Received May 10, 2020, accepted May 25, 2020, date of publication May 29, 2020, date of current version June 10, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2998452

A Centralized Cluster-Based Hierarchical Approach for Green Communication in a Smart Healthcare System

GUOJIE YANG[1], MIAN AHMAD JAN[2,3], (Senior Member, IEEE), VARUN G. MENON[4], (Senior Member, IEEE), P. G. SHYNU[5], (Member, IEEE), MIAN MUHAMMAD AIMAL[6], AND MOHAMMAD DAHMAN ALSHEHRI[7], (Member, IEEE)

[1]Affiliated Hospital of Hebei University, Hebei University, Baoding 071000, China
[2]Informetrics Research Group, Ton Duc Thang University, Ho Chi Minh City 758307, Vietnam
[3]Faculty of Information Technology, Ton Duc Thang University, Ho Chi Minh City 758307, Vietnam
[4]Department of Computer Science and Engineering, SCMS School of Engineering and Technology, Ernakulam 683576, India
[5]School of Information Technology and Engineering, Vellore Institute of Technology, Vellore 632014, India
[6]Network Research Center, Virtual University Islamabad, Islamabad 44100, Pakistan
[7]Department of Computer Science, College of Computers and Information Technology, Taif University, Taif 21974, Saudi Arabia

Corresponding author: Mian Ahmad Jan (mianjan@tdtu.edu.vn)

ABSTRACT The emergence of the Internet of Things (IoT) has revolutionized our digital and virtual worlds of connected devices. IoT is a key enabler for a wide range of applications in today's world. For example, in smart healthcare systems, the sensor-embedded devices monitor various vital signs of the patients. These devices operate on small batteries, and their energy need to be utilized efficiently. The need for green IoT to preserve the energy of these devices has never been more critical than today. The existing smart healthcare approaches adopt a heuristic approach for energy conservation by minimizing the duty-cycling of the underlying devices. However, they face numerous challenges in terms of excessive overhead, idle listening, overhearing, and collision. To circumvent these challenges, we have proposed a cluster-based hierarchical approach for monitoring the patients in an energy-efficient manner, i.e., green communication. The proposed approach organizes the monitoring devices into clusters of equal sizes. Within each cluster, a cluster head is designated to gather data from its member devices and broadcast to a centralized base station. Our proposed approach models the energy consumption of each device in various states, i.e., idle, sleep, awake, and active, and also performs the transitions between these states. We adopted an analytical approach for modeling the role of each device and its energy consumption in various states. Extensive simulations were conducted to validate our analytical approach by comparing it against the existing schemes. The experimental results of our approach enhance the network lifetime with a reduced energy consumption during various states. Moreover, it delivers a better quality of data for decision making on the patient's vital signs.

INDEX TERMS Green IoT, patient monitoring system, cluster-based hierarchical routing, cluster head, energy-efficiency.

I. INTRODUCTION

Internet of Things (IoT) allows the connectivity of physical devices to the Internet for gathering data about the real-world happening events [1]. These devices collect and exchange the gathered data among each other with little human intervention. These networks are used in an increasing number of applications to facilitate human beings with better facilities. The ubiquitous connectivity and large-scale deployment of these networks are hindered by the limited energy supply of their sensor-embedded operational devices [2]. Green IoT emphasizes on the need to preserve the energy of these devices for better and prolonged operations of the underlying applications [3]. It allows the devices to conserve energy during sensing, computation, transmission, data aggregation, and fusion. An increasing number

The associate editor coordinating the review of this manuscript and approving it for publication was Zhenyu Zhou.

of applications, e.g., smart healthcare, smart farming, smart city, and industrial automation rely on green communication to prolong their network lifetimes [4].

The smart healthcare systems use green communication to monitor the vital signs of patients in real-time with the least energy consumption [5]. Because of their patient-centric approach, these systems have found their applications in hospitals, nursing care, and in-home patient monitoring. With the outbreak of various chronic diseases, e.g., COVID-19, the role of smart healthcare systems for its mitigation and control cannot be ignored. This virus itself is highly infectious and can quickly spread at a fast pace. In this scenario, even health practitioners are at risk of being infected with minor negligence. Smart healthcare systems can effectively monitor the infected patients with health practitioners examining the gathered data from their desktops at the hospital or even at their homes [6]. Besides, these systems are intelligent enough and are capable of being instructed via commands, queries, and control signaling. The practitioners can guide the implanted devices on a patient to gather the type of data required by them.

In these systems, each monitoring device is equipped with several central and peripheral units, e.g., medical sensor, actuator, transceiver, buffer, battery, and microcontroller [7]. These units are used to sense the underlying health conditions of a patient for vital signs monitoring, processing of these signs for feature extraction, storage of the processed data, and upstream transmission towards the base station or cloud data centers [8]. The battery unit provides the required power level for the functioning of each component of the device. However, the battery itself has limitations imposed on its resources. The devices have limited battery power, and as such, the available power needs to be utilized efficiently and in an intelligent manner. Efficient utilization of battery power prolongs the lifetime of these networks, and at the same, provides seamless transmission of vital signs of a patient [9]. In these networks, increasing the battery size of devices is not a viable alternative as it will increase the cost and weight [10]. The devices need to be cost-efficient for wider deployment and enhanced coverage of the monitored region. An increase in weight will create bulky systems that affect the mobility of devices.

In smart healthcare systems, the patient monitoring devices consume a varying amount of energy in different states, i.e., sleep, awake, active, and idle [11]. As a result, a state-based scenario is required to model the energy consumption of these devices to analyze their behavior. For this purpose, Medium Access Control (MAC) and cluster-based routing protocols have been investigated in the literature. The MAC layer protocols [12] ensure the operation of these devices with minimal duty cycling. These protocols reduce energy consumption by keeping the transmitter in idle or sleep state. As a result, the transmission delay is minimized, and at the same time, the network throughput and lifetime are maximized. These protocols have an essential role in energy conservation as they control the main sources of energy wastage, i.e., packet collision, overhearing, control packet overhead, and idle listening. MAC protocols are classified as either schedule-based [13]–[15] or contention-based [16]–[18]. In the case of contention-based protocols, e.g., Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA), the devices compete with each other to access the transmission channels for data communication. They are scalable, and at the same time, do not impose strict time-synchronization on the resource-starving devices. However, they incur excessive overhead and keep the devices wait for longer than expected. The sensitivity of a patient's vital signs requires immediate transmission to the healthcare personnel. Schedule-based protocols, on the other hand, uses Time Division Multiple Access (TDMA) for efficient utilization of the transmission medium. These protocols reduce collision, overhearing, and idle listening; however, they incur excessive waiting on the part of monitoring devices.

Cluster-based hierarchical routing protocols, on the other hand, have attracted significant research in recent years for various healthcare applications [19]–[21]. These protocols operate at the network layer and are highly scalable, adaptable, self-configurable, and have the ability of self-healing [21]. These unique features make them an ideal option for adaptation in smart healthcare environments because the patient's vital signs cannot tolerate network connectivity issues, require fault-tolerant features, and, at the same time, demand a higher level of QoS. These protocols organize health monitoring devices into groups, which are known as clusters [22]. In each cluster, one single device is designated to collect data from all other devices. The former is known as cluster head, and the latter as member devices. These protocols support two modes of communication [23]: Intra and inter. In intra-cluster communication, the devices can only communicate with their designated cluster head, as shown in Fig. 1. Inter-cluster communication, on the other hand, allows communication between the devices in two or more clusters. However, the communication must be routed through the cluster heads. In literature, inter-cluster communication mainly focuses on cluster head-to-cluster head communication between two different clusters.

Inspired from the distinguishing features of a cluster-based hierarchical approach, in this paper, we present an energy-efficient technique for patient monitoring in a smart healthcare environment. The significant contributions of our work are as follows.

- We formulated the energy consumption of a health monitoring device in various states. We also evaluated the energy consumption during the states' transitions. For this purpose, we have proposed a novel energy state model that carefully compute the energy consumption during various states and their transitions.
- We presented a centralized cluster-based hierarchical routing protocol for a patient monitoring system. Unlike the existing approaches, our protocol is centralized in nature, and the base station makes the decision about cluster head election. This transfer of control from nodes

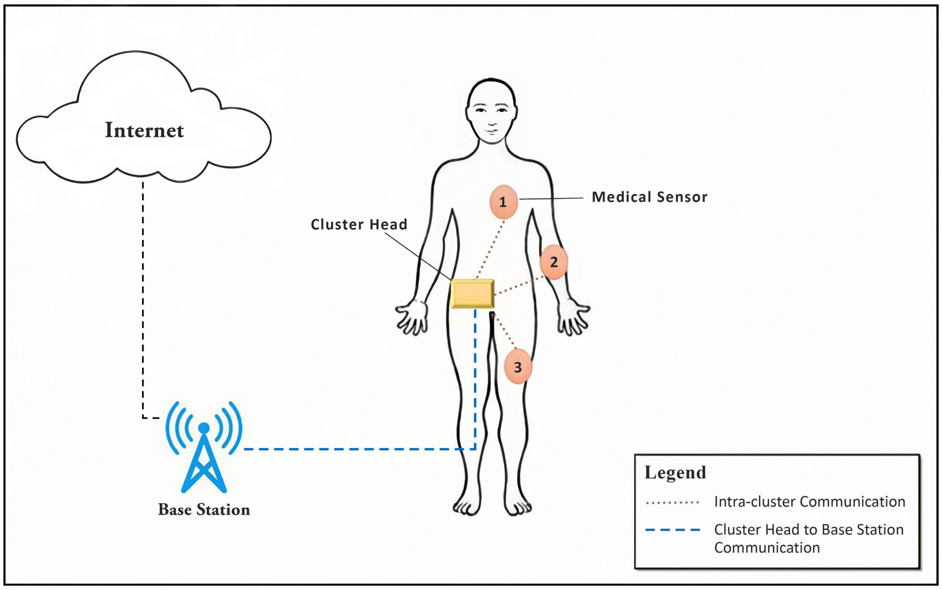


FIGURE 1. **Cluster-based communication in a smart healthcare system.**

to the base station ensures that the overall energy of the network is utilized efficiently.

- We compute the energy consumption of various devices in the network based on their run-time operational behavior. We considered numerous metrics and criteria for this purpose.

The rest of this paper is organized as follows. In Section II, we present the energy state model of a patient monitoring device. In Section III, we present our centralized cluster-based routing approach for seamless and green communication in a smart healthcare system. Section IV validate the proposed approach via experimental results. Finally, the paper is concluded, and future research directions are provided in Section V.

II. ENERGY STATE MODEL OF A PATIENT MONITORING DEVICE

The energy consumption of a health monitoring device in various states is shown in Fig. 2. A number of such devices are implanted on a patient body to monitor vital signs. Initially, the device fetches and executes various instructions to transform itself into an awake state. It dissipates a considerable amount of energy during this transition because the instruction set requires ample amount of memory space due to a larger code size. Moreover,its memory unit needs to be continuously queried for fetching and executing these instructions. Similar to other sensor nodes, the medical monitoring device wakes up periodically or at some predefined threshold parameters by broadcasting a base beacon message with no backoff field [24]. However, it cannot stay awake all the time due to restrictions on its available resources. The transition to an awake state enables it to prepare itself for reception or transmission of data. The device switches to an active state and continuously senses data of the patient. Upon capturing an event of interest, it is processed for extracting valuable information. These processed events are either transmitted to the neighbouring device or stored locally to enable it in performing various tasks such as route maintenance, neighbourhood discovery, redundancy checking and data fusion. All these operations are performed in an active state. After performing the resource-intensive tasks in an active state, the device switches to an idle state. During this state, it remains inactive and no longer performs any task. However, in idle state, a small amount of residual energy is still consumed due to the leakage of current [25]. In order to preserve energy, relevant circuitry of the device need to be switched off during this state.

The energy consumption of the patient monitoring device i in different states and transitions is shown in Equ. 1

$$E_i(\delta t) = \sum_{c=1}^{N_c} \sum_{s \in S} \sum_{st \in ST} C(e_{c,s},\ e_{c,st},\ t_{c,s}). \tag{1}$$

In this equation, N_c is the total number of units of this device and C represents the individual units, where $C \in N_c$ and $N_c = \{P_c, M_c, S_c, TR_c\}$. Here, P_c represents the processing unit, M_c represents the memory unit, S_c represents the sensing unit and TR_c represents the transceiver unit. The set of sensor's states is represented by S, where $s \in S$ and $S = \{sleep, awake, idle, active\}$. The set of state transition is represented by ST, where $st \in ST$, and $ST = \{aa, ai, ia, is, sa\}$. Here, aa represents a transition from awake to an active state, ai represents a transition from active to an idle state, ia represents a transition from idle to an active state, is represents a transition from idle to sleep state and sa represents a transition from sleep to an active state. In this

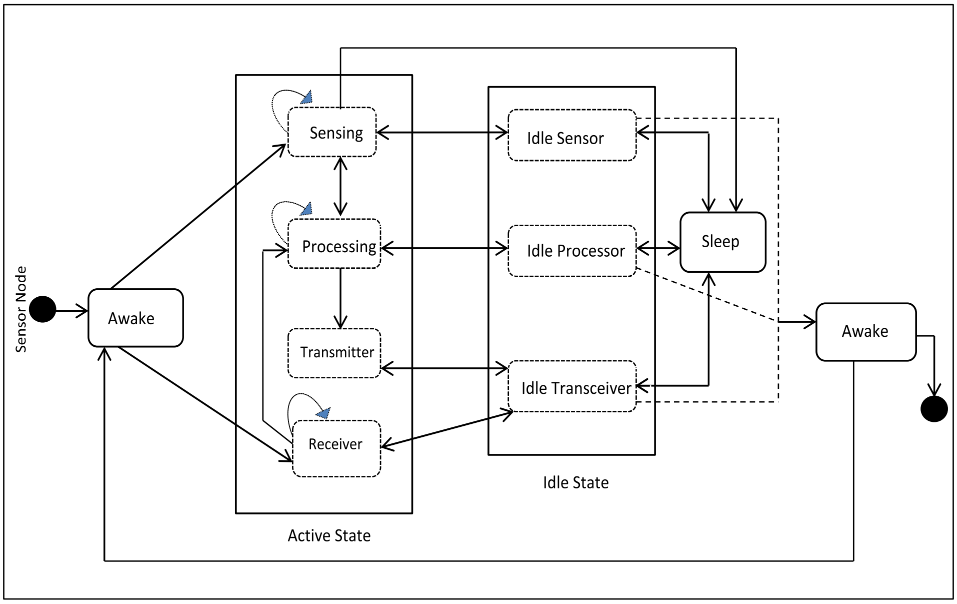


FIGURE 2. Energy consumption of a device in various states.

equation, $e_{c,s}$ represents the energy consumption of unit c in state s, $e_{c,w}$ represents the energy consumption of unit c in state transition w and $t_{c,s}$ defines the duration of states for a unit c.

In smart healthcare systems, energy is consumed not only by the individual states but also by the state transition, i.e., switching from one state to another [26]. As a result, the number of state transitions needs to be reduced without compromising the operation of the device. State transition can be reduced in a number of ways. For example, memory read and write operations need to be performed for multiple packets, i.e., a bulk, rather than a single read and write operation upon an individual packet arrival and departure [27]. State transition can also be reduced if the processor decreases the number of memory queries and increases the number of processed packets sent to a transceiver [28].

III. A CENTRALIZED CLUSTER-BASED ROUTING APPROACH FOR PATIENT MONITORING SYSTEM

Upon energy evaluation of a patient monitoring device in different states and transitions, we present a centralized cluster-based hierarchical routing approach for an underlying smart healthcare network. Our approach can be used by a number of such devices to transmit their gathered data in an efficient way. The proposed approach achieves its objective of data transmission in two phases: set-up and steady-state. The set-up phase has four sub-phases.

- Status
- Cluster Head Selection
- Cluster Formation
- Schedule Creation

During status sub-phase, each sensor device transmits a status message to it's nearest aggregator device before the start of a particular round. This message has an 8 bit source's identity (ID), 8 bit destination's identity (ID) and a variable-length residual energy field. The source ID is the identity of the transmitter device, whereas, the destination ID is the identity of the nearest aggregator. The frame format of status message is shown in Fig. 3

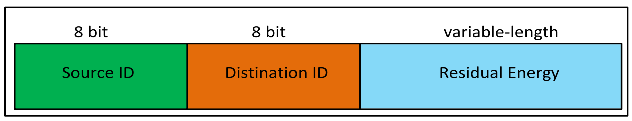


FIGURE 3. Frame format of a status message.

Each aggregator accumulates multiple status messages from its neighbouring medical devices and broadcast a single message to the base station. Upon transmission, each aggregator goes to sleep mode until the beginning of next round. The base station retrieves the source ID and residual energy from each status message and stores locally within a queue. It then calculates the average residual energy ($E_{average}$) using Equ. 2.

$$E_{average} = \sum_{j=1}^{n} (\frac{E_j}{n}). \tag{2}$$

Here, E_j represents the residual energy of the medical device, and n denotes the total number of such devices. In our network model, the value of n is 100.

Upon the completion of status sub-phase, cluster head selection is initiated. During this phase, the base station elects an optimal number of cluster heads and maintains them in a buffer as shown in Fig. 4. The cluster heads are selected among the medical devices based on their energy levels. Any device that has E_j greater than $E_{average}$ becomes eligible to be

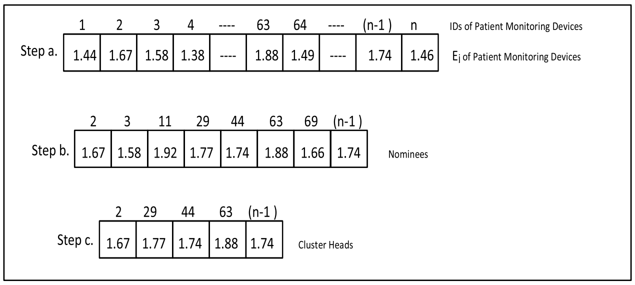


FIGURE 4. Nominee and cluster head election.

elected as cluster head. In Fig. 4, the value of $E_{average}$ is equal to 1.5 joule for the current round. There is a high probability of having a large number of devices that have E_j greater or equal to $E_{average}$ in the current round. The problem is that all these devices cannot be elected as cluster heads. Thus, we use the term nominee to represent all such devices. The nominees are the possible candidates for cluster heads. If two or more nominees are co-located in the neighborhood of each other, then such nominees are evaluated according to their residual energy values and their election as cluster heads based on their election as cluster heads in the past $\frac{1}{k_{opt}}$ rounds. This election criteria of cluster head is inspired from our previous work [29]. In our network model, we have bounded the optimal percentage of cluster heads as 5% to 10% of all devices in any given round.

Among the nominees, i.e., candidates of Fig. 4, devices 2, 3 and 11 reside in one cluster, whereas, devices 63 and 69 reside in another cluster, as shown in Fig. 5. However, each cluster is restricted to only one cluster head. It means that one among these candidates needs to be elected as cluster head. Among devices 2, 3 and 11, device 11 has the highest E_j, however, this device was previously elected as cluster head in the past $\frac{1}{k_{opt}}$ rounds which makes it ineligible for the current round. The elimination of device 11 from cluster head election paves the way for device 2 and 3 as the possible nominees for cluster head in the current round. Device 2 takes preference over 3 for cluster head election because the former has higher E_j and has not been elected as cluster head in the past $\frac{1}{k_{opt}}$ rounds. In the second cluster, the election procedure is rather straightforward. Device 63 has a higher E_j than 69. Furthermore, the former has not been elected previously over the past $\frac{1}{k_{opt}}$ rounds.

We used the term *cluster* while referring to Fig. 4 and Fig. 5 for clarity and simplification purposes. In reality, there is no such thing like cluster at the time of evaluating E_j by the base station. Once the base station performs the evaluation of residual energy of each device, only then the cluster head election takes place and the formation of cluster is initiated. Perhaps, *region* will be a better term in this context because, initially all these medical devices reside in one or more regions of the deployed field.

The cluster head election is a complex resource-intensive task that incurs high processing overhead and network delay. As a result, the monitoring devices and aggregators remain

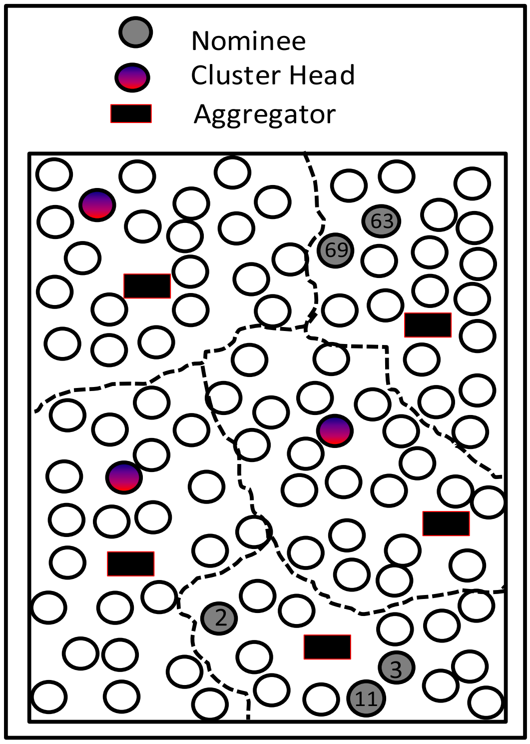


FIGURE 5. Cluster head selection.

inactive to conserve their energy. Once an optimal number of cluster heads are elected for the current round, the base station transmits a message to each device. This message contains ID of each patient monitoring device and ID of its respective cluster head. At this point of time, there are two types of operational devices within the network: cluster heads and patient monitoring devices. The latter are those devices that participated in cluster head election but were unable to satisfy the criteria for election. Their residual energy were lower than average threshold energy required as part of the election criteria. The base station assigns a cluster head to each patient monitoring device in order to form a group, known as cluster. In other words, the geometry of a cluster has two types of devices: a cluster head and multiple patient monitoring devices. The latter senses the patient data and transmit to its respective cluster head. The patient monitoring devices are the member nodes of a given cluster head within each cluster. The formation of a cluster around each cluster head signals the end of cluster formation sub-phase. The direct association of a member node with its respective cluster head enhances the network lifetime because a cluster head is no longer required to advertise itself. Moreover, the member node, i.e., patient monitoring device, avoids the transmission of join-request messages to its respective cluster head.

The completion of cluster formation initiates the schedule creation phase. During schedule creation, every cluster head allocates TDMA slots to its patient monitoring devices, i.e., member devices, that allow the latter to transmit their data using these slots. Furthermore, the creation of schedule allows the member devices to remain inactive and periodically wake up to gather data and transmit using their assigned slots. The assignment of TDMA slots signals the end of set-up phase.

Upon completion of set-up phase, the member devices gather a patient data and transmit to their respective cluster heads. This is the steady-state phase of our proposed centralized routing approach for patient monitoring. During steady-state phase, each member device collects the patient data according to a predefined condition and transmits to its designated cluster head, using its assigned TDMA slot. When all the member devices within each cluster have transmitted their data, the cluster head performs necessary signal processing to eliminate redundant data packets. Because multiple cluster heads are involved during this process, it would be a resource-consuming task if all the member devices transmit their gathered data directly to a base station. To reduce their energy consumption, the cluster head with highest energy among it's peers is selected as a leader, shown by Fig. 6. The leader collect data from each cluster head and broadcast to the base station on their behalf. The whole procedure is shown in the Algorithm 1.

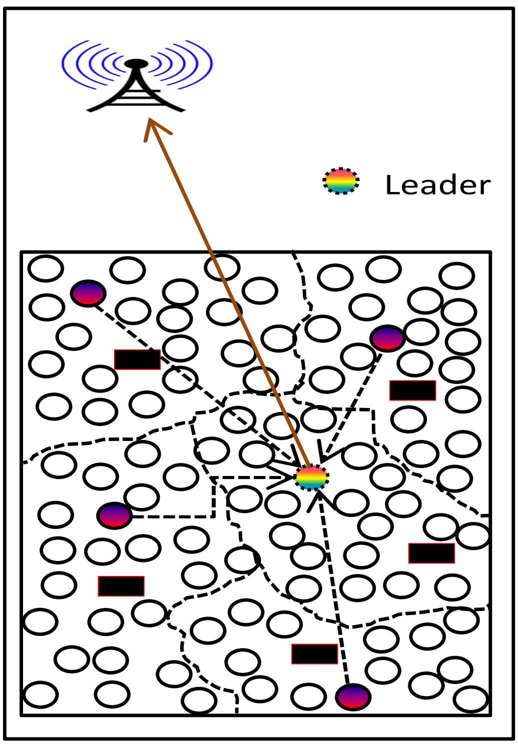


FIGURE 6. **Data transmission to a base station.**

The leader performs further aggregation to eliminate redundant patterns and transmits highly refined data to the base station. The task performed by a leader is resource-consuming, and as a result, the cluster heads take turn to become leader in consecutive rounds. Once the leader performs its task of data offloading to the base station, steady-state is accomplished. During each round, these two phases

Algorithm 1 Green Communication for Smart Healthcare System

Initialization: E_j, n ▷ n is the number of devices
Input: E_j

procedure
  BS compute $E_{average}$ and retrieves E_j ▷ Set-up phase
  if $Ej > E_{average}$ **then**
   j is a nominee
  else
   j is patient monitoring device
   Sleep & wait for Cluster Head announcement
  end if
  if multiple nominees in the same region **then**
   if j was elected in previous $1/k_{opt}$ rounds **then**
    j is not illegible for current round
  go to to sleep state
   else
    Wait for the nomination packet
    i is a cluster head
  end if
  if j receives announcement from i **then**
   j sends Join-Request message to elected i
   i forms cluster ▷ Upon receiving Join-Request message from j
  end if
  i collects data from member devices ▷ Steady-state phase
  l delivers data to Base Station ▷ Leader $l \in i$
end procedure

are performed: set-up and steady-state. In cluster-based routing protocols, a round is measured in terms of time required to perform control signaling and data transmission. Set-up deals with control signaling and steady-state deals with data transmission. The complete set of operations performed during each round is shown in the flowchart of Fig. 7.

A. ENERGY EVALUATION MODEL OF THE NETWORK

Both set-up and steady-state phases are resource-consuming tasks and need to be dealt with utmost care to model the energy of each device. The amount of energy consumed by each individual device differs and depends on its operational behavior at a given time. Besides, the energy consumption depends on the distance metric between the member device and its cluster head. In this section, we present the energy evaluation model of each device in various states of our network. We considered patient monitoring member device, cluster head and the aggregator for this purpose as these are the three main devices in our underlying network.

At the time of transmitting the status messages, the patient monitoring device broadcast its location, residual energy and identities. The energy consumption during the status

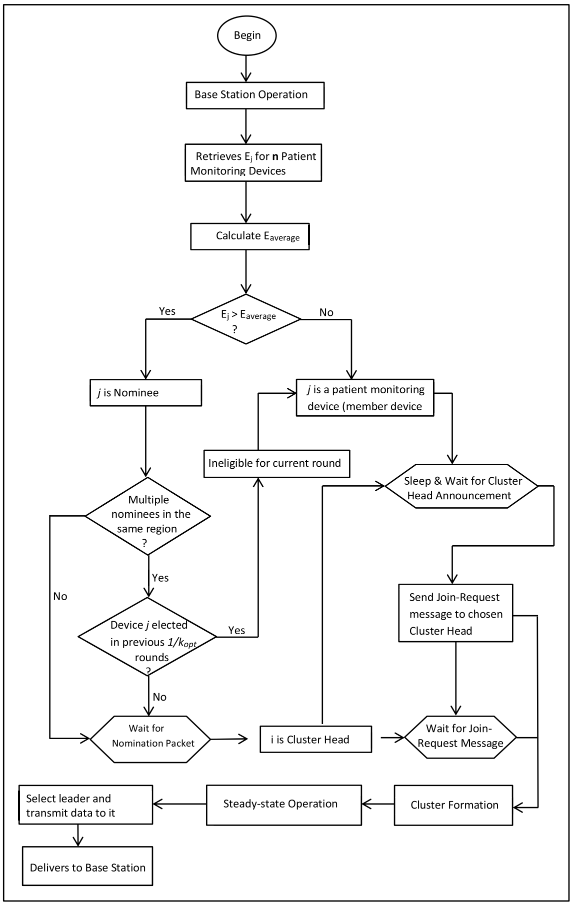


FIGURE 7. Flowchart of set-up and steady-state phases.

sub-phase (E_{status}) is computed using Equ. 3.

$$E_{status}(m, d) = mE_{elec} + m\epsilon_{fs}d_{HEN}^2, \quad d_{HEN} < d_c. \tag{3}$$

In this equation, d_{HEN} represents the distance of a monitoring device from its nearest aggregator and m is the message size. Here, E_{elec} denotes the energy consumed by the device in processing the data gathered from a patient and ϵ_{fs} is its energy consumption while transmitting the gathered data to the aggregator. The aggregators are high energy devices as compared to cluster heads and patient monitoring devices. They are expected to stay alive longer due to their highly-resource intensive operations of gathering status messages from all the devices in the field. Lastly, d_c represents the crossover distance [30] between the monitoring device and the aggregator. It is approximately equal to 87m, and $d_{HEN} < d_c$ decides the type of model to be used, either free-space or multipath ground propagation [29], [31].

Each aggregator receives status messages from a number of neighboring monitoring devices. They aggregate the gathered data, fuse it, and broadcast to the base station. In this context, the energy consumption of aggregator is pivotal for the network operation. During the status sub-phase, the energy consumed by an aggregator (E_{HEN}) is computed using Equ. 4.

$$E_{HEN}(m, d) = \begin{cases} mE_{elec}x + m\epsilon_{fs}\, d_{BS}^2, & d_{BS} < d_c, \\ mE_{elec}x + m\epsilon_{mp}\, d_{BS}^4, & d_{BS} \geq d_c. \end{cases} \tag{4}$$

Here, x is a subset of monitoring member devices that communicate with a particular aggregator, $\forall\, x \in n \wedge x < n$. In this equation, d_{BS} represents the distance between an aggregator and the base station. If the base station is located at a distance greater than d_c, multipath model is used for communication, otherwise, free-space model is utilized.

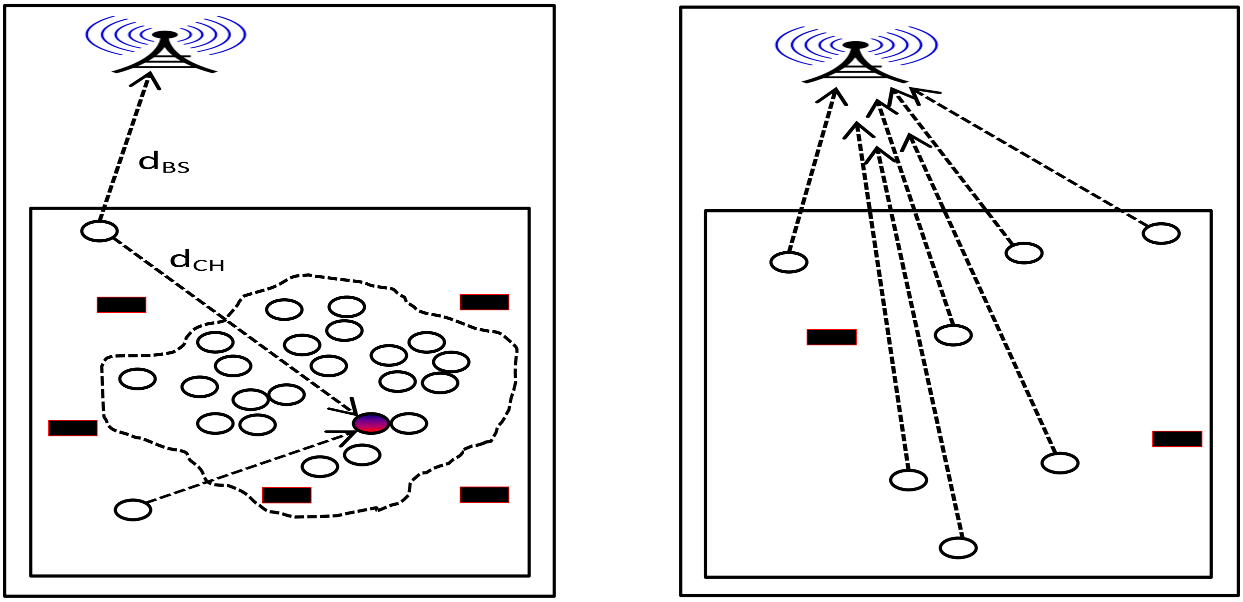
The base station elects an optimal number of cluster heads and advertise them in the network. Upon election, each cluster head gather data from its monitoring member devices, perform fusion and broad to base station. The amount of energy consumed by each cluster head (E_{CH}) is computed using Equ. 5.

$$E_{CH}(m, d) = \begin{cases} mE_{elec}(\frac{n}{k_{opt}}) + mE_{DA}(\frac{n}{k_{opt}}) + \\ m\epsilon_{fs}d_{LN}^2, \quad d_{LN} < d_c, \\ mE_{elec}(\frac{n}{k_{opt}}) + mE_{DA}(\frac{n}{k_{opt}}) + \\ m\epsilon_{mp}d_{LN}^4, \quad d_{LN} \geq d_c. \end{cases} \tag{5}$$

In this equation, k_{opt} denotes the optimal number of cluster heads [32], [33]. The number of cluster heads and clusters are always equal because there is always one cluster head per cluster. Here, d_{LN} denotes the distance of a cluster head from its leader. Recall that a leader is one of the cluster head that has the highest energy among all.

Our proposed approach achieves equal-sized clusters using the balanced-clustering approach [34]. It means that each cluster has the same number of patient monitoring devices. The location of these devices are known to the base station and the latter always elect cluster heads that were not previously elected in k_{opt}. Besides, the elected cluster heads are always nearer and easily accessible to the monitoring devices. We have considered a network size of 100. Using balanced-clustering approach, there are always 20 nodes in each cluster. Based on this calculation, the optimal value of k_{opt} is 5 for our network. Balanced-clustering ensures that our proposed approach forms equal-sized clusters in which the load is uniformly distributed on the cluster heads. The rotation of cluster heads in each round distribute the load uniformly on all monitoring devices. Hence, this approach enhances the lifetime of the network. Each cluster head performs data processing, data aggregation, and data transmission to the leader. It means that a given cluster head consumes energy while processing (E_{elec}), aggregation (E_{DA}) and transmission ($\epsilon_{mp}/\epsilon_{fs}$).

In Equ. 5, each cluster head only performs data processing, data aggregation and data transmission to a leader. They were not assumed to sense data within their respective clusters, a role similar to the member devices. In case, if each cluster head monitors the patient as well, their energy consumption will be much higher. This is mainly because they will not only gather, process, aggregate and transmit data from member



(a) Isolated Nodes

(b) Insufficient Nodes to Form Clusters

FIGURE 8. Energy consumption in different scenarios.

devices, but similar functionalities for its own collected data need to be performed. Recall that each cluster head is one of the patient monitoring member device. The only difference is that it has higher energy among its peers within its neighborhood, in that particular round. If each cluster head monitors the patient for data collection, then its energy consumption can be calculated using Equ. 6.

$$E_{Sensing-CH}(m,d) = \begin{cases} \alpha I + mE_{elec}(\frac{n}{k_{opt}}) + mE_{DA}(\frac{n}{k_{opt}}) \\ +m\epsilon_{fs}d_{LN}^2, \quad d_{LN} < d_c, \\ \alpha I + mE_{elec}(\frac{n}{k_{opt}}) + mE_{DA}(\frac{n}{k_{opt}}) \\ +m\epsilon_{mp}d_{LN}^4, \quad d_{LN} \geq d_c. \end{cases} \tag{6}$$

Here, α represents the energy consumption of a cluster head while sensing one bit of data, and I denotes the total number of such bits within the data.

The energy consumption by a member device, i.e., patient monitoring device (E_{member}) within its cluster is computed using Equ. 7.

$$E_{member} = \alpha I + mE_{elec} + m\epsilon_{fs}d_{CH}^2, \qquad d_{CH} < d_c. \tag{7}$$

In this equation, d_{CH} denotes the distance of a member device from its cluster head. Since, the member device is located in vicinity of cluster head, free-space propagation model is an obvious choice because $d_{CH} < d_c$ is always true for their communication.

Upon data collection from their member devices, the cluster heads do not broadcast the gathered data directly to base station. Rather they elect one among themselves as leader to represent all the cluster head. The leader gathers the data from each cluster head, aggregate it, and broadcast to base station. Leader nodes are always rotated in each round to balance the energy utilization and distribute the load uniformly among the elected cluster heads in subsequent rounds. The energy consumption of a leader (E_{LN}) is computed using Equ. 8.

$$E_{LN}(m,d) = \begin{cases} mE_{elec}(\frac{n}{k_{opt}}) + mE_{DA}(\frac{n}{k_{opt}}) + mE_{DA} \\ (\sum_{i=1}^{k_{opt}-1} CH_i) + m\epsilon_{fs}d_{BS}^2, \quad d_{BS} < d_c, \\ mE_{elec}(\frac{n}{k_{opt}}) + mE_{DA}(\frac{n}{k_{opt}}) + mE_{DA} \\ (\sum_{i=1}^{k_{opt}-1} CH_i) + m\epsilon_{mp}d_{BS}^4, \; d_{BS} \geq d_c. \end{cases} \tag{8}$$

Here, d_{BS} denotes the distance of a leader from the base station. In each round, the energy of a leader is consumed in data processing, data aggregation and data transmission to the base station. Besides, the leader itself is a cluster head, so it consumes a considerable amount of energy while aggregating the gathered data of its own member devices. In this equation, CH_i denotes the remaining cluster heads from whom the leader gather the data.

In any given round, one or perhaps more member devices may be located farthest from their nominated cluster heads. In this case, the member device may choose not to join this cluster head. Rather, it may broadcast its gathered data directly to base station as this approach is more energy-efficient. Neither it has to wait for its allocated TDMA slot nor it has to perform set-up operations. In Fig. 8a, we have represented this type of scenario. If the devices choose to transmit directly to the base station, such devices are known as isolated devices and in fact, a very common practice in smart healthcare infrastructures, e.g. telemetry or an Intensive Care Unit (ICU). The energy consumption of isolated nodes ($E_{isolated}$) can be computed using Equ. 9.

$$E_{isolated}(m, d) = \begin{cases} mE_{elec}+m\epsilon_{fs}d_{BS}^{2}, & d_{BS} < d_c < d_{CH}, \\ mE_{elec}+m\epsilon_{mp}d_{BS}^{4}, & d_c \leq d_{BS} < d_{CH}. \end{cases} \tag{9}$$

In this equation, d_{BS} denotes the distance of an isolated device from the base station, and d_{CH} denotes its distance to a cluster head located in its vicinity. An isolated device can only transmit its gathered data directly to base station without the intervention of cluster head when $d_{BS} < d_{CH}$.

In smart healthcare systems, there are very few devices that are still capable of data transmission towards the base station, towards the end of network lifetime. Most of the devices deplete their energy while performing the resource-intensive operations during various states within the setup and steady-state phases. Due to the lowered number of alive devices towards the end of network lifetime, cluster formation becomes extremely difficult. In this case, a member device is left with no other choice but to transmit gathered data directly towards the base station, as depicted by Fig. 8b. We call this state as *End State*. In this state, the energy consumption of each device (E_{end}) is formulated using Equ. 10.

$$E_{end}(m, d) = \begin{cases} mE_{elec} + m\epsilon_{fs}d_{BS}^{2}, & d_{BS} < d_c, \\ mE_{elec} + m\epsilon_{mp}d_{BS}^{4}, & d_{BS} \geq d_c. \end{cases} \tag{10}$$

After formulating the energy consumption of the devices in various states and phases, we calculate the energy consumption in a particular round (E_{round}), using Equ. 11.

$$E_{round} = E_{status} + E_{HEN} + E_{CH} + E_{member} + E_{LN} + E_{isolated}. \tag{11}$$

E_{round} represents the energy consumption in one complete round. It comprises the energy consumed in the set-up and steady-state phases. During these two phases, E_{status}, E_{HEN}, E_{CH}, E_{member}, E_{LN}, and $E_{isolated}$ are involved. E_{round} is calculated towards the end of network lifetime because among all the parameters of this equation, $E_{isolated}$ is the only parameter that can only be calculated toward the end of network lifetime. In the early stages of network operation, E_{round} does not comprise $E_{isolated}$ because the network is fully operational and balanced clusters are formed easily due to sufficient number of cluster heads in each round.

Finally, the total amount of energy consumption (E_{Total}) over the period of time, i.e., network lifetime, is computed using Equ. 12.

$$E_{Total} = \sum_{i=1}^{i=r} E_{round} + \sum_{i=1}^{i=r} E_{end} \tag{12}$$

In this equation, r represents the total number of rounds over which the network remains operational. When there are one or more clusters within a network, E_{round} is the end result. However, towards the end of network lifetime, there are hardly enough devices to create one or more balanced clusters in any round and the end result is E_{end}. The sum of E_{round} and E_{end} denotes the total energy consumed by the patient monitoring devices and aggregators during their lifetime.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

In this section, we present the experimental results of our proposed centralized cluster-based approach for patient monitoring system. We compared our approach against LEACH and DEEC algorithms by analyzing various simulation metrics. For our experiments, we considered Matlab 2018a with Intel Core i7. The values of various parameters are as follow: E_{elec} is 50nJ/bit, n is 100, ϵ_{fs} is 10pJ/bit/m^2, ϵ_{mp} is 0.0013pJ/bit/m^4, d_c is 87m, k is 500 bytes and r is 10000. Recall that E_{elec} is the energy consumed by electronic component of a patient monitoring device, cluster head, and of the aggregator during data processing, n is the total number of monitoring devices, ϵ_{fs} represents the energy consumed in free-space model by these devices, ϵ_{mp} denotes the energy consumption in multipath model and d_c is the crossover distance between the nodes. Moreover, the size of each message containing data of a patient is represented by k. Finally, r is the total number of rounds for which the network remains operational. For comparison, we considered the network lifetime, data aggregation quality of data, and energy efficiency, respectively.

A. LIFETIME OF THE NETWORK

The network lifetime is computed based on two terms: stability and instability periods. Stability period is calculated when the first device of a network runs out of energy. For example, if in round 1000, one of the device completely depletes its energy, the stability period is 1000. Instability period, on the other hand, is the period of time when the last device becomes non-functional. However, in cluster-based routing protocols, instability period is computed from the time when 97% of the devices become non-functional. At this percentage, there are not sufficient devices to form balanced clusters. To compute these two terms, we compared our centralized approach against the state-of-art LEACH and DEEC protocols, in Fig. 9. As the figure shows, our proposed approach has much better stability and instability periods, as compared to the existing approaches.

In our centralized routing approach, the cluster heads are elected by the base station. Besides, the cluster heads are no longer required to advertise themselves in their neighborhood. As a result, the cluster formation consumes no energy on part of the cluster heads. These steps conserve the energy of these resource-constrained devices and at the same time, prolongs the overall network lifetime. There is a tradeoff between the resource-intensive operations of base station and energy consumption by the devices. Apart from cluster heads, the patient monitoring devices are no longer required to transmit join-request messages to the cluster heads for cluster formation. This in turn, conserves their energy and enhances the network lifetime. In comparison, LEACH and DEEC

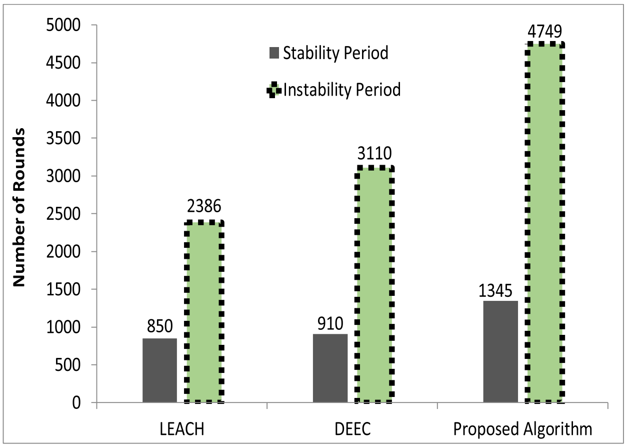


FIGURE 9. Lifetime of the network.

use randomly distributed approach for cluster formation. The cluster heads consume a large amount of their energy in advertising themselves and at the time of cluster formation. The patient monitoring devices, on the other hand, need to send join-request messages. As a result, their energy depletes that deteriorate the overall network lifetime.

B. DATA AGGREGATION

In cluster-based hierarchical smart healthcare system, data aggregation and data fusion are performed at the local and global level, i.e., at the patient monitoring devices and at the cluster heads. The focus of our approach is more on the global level. We calculated the overall data aggregated by the cluster heads over their network lifetime. The efficiency of robust data aggregation at the cluster heads depends on how many packets it received and how many it transmitted to the base station via the leader. An effective data aggregation approach should eliminates all the redundant packets and transmits only highly refined packets. We also calculated the number of packets received by the base station to show the effectiveness of our data aggregation approach at the cluster heads. In Fig. 10, we made a comparison of data aggregation for our proposed algorithm, LEACH and DEEC, respectively.

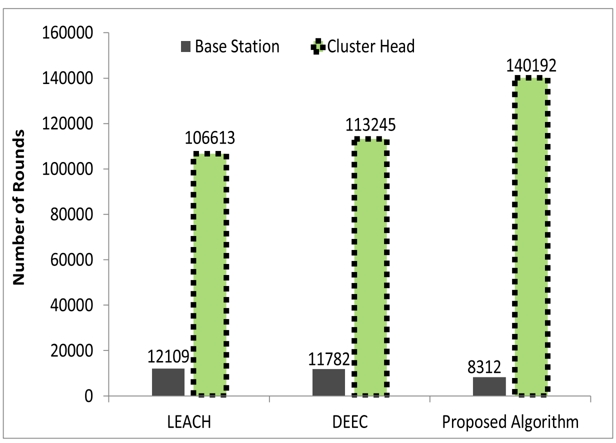


FIGURE 10. Data aggregation.

In our approach, the cluster heads received 140192 packets from the patient monitoring devices over the entire network lifetime. After performing data aggregation and fusion for the elimination of redundant and correlated packets, only 8312 packets were transmitted to the base station. In comparison, the cluster heads in DEEC received 113245 packets from the patient monitoring devices and transmitted 11782 packets to the base station. LEACH, on the other hand, received 106613 packets at the cluster heads and transmitted 12109 packets to the base station. Among all these approaches, ours has the best results in term of data aggregation.

C. QUALITY OF DATA

Quality of data (QoD) is computed as the ratio of sum of all packets received at the base station to the sum of all packets received and processed by the cluster heads. It is calculated as a percentage value and is used to measure the QoS level of a network. However, it is different than QoS because it depends on the results of data aggregation. Better the data aggregation approach, lower will be the number of packets received at the base station, and minimum will be the value of QoD. In Fig. 11, we compared the QoD for our approach in comparison to LEACH and DEEC.

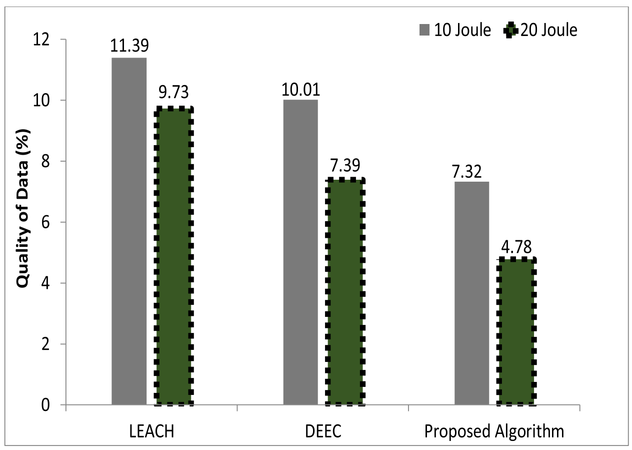


FIGURE 11. Quality of data (QoD).

In this figure, we made a comparison for a network of 100 devices. First we compared the results when each node has 10 joule of energy and then we made a comparison for 20 Joule. The assumption of 10 and 20 joules are in contrary to Fig 4 but there is a logical reason for these energy values. The difference of QoD is much more visible and significant with these values. In case of 10 Joule, the QoD of our proposed algorithm is 7.32%, whereas, DEEC and LEACH have 10.01% and 11.39%, respectively. It means that for every 100 packets, the cluster heads transmit these percentages of packets to the base station after data aggregation and fusion. In case of 20 Joule, the QoD of our proposed algorithm is 4.78%, whereas, DEEC and LEACH have 7.39% and 9.73%, respectively. In either case, our approach is much better in terms of QoD for the underlying network.

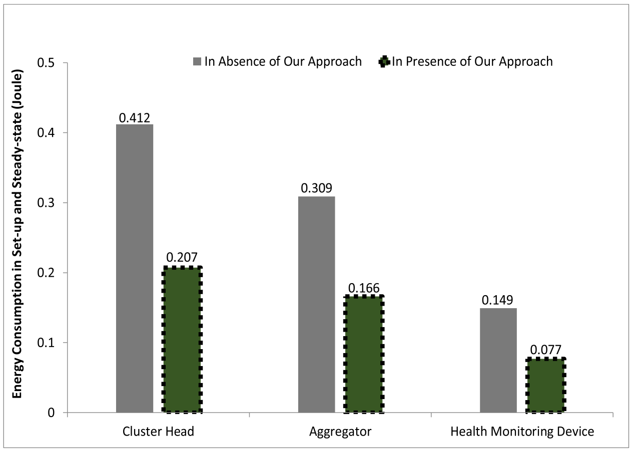


FIGURE 12. Energy consumption in one round: set-up and steady-state.

D. ENERGY CONSUMPTION

Finally, we compute the energy consumption of different devices in one complete round. A round comprises set-up and steady-state phases. A comparison is made in presence and absence of our approach for cluster head, aggregator and patient monitoring devices, i.e., the member device, as shown in Fig. 12. In this figure, each cluster head consumes 0.412 joule of energy in absence of our approach. However, the same cluster head consumes almost half of the energy, i.e., 0.207 joule when our approach of centralized clustering is adopted. Each aggregator, on the other hand, consumes 0.309 joule in absence and 0.166 joule in presence of our approach. The resource-constrained patient monitoring devices, implanted on the patient body, consumes 0.149 joule in absence of our approach and 0.077 joule in presence of our approach. The main reason for the reduction in energy consumption by these devices in any given round is the use of state-based mechanism of our approach. We have modeled these devices so that they consume very small portion of their energy in order to operate over a longer period of time.

V. CONCLUSION AND FUTURE WORK

In this paper, we presented an intelligent green communication approach for monitoring the patients within the smart healthcare system. The proposed approach used a centralized cluster-based hierarchical routing mechanism to partition the health monitoring devices into clusters. Each cluster is administered by a cluster head, which is selected by a centralized base station. The cluster heads are responsible for data collection, scheduling, and data transmission to the base station. They rotate in each round to balance the network load and optimize the efficiency of the underlying devices. The cluster heads themselves experience a significant amount of energy utilization in each round. To conserve their energy, one among them is elected as a leader to transmit data to the base station on their behalf. Our proposed approach administered the energy conservation of devices in various roles, states, and the transition among these states. Each device is modeled as an entity to extract the best out of it in terms of energy utilization. We compare our approach against the existing approaches in terms of network lifetime, amount of aggregated data, the quality of gathered data, and the energy consumption of the underlying medical devices. Our experimental results verify the efficiency of our approach. In the future, we aim to extend our approach by incorporating security primitives in it to make it resilient against various attacks. Besides, we also aim to study the effect of congestion on QoS in both intra-cluster and inter-cluster communication frameworks of our approach.

REFERENCES

[1] G. Mei, N. Xu, J. Qin, B. Wang, and P. Qi, "A survey of Internet of Things (IoT) for geohazard prevention: Applications, technologies, and challenges," *IEEE Internet Things J.*, vol. 7, no. 5, pp. 4371–4386, May 2019.

[2] A. Kumar, M. Zhao, K.-J. Wong, Y. L. Guan, and P. H. J. Chong, "A comprehensive study of IoT and WSN MAC protocols: Research issues, challenges and opportunities," *IEEE Access*, vol. 6, pp. 76228–76262, 2018.

[3] R. Arshad, S. Zahoor, M. A. Shah, A. Wahid, and H. Yu, "Green IoT: An investigation on energy saving practices for 2020 and beyond," *IEEE Access*, vol. 5, pp. 15667–15681, 2017.

[4] J. Ma, S. Shi, S. Gu, N. Zhang, and X. Gu, "Age-optimal mobile elements scheduling for recharging and data collection in green IoT," *IEEE Access*, vol. 8, pp. 81765–81775, 2020.

[5] J. J. P. C. Rodrigues, D. B. De Rezende Segundo, H. A. Junqueira, M. H. Sabino, R. M. Prince, J. Al-Muhtadi, and V. H. C. De Albuquerque, "Enabling technologies for the Internet of health things," *IEEE Access*, vol. 6, pp. 13129–13141, 2018.

[6] J. Arboleda, J. Aedo, and F. Rivera, "Wireless system for supporting home health care of chronic disease patients," in *Proc. IEEE Colombian Conf. Commun. Comput. (COLCOM)*, Apr. 2016, pp. 1–5.

[7] P. G. Vinoj, S. Jacob, V. G. Menon, S. Rajesh, and M. R. Khosravi, "Brain-controlled adaptive lower limb exoskeleton for rehabilitation of post-stroke paralyzed," *IEEE Access*, vol. 7, pp. 132628–132648, 2019.

[8] M. M. Hassan, K. Lin, X. Yue, and J. Wan, "A multimedia healthcare data sharing approach through cloud-based body area network," *Future Gener. Comput. Syst.*, vol. 66, pp. 48–58, Jan. 2017.

[9] O. Amjad, E. Bedeer, N. Abu Ali, and S. Ikki, "Robust energy efficiency optimization algorithm for health monitoring system with wireless body area networks," *IEEE Commun. Lett.*, vol. 24, no. 5, pp. 1142–1145, May 2020.

[10] S. M. Demir, F. Al-Turjman, and A. Muhtaroğlu, "Energy scavenging methods for WBAN applications: A review," *IEEE Sensors J.*, vol. 18, no. 16, pp. 6477–6488, Aug. 2018.

[11] M. M. Alam, E. Ben Hamida, O. Berder, D. Menard, and O. Sentieys, "A heuristic self-adaptive medium access control for resource-constrained WBAN systems," *IEEE Access*, vol. 4, pp. 1287–1300, 2016.

[12] N. Bradai, L. C. Fourati, and L. Kamoun, "Investigation and performance analysis of MAC protocols for WBAN networks," *J. Netw. Comput. Appl.*, vol. 46, pp. 362–373, Nov. 2014.

[13] S. Rajesh, V. Paul, V. G. Menon, S. Jacob, and P. Vinod, "Secure brain-to-brain communication with edge computing for assisting post-stroke paralyzed patients," *IEEE Internet Things J.*, vol. 7, no. 4, pp. 2531–2538, Apr. 2020.

[14] N. Bradai, E. Charfi, L. C. Fourati, and L. Kamoun, "Priority consideration in inter-WBAN data scheduling and aggregation for monitoring systems," *Trans. Emerg. Telecommun. Technol.*, vol. 27, no. 4, pp. 589–600, Apr. 2016.

[15] M. Salayma, A. Al-Dubai, I. Romdhani, and Y. Nasser, "New dynamic, reliable and energy efficient scheduling for wireless body area networks (WBAN)," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2017, pp. 1–6.

[16] D. Liu, J. Wang, C. Jiang, F. Ren, and Y. Ren, "A contention-oriented node sleeping MAC protocol for WBAN," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2018, pp. 1–6.

[17] F. Ullah, A. H. Abdullah, O. Kaiwartya, and Y. Cao, "TraPy-MAC: Traffic priority aware medium access control protocol for wireless body area network," *J. Med. Syst.*, vol. 41, no. 6, p. 93, Jun. 2017.

[18] B. Liu, Z. Yan, and C. W. Chen, "Medium access control for wireless body area networks with QoS provisioning and energy efficient design," *IEEE Trans. Mobile Comput.*, vol. 16, no. 2, pp. 422–434, Feb. 2017.

[19] S. R. Chavva and R. S. Sangam, "An energy-efficient multi-hop routing protocol for health monitoring in wireless body area networks," *Netw. Model. Anal. Health Informat. Bioinf.*, vol. 8, no. 1, p. 21, Dec. 2019.

[20] K. S. Kathe and U. A. Deshpande, "A thermal aware routing algorithm for a wireless body area network," *Wireless Pers. Commun.*, vol. 105, no. 4, pp. 1353–1380, Apr. 2019.

[21] A. Sundar Raj and M. Chinnadurai, "Energy efficient routing algorithm in wireless body area networks for smart wearable patches," *Comput. Commun.*, vol. 153, pp. 85–94, Mar. 2020.

[22] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. 33rd Annu. Hawaii Int. Conf. Syst. Sci.*, 2000, p. 10.

[23] 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, Aug. 2006.

[24] M. Ghribi and A. Meddeb, "Survey and taxonomy of MAC, routing and cross layer protocols using wake-up radio," *J. Netw. Comput. Appl.*, vol. 149, Jan. 2020, Art. no. 102465.

[25] V. L. Quintero, C. Estevez, M. E. Orchard, and A. Pérez, "Improvements of energy-efficient techniques in WSNs: A MAC-protocol approach," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1188–1208, 2nd Quart., 2019.

[26] M. Salayma, A. Al-Dubai, I. Romdhani, and Y. Nasser, "Wireless body area network (WBAN): A survey on reliability, fault tolerance, and technologies coexistence," *ACM Comput. Surv.*, vol. 50, no. 1, pp. 1–38, Apr. 2017.

[27] N. Saleh, A. Kassem, and A. M. Haidar, "Energy-efficient architecture for wireless sensor networks in healthcare applications," *IEEE Access*, vol. 6, pp. 6478–6486, 2018.

[28] S. Bhandari and S. Moh, "A priority-based adaptive MAC protocol for wireless body area networks," *Sensors*, vol. 16, no. 3, p. 401, Mar. 2016.

[29] M. A. Jan, P. Nanda, and X. He, "Energy evaluation model for an improved centralized clustering hierarchical algorithm in WSN," in *Proc. Int. Conf. Wired/Wireless Internet Commun.* Saint Petersburg, Russia: Springer, 2013, pp. 154–167.

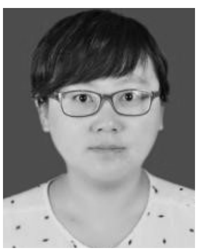
[30] M. A. Jan, P. Nanda, X. He, and R. P. Liu, "PASCCC: Priority-based application-specific congestion control clustering protocol," *Comput. Netw.*, vol. 74, pp. 92–102, Dec. 2014.

[31] M. D. Alshehri and F. K. Hussain, "A comparative analysis of scalable and context-aware trust management approaches for Internet of Things," in *Proc. Int. Conf. Neural Inf. Process.* Turkey: Springer, 2015, pp. 596–605.

[32] Z. Tang and M. Gong, "Adaptive multifactorial particle swarm optimisation," *CAAI Trans. Intell. Technol.*, vol. 4, no. 1, pp. 37–46, Mar. 2019.

[33] M. D. Alshehri, F. K. Hussain, and O. K. Hussain, "Clustering-driven intelligent trust management methodology for the Internet of Things (CITM-IoT)," *Mobile Netw. Appl.*, vol. 23, no. 3, pp. 419–431, Jun. 2018.

[34] M. A. Jan, P. Nanda, X. He, and R. P. Liu, "A Sybil attack detection scheme for a centralized clustering-based hierarchical network," in *Proc. IEEE Trustcom/BigDataSE/ISPA*, vol. 1, Aug. 2015, pp. 318–325.



GUOJIE YANG graduated from Hebei University, in 2009. She currently works with the Affiliated Hospital of Hebei University, Hebei University. She has published her research articles in various IEEE journals and conferences. Her research interests include information system development, smart healthcare systems, and the Internet of Things.

MIAN AHMAD JAN (Senior Member, IEEE) received the Ph.D. degree in computer systems from the University of Technology Sydney (UTS), Australia, in 2016. He is a Researcher with Ton Duc Thang University, Ho Chi Minh City, Vietnam. His research articles have been published in various prestigious IEEE TRANSACTIONS and journals (Elsevier). His research interests include security and privacy in the Internet of Things and wireless sensor networks. He had been the recipient of various prestigious scholarships during his studies, notably the International Research Scholarship (IRS) from the UTS, Australia, and Commonwealth Scientific Industrial Research Organization (CSIRO) Scholarships. He was awarded the Best Researcher Award from the UTS, in 2014. He was the General Co-Chair of Springer/EAI Second International Conference on Future Intelligent Vehicular Technologies, in 2017. He has been a Guest Editor of numerous special issues in various prestigious journals such as *Future Generation Computing Systems* (Elsevier), *Mobile Networks and Applications* (MONET) (Springer), *Ad Hoc and Sensor Wireless Networks*, and *Information* (MDPI).

VARUN G. MENON (Senior Member, IEEE) is currently an Associate Professor with the Department of Computer Science and Engineering, SCMS School of Engineering and Technology, India. He is a Distinguished Speaker of the ACM. His research interests include the Internet of Things, fog computing and networking, underwater acoustic sensor networks, cyberpsychology, hijacked journals, ad-hoc networks, and wireless sensor networks. He is currently a Guest Editor of the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, the IEEE SENSORS JOURNAL, the *IEEE Internet of Things (IoT) Magazine*, and *The Journal of Supercomputing*. He is an Associate Editor of *IET Quantum Communications* and also an Editorial Board Member of the IEEE FUTURE DIRECTIONS NEWSLETTER: TECHNOLOGY POLICY AND ETHICS EDITORIAL BOARD.

P. G. SHYNU (Member, IEEE) received the M.E. degree in computer science and engineering from the College of Engineering, Anna University, Chennai, India, and the Ph.D. degree in computer science from the Vellore Institute of Technology (VIT), Vellore, India. He is currently working as an Associate Professor with the School of Information Technology and Engineering, VIT. He has published over 30 research papers in refereed international conferences and journals. His research interests include deep learning, cloud security and privacy, ad-hoc networks, and big data.

MIAN MUHAMMAD AIMAL received the Ph.D. degree from Abdul Wali Khan University Mardan, Pakistan. He has been working as a Senior Researcher with the Network Research Center, Virtual University Islamabad, Pakistan, since 2018. He worked on energy efficiency in wireless sensor networks during the Ph.D. studies. He has been actively involved in the Internet of Things test-beds for energy efficiency in extreme resource-constrained devices (having less than 100-MHz processing speed and 100 K RAM). In his current role, he has been focusing mainly on test-beds as a prototype for large-scale commercial deployment. He has published his research articles in various journals and has submitted his latest research findings in the IEEE, Springer, and MDPI venues.

MOHAMMAD DAHMAN ALSHEHRI (Member, IEEE) received the bachelor's degree in computer science from King Khalid University, Saudi Arabia, and the master's degree in information technology and the Ph.D. degree in AI of cybersecurity for the IoT from the University of Technology Sydney (UTS), Australia. He is an Assistant Professor with the Department of Computer Science, Taif University, Saudi Arabia, a Visiting Fellow of the School of Computer Science, and a member of the Centre for Artificial Intelligence (CAI), UTS. He did a number of intensive advanced courses on the Internet of Things and cybersecurity. His main current research interests include cybersecurity, artificial intelligence, and trust management for the Internet of Things (IoT). Furthermore, he received a number of international awards and prizes.