noise-Ratio (SNR) and total network energy loss. In order to distribute load on one CH, E-HARP selects new CH in each data transmission round. In the second phase of E-HARP, data is routed with cooperative effort of the SN, which saves the node energy by prohibiting the transmission of redundant data packets. To evaluate the performance of the proposed technique, comprehensive experimentations using NS-2 simulation tool has been conducted. The results are compared with some latest techniques named as EH-RCB, ELR-W, Co-LAEEBA, and EECBSR. The acquired results show a significant enhancement of E-HARP in terms of network stability, network life time, throughput, end-to-end delay and packet delivery ratio.

INDEX TERMS Clustering, end-to-end delay, Harvesting, Network Life-time, Network stability, packet delivery ratio, throughput, Path-loss, WBANs.

I. INTRODUCTION

GROWTH in the field of electronics has reshaped the technology of Micro-Electro-Mechanical Systems (MEMS) which further made the sensors more powerful and smart. MEMS sensors are small size devices with the ability of sensing the environment, data gathering, processing and transmission. To take advantage of development in wireless communication, sensors became able to communicate by utilizing this technology in an untied manner [1]. These sensors have the capability to sense surrounding environment for different parameters, process the data, generate useful information and then communicate it to other nodes using wireless medium [2]. These developments also provided a platform for sensor networks to communicate with a base station (BS) by making ad-hoc connections for data transmissions. BS or also known as sink, is a device with considerably large storage and processing power as compared to normal sensor nodes (SNs). BS gathers data from SNs deployed in the field. Among various types of sensor networks, wireless body area network (WBAN) is special type of network

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which is used for monitoring health-related parameters of human body without disturbing his/her daily life routine. The composition of WBAN includes small size SNs deployed on different parts of human body which observe different physiological parameters such as blood pressure, rate of heart beats, glucose level etc. These deployed SNs record and process the sensed data of a human body and then transmit it to BS/Sink [3]. This recorded data can be directed to an external network by providing an interface between local network and internet or cloud storage from where different medical professionals located remotely can access the patient body data. This phenomenon is shown in Figure 1 [4], [5].

The continous increase in number of patients suffering from different diseases world-wide such as diabetes, asthma, cardiovascular etc. is one of the reasons that greatly influenced the researchers to take interest in providing effcient health-care solutions. WBANs provides one of the cost-effective health-care solutions for this issue. It is made up of small and light-weighted biological SNs so that they can be deployed on a human body with ease and comfort. The main drawback of these small-sized SNs is their limited resources such as battery capacity, which drain quickly due to different operations. The quick depletion of battery energy mostly occurs due to; repetitive transmission of redundant sensed data in successive rounds and re-transmission of data packets. The retranmission of data packets is carried out due to unsuccessful data reception at destination which mostly occurs due to path-loss, and selection of inefficient routes among the SNs [6], [7]. The energy drainage results in early death of SNs which severely affect the network life-time [8].

The high-mobility of SNs due to human body movement, creates path-loss/path dis-connectivity issue the result of which is data-loss during data transmission. The maximum amount of battery power is consumed by data transmissions performed by onboard transmitter unit [8]. The retransmission of redundant data, consumes more energy unnecessarily that needs to be avoided for better network performance [9], [10].

The biggest design challenge faced by WBANs is to achieve reliable data delivery and enhance the network life-time under the imposed limited power supply constraint. A proper and well-designed routing scheme offers prolong network life-time with high quality of services by efficient resource management strategies. As WBANs operating conditions and its architecture are different than other traditional sensor networks, therefore the routing schemes designed for those networks [11]–[17], are not suitable to be implemented in WBANs applications. A typical WBAN contains a limited number of SNs with no provision of redundancy [23]. These nodes have limited computational, storage and power capacity [24]. Therefore, routing protocols for WBANs needs to be designed in such as way that considers these limitations of SNs.

The routing protocols which is based on clustering mechanism are appropriate in applications related to WBANs. In clustering approach, the network is partitioned into different logical sub networks called clusters. Each cluster contains one header node called cluster head (CH) and other cluster member nodes. The cluster member nodes transmit their sensed data to the CH in a single-hop manner. The CH of each cluster gathers the received data into a single packet called datum. CH then forwards this compressed datum to the BS/Sink. In this manner the clustering approach ensures minimum utilization of energy and offers maximum data delivery with appropriate end-to-end delay [25]–[28]. As the CH performs aggregation and forwarding of data toward sink, it consumes more energy than member nodes. Therefore, in order to create balance in the energy consumption, new CHs are selected dynamically for each transmission round. The dynamic selection of CHs distributes the load among different nodes throughout the life-time of the network and hence uniform energy consumption is achieved [29]–[32].

The dynamic selection of CHs is a challenging job [33] in which multiple aspects should be taken into account. The selection of suitable node for CH role is greatly dependent on multi-attribute decision making techniques. Such techniques determine high-ranked nodes as CH candidates based on required attributes of nodes. These attributes include residual energy, proximity to sink etc. [34]–[36]. The node with high rank value according to the requirements of the network gets selected as CH. Background and Motivation section presents some of the existing schemes which incorporate multiple attributes of nodes for CH selection decision.

This research article presents an Energy efficient Harvested-Aware clustering and cooperative Routing Protocol for WBAN (E-HARP). As depicted in Figure 6 and Algorithm 1, the presented technique includes:

1) Dynamic CH selection using CF which is based on multiple parameters. For CH selection, the proposed scheme considers four parameters of SN i.e. current/residual energy of SN, link statistics (SNR), required Transmission power and estimated total network energy loss.
2) Cooperative efforts-based communication in which redundant sensed data by SNs in consecutive tranmission rounds is omitted and not sent to the CH or sink. In the proposed scheme, each SN check the sensed data for possible similarlity. The sensed data is transmitted only if it is critical in nature or different from the data that is sensed in the previous transmission rounds else it is considered redundant and therefore it is discarded. Hence, energy of SN is saved from unnecessary consumption by not sending the redundant data repeatedly.

To evaluate the performance of the presented technique, comprehensive experimentation using NS-2 simulation tool has been conducted. The results are compared with some of the state-of-the-art techniques named as EH-RCB [37], ELR-W [38], Co-LAEEBA [39] and EECBSR [40]. The acquired results indicate a significant enhancement of E-HARP in terms of network stability period, network life-time, throughput, and end-to-end delay.

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This research article is organized as follows; In section 2, some state-of-the-art routing protocols are discussed with a detailed summary presented at the end. WBAN System model and some assumptions about the system are briefly explained in section 3. Section 4, defines the presented routing and CH selection protocol in detail. Performance and Evaluation of proposed protocol is discussed in section 5. Section 6, concludes the paper and discusses the future work.

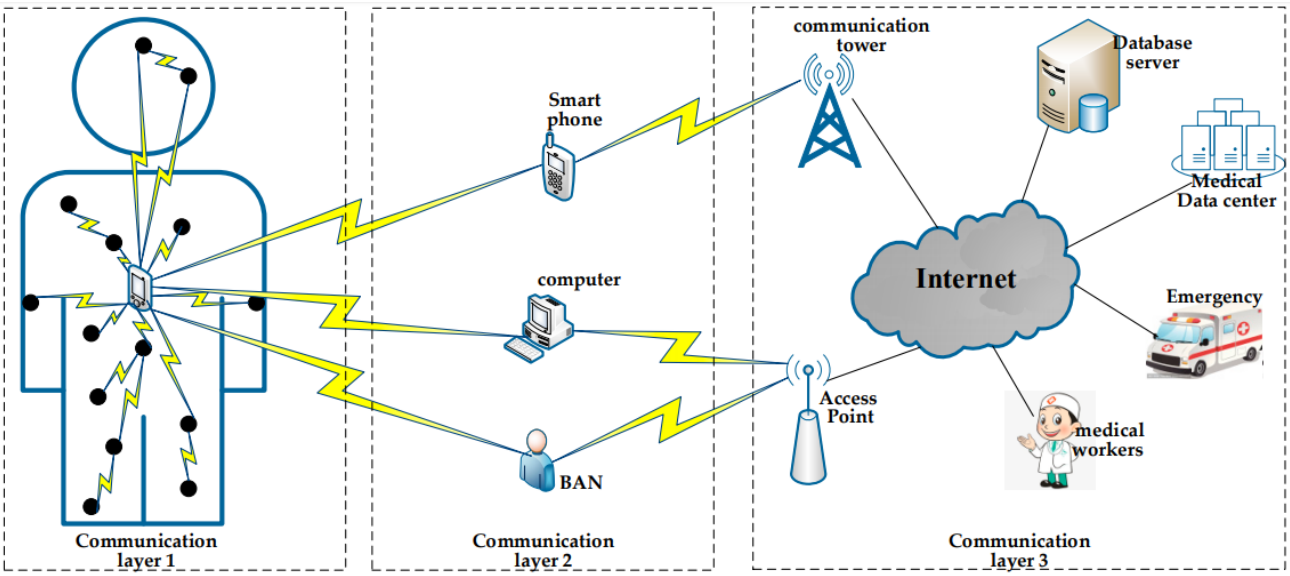

FIGURE 1. A typical WBAN Architecture [5]

II. BACKGROUND AND MOTIVATION

There are lots of different protocols and techniques developed for traditional sensor networks or other wireless networks [11]–[22], but due to different working environment, those protocols cannot be directly used in WBAN applications. WBANs are formed in or around the human body, which has different network structure/environment as compare to other wireless networks. As WBANs is mainly used in medical/health-related applications which can sense critical data from human body therefore timely forwarding it to medical server for further analysis is of utmost importance. Data gathering, and forwarding are typically done using technologies of different layers such as application, hardware/devices, security, network layer, MAC layer technologies etc. Among all these mentioned technologies, routing is one of the main technologies, because the sensed data by the SN needs to be forwarded to the medical server quickly and efficiently. Furthermore, clustering mechanism is considered as an optimum approach for routing schemes, which has many advantages such as network load balancing etc. Therefore, researchers nowadays are more focused on developing efficient CH selection and routing mechanism for WBANs. The aim of developing an efficient CH selection and routing mechanism is to enhance the network lifetime, network stability, throughput, and end-to-end delay etc. Few of the cluster-based and multi-hop routing protocol are reviewed in this section. Main focus is given to the techniques which use multiple-attributes for decision making specifically for CH selection and efficiently routing the data. Some of the techniques are discussed below, and its summary is shown in Table 1.

IRMB protocol [42] which is proposed to improve the performance of CICADA protocol. CICADA is a cross-layered protocol which works on MAC and routing layer, which support multi-hop communication scenario. It supports high energy efficiency and offers low end-to-end delay by setting up the data gathering tree. It is based on the model of multi-hop probabilistic network connectivity. The main aim of this work is to enhance the reliability of data transmission in WBANs. It uses path-loss model to cover the whole human body instead of covering only the circular area, as normally done in most schemes. In the proposed protocol, time slot-based mechanism is used which assigns short but equal interval time slots are assigned to each SN in the network. Furthermore, this proposed work analyses the CICADA protocol and some modification is done such as to achieve high reliability.

L. Liang et al. [43] presented an energy-efficient routing mechanism called as low-overhead tree based energy efficient routing scheme (EERS) for multi-hop WBANs. The proposed scheme mainly focuses on efficient utilization of energy and transmission power. In order to support their proposition, the authors have done some experimentation to describe the problem i.e. energy-loss due to low-reliability in transmission. The low-reliability in transmission occurs due to body shadowing and fixed transmission power in WBANs by not considering the wireless link quality. To solve these problems, the proposed routing scheme establishes

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tree-based and energy efficient end-to-end wireless communication path by choosing the appropriate transmission power for each SN. The proposed protocol was implemented using real-time test bed of MicaZ WBAN test-bed and extensive experimentation was done. The performance of the proposed scheme was compared with collection tree protocol (CTP) in terms of end-to-end delay, packet delivery ratio (PDR), and energy consumption/balancing. The results depicted that the proposed scheme works better than the compared scheme in the mentioned parameters.

N. Javaid et al. [34] proposes IM-SIMPLE which is an improved version of their previously proposed protocol, called as SIMPLE. It is claimed to be a reliable and energy efficient routing scheme which offers high network throughput. In order to select the forwarder node, cost function is used which is based on distance of the SN from the sink and residual energy of the SN. A SN having least distance from the sink and maximum residual energy, gets minimum cost function and is therefore selected as forwarder node. Residual energy parameter used in cost function is said to balance the energy consumption among the SN. Whereas, the least distance parameter improves packet delivery ratio to the sink, and also reduces the path-loss effects in data transmission. The performance results after experimentation show that IM-SIMPLE routing protocol in comparison with SIMPLE and M-ATTEMPT performs well in terms of network stability period, network throughput and network life-time.

Z. ullah et al. [33] proposed Dual Sink approach using clustering in Body area network (DSCB). The aim of the proposed protocol is to cover the path-loss issue using clustering approach with the use of dual sinks. Two sink nodes are deployed on human body at front and back side. In order to select the best forwarder node, cost function is used which is based on residual energy of the SN, distance between the SN and required transmission power. SN with minimum cost function is selected as forwarder node. DSCB is compared with DARE and SIMPLE routing protocols in order to check its performance.

Z. ullah et al. [37] proposed a novel energy efficient and harvested-aware protocol named as EH-RCB. This protocol aims to improve the energy efficiency in routing process. It uses clustering approach in WBAN, by forming two clusters with sink nodes as their pre-defined cluster heads to overcome the path-loss issue. To further enhance the energy efficiency, EH-RCB uses energy harvesting mechanism which generates energy from human surrounding. In order to select the best forwarder node for data transmission, the proposed protocol calculates cost function for each SN in the network. The parameters used for calculation of cost function are total energy (sum of harvested energy and residual energy), distance of the SN from the sink and required transmission power. The performance of EH-ECB is compared with DSCB, EERP, RE-ATTEMPT and EECBSR. The results showed that EH-RCB outperforms the compared protocols in terms of network life-time, stability, throughput, end to end delay and packet delivery ratio.

M. Anwar et al. [38], proposed efficient routing protocols in terms of energy-aware links. It is mainly focused on developing framework for green communication. In the first phase of its two-phased scheme, it presents a network model for efficient link selection. While in the second phase a model for path-cost calculation is presented. Using these two models, the proposed protocol focuses on to select efficient and energy-aware communication link. The proposed protocol is compared with some state-of-the-art techniques and achieves better results in the defined parameters.

Ha et al. in [40], proposed EECBSR protocol which mainly focuses on balancing energy consumption and routing among the nodes that are deployed on back side of human body. This protocol is mainly proposed for efficient data transmission in WBANs in order to cover the path-loss issue (for the nodes that are attached to back side of human body) and enhance network life-time. M-Attempt is used as base protocol and its improved version is presented. Based on the experimentation conducted using simulation tool, the authors have claimed that EECBSR achieves better results as compared to its counterpart in terms of network stability and throughput.

Sheeraz et al. [39], proposed Co-Laeeba protocol which focuses on cooperative awareness of link and energy efficiency. Its main focus is to cover the path-loss issue for the SNs that are placed on high mobility parts of human body. Furthermore, in order to enhance the communication, cooperative learning technique is used, in which data is sent to more than one intermediate nodes on the way to sink node. To select the most feasible route and intermediate node, cost function is used. Cost function is calculated using residual energy of the SN and distance of the SN from other nodes and sink.

Heinzelman et al. in [26] proposed a clustering protocol named as LEACH. It is one of the pioneer protocols in WSN which uses the concept of clustering and CH selection. It uses multiple attributes probability-based weight function for selection of CH. CH is randomly selected and is used as the coordinator for its defined cluster. It receives the sensed data from cluster members and after aggregation, forwards it to sink node. The main aim of proposing the concept of randomly selection of CH is to distribute the load evenly among all the SNs in the network.

M-ATTEMPT [44], is another routing protocol which is claimed to be an energy efficient and thermal-aware routing protocol that supports nodes mobility in heterogeneous WBANs. In this protocol SNs having high data-rate capability and with more battery energy are placed on less mobile places of human body. SNs transmit the data to sink node either using single-hop or multi-hop communication scenario. The critical or on-demand data is always sent directly to sink using single-hop communication, whereas normal data follows multi-hop communication. The proposed protocol estimates hot-spot in wireless link and avoids those links for data communication. Battery energy is properly managed in order to enhance the network life-time. The results achieved after simulation show that the proposed protocol works better

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TABLE 1. Detail description of some state-of-the-art protocols

Protocol Name	Cluster Head and Forwarder node selection criteria								
	Hop count	Temperature consideration	Path-loss	Energy consideration	Link statistics	Nodes density	Distance	Residual energy	Transmission power
IRMB	No	No	Yes	Yes	No	No	Yes	Yes	No
EERS	No	No	No	Yes	No	Yes	Yes	Yes	No
IM-SIMPLE	Yes	No	No	Yes	No	Yes	Yes	Yes	No
DSCB	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes
EH-RCB	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes
ELR-W	Yes	No	No	Yes	Yes	No	No	Yes	No
EECBSR	No	No	Yes	Yes	No	No	Yes	Yes	No
Co-LAEEBA	Yes	No	Yes	Yes	No	No	Yes	Yes	No
M-ATTEMPT	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
LEACH	Yes	No	No	Yes	No	Yes	Yes	Yes	No
E-HARP	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes

as compared to energy consumption, packet delivery and reliability ratio.

III. SYSTEM MODEL

The proposed WBAN system consists of fourteen homogenous SNs having limited hardware resources due to its small size. These SNs are deployed in/on front side of human body along with two sink nodes. Sink nodes are placed on right and left hips of human body. These locations of the sink nodes help in providing direct connectivity to all deployed SNs. Both of these sinks are advanced nodes with high performance hardware as compared to SNs. SNs are placed at different locations of human body as shown in Figure 2 and their details are mentioned in Table 2. The SNs sense physiological data of human body and transmit it to sink either directly or through selected CH after minimal local processing. Sink node after receiving the data from the SN, aggregates it and forwards it to personal server for further analysis. The communication scenario used in this scheme is both singe-hop and multi-hop communication. Direct/Single-hop communication is done in the following cases i.e.

1) If the sensed data is critical (different from the pre-defined upper and lower threshold limit)
2) If the sensing node is closer to sink node.
3) If the sensor node is a selected CH.

If it is not the above-mentioned cases, then the SN transmits its data to sink using multi-hop scenario, by forwarding it to CH first. CH after receiving the data from SNs, aggregates it and then forwards it to sink node. Sink is responsible for selection of CH, based on the calculated Cost Factor (CF). The parameters for CF computation are estimated/calculated by SNs and are sent to sink node. Newly CH after its selection, assigns time-slots to each SN in the cluster at the beginning of each sensing/transmission round using Time Division Multiple Access (TDMA) protocol.

There are few assumptions in the proposed work i.e.

1) Due to high mobility of human body, the positions of the SNs may change frequently.
2) The power consumption of SNs during processing the data is ignored as it is very limited as compared to power consumption during transmission/reception of data [8].
3) In order to cater the limited energy issue in WBANs, and to provide continuous energy supply, each SN is equipped with Energy Harvesting (EH) functionality which generates energy from human surrounding based on solar energy and supply it to SN. To predict the expected Harvested Energy $E_{Harvest_i}(t, P_{setup})$ of each SN, a common model named as Exponentially Weighted Moving-Average (EWMA) [45] is used (expressed in Equation (1)).

$$E_{Harvest_i}(t, P_{Setup}) = \int_{t}^{(t+P_{Setup})} \lambda_i(\Gamma) d\Gamma \quad (1)$$

Where $E_{Harvest_i}$ is the estimated harvested energy by a SN i in a defined time Γ period, while the charging rate of node i in time Γ is represented by $\lambda_i(\Gamma)$.

4) As total fourteen SNs are deployed on the human body, so, two clusters are formed in cluster formation phase, each having its own dynamically selected CH in each sensing/transmission round as shown in Figure 4. The CH after reception of data from its cluster members, aggregates it and forwards it to the nearest available sink node.
5) The on-body path-loss propagation model used in this proposed scheme is same which is used in IEEE 802.15.6 BAN channel modeling project [46]. It is expressed in Equation (2).

$$P_{Loss}(dB) = \alpha \times log_{10}(D) + \beta \times log_{10}(f) + N_{df} \quad (2)$$

Whereas P_{Loss} is the path-loss or path-attenuation (in dB), D represents the distance among the SNs and the sink, f is the operating frequency, N_{Df} is the

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distributed variable (158 dB), α and β are the linear coefficient whose values are -27.6 and -46.5 respectively [46].

6) The distance among the SNs and the sink is calculated by Euclidean distance [47], which is expressed in Equation (3). As the distance has effects on path-loss, therefore path-loss factor is also included in calculation of the distance.

$$D(i,j) = 10\left(\frac{P_{Loss-j,i}(dB) - \beta \times log_{10}(f) + N_{df}}{\alpha}\right) \quad (3)$$

7) The estimation/prediction of energy-consumption during data transmission, reception and processing is done using first-order radio model [26]. Equation (4) expresses the energy consumption during transmission of K bit of data to destination SN at distance D. Whereas, energy consumption while receiving the K bits of data is expressed using Equation (5). Equation (6) represents the energy consumption during data aggregation process done by CH.

$$E_{Tx}(K,D) = E_{Tx-Electronics} \times K + E_{Amplifier} \times n \times K \times D^i \quad (4)$$

$$E_{Rx}(K) = E_{Rx-Electronics} \times K \quad (5)$$

$$E_{D-Aggregation}(K) = E_{D-Aggregation} \times K \quad (6)$$

$E_{Tx-Electronics}$, $E_{Rx-Electronics}$ and $E_{Amplifier}$ are the required amount of energy (Joule/bit) or can be called as energy consumption respectively by SN transmission unit, reception unit and amplifier circuitry. Whereas $E_{D-Aggregation}$ is the required energy for data aggregation (Joule/bit), and n represents the path loss coefficient of a human body.

TABLE 2. Detail description of used nodes in E-HARP

Node #	Description	Node location x-axis (m)	Node location y-axis (m)	Position on human body	Application Type
1	EEG Sensor	0.32	1.77	Head front side	On body
2	ECG Sensor	0.35	1.37	Chest (left-side)	On body
3	ECG Sensor	0.22	1.35	Chest (Right-side)	On body
4	Glucose Sensor	0.36	1.01	Stomach (Left-side)	In body
5	Glucose Sensor	0.35	0.01	Stomach (Right-side)	In body
6	Motion Sensor	0.08	1.45	Right-side Shoulder	On body
7	EMG Sensor	0.06	0.98	Right hand wrist	On body
8	Blood Pressure Sensor	0.37	1.27	Left hand triceps	On body
9	Pulse Oximeter Sensor	0.4	1.01	Left hand wrist	On body
10	Lactic Acid Sensor	0.22	0.91	Right-side thigh	In body
11	Accelerometer/ Gyroscope Sensor	0.45	0.45	Right-Side Knee	In body
12	Respiration Sensor	0.15	0.5	Left-side Thigh	On body
13	Pressure Sensor	0.15	0.45	Left-side lower leg	On body
14	Pressure Sensor	0.25	0.17	Right-side Lower leg	On body
Sink 1	Central Coordinator (Right-side)	0.3	1.03	Right-side Hip	On body
Sink 2	Central Coordinator (Left-side)	0.09	1.05	Left-side Hip	On body

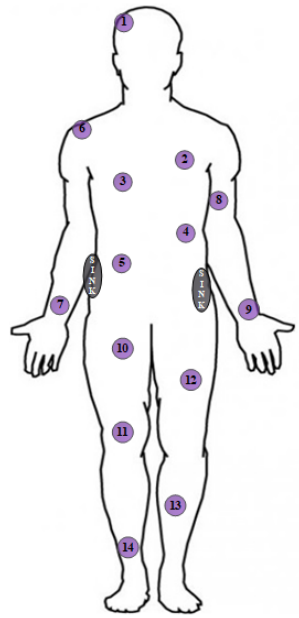

FIGURE 2. Nodes deployment location in E-HARP

IV. PROPOSED SCHEME

In the proposed protocol, each sensing/transmission round works in following phases;

A. INITIALIZATION PHASE

The initialization phase starts after the deployment of all the SNs along with both the sink nodes. The SNs and both sinks estimate/calculate their locations and calculate the distance from their neighbor nodes and sinks using Received Signal Strength Indicator (RSSI) technique. After the calculation of the distance, all SNs including both sinks broadcast BEACON message in the network. As first time-slot is assigned to sink node by TDMA protocol, therefore this process is initiated by sink node. The BEACON message contains the sender node ID, distance from the neighbor nodes, destination node ID, current/residual energy (sum of Harvested energy and residual energy) of the source node, node location and transmitted signal power.

Upon reception of BEACON message, each SN, identifies the sender node from its address and calculates the path-loss between itself and the SN. The computed path-loss between the receiving SN and transmitting node is expressed in Equation (7). The receiving SN j also calculates the distance from sender SN i using path loss model, as expressed in Equation (3).

$$P_{Loss-j,i}(dB) = P_t(dBm) - P_{rj,i}(dBm) \quad (7)$$

Where $P_{(rj,i)}$ is the power of the received BEACON signal at SN j.

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With this whole process, SNs and both sinks in the network get information about their neighbor nodes, their position and distance from other nodes, and all possible routes leading to the sink node. Each node including sink, saves these information in its local memory for future use.

B. CLUSTER HEAD SELECTION AND CLUSTER FORMATION PHASE

After initialization phase is carried out, the proposed protocol selects CHs for both clusters. Clusters are the partitioned regions of the whole network each having its own coordinator/CH as shown in Figure 3. The purpose of creating the cluster is to ease the network convergence and data transmission process, as only the defined cluster members communicate inside a cluster.

Based on the collected information in the initialization phase, the process of CH selection and cluster formation is carried out. Two clusters are formed (one on upper and other on lower part of the human body) with a dedicated sink node as shown in Figures 4. In each transmission round a SN, which fulfills the defined selection criteria is selected as CH dynamically in its respective cluster. The rationale of efficient CH selection is that it should be in a location where communication link does not face high interferences. Furthermore, it should have maximum available total energy (i.e. sum of residual/current and harvested energy), and it should perform data routing process at very low network energy consumption. The dynamic CH selection process is discussed in the following subsections.

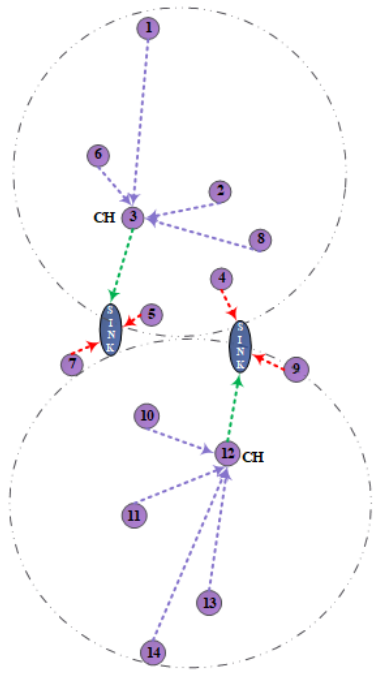

FIGURE 3. Cluster Head Selection and Communication Architecture in E-HARP

1) Cost Factor computation for CH selection

Based on the information attained in the initialization phase, each SN predicts the estimated total energy consumption/loss of the network and total residual energy of the candidate SN in order to select the optimum CH for both the clusters. The energy consumption/loss occurs due to the transmission, reception and processing (aggregation) of data in the network. Total network energy loss is the sum of two energy losses i.e. energy loss of all cluster members and the loss of energy in SN itself.

1) **Estimation of Energy Loss of cluster members**
In this step, each SN in the network imagine itself as the CH of the respective cluster and then predicts the total estimated energy loss of all the cluster members in the cluster, which can be expressed using Equation (8). Energy of cluster members is consumed during different operations, such as sensing, local aggregation/processing, transmission and reception of data.

$$E_{C-member}(i) = \sum_{j=1}^{N} \left\{ E_{Amplifier} \times n \times K \times D(i,j)^{i} + E_{Tx} \times K \right\} \quad (8)$$

Where $E_{C-member}(i)$ is the estimated total energy loss of cluster member i, the total number of SNs in the network is represented by N. E_{Tx} and $E_{Amplifier}$ are the required amounts of energy (Joule/bit) required by a SN i for transmission, and amplification of K bit size of data at a distance Di, j from node i to node j. The lower/minimum value of $E_{C-member}$ represents the better connectivity with neighbor SNs.

2) **Estimation of Energy loss for SN**
After the estimation of energy loss of all cluster members, the SN calculates its energy loss from its current energy which occurs due to sensing, reception, aggregation and forwarding the data. The SN considers itself as a CH of the respective cluster and then calculates the energy loss if it receives the data from all of its cluster members, aggregates it and forwards it to the sink node. The estimated energy loss from the current energy of the SN is expressed using the Equation (9) below;

$$\begin{aligned} E_{Loss-SN}(i) = (E_{Tx} + E_{D-Aggregation}) \times K \\ + E_{Amplifier} \times n \times K \times D(i, sink) \\ + (N-1) \times E_{Rx} \times K \end{aligned} \quad (9)$$

Where $E_{Loss-SN}(i)$ represents the total estimated energy loss of the considered SN (CH candidate), E_{Rx},

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$E_{D-Aggregation}$, $E_{Amplifier}$ and E_{Tx} are the energy consumption/loss in data reception, aggregation, amplification and transmission respectively, $D(i, sink)$ is the total distance from node i to sink. The lower value of $E_{Loss-SN}(i)$ represents the better/closer proximity of SNs to sink node.

The sum of both energy loss (expressed in Equation (10)) represents the predicted total network energy loss/consumption $E_{Total-loss}(i)$ for the SN i.

$$E_{Total-loss}(i) = E_{C-member}(i) + E_{Loss-SN}(i) \quad (10)$$

3) **Calculation of sensor node energy**

One of the other parameters used for selection of CH is total residual/current energy of the SN. The total residual energy (expressed in Equation (11) is the sum of harvested energy (generated from external environment by SN) and residual/remaining energy of the SN.

$$E_{Total-curr}(i) = E_{Res}(i) + E_{Harvest}(i) \quad (11)$$

$E_{Total-curr}(i)$ represents the total current energy of the node i, $E_{Res}(i)$ is the residual/remaining energy (difference of Initial energy and consumed energy) of the SN and $E_{Harvest}(i)$ is the total harvested energy from energy harvester embedded inside the SN. The residual energy $E_{Res_i^j}$ of the SN at time t can be expressed using the Equation (12).

$$\begin{aligned} E_{Res_i^j}(t + P_{setup}) = E_{Initial_i^j}(t) - E_{T-round_i^j}(t) \\ + E_{Harvest_i^j}(t, P_{setup}) \\ 0 < E_{Harvest_i^j}(x) < E_{Max_i} \end{aligned} \quad (12)$$

Initial energy $E_{Initial}(i)$ of the SN i is provided at the start of the deployment phase. $E_{T-round_i^j}(t)$ is the total energy consumed during the setup period P_{setup} . E_{Max_i} is the total capacity of the battery in the SN.

4) **Estimation of required Transmission power**

In order to estimate the total required transmission power which is expressed in Equation (13), SNR of the communication link needs to be calculated first.

$$TP = \frac{SNR}{\alpha} \quad (13)$$

("α" means path-loss exponent)

SNR is ratio of the power of meaningful/useful signal P_{signal}, to the power of unwanted (noise) signals P_{noise}, which can be expressed using the Equation (14).

$$SNR = \frac{P_{signal}}{P_{noise}} \quad (14)$$

2) **REPLY to sink node**

After the necessary estimation and calculation, each SN sends the complete information in REPLY message to sink node. This message contains the SN ID, total current energy of the SN $E_{Total-curr}(i)$, predicted total network energy loss $E_{Total-loss}(i)$, required transmission power $T.P$ and other related information. These bits of information are useful for the sink node to take decision about CH selection.

3) **Cost Factor computation**

The sink node after receiving the REPLY messages from all SNs, computes the number of alive/dead nodes in the network, Total current energy $E_{total-curr}(i)$ of all alive SNs and required Transmission power (TP) by SNs for transmitting data to sink node. Using these calculated parameters, sink node computes the Cost Factor (CF) for all the SNs in the network as expressed in Equation (15).

$$CF(i) = \frac{E_{Total-loss}(i)}{E_{Total-curr}(i)} \times TP \quad (15)$$

The SN having minimum CF is selected as the CH for the next sensing/transmission round. Thus, the CH is selected with minimum total network energy loss $E_{Total-loss}(i)$ and maximum total current energy $E_{total-curr}(i)$. The selected CH having these qualities is predicted to perform the data transmission, reception and aggregation in the cluster with minimum energy loss from its residual energy.

4) **Cluster Formation and Scheduling**

After the selection of the CH, the sink node broadcast an ANNOUNCMENT message to all nodes in the network. All SNs upon reception of this broadcast message, decides to which CH will they register themselves. The SNs register with that CH, whose RSSI parameter is high. After this decision, each SN in the network sends JOIN-REQUEST to the newly selected CH. Based on this request message, the CH registers the SNs in its cluster. This process results in cluster formation. Once the cluster formation is done, the respective CH assigns time-slots to each cluster member SN for communication on the shared wireless medium using TDMA protocol.

C. DATA SENSING PHASE

Based on the allocated time-slot by the respective CH, each SN senses the physiological data of human body such as blood pressure, blood glucose level, ECG, EEG, EMG, heart beat etc. After sensing the data, the Analog to Digital Convertor (ADC) on-board unit in SN converts it to digital form for further processing. This data is also stored in its on-board memory unit for further use.

D. COOPERATIVE DECISION-BASED DATA TRANSMISSION

Once the SN senses some data, it needs to send it to its respective CH. Before transmitting the sensed data, each SNs checks its total current energy $E_{total-curr}(i)$ against the defined energy threshold. If the total current energy is found lesser than the defined threshold, then the SN has to wait

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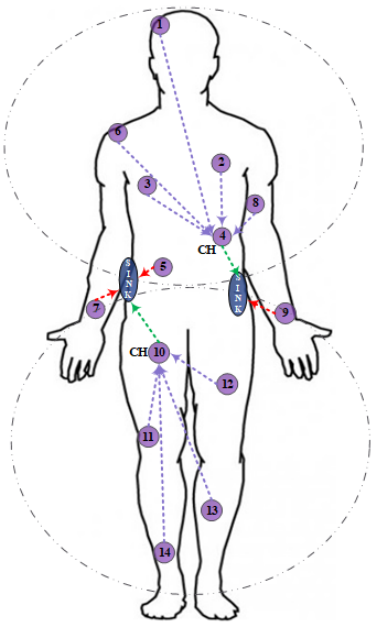

FIGURE 4. Data Communication Architecture of E-HARP

for next data sensing/transmission round, so that its on-board energy harvester unit, harvest enough energy for operation. If the total current energy $E_{total-curr}(i)$ is lesser than the threshold energy, this means it has got very limited energy and there are very high chances of its death if this SN starts transmission.

SNs in WBAN may sense similar data in the repetitive/successive data sensing/transmission rounds. By sending the redundant data for multiple times, will result in more energy consumption. Significant amount of battery energy during transmission can be saved by avioding the transmission of redundant/duplicate data. In E-HARP protocol (shown in Figure 6 and also represented in Algorithm 2), redundant sensed data in consecutive rounds is restricted and not transmitted to sink node. This is done by using the cooperative decision-based data transmission technique. In this technique, sensed data is first checked for any possible redundancy/similarity and then transmission phase is followed. Each SN stores the data in its on-board local memory for each data sensing/transmission round. So, in each new data sensing/transmission round, the SN compares this new sensed data with the stored data from previous round for any possible redundancy. This minimal local processing is done before deciding either to transmit the data to CH or not. The data is transmitted if either of the following conditions is true, else data is considered as redundant and is therefore discarded.

1) Data is transmitted to CH if it is different from the data stored in previous data sensing/transmission round.
2) Data is considered critical and is transmitted to sink directly if it is beyond the upper/lower limits of the defined threshold.

Algorithm 1 CH Selection and Cluster Formation

U: Set of total nodes in the network
$P_{r(j)}$: Signal power of the received signal from node j
P_t: Required transmission power (in dBm)
$E_{Initial}$: SN Initial energy
$E_{Res}(i)$: Current energy status of SN (i)
$E_{Harvest}(i)$: Harvested energy of SN (i)
N: Set of cluster SNs
Initialization Phase:
for each node-i of U **do**
  node-i estimates the distance of U based on RSSI
  node-i broadcasts the BEACON message
  for each node-j of U **do**
    node-j receives the BEACON from node-i
    node-j computes its distance and path-loss from node-i
    $P_{Loss-j,i}(dB)$=$P_t(dBm) - P_{rj,i}(dBm)$
    $D(i,j)$=$10(\frac{P_{Loss-j,i}(dB)-\beta\times log_{10}(f)-N_{df}}{\alpha})$
    node-j saves the distance
  end for
end for
CH selection phase:
for each node-i of U **do**
  node-i compute energy loss of U in the cluster
  $E_{C-member}$=$E_{Amplifier} \times n \times K \times D(i,j)^i + E_{TX} \times K$
  node-i compute its total energy loss
  $E_{Loss-SN}(i)$=$(E_{TX}+E_{D-Aggregation})\times K+E_{Amplifier}\times n \times K \times D(i,sink) + (N-1) \times E_{RX} \times K$
  node-i compute its total current energy
  $E_{Total-curr}(i)$=$E_{Res}(i) + E_{Harvest}(i)$
  node-i compute the required transmission power
  TP=$\frac{SNR}{\alpha}$
  node-i transmit REPLY message to sink,
  Containing $E_{Total-curr}(i)$, $E_{c-member}(i)$, $E_{Loss_SN}(i)$, TP
  sink compute Cost Factor CF(i) of node-i
  $CF(i)$= $\frac{E_{Total-loss}(i)}{E_{Total-curr}(i)} \times TP$
end for
for each node-i of N **do**
  if node-i has minimum CF **then**
    sink declare node-i as CH
  end if
end for
Cluster formation phase:
sink broadcast ANNOUNCEMNET to each node-i of U.
for each node-i **do**
  node-i compute: RSSI value of received signal
  node-i send JOIN-REQUEST back to CH
  based on JOIN-REQUEST, CH register sensor nodes.
end for

Furthermore, the distance from the SN to the CH and sink is checked if condition 1 becomes valid. If the distance between the SN and CH is lesser than the distance between SNs and sink $(D(i,CH) < D(i,sink))$, data is forwarded to CH else it is transmitted directly to sink node using single-hop communication. As shown in Figure 4, SN 5, 7 and 9 are deployed closer to sink node therefore the distance between these nodes and sink is lesser than the distance between these nodes and their respective CHs. So, in this case the SN 5, 7 and 9 will send the data directly to sink node. This cooperative decision-based data transmission minimizes the burden on the respective CH node. With this process the overall network performance also improves. Furthermore, the critical sensed data is also sent quickly without any delay by utilizing the communication channel bandwidth in an

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efficient way.

E. PROCESS AT CLUSTER HEAD

After the reception of data forwarded from all the cluster members in a transmission round, CH aggregates the whole data into single packet/message. This packet contains the cluster member IDs and their forwarded data. The CH adds Cyclic Redundancy Check (CRC) bits at the end of this packet as shown in Figure 5. CRC bits are added for detection and correction of errors in the packet at the sink. The addition of the CRC bits ensures that the data packets are forwarded to sink node are error free and is the same data which is sent by CH.

FIGURE 5. Cluster Head data packet format

Algorithm 2 Data Sensing and Transmission

CH: Cluster head for current Sensing/Transmission round
$D(i,j)$: Distance between node i and node j
$D(i,CH)$: Distance between node i and CH
$D(i,sink)$: Distance between node i and Sink
N: Total number of sensor nodes in the Cluster
Condition 1: New sensed data is different from previously stored data
Condition 2: Data is critical
Intra-Cluster Data transmission:
for each node-i of U **do**
  if (Condition 2 is true) **then**
    Node-i Transmit data directly to Sink
  else
    if (Condition 1 is true) **then**
      if $D(i,CH) < D(i,sink)$ **then**
        Node-i Transmit data to CH
      else
        if $D(i,sink) < D(i,CH)$ **then**
          Node-i Transmit data directly to Sink
        end if
      end if
    else
      Data is discarded as it is redundant
    end if
  end if
end for
Data Aggregation at CH:
CH receives the data from cluster members, aggregates it
Adds CRC bits to data packet and forward it to sink

V. PERFORMANCE AND EVALUATION OF PROPOSED PROTOCOL

An extensive experimentation using NS-2 simulation tool is performed to evaluate the working of E-HARP proposed protocol. The WBAN topology used for E-HRAP has total fourteen SNs and two sink nodes, that are deployed on different location of human body as shown in Figure 2 and its detail is given in Table 2. These SNs sense physiological data related to human body such as blood pressure, glucose level, ECG, EMG, heart rate etc. The proposed E-HARP protocol is compared with state-of-the-art protocols from literature, named as EH-RCP [37], Co-Laeeba [39], ELR-W [38] and EECBSR [40]. The comparison is done on the basis of network Life-time, network stability, residual energy, throughput, and end-to-end delay. The detail information about all the simulation parameters used such as, Initial energy provided to all SNs, simulation area, number of deployed nodes and their positions etc. are shown in Table 3.

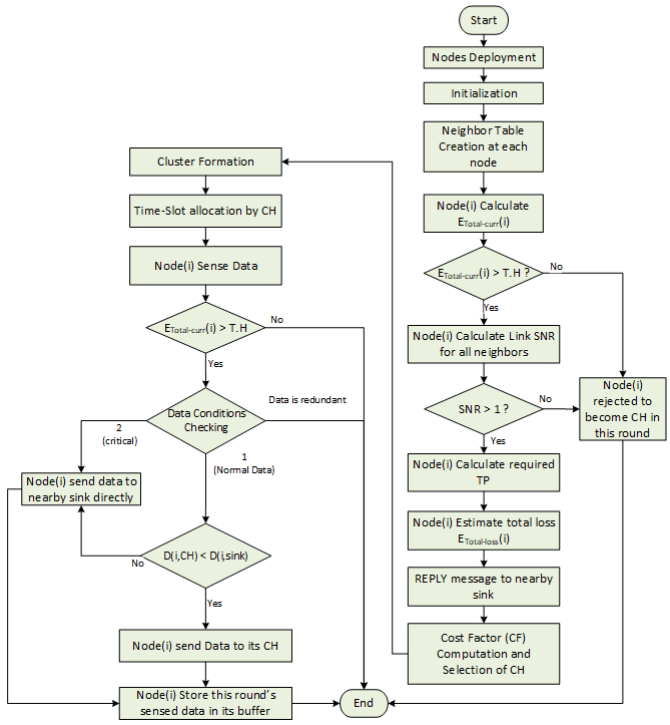

FIGURE 6. Flow Chart of E-HARP

TABLE 3. Simulation parameters for E-HARP

PARAMETERS	VALUES
Simulation Area	$2 \times 2\ m^2$
Number of Sensor nodes	14
Number of Sinks	02
Positions of Sensor nodes and sinks	Shown in Table 2
$E_{initial}$	$0.5J$
$E_{Tx-electronics}$	$16.7nJ/bit$
$E_{Rx-electronics}$	$36.1nJ/bit$
$E_{Amplifier}$	$1.98nJ/bit$
Wavelength (λ)	$0.138m$
Frequency	$2.4GHz$
Payload	$3000bits$

A. NETWORK LIFE-TIME

Network life-time refers to the total working time of any network. The time starts from the deployment of the all nodes till

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TABLE 4. Average rate of Dead nodes vs. Rounds

S.No	Protocol Name	1st Node die at	Number of Dead Nodes at Different number of rounds							
			2000	4000	6000	8000	10000	12000	14000	16000
1	E-HARP	7500	0	0	0	1	3	5	10	14
2	EH-RCP	4950	0	0	1	3	4	5	10	14
3	Co-LAEEBA	6283	0	0	0	4	6	8	-	-
4	EECBSR	3000	0	1	4	10	-	-	-	-
5	ELR-W	6500	0	0	0	4	8	-	-	-

TABLE 5. Number of Alive nodes at different rounds

S.No	Protcol Name	Number of Alive Nodes at Different number of rounds								
		1000	2000	4000	6000	80000	10000	12000	14000	16000
1	E-HARP	14	14	14	14	13	11	9	4	0
2	EH-RCP	14	14	14	13	12	10	8	0	-
3	Co-LAEEBA	8	8	8	8	4	2	0	-	-
4	EECBSR	10	10	9	6	0	-	-	-	-
5	ELR-W	8	8	8	8	4	0	-	-	-

their death. It is one of the main performance characteristics of those networks where nodes are mostly mobile and are battery operated, especially in all sensor networks. Enhanced network life-time counts towards the best performance of any network. In order to compare the performance of E-HARP with EH-RCP, Co-Laeeba, ELR-W and EECBSR, rigorous experimentation using NS-2 simulator is performed. The acquired result of network life-time with respect to number of rounds is shown in Figure 7. The achieved results which are listed in Table 4 attest that the first node of the proposed protocol dies at 7500th transmission round, which is greater than all other compared protocols. Similarly, the last SN of the proposed protocol dies at almost 16000th round, whereas in case of other compared protocols, (except for EH-RCP) their last node dies at maximum of 12000th round. This shows that the network life-time of E-HARP is higher from other compared protocols. The enhancement of the network life-time is due to embedded energy harvesting mechanism in each SN. Furthermore, the efficient selection of CH and the cooperative communication also contribute towards the enhancement in network life-time.

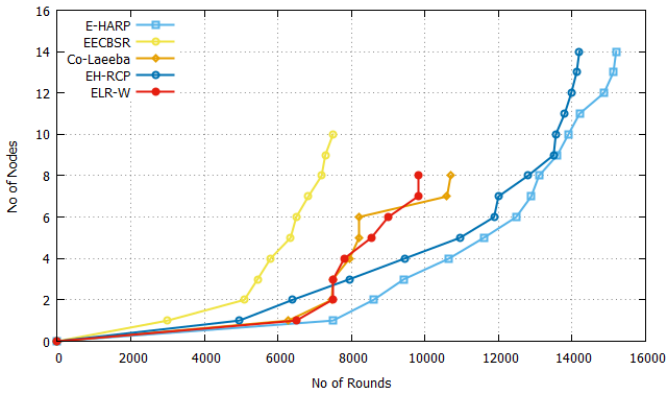

FIGURE 7. Analysis of Network Life-time

B. STABILITY PERIOD

It is referred to as the period/time before the death of the first SN in the network. It can also be defined as the period till all SN stay alive. It is one of the main performance criteria to judge any technique in a sensor network. The SNs in the networks having better stability period, live for longer period of time. The results of network stability period for the proposed protocol in comparison with other protocols are shown in Figure 8 and 9. The results listed in Tables 5 and 6 show that the first node of the proposed protocol dies at 7500th round. Whereas the first node of EH-RCP, Co-Laeeba, EECBSR, ELR-W dies at round 4950, 6283, 3000 and 6500 respectively. This attests that the proposed E-HARP routing and CH selection protocol achieves high stability period as compared to other protocols. The enhanced performance of E-HARP in terms of high network stability is due to presence of energy harvesting scheme, efficient selection of CH and restriction in transmission of redundant data in successive transmission rounds.

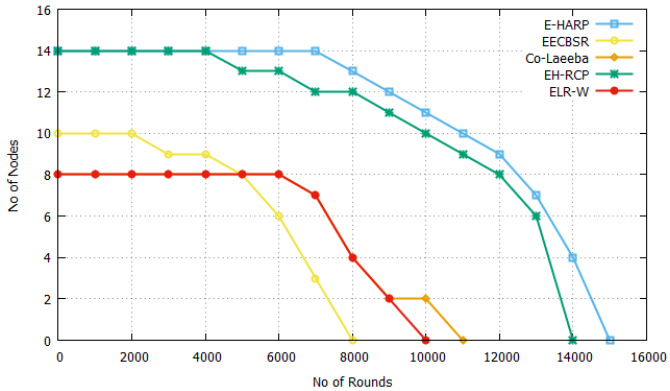

FIGURE 8. Analysis of Network Stability

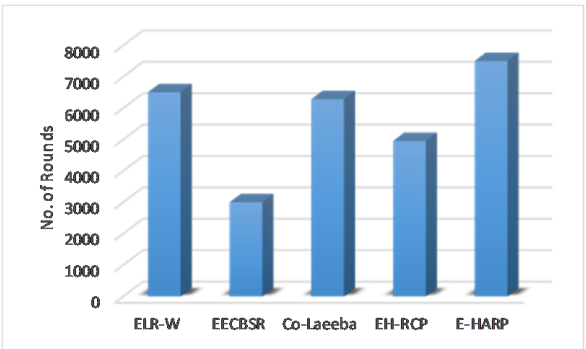

FIGURE 9. Analysis of Network Stability (First Node Death)

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TABLE 6. First Node Death Analysis

S.No	Protocol Name	First Node Death at Round number
1	E-HARP	7500
2	EH-RCP	4950
3	Co-LAEEBA	6283
4	EECBSR	3000
5	ELR-W	6500

TABLE 7. Total Network Residual Energy vs. Time

S. No	Protcol Name	Network Residual Energy (Joule) after interval of time (sec)							
		0	2500	5000	7500	10000	12500	15000	16000
1	E-HARP	7 J	6 J	4.8 J	4.2 J	3.2 J	2.6 J	1.4 J	0.9 J
2	EH-RCP	8 J	6.5 J	5.2 J	4.56 J	3.3 J	2.4 J	1.0 J	0.1 J
3	Co-LAEEBA	5 J	3.8 J	2.0 J	0.5 J	0.06 J	0.0 J	-	-
4	EECBSR	4 J	2.9 J	1.9 J	1.25 J	0.72 J	0.55 J	0.04 J	0.0 J
5	ELR-W	4 J	2.5 J	1.2 J	0.25 J	0.0 J	-	-	-

C. RESIDUAL ENERGY

Residual energy refers to the remaining battery energy of any SN in the network. Whereas, the total network residual energy refers to the sum of current/remaining energy of all the SNs in the network. Energy is consumed by different operations done in the SN i.e. sensing, processing, transmitting and receiving the data. In order to extend the life-time of the network and make the network stable, different efforts are taken to minimize the energy consumption of the SNs in their processing. The Figure 10 below shows the comparison of E-HARP with other protocols in terms of residual energy of the network. It can be viewed in Table 7, that the network energy of E-HARP lasts for very long i.e. more than 16000th round, whereas the energy of other protocols lasts at 16000th, 12500th, 15000th, and 10000th rounds for EH-RCP, Co-Laeeba, EECBSR and ELR-W respectively. So, these results attest that the proposed protocol works efficiently as compared to other protocols in terms of residual energy.

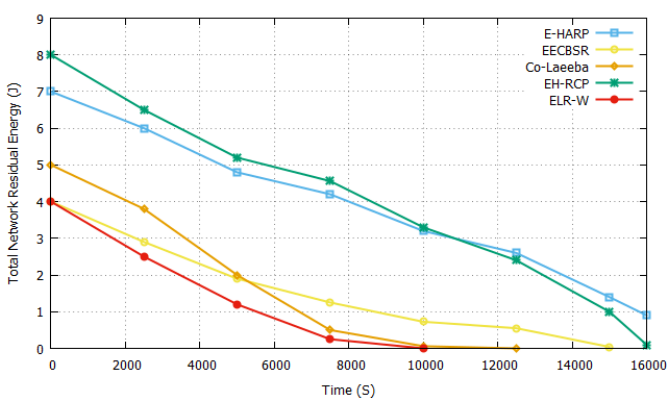

FIGURE 10. Analysis of Energy Consumption

TABLE 8. Average Network Throughput vs. Time

S. No	Protcol Name	Number of packets received (*104) at different interval of time (sec)							
		0	2500	5000	7500	10000	12500	15000	16000
1	E-HARP	0	2.1	4.23	6.1	6.8	7.4	8.56	9.6
2	EH-RCP	0	1.56	3.49	5.92	7.04	7.9	8.79	9.04
3	Co-LAEEBA	0	0.9	1.8	2.7	3.6	3.7	-	-
4	EECBSR	0	2.5	4.5	3.46	7.89	-	-	-
5	ELR-W	0	1.2	2.7	3.25	3.75	3.9	-	-

D. THROUGHPUT

Throughput refers to the successful transmitted data from the SN to the sink in defined time. It is one of the most important performance parameters for any network. One of the main goals of designing any protocol (especially routing protocol) is to enhance the maximum successful delivery of data packets. The network with a high throughput is considered best network in terms of performance. The comparison of the proposed protocol with other protocols is shown in Figure 11. The results shown in Table 8, attest that achieved throughput of the proposed protocol is high as compared to other protocols. In the starting rounds, the other two compare protocols named as EECBSR and EH-RCP outperforms the proposed protocol, but ultimately the performance of E-HARP enhances from 15000th onwards. The poor performance in the starting rounds is due to the rigorous processing done for the selection of CH and cluster formation. The processing is minimized in the later rounds, as the information acquired after processing in starting rounds is reused. The enhanced performance in terms of network throughput is due to the presence of dual sink on the body. The SNs are always connected to either one (closer) of the available sinks. Furthermore, the efficient selection is also one of the main reasons for high throughput.

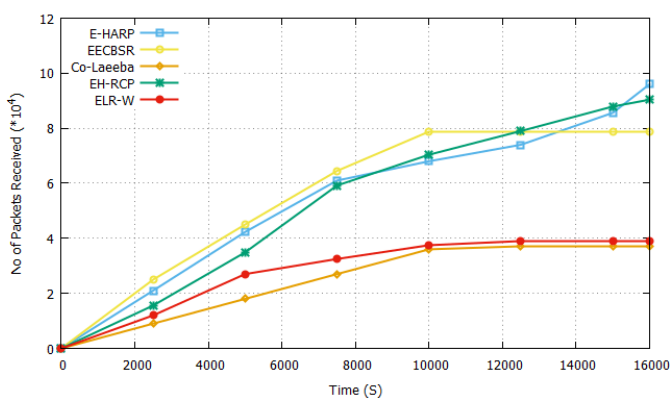

FIGURE 11. Analysis of Network Throughput

E. END-TO-END DELAY

End-to-End Delay is referred as the time taken by a data packet to travel from source node to destination node. Or it can be defined as the time a first bit of the data packet

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from the source node is put on the transmission medium to the time the last bit received on the destination node. One of the main goals in the networks such as WBANs is to minimize the end-to-end delay. As WBANs are normally used in medical/health related applications therefore, the data sensed by the SNs may be critical in nature and hence needs to be transferred to the destination system quickly. Keeping in view the importance of end-to-end delay parameter, E-HARP is designed with the intention to minimize this delay. Simulation results, which are shown in Figure 12 and data listed in Table 9, attest that E-HARP achieves overall minimum end-to-end delay as compared to other compared protocols. It can be viewed in the achieved results, that the end-to-end delay of the proposed protocol is high (i.e. 515 milli seconds) in early stages as compared to other compared protocols but in later stages, this delay gets minimized. One of the reasons of high end-to-end in early rounds is due to the intense calculation used for the finding the optimal CH and cluster formation. The achieved results from the calculation/estimation in early rounds are used in later stages and no further intense calculation/estimation is done in later rounds, therefore the performance of the proposed protocol is improved in terms of end-to-end delay. One of the other reasons of low end-to-end delay is due to the presence of dual sinks on the human body, which minimizes the distance between the SNs and the sink node. The clustering mechanism also helps in minimizing the end-to-end delay, because the load of the whole network is reduced on the single sink and only the specified cluster members communicate with the sink node.

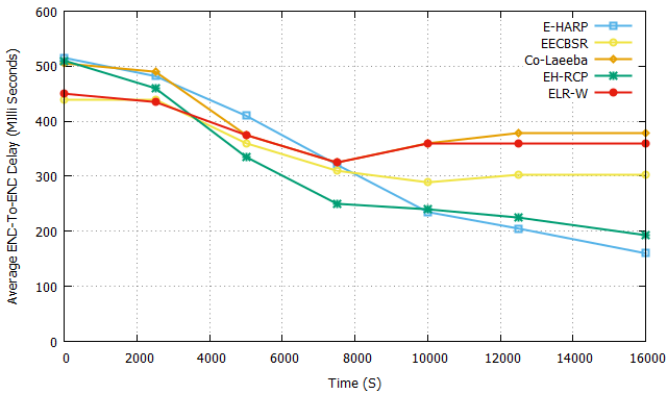

FIGURE 12. Analysis of End-to-End Delay

VI. CONCLUSION AND FUTURE WORK

In this research paper, an Energy-efficient Harvested-Aware clustering and cooperative Routing Protocol for WBAN (E-HARP) is presented. This protocol mainly proposes two mechanisms to improve the performance of WBANs i.e. selection of dynamic CH among the cluster members and the mechanism which omits the transfer of redundant data sensed by SNs in successive transmission rounds. The main goal of this research work is to enhance the network life-time, stability, throughput and end-to-end delay. In order to enhance the network life-time and stability in WBAN, a technique named as energy harvesting is used, which continuously provides energy to the SNs that is generated from the human surrounding (solar energy). Furthermore, dual sinks are used which help to cover the path-loss issue and also balances the network load. In order to distribute the network load evenly, E-HARP uses the concept of CH inside the cluster. The CH is selected on the basis of Cost Factor which uses multiple attributes such as link SNR, total current energy of the SN, total network energy loss and required transmission power. To further enhance the network performance, E-HARP uses cooperative effort mechanism in SN, in which the redundant/similar data from the consecutive transmission rounds is ignored and not forwarded to the CH or sink. This saves the bandwidth of the overall network and also reduces the load on the CH and sink and ultimately improves the performance of the overall network. The presented protocol is compared with some state-of-the art protocols named as EH-RCP, Co-Laeeba, EECBSR and ELR-W. The compared results show that E-HARP outperforms the compared protocols in terms of network life-time, network stability, throughput, and end-to-end delay. It is planned to implement the proposed protocol in real platform of WBAN in future and get the real time performance data.

TABLE 9. Average End-to-End Delay vs. Time

S. No	Protcol Name	Total end-to-end delay at different interval of time (milli sec)						
		0s	2500s	5000s	7500s	10000s	12500s	16000s
1	E-HARP	515	482	410	321	235	205	160
2	EH-RCP	510	460	335	250	240	225	193
3	Co-LAEEBA	505	490	375	325	360	378	-
4	EECBSR	450	435	375	325	360	-	-
5	ELR-W	440	440	360	310	289	302	-

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