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SDN-based wireless body area network routing algorithm for healthcare architecture

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The use of wireless body area networks (WBANs) in healthcare applications has made it convenient to monitor both health personnel and patient status continuously in real time through wearable wireless sensor nodes. However, the heterogeneous and complex network structure of WBANs has some disadvantages in terms of control and management. The software-defined network (SDN) approach is a promising technology that defines a new design and management approach for network communications. In order to create more flexible and dynamic network structures in WBANs, this study uses the SDN approach. For this, a WBAN architecture based on the SDN approach with a new energy-aware routing algorithm for healthcare architecture is proposed. To develop a more flexible architecture, a controller that manages all HUBs is designed. The proposed architecture is modeled using the Riverbed Modeler software for performance analysis. The simulation results show that the SDN-based structure meets the service quality requirements and shows superior performance in terms of energy consumption, throughput, successful transmission rate, and delay parameters according to the traditional routing approach.

KEYWORDS

802.15.6, IoT, routing, software defined network, wireless body area network

1 | INTRODUCTION

The advances in the miniaturization of electronic devices as well as the increase in health costs have led to the development of wireless body area networks (WBANs). The development of sensing, battery, and wireless communication technologies in sensor nodes creates new possibilities for the use of WBAN architecture in healthcare applications [1]. In the field of health, a WBAN user comprises a number of sensor nodes (eg., ECG, EEG) and a coordinator placed inside or on the human body. The coordinator node is called HUB in the IEEE 802.15.6 standard. These nodes aim to collect, store, and process the physiological parameters of the patient, and to provide health services everywhere. WBANs have different and specific features such as small size, different data rates, limited battery life, quality of service (QoS) requirements, and heterogeneous network traffic. New approaches to WBAN architecture have been proposed to meet these specific requirements. The internet of things (IoT) is a new technology that aims to connect anything at anytime and anywhere. Recent developments in hardware, software, and networking (eg., wireless sensor networks, radio frequency identification) technologies have contributed to the emergence of IoT. In this context, WBAN technology with IoT technology makes new applications more powerful. Different types of sensors and HUBs in the WBANs can collaborate with various wireless technologies using IoT architecture [2,3].

To develop cost-effective, scalable, reliable, and flexible e-health services, WBAN technologies need to be simple, uniform, and support a secure communication infrastructure.

The most important problems of WBAN architecture are heterogeneity, scalability, and energy efficiency. Unlike conventional devices with sufficient computing, processing, and storage resources, the sensor nodes and mobile devices used in WBAN technologies have limited capabilities. In this context, the different resource capabilities of heterogeneous devices used in the WBAN environment should be considered when designing the medium access control (MAC) protocols for WBAN. The reason scalability is a major problem in WBANs is that a WBAN needs to provide a communication medium for many devices to interact with each other. This study discusses how the SDN approach can be used to solve heterogeneity, scalability, and energy efficiency problems.

SDN is a promising technology that defines a new design and management approach for networking. The main feature of this paradigm is the abstraction of the control and data planes [4,5]. While the switches only forward the data, the SDN controller provides the forwarding decisions. Since decision algorithms do not work on network devices in an SDN paradigm, it is possible to use simpler network devices instead of complex routers. Furthermore, in conventional networks, each router has its own routing mechanism. If any of these mechanisms need to be updated, each network device must be managed separately. As a solution to this problem, the SDN approach suggests a centralized management approach, which provides a more dynamic network environment. These features of SDN are thought to be used by WBAN to solve problems such as heterogeneity and scalability.

Another problem in WBANs is the need to develop an efficient routing protocol. The limited availability of bandwidth, fading, noise, and interference may cause problems due to limited network protocol information [6]. In addition, the nodes forming the network can be heterogeneous in terms of the current energy or computational power. Therefore, one of the most important contributions of our study is the use of a central controller. With this approach, the energy consumption of WBAN HUBs and unnecessary traffic in the network are reduced. In this study, a general review of the recently proposed SDN solutions to improve network performance in the WBAN environment is conducted. To the best of our knowledge, this is the first study that focuses on the SDN approach for WBAN based on IEEE 802.15.6 and proposes an energy-aware and controller-based routing algorithm (SDNRouting) with a new interface protocol (WBANFlow). Furthermore, this study proposes a new architecture consisting of data, control, and application planes for the SDN-based WBAN environment. Finally, new areas of study where SDN solutions can be used to improve the performance of WBAN technologies are mentioned.

The remainder of this paper is organized as follows. In Section 2, relevant studies that point to the necessity of this study are discussed. In Section 3, the proposed architecture and the technologies used are described: SDN based WBAN, IEEE 802.15.6, WBANFlow, and SDNRouting algorithm. The simulation results are given in Section 4.

2 | RELATED WORKS

Although there are many studies on WBAN and SDN in the literature, few studies have dealt with the WBAN issue based on the SDN approach. Hu et al. [7] proposed a flexible network architecture that deals with both intelligent health monitoring and emotional care. In particular, they developed an architecture based on an SDN approach named HealthIoT by isolating the application plane from the physical infrastructure. With their architecture, healthcare services acquire the ability to customize their own data collection, transfer, processing, and emotion feedback through well-defined APIs, and to enable multiple applications in a shared infrastructure to reduce costs in general. It provides flexible control and management of the physical infrastructure. In their study, the focus is on the application plane of the proposed architecture; the MAC technique used for the architecture and its details are not mentioned. In addition, important QoS parameters such as latency, energy efficiency, and throughput for WBAN are not studied.

Jeong et al. [8] proposed a supportive service flow and a new cloud-based personalized healthcare system architecture in both home and hospital settings to provide effective care for patients with chronic disease. The system took into account the different characteristics of the environment in the hospital and at home, and enabled various chronic disease care services. Li et al. [9] proposed the use of SDN, service function chain (SFC), and intuitive simulate anneal (SA) algorithms to reduce the IoT data transmission time in e-health services networks. The SA algorithm was found to be better at optimizing the data transmission time with lower user numbers, while the Greedy algorithm was more suitable for more users. They suggested that e-health network design could be improved with the proposed methods and that more reliable services could be enabled by using sensor nodes to provide chronic care and treatment remotely and to identify medical emergencies. In their study, the delay, energy efficiency, and throughput were not investigated.

Izaddoost and McGregor [10] used an SDN to transfer physiological data streams through alternative ways having better quality instead of the shortest possible path, in order to increase the reliability of data transfer and to improve the quality of data processing in real time. They explained how to improve the performance of the communication network between a rural hospital and a cloud-based Artemis platform to achieve the desired level in the transmission of health technology data. In terms of overcoming the density in the network, they described SDN as an effective communication infrastructure on a remote health platform. SDN with a wide network view enables the selection of the most appropriate path possible. In their study, all other parameters were ignored except the throughput. Gao et al. [11] proposed a power management system for the WBAN architecture (IEEE 802.15.6), which can improve energy efficiency by adjusting the transmit power to adapt to varying channel environments.

Bera et al. [12] proposed a software-defined wireless sensor network architecture (Soft-WSN) to support service delivery with IoT. The detailed architecture of the proposed system included application, control, and infrastructure planes to provide SDN communication in IoT. An SDN controller with two management policies, device management, and network management was designed. Device management made it easier for users to control their devices on the network. They examined the detection task, detection delay, and active sleep states in a sensor node to activate the device control mechanisms. The topology of the network was controlled by network management policies that could be modified at runtime to cope with the IoT's dynamic needs. In addition, the proposed scheme was implemented on a real hardware platform without altering the underlying concepts of sensor network communication, and therefore, the existing sensor devices could be integrated seamlessly. Experimental results on a real hardware-based testbed showed that the proposed approach was useful to meet the real-time application-specific requirements of IoT while providing significant improvements in network performance over traditional approaches.

In order to accomplish enhanced performance results for wireless sensor actuator network (WSAN) systems, an interface protocol called WSANFlow, which is responsible for all communications between the SDN controller (SDNC) and the SDN oriented end devices, was suggested in Ref. [13]. The developed SDNC could perform all processes related to network control and management. Hence, by using the WSANFlow interface protocol, the SDN controller could optimize the instructions to be delivered to the end devices in a manageable and efficient manner. Al-Hubaishi et al. [14] proposed an SDN-enabled wireless sensor and an actuator network architecture with a new routing discovery mechanism. The new routing decision approach could change the existing path using fuzzy-based Dijkstra algorithm during data transmission.

Silva et al. [15] proposed a new network infrastructure based on the SDN paradigm. In their study, a prediction application with a quality-based mobility control was developed with the approach of context-aware mobile approach (CAA) based on SDN. By deciding the point of attachment (PoA), the proposed method could meet application quality requirements as well as improve the existing wireless quality conditions. In addition, they tried to increase the reliability and resilience of e-health bio-feedback systems. Al Shayokh et al. [16] suggested a virtual hospital architecture based on an SDN for WBAN. They proposed a new and simplified architecture that takes advantage of the SDN to reduce the complexity of cloud architecture resulting from the integration of cloud architecture into WBAN for virtual hospital architecture concepts. However, it was studied more at the architectural level and was not implemented in the SDN environment, and no performance evaluation was performed. Although these studies are very useful, the main disadvantage is that IEEE 802.15.6 is not used as the recommended protocol for WBAN architecture.

Abidi et al. [17] proposed an energy efficient routing protocol for WBANs to minimize energy consumption and maximize network life. Kara [18] proposed on-demand and position-based algorithms that minimize the end-to-end packet delays and utilized node energies in the most efficient manner for wireless ad hoc networks. There are many routing algorithms in the literature. Al-Karaki and Kamal [19] detailed the characteristics of these algorithms and the differences between them. The ad hoc on-demand distance vector (AODV) [20] routing algorithm is used more widely in WBAN. In this context, we propose the (SDNRouting) algorithm and compare it with the AODV (traditional routing) algorithm.

When the different protocols in the literature were examined, it was found that many routing protocols consider only the routing parameters. However, the routing parameters that need to be considered in WBANs with a dynamic and heterogeneous network structure are very important and complex. The sensing processes used to access the environment and the routing procedures used to find the most suitable path are important parameters that should be considered in terms of energy consumption. In this study, a new routing protocol (SDNRouting) and an interface protocol (WBANFlow) are developed. The developed SDNRouting algorithm runs on the controller. This algorithm determines new routes based on the signal-to-noise ratio (SNR) and battery levels. The obtained results show that energy efficiency is ensured, and the link quality and throughput are increased. To the best of our knowledge, the differences from the studies in literature are as follows:

- By using the Riverbed Modeler software [21], IEEE 802.15.6 for intra-WBAN communication and the proposed WBANFlow interface protocol for inter-WBAN communication are developed, and the SDN-based WBAN architecture is simulated.
- A new energy-aware SDNRouting algorithm running on the controller is proposed.
- The proposed system is a part of IoT technology.
- The proposed system is developed for healthcare applications.

There is no study in the literature involving a new interface protocol that uses the IEEE 802.15.6 protocol on SDN-based WBAN architecture and a new energy-aware routing algorithm running on the controller.

3 | PROPOSED ARCHITECTURE

The proposed architecture is shown in Figure 1. Each person having sensor nodes and a HUB is defined as a WBAN user. All the sensor nodes send their data to the HUB to which they are connected. This communication is called intra-WBAN communication. In addition, each WBAN user can communicate with other WBAN users. This communication is called inter-WBAN communication. The controller, which is added to our architecture based on the SDN approach, is responsible for the control and management of the inter-WBAN communication.

The HUB transmits the data collected from the sensor nodes to the gateway, such as a Wi-Fi access point (AP), to transmit data to the relevant units. If a HUB is outside the coverage area of an AP, or if the HUB is inside the coverage area of an AP with low SNR, it must send the collected data through the optimum route. One contribution of our study is the energy-aware routing algorithm performed by the controller. The proposed architecture is based on the IEEE 802.15.6 data link/ MAC layer for intra-WBAN communications. The different parts of this architecture are explained in detail in the following sections.

3.1 | SDN for WBAN

Many researchers and service providers focus on alternative solutions such as SDN to increase the bandwidth and flexibility of the WBAN architecture. The requirements of WBANs, which have a very dynamic structure, cannot be

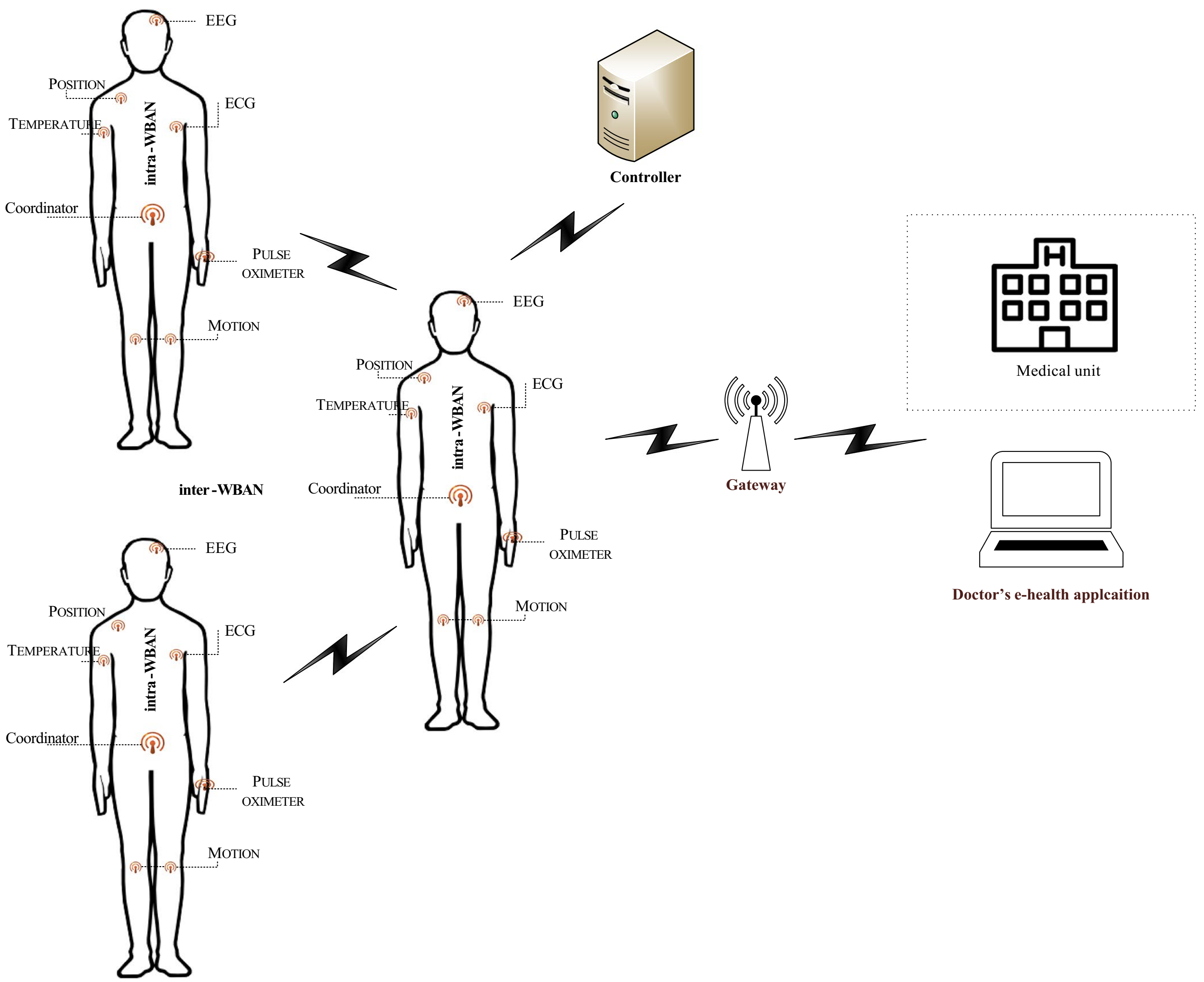

FIGURE 1 Proposed architecture

met by traditional network solutions. SDN transforms the static network paradigm into a programmable and adaptive network paradigm. The SDN paradigm, which has a general view of the network and has a controller that can redirect traffic when required, provides intelligent routing that can prevent network bottlenecks. In this context, the SDN approach also enables network analysis and decision-making processes for WBANs. In addition, SDN provides a variety of algorithms that can be used in the WBAN environment to improve the control and management capability of the network. 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.

3.2 | IEEE 802.15.6 for intra-WBAN communications

The IEEE 802.15.6 standard was developed to address service differences in short-range communications between small devices surrounding the human body. This standard, which works in the physical and data link layers, proposes one-hop and two-hop star topologies. In addition, the IEEE 802.15.6 based WBAN architecture consists of one HUB and many nodes connected to it. The HUB uses the beacon mode with beacon period superframe boundaries phase for coordinating the network. The IEEE 802.15.6 standard can utilize carrier sense multiple access (CSMA) and slotted aloha techniques. However, to obtain more realistic results, the CSMA technique is preferred in this study. This standard uses carrier sense multiple access with collision avoidance (CSMA/CA)-based medium access control (MAC) protocol and eight priority levels as listed in Table 1. The detailed information about IEEE 802.15.6 can be found in Ref. [22].

TABLE 1 User priorities (D: Data; M: Management)

UP	Traffic	Packet Type	CSMA/CA	
			CW_{min}	CW_{max}
0	Background	D	16	64
1	Best effort	D	16	32
2	Excellent effort	D	8	32
3	Video	D	8	16
4	Voice	D	4	16
5	Medical data	D/M	4	8
6	High priority medical data	D/M	2	8
7	Emergency	D	1	4

3.3 | WBANFlow interface protocol for inter-WBAN communications

The IEEE 802.15.6 standard has developed data link and MAC techniques for intra-WBAN communication, but no development has been made for inter-WBAN communication. Therefore, a new MAC technique is developed in our study. WBANFlow is an interface protocol that includes control and management message mechanisms used between the HUB and controller. All the control and management messages related to topology discovery, dynamic channel allocation, and routing decision operations are distributed using this interface protocol. WBANFlow is developed considering IEEE 802.15.6. The following units are defined in the controller.

3.3.1 | Topology discovery

The controller periodically sends "HELLO" packets to the environment and forms a list of the HUBs within the coverage area. This unit is called topology discovery unit. The HUBs receiving the "HELLO" packets send the SNR and battery level information to the controller with the "ECHO" packet. The controllers obtain the statistical information of the HUBs with the "ECHO" packets received.

3.3.2 | Dynamic channel allocation

The HUBs request the appropriate channel from the controller to send packets received from the sensor nodes connected to them to the gateway (ie., for inter-WBAN communication). The aim here is to prevent the HUBs from being in a state of continuous sensing to find the appropriate channel, thereby reducing the interference between the WBANs. Thus, the HUBs can use the appropriate channel in a fair and dynamic manner with the help of the controller without using a sensing process. By eliminating the need for sensing for proper channel use, unnecessary energy consumption is also avoided. Using the information obtained in the topology discovery process, the controller dynamically allocates channels to all HUBs within the coverage area. The proposed MAC technique also uses the access phases (RAP and MAP) [22] defined by the IEEE 802.15.6 protocol. RAP is used for intra-WBAN while MAP is used for inter-WBAN. In this way, intra-WBAN and inter-WBAN communications are not compatible with each other. Detailed information is given in Figure 2.

3.3.3 | Routing decision (SDNRouting)

This algorithm works as soon as a new route is requested by a HUB. The controller requires information from all HUBs regarding neighbor tables and battery levels in the

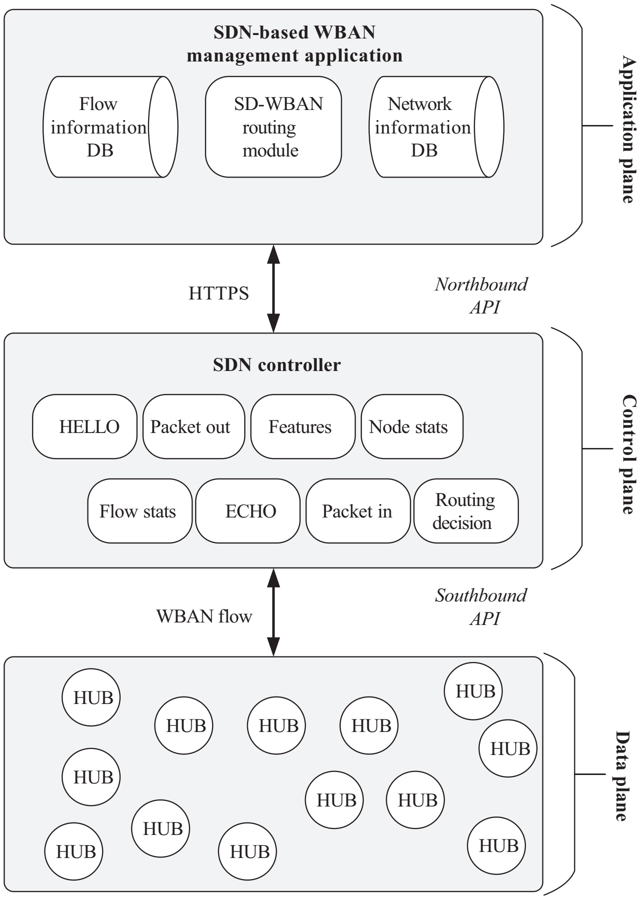

FIGURE 2 Proposed SDN-based WBAN architecture

neighbor tables, each HUB has a neighbor ID and SNR value. Based on this information, the best route is determined using the Dijkstra algorithm. The route information obtained is transmitted to all relevant HUBs via the installation of flow tables. The details of the flow table are given in Section 3.4.

Figure 2 shows the structure of the proposed architecture. Based on the SDN approach, the WBAN architecture is designed as a three-tiered architecture, with data, control, and application planes. The HUBs are at the data plane, the controller is at the control plane, and various applications are defined at the application plane. The control and data planes that are proposed by the SDN approach are isolated from each other and in inter-WBAN communication, the control and management processes are transferred to the controller.

3.4 | SDNRouting algorithm

While the most appropriate route is found using traditional routing algorithms, all nodes calculate the most appropriate routes depending on the algorithm used, and then create alternative routes and store them. This causes more network traffic and more energy consumption. These operations are performed by a controller; assigning the most appropriate route (when requested) to each relevant node provides multiple advantages. With the SDN approach, the network control and management processes are transferred to the controller, and the HUBs are transformed into simple forwarding devices.

In some cases, a direct communication between the HUB and the gateway is impossible. In other words, a relayed HUB is needed. This can either take place with a single HUB (single-hop) or through more than one HUB (multi-hop). In this context, it becomes necessary to find the most appropriate HUB or HUBs to send the packet. This section describes how the routing process is performed by the controller. The proposed routing algorithm (SDNRouting) is only used for inter-WBAN communication.

Each HUB has a neighbor table. This table keeps the neighbors of each HUB and the SNR information of these neighbors. The SNR and battery values are sent to the controller if requested by the controller. The SNR values vary between 10 and 30, and the battery threshold value is defined as 2 J. The HUB that has an SNR value below 10 and a battery level below 2 J is not selected as a forwarding device. The controller uses this information to determine the most appropriate routes using the Dijkstra algorithm. The discovered route is transmitted to the requesting HUB. Other HUBs included in this route are also informed by the controller.

The flow table is another table in the SDN enabled HUBs. This table is used to determine how to handle the packets (forward or drop) coming to the HUBs. Owing to the flow tables, which are set and updated by the controller periodically, HUBs only deal with packet forwarding. Furthermore, the new route information that is generated as a result of the routing process is transmitted to the relevant nodes via the flow tables.

Figure 3 shows the proposed SDNRouting algorithm. As shown in the figure, the route is requested from the controller. The controller detects the most appropriate route according to the status information (SNR and battery level) obtained

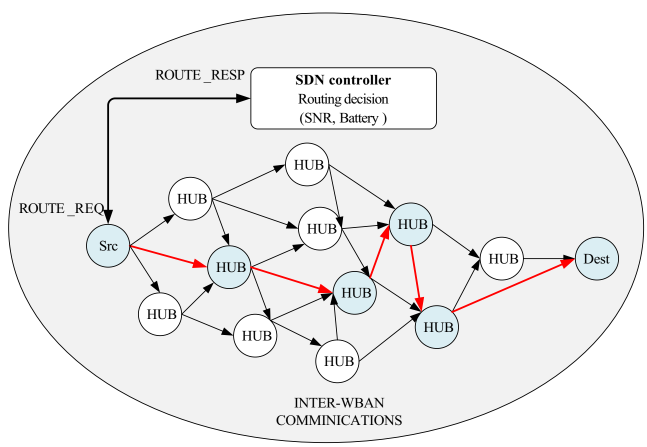

FIGURE 3 SDNRouting-based WBAN architecture

from the HUBs. The sequence diagram of the proposed system is shown in Figure 4. The HUBs first communicate with the controller and request the appropriate channel for inter-WBAN communication. The controller performs dynamic channel allocation and routing procedure for inter-WBAN communication as shown in Figure 4.

4 | SIMULATION RESULTS

Two simulation cases are used to evaluate the performance of the models and the algorithms developed in this study. In the first case, only 1 HUB among 10 HUBs is excluded from the gateway coverage area and a single-hop routing operation is performed by the controller. The proposed energy-aware "SDNRouting" algorithm (where the controller determines the routes) is compared with the "traditional routing (AODV)" algorithm (where each node determines its own route) and the "noRouting" algorithm (no reliability-based routing, where packets are forwarded to random next hop devices instead of the routing algorithm). According to the results, SNDRouting performs better than others in terms of the energy consumption levels and successful transmission rates.

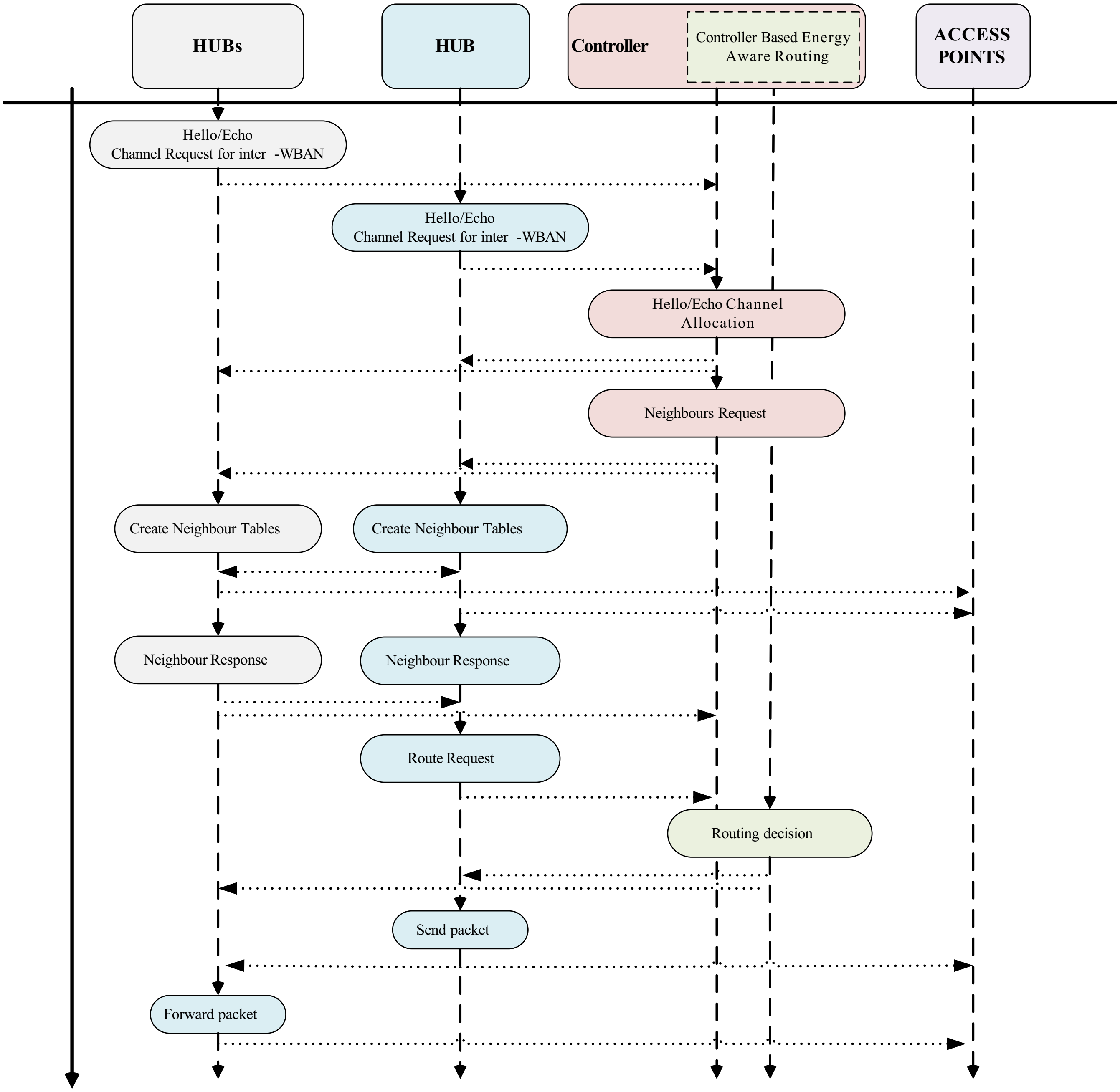

FIGURE 4 Sequence diagram of the proposed system

In the second case, the routing operations are performed with 20 HUBs, and 9 HUBs are excluded from the gateway coverage area. New multi-hop routes are obtained by requesting the controller. The goal here is to find new routes in the network for routing algorithm detection and to reduce unnecessary network traffic while updating the routes. In this context, our proposed SDNRouting algorithm proceeds as follows: a HUB requests a new route from the controller; the controller finds the most appropriate route through the Dijkstra algorithm by using the data obtained from the HUBs; it assigns these routes to all relevant HUBs.

The priority values are classified from high to low in the following order: UP7, UP6, UP5, UP4, UP3, UP2, UP1, and UP0. The data rates are as follows: UP7-2 packets/second, UP6-2 packets/second, UP5-1 packet/second, UP4-1 packet/second, UP3-0.5 packet/second, UP2-0.5 packet/second, UP1-0.05 packet/second, and UP0-0.05 packet/second. Because WBAN has a heterogeneous network structure, each node has different data rates and different tasks. The simulation results of these cases are examined, and the effect of the proposed approach on SDN-based WBAN architecture is determined. Each case is simulated using the Riverbed Modeler software. Table 2 summarizes the simulation parameters used in both cases. No hardware has been developed to support the IEEE 802.15.6 standard. MicaZ values are generally used in the literature for WBANs. The MicaZ parameters are used with the default values given in the datasheet [23].

TABLE 2 Simulation parameters

Parameter	Value
Simulation time	1,200 s
Region	300 m × 300 m
Frequency	2,400 GHz–2,483.5 GHz
Number of nodes	Case 1:80 nodes 10 HUBs Case 2:160 nodes 20 HUBs 1 Controller both cases
MAC protocol	IEEE 802.15.6 and WBANFlow
Bandwidth	1 MHz
Data rate	971.4 kbps
Packet size	1,020 bits
Initial node energy	10 J
Threshold energy	2 J
MicaZ parameters [23]	
Battery	2 AA (3 V)
P_{TX} (Power consumed by the node during transmission state)	−10 dBm = 11 mA −5 dBm = 14 mA 0 dBm = 17.4 mA
P_{RX} (Power consumed by the node during receive state)	27.7 mA
P_{Idle} (Power consumed by the node during idle state)	35 µA
P_{Sleep} (Power consumed by the node during sleep state)	16 µA

4.1 | Case 1

In our scenario, there are 8 sensor nodes with different priorities connected to each HUB. In total, there are 80 sensors, 10 HUBs, 1 gateway, and 1 controller. The IEEE 802.15.6 protocol is used between each of the HUBs and sensor nodes (intra-WBAN). The HUBs use the WBANFlow interface protocol, which is developed for inter-WBAN between the HUBs, controller, and the gateway. The controller performs control and management operations in the inter-WBAN communication. It performs dynamically appropriate channel assignment, flow table setup, and routing for each HUB. In this way, the WBAN architecture, which has a heterogeneous and complex network structure, is logically managed from a central point. With this approach, the network control and management processes have become more flexible and dynamic.

Figure 5 shows the single-hop routing case. In this scenario, only WBAN User1 is outside the gateway coverage area. Like all nodes trying to access the environment with the help of the controller, WBAN User1 tries to access the environment. Unlike other HUBs, WBAN User1, which is outside the coverage area, requests a route from the controller at 5th second. Through the routing process performed by the controller, the packets in WBAN User1 queue reach the gateway.

Figure 6 shows the results of the throughput of different priority packets owned by WBAN User1. These priorities vary according to Table 1 and the contention window values standardized by IEEE 802.15.6. In this way, only three out of 8 different priority packets (UP7, UP5, and UP3) are provided. In our Case 1 scenario, WBAN User1 is excluded from the gateway coverage area, and it requests

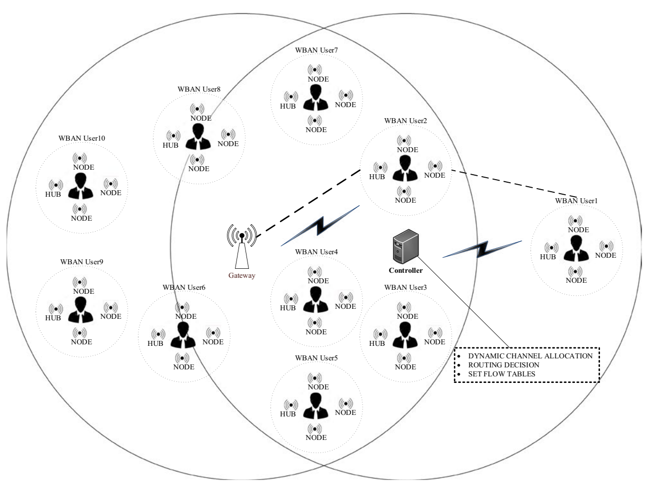

FIGURE 5 Single-hop routing case 1

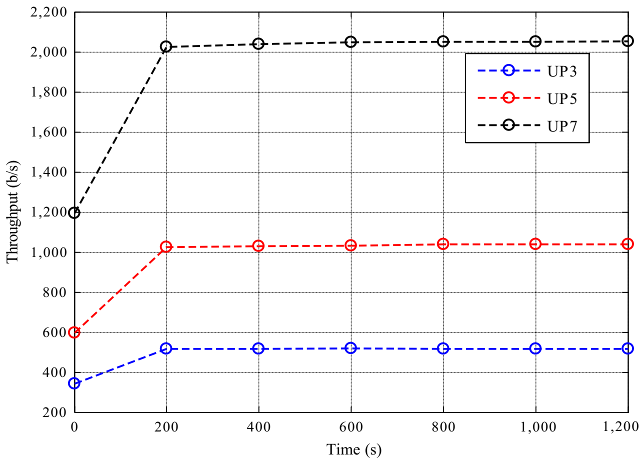

FIGURE 6 WBAN User1 throughput values of different priority packets

the appropriate route from the controller in the 5th second. WBAN User1, who continues to receive packets from eight different priority nodes connected to him, is shown to successfully forward different priority packets (UP7, UP5, and UP3) to the gateway with the help of the controller. The controller assigns the appropriate channel for the inter-WBAN communication to WBAN User1 and assigns an appropriate route using the SDNRouting algorithm. Thus, WBAN User1 reaches the gateway via WBAN User2 HUB. The results obtained are found to meet the QoS requirements for the WBAN architecture [24,25]. The results are compared with the literature and are found to be consistent [26,27].

Figure 7 shows end-to-end delay results of different priority packets owned by WBAN User1. As can be seen from the figure, the minimum delay value is seen in the packets with the highest priority level (UP7). The highest delay belongs to the lower priority (UP3) packets. The difference between these delay values is that different contention windows defined for the priority classes in the IEEE 802.15.6 standard are assigned to nodes of different priorities. UP7 node packets with a smaller contention window can be sent more quickly. Accessing the medium first and having the possibility of resending the collision packets reduce the delay. These delays are found to meet the service quality requirements of ISO/ IEEE 11073, and they are consistent with the results in the literature [26,28]. Figure 8 shows the successful transmission rate at different time intervals. The energy-aware SDNRouting approach for the SDN-based WBAN architecture that works on the controller is compared to "traditional routing" and "noRouting," The details of the proposed SDNRouting algorithm are described in Section 3.4. When the successful transmission rates are compared, SDNRouting is found to be about 98%, traditional routing is 95%, and noRouting is 52%.

When the results of these three approaches are considered, it is seen that the SDNRouting approach gives more successful results. The most important reason for this is that the controller, which has the topology of the entire network, is involved in the routing process. In the traditional routing algorithm, the SNR and battery level are ignored, and the packets cannot reach the gateway after a certain time; in the noRouting algorithm, the packets are sent to the next node randomly, causing the packets to drop on some nodes. In the SDNRouting algorithm, consideration of both SNR and battery level has a positive effect on the success rate. While the HUBs manage data forwarding, the SDN controller decides the forwarding routes. Because decision algorithms do not work on network devices, HUBs become simpler network devices than complex devices. Furthermore, in the traditional routing algorithms, each HUB has its own routing table. When any of these tables are updated, all the relevant HUBs must update their routing tables. This increases network traffic and can sometimes

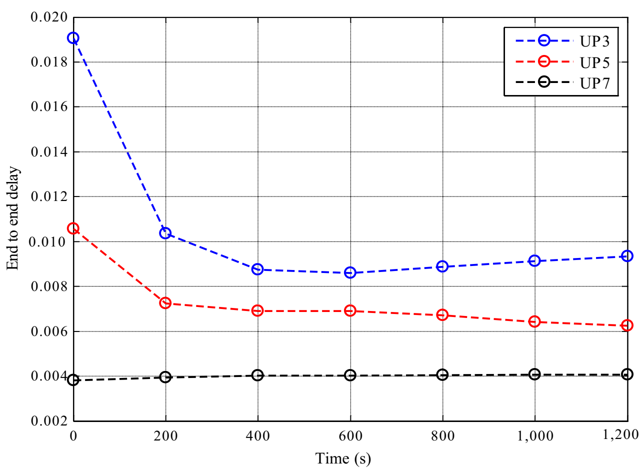

FIGURE 7 WBAN User1 end-to-end delay values of different priority packets

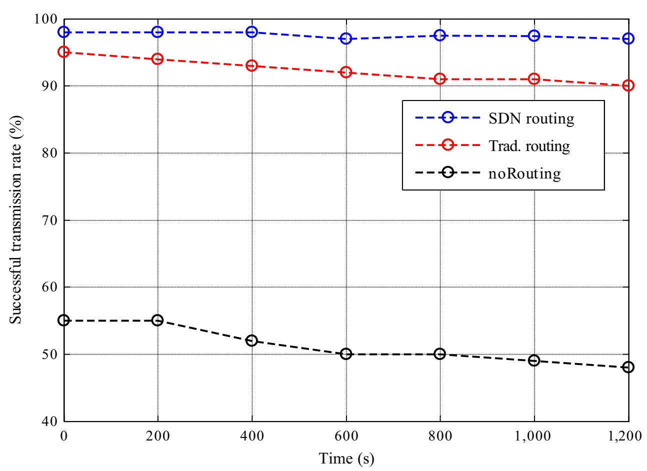

FIGURE 8 Successful transmission rate at different time periods

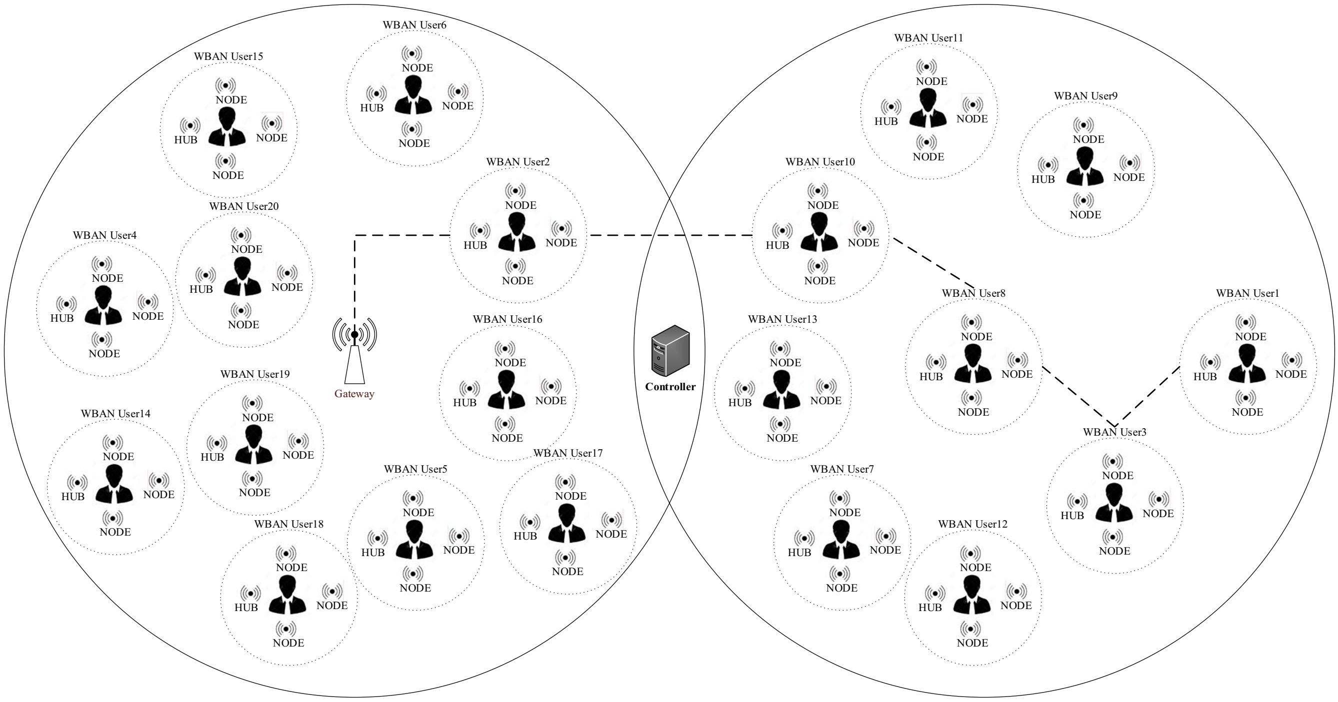

FIGURE 9 Multi-hop routing case 2

cause bottlenecks. In addition, the successful transmission rate is found to decrease.

4.2 | Case 2

Figure 9 shows the multi-hop routing case. In this scenario, WBAN User1, which is still outside the gateway's coverage area, requests a route from the controller. The controller takes the neighbor tables including the SNR data and battery level obtained from all the HUBs. The new route information is sent to all HUBs on that route by finding the most appropriate route with the Dijkstra algorithm. In this way, the data of WBAN User1 reach the gateway by following the proposed route. As seen in the figure, the other HUBs on the route process the incoming packets according to the data in the flow tables generated by the controller (forward, drop). In this scenario, there are 20 HUBs, and each HUB has 8 sensor nodes. In total, there are 160 sensor nodes, 1 controller, and 1 gateway. WBAN User1 demands a route from the controller in the 5th second. The controller identifies the new route by determining the most appropriate route using the SDNRouting algorithm.

Figure 10 shows the throughput results of different priority packets owned by WBAN User1. In our Case 1 scenario, only WBAN User1 was outside the coverage area of the gateway. In this scenario, nine WBAN user HUBs are excluded from the coverage area, and WBAN User1 again requests the appropriate route from the controller at the 5th second. Multi-hop routing is performed, and the most appropriate route is assigned by the controller to WBAN User1 and other relevant HUBs on the route. As can be seen from Figure 10, WBAN User1 successfully delivered different priority packets to the gateway. The results obtained are found to meet the service quality requirements for the WBAN architecture [24,25]. The results are compared with the literature and are found to be consistent [26,27].

Figure 11 shows the end-to-end delay results of different priority packets owned by WBAN User1. Similar results are obtained from the results in Figure 7. The reason for the increase in delay is that the gateway is reached through more than one HUB. Considering both

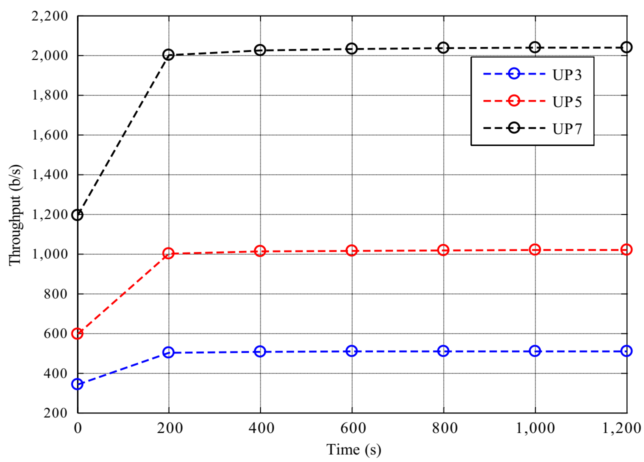

FIGURE 10 WBAN User1 node throughput values according to different priority packets

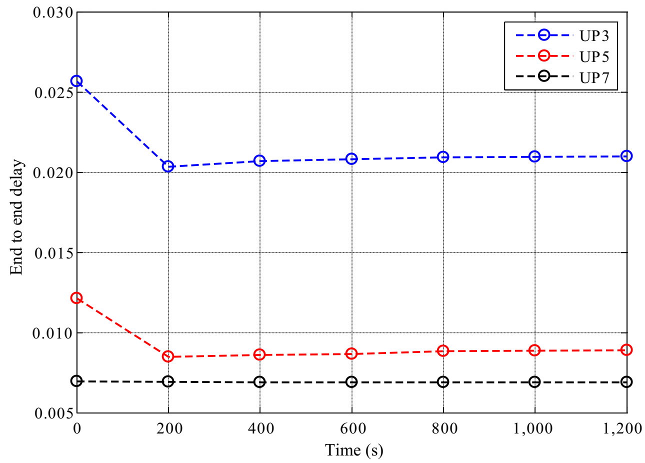

FIGURE 11 WBAN User1 end-to-end delay results of different priority packets

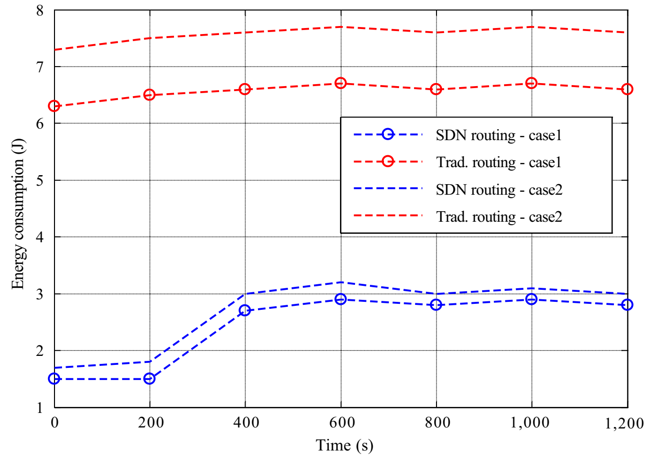

FIGURE 13 Energy consumption in the network at different time periods

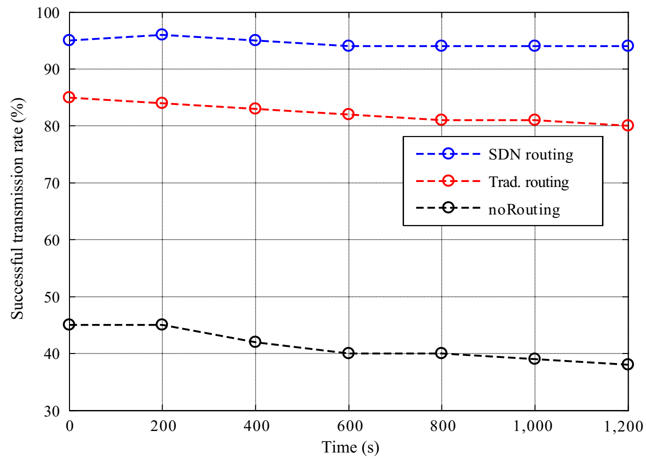

FIGURE 12 Successful transmission rate at different time periods

the throughput and delay values, the SDNRouting algorithm appears to be a suitable solution for the SDN-based WBAN architecture. In the first scenario, the delay was found to increase slightly. The SDNRouting algorithm increased the delay since the HUBs on the route take into account the battery and SNR values. However, these delays are found to meet the QoS requirements of ISO/ IEEE 11073 [22,24,28].

Figure 12 shows the successful transmission rate at different time intervals. Although we added more HUBs to the environment in this case, the successful transmission rate in the SDNRouting algorithm did not decrease much. However, it is observed that this ratio is very low in traditional routing and noRouting algorithms. SDNRouting, which is developed for SDN-based WBAN architecture and works on the controller, shows more successful results compared to “traditional routing” and “noRouting” algorithms. With regard to the successful transmission rates, SDNRouting was approximately 95%, traditional routing was 84%, and noRouting was 41%. According to the results, for both single-hop and multi-hop routing cases, SDNRouting algorithm performs better than the other two algorithms. The controller assigns the appropriate channel for the inter-WBAN communication to WBAN User1 and assigns the most appropriate route using the SDNRouting algorithm. Thus, WBAN User1 reaches the gateway through the HUBs of WBAN User3, WBAN User8, WBAN User10, and WBAN User2 HUBs. The most important reason for this is that the controller, which has the topology of the entire network, is involved in the routing process. While the HUBs manage data transmission, the SDN controller decides the routing process. Because decision algorithms do not work on network devices, HUBs become simpler network devices than complex routers. In Figure 13, the energy consumption rates of SDNRouting and the traditional routing algorithm at different time intervals in both scenarios are compared. As can be seen from the figure, the SDNRouting algorithm, which is an energy-aware routing algorithm working on the controller, spent less energy in both cases than the traditional routing algorithm. Considering the battery level values in the SDNRouting algorithm, which runs the routing decision mechanism on the controller, the conversion of HUBs into simple routing devices has positive effects on energy consumption.

5 | CONCLUSIONS

The heterogeneous and complex structure of WBANs has some disadvantages in terms of control and management. A centralized control panel architecture allows the SDN to integrate and manage all network infrastructures through a standardized interface. In this study, controller and sensor node architectures, which are new architectures based on the SDN approach, are proposed for WBANs with a dynamic and heterogeneous network structure. As a result, IEEE 802.15.6 for intra-WBAN communication and WBANFlow architecture for inter-WBAN communication are developed, and all the QoS requirements are met. The throughput, delay, successful transmission rate, and energy consumption rates are given. At the same time, a new energy-aware routing algorithm named SDNRouting, which runs on the controller, is proposed, and its performance is analyzed for different cases. In future studies, we plan to develop new algorithms using fuzzy logic for multi-attribute decision making, considering different parameters such as specific absorption rate (SAR) and data rate to improve our routing algorithm. In addition, the routing algorithm is designed only for inter-WBAN communication. It is therefore planned to use the routing algorithm developed in future studies in intra-WBAN communication.

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