IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 12, 2020, accepted February 23, 2020, date of publication February 27, 2020, date of current version March 10, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2976819

Energy Optimized Congestion Control-Based Temperature Aware Routing Algorithm for Software Defined Wireless Body Area Networks

OMAR AHMED[1], FUJI REN[2], (Senior Member, IEEE), AMMAR HAWBANI[3], AND YASER AL-SHARABI[1]

[1]School of Computer Science and Technology, Hefei University of Technology, Hefei 230009, China
[2]Faculty of Engineering, Tokushima University, Tokushima 770-8506, Japan
[3]School of Computer Science and Technology, University of Science and Technology of China, Hefei 230026, China

Corresponding author: Omar Ahmed (omar@mail.hfut.edu.cn)

This work was supported by the National Natural Science Foundation of China under Grant 61432004 and Grant U1613217.

ABSTRACT Wireless Body Area Network (WBAN) is a promising cost-effective technology for the privacy confined military applications and healthcare applications like remote health monitoring, telemedicine, and e-health services. The use of a Software-Defined Network (SDN) approach improves the control and management processes of the complex structured WBANs and also provides higher flexibility and dynamic network structure. To seamless routing performance in SDN-based WBAN, the energy-efficiency problems must be tackled effectively. The main contribution of this paper is to develop a novel Energy Optimized Congestion Control based on Temperature Aware Routing Algorithm (EOCC-TARA) using Enhanced Multi-objective Spider Monkey Optimization (EMSMO) for SDN-based WBAN. This algorithm overcomes the vital challenges, namely energy-efficiency, congestion-free communication, and reducing adverse thermal effects in WBAN routing. First, the proposed EOCC-TARA routing algorithm considers the effects of temperature due to the thermal dissipation of sensor nodes and formulates a strategy to adaptively select the forwarding nodes based on temperature and energy. Then the congestion avoidance concept is added with the energy-efficiency, link reliability, and path loss for modeling the cost function based on which the EMSMO provides the optimal routing. Simulations were performed, and the evaluation results showed that the proposed EOCC-TARA routing algorithm has superior performance than the traditional routing approaches in terms of energy consumption, network lifetime, throughput, temperature control, congestion overhead, delay, and successful transmission rate.

INDEX TERMS Wireless body area network, software-defined network, enhanced multi-objective spider monkey optimization, remote health monitoring, specific absorption rate, energy-efficiency, congestion avoidance, temperature aware routing.

I. INTRODUCTION

The recent advancements in information and communication technology have led to the modernization of the applied sciences. Particularly, the minimization of wireless sensors and other electronic devices has improved the applications in the healthcare field by forming the Wireless Body Area Network (WBAN) [1]. The new possibilities created by technological developments have also reduced the health costs and delay in treatment. The WBANs are cost-effective, smaller size, limited battery life, better quality of service (QoS) requirements, and heterogeneous network traffic [2]. Internet-of-Things (IoT) is a novel technology that connects any object to a network, and this strategy is most effective for the WBAN architecture of healthcare services [3], [4]. WBANs with IoT technology provide

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

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see http://creativecommons.org/licenses/by/4.0/

solutions for powerful applications with scalable, reliable, flexible, and cost-effective service features. WBAN architecture must assure these features to provide a uniform and secure communications [4]. Irrespective of the use of IoT technology, the WBANs face problems of heterogeneity, scalability, and energy-efficiency that degrade the desired performance [5], [6]. The latest studies have pointed towards incorporating the Software-Defined Network (SDN) approach as a feasible solution to ensure these features [7]. SDN is a highly promising tool that offers approaches for designing and handling the networks, especially the abstraction of the control and data planes. The use of centralized and programmable management of the SDN-based WBANs provides better scalability and heterogeneity for secured data transmission [8]. Therefore, the other problem of energy-efficient routing is prioritized in the latest studies. Apart from energy-efficiency, there are few more problems, namely the temperature and congestion, which are considered in this work as it needs attention in the SDN-based WBANs.

Energy consumption is one of the most common problems in WBANs as it is vital in prolonging the network lifetime [9]. In WBAN based applications, the energy-efficiency and network lifetime are considered as significant factors as the energy resources are limited in the compact architecture. Direct communication between the source and destination nodes provides less delay but consumes higher energy because of the short communication range and high possibility of loss and subsequent retransmission. In order to avoid these problems, the multi-hop transmission was introduced to provide data transmission through intermediate nodes, but the energy consumption becomes higher for all forwarding nodes in the path and also creates issues in the QoS necessities [10]. Therefore the energy-efficiency can be achieved through the development of an effective routing mechanism to ensure QoS along with reducing the energy constraints on forwarding nodes and minimizing the delay and path loss.

The second vital problem is the thermal dissipation of the sensor nodes and its subsequent effect on the human tissues underneath the positioned node [11]. The nodes in WBAN communicate with each other using radio frequency (RF) signals. This RF communication dissipates heat and is absorbed by the tissues that raise the temperature in that particular region. Another factor influencing the temperature is the heat generated by the nodes' internal circuitry during the handling of data processing. The rise in temperature results in the formation of hot-spot nodes, which affects the property of human tissues [12]. This paper focuses on avoiding these hot-spot nodes by preventing the heated node from the transmission process until the temperature is reduced to attain safe transmission. Another vital factor considered in this paper is the congestion in routing paths, mainly due to the overburden of data in the selected shortest routes [13]. The other factors of congestion are the unbalanced load distribution, delayed transmission, retransmission of lost data, the minimum lifetime of forwarding nodes, etc. The congestion avoidance must be implemented in order to reduce energy wastage and improve packet transmission [14]. The congestion control is achieved in the proposed work by introducing the congestion queue length as a factor in the routing cost model.

The three vital problems of energy consumption, temperature, and congestion in SDN-based WBANs must be handled effectively to achieve superior routing, which is very important in healthcare and military applications. This paper consolidated the above-presented suggestions for these three vital issues and developed an energy-efficient, temperature, and congestion aware routing algorithm named EOCC-TARA using the EMSMO algorithm. Spider Monkey Optimization (SMO) is a global optimization algorithm motivated by the Fission-Fusion social (FFS) structure of spider monkeys during their foraging behavior. SMO intricately represents two essential theories of swarm intelligence: self-organization and division of labor. First, the spider monkey population will be initialized, and they self-organized into a local leader, global leader, and member monkeys. Then the learning and action phases are performed to iteratively select the best solutions. However, the convergence rate is slow in SMO, and hence modifications are suggested. The proposed EMSMO algorithm improves the performance of the basic SMO algorithm. It introduced a new Position update equation that takes an average of the difference of current position and randomly generated positions. It generates a random position in a given range for a particular problem. This suggested modification accelerates the convergence rate and increases reliability. Here, it is assumed that a better-fitted solution has an optimal solution in their proximity.

The proposed routing algorithm employs the optimization of the cost model formulated based on the parameters: residual energy, link reliability, path loss, and queue length. While the residual energy, link reliability, and path loss are associated with the energy-efficiency of WBANs, the queue length determines the congestion. Prior to the routing, the temperature control is implemented at the forwarding nodes' selection stage based on the current temperature of nodes and also the temperature rise in the underlying tissues. By considering these approaches, efficient routing is achieved in the SDN-based WBAN and it helps in stabilizing the applications developed using it. The experimental results are conducted to evaluate and justify the efficiency of the proposed EOCC-TARA routing algorithm. The remainder of the paper is organized as: Section II presents the literature survey of recent related works. Section III presents the system model and also the methodology of the proposed routing algorithm. The experiments and the result discussions are provided in section IV, while section V presents a conclusion to this paper.

II. RELATED WORKS

WBANs and remote health monitoring are widely studied research topics in modern internet society as it considerably reduces human efforts. SDN-based WBANs is a relatively new concept that has been gaining increased attention in recent years. Cicioğlu and Çalhan [15] introduced the

SDN-based WBAN routing algorithm for healthcare applications. This approach utilized a centralized control panel architecture to integrate and manage all network infrastructures of WBAN using the SDN controller. Additionally, an energy-efficient routing algorithm is proposed using residual energy and lifetime. This approach provided better throughput, delay, successful transmission rate, and energy consumption rates than traditional models. However, it supports only Inter-WBAN communication while the problem of node thermal dissipation is also averted for forwarding node selection.

Energy-Efficiency is a vital aspect in any network like WBAN, which supports emergency life-saving situations and it is considered as a high prioritized factor. Mu *et al.* [16] proposed a simplified energy-balanced alternative-aware routing (SEAR) algorithm for complex WBAN in which the residual energy and the current load are considered for the routing request forwarding process. SEAR also fixes the links faster by adding link fields to the routing tables to identify whether links are disconnected or nodes are invalid. This approach reduces the end-to-end delay and energy consumption and improves network throughput. However, this algorithm does not consider the effect of node temperature during the forwarding node selection, which might become a major limitation in practical applications. Chen *et al.* [17] developed power-aware 2-covered path routing algorithms for WBANs. The algorithms named graph transformation planning (GTP), 2-covered area stretching planning (TASP) and radii shrinking planning (RSP) perform discrete transmission with variable ranges and power levels. The experimental results showed that the GTP has achieved 96% power saving and also improves the network lifetime. However, the execution time of this model is significantly higher due to the presence of unnecessary nodes without proper monitoring. Abidi *et al.* [18] introduced an energy-efficient clustering based routing protocol for WBANs. This routing protocol considered the routing problem as a resource-hungry operation and utilized clustering, data aggregation, and gateway body sensor to minimize energy consumption. This process of data transmission also increases network stability and lifetime. However, the vital factor of nodes' cooperation is neglected in this operation, and it reduces the effectiveness of the protocol in real-time transmissions.

Esmaeili and Bidgoli [19] proposed an Evolutionary-based multi-hop routing protocol (EMRP) for WBANs by resolving the problems of insufficient objective metrics, manual controlling, and low-optimal route selection. This EMRP formulates a multi-objective function based on energy level, distance, estimated path loss, and estimated energy consumption, and using this function, the forwarding nodes are selected optimally by adaptive genetic algorithm. The results showed that EMRP provides better performance with maximum lifetime and throughput, and minimum energy consumption and path loss. However, this protocol is slightly on the back-foot as it considered only the static node placement while the body movements of the patients are neglected. Navya and Deepalakshmi [20] presented mobility supported priority-based energy-efficient routing protocol for critical data transmission (M-PEERPCDT) with lesser propagation delays and path loss as critical physiological parameters in WBAN. This model integrates the concepts of critical, priority, and hierarchical routing techniques to prioritize the emergency data, while also reducing energy consumption. This approach performs the elimination of redundant packets and uses a hierarchical routing scheme to minimize energy consumption in the entire network. However, the reliability of this model is questionable since the general health data of patients in the queue would wait until the emergency data is transmitted, and no solution is offered at this stage of operation.

Anwar *et al.* [21] presented an energy-aware link efficient routing approach for ensuring green communications in WBANs. In this approach, the link efficiency-oriented network model is designed considering beaconing information and network initialization process. Then, a path cost calculation model is formulated aiming at the energy-aware link efficiency for routing. This approach provided less energy consumption and packet loss, while the high throughput and network lifetime for healthcare applications. However, this model supports only a single path transmission and also subjected to unexpected link failures. Kaur and Singh [22] proposed an Optimized Cost Effective and Energy Efficient Routing Protocol (OCER) and Extended-OCER (E-OCER) for WBAN. These routing models utilized a genetic algorithm for optimizing the cost based on energy and path loss. Then the extended OCER was developed as an enhanced model for providing Inter-WBAN communication. These two models provided significantly improved energy conservation with the E-OCER model performing much better than the OCER. However, these routing models are suitable only for the simpler WBAN network structures.

The Thermal dissipation of sensor nodes becomes a vital issue when it is beyond safer levels. Kim *et al.* [23] presented an enhanced temperature aware routing model that estimates the current and expected temperature rise to model the routing algorithm. This approach also used the two hops-ahead algorithms for improving energy-efficient routing and provided increased packet delivery ratio and network lifetime. However, this model does not employ adaptive weighted selection for choosing the next-hop node and it may lead to over-exhaust nodes and increased hot-spot nodes. Javed *et al.* [24] introduced a thermal aware & energy-optimized (TAEO) routing protocol for WBAN using the detection model to identify the hot-spot nodes. This approach reduced the energy consumption through reduced usage of hot-spot nodes and enhanced the overall network lifetime and throughput of WBAN. However, this routing model has limitations in adapting to the body temperature and body movements of the patients. Jamil *et al.* [25] developed an adaptive thermal-aware routing (ATAR) protocol for WBAN to solve the existing thermal issues through the Multi-Ring Routing approach. However, it also suffers from a lack of adaptive routing based on body movements.

The third vital factor considered in this research is the congestion control which is quite difficult to achieve in WBANs but has a significant impact on the overall efficiency. Manfredi [26] proposed a congestion control for differentiated healthcare service delivery in WBAN using a proportional fair allocation control strategy. However, this strategy lacks the provision for controlling the bandwidth requirements. Majumder and Gupta [27] proposed an energy-efficient congestion avoidance priority-based routing algorithm that utilized the control information for estimating the congestion in a route. However, this model narrowly utilized the path loss parameter, and thus the routing performance is less adaptive to all applications in WBANs. Pasandideh and Rezaee [28] proposed a fuzzy priority-based congestion control scheme in WBAN routing. Awan *et al.* [29] also proposed a priority-based congestion-avoidance routing (PCAR) protocol for WBAN using IoT based heterogeneous sensor nodes. This routing model selected the next-hop node based on residual energy, congestion on the forwarder node, and the signal-to-noise ratio of the path. Using this model, the congestion in the paths is minimized to negligible ratio, and also the priority-based routing scheme is efficient for life-critical data through less delay and greater throughput. But this model does not consider the mobility of sensor nodes due to body movements.

Some authors have employed fuzzy methods to provide optimal routing. In [41], the authors have developed an energy-efficient grid-based routing algorithm based on fuzzy rules. This algorithm preserves the energy in sensor nodes and enhances the network lifetime by performing routing through a fuzzy-based Grid Coordinator. Sangeetha *et al.* [42] also developed a routing algorithm using fuzzy rules with a congestion aware concept. This algorithm detects the non-localized node paths and adds them to the current node paths from which a more reliable and congestion alleviated path is selected. However, these models must have pre-determined and fixed rules for performing the routing which is not suitable at all times.

From the above discussions, it can be inferred that the existing routing algorithms and approaches for WBAN do have limitations in handling the data transmission without congestion and inability to control the thermal dissipation in the networks. Most importantly, the energy-aware routing models have focused on improving energy conservation but do not ensure high throughput. These problems, especially the energy consumption problem, form the core research motivation of the proposed EOCC-TARA routing algorithm. The proposed algorithm focuses on tackling each of these problems in its own unique way and provides an efficient routing performance for SDN-based WBAN in healthcare and military applications.

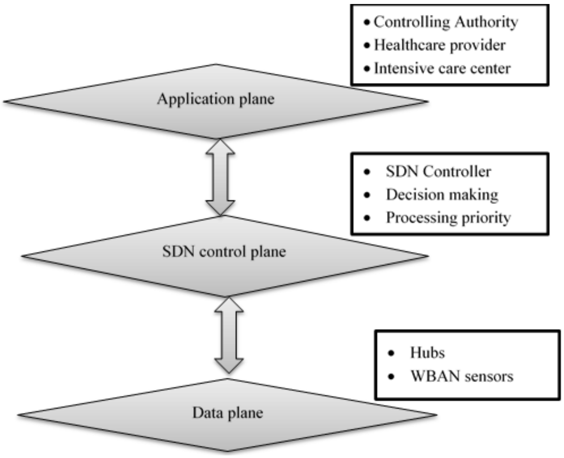

FIGURE 1. Software defined WBAN architecture.

III. EOCC-TARA METHODOLOGY

The proposed methodology aims at developing SDN for WBAN architecture with efficient control and management of Inter-WBAN transmission through the temperature and congestion aware energy-efficient routing algorithm. The primary considerations are the temperature, congestion control, and energy-efficiency related issues in the routing model. First, the network model must be designed such that the SDN approach is evolved for WBAN. In this model, each individual WBAN user will have sensor nodes and a hub in their body, where the nodes perform Intra-WBAN communication for sending data to the hub and the coordinator nodes. The WBAN users also communicate among themselves through Inter-WBAN communication.

A. SDN FOR WBAN DESIGN AND NETWORK MODEL

Incorporating the SDN technology to the ever-developing WBAN network design is highly challenging, but very efficient in the larger scheme of things. For designing the SDN based WBAN, first, the sensor nodes and Hubs are initialized, followed by the establishment of their transmission behavior and coordinator node. SDN based WBAN network can be designed based on the general modeling of SDN using the three logical planes, namely the data plane, control plane, and application plane [30]. Figure 1 shows the logical architecture of SDN based WBAN.

The data plane of the SDN based WBAN includes the hubs and sensor nodes. Hub collects the data packets collected from the sensor nodes and transmits them to the WBAN Coordinator (WBANC). Packet dissemination control data are forwarded using a set of flow commands, and the hub sends the data using them to the gateway through the WBANC. The gateway can be a Wi-Fi access point (AP), Bluetooth, or Zigbee AP. From the gateway, the data are transmitted to the appropriate entities. Each hub is designated as the primary authority of responsibility for a patient to avoid data congestion. The proposed architecture is based on the IEEE 802.15.6 data link/MAC layer for Intra-WBAN communications whose routing decisions are performed by the SDN controller through the route selection algorithm. The control plane has the administrative control of the whole network activities and is responsible for the overall infrastructure. This plane controls the packet-forwarding behavior by categorizing them based on priority and application when it receives requests from the hub. The WBANC is the authorized node to communicate with the controller. The network interface protocol named WBANFlow [15] is utilized for this purpose. The advantage of the SDN integration is the utilization of the neighbor table and flow table maintained by the HUB. The neighbor table contains the neighbors of each HUB and also the other transmission information of the nodes. The flow table contains the packet forwarding details, and the controller updates it periodically. Using these two tables, especially the flow table, the routing flow is determined. As the proposed SDN based WBAN is scalable, it is easier to add new patients to the network, and the controller plane effectively manages the packet-forwarding in the expanded network without altering or damaging the management systems. The application plane includes the controlling authority that manages the system of patients and monitors their conditions. This plane also helps the healthcare provider to install, operate, and control new WBAN applications as needed for the patients. SDN increases the bandwidth and flexibility of WBAN architecture. SDN transforms the static WBAN network paradigm into a programmable and adaptive network paradigm. The SDN-based WBAN approach will play an important role in the realization of services such as intelligent hospital, intelligent healthcare, or intelligent remote healthcare. It is possible to improve WBAN performance by using control and management mechanisms developed with SDN specifications.

The proposed routing algorithm is applied on a network model of a hierarchical WBAN hospital environment developed by having three communication layers. Figure 2 shows the network communication architecture of the proposed SDN based WBAN system. Layer 1 contains the system for providing Intra-WBAN communication using the diagnosis of the patient with different disease parameters by the sensor network. Layer 1 arranges the communication between the sensor nodes on the body using the point-to-point (P2P) links for launching a multi-hop path. It also establishes the communication between the sensors and the WBANC, which acts as a cluster head for obtaining the data from similar sensor hubs with stable energy and communication capacities. This is achieved through the assumption that all the body sensor hubs are fixed in a position and will have a similar transmission range, which remains the same during the entire transmission. However, the distance of some hubs fixed in moving body parts like arms and legs tend to change the distance between the sensors as well as the gateway. Hence the distance between any two sensor nodes or sensors and movable hubs is reduced by utilizing the multi-hop routing method.

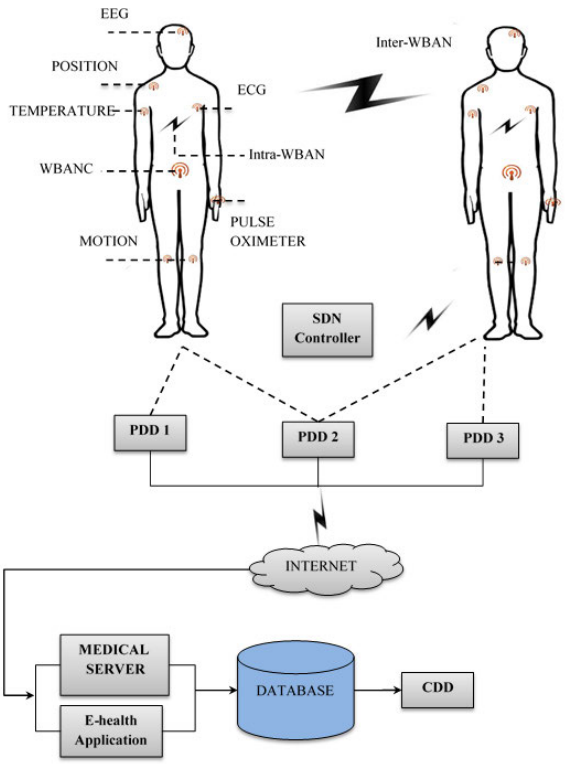

FIGURE 2. Architecture of proposed SDN based WBAN system.

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 communication devices are the Centralized Display Device (CDD), using which layer 3 performs the beyond-WBAN communication to provide patient's data remote access to the medical professionals over the Internet. It has increased the dimension of the WBAN for wide coverage and enhancement of intelligent E-healthcare. The SDN controller is used to enable the centralized management of the WBAN for enhancing dynamic networking. The sensors communicate through the IEEE 802.15.6 standard. For Inter-WBAN and Intra-WBAN communication, the IEEE 802.15.6 standard based Zigbee [43] is utilized while for beyond the network communication, the broadband or Wi-Fi networks were utilized. In the proposed system, the EOCC-TARA replaces these routing methods. Direct power sources are provided only for the CDDs, while the sensors, PDDs, and WBANCs are provided limited power supply through the consumable batteries. The network is modelled by considering the body sensor set $S = \{S_1, S_2, \ldots, S_N\}$ and the wireless link can be formed between any two sensor nodes that are inside the transmission range. The hubs are connected to the WBANC and the channels to which the requests are made by the controller to forward the received packets from the body sensor nodes to the common gateway.

B. THERMAL MODEL

The Temperature of the sensor nodes mounted on the patient body significantly impacts the underlying tissue temperature and might also result in tissue damage. In current WBAN models, there exists a trade-off between the accuracy and the thermal dissipation of sensors; however, the smaller temperature rise is neglected [44]. Moreover, the decision to avoid the node from the transmission routes for a few rounds is not significantly ensured. Consistent processing in sensor nodes increases the temperature of nodes and the respective tissues beneath the node. This increased temperature creates harmful impacts on human tissues that might result in tissue damage. This temperature issue also generates hot-spot problems in the network and reduces its stability and lifetime. For resolving this complexity, the forwarding nodes must be selected in the route initialization process by considering the impact of temperature. This proposed EOCC-TARA utilizes the node temperature and the temperature impact on the patient body tissues, apart from the energy metrics, to select the forwarding nodes.

Subject to these factors, the thermal model can be structured based on two aspects. The first aspect is the expected rise in temperature of the nodes, which is attributed to the amount of thermal dissipation from the nodes. The second aspect is the influence of temperature on the human tissues, and it is dependent on the first aspect. While the measurement of node temperature is straightforward, the estimation of the effect of temperature on human tissues can be approximated using certain parameters. The current temperature of the node is obtained through the sensor itself, while the expected temperature rise is computed as

$$\begin{aligned} &Exp.\ temp\ rise \\ &\quad = Total\ number\ of\ packets\ \times\ average \\ &\qquad \times measured\ temperature\ rise\ for\ each\ packet \end{aligned} \tag{1}$$

Therefore, the temperature of the node when transmitting packets will be

$$T = Current\ Temp + Exp.temp\ rise \tag{2}$$

Specific Absorption Rate (SAR) is an effective parameter to detect the heat absorption rate of tissues per unit of its mass [31]. It is estimated by the heat absorption on the RF wave exposure for a given time. Then the tool with the SAR threshold level, beyond which the temperature is abnormal for tissue normalcy, is initialized. SAR can be calculated based on the conductivity and density of the tissue and induced electromagnetic field of the RF wave spectrum used for communication. It is given by

$$SAR = \frac{\sigma (EMF)^2}{\rho} \tag{3}$$

where, σ denotes the conductivity rate of the tissue, ρ is the density of the tissue, and EMF is the induced electromagnetic field specifying the RF spectrum strength.

For determining the rise in temperature of the given tissue upon exposure to RF spectrum, the SAR value of the tissue is estimated [32], [33]. Therefore, the temperature rise in the tissue beneath, the sensor node is estimated as

$$\Delta T = (SAR)\,\frac{t}{c} \tag{4}$$

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

By using these temperature values, the forwarding nodes are selected with less hot-spot and balanced data transfer. When the current temperature and expected temperature of the node and the tissue is nominally higher than the threshold level, that particular node is avoided for the next few cycles of operations. Once the forwarding nodes are selected, the forwarding paths are formed in the transmission protocol.

C. ENERGY MODEL

For ensuring the energy-efficiency in routing, the residual energy, link reliability, and path loss parameters are used in this work. Energy management plays a pivotal role to increase the network lifetime as the energy resources in WBAN are limited. Direct communication between source nodes and sink nodes consumes extra energy due to the short communication range and high path loss in WBANs. Higher the energy consumption, lesser will be the network lifetime. Hence energy consumption must be minimally modeled in order to apply efficient strategies to optimize it. In WBANs, the enormous quantity of energy is depleted when the Inter-WBAN and Intra-WBAN communication takes place. The total energy consumed is estimated as the sum of sensing energy, radio transmission/reception energy, processing energy, and transient energy of the biosensor nodes and the WBANC. As all the nodes are similar, the energy consumption of all processes in each sensor node is the same. Meanwhile, WBANC consumes more energy than the other nodes as they perform more data processing and aggregation tasks. A weighting factor w_i is used for the energy consumption model and also for the cost function. When the energy consumption of a node, for example the WBANC, is higher than normal nodes, it is accounted using $w_i > 1$. An Earlier study [34] has illustrated that the sensing energy of WBANC is 10% greater than that of the standard body sensor node, while the total processing and communication energy of WBANC is 20% greater than that of the sensor nodes. Hence the three weighting factors w_1, w_2, w_3 are to be used in the energy estimation, and their values are assumed as 1.1, 1.2, and 1.2 respectively, for providing fair importance to the energy metrics. Based on these considerations, the total energy consumption is given by

$$E_{tot} = E_{tot,N} + E_{tot,C} \tag{5}$$

where $E_{tot,N}$ and $E_{tot,C}$ are the total energy consumed by the normal nodes and WBANC, respectively, which are given as the sum of sensing, radio transmission/reception, processing, and transient energies.

$$E_{tot,N} = E_{sens,N} + E_{TX/RX,N} + E_{proc,N} + E_{trans,N} \quad (6)$$

$$E_{tot,C} = E_{sens,C} + E_{TX/RX,C} + E_{proc,C} + E_{trans,C} \quad (7)$$

1) SENSING ENERGY:

It is the energy consumed for sensing nodes (E_{sens}) when they connect with the physical world is the primary factor for energy depletion [35]. If I_{sens} and T_{sens} are the total current required and time taken for sensing the sensor node, the total energy consumption for the sensing process at each node per iteration is denoted by $E_{sens,N}$. For n bit packet sensing, the energy consumption is computed as

$$E_{sens,N}(n) = n \times V_{sup} \times I_{sens} \times T_{sens} \quad (8)$$

where n denotes the number of bit packets, and V_{sup} denotes the supply voltage. Likewise, the total sensing energy for the WBANC can be computed based on node sensing energy and weighting factor $w_i \sim w_1$.

$$E_{sens,C}(w_1, n) = w_1 \times E_{sens,N}(n) \quad (9)$$

2) RADIO TRANSMISSION/RECEPTION ENERGY

The most common cause of energy dissipation in sensor networks is the operations in radio transmitter/receiver circuitry. The energy consumption because of the transmission of n bit packet from a body sensor node to WBANC per iteration can be computed as

$$E_{TX\ \ radio,N}(n,\ D_{ab}) = nE_{TX\ \ radio} + nE_{amp}D_{ab}^{pab} \quad (10)$$

where $E_{TX\ \ radio}$ denotes the energy consumed for operating the transmitter, E_{amp} denotes the energy consumed at the transmitter amplifier, D_{ab} is the distance between a and b, n denotes the number of bits transmitted or received, and p represents the distance based path loss exponent component.

Similarly, the energy consumed for receiver circuitry ($E_{RX\ \ radio}$) for n bit packet reception is estimated as

$$E_{RX\ \ radio,N}(n) = nE_{RX\ \ radio} \quad (11)$$

The energy consumed for transmitting n bit packet from WBANC to the distance D_{ab}, and the energy consumed when n bit packets are received by WBANC with weighting factor $w_i \sim w_2$ are estimated as

$$E_{TX\ \ radio,N}(w_2, n,\ D_{ab}) = w_2 nE_{TX\ \ radio} + nE_{amp}D_{ab}^{pab} \quad (12)$$

$$E_{RX\ \ radio,N}(n) = w_2 nE_{RX\ \ radio} \quad (13)$$

3) PROCESSING ENERGY

Processing energy (E_{proc}) in the SDN based WBAN includes the energy consumed for processing and accumulation of data computed using the switching energy (E_{switch}) and the leakage current energy dissipation (E_{leak}). The total energy dissipated for data processing or accumulation of n bit packet by a node per iteration and the energy consumed by the WBANC with weighting factor $w_i \sim w_3$ for n bit packet per iteration are computed as

$$E_{proc,\ N}(n,\ N_{iter}) = nN_{iter}C_{avg}V_{sup}^2 + nV_{sup}\left(I_0 e^{\frac{V_{sup}}{V_t Proc_k}}\right)\left(\frac{N_{iter}}{f}\right) \quad (14)$$

$$E_{proc,\ C}(w_3, n,\ N_{iter}) = w_3 E_{proc}(n,\ N_{iter}) \quad (15)$$

Here $E_{proc,\ N}$ is the processing energy of 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.

4) TRANSIENT ENERGY

It is the energy consumed by the network for the transition between different modes of operation, namely active, idle, and sleep, denotes the transient energy. It depends on the duty cycles and the transition time. The total transient energy by the sensor nodes is estimated per iteration as

$$E_{tran,\ N} = T_\alpha V_{sup}[I_N] \quad (16)$$

where T_α denotes the wake-up duration of nodes and I_N denotes the average current for node which is given by

$$I_N = D_N I_A + (1 - D_N) I_S \quad (17)$$

Here I_S is the current for sleeping mode, I_A is the current for active mode, and D_N is the duty cycle of the node.

Similarly, the total transient energy for WBANC per iteration is estimated as

$$E_{tran,\ C} = T_{\alpha C} V_{sup}[I_C] \quad (18)$$

where $T_{\alpha C}$ denotes the wake-up duration of WBANC and I_C denotes the average current for WBANC which is provided as

$$I_C = D_C I_A + (1 - D_C) I_S \quad (19)$$

Here D_C is the duty cycle of the node.

D. LINK RELIABILITY MODEL

The link reliability of the proposed SDN based WBAN can be estimated based on the packet drops. High link reliability ensures higher network reliability and reduces throughput degradation. Link reliability between two nodes a and b ($LinkR_{ab}$) can be estimated as

$$LinkR_{ab} = (1 - \gamma) LinkR_{ab} + \gamma \frac{Tp_{succ,ab}}{Tp_{tot,ab}} \quad (20)$$

Here $Tp_{succ,ab}$ represents the total number of successfully transmitted packets between a and b nodes; γ denotes the average weighting factor which is found to be 0.4 in the following 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.

E. PATH LOSS MODEL

Path loss in networking models is defined as the minimization of the power density of the electromagnetic waves. In the proposed SDN based WBAN, the on-body propagation model is employed, and hence the path loss equations are derived based on distance and frequency [36]. The Friis formula in free space is used for computing the path loss (PL_d) based on the distance d between two communicating nodes [37]. It is given by

$$PL_d = PL_{d_0} + 10p\log\left(\frac{d}{d_0}\right) \tag{21}$$

Here p is the path loss exponent, d_0 is the reference distance, and PL_{d_0} is the path loss in dB at d_0 which is estimated as

$$PL_{d_0} = 10 \times \log(4\pi.d_0.f) \times c \tag{22}$$

Here f is the frequency of nodes and c is the speed of light.

In the proposed SDN based WBAN model, the body movements cause variations in the packet-forwarding, and hence the path loss equation must consider the shadowing factor. Shadowing is the phenomenon when the path loss deviates from its mean value. To compensate for the deviation, the shadowing factor must be added to the path loss. Hence the path loss equation becomes,

$$PL = PL_d + X_\sigma \tag{23}$$

Here X_σ is the shadowing factor derived as a Gaussian-distributed random variable [38] whose mean is zero and standard deviation is σ.

F. CONGESTION MODEL

Congestion is one of the major factors of delay and loss in WBAN. As medical applications require precision, timely, and lossless data for analyzing the patients' health conditions, congestion avoidance is greatly required. Most studies have included the delay parameter to optimize routes. However, including the queue length can further improve the routing behavior. In EOCC-TARA, the queue length is used as a parameter to estimate and model the congestion in the cost function to optimize the routes [39]. Every node broadcasts its neighbor information along with energy level and queue size in every t time interval as control information along with the data. Every node transmits a set of data in the next interval only if there are drastic changes in data. This parameter will help to reduce congestion over the network. The threshold value is selected depending on the type of information shared by the nodes.

When the data packets continuously enter the node and are stored in the queue, the average arrival rate is denoted as λ, the averaging data processing rate as μ and the network utilization rate as ρ. In this case, the balanced collection process of packets $p(i)\,;\, i = 0, 1, \ldots n$ is represented mathematically as

$$(\lambda + \mu)\, p(i) = \lambda p(i-1) + \mu p(i+1) \tag{24}$$

For this equation, the conditions $\sum p(i) = 1$ and $p(i) = (1-\rho)\,\rho^i$ holds true and the length of packets and the waiting queue length can be computed based on the three parameters. The average length of data packets in a node is estimated as

$$L = \sum_{i=1}^{\infty} ip(i) = \sum_{i=1}^{\infty} i(1-\rho)\,\rho^i \tag{25}$$

By simplification of the equation,

$$L = \frac{\rho}{1-\rho} \tag{26}$$

Similarly, the average waiting queue length is estimated as

$$QL = \sum_{i=1}^{\infty} ip(i+1) = \frac{\rho^2}{1-\rho} \tag{27}$$

G. MULTI-OBJECTIVE COST FUNCTION

The cost function (or objective or fitness function) is formulated using the four parameters: residual energy, link reliability, path loss, and queue length. The proposed work has tried to investigate the routes followed by the nodes to transmit data from the source node to the sink in order to meet the specific requirements keeping in consideration the goal of minimum energy consumption in the network. This proposed work exploits the cost function to select an optimized route. There are four weights W_A, W_B, W_C and W_D to provide the relative importance of the four parameters (residual energy, link reliability, path loss, and queue length) within the proposed cost function. The range of weights is also determined optimally using EMSMO. Changing these parameters leads to different values of the cost function. The cost function is modeled as follows
Minimize:

$$\begin{aligned} Cost &= W_A \times residual\ energy + W_B \times link\ reliability \\ &\quad + W_C \times path\ loss + W_D \times queue\ length \end{aligned} \tag{28}$$

Subject to $W_A + W_B + W_C + W_D = 1$, It can be rewritten as

$$\begin{aligned} &Cost \\ &= W_A \times \left|1 - \frac{E_{tot}(NT)}{E_{max}}\right| + W_B \times \left|1 - \frac{LinkR(NT)}{LinkR_{max}}\right| \\ &\quad + W_C \times \left|1 - \frac{PL(NT)}{PL_{max}}\right| + W_D \times \left|1 - \frac{QL(NT)}{QL_{max}}\right| \end{aligned} \tag{29}$$

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 cost function is utilized in the proposed EMSMO algorithm to select the optimal routes. The route with the minimum value of cost is elected for sending data.

H. EMSMO ALGORITHM FOR ROUTE SELECTION

The multi-hop communication transmits the data with the assistance of intermediate nodes. But this transmission process creates more constraints on the energy dissipation of

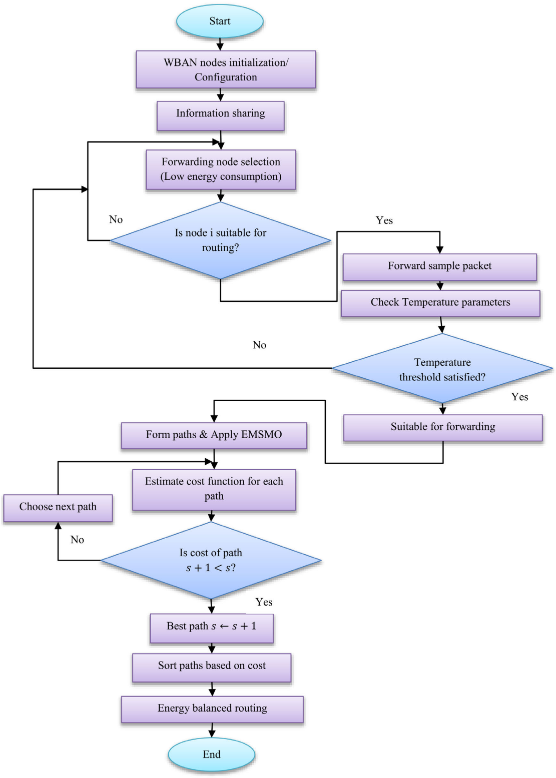

FIGURE 3. **Proposed EMSMO based EOCC-TARA Routing mechanism.**

the forwarder nodes. The routing mechanism should take the merits of both types of communication. The routes need to be discovered when there is a request made for it. The routing mechanisms will affect the end-to-end path reliability and overall energy consumption of the network. For the efficient functioning of WBAN, it is critical to obtain the minimal energy consumption with the required level of reliability as the data to be communicated is important. The multi-hop concept significantly minimizes the delay but increases the congestion, temperature, and energy consumption. Therefore, the optimized selection of routing paths based on the multi-objective cost function using EMSMO, which is a modification to the general Spider Monkey Optimization (SMO) [40]. The proposed routing model reduces the impacts of the above-mentioned issues and enhances routing performance. Figure 3 shows the proposed EMSMO based EOCC-TARA routing mechanism for the SDN based WBAN system. The energy-efficient routing protocols have to maintain reliability and also reduce the propagation loss. In addition to the energy efficiency concept, this study also considers two more vital factors: temperature and congestion control, for ensuring efficient routing.

Initially, SMO generates a uniformly distributed initial population of N spider monkeys in **Local Leader phase (LLP)**. Each spider monkey *SM* corresponds to the potential solution of the problem under consideration. Each SM_i is initialized as

$$SM_{ij} = SM_{minj} + U\,(0,1) \times \left(SM_{maxj} - SM_{minj}\right) \quad (30)$$

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

In the **Local Leader Learning (LLL) phase**, each Spider Monkey SM modifies its current position based on the information of the local leader experience as well as local group members' experience. The fitness value of the so obtained new position is calculated using the cost function. If the fitness value of the new position is higher than that of the old position, then the *SM* updates its position with the new one. The position update equation for *i*-th SM in this phase is given by

$$SM_{newij} = SM_{ij} + U\,(0,1) \times \left(LL_{kj} - SM_{ij}\right) + U\,(-1,1) \times \left(SM_{rj} - SM_{ij}\right) \quad (31)$$

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

After completion of the Local Leader phase, the **Global Leader phase (GLP)** starts. In GLP phase, all the SM's update their position using the experience of Global Leader and local group member's experience.

$$SM_{newij} = SM_{ij} + U\,(0,1) \times \left(GL_j - SM_{ij}\right) + U\,(-1,1) \times \left(SM_{rj} - SM_{ij}\right) \quad (32)$$

where GL_j represents the *j*-th dimension of the global leader position and $j \in \{1, 2, \ldots, D\}$ is the randomly chosen index.

In this phase, the positions of spider monkeys are updated based on probabilities, which are calculated using their cost-based fitness function.

$$prob = 0.9 \times \frac{Cost_i}{\max\_cost} + 0.1 \quad (33)$$

$Cost_i$ is the fitness value of the *i*-th SM based on multi-objective cost function and *max_cost* is the maximum fitness in the group.

In ***Global Leader Learning (GLL) phase***, the position of the global leader is updated by applying the greedy selection in the population. In *Local Leader Learning (LLL) phase*, the position of the local leader is updated by applying the greedy selection in that group.

In ***Local Leader Decision (LLD) phase***, if any Local Leader position is not updated up to the predetermined threshold called Local Leader Limit, then all members of that group update their positions either by random initialization or by using combined information from Global Leader and Local Leader using

$$SM_{newij} = SM_{ij} + U\,(0,1) \times \left(GL_j - SM_{ij}\right) + U\,(0,1) \times \left(SM_{ij} - LL_{kj}\right) \quad (34)$$

In ***Global Leader Decision (GLD) phase***, the position of global leader is monitored, and if it is not updated until the predetermined number of iterations called Global Leader Limit, then the global leader divides the population into smaller groups. Then the global leader combines all groups to form a single group for finding the optimal solution.

The newly proposed EMSMO algorithm improves the performance of the basic SMO algorithm. The position update equation in EMSMO takes an average of the difference between the current position and randomly generated positions. It generates a random position in a given range for a particular problem. This suggested modification accelerates the convergence rate and increases reliability. Here, it is assumed that better fitness solution has an optimal solution in their proximity.

$$SM_{newij} = SM_{ij} + U\,(0,1) \times \left(LL_{kj} - SM_{ij}\right) + U\,(0,1) \times \left(\frac{SUM}{SN}\right) \quad (35)$$

where $SUM = SUM + \left(SM_{ij} - SM_{kj}\right)$ is the average of the difference between current position and randomly generated position, and SN represents the food source that is randomly generated by the global leader. This equation updates highly fitted solutions through inspiration from the best Swarm Intelligence. This new addition in EMSMO increases the balance between exploration and exploitation for most feasible solutions.

In the proposed concept of ***modified GLL phase***, initially, the position of the global leader of the swarm is updated. Now, the position of the worst member (solution having the minimum fitness value) of the swarm is found. Then, the solutions are generated for the predefined number of times until we obtain the solution, which is better than the worst member of the swarm. For this, three points A, B, and C are chosen from the swarm, where A = GL, and B and C are positions of randomly chosen members of the swarm such that A, B, and C are all distinct. Generate a new position using the fitness function. If the fitness value of a newly generated position is better than that of the worst member of the group, then update the worst position with the new one. In the proposed concept of ***modified local leader learning phase***, the process described in the modified GLL phase repeats itself for every group. Here, the whole swarm is replaced by a particular group, and the global leader is replaced by a local leader.

IV. RESULTS AND DISCUSSION

The proposed EOCC-TARA 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 × 100m. This means each individual patient's area is 10mx10m 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 individual 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 simulations is given in Table 1.

The performance of the proposed EOCC-TARA is compared with the existing routing algorithms, namely E-OCER [22], TAEO [24], and PCAR [29] to estimate the superiority of the proposed algorithm for SDN-based WBAN in terms of energy, temperature, and congestion control aspects. The performance metrics used are energy consumption, network lifetime, throughput, temperature control, congestion overhead, delay, and successful transmission rate.

TABLE 1. The experimental setup for simulations.

Parameters	Settings
Area	100m × 100m
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	25m

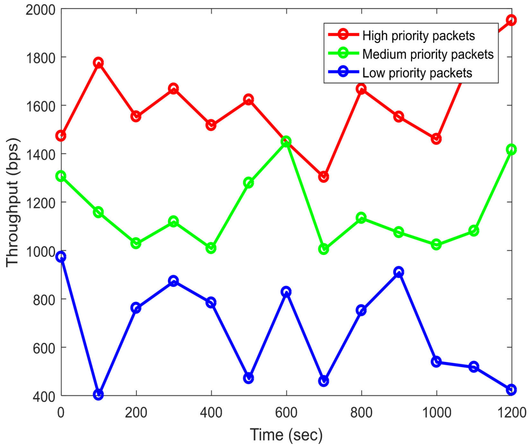

FIGURE 4. Throughput.

A. EVALUATION OF EOCC-TARA

Figure 4 shows the throughput evaluation of the proposed approach. EOCC-TARA has higher throughput for high priority packets while has lower throughput for low priority packets. This is significantly efficient in accordance with the property of priority based routing strategy such that high priority packets are transmitted through the best paths and the low priority packets are forwarded through the unoccupied paths. This property of the EOCC-TARA has an efficient routing performance.

Figure 5 shows the delay evaluation of the proposed approach. EOCC-TARA causes a higher delay for high priority packets during the initial transmission and significantly drops with the approaching time. But in low and medium priority packets, the routing is much faster and consistent. This is primarily due to the long term communication model of the proposed approach and significantly affects the complex nature of the networks. This criterion of the EOCC-TARA has

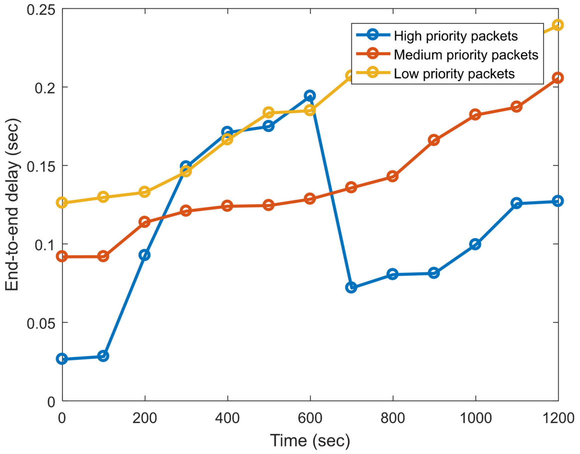

FIGURE 5. End-to-end delay.

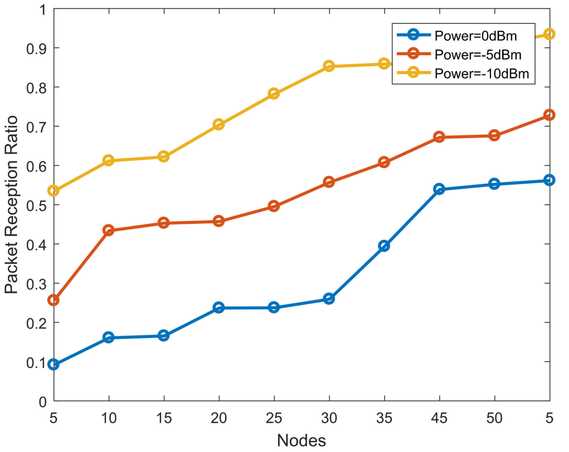

FIGURE 6. Packet reception ratio.

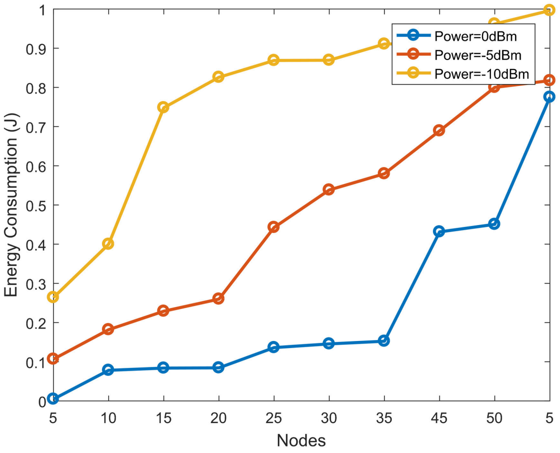

FIGURE 7. Energy consumption.

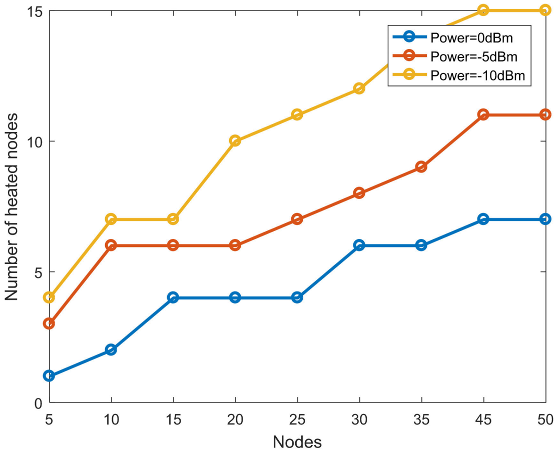

FIGURE 8. Number of heated nodes.

inverse effects and also limits the size of the network when a high number of high priority packets are generated.

Figure 6 shows the packet reception ratio of the proposed approach. EOCC-TARA achieved higher packet reception when the power is 0 dBm while the ratio is significantly reduced when the power is increased to 5 dBm and 10 dBm. Although it is reduced, the fact is that the proposed approach has also reduced the overall power consumption through an effective packet reception ratio for the routing. This can be seen in Figure 7, When the transmission power increased, the energy consumption is increased and also the consumed ratio is consistently increased. But the overall energy consumption using the proposed system has been minimum, which is evident from the consumption rate in the range of 0 to 1 Joule.

Figure 8 shows the number of heated nodes in the proposed EOCC-TARA, which is significantly less compared to the general heating patterns. With increased transmission power, the number of heated nodes is increased, but due to the adaptive selection of forwarding nodes based on thermal dissipation, the thermal hot-spot problems are reduced significantly.

B. PERFORMANCE COMPARISON OF EOCC-TARA WITH OTHER MODELS

The performance of the proposed EOCC-TARA is compared with the existing routing algorithms E-OCER [22], TAEO [24], and PCAR [29]. The comparison is to analyze the superiority or inferiority of the proposed approach for the routing in WBAN.

Figures 9, 10, 11, and 12 visualize the hop count, queue length, packet delivery ratio, and delay comparisons, respectively, of the proposed EOCC-TARA with the existing E-OCER [22], TAEO [24], and PCAR [29]. It can be seen from the figures that the proposed EOCC-TARA has outperformed the other models with improved performance. EOCC-TARA has less hop counts, less queue length, less delay, and improved packet delivery ratio.

Figures 13 and 14 visualize the network lifetime and the number of dead nodes comparisons, respectively, of the proposed EOCC-TARA with the existing E-OCER [22], TAEO [24], and PCAR [29]. It can be seen from the figures that the proposed EOCC-TARA has a higher lifetime and a reduced number of dead nodes than the existing algorithms.

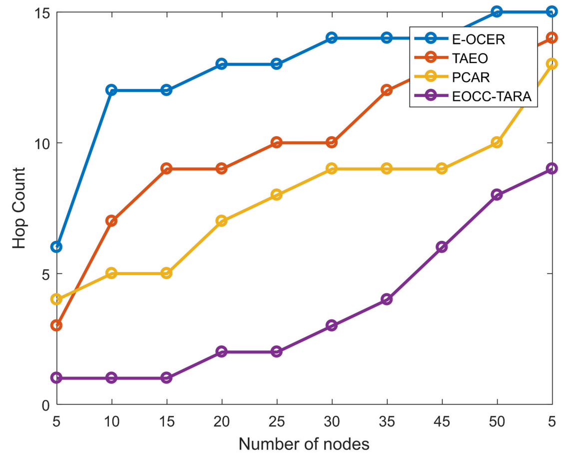

FIGURE 9. Hop count.

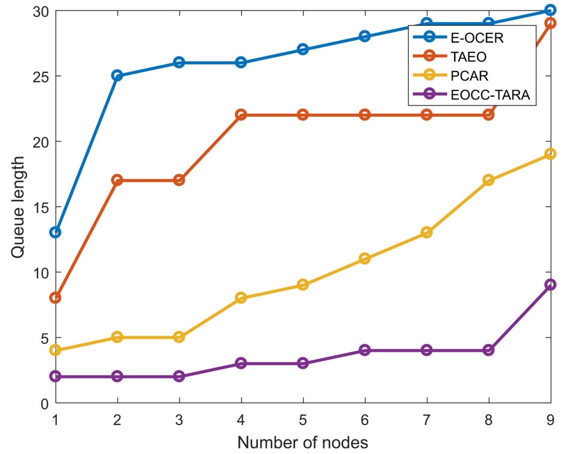

FIGURE 10. Queue length.

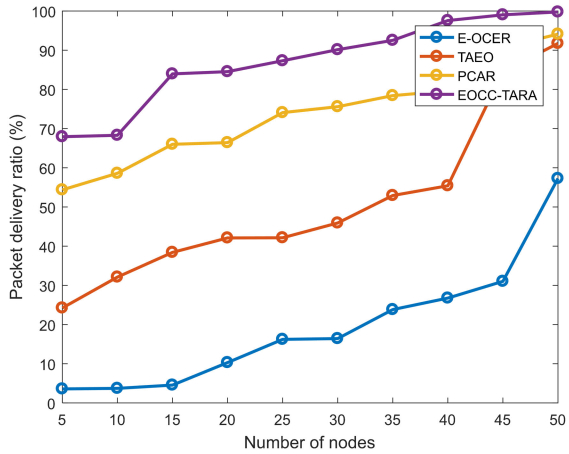

FIGURE 11. Packet delivery ratio.

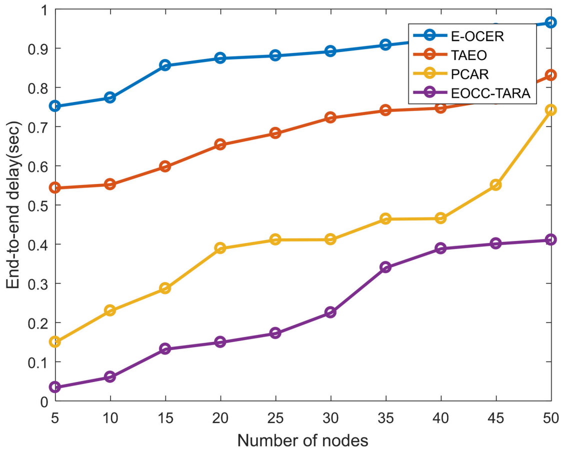

FIGURE 12. End-to-end delay comparison.

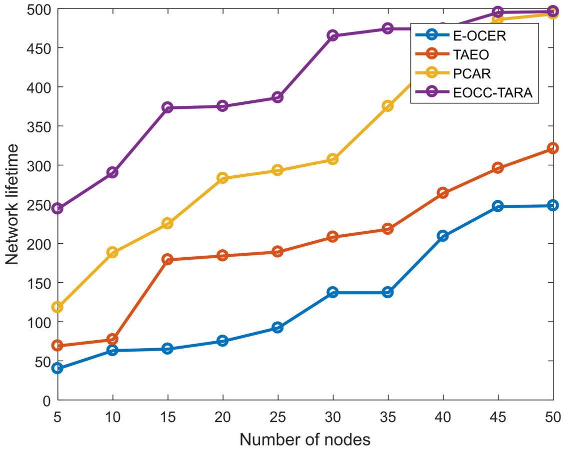

FIGURE 13. Network lifetime.

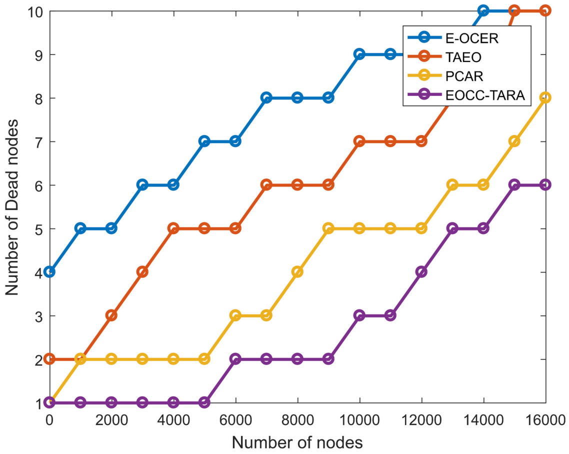

FIGURE 14. Number of dead nodese.

Figure 15 shows the throughput comparison of the proposed EOCC-TARA with the existing E-OCER [22], TAEO [24], and PCAR [29]. It can be seen that the proposed EOCC-TARA has a higher throughput than the existing algorithms, which is mainly due to the improved packet delivery ratio.

Figures 16 and 17 visualize the residual energy and energy consumption comparisons, respectively, of the proposed

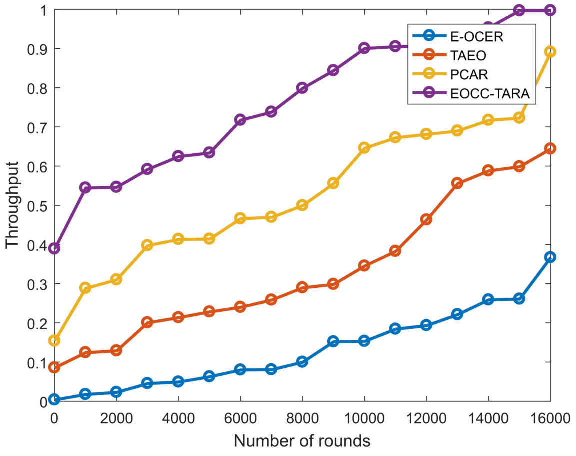

FIGURE 15. Throughput.

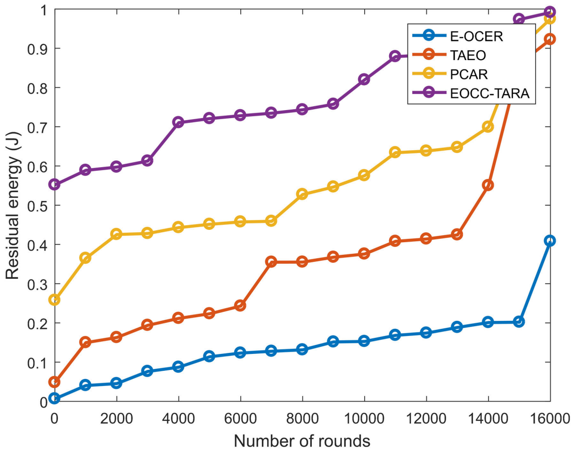

FIGURE 16. Residual energy.

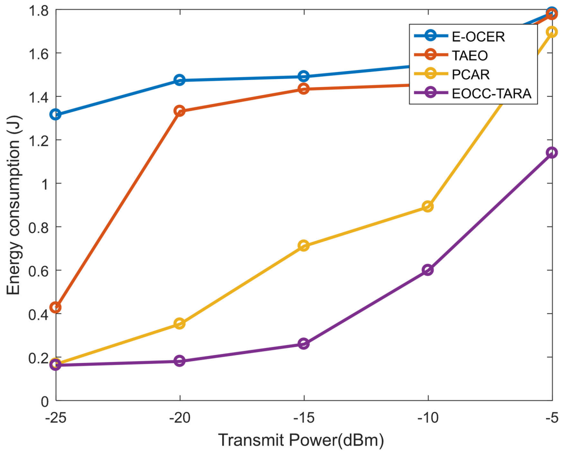

FIGURE 17. Energy consumption.

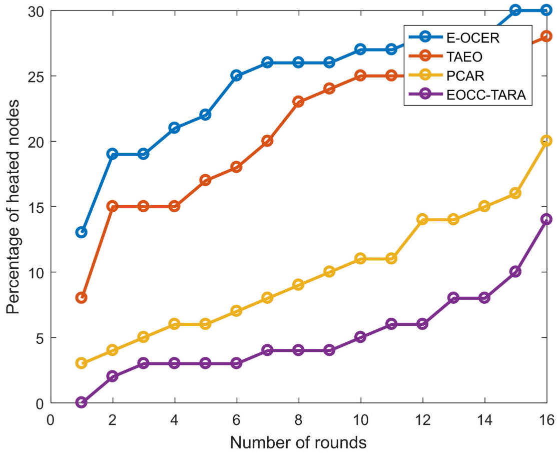

FIGURE 18. Percentage of heated nodes.

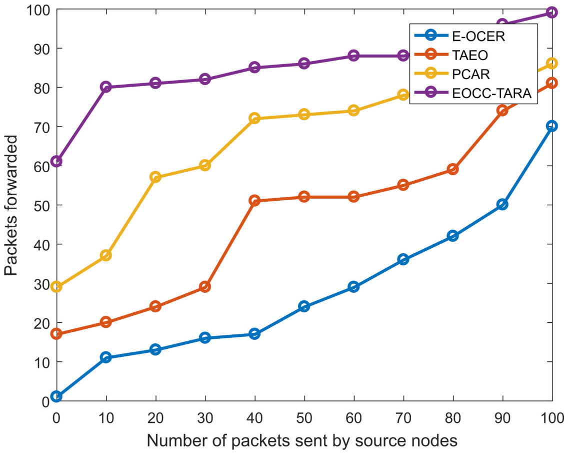

FIGURE 19. Packets forwarded by intermediate nodes.

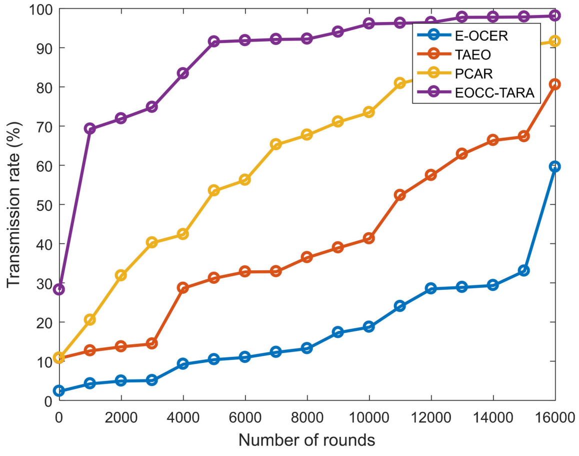

FIGURE 20. Transmission rate.

EOCC-TARA with the existing E-OCER [22], TAEO [24], and PCAR [29]. The energy consumption of EOCC-TARA is lesser than the existing models due to the enhanced concepts of thermal aware and congestion aware routing with EMSMO optimized routing.

Figure 18 shows the percentage of heated nodes of the proposed EOCC-TARA with the existing E-OCER [22], TAEO [24], and PCAR [29]. Due to the improved effective routing in EOCC-TARA, the number of heated nodes is reduced significantly with 14% maximum nodes in the proposed approach, compared to the maximum of 30% in the existing E-OCER scheme.

Figures 19 and 20 visualize the Packets forwarded by the intermediate nodes and the transmission rate comparisons, respectively, of the proposed EOCC-TARA with the existing E-OCER [22], TAEO [24], and PCAR [29]. As the number of lost packets is minimized due to the less path loss and packet drop ratio, the intermediate nodes which are free from hot-spot problems forwarded the maximum packets and also increased the successful packet transmission than the existing models.

V. CONCLUSION

This paper was focused on developing an energy-efficient and temperature aware routing algorithm for SDN-based WBAN that also incorporates the congestion control to provide optimal performance. For achieving this objective, three vital problems, namely energy consumption, thermal dissipation of nodes, and path congestion are considered, and an effective solution is ensured in the proposed routing algorithm. The proposed EOCC-TARA routing algorithm initially selects the forwarding nodes based on energy and temperature as priority objectives and does not include the node with high temperature for route formation. Then the cost model was derived using residual energy, link reliability, path loss, and queue length to select the optimal routing paths using EMSMO. Results obtained from simulations prove that the proposed EOCC-TARA routing algorithm performs better than the traditional routing models for the SDN-based WBAN. The proposed method has shown improved energy conservation, less congestion, and high throughput along with balanced temperature in the network as well as the patient's body. Future works include the examination of the adverse environmental factors and the mobility issues that will be associated with the practical implementation of the SDN-based WBANs.

REFERENCES

[1] J. Y. Khan, M. R. Yuce, G. Bulger, and B. Harding, "Wireless body area network (WBAN) design techniques and performance evaluation," *J. Med. Syst.*, vol. 36, no. 3, pp. 1441–1457, 2012.

[2] J. Y. Khan, "Network and medium access control protocol design for wireless body area networks," in *Wireless Body Area Networks*. New York, NY, USA: Jenny Stanford, 2011, pp. 279–314.

[3] T. Wu, F. Wu, J.-M. Redoute, and M. R. Yuce, "An autonomous wireless body area network implementation towards IoT connected healthcare applications," *IEEE Access*, vol. 5, pp. 11413–11422, 2017.

[4] G. Elhayatmy, N. Dey, and A. S. Ashour, "Internet of Things based wireless body area network in healthcare," in *Internet of Things and Big Data Analytics Toward Next-Generation Intelligence* (Studies in Big Data). Cham, Switzerland: Springer, 2018, pp. 3–20.

[5] W. A. N. W. Abdullah, N. Yaakob, M. E. Elobaid, M. N. M. Warip, and S. A. Yah, "Energy-efficient remote healthcare monitoring using IoT: A review of trends and challenges," in *Proc. Int. Conf. Internet Things Cloud Comput.* New York, NY, USA: ACM, 2016, p. 29.

[6] C. Chakraborty, B. Gupta, and S. K. Ghosh, "A review on telemedicine-based WBAN framework for patient monitoring," *Telemedicine e-Health*, vol. 19, no. 8, pp. 619–626, Aug. 2013.

[7] A. Volkov, A. Muhathanna, R. Pirmagomedov, and R. Kirichek, "SDN approach to control Internet of Thing medical applications traffic," in *Proc. Int. Conf. Distrib. Comput. Commun. Netw.* Cham, Switzerland: Springer, Sep. 2017, pp. 467–476.

[8] K. Hasan, X.-W. Wu, K. Biswas, and K. Ahmed, "A novel framework for software defined wireless body area network," in *Proc. 8th Int. Conf. Intell. Syst., Model. Simul. (ISMS)*, May 2018, pp. 114–119.

[9] C. Yi, L. Wang, and Y. Li, "Energy efficient transmission approach for WBAN based on threshold distance," *IEEE Sensors J.*, vol. 15, no. 9, pp. 5133–5141, Sep. 2015.

[10] L. Liang, Y. Ge, G. Feng, W. Ni, and A. A. P. Wai, "A low overhead tree-based energy-efficient routing scheme for multi-hop wireless body area networks," *Comput. Netw.*, vol. 70, pp. 45–58, Sep. 2014.

[11] M. Monowar and F. Bajaber, "On designing thermal-aware localized QoS routing protocol for *in-vivo* sensor nodes in wireless body area networks," *Sensors*, vol. 15, no. 6, pp. 14016–14044, Jun. 2015.

[12] M. M. Monowar, M. Mehedi Hassan, F. Bajaber, M. A. Hamid, and A. Alamri, "Thermal-aware multiconstrained intrabody QoS routing for wireless body area networks," *Int. J. Distrib. Sensor Netw.*, vol. 10, no. 3, Jan. 2014, Art. no. 676312.

[13] V. Tickoo and S. Gambhir, "A comparison study of congestion control protocols in WBAN," *Int. J. Innov. Advancements Comput. Sci.*, vol. 4, no. 6, pp. 121–127, 2015.

[14] K. Kharb, B. Sharma, and C. A. Trilok, "Reliable and congestion control protocols for wireless sensor networks," *Int. J. Eng. Technol. Innov.*, vol. 6, no. 1, pp. 68–78, 2016.

[15] M. Cicioğlu and A. Çalhan, "SDN-based wireless body area network routing algorithm for healthcare architecture," *ETRI J.*, vol. 41, no. 4, pp. 452–464, Jul. 2019.

[16] J. Mu, X. Liu, and X. Yi, "Simplified energy-balanced alternative-aware routing algorithm for wireless body area networks," *IEEE Access*, vol. 7, pp. 108295–108303, 2019.

[17] D.-R. Chen, C.-C. Hsu, M.-Y. Chen, and C.-F. Guo, "A power-aware 2-covered path routing for wireless body area networks with variable transmission ranges," *J. Parallel Distrib. Comput.*, vol. 118, pp. 379–397, Aug. 2018.

[18] B. Abidi, A. Jilbab, and E. H. Mohamed, "An energy efficiency routing protocol for wireless body area networks," *J. Med. Eng. Technol.*, vol. 42, no. 4, pp. 290–297, Jul. 2018.

[19] H. Esmaeili and B. Minaei Bidgoli, "EMRP: Evolutionary-based multi-hop routing protocol for wireless body area networks," *AEU-Int. J. Electron. Commun.*, vol. 93, pp. 63–74, Sep. 2018.

[20] V. Navya and P. Deepalakshmi, "Energy efficient routing for critical physiological parameters in wireless body area networks under mobile emergency scenarios," *Comput. Electr. Eng.*, vol. 72, pp. 512–525, Nov. 2018.

[21] M. Anwar, A. Abdullah, A. Altameem, K. Qureshi, F. Masud, M. Faheem, Y. Cao, and R. Kharel, "Green communication for wireless body area networks: Energy aware link efficient routing approach," *Sensors*, vol. 18, no. 10, p. 3237, Sep. 2018.

[22] N. Kaur and S. Singh, "Optimized cost effective and energy efficient routing protocol for wireless body area networks," *Ad Hoc Netw.*, vol. 61, pp. 65–84, Jun. 2017.

[23] B.-S. Kim, K.-I. Kim, and B. Shah, "An enhanced temperature aware routing protocol in wireless body area networks," in *Proc. IEEE 42nd Annu. Comput. Softw. Appl. Conf. (COMPSAC)*, Jul. 2018, pp. 789–790.

[24] M. Javed, G. Ahmed, D. Mahmood, M. Raza, K. Ali, and M. Ur-Rehman, "TAEO–A thermal aware & energy optimized routing protocol for wireless body area networks," *Sensors*, vol. 19, no. 15, p. 3275, Jul. 2019.

[25] F. Jamil, M. A. Iqbal, R. Amin, and D. Kim, "Adaptive thermal-aware routing protocol for wireless body area network," *Electronics*, vol. 8, no. 1, p. 47, Jan. 2019.

[26] S. Manfredi, "Congestion control for differentiated healthcare service delivery in emerging heterogeneous wireless body area networks," *IEEE Wireless Commun.*, vol. 21, no. 2, pp. 81–90, Apr. 2014.

[27] A. B. Majumder and S. Gupta, "An energy-efficient congestion avoidance priority-based routing algorithm for body area network," in *Industry Interactive Innovations in Science, Engineering and Technology*. Singapore: Springer, Jul. 2017, pp. 545–552.

[28] A. A. Rezaee and F. Pasandideh, "A fuzzy priority based congestion control scheme in wireless body area networks," *Int. J. Wireless Mobile Comput.*, vol. 14, no. 1, pp. 1–15, 2018.

[29] K. M. Awan, N. Ashraf, M. Q. Saleem, O. E. Sheta, K. N. Qureshi, A. Zeb, K. Haseeb, and A. S. Sadiq, "A priority-based congestion-avoidance routing protocol using IoT-based heterogeneous medical sensors for energy efficiency in healthcare wireless body area networks," *Int. J. Distrib. Sensor Netw.*, vol. 15, no. 6, Jun. 2019, Art. no. 155014771985398.

[30] H. Kim and N. Feamster, "Improving network management with software defined networking," *IEEE Commun. Mag.*, vol. 51, no. 2, pp. 114–119, Feb. 2013.

[31] A. K. M. F. Hoque, "A study on specific absorption rate (SAR) due to non-ionizing radiation from wireless/telecommunication in Bangladesh," *Amer. J. Phys. Appl.*, vol. 1, no. 3, p. 104–110, 2013.

[32] F. Ç. Kunter, C. Gunduz, and S. S. Seker, "Computation of SAR and temperature values in the human head due to 2G, 3G, 4G mobile wireless systems," *J. Aeronaut. Space Technol.*, vol. 11, no. 1, pp. 1–6, 2018.

[33] S. I. Zonoori, S. V. Makki, and A. Torabi, "The effect on a human heart model from dipole antenna, with and without shield on SAR and temperature increase," *Appl. Comput. Electromagn. Soc. J.*, vol. 30, no. 11, pp. 1188–1193, 2015.

[34] M. N. Halgamuge, M. Zukerman, K. Ramamohanarao, and H. L. Vu, "An estimation of sensor energy consumption," *Prog. Electromagn. Res. B*, vol. 12, pp. 259–295, Sep. 2009.

[35] H.-Y. Zhou, D.-Y. Luo, Y. Gao, and D.-C. Zuo, "Modeling of node energy consumption for wireless sensor networks," *Wireless Sensor Netw.*, vol. 3, no. 1, pp. 18–23, 2011.

[36] N. Katayama, K. Takizawa, T. Aoyagi, J.-I. Takada, H.-B. Li, and R. Kohno, "Channel model on various frequency bands for wearable body area network," *IEICE Trans. Commun.*, vol. E92-B, no. 2, pp. 418–424, 2009.

[37] P. Supanakoon, P. Tangtisanon, S. Promwong, and J. I. Takada, "Accurate analysis of extension of the Friis' transmission formula for UWB channels," in *Proc. ECTI Conf.*, Pattaya City, Thailand, 2004, p. 16.

[38] M. F. A. Ahmed and S. A. Vorobyov, "Collaborative beamforming for wireless sensor networks with Gaussian distributed sensor nodes," *IEEE Trans. Wireless Commun.*, vol. 8, no. 2, pp. 638–643, Feb. 2009.

[39] H. Yin, H. Qi, J. Xu, X. Huang, and A. He, "An efficient multitask scheduling model for wireless sensor networks," *J. Appl. Math.*, vol. 2014, pp. 1–7, Mar. 2014.

[40] J. C. Bansal, H. Sharma, S. S. Jadon, and M. Clerc, "Spider monkey optimization algorithm for numerical optimization," *Memetic Comput.*, vol. 6, no. 1, pp. 31–47, Jan. 2014.

[41] R. Logambigai, S. Ganapathy, and A. Kannan, "Energy–efficient grid–based routing algorithm using intelligent fuzzy rules for wireless sensor networks," *Comput. Electr. Eng.*, vol. 68, pp. 62–75, May 2018.

[42] G. Sangeetha, M. Vijayalakshmi, S. Ganapathy, and A. Kannan, "An improved congestion-aware routing mechanism in sensor networks using fuzzy rule sets," *Peer-to-Peer Netw. Appl.*, early access.

[43] L. Zhang, H. Jiang, J. Wei, J. Dong, F. Li, W. Li, J. Gao, J. Cui, B. Chi, C. Zhang, Z. Wang, "A reconfigurable sliding-IF transceiver for 400 MHz/2.4 GHz IEEE 802.15.6/ZigBee WBAN hubs with only 21% tuning range VCO," *IEEE J. Solid-State Circuits*, vol. 48, no. 11, pp. 2705–2716, Nov. 2013.

[44] Z. A. Khan, S. Sivakumar, W. Phillips, and B. Robertson, "ZEQoS: A new energy and QoS-aware routing protocol for communication of sensor devices in healthcare system," *Int. J. Distrib. Sensor Netw.*, vol. 10, no. 6, Jan. 2014, Art. no. 627689.

OMAR AHMED received the B.S. degree in communication and electronics engineering from Sana'a University, Yemen, in 2010, and the master's degree in electronics and information engineering from Northwestern Polytechnical University (NWPU), China, in 2016. He is currently pursuing the Ph.D. degree with the School of Computer and Information Sciences, Hefei University of Technology. His research interests include computer networks, wireless networks, SDN, WBAN, and the IoT.

FUJI REN (Senior Member, IEEE) received the Ph.D. degree from the Faculty of Engineering, Hokkaido University, Japan, in 1991. From 1991 to 1994, he worked with CSK, as a Chief Researcher. In 1994, he joined the Faculty of Information Sciences, Hiroshima City University, as an Associate Professor. Since 2001, he has been a Professor with the Faculty of Engineering, Tokushima University. His current research interests include natural language processing, artificial intelligence, affective computing, and emotional robots. He is the Academician of The Engineering Academy of Japan and the EU Academy of Sciences. He is the Editor-in-Chief of the *International Journal of Advanced Intelligence*, the Vice President of CAAI, and a Fellow of The Japan Federation of Engineering Societies, the IEICE, and the CAAI. He is the President of the International Advanced Information Institute, Japan.

AMMAR HAWBANI received the B.S., M.S., and Ph.D. degrees in computer software and theory from the University of Science and Technology of China (USTC), Hefei, China, in 2009, 2012, and 2016, respectively. From 2016 to 2019, he worked as Postdoctoral Researcher with the School of Computer Science and Technology, USTC. He is currently an Associate Professor of networking and communication algorithms with the School of Computer Science and Technology, USTC. His research interests include the IoT, WSNs, WBANs, WMNs, VANETs, and SDN.

YASER AL-SHARABI received the B.S. degree in computer applications from Bangalore University, Bengaluru, India, in 2008, and the M.S. degree in information science from Osmania University, Hyderabad, India, in 2011. He is currently pursuing the Ph.D. degree with the School of Computer and Information Sciences, Hefei University of Technology. His research interests primarily include data mining and wireless sensor networks.

• • •