

## Article

# PEDTARA: Priority-Based Energy Efficient, Delay and Temperature Aware Routing Algorithm Using Multi-Objective Genetic Chaotic Spider Monkey Optimization for Critical Data Transmission in WBANs

Omar Ahmed <sup>1</sup>, Min Hu <sup>1</sup>  and Fuji Ren <sup>2,\*</sup> 

<sup>1</sup> School of Computer Science and Information Engineering, Hefei University of Technology, Hefei 230009, China; omar@mail.hfut.edu.cn (O.A.); jsjxhumin@hfut.edu.cn (M.H.)

<sup>2</sup> Faculty of Engineering, Tokushima University, Tokushima 770-8506, Japan

\* Correspondence: ren@is.tokushima-u.ac.jp

**Abstract:** Software-Defined Wireless Body Area Network (WBAN)s have gained significance in emergency healthcare applications for remote patients. Prioritization of healthcare data traffic has a high influence on the congestion and delay in the WBAN routing process. Currently, the energy constraints, packet loss, retransmission delay and increased sensor heat are pivotal research challenges in WBAN. These challenges also degrade the network lifetime and create serious issues for critical health data transmission. In this context, a Priority-based Energy-efficient, Delay and Temperature Aware Routing Algorithm (PEDTARA) is presented in this paper using a hybrid optimization algorithm of Multi-objective Genetic Chaotic Spider Monkey Optimization (MGCSMO). This proposed optimized routing algorithm is designed by incorporating the benefits of chaotic and genetic operators to the position updating function of enhanced Spider Monkey Optimization. For the prioritized routing process, initially, the patient data transmission in the WBAN is categorized into normal, on-demand and emergency data transmissions. Each category is ensured with efficient routing using the three different strategies of the suggested PEDTARA. PEDTARA performs optimal shortest path routing for normal data, energy-efficient emergency routing for high priority critical data and faster but priority verified routing for on-demand data. Thus, the proposed PEDTARA ensures energy-efficient, congestion-controlled and delay and temperature aware routing at any given period of health monitoring. Experiments were performed over a high-performance simulation scenario and the evaluation results showed that the proposed PEDTARA performs efficient routing better than the traditional approaches in terms of energy, temperature, delay, congestion and network lifetime.

**Keywords:** wireless body area network; software-defined network; remote healthcare applications; multi-objective genetic chaotic spider monkey optimization; traffic priority; congestion control; critical data transmission; on-demand data



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## 1. Introduction

In recent times, the human health monitoring applications for remote patients using WBANs have gained immense interest with the development of high-performance integrated circuits, wireless communication systems and sensor networks. In combination with IoT technology, WBANs have been largely employed for healthcare applications and telemedicine [1]. IoT technology provides reliable and cost-effective healthcare solutions. However, the IoT-coupled WBANs also face practical challenges during their installation [2]. The Software-Defined Network (SDN) approach is another efficient paradigm that is being used with WBANs to tackle the installation problems of heterogeneity and scalability. This hybrid architecture is often the futuristic solution for healthcare applications such as remote patient monitoring and telemedicine [3]. The WBAN healthcare sensing consists of medical sensors implanted onto the patient's body for extracting vital signs such as pulse, heart

rate, temperature, blood pressure, etc. These sensors are connected in a network model for monitoring and collecting the medical data which are transmitted to a coordinator. The initial transmission to the coordinator is performed through a low power radiofrequency. The final transmission from the coordinator to the medical monitoring central point is performed for further analysis and processing of the data [4]. WBANs generally utilize short-range wireless communication as the radio radiation does not cause much harm to the patient's body. This type of communication is also efficient in power conservation in the nodes using tiny batteries with limited energy, which significantly prolongs the network lifetime.

WBANs have certain unique characteristics that are entirely different from wireless sensor networks (WSN). WBANs have a simpler network topology with the minimum number of nodes for sensing [5]. However, they also possess more complex channel conditions than WSNs due to the usage of in-body and on-body channels. A WBAN can also be designed with varying sensor types and different sensing rates and the network will still perform effectively. These unique characteristics of the WBAN make the existing protocols of WSN less effective for routing and sensing. Particularly, the sensing diversity and the complex channel structures limit the efficiency of the generalized WSN protocols when used for WBAN, thus making these methods less applicable [6]. Therefore, developing energy-efficient routing protocols is highly recommended, especially that exploit the use of various channels. Still, this solution is very challenging to achieve due to the limitations in energy, delay and temperature of the sensor nodes. Thus, limited energy in the WBAN network also plays a prominent role in deciding the routing paradigm [7]. Apart from energy efficiency, the delay and temperature issues also play a significant part in designing the routing protocol.

Heat issues are one of the most traditionally common performance issues in sensor networks. Implanted WBAN or in vivo WBANs can be applied to various medical services such as pacemakers, cardio meters, glucose sensing, tumor detection, etc., for patients from remote medical facilities. The in vivo sensor nodes are mounted on the patient body to sense and transmit information to the out-of-the-body remote server for the physicians via multi-hop transmission. This sensing and transmission among the sensor nodes produces excessive radiation and heat dissipation. The patient body tissues covering the sensor nodes are often impacted by these radiations and their temperature rise [8]. This can be harmful both for the tissue damage in patients as well as the overall network performance. Hence, the routing protocol must also consider the temperature as a factor in selecting the transmission routes such that the sensor nodes, as well as tissues, are protected from thermal damage.

Similarly, congestion and delay are other pivotal factors that determine the routing paths. The transmitted data are often overflowed at the forwarder nodes and cause congestion, transmission delay or data loss [9]. WBANs with high congestion are often avoided as they are less reliable in sensitive healthcare applications. In some cases, the dead nodes in a route also cause data loss. Delay is also caused due to congestion and data loss which initiate retransmissions that incur additional overhead. Likewise, if a path is engaged by some nodes, the other nodes must wait until the path is clear to transmit. This scenario is highly impactful in WBAN as the data are sensitive to noise and most often are deadline-based physiological information. For example, blood glucose is monitored before and after food consumption to identify the rise/fall in diabetes patients. If the data are not transmitted in time or lost due to loaded paths, the precise information is lost and even retransmissions are not helpful. Such delay is a critical factor as it might deal with emergency patients in certain cases. Additionally, the congestion and delay also influence energy consumption and subsequent radiation transmission that increases the temperature. Hence, all these challenging factors are interlinked in the development of energy-efficient delay and temperature-aware routing protocol.

Existing routing protocols have been focused on resolving the routing problem by collaboratively considering the energy, delay and temperature. Temperature-aware routing

algorithms have considered the temperature of the nodes and also where the sensor is placed on the human body. However, they transmit data to the nodes that have a minimum temperature which might result in longer transmission paths and the physiological data staying in the network for a long time. This evades the ideal condition for WBAN healthcare applications and results in delayed transmission and less energy efficiency. The consideration of the priority of the data packets can be effective in tackling these issues. This can make the routing paths more available for emergency data while also maintaining the minimum temperature, delay and energy consumption. Hence, in this paper, PEDTARA has been developed by assigning different priorities to the data traffic and allocating energy efficient and delay- and temperature-aware routes to data packets based on the level of priority. The major contributions of this research work are:

- The development of PEDTARA using a hybrid optimization algorithm of Multi-objective Genetic Chaotic Spider Monkey Optimization (MGCSMO) to harvest the benefits of enhanced SMO, genetic algorithms and chaotic optimization. The MGCSMO enhances the optimal routing path selection based on priority and quality metrics of energy, delay, path loss and reliability;
- The utilization of residual energy, link reliability, path loss and queue length in PEDTARA traffic priority-based routing objective modelling where the temperature factor is considered in the forwarding node selection process. This objective modelling improves energy efficiency, reduces congestion and delay and achieves emergency transmission when needed;
- The patient data in the WBAN are classified into three priority classes: normal data, on-demand data and emergency data based on the severity of physiological information. Then, the PEDTARA protocol is applied adaptively for each priority class;
- The normal data are transmitted through available optimal paths selected by PEDTARA while the emergency data transmit all possible energy-efficient optimal shortest paths without conflicts. In the case of on-demand data, the on-demand PEDTARA is adapted to ensure effective transmission without delay.

The simulations are performed in a realistic healthcare environment to evaluate the proposed PEDTARA protocol and compare its performance with the prominent existing routing models. This research paper is structured as follows. Prominent routing models for WBAN in the recent research works are discussed briefly in Section 2. The research contributions and the proposed PEDTARA are presented in Section 3. The simulations and comparison results are presented in Section 4, while Section 5 concludes this article.

## 2. Related Works

Routing algorithms for WBAN have been developed in wide numbers in recent years because of their considerably increasing real-time applications. This section focuses on three categories of routing algorithms, namely energy-efficient routing, temperature-aware routing and priority aware routing protocols. The introduction of SDN is also stressed for the three categories. Previously, an extensive systematic review was conducted over a vast number of recent related studies about these topics. In addition, the latest reviews were also studied to understand the mechanisms of energy-efficient routing, temperature aware routing and priority aware routing protocols. From these reviews, some prominent studies were selected based on their efficient performance and are discussed in this section.

### 2.1. Energy-Efficient Routing Models

WBAN sensor nodes are modelled with limited energy sources and, hence, energy depletion must be reduced by the routing protocols. Kaur and Singh [10] proposed an Optimized Cost-effective and Energy-efficient Routing (OCER) protocol and which they extended by using the genetic algorithm for optimal path selection. The OCER focuses on intra-WBAN routing while extended OCER aims to enhance the inter-WBAN routing. These protocols reduced the energy consumption and path loss and increased the link reliability and network lifetime. However, these models are more suitable for simpler networks.

Yan et al. [11] designed a green routing mechanism using the Artificial Bee Colony (ABC) based on the Optimal Path of Energy Consumption (OPEC). These protocols also solve the NP problem and improve convergence. The energy consumption and throughput are efficient in this approach, however, the limitation stems from the use of more eco-friendly routing which might be awkward in emergencies. Abidi et al. [12] developed a clustering-based routing protocol for WBAN (CRPBA) that enhances energy efficiency, lifetime and network stability. However, this model does not consider the cooperation between the nodes at the final stages of the network life.

Ullah et al. [13] presented Energy-efficient Harvested-Aware clustering and cooperative Routing Protocol (E-HARP) to effectively select the cluster heads and perform cooperative routing. This process is done using the calculated cost factor and multiple objective parameters. This approach reduced the overload conditions and reduced the energy, delay and loss. However, this model has limitations in supporting critical data delivery due to the longer route discovery process. Cicioğlu and Çalhan [14] presented an SDN-based WBAN routing algorithm to improve energy efficiency and critical data transmission effectiveness. The SDN model improved the network performance and helped in reducing the delay, energy consumption and path loss. However, this model did not consider the impact of temperature and has limitations in normal data transmission rate. Qu et al. [15] presented another energy-efficient routing protocol that used a maximum benefit function based on multiple QoS parameters. It effectively integrated the energy and priority data transmission problems and provided reliable routing. It also minimized the delay and increased the network lifetime. However, this model provides equal importance to all the parameters by assigning equal weights randomly without prioritizing the energy.

Chavva & Sangam [16] proposed an energy-efficient multi-hop routing protocol using the Mamdani Fuzzy Logic approach to improve the network lifetime. Although it reduces the energy consumption and delays to prolong the lifetime, it has restrictions in handling the path loss problem. Yang et al. [17] designed the energy-efficient routing protocol that also performs the scheduling through adaptive slot assignment. This protocol has employed a channel competition strategy to reduce flooding and considered energy, path loss and traffic type for the routing and scheduling. This approach has improved energy efficiency, reduced delay and improved lifetime with effective channel utilization. However, this protocol does not consider the impact of relay nodes additionally employed for adverse locations. Sagar et al. [18] developed critical data routing (CDR) for ensuring energy-aware data transmission without redundant data. This routing model saves the energy by transmitting only the critical data without duplication but discards the non-critical data. Though it is efficient, the decision module that discards the non-critical data is often determined through a fixed threshold. This fixed threshold value is not suitable for different aged patients as well as their varying body strengths. Cicioğlu and Çalhan [19] presented an Energy-efficient and SDN-enabled Routing algorithm for WBANs (ESR-W) utilizing the Fuzzy-based Dijkstra technique to select the shortest paths. This protocol reduces the noise ratio in the transmitted data and enhances energy efficiency with limited dissatisfaction among SDN users. Although efficient results were obtained, this protocol has security limitations, especially against the link faults.

Raj and Chinnadurai [20] proposed an Opportunistic Energy-efficient routing with Load Balancing (OE2-LB) algorithm for effective data transmission in smart wearable patch sensors. This OE2LB reduces the data aggregation delay and also balances the data load among the paths without becoming stuck in loops. Although it reduces the energy, delay and increases the throughput and network lifetime, the nodes are often not aware of the distance to the neighbors, resulting in sub-optimal neighbor node selection. Qureshi et al. [21] presented Energy-Aware Routing (EAR) with link quality and energy consumption based on better next-hop selection. This routing algorithm reduced the energy consumption and improved the reliability in routes. It also reduced overhead and computational complexity. However, this approach also did not consider the node mobility and its impact on routing. Khan et al. [22] developed another energy-efficient

routing protocol using multi-hop path selection based on distance and maximum residual energy. It increased the network lifetime, energy efficiency and network stability. However, this model does not have a provision for resolving the conflicts between different priority data. Newell and Vejarano [23] developed a motion-based routing and transmission power control approach that reduces the power consumption during the patient periodic body movements. This strategy increased the packet delivery ratio by 5.6% while reducing the power consumption by 39%. However, this model has limitations in handling the interference between WBAN users at proximity.

## 2.2. Temperature Aware Routing Models

Temperature or heat dissipation is a big issue in WBANs as it not only impacts the sensor nodes but also impacts the patients' skin and tissues beneath the sensor nodes. Several methods have tried to introduce temperature-aware routing models in recent years. Monowar and Bajaber [24] proposed a Thermal-aware Localized QoS (TLQoS) routing protocol that exploits all the modules in the network to reduce the hotspots and maintain the temperature under an acceptable level. However, this model has poor performance when the bit error rates are higher. This limitation is due to the inaccurate routing information and the increased convergence time. El Azhari et al. [25] developed Relay-based Thermal aware and Mobile Routing Protocol (RTM-RP) for performing effective patient data transmission even with mobility issues. This protocol tackles the energy and temperature rise problems by dividing the patient body into relay zones. This approach reduces the energy and temperature rise and increases flexibility. However, this protocol does not have provision for emergency data transmission when all optimal paths are occupied. Maymand et al. [26] proposed thermal-aware routing with a traffic control function to minimize the temperature rise. This model reduced temperature rise and packet delay. However, the energy consumption is not reduced and, also, the body movements are not considered. Bhangwar et al. [27] combined Trust aware and Thermal aware Routing Protocol (TTRP), which considers the trust and temperature among the nodes to perform routing. In addition to energy, temperature and reliability, the TTRP model has effective performance in terms of packet drop ratio and delay. However, this model lacks an efficient solution for the faults in the routing paths during data transmission.

Bhangwar et al. [28] proposed Weight based Energy and Temperature aware Routing Protocol (WETRP), which considers the QoS metrics, energy, delay and temperature. This approach has assigned equal weights to all the metrics and, also, provides the option for adapting them based on application requirements with effective packet-level priority. It results in less temperature rise and a high network lifetime and packet delivery ratio. However, this model does not consider the impact of link failures. Kim et al. [29] developed an enhanced mobility and temperature-aware routing protocol through the analytical hierarchy process and simple additive weighting method. This routing protocol considers multiple parameters to select the optimal routes and achieve a high packet delivery ratio and lower hot spot ratio. Although the analytical hierarchy process helps in accurate routing decision making, it suffers from irregularities in ranking due to the static changes in alternatives. Kim et al. [30] also developed a Forwarder based Temperature Aware Routing (FTAR) protocol to support multiple traffic transmissions. This protocol has a provision for transmitting critical data more effectively with a better hot spot ratio and packet delivery ratio. However, this model has limited control over the paths once the critical data transmission is completed. Kathe and Deshpande [31] presented a thermal-aware routing algorithm using data priority and temperature monitoring. It reduces the latency, energy consumption, hop count and temperature rise but has limitations in handling multiple patients' data. Javed et al. [32] presented a Thermal-Aware and Energy-Optimized (TAEO) routing protocol based on the Specific Absorption Rate (SAR) and energy consumption. This protocol reduces the energy, delay and temperature rise and increases the network lifetime. However, this model has limitations in critical data decision making when more than one set of data is critical.



Selem et al. [33] developed Temperature Heterogeneity Energy (THE) aware routing protocol for one-hop and multi-hop transmission. This protocol provided a long node lifetime, high packet throughput of 14% and 7% reduced energy consumption. However, this model has a higher delay than that required for emergency data transmission. Jamil et al. [34] designed an Adaptive Thermal-aware Routing (ATOR) protocol using the multi-ring routing strategy. This patient-oriented routing protocol reduced the overall temperature rise, tissue damage and packet loss through adaptive forwarding node selection. However, this protocol has resulted in additional delay which could impact the emergency data transmission. Banuselvasaraswathy and Rathinasabapathy [35] presented an Optimum Path Optimum Temperature (OPOT) routing protocol that controls self-heat radiations of the nodes. This OPOT protocol monitors the minimum and maximum temperature of the nodes and then selects the optimal paths for the critical data transmission. This mechanism reduces the delay, energy, data loss and improves the network lifetime with heat adaptive node selection, yet this protocol has limitations in handling high data arrival rates. Caballero et al. [36] proposed the Link-Quality Aware and Thermal aware On-Demand Routing (LATOR) protocol for avoiding the overheating problem and increasing the reliability in packet delivery rate. The link quality information is utilized to select reliable paths with minimum heating and maximum throughput. However, this protocol also increases the end-to-end latency. Shahbazi and Byun [37] proposed a blockchain-based Adaptive Thermal-/Energy-Aware Routing (ATEAR) protocol which increases the network lifetime and also reduces the heating impacts. The residual energy is better conserved and the protocol is also secured against the crash faults and byzantine faults. However, this model is not supportable for the postural movements in the patient's body, which also reduces the control over temperature.

### 2.3. Priority Aware Routing Models

Delay must be as low as possible for critical data transmission in WBANs. The priority-based models have constantly reduced the delay associated with the allocation and transmission of critical data from the patient to the processing units. The specialized priority aware routing models for WBANs have been introduced in large numbers in the last decade. Elhadj et al. [38] introduced a priority-based cross-layer routing protocol (PCLRP) using a priority-based access channel for cross layers. This combination of the access channel and the data dissemination through the routing protocol provides reliable and customizable communications. This routing model minimizes delay and energy consumption while increasing the packet delivery ratio significantly. However, the regular data transmission is halted or delayed when critical data are prioritized. Ahmed et al. [39] developed a Priority-based Energy-efficient Routing Algorithm (PERA) using two non-linear programming models. This routing model analyzed the critical data constraints and modelled routing paths with an additional fraction of bandwidth specifically allotted for critical data with high priority. This model reduces the delay and energy consumption with almost negligible path loss and higher throughput. However, this model has limitations in handling the hotspot problem of sink nodes for critical, high priority data transmission.

ShariatmadariSerkani et al. [40] presented a reliable delay sensitive routing protocol that ensures high priority path allocation for critical data. Firstly, the patient data are classified into sensitive and non-sensitive data and paths are assigned with the least delay and highest reliability for sensitive data. While sensitive data are transmitted through high priority paths, the non-sensitive data are also transmitted through other available paths in parallel. This approach increases the throughput and reduces the delay. Still, this approach considers all patients as static and neglects the mobility problems. Majumder and Gupta [41] developed an energy-efficient congestion avoidance priority-based routing algorithm based on energy, hop count and queue length. The consideration of congestion reduces the energy wastage and increases the network lifetime. It also ensures high throughput and less path loss. However, this algorithm does not consider the delay incurred in non-critical data transmission due to critical data transmission. Ventura et al. [42] also

presented a priority-based routing algorithm that provides QoS-aware path selection with multiple queues for different categories of data. Although this queueing model effectively reduces the complexity in handling critical data, the delay incurred in some queues is large.

Awan et al. [43] designed a priority-based congestion-avoidance routing protocol using an effective data classification process. First, the data are classified into normal and critical data for effective priority handling. The normal data paths are assigned by next-hop selection using the QoS metrics, while the critical data paths are assigned using priority-based routing. This reduces the delay, energy and data loss while increasing the lifetime and packet delivery ratio. However, the mobility of sensor nodes due to body movements is neglected to minimize the routing complexities. Wang et al. [44] developed a traffic priority aware and energy-efficient routing protocol to reduce latency and increase the lifetime. The consideration of traffic data priority has reduced the latency in critical data transmission. However, this model has limitations in transmitting data of the patients with mobility. Ullah et al. [45] presented the Traffic priority-based delay-aware and energy-efficient path allocation routing protocol (Tripe-EEC), which ensures priority aware on-demand routing. This protocol reduces the delay, energy and temperature rise and ensures emergency data transmission without interruptions. However, this protocol has limitations in handling the faults in the routing paths. Geetha and Ganesan [46] developed the Cooperative Energy-efficient and Priority-based Reliable routing protocol with Network coding (CEPRAN). This protocol designed an Enhanced Cuckoo Search Optimization algorithm to select the relay nodes and Cooperative Random Linear Network Coding for cooperative packet transfer. Although this protocol improves the throughput to 93% and also reduces energy and distance in routing, this model has a considerable delay due to its mobility issues.

Arghavani et al. [47] developed Chimp, a learning-based power-aware communication protocol for WBANs in which each sending node can self-learn the channel quality and choose the best transmission power level to reduce energy consumption and interference range without degrading the communication reliability. Likewise, Arghavani et al. [48] also developed Tuatara, the novel power-aware communication protocol that allows each sensor node to dynamically adjust its transmission power based on the channel status to save energy, reduce interference and improve communication reliability. This protocol utilized a probabilistic model to calculate the optimal probability of selecting each power level to reduce the transmission cost, while a reinforcement learning scheme was used to adaptively update the power level selection probabilities.

#### *2.4. Limitations of Methods in the Literature*

From this extensive review of the literature, the common observation is that the efficient routing algorithms have limitations in providing better throughput due to temperature loss and congestions. The energy-efficient routing protocols must maintain reliability and also reduce the propagation loss. In addition to the energy efficiency concept, this work also considers two more vital features, temperature and congestion control, to ensure the efficiency of the routing. The multi-hop concept significantly minimizes the delay but increases the congestion, temperature and energy consumption. Studies that considered the temperature and congestion in routing have gained significantly improved performance. Priority-based routing models have tried to avoid the delay in routing the critical data. Still, these models face complexities in the routing because of the inefficient path allocation for critical data and uncooked solutions for normal data transmission during such emergencies. For such problems, this paper has presented an efficient priority routing model with an energy-efficient and congestion- and temperature-controlled methodology. This proposed PEDTARA protocol is initially formulated using the optimization algorithm of MGCSMO for selecting optimal shortest paths based on multiple objectives to solve the energy, temperature and congestion problems. Then, PEDTARA utilizes the data classification process to group the patient data into different priorities. Based on the priority, the routing process is altered to meet the time deadlines in emergency and critical situations.

### 3. PEDTARA Methodology

PEDTARA has been developed by using the Multi-objective Genetic Chaotic Spider Monkey Optimization-based energy efficient and congestion- and temperature-aware priority routing for the SDN-coupled WBAN transmission of patient data. Initially, the patient data are classified and the priorities are assigned to each set of readings which contains the vital critical signs. Then, the routing process is initiated by the formation of paths from the past routing knowledge to minimize the time for route discovery. As the SDN approach has provided flexible and high-efficiency architecture, the WBAN can enable the selection of paths with minimum energy consumption, less congestion and low heated nodes for handling the critical data. The WBAN is designed with multiple sensor nodes for collecting the vital signs of the patients and the sensor nodes transmit to the hub or the main sensor. Then, the data are, together, transmitted to the physicians for further evaluation.

#### 3.1. Classification of Patient Data

The proposed PEDTARA protocol classifies the incoming patient vital signs' data into normal, on-demand and emergency data. The normal data contain the normal patient readings of the determining vital signs, namely blood pressure, and they denote the healthy values. The on-demand data are those data that are collected at the request of the doctors for accessing them against the emergency data for critical care. The emergency data are the critical and crisis data which denote the unhealthy situations. They are further classified into the critical data-low threshold and critical data-high threshold data. The critical data contain the patient life-critical data which might not be delay-sensitive but require high consideration from the doctors. The high threshold data are delay sensitive data with acceptable short delays beyond which the data become highly critical and might result in loss of life. The critical data must be provided with the high priority paths without delay and loss while delay-sensitive data must also be assigned with similar paths but with a faster transmission rate, acceptable to match the determined short time. Hence, the data transmission requires highly reliable and dedicated paths based on priority and also less delay, energy consumption, congestion and heated nodes. Table 1 shows the ranges of threshold values set for each of the vital signs which comprise the three classes.

**Table 1.** Threshold values for each vital sign.

Vital Sign	Regular Value for a Healthy Person	Critical Thresholds	
		Low Threshold	High Threshold
Temperature (Celsius)	36.5–37.5	Below 35	Above 40
Heart rate (beats/min)	51–119	0–50	120–140
Blood pressure (mmHg)	90–120	70–90	140–190
BP Diastolic (mmHg)	60–80	40–60	90–100
Respiration rate (breaths/min)	12–49	0–11	Above 50

#### 3.2. Network Model

The proposed network is designed based on SDN technology. First, the sensor nodes are initialized with their transmission and coordinator behaviors. SDN-based WBAN includes the three logical planes as in the general model of SDN, namely the data plane, the control plane and the application plane. These planes form the three layers of the proposed network model. Layer 1 includes the sensors for sensing data, the main sensor for data gathering and the WBAN coordinator (WBANC). The sensory data must be collected by the medical sensors for each vital sign. The main sensor acts as the server and performs the process of collecting data from all deployed sensors and transmitting them to the WBANC. The functions of the main sensor and the WBANC are almost similar, yet both



are deployed to reduce the energy sink-hole problem. In this manner, layer 1 is formed, which is responsible for the intra-communication. The sensors in this layer are placed at different junctions of the patient body to monitor different vital signs for the diagnosis of different health conditions. These sensors communicate through point-to-point (P2P) for neighbor node property identification and path formation. A gateway of Bluetooth is used in between the sensors and main sensors to limit the congestion of data moving towards the main sensor. Layer 2 forms the inter-WBAN communication model between the WBANC and the Patient Data Display (PDD) devices. PDD is maintained by layer 2 as the next possible hop for the WBANC, and enables PDD to forward the patient data to the communication device in the next layer. Layer 3 includes the Centralized Display Device (CDD), in using which the beyond-WBAN communication is performed to provide patient’s data remote access to medical professionals over the Internet. For inter-WBAN and Intra-WBAN communication, the IEEE 802.15.6 standard-based Zigbee is utilized while broadband or Wi-Fi are used for beyond-the-network communication. The power sources for the sensors, WBANC and PDDs are limited battery supplies. Only the CDDs are powered by direct supplies and, hence, the energy conservation is necessarily employed to maintain the consistent operation of the network. Figure 1 shows the network architecture of the proposed SDN-based WBAN model.

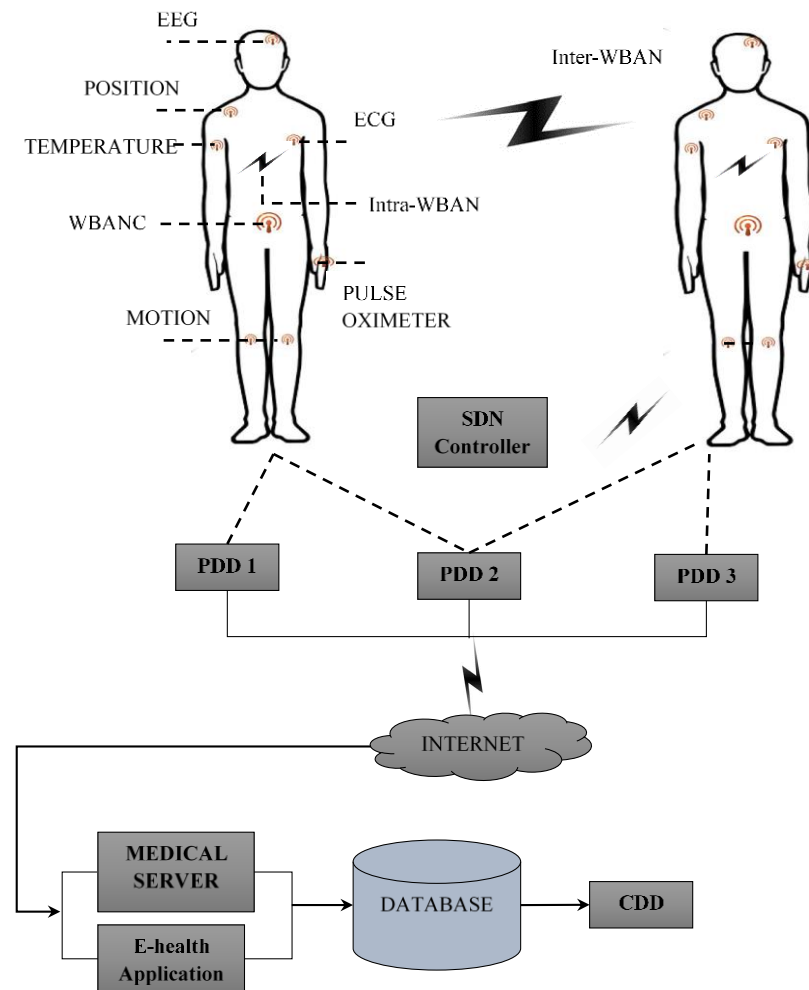


Figure 1. Architecture of proposed SDN-based WBAN system.

### 3.3. Multi-Objective Fitness Function for Routing Model

The fitness function is formulated using four parameters—residual energy, link reliability, path loss and queue length. The proposed PEDTARA considers these four parameters since they constitute the energy and congestion objectives. Similar to EOCC-TARA [49], the

goal is to optimize the energy consumption in the routing paths using the fitness function. Four weights,  $W_A$ ,  $W_B$ ,  $W_C$  and  $W_D$ , are used to provide relative priorities to the selected parameters. Assigning different values to these weights will result in different fitness values. The ranges of the weights are optimally determined using the same proposed MGCSMO algorithm. The fitness function is modelled as follows:

Minimize:

$$f = W_A \times \text{residual energy} + W_B \times \prod \text{link reliability}_i + W_C \times \text{path loss} + W_D \times \sum \text{queue length}_i \quad (1)$$

Subject to  $W_A + W_B + W_C + W_D = 1$

Now, the four parameters must be computed using suitable techniques to form the final fitness functions.

### 3.3.1. Energy Model

The energy model of this proposed PEDTARA enables the effective management of energy efficiency in routing. As higher energy consumption leads to reduced network lifetime, this model emphasizes the proficient usage of the limited WBAN power source. During the Inter-WBAN and intra-WBAN communications, the energy depletion is higher and also leads to early dead nodes in the network. Hence, the proposed routing model constitutes the energy parameter in the objective function. The energy consumed in the WBAN network can be computed by estimating the remaining energy in the network after certain transmissions. In the proposed network model, WBANC consumes higher energy than other biosensor nodes, while the remaining nodes consume an almost similar amount of energy. The total energy used by the entire WBAN network is calculated as the sum of sensing energy, radio transmission/reception energy, processing energy and transient energy of the biosensor nodes and the WBANC. To differentiate the impact of certain energy parameters, the weighting factor  $w_i = \{w_1, w_2, w_3, \dots, w_n\}$  is used. Based on the EOCC-TARA model, the weights are assigned because the WBANC consumes 10% greater sensing energy than the standard sensor node. Similarly, the WBANC also consumes 20% greater processing and communication energy. Therefore, the weights are assigned with fair impact consideration as  $\{w_1, w_2, w_3\} = \{1.1, 1.2, 1.2\}$ , such that sensing energy has 10% while the remaining energy has a 20% higher ratio for WBANC. The total energy  $E_{tot}$  can be, thus, computed as the sum of total energy consumed by the normal nodes ( $E_{tot,N}$ ) and total energy consumed by the WBANC ( $E_{tot,C}$ ), i.e.,

$$E_{tot} = E_{tot,N} + E_{tot,C} \quad (2)$$

Here,  $E_{tot,N}$  and  $E_{tot,C}$  are computed as the sum of sensing, radio transmission/reception, processing and transient energies of normal nodes and the WBANC, respectively.

$$E_{tot,N} = E_{sens,N} + E_{TX/RX,N} + E_{proc,N} + E_{trans,N} \quad (3)$$

$$E_{tot,C} = E_{sens,C} + E_{TX/RX,C} + E_{proc,C} + E_{trans,C} \quad (4)$$

Here,  $E_{sens,N}$ ,  $E_{TX/RX,N}$ ,  $E_{proc,N}$  and  $E_{trans,N}$  are the sensing, radio transmission/reception, processing and transient energies of the normal sensor node while  $E_{sens,C}$ ,  $E_{TX/RX,C}$ ,  $E_{proc,C}$  and  $E_{trans,C}$  are the sensing, radio transmission/reception, processing and transient energies of the WBANC.

The sensing energy  $E_{sens,N}$  of the normal node and the WBANC,  $E_{sens,C}$ , are computed as

$$E_{sens,N}(n) = n \times V_{sup} \times I_{sens} \times T_{sens} \quad (5)$$

$$E_{sens,C}(w_1, n) = w_1 \times E_{sens,N}(n) \quad (6)$$

Here,  $n$  represents the number of bit packets sensed by the nodes;  $V_{sup}$  is the supply voltage;  $I_{sens}$  is the total current;  $T_{sens}$  are the time taken for sensing; the weighting factor is  $w_i \sim w_1$ .

The radio transmitter/receiver circuitry energy can be computed for the normal nodes during the transmission of  $n$  bit packets from the node to the WBANC.

$$E_{TX \text{ radio},N}(n, D_{ab}) = nE_{TX \text{ radio}} + nE_{amp}D_{ab}^{pab} \quad (7)$$

$$E_{RX \text{ radio},N}(n) = nE_{RX \text{ radio}} \quad (8)$$

Here,  $E_{TX \text{ radio}}$  indicates the transmitter circuitry energy,  $E_{RX \text{ radio}}$  denotes the receiver circuitry energy,  $E_{amp}$  represents the energy consumed at the transmitter amplifier,  $D_{ab}$  is the distance between  $a$  and  $b$  and  $p$  represents the distance-based path loss exponent component.

The radio transmitter/receiver circuitry energy consumed for transmitting or receiving  $n$  bit packets by WBANC is estimated with a weighting factor  $w_i \sim w_2$

$$E_{TX \text{ radio},N}(w_2, n, D_{ab}) = w_2nE_{TX \text{ radio}} + nE_{amp}D_{ab}^{pab} \quad (9)$$

$$E_{RX \text{ radio},N}(n) = w_2nE_{RX \text{ radio}} \quad (10)$$

The total processing energy dissipated for  $n$  bit packets by a node per iteration and the energy consumed by the WBANC with the weighting factor  $w_i \sim w_3$  are computed based on the switching energy ( $E_{switch}$ ) and the leakage current energy dissipation ( $E_{leak}$ ).

$$E_{proc, N}(n, N_{iter}) = nN_{iter}C_{avg}V_{sup}^2 + nV_{sup} \left( I_0 e^{\frac{V_{sup}}{V_t Proc_k}} \right) \left( \frac{N_{iter}}{f} \right) \quad (11)$$

$$E_{proc, C}(w_3, n, N_{iter}) = w_3E_{proc}(n, N_{iter}) \quad (12)$$

Here,  $E_{proc, N}$  is the processing energy of the sensor node,  $E_{proc, C}$  is the processing energy of WBANC,  $N_{iter}$  denotes the number of iterations or clock cycles per operation,  $C_{avg}$  denotes the average capacitance switched per iteration cycle,  $V_{sup}$  is the supply voltage,  $I_0$  is the leakage current,  $V_t$  denotes the thermal voltage,  $f$  denotes the frequency of the body sensor and  $Proc_k$  is the processor constant.

The transient energy consumed by the network for operating at different modes depends on the duty cycles and the transition time. The total transient energy by the sensor nodes and WBANC are calculated as

$$E_{tran, N} = T_\alpha V_{sup} [I_N] \quad (13)$$

$$E_{tran, C} = T_{\alpha C} V_{sup} [I_C] \quad (14)$$

where  $T_\alpha$  and  $T_{\alpha C}$  are the wake-up duration of nodes and WBANC, respectively, and  $I_N$  and  $I_C$  are the average current for a node and WBANC, respectively.

Applying Equations (5)–(12) on Equations (3) and (4) provides the total energy consumed by the normal nodes ( $E_{tot,N}$ ) and the total energy consumed by the WBANC ( $E_{tot,C}$ ), using which, the total energy consumption in the network ( $E_{tot}$ ) is computed for the energy model.

### 3.3.2. Link Reliability Model

Link reliability is a parameter used to assess the reliability of the routing paths. When the links in a path are stronger, the transmission is reliable. The link reliability between two nodes,  $a$  and  $b$  ( $LinkR_{ab}$ ), is modelled as

$$LinkR_{ab} = (1 - \gamma)LinkR_{ab} + \gamma \frac{Tp_{succ,ab}}{Tp_{tot,ab}} \quad (15)$$

Here,  $Tp_{succ,ab}$  represents the total number of successfully transmitted packets between  $a$  and  $b$  nodes;  $\gamma$  denotes the average weighting factor (set as 0.4 in simulations).  $Tp_{tot,ab}$

denotes the total number of packets transmitted between  $a$  and  $b$  nodes, including the multiple transmissions and retransmission attempts for all packets.

### 3.3.3. Path Loss Model

Path loss is another parameter to analyze path reliability. It is performed by analyzing the number of packets dropped during a transmission, which is a direct resemblance of the reliable data transmission. Path loss ( $PL_d$ ) is computed using the Friis formula in free space based on the distance  $d$  between two communicating nodes.

$$PL = PL_{d_0} + 10p \log\left(\frac{d}{d_0}\right) + X_\sigma \quad (16)$$

Here,  $p$  is the path loss exponent,  $d_0$  is the reference distance,  $X_\sigma$  is the shadowing factor and  $PL_{d_0}$  is the path loss in dB at  $d_0$ .

### 3.3.4. Congestion Model

The congestion model estimates the length and queue length of the transmitted packets in the routing paths. When the data packets are stored in the queue, the network utilization rate ( $\rho$ ) determines the average waiting queue length. It is given as

$$QL = \frac{\rho^2}{1 - \rho} \quad (17)$$

Queue length is computed for all such data packets in the path for all hops and the sum of all queue lengths will be used in the objective function. By using these WBAN modelling strategies, the objective parameters can be estimated and applied to the fitness function. After simplifying the fitness function using the objective parameters, it can be rewritten as

$$f = W_A \times \left| 1 - \frac{E_{tot}(NT)}{E_{max}} \right| + W_B \times \prod \left| 1 - \frac{LinkR(NT)}{LinkR_{max}} \right| + W_C \times \left| 1 - \frac{PL(NT)}{PL_{max}} \right| + W_D \times \sum \left| 1 - \frac{QL(NT)}{QL_{max}} \right| \quad (18)$$

where  $NT$  represents the number of nodes  $N$  in each iteration at given time  $T$  while  $E_{max}$ ,  $LinkR_{max}$ ,  $PL_{max}$  and  $QL_{max}$  are the maximum values of residual energy, link reliability, path loss and queue length, respectively. This fitness function is utilized in the proposed MGCSMO algorithm to select the optimal routes.

### 3.4. Multi-Objective Genetic Chaotic Spider Monkey Optimization Algorithm for Path Selection

The Spider Monkey Optimization (SMO) is based on the social behavior of spider monkeys, including their food search process. The food sources are searched for by the large groups of spider monkeys based on the fission-fusion structure. This is performed by the splitting of the larger living group of the spider monkeys into small groups (fission operation) for searching for the food sources. Then, the spider monkey groups are combined (fusion) to obtain the best food source. In SMO, the search space for the optimization solution is obtained by representing them as the food source and each swarm has a solution that forms the solution set. The fitness function is often the distance between the current positions of the spider monkey to the food source. As a food source is identified as the optimal solution, each swarm moves towards it in intelligent foraging behavior. The standard SMO has six main stages, i.e., local leader phase (LLP), global leader phase (GLP), global leader learning phase (GLLP), local leader learning phase (LLLP), local leader decision phase (LLDP) and global leader decision phase (GLDP). These phases of the SMO help in determining the best solution for the optimization problem. However, the SMO still suffers from a below-par convergence rate. To improve the convergence rate of SMO, EMSMO was presented in [47] by modifying the position update equations.

Although efficient, the EMSMO can also be improved further based on the no free lunch ideology. Through extensive analysis, it has been found that two more improvements can be made to the EMSMO to form the proposed MGCSMO. First, the genetic operators, namely selection, cross over and mutation, from the genetic algorithm are introduced to the EMSMO. The genetic operators' phase (GOP) is introduced in the LLP and GLP. In this proposed algorithm, the random selection, cycle crossover and swap mutations are performed. This phase employs genetic operators and improves exploration capability. Secondly, a chaotic factor, learning technique and exploring techniques are incorporated to the position update equations in GLP, LLP and LLDP, respectively. These two modifications are used to enhance the exploration and exploitation abilities of the spider monkey swarms. The proposed MGCSMO is explained in this section.

Initially, the MGCSMO creates the initial population of  $N$  spider monkeys where each monkey  $SM_i$  ( $i = 1, 2, \dots, N$ ) is considered as a  $D$ -dimensional vector.  $D$  denotes the number of variables in the optimization problem of the  $i$ -th spider monkey  $SM_i$ . Each  $SM_i$  position can be initialized as

$$SM_{ij} = SM_{minj} + U(0, 1) \times (SM_{maxj} - SM_{minj}) \tag{19}$$

where  $SM_{minj}$  and  $SM_{maxj}$  are the minimum and maximum bounds of  $SM_i$  in  $j$ -th direction and  $U(0, 1) \in [0, 1]$  is a uniformly distributed random number.

During the Local Leader Phase (LLP), the Local Leader has been selected in a uniform distributed manner from the initial local group. Before updating the position of the spider monkeys, the GOP is applied. A spider monkey  $SM_i$  is randomly selected and considered as the parents along with the selected local leader. The cycle crossover is applied to the parents to form the children which undergo swap mutation to form the new population of the local group. After obtaining the new population, the new local leader is selected and the positions of the spider monkey in the new population are updated. The positions of the spider monkeys from the new local population are updated based on the local leader's current position and travelling in the  $j$ -th direction.

$$SM_{newij} = SM_{ij} + U(0, 1) \times (LL_{kj} - SM_{ij}) + U(-1, 1) \times (SM_{rj} - SM_{ij}) \tag{20}$$

where  $SM_{rj}$  is the  $j$ -th dimension of the  $r$ -th  $SM$  which is chosen randomly within the  $k$ -th group such that  $r$  is not equal to  $i$ , and  $LL_{kj}$  is the  $j$ -th dimension of the  $k$ -th local group leader position.

In addition to the GOP, the proposed MGCSMO includes a learning method in this phase. The learning method is intended to improve the position update process of LLP. The position update process in Equation (2) is suitable when the  $r$ -th solution  $SM_{rj}$  has better fitness than the  $i$ -th solution  $SM_{ij}$ . This enables the  $i$ -th solution to update its position towards the  $r$ -th solution. In the alternate case, when the fitness  $f_{ij}$  of  $SM_{ij}$  is greater than the fitness  $f_{rj}$  of the  $r$ -th solution  $SM_{rj}$ , Equation (2) does not provide the correct position update. This leads to increased exploitation time and, hence, Equation (2) must be modified as

$$SM_{newij} = \begin{cases} SM_{ij} + U(0, 1) \times (LL_{kj} - SM_{ij}) + U(-1, 1) \times (SM_{rj} - SM_{ij}) & \text{when } f_{rj} > f_{ij} \\ SM_{ij} + U(0, 1) \times (LL_{kj} - SM_{ij}) + U(-1, 1) \times (SM_{ij} - SM_{rj}) & \text{when } f_{rj} < f_{ij} \\ SM_{ij} + U(0, 1) \times (LL_{kj} - SM_{ij}) & \text{when } f_{rj} = f_{ij} \end{cases} \tag{21}$$

Once the LLP is completed, the Global Leader Phase (GLP) begins by selecting the Global Leader. In GLP, the positions of spider monkeys are updated based on probabilities which are calculated using their fitness function.

$$prob = 0.9 \times \frac{f}{\max\_f} + 0.1 \tag{22}$$



$f$  is the fitness value of the  $i$ -th  $SM$  based on the multi-objective fitness function and  $\max\_f$  is the maximum fitness in the group.

Then, the GOP is applied by randomly selecting a spider monkey as one of the parents and the global leader has been selected as the other parent. Then the cycle crossover is applied between the parents, the global leader and the selected member to form the children, which undergo swap mutation to form the new population of the global group. After obtaining the new population, the new global leader is selected. Finally, the positions of the spider monkey in the new population are updated based on the knowledge of the global leader and the travelling direction of the selected random spider monkey. In this position update process, the chaotic optimization mechanism is applied to improve the search process stochastically. It is achieved through the inclusion of a chaotic factor  $\omega$ . This factor improves the randomness and regularity in selecting the best results.

$$SM_{newij} = SM_{ij} + \omega \times (GL_j - SM_{ij}) + U(-1,1) \times (SM_{rj} - SM_{ij}) \times \left( \frac{SUM}{SN} \right) \quad (23)$$

Here,  $\omega = 0.5 \times U(0,1) + 0.5 \times (4 \times U(0,1) \times (1 - U(0,1)))$  is the chaotic factor.  $GL_j$  represent the  $j$ -th dimension of the global leader position and  $j \in \{1, 2, \dots, D\}$  is the randomly chosen index.  $SUM = SM_{ij} + (SM_{ij} - SM_{kj})$  is the improvement presented in EMSMO which is the sum of the  $i$ -th spider monkey  $SM_{ij}$  and the difference between the  $i$ -th spider monkey  $SM_{ij}$  and a randomly selected  $k$ -th local group member  $SM_{kj}$ .  $SN$  is the randomly generated solution by the global leader.

In the Global Leader Learning (GLL) phase, the position of the best global leader is selected based on the fitness values by applying greedy selection in the population. A counter is set for updating the position of the global leader. When the global leader does not update the position in each iteration, the counter value is incremented by one.

In the Local Leader Learning (LLL) phase, the position of the best local leader is updated by applying the greedy selection in that group based on the fitness values. The local leader with the best fitness is selected and similar to the GLL, and a counter is set to monitor the position update.

In the Local Leader Decision (LLD) phase, if any local leader position is not updated up to a predetermined threshold called the local leader limit, then the local leader is regarded as stuck in the local optima. To avoid such a situation, the local group spider monkeys are updated either by random initialization or by using a disturbance process through combined information from the global leader and the local leader. In addition to this combined information, a new factor  $U(0,1) \times (GL_{worstj} - SM_{ij})$  is included to divert the stuck solutions towards the worst solutions for increasing the exploration ability of the GLP.

$$SM_{newij} = SM_{ij} + U(0,1) \times (GL_j - SM_{ij}) + U(0,1) \times (SM_{ij} - LL_{kj}) + U(0,1) \times (GL_{worstj} - SM_{ij}) \quad (24)$$

In the Global Leader Decision (GLD) phase, the position of the global leader is monitored and, if it is not updated until a predetermined number of iterations called global leader limit, then the global leader divides the population into smaller groups. The maximum group limit is maintained by the global leader, which is the total population divided by 10. The complete steps in the proposed MGCSMO are shown in Algorithm 1:

**Algorithm 1** MGCSMO

---

```

Begin
  Initialize Population size N, Local Leader Limit, Global Leader Limit, Max Group Limit,
  Perturbation rate  $pr$ 
  Determine the Max iterations, Dimension (D)
  Initialize  $SM_{ij}$  using Equation (19)
  Set Iterations = 1
  Compute fitness  $f$  for all the solutions (spider monkey food sources)
  While Iterations  $\leq$  Max iterations do
    Select Local Leader for each local group and Global Leader
    For each solution,
      Randomly select a solution from the local group
      Crossover Local Leader (or Global Leader) and randomly selected solution
      Perform mutation on the crossover result
    End for
    Evaluate the whole population
    Update solutions in local groups using Equation (21)
    Apply the greedy selection process based on fitness values of new solutions
    Calculate probability  $prob$  for all group members using Equation (22)
    Produce new solutions for all the group members using Equation (23)
    Update positions of the local and global leader through the greedy selection process
    If any Local group leader reaches Local Leader Limit
      Update Local Leader and Global leader using Equation (24)
    End if
    If Global leader reaches Global Leader Limit
      Split the group into smaller groups
    End if
  End while
  If the best solution is improved
    Increment Iteration by 1
    Return the best solution
  Else
    Merge all the groups & re-split the groups until Max group limit
  End if
End

```

---

**3.5. MGCSMO Based PEDTARA Routing Procedure**

The proposed PEDTARA model using the MGCSMO for route optimization forms the strategy for the different traffics classified in this work. The routing model performs differently for each of the normal, on-demand and emergency data.

Normal data transmission: For normal data, the node sensor-x collects and transmits the data to the main sensor which is forwarded to the WBANC. First, the connectivity between the sensor-x and the main sensor is verified. If there are no previous connections between them, the setup request is sent from sensor-x to the main sensor. When the request is received by the main sensor, the energy level of the sensor-x is analyzed to check whether it has sufficient energy for data transmission. Considering the heat issues is also important in this stage. When the sensor-x's energy is higher than the Specific Absorption Rate (SAR), then there is the possibility of overheating. In this situation, the sensor-x is deemed unfit for data transmission. Hence, the sensor-x must satisfy two thresholds to be selected as the forwarding node.

If the energy level of the sensor-x is greater than the energy threshold ( $TH_{energy}$ ), then the sensor-x has sufficient energy for data transmission to the main sensor. Similarly, the SAR of the sensor-x must be less than the heat threshold ( $TH_{heat}$ ), above which the sensor node becomes overheated and might damage the tissues in the patients' body. The SAR

is estimated by the heat absorption on the RF wave exposure for a given time. Its unit is W/kg.

$$SAR = \frac{\sigma(EMF)^2}{\rho} \quad (25)$$

where  $\sigma$  denotes the conductivity of the tissue,  $\rho$  is the density of the tissue and  $EMF$  is the induced electromagnetic field specifying the RF spectrum strength. The temperature rise in the tissue beneath the sensor node is estimated as

$$\Delta T = (SAR) \frac{t}{C} \quad (26)$$

where  $t$  is the time interval for which the tissue is exposed to electromagnetic emission and  $C$  is the specific heat capacity.

When the SAR value of the sensor-x is below  $TH_{heat}$ , the main sensor establishes the connection and sends the response to the setup request. Once the forwarding nodes are selected, the multiple forwarding paths are established by the main sensor. The MGCSMO presented in the previous section selects the optimal path from this set of available paths. Once the path is selected, the sensor-x sends the data and the main sensor responds with the acknowledgment. This procedure will be performed at the main sensor for collecting data from all similar nodes. However, during the on-demand and critical data transmission, the best or the optimal paths might not be available for normal data transmission. In such cases, the transmission takes place in the next best path from the available list.

On-demand data transmission: the transmission of on-demand data is slightly trickier than for normal data. The on-demand data are a continuous process generated at the immediate request of the physician. The physician sends the request regarding sensory data for the heartbeat, pulse reading, blood pressure or sugar level of the patient. The WBANC receives this request and forwards it to the corresponding sensor node for collecting the required data readings. The corresponding sensor-x will gather the data and send them to the main sensor, which transmits the data to WBANC for final transmission to the physician. As in the normal data transmission, the connectivity between the sensor-x and main sensor will be tested. If there is no connection, the setup request will be sent to the main sensor which sends the response message. When the sensor-x is not in direct connection, the main sensor utilizes the neighboring sensors of sensor-x as relay nodes and sends the response and acknowledgment. In this way, the possible paths are analyzed and the optimized path is chosen by the MGCSMO. Before starting the transmission, the energy level of the sensor-x and the SAR value of the sensor-x and the neighboring relay nodes are also analyzed. If they satisfy the two thresholds  $TH_{energy}$  and  $TH_{heat}$ , then the transmission is started. If they do not satisfy the  $TH_{energy}$ , then the possibility of transmitting the data to the relay is analyzed and selected as the current sensor node. Likewise, if  $TH_{heat}$  is not satisfied, then the sensor-x request will be placed in the buffer state until the time-to-live session expires.

Critical data transmission: the critical data during emergency conditions contain both high and low threshold readings of vital health conditions. The proposed PEDTARA must transmit the emergency data of vital health signs based on priority without delay or packet loss. This can be done by selecting the routing paths with no conflicts. To achieve this objective, the patients' traffic priority must be computed using the following equation.

$$\text{traffic priority} = \frac{\text{sensor threshold readings}}{\text{Packet capacity} \times \text{generation time}} \quad (27)$$

The *sensor threshold readings* value can be either a high or low reading, based on which the paths will be allocated. The generation time denotes the data generation time, and it must have a packet size greater than zero. This priority helps in eliminating the conflicts in allocating the paths and related resources to the sensor nodes.

The transmission of emergency data takes place in three scenarios. In the first scenario, the obtained readings are all low threshold data readings. In the second scenario, they are

all high threshold readings and, in the third scenario, they are a combination of both low and high threshold readings. As presented in Table 1, the threshold value ranges are critical. In the first scenario, two sensors, sensor-x and sensor-y, are taken, which provide low threshold readings. Sensor-x has the earlier reading while sensor-y has the recent readings. As heartbeat, sugar, blood pressure readings, etc. are more likely to hit the low threshold than the high threshold, which is dangerous, sensor-x, which has the earlier reading of vital signs, will be transmitted first.

In the second scenario, two cases are possible: the first case is when sensor-x has a recently-generated low threshold and sensor-y has, earlier, generated a high threshold. In this case, sensor-x will be transmitted first. Alternatively, if sensor-x has, earlier, generated a low threshold and sensor-y has a recently-generated high threshold, then the priority will be given to the low threshold. The second case is when sensor-x has recently generated a high threshold and sensor-y has, earlier, generated a low threshold. Similar to the first case, the low threshold readings from sensor-y will be transmitted first, irrespective of the generated time. The same procedure is applied even when sensor-x has, earlier, generated a high threshold and sensor-y has recently generated a low threshold such that the low threshold readings will be transmitted first.

In the third scenario, both sensor-x and sensor-y provide a high threshold reading of vital signs. In this scenario, the sensor data which have the earlier generation time will be transmitted. In all these three scenarios, the generation time is also monitored. Likewise, the connectivity setup and sensor selection for forwarding are done based on the energy and SAR thresholds. When sensor-x or sensor-y are in direct connection with the main sensor, the transmission is direct. If there is no direct connection, the neighbor nodes are utilized as in normal and on-demand transmission. In some cases, the emergency-based node does not receive any response from neighbor nodes, and then, sensor-x or sensor-y will send a direct request for allocation of timeslot for instant transmission to the main sensor. In this manner, the transmission is done using the proposed methodology.

#### 4. Results and Discussion

The proposed PEDTARA routing algorithm is simulated and evaluated using MATLAB (R2016b) with the suggested experimental setup. The proposed system model is designed to accommodate 10 patients utilizing a total of 100 nodes placed in the area of  $100\text{ m} \times 100\text{ m}$ . This means that each patient's area is  $10\text{ m} \times 10\text{ m}$  and uses a maximum of 10 nodes. The complete network structure is flexibly designed so that additional patients can be accommodated by expanding the location and number of nodes. Each patient has an SDN-based WBAN setup with 10 nodes, among which 1 WBANC, 2 PDD and 1 CDD nodes are assigned for controlling and processing the data. The experimental setup for the simulations is given in Table 2.

**Table 2.** Experimental setup.

Parameters	Settings
Area	100 m × 100 m
Type of deployment	Fixed and movable
Number of nodes	100
Initial node energy	Normal node: 100 Joules WBANC: 200 Joules
Transmission power	−25 dBm, −15 dBm, −10 dBm
Reception power	7 dBm
MAC	IEEE 802.15.6
Channel type	Wireless Channel
Traffic type	CBR
Packet size	32 bytes
Packet rate	8 packets/sec
Radio transmission range	25 m

The proposed method is implemented in MATLAB by initializing the above parameters. The implementation is started by forming the function for obtaining channel realizations for the Hospital WBAN channel as in the standard WBAN defined for the base architecture. Then, the sensors are configured by assigning the location, energy and other basic properties. Next, the specified sensors are randomly assigned to their tasks of collecting the particular vital signs. The model for forming the paths between the sensors is established by computing the current distance between the source nodes to the sink. Then, the sender and receiver nodes are found based on the current requirements. Then, the routing model is incorporated as the routing selection approach. Next, the sensors and the routing model are plotted in the network area described in Table 2. After the completion of each transmission, the routing paths are reset to define different paths that are energy efficient. Finally, the module is set for sending and receiving the packets. The system is designed in such a manner that, when the MATLAB is restarted, the sensors will initialize to their starting points with full energy and other properties. The last step in the implementation will be providing the computation equations for calculating the performance metrics and other vital parameters to evaluate the efficiency. The experiments are conducted many times to establish reliability in the evaluation. Thus, the implemented model will be used for the evaluation process.

#### 4.1. Evaluation of PEDTARA for Different Traffic Classes

The proposed PEDTARA routing model has been evaluated under controlled environments to estimate its efficiency for different traffic classes. For the normal data, the routing can be pre-planned and the consistency might be the same until the on-demand or critical data transmission interferes. To analyze the three classes of traffics, the parameters, namely end-to-end delay, packet reception rate, energy consumption and the number of heated nodes are considered. The experiments are conducted 10 times by setting the proposed model program in a loop to obtain varying results, which are summarized, and mean values are plotted in the graphs. Additionally, the experiments are conducted many times based on varying the number of input nodes from 5 to 50 in intervals of 5 nodes.

Figure 2 illustrates the end-to-end delay assessment of the proposed PEDTARA model for the three traffic classes. PEDTARA has greatly reduced the delay for critical data to reduce the risk of emergency by employing the optimal route selection and minimized queue length. As it reduces the delay for critical data transmission, it directly increases the normal data transmission. Although not equivalent to the critical data, the on-demand data transmission is also considerably more efficient than the normal transmission. The major reason for this enhancement is the use of temperature, energy and delay-aware optimized routing on a priority basis.

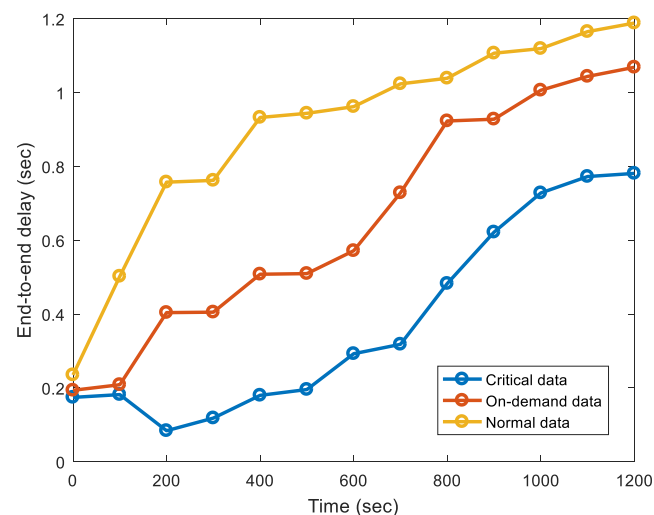


Figure 2. End-to-end delay.



Figure 3 shows the packet reception ratio for the three traffic classes of the proposed PEDTARA model. It can be seen that the packet reception is higher during critical data transmission while the normal transmission incurs a good ratio but less than the critical and on-demand data transmission. This is orchestrated by the PEDTARA to limit the normal transmission during emergencies and also to ensure a high priority of the critical data.

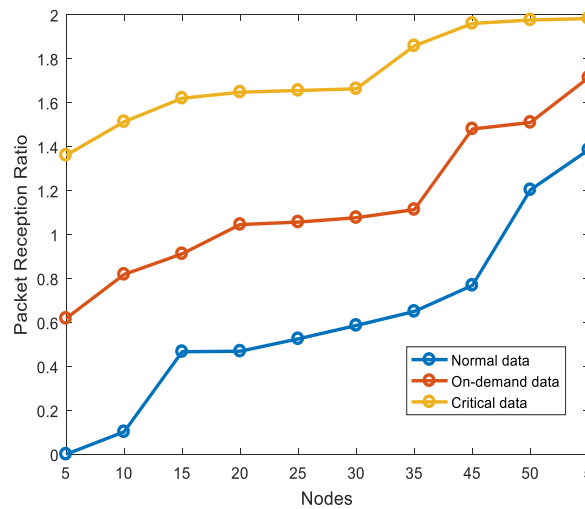


Figure 3. Packet reception ratio.

Figure 4 illustrates the energy consumption for all three traffic classes. The proposed PEDTARA has achieved better energy conservation during all three types of traffic. It must be noted that critical data have consumed the highest energy since they include a high transmission rate. However, it is considerably below 2 Joules, thus limiting the energy consumption and, in turn, reducing the heat nodes. Considering the heat nodes, the energy consumption of critical data transmission tends to increase the SAR value of the nodes in the selected paths more than the on-demand and normal data transmission.

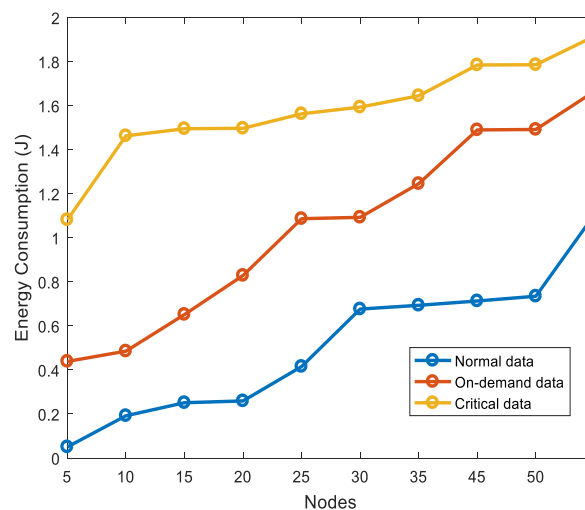


Figure 4. Energy consumption.

Figure 5 shows the number of heated nodes during the three traffic classes of the proposed PEDTARA. As stated above, due to the high transmission rate for critical data, energy consumption and SAR have been considerably increased. This leads to a high number of heated nodes in the network. However, after certain iterations, the number of heated nodes is steady. In normal and on-demand data transmissions, the number of heated nodes is reasonable. Thus, it can be justified that the consideration of temperature, delay, energy and traffic priority does not degrade the transmission quality.

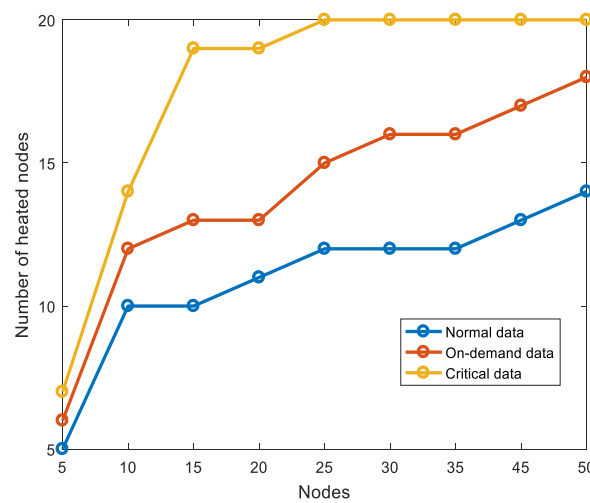


Figure 5. Number of heated nodes.

4.2. Performance Comparison of PEDTARA with Other Models

The performance of the proposed PEDTARA is compared with the existing routing algorithms from the literature, namely CDR [18], TAE0 [32], Tripe-EEC [45] and EOCC-TARA [47], to estimate its superiority. PEDTARA has been designed for the SDN-based WBAN and, hence, the selected existing models have the compatibility to work in the proposed experimental environment. The comparisons are made in terms of energy, temperature and congestion control aspects. The performance metrics used are end-to-end delay, queue length, energy consumption, residual energy, packet delivery ratio, throughput, network lifetime, transmission rate, number of dead nodes and percentage of heated nodes. The experiments are conducted 10 times by setting the MATLAB-compiled program in a loop to run 10 times. The results obtained in each execution are stored and added in the matrices and the mean values are calculated in the background and can be visualized by clicking the parameter name in the program code. These mean values are used to plot the below comparison graphs. Additionally, the program code is run with a different number of nodes varying from 5 to 50 in intervals of 5, thus increasing the number of experiments to 10 × 10. Therefore, the obtained results can be highly reliable. The comparison results highlight the effectiveness of the proposed approach.

Figure 6 displays the comparison of PEDTARA performance with that of the existing methods in terms of (a) end-to-end delay and (b) queue length. From Figure 6a, it can be seen that the delay of PEDTARA is considerably lower than the other compared models. It has an average of 0.1 to 0.2 s less than the second-best EOCC-TARA model. Likewise, from Figure 6b, it is proven that the proposed model has lesser congestion, justified through lower queue length. Since the queue length is minimized, the delay in the optimized routing process is automatically reduced. Tables 3 and 4 illustrate the end-to-end delay and queue length results, respectively, of the proposed PEDTARA and existing routing protocols.

Table 3. End-to-end delay (seconds).

Methods	Number of Nodes									
	5	10	15	20	25	30	35	40	45	50
CDR	0.6569	0.6981	0.8034	0.8314	0.9427	0.9516	0.9816	0.9831	0.9841	0.9991
TAE0	0.3724	0.3909	0.5269	0.6280	0.6665	0.6692	0.7011	0.7379	0.8819	0.9203
Tripe-EEC	0.1734	0.1981	0.4168	0.4317	0.4607	0.4897	0.5391	0.5479	0.5612	0.6663
EOCC-TARA	0.1332	0.1672	0.1711	0.1781	0.2920	0.3395	0.3689	0.3993	0.4177	0.4228
PEDTARA	0.0155	0.0326	0.0527	0.0605	0.0835	0.1062	0.1280	0.1904	0.2691	0.3015

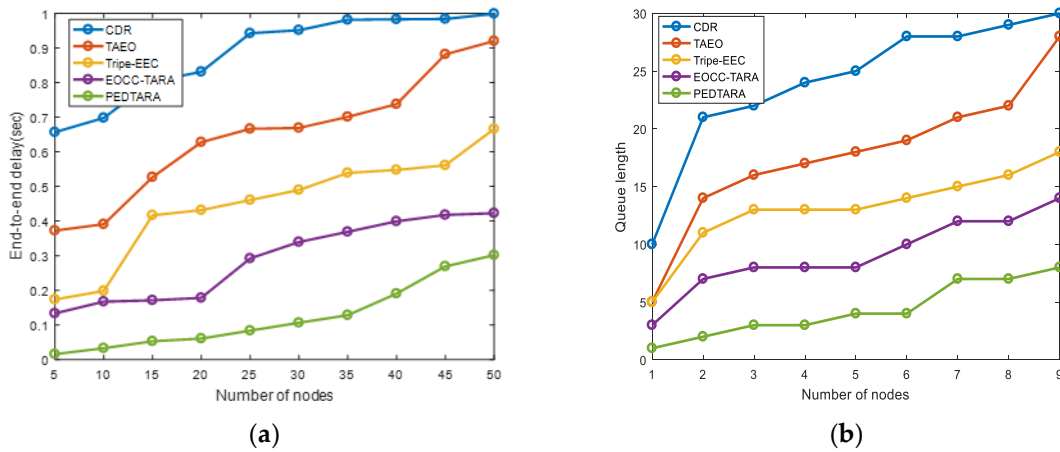


Figure 6. End-to-end delay and queue length comparisons: (a) end-to-end delay; (b) queue length.

Table 4. Queue length.

Methods	Number of Nodes								
	1	2	3	4	5	6	7	8	9
CDR	10	21	22	24	25	28	28	29	30
TAEO	5	14	16	17	18	19	21	22	28
Tripe-EEC	5	11	13	13	13	14	15	16	18
EOCC-TARA	3	7	8	8	8	10	12	12	14
PEDTARA	1	2	3	3	4	4	7	7	8

Figure 7 illustrates the comparison results of the PEDTARA model with that of the existing methods in terms of (a) energy consumption and (b) residual energy. From Figure 7a, it can be seen that the PEDTARA consumes much less energy than the other compared models. It has an average of 0.2 J less than the next-best EOCC-TARA model. As the energy consumption is greatly reduced by the MGCSMO-based routing process, the residual energy is surplus in the WBAN, and it is also 0.2 J higher than the EOCC-TARA model as shown in Figure 7b. Tables 5 and 6 illustrate the energy consumption and residual energy results, respectively, of the proposed PEDTARA and existing routing protocols.

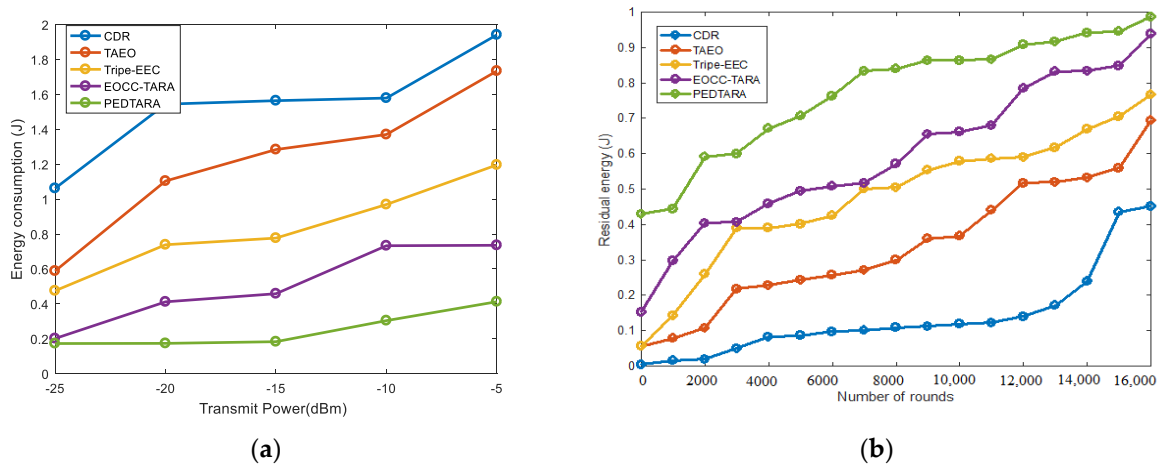


Figure 7. Energy consumption and residual energy comparisons: (a) energy consumption; (b) residual energy.

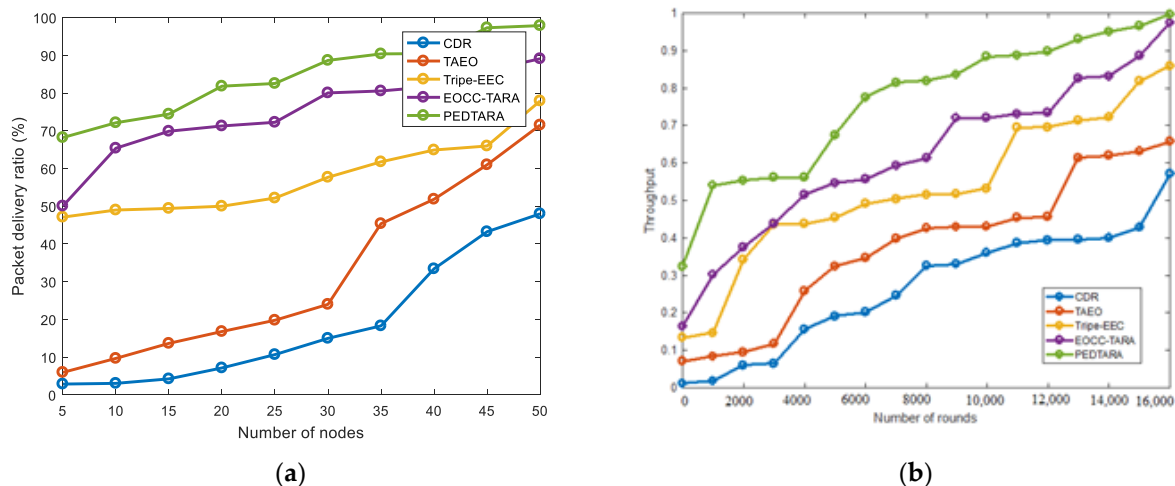
**Table 5.** Energy consumption (J).

Methods	Transmit Power (dBm)				
	−25	−20	−15	−10	−5
CDR	1.0617	1.5439	1.5639	1.5787	1.9412
TAE0	0.5881	1.1036	1.2839	1.3701	1.7339
Tripe-EEC	0.4747	0.7384	0.7765	0.9690	1.1959
EOCC-TARA	0.2012	0.4113	0.4579	0.7329	0.7353
PEDTARA	0.1725	0.1733	0.1830	0.3037	0.4121

**Table 6.** Residual Energy (J).

Methods	Number of Rounds								
	0	2000	4000	6000	8000	10,000	12,000	14,000	16,000
CDR	0.0196	0.0636	0.1058	0.1500	0.1673	0.2160	0.3912	0.4795	0.6279
TAE0	0.1097	0.1999	0.2428	0.2703	0.3309	0.3947	0.4386	0.5439	0.7635
Tripe-EEC	0.1920	0.3181	0.3774	0.4243	0.5201	0.5303	0.6713	0.7551	0.8620
EOCC-TARA	0.4046	0.4424	0.5861	0.6456	0.6878	0.7487	0.7691	0.8217	0.9329
PEDTARA	0.4484	0.6963	0.7363	0.7549	0.8256	0.8611	0.9398	0.9727	0.9937

Figure 8 shows the (a) packet delivery ratio and (b) throughput comparison results of the PEDTARA and the existing routing models. From Figure 8a, it can be seen that the PEDTARA delivers the transmission data packets with a higher success rate than the existing models. It has an increase in packet delivery ratio which is 12% higher than EOCC-TARA, which provided the next-best performance. Since the packet transmission is better in the PEDTARA, the throughput is also improved significantly as shown in Figure 8b. It has increased by 2% higher than the EOCC-TARA model. Tables 7 and 8 illustrate the packet delivery ratio and throughput results, respectively, of the proposed PEDTARA and existing routing protocols.



**Figure 8.** Packet delivery ratio and throughput comparisons: (a) packet delivery ratio; (b) throughput.

Figure 9 demonstrates the (a) network lifetime and (b) the number of dead nodes comparison results of the PEDTARA and the existing routing models. From Figure 9a, it can be seen that the PEDTARA has a longer network lifetime than the existing models due to its energy conservation and lesser loss of transmission packets. It has an increase in lifetime that is 40 min longer than EOCC-TARA because of the optimized routing process and lower energy wastage. These advantages also reduce the number of dead nodes as shown in Figure 9b. This property makes the network survive longer than the initial expectation. On average, the PEDTARA has resulted in three less dead nodes during the transmission

rounds. Tables 9 and 10 illustrate the network lifetime and the number of dead nodes, respectively, of the proposed PEDTARA and existing routing protocols.

Table 7. Packet delivery ratio (%).

Methods	Number of Nodes									
	5	10	15	20	25	30	35	40	45	50
CDR	2.86	3.05	4.24	7.14	10.67	14.98	18.29	33.41	43.23	47.99
TAE0	5.96	9.67	13.63	16.79	19.78	23.99	45.37	51.85	60.98	71.50
Tripe-EEC	47.18	48.91	49.44	50.02	52.16	57.67	61.76	64.89	65.96	77.90
EOCC-TARA	50.02	65.37	69.86	71.26	72.24	80.03	80.54	81.75	85.94	89.09
PEDTARA	68.12	72.17	74.47	81.82	82.53	88.65	90.37	90.47	97.29	97.86

Table 8. Throughput.

Methods	Number of Rounds									
	0	2000	4000	6000	8000	10,000	12,000	14,000	16,000	
CDR	0.0012	0.0358	0.0908	0.1194	0.1537	0.2407	0.3225	0.4257	0.4574	
TAE0	0.1056	0.1917	0.2240	0.2665	0.2891	0.3868	0.4243	0.5181	0.6358	
Tripe-EEC	0.2362	0.2691	0.3411	0.4609	0.4714	0.5822	0.6377	0.6620	0.6753	
EOCC-TARA	0.4401	0.5762	0.6074	0.6135	0.6619	0.6761	0.7655	0.7805	0.8754	
PEDTARA	0.5271	0.6834	0.7218	0.7703	0.7847	0.8444	0.9160	0.9436	0.9577	

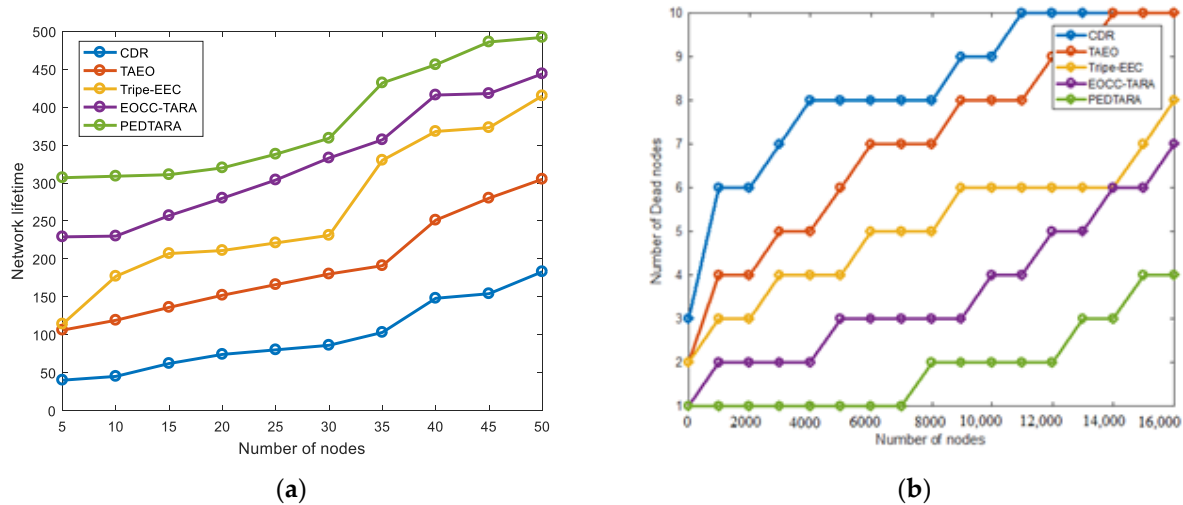


Figure 9. Comparison of network lifetime and number of dead nodes: (a) network lifetime; (b) number of dead nodes.

Table 9. Network Lifetime.

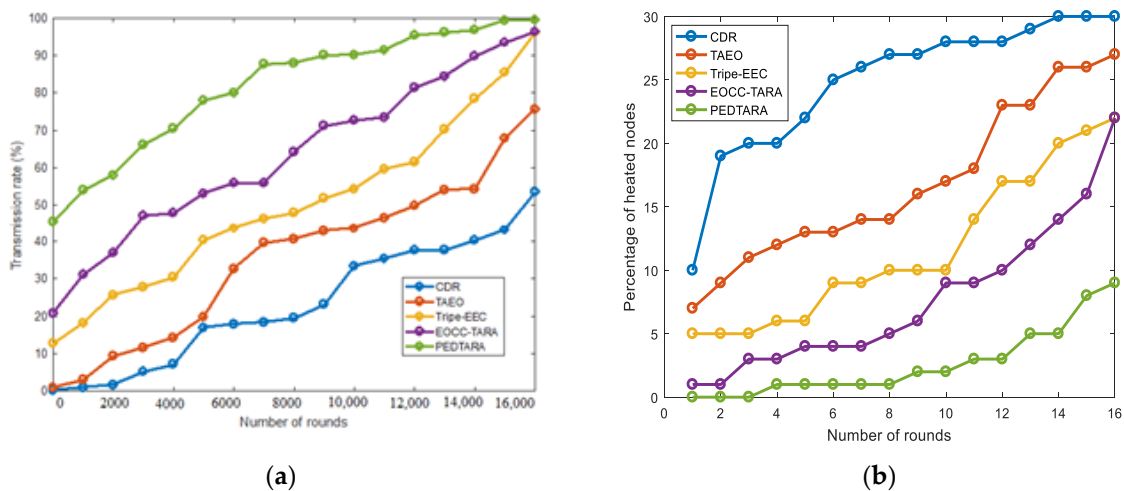
Methods	Number of Nodes									
	5	10	15	20	25	30	35	40	45	50
CDR	40	45	62	74	80	86	103	148	154	183
TAE0	106	119	136	152	166	180	191	251	280	305
Tripe-EEC	114	177	207	211	221	231	330	368	373	415
EOCC-TARA	229	230	257	280	304	333	357	416	418	444
PEDTARA	307	309	311	320	338	359	432	456	486	492



**Table 10.** Number of dead nodes.

Methods	Number of Rounds								
	0	2000	4000	6000	8000	10,000	12,000	14,000	16,000
CDR	3	7	8	9	9	9	10	10	10
TAE0	2	5	6	6	7	7	9	9	10
Tripe-EEC	2	4	5	5	6	6	6	7	9
EOCC-TARA	2	2	2	2	3	5	6	7	8
PEDTARA	1	1	1	1	1	2	3	3	6

Figure 10 displays the comparison of PEDTARA and the existing routing models in terms of (a) transmission rate and (b) percentage of heated nodes. From Figure 10a, it is evident that the PEDTARA has a higher transmission rate than the existing models due to its successful transmission and efficient routing for all three classes of traffic. It has an increase in transmission rate that is 2% higher than EOCC-TARA. Since the higher transmission rate leads to increased network usage and energy consumption, the SAR value of the nodes also increases. This leads to an increased number of heated nodes in the network. Figure 9b shows the percentage of heated nodes, and it is found that the PEDTARA has reduced the heated nodes by using the resting periods for the nodes in the selection process of forwarding nodes. This behavior of the PEDTARA gradually reduces the heating time of the nodes and reduces the number nodes being overheated by about 10%. Tables 11 and 12 illustrate the transmission rate and percentage of heated nodes, respectively, of the proposed PEDTARA and existing routing protocols.



**Figure 10.** Comparison of transmission rate and percentage of heated nodes: (a) transmission rate; (b) percentage of heated nodes.

**Table 11.** Transmission rate (%).

Methods	Number of Rounds								
	0	2000	4000	6000	8000	10,000	12,000	14,000	16,000
CDR	0.78	5.94	7.73	10.48	10.97	16.62	19.62	29.42	43.24
TAE0	9.23	12.65	17.04	21.20	27.29	31.58	35.07	39.67	60.35
Tripe-EEC	12.52	25.10	29.15	40.23	43.26	53.06	55.77	63.17	69.47
EOCC-TARA	13.01	31.64	40.53	59.74	65.54	68.40	70.32	75.81	76.89
PEDTARA	16.82	42.31	67.32	77.27	79.78	87.11	91.38	96.44	98.79

**Table 12.** Percentage of heated nodes.

Methods	Number of Rounds								
	0	2	4	6	8	10	12	14	16
CDR	10	20	22	26	27	28	29	30	30
TAE0	7	11	13	14	16	18	23	26	28
Tripe-EEC	5	5	6	9	10	14	17	21	26
EOCC-TARA	1	6	4	4	6	9	12	16	24
PEDTARA	0	0	1	1	2	3	5	8	15

The proposed PEDTARA might face a few challenges in real patient scenarios. Although it is efficient and suitable to include more vital signs apart from EEG, ECG, temperature, position, motion and pulse rate, it might cause additional complexities. Some tests such as X-rays, CT or MRI scans can be included in the architecture but might face performance issues due to the need for manual monitoring at the patients' locations. While these constraints cannot be termed as drawbacks, the proposed PEDTARA might require adequate modifications to include complex medical test analysis. Apart from this constraint, this research has limitations in handling the environmental factors and mobility issues. Although the motion sensors are used to monitor the movements of the patients, the PEDTARA is not adequate to monitor all the activities of the patients.

## 5. Conclusions

An efficient routing model named the Priority-based Energy Efficient, Delay and Temperature Aware Routing Algorithm has been developed in this paper for SDN-based WBAN. The proposed PEDTARA model employed the use of an advanced optimized algorithm of MGCSMO for route optimization based on energy, queue length, link reliability and path loss with thermal dissipation of nodes considered for the forwarding node selection. The proposed PEDTARA model initially selects the forwarding nodes based on energy and temperature. It makes the heated nodes rest for a few cycles to reduce the possibility of over-heating. Then, the fitness function was derived and used in MGCSMO to select the optimal routing paths. Experimental results attained from simulations prove that the proposed PEDTARA model performs better than the traditional routing models for the SDN-based WBAN. In the future, the adverse environmental factors and the mobility issues in the practical environment will be assessed. The possibility of reducing the delay by splitting the network routes for different traffic classes will also be investigated.

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