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RESEARCH ARTICLE

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Relay selection, clustering, and data aggregation routing in wireless body area networks

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Summary

This paper addresses the problems of relay selection, clustering, and routing to extend the lifetime of wireless body area networks. We first propose an efficient algorithm called "Energy-aware Relay Selection and Cluster-based Routing (ERSCR)" to develop a hybrid data aggregation tree in the network. ERSCR has three phases, including the relay selection, clustering and Cluster Head (CH) selection, and data transmission. It divides the biosensors into several clusters and selects an appropriate CH for each cluster. Each biosensor transmits data to its CH or relay node. The aggregated data are then routed to the sink through an energy-balanced routing tree. The proposed scheme considers both residual energy and distance for routing data of biosensors. It not only reduces the energy consumption in the network but also balances the energy consumed by different biosensors. Subsequently, we improve the ERSCR algorithm and introduce the "Joint Relay Selection, Clustering, and Routing (JRSCR)" algorithm to achieve a better network performance. JRSCR benefits from the advantages of the ERSCR algorithm. Moreover, it reduces the number of transmissions with the direct use of the relay nodes as CH. As another advantage, both ERSCR and JRSCR algorithms are compatible with the natural physical states of the human body. Simulation results demonstrate the efficiency of the proposed algorithms in terms of energy consumption, network lifetime, and maximum hop count.

KEYWORDS

clustering, data aggregation, energy-aware, mobility model, relay selection, wireless body area networks

1 | INTRODUCTION

Wireless body area networks (WBANs) have recently received a lot of attention due to their wide range of applications in medical and nonmedical fields such as healthcare, sports, entertainment, and military.[1,2] For medical purposes, these networks can be used to monitor the heart rate, blood pressure, and blood oxygen level, as well as control diabetes, sleep staging, cardiovascular disease, and cancer diagnosis. Most of these services are related to chronic patients who need to constantly monitor their vital signals. WBANs allow patients to perform normal activities instead of staying at home or in the hospital. Smart gaming and authentication are two main examples of nonmedical applications of these networks. WBANs can be used to control the game with hand gesture and body mobility. Recent studies show the effective realization of human emotions via speech and visual data analysis.[2,3] Biometric characteristics such as fingerprint, face recognition, hand geometry, iris recognition, and odor detection can be used for secure authentication purposes. In fact, these biometric characteristics provide unique biometric signatures that cannot be stolen, copied, or forged.

A WBAN consists of a set of wearable or implantable tiny biosensors to monitor the biometric signals and send the sensed information to the sink node. All data gathered by the monitoring system are stored and analyzed to respond to the body requirements from any remote location.[4] Because the wireless technologies adopted in traditional networks did not meet the WBAN requirements, a standardization group called IEEE 802.15.6 Task Group (TG6) was established. This group aims to develop a standard optimized for low-power, short-range, and reliable wireless transmissions. According to the IEEE 802.15.6 standard, WBANs should support bit rates in the range of 10 Kbps to 10 Mbps.[2] It uses the existing Industrial Scientific Medical (ISM) bands as well as frequency bands approved by national medical and/or regulatory authorities. Packet error rate should be less than 10% for a 256 octet payload. Also, nodes must be removed or added to the network in less than 3 s. Latency in medical and nonmedical applications should be less than 125 and 250 ms, respectively, and power-saving mechanisms should be followed when WBAN operates in the power-constrained environments.[2,3]

In recent years, several approaches have been presented to study different problems of WBANs. In particular, some literature works aim to reduce the interference in the network and present efficient MAC schemes, whereas others provide heuristic/optimal solutions for routing and data aggregation process. Limited battery capacity, constrained by the size and weight of biosensors, cannot support the long-term operation without interruption. Thus, energy conservation becomes a critical issue for WBAN applications.[5] A WBAN should use the power-saving mechanisms to work for a long time without any recharging the biosensor batteries. In this regard, fair energy consumption by different biosensors minimizes the death time between the first and the last node and increases the network lifetime. Short transmission range is a limitation for low-power radiofrequency (RF) transceivers, which prevents the use of star topology in WBANs. Thus, a low-power, short-range, and reliable routing protocol is required to satisfy the quality of service (QoS) requirements of traffic flows.

Cluster-based routing is an efficient method in which biosensors are grouped into a number of clusters. Each cluster has a Cluster Head (CH) to collect and compress data of other nodes and forward the aggregated data to the sink node.[6] Due to the fundamental role of CHs in forwarding a large number of data, these nodes consume more energy than other biosensors. Therefore, this role should be rotated fairly between different biosensors. In WBANs, unlike the traditional wireless sensor networks, clustering problem is affected by the body positions, for example, sitting, running, walking, sleeping, and standing. Despite the body mobility, the network reliability should be maintained. Using the relay node as an intermediate node between the biosensors and sink is an efficient solution that not only increases the network flexibility but also reduces the transmission power of the biosensors. It is obvious that the position of the relays on the body significantly affects the performance of the network. This problem is raised in two ways: "relay placement" and "relay selection." In the relay placement problem, determining the best location for the relay nodes is investigated, whereas in the relay selection problem, selecting the best relay among the available relays is considered to reduce the energy consumption in the network.

Although many recent works have focused on different aspects of WBANs,[3] the ability to jointly address the problems of energy-aware relay selection, clustering, and data aggregation routing can significantly improve the performance of the network. One drawback of the previous works is that they ignore this issue in data collection process. Taking the above challenges into account, this work aims to not only improve the network lifetime but also balance the energy consumption in WBANs. In summary, the paper makes the following key contributions:

1. In the first part of the paper, considering a real traffic model, we propose an efficient algorithm, called "Energy-aware Relay Selection and Cluster-based Routing (ERSCR)," which creates a hybrid data aggregation tree in the network.
2. In the second part of the paper, we extend the ERSCR algorithm to "Joint Relay Selection, Clustering, and Routing (JRSCR)" algorithm to reduce the number of transmissions and consequently increase the network lifetime.
3. ERSCR and JRSCR consider the presented mobility model that is compatible with different physical states of the human body.
4. We jointly address the problems of energy-aware relay selection, clustering, and data aggregation routing in WBANs.
5. The proposed algorithms use energy- and distance-aware metrics to appropriately select the best CH/relay for each biosensor.

6. Eventually, a comprehensive simulation study is conducted. The results show the efficiency of the proposed algorithms in terms of energy consumption, network lifetime, and maximum hop count.

The remainder of this paper is organized as follows. Section 2 surveys the previous related works. In Section 3, we first describe the network model, energy consumption model, and mobility model. Then, the problem statement is presented. Section 4 introduces the proposed algorithms in detail. The simulation results are investigated in Section 5. Finally, Section 6 concludes the paper.

2 | RELATED WORK

Over the past decade, many research studies have been conducted on various topics of WBANs, including communication architecture, candidate technologies, propagation modeling, and implementation requirements.[3] A variety of protocols has been also presented in the literature to address the problems of routing, channel access control, security, energy efficiency, interference, latency, and node failure recovery.[2,3] In this regard, IEEE 802.15.6 has introduced efficient physical and MAC layers that provide low-complexity, low-cost, high-reliability, and short-range wireless communication for WBANs.[2]

Among the existing research, several studies have been presented to investigate the problems of relay selection/placement and routing in WBANs.[7–15] In Kim et al.,[7] an analytical hierarchy process (AHP)-based flexible relay selection is presented by considering different factors, such as average signal-to-noise ratio (SNR), residual energy, and traffic load. The work in Ahmed et al.[8] proposes two routing schemes named Link-Aware and Energy Efficient protocol for wireless Body Area networks (LAEEBA) and Cooperative LAEEBA (Co-LAEEBA). LAEEBA uses single-hop communication for emergency data and multi-hop communication for normal data. In this method, the relay selection is based on the minimum distance to the sink node and the maximum residual energy of nodes. Co-LAEEBA extends the LAEEBA algorithm by using a cooperative routing to maximize the network throughput. However, it also increases the network delay.

In Wu et al.,[9] an energy-efficient data forwarding strategy (EDFS) is proposed to balance the energy consumption and improve the network lifetime. It processes the original physiological data by compressed sensing to reduce the size of the transmitted data. Furthermore, the residual energy, sampling frequency, and sensor importance are jointly considered by EDFS for optimal relay selection. Su et al.[10] present a relay selection protocol for energy-harvesting WBANs with buffer. The proposed scheme considers both energy of relay nodes and channel state information. It selects a relay with maximum energy for receiving data and a relay with the best relay-destination channel for transmitting data. In Khan et al.,[11] an energy-efficient routing protocol is proposed, which selects a forwarder node based on the distance and residual energy metrics. The forwarder is responsible for collecting data from other biosensors and sending the result to the sink node by a two-hop communication.

The work in Elias[12] investigates the optimal design of WBANs by studying the joint routing and relay placement problem. The author proposes a mixed-integer linear programming model to optimize the number and location of relay nodes. She solves the proposed model in both realistic WBAN scenarios and general topologies. This model provides a good trade-off between the energy consumption and the number of relays installed in the network. Wang et al.[13] propose a simultaneous transmission model, in which the relay node can send its own collected data to the source node and can also serve as a relay node to help the source node to transmit its data. In literature,[14] a mathematical model for relay placement in WBANs is proposed using Free Search Krill Herd (FSKH) algorithm. The proposed scheme decreases the energy consumption and delay and increases the throughput in the network. In Javaid et al.,[15] a relay-based routing protocol is presented for in vivo WBANs. This protocol is provided with a linear programming model to maximize the network lifetime and minimize the end-to-end delay.

In literature,[16] a reliable, power-efficient, and high-throughput routing protocol is proposed, which balances the energy consumption of biosensors. It introduces a cost function to select an efficient forwarding node with maximum residual energy and minimum distance to the sink. Cui et al.[17] study a joint relay selection and power control scheme to improve the transmission reliability based on the link quality. They consider the motion and position of biosensors in running activity. In Michaelides et al.,[18] an improved mobility-aware relaying scheme is proposed to improve the packet delivery in WBANs. The proposed scheme uses an emergency phase after the regular random access phase of the superframe. The connected nodes transmit rescue beacons to reach disconnected nodes. When a disconnected node receives a rescue beacon, it participates in the current emergency phase. In literature,[19] a predecessor-successor-node

(PSN) routing technique is presented that uses a random walk mobility model and a communication cost function metric to find out the changes in the distance between the biosensors and the sink. It uses a dynamic routing strategy to select a possible communication technique to route data of the biosensors. This approach eliminates redundant packets and uses a hierarchical routing scheme to minimize energy consumption in the network.

The work in Raj et al.20 improves the network lifetime by applying the Opportunistic Energy-Efficient routing with Load-Balancing (OE2-LB) algorithm. OE2-LB reduces data aggregation delay and also avoids the routing loops with an effective manner for the smart wearable patches. In Amjad et al.,[21] the authors present an optimization problem to maximize the energy efficiency in WBANs subject to power budget and limited energy-harvesting constraints. They also provide a suboptimal solution with low computational complexity and derive the upper and the lower bounds of the source rates. The proposed scheme in Shih et al.[22] parasitizes data in surrounding Wi-Fi networks whenever temporary disconnection occurs. It models data parasitizing as an optimization problem to maximize the network lifetime without any data loss. Also, an optimal offline algorithm is introduced to solve the problem, as well as an online algorithm that allows practical implementations.

In Mu et al.,[23] a Simplified Energy-balanced Alternative-aware Routing (SEAR) algorithm is proposed, which balances the energy consumption and reduces the transmission delay in WBANs. The residual energy and current load of a candidate for the next-hop destination are considered during the routing procedure. Furthermore, the required information is exchanged during the improved routing request and routing request response procedures, and the routing cost is modified accordingly. In Zhang et al.,[24] an adaptive energy-aware relay mechanism is proposed to improve the network lifetime in WBANs. The proposed mechanism is based on the framework specified in IEEE 802.15.6 standard and includes the initialization phase and update phase. It considers the energy level of each node to adaptively adjust the network topology and conserve the low-energy nodes.

Sara et al.[25] present a relay-based routing protocol, where all biosensors are divided into two clusters: one in the upper part and the other in the lower part of the body. The position of CHs is considered as the position of the relay node. Three different scenarios are investigated: In Scenario 1, biosensors send data to the sink directly; in Scenario 2, they send data through relay nodes; and in Scenario 3, biosensors transmit data through the shortest paths. In fact, biosensors close to the sink send data directly, and other biosensors transmit data through the relay nodes. In literature,[26] a new energy-efficient and software defined networking-enabled routing algorithm is developed, which uses the fuzzy-based Dijkstra method. It uses the SNR, energy level, and hop-count metrics for routing decisions. The work in Ahmed et al.[27] develops an Energy Optimized Congestion Control based on Temperature Aware Routing Algorithm (EOCC-TARA) using Enhanced Multi-objective Spider Monkey Optimization (EMSMO) for software-defined WBANs. This algorithm overcomes the vital challenges, namely, energy efficiency, congestion-free communication, and reducing adverse thermal effects in WBAN routing.

In addition to the works discussed above, there are also some references that study different aspects of other wireless networks. For example, Shamshirband et al.[28] present a comprehensive survey of intrusion detection systems (IDSs) that use the computational intelligence (CI) methods in a mobile cloud environment. They first provide an overview of cloud computing, mobile cloud computing paradigms, and service models, as well as the security threats in these contexts. Then, a classification for IDS is defined, and the CI-based techniques are classified into single and hybrid methods. Finally, the open issues and future directions for research on this topic are highlighted. In literature,[29] a lightweight clear channel assessment (LW-CCA) is proposed as an extension to ContikiMAC for Internet of things networks to reduce the radio duty cycles in false WakeUps and idle listening though using dynamic received signal strength indicator status check time.

3 | NETWORK MODEL AND PROBLEM STATEMENT

3.1 | Network architecture

This work focuses on the remote health monitoring systems, where a sink node aggregates data of biosensors. As shown in Figure 1, consider a WBAN consisting of n nodes, including n_s biosensors, n_r relays, and a sink. This figure indicates two layouts for nodes, which differ mainly in the middle part of the body. Table 1 describes the medical application of each biosensor. According to Figure 1, the relay nodes are located on the arms, thighs, and center of the body to efficiently forward data of biosensors. Because the heat generated by biosensors depends on the transmission power, we consider a low-power transmission model, which leads to the short-range WBAN. However, relay nodes have fewer

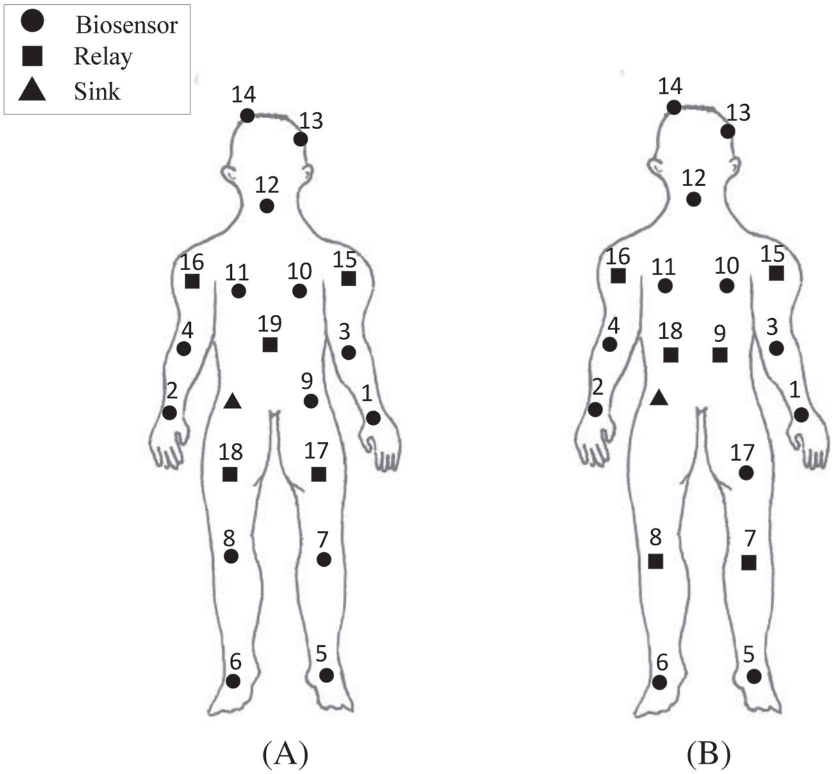

FIGURE 1 Applied layout for nodes in WBAN: (A) first layout and (B) second layout

TABLE 1 Medical application of each biosensor in the network

Biosensor no.	Medical application
1	Pulse oximetry (SpO2)
2	Temperature biosensor
3	Blood pressure
4	Insulin
5 and 6	Pressure biosensor
7 and 8	Motion biosensor
9	Glucose biosensor
10	Electrocardiography (ECG)
11	Pulse maker
12	Thyroid
13	Hearing aid
14	Electroencephalography (EEG)
15 and 16	Motion biosensor
17 and 18 (first layout)	Electromyography (EMG)
18 (second layout)	Capsule endoscopy
19	Capsule endoscopy

restrictions on transmission power. Let R_1 and R_2 denote the transmission range of biosensors and relays, respectively. The network is modeled as a graph $\boldsymbol{G(V, E)}$, where $\boldsymbol{V}$ consists of n nodes and $\boldsymbol{E}$ represents the wireless links between them. Link $(i,j) \in \boldsymbol{E}$ means that nodes $i \in \boldsymbol{V}$ and $j \in \boldsymbol{V}$ are located in the transmission range of each other and can exchange data directly.

The patient's vital signals are regularly sampled at equal intervals and sent to the sink node. A round refers to the time between two consecutive sampling of the body during which data from all biosensors are collected and sent to the sink node. According to the intended application, it is assumed that the duration of a round is set, such that there is ample opportunity to aggregate data from all biosensors. First Node Dies (FND) is used to evaluate the network lifetime. FND refers to the round number in which the first node completely loses its energy.[30] In fact, it is an appropriate metric to evaluate the energy balancing in the network. If biosensors consume energy at the same rate, the time interval between the death of the first node and the last node is minimized. As a result, FND will be postponed. This is important because each biosensor measures a vital signal of the body and the death of the first biosensor impairs the network performance.

3.2 | Mobility model

During daily routine activities, the body experiences various postures, such as sitting, standing, sleeping, walking, and running, which affect the network topology and route discovery. According to the IEEE 802.15.6 standard, nodes should be able to communicate reliably even when the person is moving. Thus, a mobility-aware routing protocol is required to select the best possible paths depending on the network topology at the sampling time. In this paper, we consider a group-based mobility model, where the nodes of each group move synchronously with a specific mobility pattern. Thus, the position of the nodes of each group does not change relative to each other. In Figure 2, different groups of nodes are highlighted for both intended layouts. Our model considers the natural mobility of different limbs of the human body. In this regard, the position of hands changes from the elbow and shoulder regions, the position of feet changes from the pelvis and knees regions, and the head moves from the neck at the normal angles. Figure 3 presents the details of the mobility model, including the point and the angle of the limb movement. Because the body may be in any position at the sampling time, we use a random strategy to determine the body position. According to the applied model, the hands, feet, and head randomly change based on the body's natural postures as shown in Figure 3.

3.3 | Energy consumption model

In this paper, we use the well-known first-order radio model to calculate the energy consumption in the network.[31–33] According to this model,

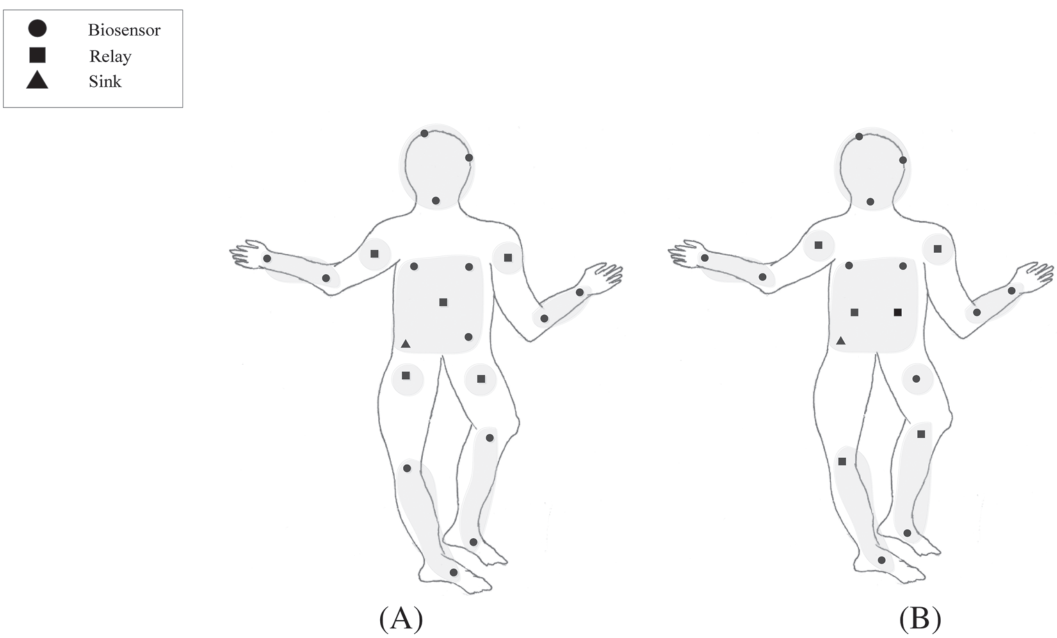

FIGURE 2 Different groups of nodes in the applied mobility model: (A) first layout and (B) second layout

FIGURE 3 Details of the mobility model

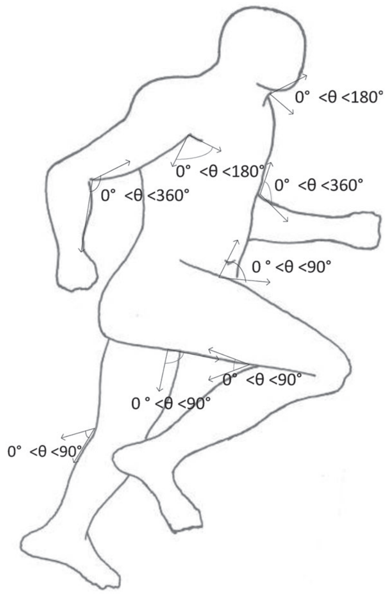

TABLE 2 List of parameters used in the paper

Notation	Definition	Notation	Definition
C (*k*)	Set of biosensors of cluster *k*	*I*(*k*)	Intermediate biosensor of CH *k*
CH(*k*)	CH of cluster *k*	*L*	Packet length
CR (*i*)	Set of candidate relays for biosensor *i*	*n*	Number of nodes
d(*i*, *j*)	Distance between node *i* and node *j*	n_c	Number of clusters
$d_s(i)$	Distance between node *i* and sink node	n_r	Number of relay nodes
ϵ_{amp}	Energy consumption of the transmission amplifier	n_s	Number of biosensors
E_{elec}	Required energy to run the electrical circuitry in transceivers	**N** (*k*,*j*)	Set of biosensors located in the common transmission range of CH *k* and relay *j*
$E_0(r)$	Initial energy of relay nodes	**P** (*j*,*s*)	Set of all paths that connect relay *j* to the sink node
$E_0(s)$	Initial energy of biosensors	$p_{opt}(j,s)$	Optimal path that connect relay *j* to the sink node
$E_{Rx}(L)$	Energy consumption for receiving an *L*-bit data packet	R_s	Transmission range of biosensors
$E_{Tx}(L,d)$	Energy consumption for transmitting an *L*-bit data packet over distance *d*	R_r	Transmission range of relay nodes

$$E_{Tx}(L,d) = E_{elec} \times L + \varepsilon_{amp} \times L \times d^2, \tag{1}$$

$$E_{Rx}(L) = E_{elec} \times L, \tag{2}$$

where $E_{Tx}(L,d)$ and $E_{Rx}(L)$ denote the energy consumption for transmitting and receiving an *L*-bit data packet over distance *d*, respectively. Also, E_{elec} is the energy consumed by the electrical circuits for transmitting or receiving, and ε_{amp} shows the energy consumption of the transmission amplifier. Table 2 summarizes the parameters used in the paper.

3.4 | Problem statement

Given the above network model, our goal is to construct an efficient cluster-based data aggregation routing tree for mobile WBANs. We aim to not only reduce the energy consumption in the network but also distribute the traffic among different biosensors fairly. This postpones FND and increases the network lifetime. As shown in Figure 4, the main issues to be discussed include:

- Employing a mobility-aware metric for relay selection to fairly distribute the energy consumption among different nodes and reduce the number of transmissions,
- Clustering the biosensors in the network and selecting an appropriate CH for each cluster,
- Developing an energy-balanced data aggregation routing tree, which efficiently connects all biosensors to the sink node. "Energy-balanced tree" refers to the tree that leads to the fair energy consumption throughout the network.

4 | PROPOSED ALGORITHMS

In this section, we first introduce the ERSCR algorithm for the described WBAN model. Then, we improve this scheme by proposing the JRSCR algorithm.

4.1 | ERSCR

ERSCR uses a multi-hop scheme to collect data of biosensors and send the aggregated data to the sink node. It first organizes the biosensors into n_c clusters. Each biosensor transmits its data to the corresponding CH or the selected relay. Then, the aggregated data is routed to the sink via a weighted Shortest Path Tree (SPT). The pseudo code of ERSCR is summarized in Algorithm 1. This algorithm has three phases, including the relay selection, clustering and CH selection, and data transmission. In the following, different phases of the algorithm are explained in more details.

4.1.1 | Phase 1: Relay selection

As mentioned before, a set of predetermined relay nodes is considered for routing process. However, depending on the body position at the sampling time, a relay node may or may not participate in the routing tree. In fact, we should address the "relay selection" problem instead of "relay placement" problem. In the first phase, each biosensor selects its

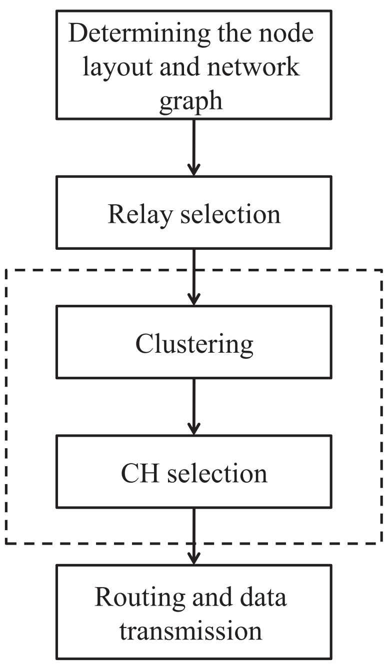

FIGURE 4 Main steps of the proposed algorithms

relay in a way that improves the energy consumption in the network (Lines 3–6 of Algorithm 1). For this purpose, ERSCR considers both metrics of Euclidean distance and residual energy as follows:

$$R_s(i) = \arg \max_{j \in \boldsymbol{CR}(i)} \left(\frac{E(j)}{d(i,j) + d_s(j)} \right), \tag{3}$$

where $R_s(i)$, $d(i,j)$,$d_s(j)$, and $E(j)$ denote the selected relay node for biosensor i, Euclidean distance between biosensor i and relay j, Euclidean distance between relay j and sink, and residual energy of relay j, respectively. Also, $\boldsymbol{CR}(i)$ is the set of candidate relays for biosensor i, which includes the relay nodes located in its transmission range. Certainly, if a typical biosensor has no relay in its transmission range, it does not select any relay node. The proposed metric balances the energy consumption among different relay nodes by considering the residual energy of each relay. It also reduces the energy consumption in the network by considering the distance factor. Using both $d(i,j)$ and $d_s(j)$ gives the relay nodes close to the direct path between each biosensor and the sink node more priority to be selected as the relay of that biosensor.

To get more insight into the problem, consider Figure 5, which shows a typical body position for the first applied layout. If only the distance between a biosensor and its relay nodes is considered, Biosensor 11 selects Relay 16, which leads to a longer path to the sink node. While considering both the distance between the biosensor and relay and the distance between the relay node and sink, Biosensor 11 selects Relay 19 to connect to the sink node. As a result, its path to the sink will be shorter, which saves more energy in the network.

Algorithm 1: Procedure of ERSCR

```
1.  Input: Network graph G = (V, E) and residual energy of nodes
2.  Output: Hybrid data aggregation routing tree
3.  ▷ Phase 1: relay selection
4.  for each biosensor i ∈ V  do
5.      Select R_s(i) according to (3)
6.  end for
7.  ▷ Phase 2: clustering and CH selection
8.  Run the k-means algorithm to divide the biosensors into n_c clusters
9.  for k = 1 : n_c do
10.     Determine CH(k) according to (4)
11. end for
12. if (distance from a biosensor to the sink is less than its distance to the corresponding CH) then
13.     That biosensor joins the sink's cluster
14. end if
15. ▷ Phase 3: data transmission
16. for each biosensor i ∈ V  do
17.     if (biosensor i belongs to the sink's cluster) then
18.         biosensor i sends its data directly to the sink
19.     elseif ( R_s(i) == ∅ ) or (distance from biosensor i to its CH is less than distance to its relay) then
20.         biosensor i selects its CH as the next forwarding node
21.         CH of biosensor i sends the aggregated data to its relay node either by a single-hop transmission
            or an intermediate biosensor selected according to (5)
22.     else
23.         biosensor i selects its relay as the next forwarding node
24.     end if
25. end for
26. ERSCR uses (7) to weight the links of graph G_w(V_w, E_w)
27. Run the Dijkstra algorithm to develop a weighted SPT for routing data from the relays to the sink
28. return the hybrid data aggregation routing tree
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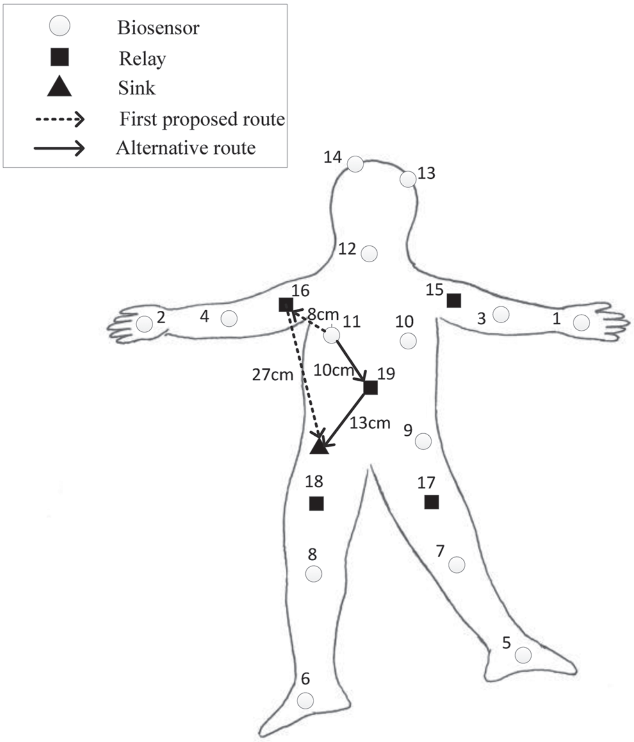

FIGURE 5 An example for relay selection in the first applied layout

4.1.2 | Phase 2: Clustering and CH selection

ERSCR uses the k-means algorithm to divide the biosensors into n_c clusters (Line 8 of Algorithm 1). The reason for choosing the k-means algorithm is its simplicity and compatibility with the first-order radio model. Accordingly, each biosensor is allocated to a cluster in such a way that the average distance of biosensors in each cluster from the center of that cluster is minimized. For each cluster, CH is determined using both distance and residual energy factors as follows (Lines 9–11 of Algorithm 1):

$$CH(k) = \arg \max_{i \in \boldsymbol{C}(k)} \left(\frac{E(i)}{d(i, R_s(i)) + d_s(R_s(i))} \right), \tag{4}$$

where $CH(k)$, $d(i, R_s(i))$, and $d_s(R_s(i))$ show the selected CH for cluster k, Euclidean distance between biosensor i and its relay node, and Euclidean distance between the selected relay for biosensor i and the sink node, respectively. Also, $\boldsymbol{C}(k)$ denotes the set of biosensors of cluster k. Considering both the Euclidean distance between a biosensor and its relay node and the Euclidean distance between the relay node and the sink node decreases energy consumption in the network. Furthermore, the residual energy factor causes the high-energy biosensors to be selected as CH, which leads to fair energy consumption in the network.

In order to reduce the number of transmissions, the sink also forms a cluster (Lines 12–14 of Algorithm 1). Minimizing the number of transmissions reduces the energy consumption and improves the utilization of network resources. If the distance from a biosensor to the sink is less than its distance to the corresponding CH, that biosensor joins the sink's cluster and sends its data directly to the sink.

4.1.3 | Phase 3: Data transmission in ERSCR

In this phase, ERSCR uses a hybrid data aggregation routing tree to efficiently transmit data of biosensors to the sink node (Lines 15–27 of Algorithm 1). With the exception of biosensors belonging to the sink's cluster, other biosensors use their CH and relay node to send data to the sink node. Let consider the problem for biosensor *i*. It first selects either its CH or its relay as the next forwarding node based on the minimum distance metric. For the case when a biosensor selects its CH as the next forwarding node, CH sends the aggregated data to its relay node by a single-hop transmission. If there is not any relay node in the transmission range of a CH, for example, CH *k*, it sends its data to the nearest relay node through an intermediate biosensor denoted by $I(k)$:

$$I(k) = \arg \max_{i \in \boldsymbol{N}(k,j)} \left(\frac{E(i)}{d(k,i) + d(k,j)} \right), \tag{5}$$

where $\boldsymbol{N}(k,j)$ is the set of biosensors located in the common transmission range of CH *k* and the selected relay node *j*. In this way, data of all biosensors are delivered to an appropriate relay node. In order to get more insight into the problem, consider Figure 6A, which shows a typical WBAN organized into four clusters with the following CHs: 8, 9, 11, and 12. In this figure, in cases where a biosensor selects its CH as the next forwarding node, the corresponding link is showed with the dotted line, and if it selects its relay as the forwarding node, the corresponding link is showed with the dashed line. Also, CHs send the aggregated data to the selected relay node via the dot-dashed lines. For example, Biosensors 5 and 6 select their CH, that is, Biosensor 8, as the forwarding node, whereas Biosensor 7 selects its relay, that is, Node 17, as the forwarding node.

Here, a weighted SPT is developed for routing data from the relay nodes to the sink node (Lines 26 and 27 of Algorithm 1). For this purpose, ERSCR uses the Dijkstra algorithm on graph $\boldsymbol{G}_w(\boldsymbol{V}_w, \boldsymbol{E}_w)$, where $\boldsymbol{V}_w$ consists of the relay nodes and sink and $\boldsymbol{E}_w$ represents the wireless links between them. Let $\boldsymbol{P}(j,s)$denote the set of all possible paths that connect relay *j* to the sink node. The optimal path, denoted by $p_{opt}(j,s)$, is defined as the path with minimum weight among all paths in $\boldsymbol{P}(j,s)$, that is,

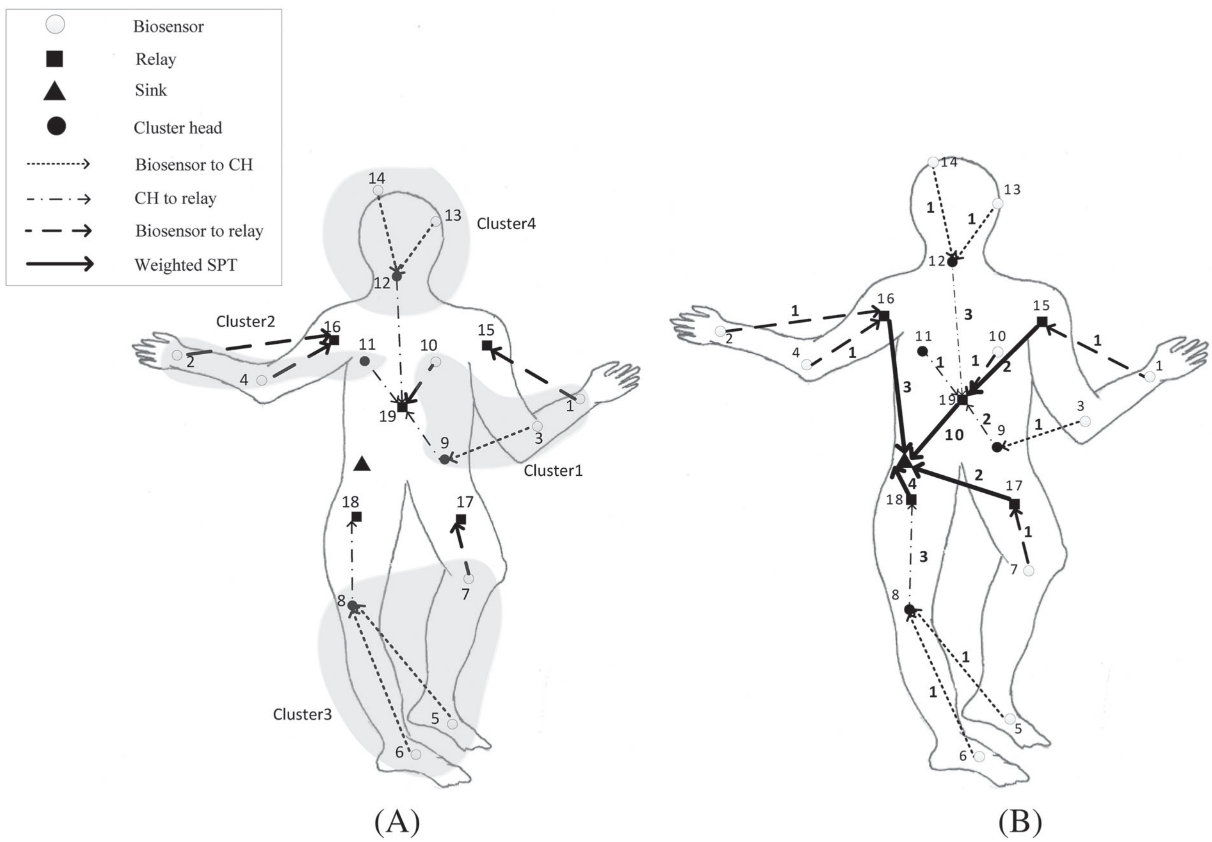

FIGURE 6 (A) An example for clustering and selecting the first forwarding node in ERSCR algorithm and (B) weighted SPT constructed between relays and sink node

$$p_{opt}(j,s) = \arg \min_{p(j,s) \in \boldsymbol{P}(j,s)} \left\{ \sum_{(x,y) \in p(j,s)} W(x,y) \right\}, \tag{6}$$

where $(x,y) \in p(j,s)$ shows the links of path $p(j,s)$ and the weight of link (x,y), denoted by $W(x,y)$ is defined as follows:

$$W(x,y) = \frac{d(x,y)}{E(x) + E(y)}. \tag{7}$$

This weighting leads to a routing tree with shorter links on the relays with more residual energy, which not only reduces the energy consumption but also balances the energy over the relay nodes. Thus, the network lifetime will increase.

Certainly, due to the dynamic conditions of the network, such as the residual energy of nodes and body position, the clusters and routing tree change round by round. Given the intended application for WBANs, it is assumed that the duration of a round is such that the system has the opportunity to recalculate the new routing paths and clustering.

Figure 6B completes the routing tree of Figure 6A. As shown in this figure, the relay nodes send their data to the sink node via the weighted SPT (solid bold arrows). The bold number written next to each link represents the number of data packets sent by that link. For example, Biosensors 5 and 6 transmit only one packet to CH 8. This node transmits the received data packets and its own data packet to Relay 18, that is, three packets. Finally, four data packets are sent to the sink via Relay 18. Table 3 shows the details of the hybrid routing tree presented in Figure 6B.

4.2 | JRSCR

Although ERSCR considers both energy and distance factors to create an efficient routing tree, it increases the number of transmissions. This intensifies the energy consumption in the network. In order to solve the problem, this section presents the JRSCR algorithm, which consists of two phases: (1) joint relay selection and clustering and (2) data transmission. The pseudo code of JRSCR is summarized in Algorithm 2. In the following, different phases of this algorithm are explained in detail.

TABLE 3 Details of the hybrid routing tree presented in Figure 6B

Biosensor	Cluster	Relay	Path to sink
1	1	15	{1, 15, 19, sink}
2	2	16	{2, 16, sink}
3	1	-	{3, 9, 19, sink}
4	2	16	{4, 16, sink}
5	3	-	{5, 8, 18, sink}
6	3	-	{6, 8, 18, sink}
7	3	17	{7, 17, sink}
8	3	18	{8, 18, sink}
9	1	19	{9, 19, sink}
10	1	19	{10, 19, sink}
11	2	19	{11, 19, sink}
12	4	19	{12, 19, sink}
13	4	-	{13, 12, 19, sink}
14	4	-	{14, 12, 19, sink}

4.2.1 | Phase 1: Joint relay selection and clustering

JRSCR first clusters the biosensors by selecting an appropriate relay for each biosensor (Lines 3–14 of Algorithm 2). As mentioned before, CHs lose their energy faster than other nodes due to their responsibility for receiving, aggregating, processing, and transmitting a large amount of data. Thus, in the JRSCR algorithm, the relay nodes directly play the role of CH thanks to having more initial energy and rechargeable battery. For this purpose, each biosensor first selects its relay node using the metric presented in (3) and forms a cluster with other biosensors that select the same relay. If a biosensor has no relay in its transmission range due to the body position, it uses (5) to join to the nearest relay node through an appropriate intermediate biosensor. Those biosensors where the sink is in their transmission range do not participate in the relay selection process. They send data directly to the sink node in the form of a star topology (Line 15 of Algorithm 2). Each relay may have a different number of biosensors in its cluster depending on the body position at the sampling time. It is also possible that no biosensor is assigned to a relay node. Thus, the number of clusters is equal to or less than the number of relays and sink node.

Algorithm 2: Procedure of JRSCR

1. **Input:** Network graph $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$ and residual energy of nodes
2. **Output:** Hybrid data aggregation routing tree
3. ▹ Phase 1: joint relay selection and clustering
4. **for** each biosensor $i \in \boldsymbol{V}$ that does not contain the sink in its transmission range **do**
5.   **if** $(\boldsymbol{CR}(i) \sim= \emptyset)$ **then**
6.   Select $R_s(i)$ according to (3)
7.   **else**
8.   biosensor i uses (5) to join to the nearest relay node through an appropriate intermediate biosensor
9.   **end if**
10. **end for**
11. All biosensors that select the same relay node form a cluster together
12. **for** each cluster k **do**
13.   The corresponding relay node plays the role of $CH(k)$
14. **end for**
15. Biosensors that contain the sink in their transmission range join the sink's cluster
16. ▹ Phase 2: data transmission
17. **for** each biosensor $i \in \boldsymbol{V}$ **do**
18.   **if** (biosensor i belongs to the sink's cluster) **then**
19.   biosensor i sends its data directly to the sink
20.   **else**
21.   biosensor i sends data to its relay either by a single-hop transmission or through an intermediate biosensor selected according to (5)
22.   **end if**
23. **end for**
24. JRSCR uses (7) to weight the links of graph $\boldsymbol{G}_w(\boldsymbol{V}_w, \boldsymbol{E}_w)$
25. Run the Dijkstra algorithm to develop a weighted SPT for routing data from the relays to the sink
26. **return** the hybrid data aggregation routing tree

4.2.2 | Phase 2: Data transmission in JRSCR

Each biosensor (excluding the neighbors of the sink node) first transmits its data to its selected relay through a single-hop or two-hop transmission. In fact, if a biosensor has a relay node in its transmission range, it transmits its data to the selected relay node through a single-hop transmission, and otherwise, it uses an intermediate biosensor to transmit its data to the nearest relay node (Lines 16–23 of Algorithm 2). Then, similar to the ERSCR algorithm, a weighted SPT is constructed on graph $\boldsymbol{G}_w$ for routing data from the relay nodes to the sink node. It is worth noting that the weight of each link in $\boldsymbol{G}_w$ is calculated according to (7) (Lines 24 and 25 of Algorithm 2).

In order to get more insight into the problem, consider Figure 7, which shows a WBAN for the first applied layout. The network is divided into five highlighted clusters. Biosensors 2, 4, and 8 directly join to the sink cluster. However, Biosensors 5 and 6 select Biosensors 7 and 8 as intermediate nodes to join to clusters of Relay 17 and sink, respectively. Other biosensors first transmit data to their selected relay nodes via the dashed lines. Then, the relay nodes transmit the aggregated data to the sink node via the weighted SPT shown by the solid bold arrows. Table 4 shows the details of the routing tree presented in Figure 7.

5 | PERFORMANCE EVALUATION

In this section, we evaluate the proposed algorithms compared to the LAEEBA algorithm[8] and the RK algorithm[11] in terms of energy consumption, network lifetime, and maximum hop count of routing trees. With the aim of performing a fair comparison, the LAEEBA scheme is modified, where biosensors are first clustered by the described strategy in Section 4.1. For each cluster, a biosensor is selected as the relay node according to the metric presented in Ahmed et al.[8] Finally, each relay node transmits data to the sink via an SPT with minimum-hop paths. Energy consumption indicates the total energy consumed by all nodes in the network. FND is used to evaluate the network lifetime. Maximum hop count represents the average of the maximum number of hops required in a routing tree to connect a biosensor to the sink node. It is worth noting that the results of energy consumption and maximum hop count are presented after 10 rounds unless otherwise is described.

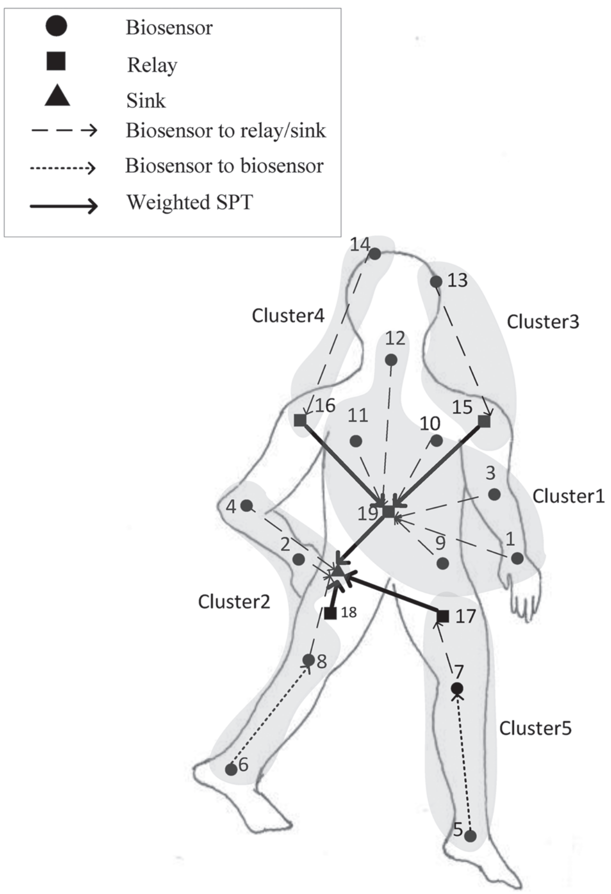

FIGURE 7 An example for clustering and routing in JRSCR

TABLE 4 Details of the routing tree presented in Figure 7

Biosensor	Cluster	Relay	Path to sink
1	1	19	{1, 19, sink}
2	2	-	{2, sink}
3	1	19	{3, 19, sink}
4	2	-	{4, sink}
5	5	-	{5, 7, 17, sink}
6	2	-	{6, 8, sink}
7	5	17	{7, 17, sink}
8	2	-	{8, sink}
9	1	19	{9, 19, sink}
10	1	19	{10, 19, sink}
11	1	19	{11, 19, sink}
12	1	19	{12, 19, sink}
13	3	15	{13, 15, 19, sink}
14	4	16	{14, 16, 19, sink}

TABLE 5 Simulation parameters

Parameter	Value	Parameter	Value
n_s	14 (in the first layout) 12 (in the second layout)	$E_0(r)$	1 J
n_r	5 (in the first layout) 6 (in the second layout)	$E_0(s)$	0.5 J
R_s	0.5 m	E_{elec}	50 nJ/bit
R_r	0.7 m	ε_{amp}	1.97 nJ/bit/m^2
L	5 × 1024 × 8 bits	Body dimensions	1.9 × 0.45 m

5.1 | Simulation setup

As mentioned in Section 3, it is assumed that the patient's vital parameters are sampled at the regular intervals and sent to the sink node. At each round, five samples of each vital parameter are measured. The length of each sample is 1024 bytes. The packets sent by each node consist of two parts, including the header part and data part. Ten percent of each packet is intended for transmitting the control data and the updated local information for recalculations. According to the IEEE 802.15.6 standard, we implement the proposed schemes for a short-range WBAN, where the transmission range of biosensors (R_s) and transmission range of relay nodes (R_r) are set to 0.5 and 0.7 m, respectively. The maximum radiated transmission should not exceed 0 dBm.[2] In addition, based on this standard, the network support bit rates in the range of 10 Kbps to 10 Mbps. In order to calculate the energy consumed by sending and receiving data, the first-order radio model is used, in which E_{elec} and ε_{amp} are set to 50 nJ/bit and 1.97 nJ/bit/m^2, respectively. Also, the initial energy of biosensors is 0.5 J, that is, $E_0(s) = 0.5$ J, and the initial energy of relay nodes is 1 J, that is, $E_0(r) = 1$ J. Table 5 summarizes the simulation parameters.

All nodes are placed according to two layouts shown in Figure 1. Based on the IEEE 802.15.6 standard, a maximum of 256 nodes can exist in each WBAN. However, we use far fewer biosensors to prevent disruption to the patient's daily activities (as described in Table 5). The implanted biosensors use the micro/nanotechnology. On the other hand, the relay nodes are wearable and easily replaceable. Body dimensions, including the height and shoulder width, are set to 1.9 and 0.45 m, respectively. We also use the group-based mobility model described in Section 3, where the nodes of each group move synchronously with a specific mobility pattern. Because the body may be in any position at the sampling time, we use a random strategy to determine the body state. In fact, at each sampling time, the body may be in a random state according to the described mobility model. In this model, the hands, feet, and head randomly change based on the body's natural postures as shown in Figure 3. We also consider a scenario, that is, Scenario 4, to evaluate the performance of the network in several specific body states. Each simulation result is averaged over at least 20 individual runs.

5.2 | Results and discussion

Taking the above considerations into account, we present several scenarios to investigate the effect of different conditions on the performance of the network.

Scenario 1: In the first scenario, we study the network performance for two described node layouts. The results are shown in Figure 8. In the first layout, Relay 19 suffers from the high traffic due to its responsibility to forward data of other nodes. Thus, it loses its energy quickly, and FND decreases. To solve this problem, the second layout uses two relay nodes side by side to distribute the load on both relays. This not only decreases the energy consumption (Figure 8A) but also increases the network lifetime (Figure 8B). However, the second layout has a slightly higher maximum hop count than the first layout (Figure 8C).

Another important point is the superiority of the proposed schemes compared with the LAEEBA and RK algorithms in terms of energy consumption and network lifetime. ERSCR and JRSCR consider both residual energy and distance to create a hybrid data aggregation tree. For this purpose, relay selection, clustering, and routing are addressed jointly.

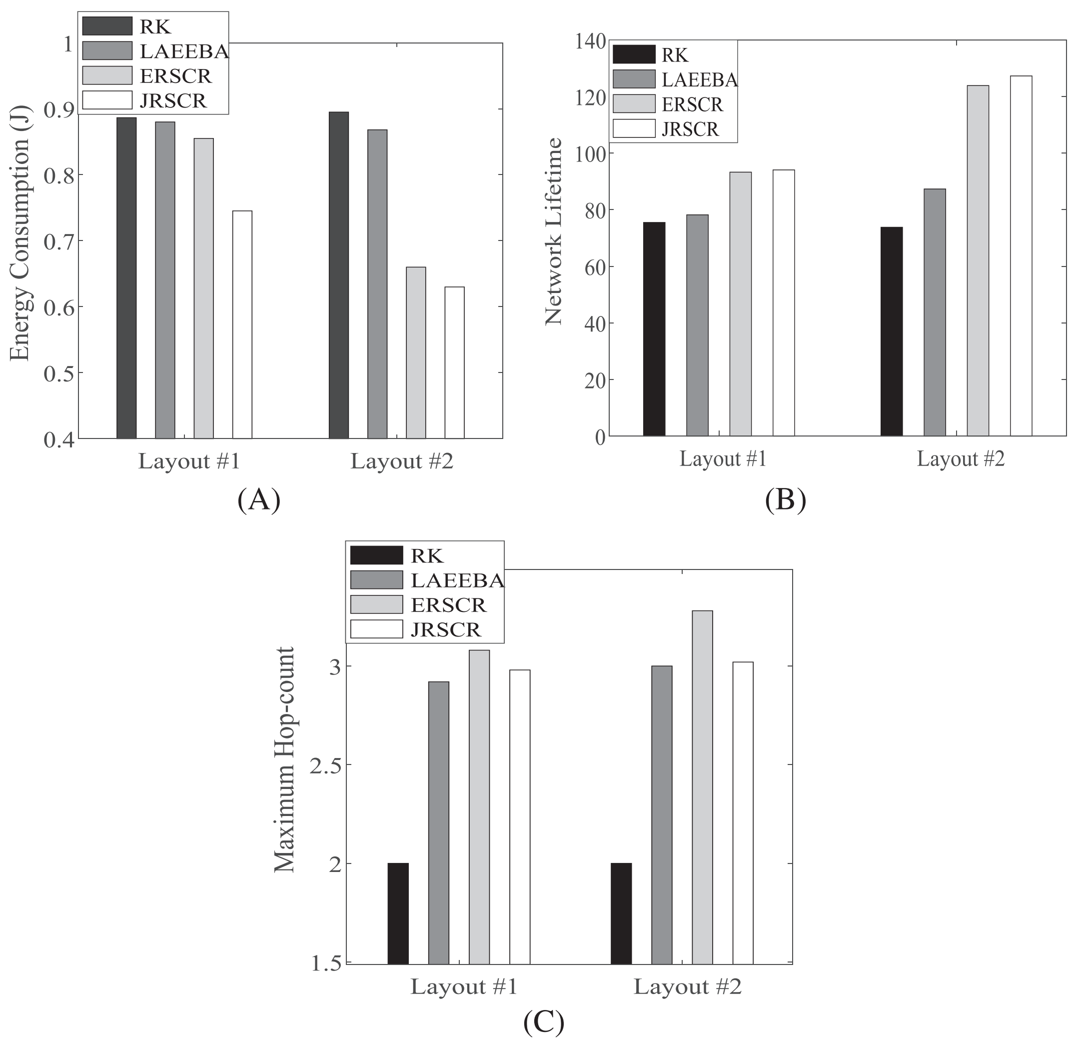

FIGURE 8 Network performance for two applied node layouts: (A) energy consumption, (B) network lifetime, and (C) maximum hop count

The proposed algorithms rotate the CH role between different biosensors/relays so that they lose the energy synchronously. This balances the energy consumption in the network fairly. Thus, FND will be postponed. However, JRSCR reduces the number of transmissions more effectively. It also reduces the maximum hop count of routing trees thanks to the direct use of relay nodes as CH. Thus, JRSCR consumes less energy than the ERSCR algorithm and results in a better FND. LAEEBA selects the minimum-hop paths to route data from relays to the sink.[8] Accordingly, its maximum number of hop count is less than the proposed algorithms. In addition, because, in the RK algorithm,[11] all biosensors send data to the sink through only one relay node, it has the minimum number of hops.

Scenario 2: In this scenario, we compare the energy consumption of the algorithms for consecutive rounds. The results are shown in Figure 9A,B for the first and the second layout of nodes, respectively. As justified before, the proposed algorithms have less energy consumption than the LAEEBA and RK algorithms at different rounds. This is especially evident in the second layout. Furthermore, in confirming the results of the previous scenario, JRSCR shows a better performance than the ERSCR algorithm. By reducing the number of transmissions in JRSCR, the energy consumption is reduced, and the utilization of network resources is improved. Naturally, during the network activity and increasing the number of rounds, more data are collected from different biosensors to be sent to the sink node. Thus, the energy consumption gradually increases.

Scenario 3: Because the main goal is to deliver data to the sink node, its location plays an important role in the performance of the network. In this scenario, we examine the algorithms for different sink locations in the second layout of nodes, including the left arm, left thigh, waist, and back of the neck. As shown in Figure 10, in each case, the corresponding biosensor is replaced with the sink node. The presented results in Figure 11 confirm the obtained observations in previous scenarios. For example, as justified before, JRSCR has the best energy consumption and network lifetime for different locations of sink (Figure 11A,B).

On the other hand, the proposed algorithms show a better lifetime for two cases of waist and neck compared with other locations. In fact, placing the sink on the waist or neck not only consumes less energy but also distributes the load over the network more fairly. Thus, the network lifetime increases. Conversely, placing the sink on the thigh increases the energy consumption and consequently reduces the network lifetime. Another important point is that for all sink locations, ERSCR has the maximum number of hops (see Figure 11C). However, in the JRSCR algorithm, the relay nodes directly play the role of CH. This reduces the maximum hop count compared with the ERSCR algorithm.

Scenario 4: Unlike the previous scenarios where the body position changes randomly at the consecutive times, in this scenario, three fixed positions are considered as shown in Figure 12. We assume the second layout of nodes. The goal is to investigate which position of the body consumes less energy and has a better performance. The results are shown in Figure 13. In confirmation of the previous results, the JRSCR algorithm has the best performance for different positions in terms of energy consumption and network lifetime. Furthermore, as can be seen, Positions 1 and 3 lead to the maximum and the minimum lifetime, respectively. According to the first-order radio model, when the body organs are farther apart, that is, Position 3, the network consumes more energy; consequently, the network lifetime is reduced. This also increases the maximum hop count of routing trees due to the greater distance of biosensors to the sink node.

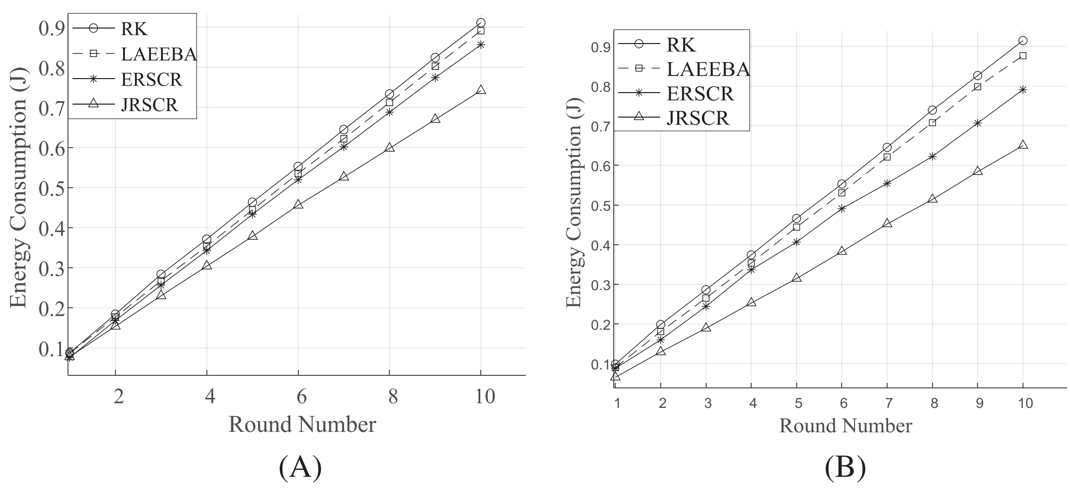

FIGURE 9 Energy consumption at different rounds: (A) first layout and (B) second layout

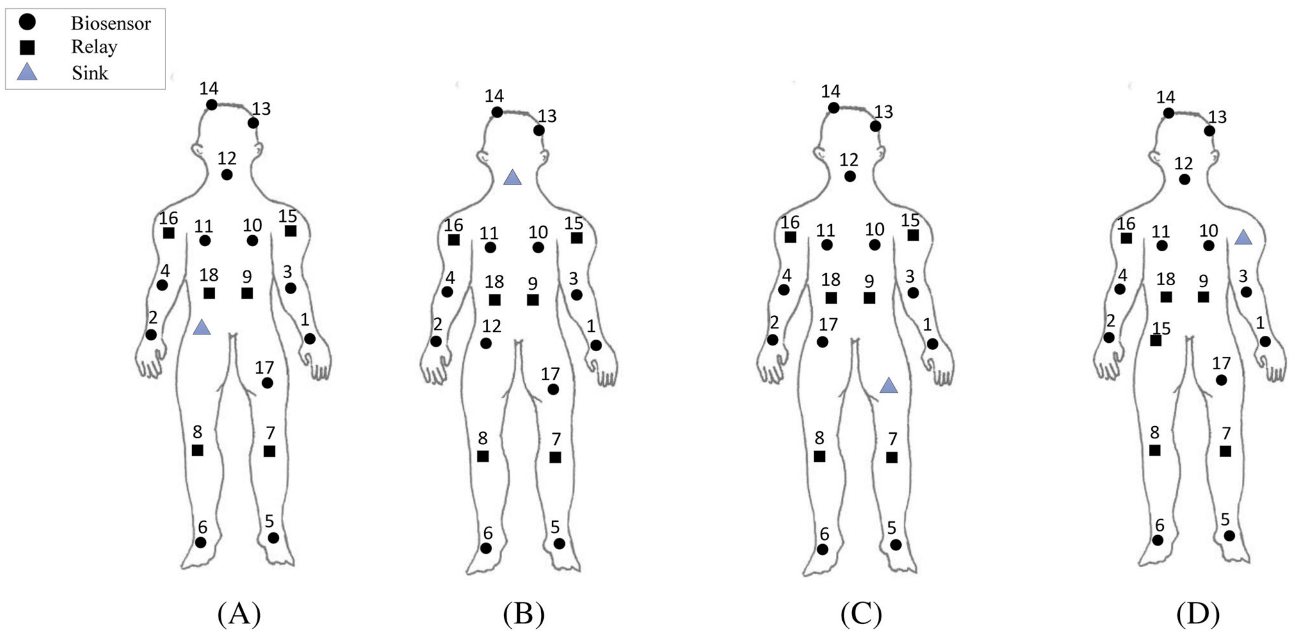

FIGURE 10 Different locations of sink in the second applied layout: (A) waist, (B) back of the neck, (C) left thigh, and (D) left arm

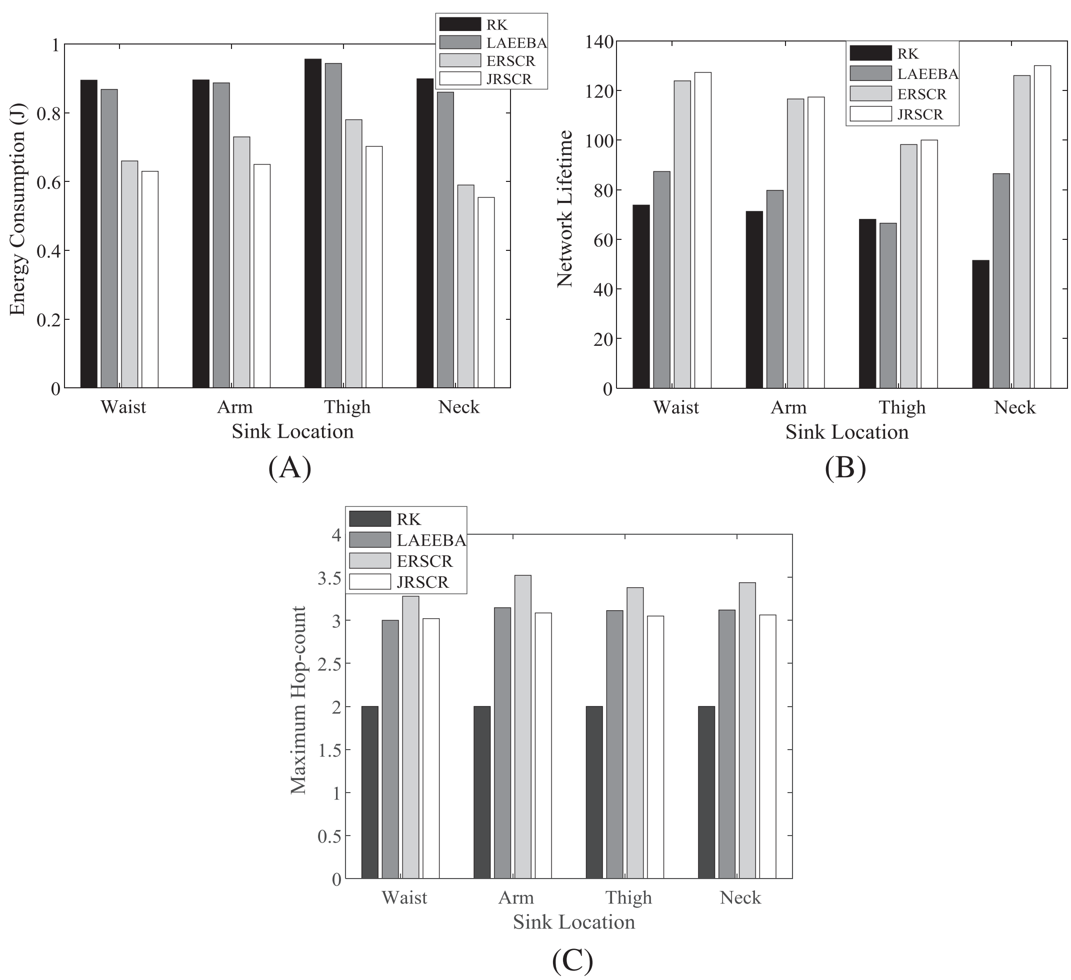

FIGURE 11 Network performance versus different sink locations: (A) energy consumption, (B) network lifetime, and (C) maximum hop count

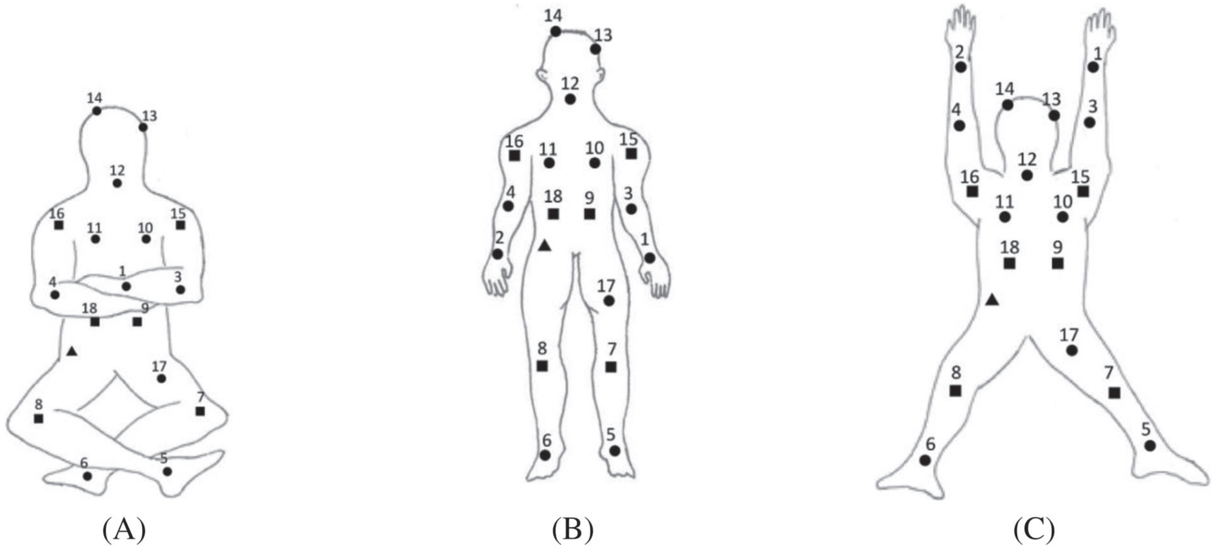

FIGURE 12 Different applied body positions in Scenario 4: (A) Position 1, (B) Position 2, and (C) Position 3

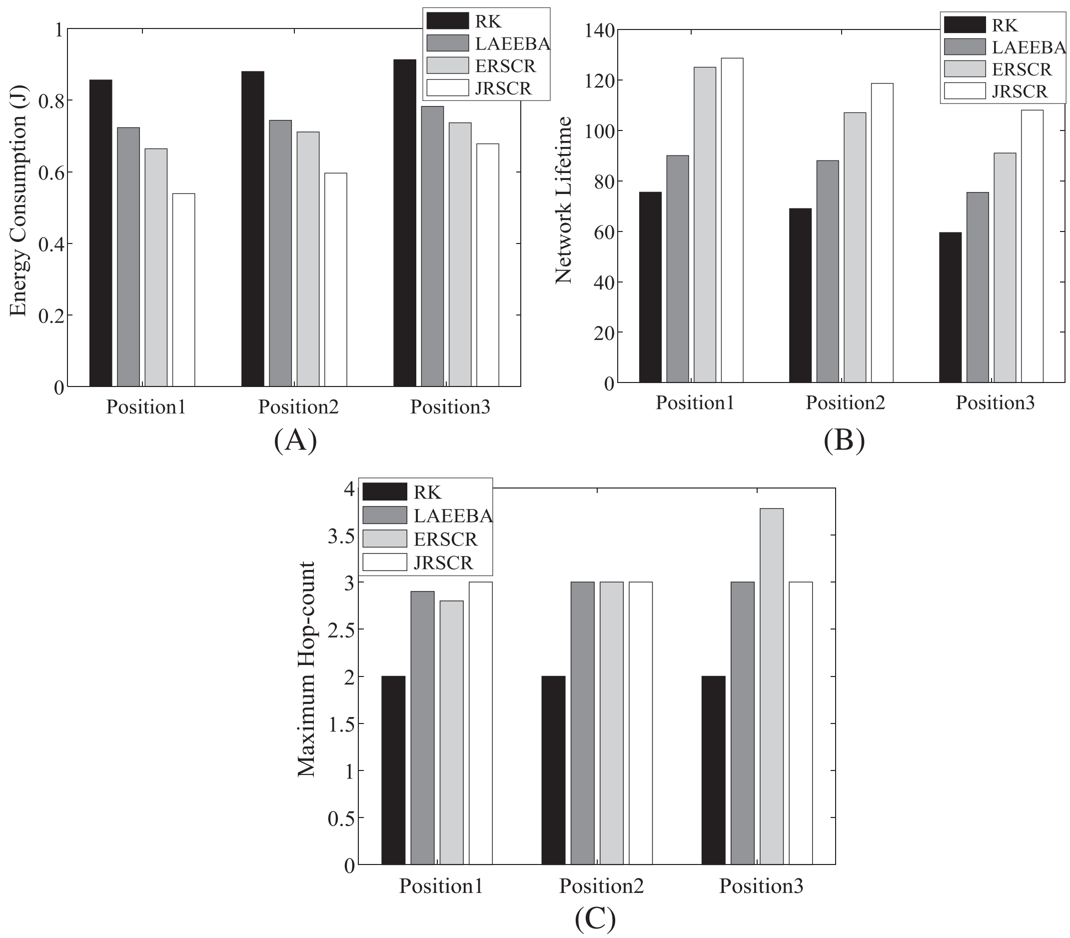

FIGURE 13 Network performance versus different body positions: (A) energy consumption, (B) network lifetime, and (C) maximum hop-count

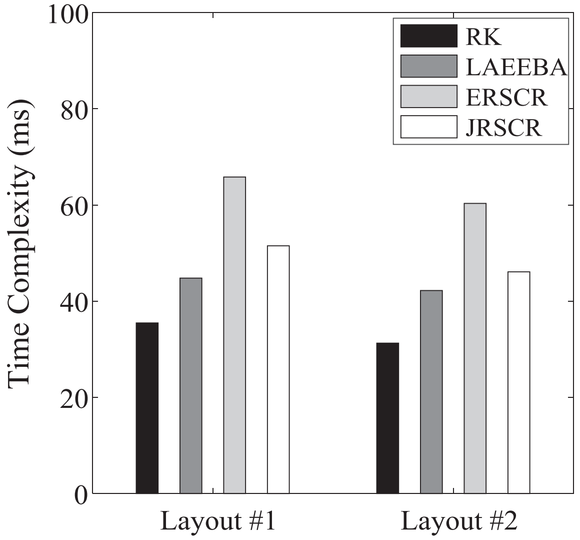

FIGURE 14 Time complexity for two applied node layouts

In contrast, in the first case, the biosensors get closer to the sink, and the network lifetime is increased. However, the JRSCR algorithm has the same maximum hop count in all three positions. This is because in all three positions, Biosensors 1, 3, 10, 12, and 13 select Relay 15 for forwarding their data. The distance of this relay from the sink node leads to an increase in the maximum hop count to three hops.

5.3 | Time complexity evaluation

In this section, we evaluate the time complexity of the algorithms for both intended layouts.

Scenario 5: All measurements are made on a computer equipped with an Intel Core i7 2.4 GHz processor and 8 GB of memory. Figure 14 shows the time complexity or equivalently the run time of the algorithms for both layouts. Although the performance of ERSCR and JRSCR algorithms is better than LAEEBA and RK in terms of energy consumption and network lifetime, the LAEEBA and RK algorithms have less time complexity due to their simplicity. Our algorithms jointly address the problems of energy-aware relay selection, clustering, CH selection, and energy-balanced routing tree; this is certainly associated with an increase in computational complexity. In this regard, ERSCR is slightly more complex than JRSCR due to its strategy for clustering and CH selection.

Another important point is that we see more time complexity in the first layout. This is justified by the use of more nodes in the first layout. As the number of nodes increases, the time required for clustering increases. It also increases the connectivity degree of the network graph, which leads to more time to build a routing tree.

6 | CONCLUSION

In this paper, the construction of energy-balanced routing trees for WBANs was studied. For this goal, two different practical layouts for nodes were considered. We proposed two energy- and distance-aware algorithms called ERSCR and JRSCR that use clustering and relay nodes to develop the data aggregation routing trees. Both algorithms are compatible with different physical states of the human body. ERSCR considerably reduces the energy consumption by efficiently selecting the relay of each biosensor. It also rotates the CH role between biosensors so that they lose the energy at the same rate. This balances the energy consumption in the network. Thus, FND will be postponed. In JRSCR, CHs are selected among the relay nodes to reduce the number of transmissions. This further decreases the energy consumption and leads to a better FND in the network. Improving the network performance by placing the sink on the waist is another result of this paper. Given the advantages mentioned for the proposed algorithms, they can be used in various practical scenarios for health monitoring systems, including monitoring of the heart rate, blood pressure, and blood oxygen level, as well as controlling the diabetes, sleep staging, and cardiovascular disease.

DATA AVAILABILITY STATEMENT

The data of this paper are the result of simulation, and all data are presented in the form of graphs within the paper. Further details that support the findings of this study are available from the corresponding author upon reasonable request.

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