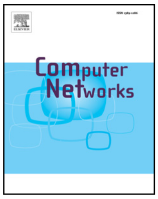
Computer Networks 160 (2019) 105–117

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet



HUBsFLOW: A novel interface protocol for SDN-enabled WBANs

Murtaza Cicioğlu[a,*], Ali Çalhan[b]

[a] School of Electrical-Electronic and Computer Engineering, Düzce University, Düzce, Turkey
[b] Computer Engineering Department, Düzce University, Düzce, Turkey

ARTICLE INFO

Article history:
Received 24 March 2019
Revised 8 May 2019
Accepted 9 June 2019
Available online 11 June 2019

Keywords:
Wireless body area networks
Software-defined networking
IEEE 802.15.6
HUBsFlow
IEEE/ISO 11073

ABSTRACT

Wireless Body Area Network (WBAN) concept is one of the most promising technologies for healthcare applications. In WBANs, sensor nodes are capable of sensing, gathering the human body signs and sending them to the HUB; the communication between nodes and HUB is called as intra-WBAN communications. Inter-WBAN communication manages all HUBs for communications of various WBANs. WBANs have inherently heterogeneous structures and limited energy sources, and also, installation/configuration network management processes are increasingly quite complex. New approaches are required to implement WBANs in order to overcome these challenges. We propose the Software Defined Networking (SDN) approach aims at constructing a flexible and manageable structure for inter-WBAN communications. Therefore, a new SDN-enabled WBAN architecture with HUBsFlow interface protocol is proposed in this paper. The proposed architecture provides a flexible, manageable, and an energy sensitive structure. Hence, a controller that is a key component for SDN undertakes all management and control processes about network. HUBsFlow interface protocol is utilized on the controller that provides the communications among the controller and HUBs in inter-WBAN communications. All components, protocols, and algorithms of the proposed architecture are developed and simulated using Riverbed Modeler software. Throughput, delay, packet loss ratio, bit error rate, and energy consumption parameters are taken into account for performance evaluation of the proposed architecture. The results show that the proposed architecture outperforms when comparing with traditional WBAN architecture and satisfies IEEE/ISO 11073 service quality requirements.

1. Introduction

WBAN has a heterogeneous network architecture consisting of many sensor nodes, and each node has different tasks and functions. The sensor nodes collect, process and transmit the data to the HUB. HUB is a central node or coordinator in WBAN that manages several sensor nodes. The data usually can be the vital signs and some environment variables [1,2]. The most significant shortage of WBAN is the complexity of the network management functions resulting from the limited resources and physical environments that they have [3,4]. Various data traffic from heterogeneous sensor nodes are transmitted to the target at different sampling times, so the heterogeneity of the network traffic flow makes the service quality requirements and network management more complex.

SDN is a new network approach that has been put forward to ensure that the control and the data planes existing together in the traditional network infrastructure are abstracted from each other. With the SDN approach, the control and the management processes logically converge at a central point, and the network control and the management processes become more flexible and easier [5–8].

One of the popular topics for solving the network complexity is thought to be the solution of the SDN approach to the WBAN architecture. As a result of the SDN approach, the WBAN architecture (SD-WBAN) in this study allows the entire network to be managed via a controller [9]. By the way, a new energy-sensitive interface protocol (HUBsFlow) is developed with the SDN approach, instead of a distributed protocol that causes too much energy consumption among inter-WBAN communications. The control and the management operations on the HUBs are transferred to the controller and the energy consumption of the HUB is reduced dramatically. In addition, with the help of the controller, the network control, and the management operations are carried out from a central point for providing dynamic, effective and efficient resource allocation.

WBAN architecture has important problems, such as not being able to program sensors in real time, having many sensors with manufacturer-specific architectures, having limited resources and limited memory, not being able to perform complex calculations,

---

[*] Corresponding author.
E-mail address: murtazacicioglu@gmail.com (M. Cicioğlu).

https://doi.org/10.1016/j.comnet.2019.06.007

and not being able to implement multiple control algorithms. SD-WBAN was proposed as a solution to these problems.

The proposed SD-WBAN architecture consists of three parts: The first part is the SDN controller, which is responsible for the network control and the management operations. All tasks performed in this part take place in the control plane. In the second part, the HUBs are located in the data plane that coordinate the sensor nodes connected to them. The last part is the southbound interface standard (HUBsFlow), which is responsible for the configuration and the management between the control plane and the data plane. This study focuses on the HUBsFlow interface protocol developed for WBAN architecture, for this reason OpenFlow protocol has been examined and developed using IEEE 802.15.6 standard for SDN approach. The proposed architecture (SD-WBAN) is modeled and simulated using Riverbed Modeler simulation software for more realistic performance evaluation.

The contributions of our study are listed as below;

- We propose a software-defined wireless body area network architecture to support application-specific requirements of WBAN, named as SD-WBAN.
- For the SD-WBAN architecture, a software-defined controller with three different management algorithms as topology discovery, slot allocation, and channel bonding is designed. The topology discovery algorithm is responsible for topology management, the slot allocation algorithm is responsible for medium access of the sensor nodes, and the channel bonding algorithm is responsible for prioritization.
- The real-time variation of the sensor nodes and network topology functions is achieved by the flow definition rules defined on the controller.
- Being distributed of the control and the management processes is a major problem for inter-WBAN communications. In order to overcome this problem, all control and management operations are performed by the controller.
- With the transfer of all control and management processes to the controller, the HUB tasks are reduced and simplified and so the HUB becomes a simple forwarding node. Therefore, the energy consumption and the delay ratios are reduced considerably.
- For the performance evaluation of the SD-WBAN, a simulation model is designed using Riverbed Modeler software. The HUBsFlow interface protocol is developed for enabling the controller to communicate with the HUBs, and the controller is modeled that is a control plane element to perform all network control and management operations.

The rest of the paper is organized as follows. In Section 2, the literature about the WBAN and the SDN is given. The SDN solution for WBANs is presented in Section 3. In Section 4 the proposed SD-WBAN architecture and the HUBsFlow Interface Protocol are given in detail. The performance analysis of the SD-WBAN is given in Section 5. The conclusions of the paper are discussed in Section 6.

2. Related works

Although there are plenty of studies that pertain to the WBAN and the SDN in the literature, few examples of the studies that consider the SDN based WBAN can be found. In [10], the authors' paper is about SDN e-health network, and they propose SDN based Context-Aware Mobile Approach (CAMA). Their paper presents a network infrastructure based on the SDN paradigm for improving the dependability and reliability of the eHealth biofeedback systems. Silva et al. [10] suggest a three-tier software-defined WBAN network architecture, with clear separation of data and control planes when examined. However, they introduce flow tables and other modules without simulation, emulation or experimental realization. It is also observed that the performance analysis is not performed, only a framework approach is recommended. Unlike this work, a new approach is proposed by using the 802.15.6 protocol which is standardized for WBAN in the simulation environment and performance analyzes are performed in Riverbed Modeler software in our study.

The authors of [11] conduct a paper on effective and reliable data transmission in software-defined wireless body area networks for the virtual hospital. Software-defined an efficient data distribution system with a secure network authentication protocol called Kerberos for a virtual hospital system is proposed. The authors of [12,13] develop a WBAN application with three different scenarios for medical environments. With the developed hardware and software, the medical data obtained from the wireless sensors are collected in a central node and then transferred to local and wide network environments respectively. In the project called CodeBlue, is conducted at Harvard University, the application possibilities of Wireless Sensor Networks in the field of medicine are investigated using MICA nodes in [14]. The aim of their paper is to record SPO_2 and ECG signals belonging to many individuals. Their study can be used as an emergency messaging system in emergency departments of the hospitals and the disaster areas.

The increasing importance of WBAN from medical applications to entertainment is talked in [15]. The authors say that WBAN technology provides real-time and reliable data transmission for medical personnel. The upper limit of IEEE 802.15.6 standard is tried to determine with optimizing packet size. An analytical model is developed for performance evaluation of IEEE 802.15.6 based WBAN in [16]. The authors provide a standard by using the probability approach in the paper. According to the simulation results, while the priority nodes are starving, the nodes below the saturation level are mostly evaluated by the high-power distribution unit. The authors of [17] deal with the IEEE 802.15.6 standard for wireless communication with extremely low power requirements, at speeds up to 10 Mbps around any living tissue in short-range fields. In their paper, reliability analysis with CSMA/CA-based WBAN under saturation condition and discrete time Markov model for transaction volume are developed. The authors of [18] introduce the different protocols that the IEEE 802.15.6 standard uses for resource allocation.

In order to achieve better performance results for WSAN (Wireless Sensor Actuator Network) systems, an interface protocol called WSANFlow, which is responsible for all communications between the SDN controller (SDNC) and the SDN oriented end devices, is proposed by authors of [19]. The proposed SDNC can perform all network control and management operations. As a result, using the WSANFlow interface protocol, the SDN controller can optimize the instructions to be delivered, manageable and efficient to the end devices. The authors of [20] propose SDN-enabled wireless sensor and actuator network architecture that has a new routing discovery mechanism. This new routing decision approach that can change the existing path during data transmission using a fuzzy-based Dijkstra's algorithm. The authors of [21] work on Software Defined Mobile Networks (SDMN) and put forward the concept of SDMN. By focusing on software-defined design for radio access networks, the requirements of the SDMN architecture are addressed. They analyze the fundamental problems of architectural radio access networks presented as SDMN concept and give valid solutions for SDMN and standardization activities. The authors of [22] work on the SDN approach of wireless networks. In their study, the SDN architecture is examined in the context of wireless network and general information about main design models is given.

When the studies in the literature are examined, there is no WBAN architecture is found that is based on ISO/IEEE 11073 service quality requirements, and integrated with the SDN approach, and

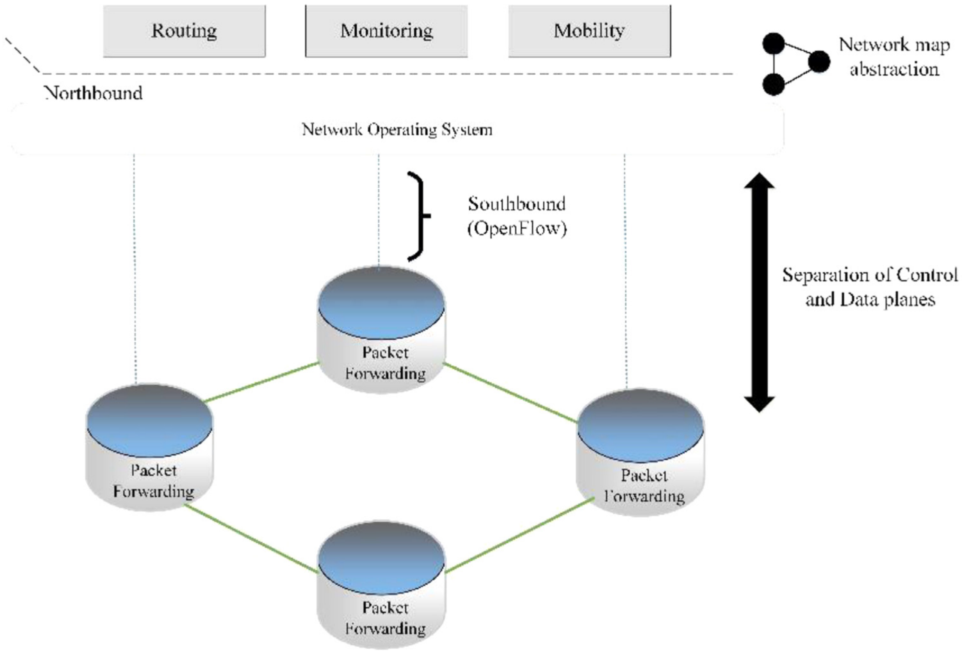


Fig. 1. The SDN architecture.

also supports inter-WBAN communications. In this paper, to show off these novelties, a simulation environment is constructed and each individual has own WBAN and a controller that controls these WBANs are designed.

3. The SDN solution for the WBANs

The SDN approach has recently attracted a great deal of attention in the academic and industrial communities. To overcome the limitations of today's network infrastructure, the SDN paradigm proposes a separation of the data plane and the control plane unlike the traditional network architecture [5] and provides simplification of the control and management operations of network [23]. Thus, the control plane ensures a dynamic, high-performance, efficient and scalable communication infrastructure [24]. The SDN provides the ability to integrate and manage all network infrastructures via the centralized control panel architecture and a standardized interface. This allows changes to be made on existing network infrastructures to be implemented much more quickly. In addition, new technologies to be built on the network infrastructure are becoming easier to implement. This increases the service performance and the resource utilization. Also, the SDN offers a controllable, end-to-end real-time traceable and programmable network infrastructure. Fig. 1 shows the basic architecture of the SDN approach. As shown in Fig. 1, the architecture consists of the data plane, the control plane and the application plane. There are also southbound and northbound interfaces for communications between these planes [25,26].

The general characteristics of the SDN approach are;

- Separation of the control and the data planes gives the network the ability to be programmable and the abstraction of the planes,
- All network control and management tasks are transferred to a central unit, this makes the network simpler and more manageable. In this regard, the control and the management functions on the HUBs in inter-WBAN communication are transferred to the controller, so the energy efficiency of the HUBs increases,
- The controller that can define the flows to the HUBs transforms the network to more dynamic and autonomous structure,
- With the HUBsFlow interface protocol, the network control and the management functions are transferred from HUBs to the controller.

4. The proposed SD-WBAN architecture and HUBsFlow interface protocol

This section describes the SD-WBAN architecture and its components. In this architecture, there are three different nodes; the controller, the HUBs and the sensor nodes, with the HUBsFlow interface protocol which is the communication interface protocol among the nodes and the HUB at the control and data plane. The structure of the SD-WBAN architecture is detailed in Section 4.1, and the controller of the SD-WBAN architecture and its tasks are described in Section 4.2. In Section 4.3 SDN-enabled HUB are explained. The tasks of the HUBsFlow protocol are briefly described in Section 4.4 and in Section 4.5 the IEEE 802.15.6 standard is given in detail. Finally, an example scenario is given in Section 4.6.

4.1. SD-WBAN approach

The SD-WBAN approach is proposed to enable the WBAN architecture to become more flexible, faster, and programmable. In this approach, there are several WBAN sensor nodes for sensing the vital signs, and HUBs that manage and coordinate each WBAN sensor group, and the controller that provides coordination and management operations among these HUBs, and a gateway. WBANs consist of the sensor nodes which have various tasks and priorities, and HUBs that coordinate those nodes for collecting the data from all sensor nodes, and process and send the data to the relevant units. If there is more than one WBAN, a coordinator is needed to manage all HUBs who can manage the environment and ensure that the appropriate channels or timeslots can be used fairly and efficiently. This is the most important goal of our work to integrate all the HUBs for inter-WBAN communications with the controller that will take over the network management responsibilities. With this

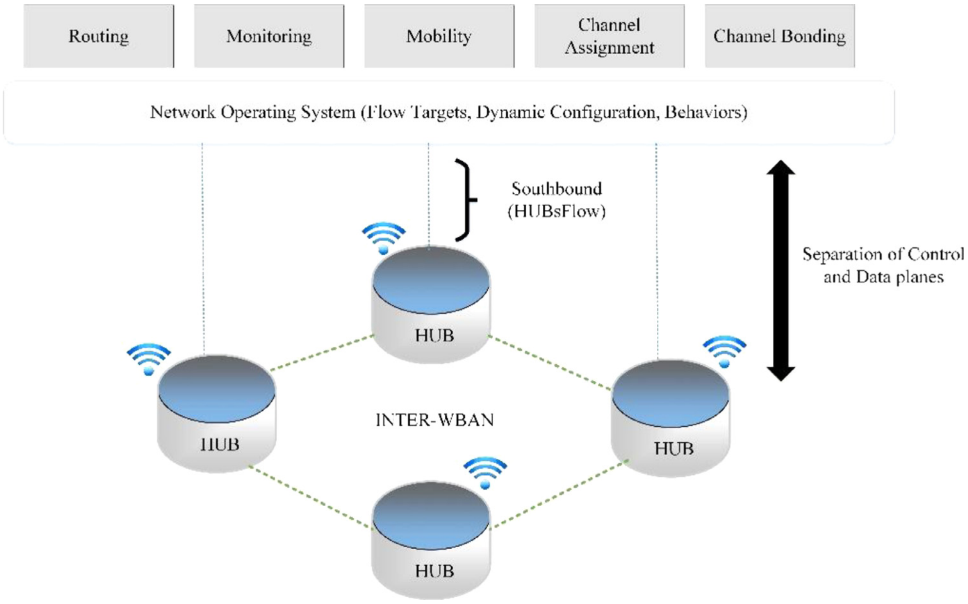


Fig. 2. General structure of the proposed SD-WBAN approach.

approach, it is aimed to gain a new perspective on WBAN architecture. The designed controller undertakes coordination function between the HUBs and provides effective and efficient network management with the various network control operations. So, the controller and the HUBs have to communicate in some cases. For this purpose, a new interface protocol (HUBsFlow) is required for SD-WBAN communication. Fig. 2 shows the general structure of the SD-WBAN. Based on the proposed SDN approach, each HUB becomes a simple wireless forwarding device.

4.2. SD-WBAN controller

The SD-WBAN architecture is built on top of the IEEE 802.15.6. The IEEE 802.15.6 is standardized for WBANs as Physical/Datalink MAC protocol. The main goal of the controller is the network management in this standard. The duties of the controller are listed below;

- *Topology Discover:* Each HUB periodically sends status information to the controller. The status information includes slot information, gateway or destination address information, packet priority, and packet size information.
- *Slot Allocation:* The controller performs the most appropriate slot assignment operations for the HUBs that are within the coverage area of the controller or are subsequently covered. The controller performs these assignments using the status information database obtained from the HUBs. The slot assignment process to the HUBs is as follows;
  - Dynamic flow tables: The flow tables, which are the most important contribution of the SDN approach, are generated by the controller and transmitted to the relevant HUB nodes. The HUBs process the packets in their queues with the help of flow tables (forward, drop). Thus, the controller can intervene in real time and dynamically with new flows to the HUBs. This approach enables the HUBs to access the environment through a central node in inter-WBAN communication.
  - Management Access Phase (MAP) Identifier: MAP identifiers refer to the controller-managed access phase defined by the IEEE 802.15.6 standard for medium access management. The types and details of the MAP are described in Section 4.5.
- *Channel Bonding:* The channel bonding technique is performed by the controller according to the status of the HUB while maintaining the slot assignment operation. The Packets in the queues of the HUBs can sometimes be filled with large data (ECG, EEG) and sometimes with urgent data with high priority. Due to the limited channel capacity, the HUBs cannot make efficient communication to meet QoS requirements. The channel bonding technique is used to solve this problem. In this technique, the HUBs demand a communication channel with more bandwidth from the controller. The controller assigns priority to the HUBs and allocates more than one channel to the high priority HUBs. The HUBs with high priorities can access the environment earlier, if there is not enough channel.

Channel bonding is a technique used for wireless networks. With the channel bonding process, adjacent channels are combined as a single channel. As channel bandwidth increases with the channel bonding process, it is aimed to reduce packet transmission times. In Fig. 3, the channel bonding mechanism is provided. As a result of the channel bonding, Packet 1 is sent in T time instead of dividing the packet into two parts. In the chart without channel bonding mechanism, the transmission time of Packet 1 is seen as 2T times. In our work, the channel bonding mechanism is carried out as follows: if the packet requires more than one time frame due to its size, the controller detects two adjacent time slots with the help of the channel bonding algorithm. Then, at the beginning of the adjacent time slot, the detection based approach is used to ensure that the adjacent time slot is empty. If the adjacent time slots are empty, the transmission process is initiated.

The flow tables and MAP identifiers (MAP identifiers is described in detail in Section 4.5) are generated by the controller and transmitted to the HUBs via beacon packets. MAP identifiers are considered as the start and end time intervals of the MAP1 access phase. SD-WBAN architecture is shown in Fig. 4. The control and data planes are abstracted from each other, and a controller is added to the network. The HUBs with sensor nodes are in the data plane, the controller is placed in the control plane. The HUBs talk with the sensor nodes as intra-WBAN communications. Also, the other HUBs communicate with controller as inter-WBAN communications by using flow tables at the HUBs.

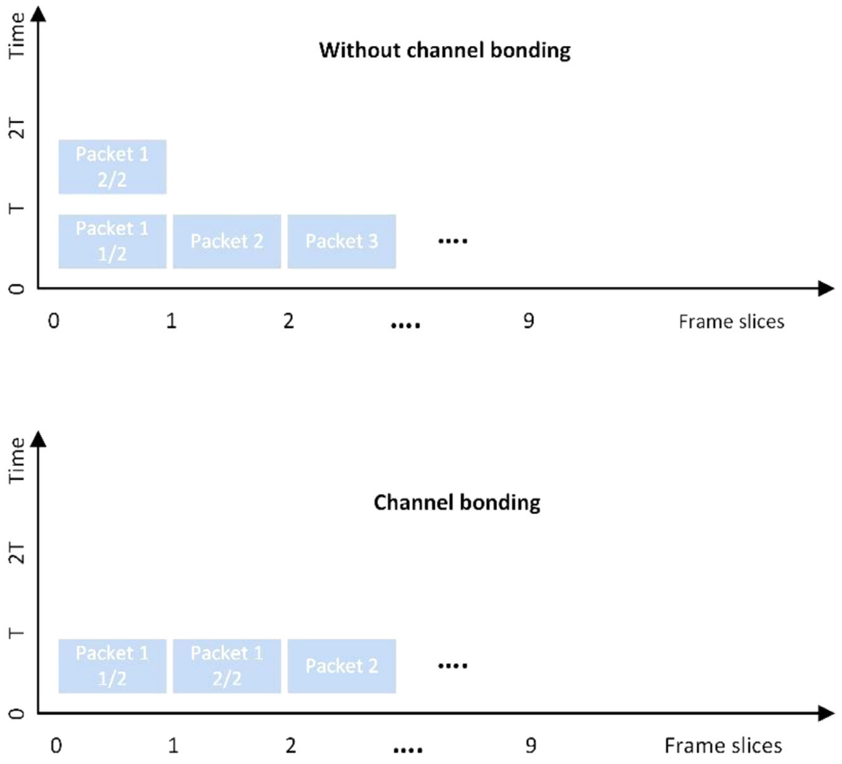


Fig. 3. Channel bonding technique.

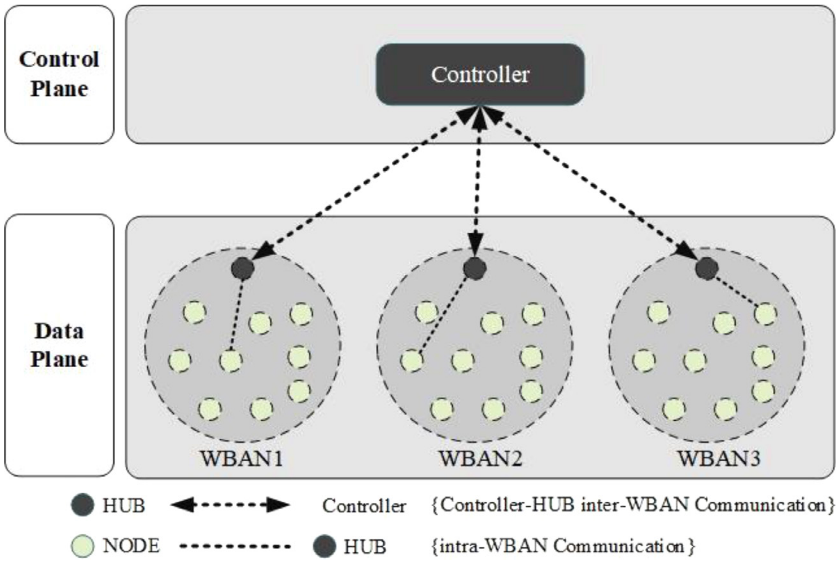


Fig. 4. The proposed SD-WBAN architecture with controller.

4.3. SDN-enabled HUB

In the proposed SD-WBAN architecture, HUBs have the task of managing sensor nodes connected to them, getting related data, sorting according to the priority levels, and transmitting these data to the relevant units according to their order in the queue. The protocol architecture of the HUB's main module is given in Fig. 5. A new SDN layer is added with this approach which is built on IEEE 802.15.6. This layer contains forwarding, status information, and flow tables. This layer periodically communicates with the controller to transmit relevant information, and the behaviors of the HUBs are determined according to the commands in the flow table. The main components of SDN layer are listed below;

- *Status Collector:* The status information of the relevant HUB is recorded in this section. This information is periodically transmitted to the controller. The information includes slot information, gateway or destination address information, packet priority and size information to be sent.
- *Flow Tables:* This section can be formed by the controller. It contains information about what to do with the packet (forwarding or dropping packets) when there is a flow in the HUB. Table 1 shows the sample flow table used in the HUB-sFlow interface protocol. The flow tables, which have three fields (Match Rule, Action, and Statistics) process the incoming packet according to the matching rule ($= / \neq$).

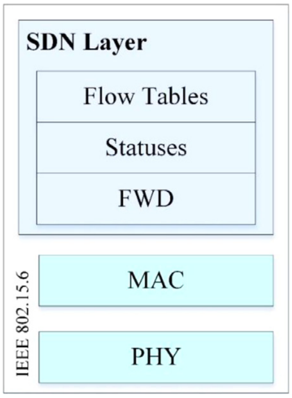


Fig. 5. SDN-enabled HUBs protocol architecture.

Table 1
Flow table in HUBsFlow interface protocol.

HUB	Match Rule *Comparator (= / ≠)*	Action *Forward / Drop*	Statistics *Number of packets*
1	=	Forward	10
2	≠	Drop	15
3	=	Forward	25

SDN architecture consists of three different layers. The main purpose in the SDN approach is to convert the HUBs in the data layer into programmable nodes with the help of flow rules given by the controller. The flow tables are saved in the HUBs. In this context, the controller generates the flow rules with the help of the topology discover algorithm and can transmit these flow rules to HUBs via flow table. Given these considerations, it is not difficult to conclude that the integration of SDN technology into the existing WBAN architecture is one of the vital approaches to the new generation of WBAN systems.

The flow tables are created by the controller and work on HUBs. When a transmission request is received to the controller or periodic status reports are received (topology discover), the flow tables are updated in a possible change in the network. These flow tables are transmitted to the corresponding nodes in the MAP1 access phase, which is one of the access phases in the superframe structure of the IEEE 802.15.6 standard. As can be seen in Table 1, the flow tables are mainly composed of match rule, action and statistics fields. The match rule section contains information about who the packet came from and for whom. In Action section, it refers to forward or drop action to be applied to the packet. In the statistics section, statistical data about the packets are kept.

4.4. HUBsFLOW interface protocol

The southbound interface is responsible for communication between the data and control planes. With the traditional SDN approach, OpenFlow is the running protocol at the southbound interface. OpenFlow was created for wired networks. OpenFlow is not sufficient for low-power networks such as WBAN because of not being energy-sensitive and having many rule-matching fields. To solve this problem, Luo et al. [27] propose Sensor OpenFlow, Bera et al. [28] develop SOFT-WSN, and Galluccio et al. [29] propose the work of SDNWISE. However, these studies are designed for WSN networks and do not support the IEEE 802.15.6 protocol, which has become the standard for WBANs. Therefore, a new protocol must be needed to develop for WBANs.

Recently, several studies have been conducted on the adaptation of the SDN approach to the wireless networks [22,30,31]. However, in these studies, it seems that the IEEE 802.15.6 standard, which became a standard in WBAN architecture for physical and data link layers, is not used. In this paper, a new southbound interface protocol (HUBsFlow) that is built on top of the IEEE 802.15.6 is proposed with the help of OpenFlow for requirements of WBAN architecture. This protocol is used for wireless communication among the HUBs and the controller. HUBs are communicated with the controller by using HUBsFlow. Therefore, the controller manages the whole network from a central point. And the control and management functions of HUBs are given to the controller and energy efficiency is provided by this way. Consequently, a new network architecture with manageable and programmable capabilities for WBAN architecture is proposed.

Fig. 6 shows the communication mechanism of the HUBsFlow. It used among the controller and the HUBs. In addition, this protocol is developed for the requirements and problems of WBANs. As shown in Fig. 6, the contention-based IEEE 802.15.6 standard is used between the HUBs and the sensor nodes connected to the HUBs. This standard also supports CSMA/CA or Slotted-Aloha. In this paper, CSMA/CA is preferred to achieve more realistic performance results. Fig. 6 also shows the control and management duties of the controller in SD-WBAN. The controller controls the HUBs, manages the network, monitors the network traffic, and keeps network statistics. It also provides effective and efficient dynamic channel assignment, executes channel bonding for QoS requirements if necessary, updates dynamically the flow tables, constructs a scalable network environment with a number of HUBs, and so on. These tasks provide a new network approach that addresses energy-sensitive, scalable, and collaborative.

The controller sends “HELLO” packets periodically to the HUBs which are in its coverage area for listing the HUBs. This process is called Topology Discover. The HUBs which get “HELLO” packets send status information with “ECHO” packets to the controller. The controllers obtain the status statistics of the HUBs via “ECHO” packets. Also, the HUBs request appropriate channel from the controller for sending data. The controller provides fair and efficient resource utilization with the statistical information based on status information database. The controller, which continuously controls the environment for effective and efficient resource allocation, also provides dynamic resource utilization by assigning the idle channels to the requested HUBs.

With the traditional approach for communication among HUBs, environment sensing process using a contention-based protocol like CSMA/CA has to follow some stages after finding an idle channel. This situation causes starvation that is expressed as a HUB that never can find idle channels among other HUBs. However, it is also seen that the HUBs with limited battery life waste some energy by the sensing process. In our approach, the HUBs can obtain the appropriate channel information (without sensing process) with the help of a controller. So, the HUBs do not have to sense the environment in order to be able to send their data. In addition, the waste of energy for these operations is also preserved and the delay caused by this operation is also removed. Thus, an important contribution is made to the delay and energy efficiency, which are very important network performance parameters for the WBAN architecture.

In our SD-WBAN architecture, depending on the flow rule (in the flow table) defined by the controller, HUB nodes send their information to their neighbors and controller as unicast or multicast (not broadcast). Therefore, the creation of data packets duplicate can be controlled. In traditional WBAN architecture, however, HUBs broadcast the data packets continuously on the network. So, overhead for data packets in conventional WBAN is higher than the proposed SD-WBAN.

In the SDN approach, firstly SDN enabled HUB checks the flow rules in the flow table when a packet that needs to be forwarding to the other HUB (as relay nodes) or when needs to send the

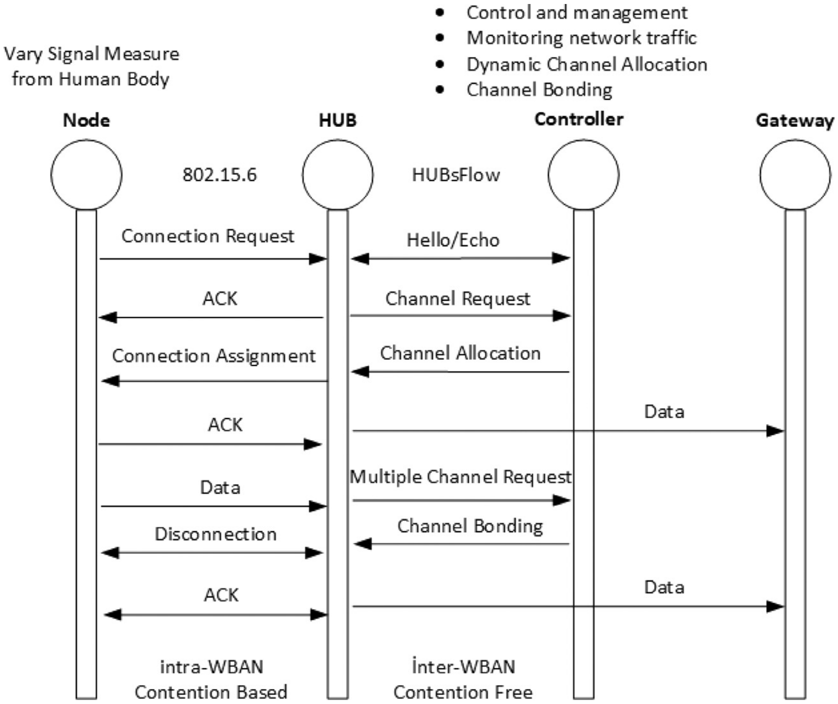


Fig. 6. Communication mechanism of HUBsFlow Interface Protocol.

packet (in its queue) to a destination. If there is no corresponding flow rule, the HUB node sends a message to the controller, which we call PACKET-IN. Then the controller defines a new flow rule according to this request from the HUB and sends the message to the HUB node. Thus, this flow rule takes place in the flow table of HUB and HUB performs packet forwarding according to this rule. All of the above actions cause some delay. The delay was found to be not more than about 3–5 ms in both our study and in the literature [32,33]. The delay values have also been shown to support the ISO / IEEE 11073 service quality requirement standard defined for WBAN. The controller can also manage delays in real time. The statuses of the HUBs, which are periodically taken from the HUBs, can be determined by the controller and thus the more prioritized HUB can bring the packets to the target with less delay.

In many protocols used for inter-WBAN, HUBs must continuously sense the environment (to determine the state of idle channel) for sending the packets in their queues. This process causes more energy consumption in dense sensor networks. In addition, one of the most important advantages of the 802.15.6 standard is that many sensors can be conveniently managed by a HUB. In this way, the sensors are active only in the time periods specified by HUB, while in other cases they are put into sleep mode, thus minimizing energy consumption (superframe and duty cycle approach) is provided. However, this approach is not developed for inter-WBAN in the 802.15.6 standard [34]. In this context, as in the intra-WBAN architecture, inter-WBAN architecture is also provided with a central controller to control and manage the network and to develop a mechanism for active and sleep modes. Active and sleep modes can be changed dynamically by the controller. Thus energy efficiency of HUBs has been ensured. (Similar to the IEEE 802.15.6 protocol's superframe and duty cycle approach).

4.5. IEEE 802.15.6 standard

The IEEE 802.15.6 standard [34] was developed to address service differences in short distance communications between small devices that surround the human body. This standard that works on physical and data link layers, suggests a star topology with one and two hops. In addition, the 802.15.6-based WBAN architecture consists of only one HUB and a large number of nodes connected to it. The detailed performance analysis of WBAN architecture with IEEE 802.15.6 standard was performed in our another study [35].

In order to obtain appropriate results for different situations in the WBAN architectures, the IEEE 802.15.6 standard defines three-channel access methods. These are beacon mode with beacon period superframe boundaries, non-beacon mode with superframes, and a non-beacon mode without superframe. Each of these methods defines a superframe structure that better meets the specific needs of the application. When the IEEE 802.15.6 standard is used for vital healthcare applications, the received information must be sorted according to the emergency traffic and to provide service quality requirements over various appropriate time periods. In this study, the beacon mode with beacon period superframe boundaries is used.

With the Beacon mode with beacon period superframe boundaries, the working time is divided into time slots by the HUB as superframes. A beacon (B) is sent at the beginning of each slot. This beacon contains the network information and the details of the time slot. The nodes that want to connect to the network send connection request using information from beacon after getting a beacon. Also, a beacon is used to synchronize to the HUB since the beacon marks the beginning of the time slot. A beacon2 (B2) is the packet used for contention access phase. In this phase, all nodes reach the environment in a contention based manner without priority. The details about the other modes are given in the reference [34].

IEEE 802.15.6 standard defines three types of access mechanism named Random Access mechanism, Improvised and Unscheduled Access Mechanism and Scheduled and Scheduled-Polling Access Mechanisms. In this study, Random Access mechanism is used and the details of this mechanism are given below. The details of the other mechanisms are given in the reference [34].

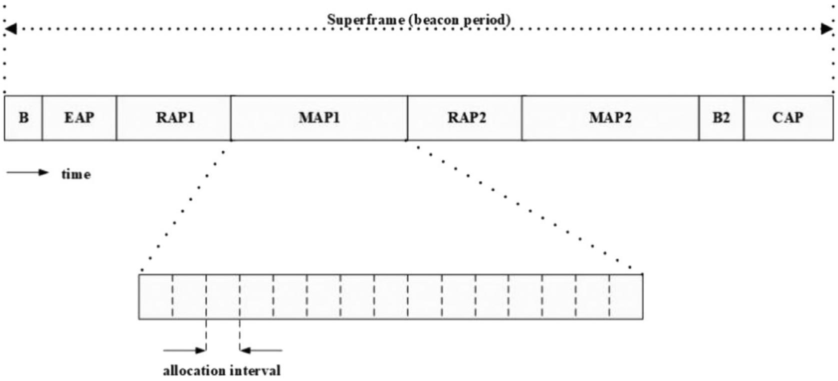


Fig. 7. Beacon mode with superframe boundaries.

Table 2
User priority mapping (D: Data – M: Management).

UP	Traffic	Packet Type	CSMA/CA		Slotted-ALOHA	
			CW_{min}	CW_{max}	CP_{max}	CP_{min}
0	Background	D	16	64	0.125	0.0625
1	Best effort	D	16	32	0.125	0.0937
2	Excellent effort	D	8	32	0.25	0.0937
3	Video	D	8	16	0.25	0.125
4	Voice	D	4	16	0.375	0.125
5	Medical data	D/M	4	8	0.375	0.1875
6	High priority medical data	D/M	2	8	0.5	0.1875
7	Emergency	D	1	4	1	0.25

Random Access mechanism: CSMA/CA or Slotted Aloha techniques can be used for narrow and ultra-wideband physical layers in this mechanism. As seen in Fig. 7, these are the exclusive access phase (EAP1, EAP2), the random access phase (RAP1, RAP2), the management access phases (MAP1, MAP2) and the contention access phases (CAP). While EAPs are used for high-priority network traffic, RAP and CAP are used for contentious access. (Each access phase, except RAP1, is optional.) So EAP, MAP2, RAP2 and CAP access phases are zero length in our work. The access phases RAP1 and MAP1 are used in our superframe structure. RAP1 is used between the HUBs and the sensor nodes, while MAP1 is used between the HUBs and the controller. In the RAP1 access phase, the different priorities given in Table 2 are used with the CSMA/CA proposed by the IEEE 802.15.6. In MAP1, the HUBs and the controller communicate with the HUBsFlow interface protocol.

SD-WBAN is designed to be completely wireless. MAP (Management Access Phase) is one of the access techniques used in the IEEE 802.15.6 superframe structure. The MAP identifiers herein are considered as the start and end time intervals of the MAP1 access phase. The HUBsFlow interface protocol is intended for communication between the HUBs and the controller. The proposed protocol developed here is based on the 802.15.6 standard (physical and data link layers properties). When the 802.15.6 standard is examined [34], superframe structure and access methods are used for communication between HUBs and sensor nodes. The use of RAP1 from these access phases is mandatory. In our study, we defined two phases in superframe structure as RAP1 and MAP1 access phases. RAP1 is allocated for communication between HUB and its connected nodes with, and MAP1 is allocated for communication between HUBs and controller. In this way, the intra-WBAN and inter-WBAN communication time frames are isolated from each other. This approach has enabled the use of the duty cycle technique in both HUB and sensors (This approach normally used only in intra-WBAN.). HUBs like sensor nodes are going to sleep in certain periods to avoid wasting their energy instead of staying active in their time period.

The user priorities (UP) for medium access in the IEEE 802.15.6 standard are divided into 8 different access categories. The values in the frame specify these priority values. These different types of traffic are separated as urgent data, high priority medical data or network control, medical data or network control, voice (VO), video (VI), excellent effort (EE), best effort (BE). Also, these different data traffics perform user preference with minimum and maximum contention window (CW) values for the CSMA/CA mechanism. The minimum and maximum CW values for different users and traffic are shown in Table 2.

ISO/IEEE 11073 defines a set of medical application classes for medical devices. Table 3 gives the bandwidth and delay values supported by the ISO/IEEE 11073 standard [36]. The service quality requirements for the architecture proposed in this paper are based on this table. ISO/IEEE 11073 personal health data standard; is a set of standards that determine the interoperability of blood pressure, blood, glucose monitors and similar personal health devices. Recently, the need for a standard has arisen due to the increasing popularity of the personal use of healthcare services and their simpler communication model devices. For this reason, the ISO/IEEE 11073 personal health data standard achieving interoperability of these devices is an important part of the WBAN architecture.

4.6. SD-WBAN case scenario

A case scenario is shown in Fig. 8 for SD-WBAN and a floor of the hospital is taken into consideration. Designing the MAC technique for a multi-storey building is very difficult for mobile WBAN users. In this context, a new dynamic, flexible, and hardware independent approach that can respond quickly to network topology changes, such as the SDN approach will be a viable solution to this problem [37].

HUBs that periodically communicate with the controller in each floor will be in touch with other controllers as soon as they arrive at another coverage area of the controller and continue its transmission an appropriate channel. So, collisions, starvation, energy

Table 3
Applications from IEEE from 11073.

Class: Data Type	Latency	Bandwidth
A: Alarms/Alerts/Positional Alerts (real-time)	A1: <200 ms A2: <3 s	64 bytes per alarm
B: Patient State	< 3 s	64 bytes per alarm
C: Sensor watchdog/heartbeat	< 60 s	64 bytes per hour
D: Reminder	< 3 s	1632 bytes per alarm
E: Physiologic parameters (real-time)	< 3 s	20 bytes/param at E1: 0.5 to E2: 5 Hz
F: Telemetry Waveforms (real-time)	< 300 ms	ECG: [F1: 3-lead 2.4 kbps, F2: 5-lead 10 kbps, F3: 12-lead 72 kbps], F4: Ventilator: 50–60 bps, F5: SpO2: 20–120 bps

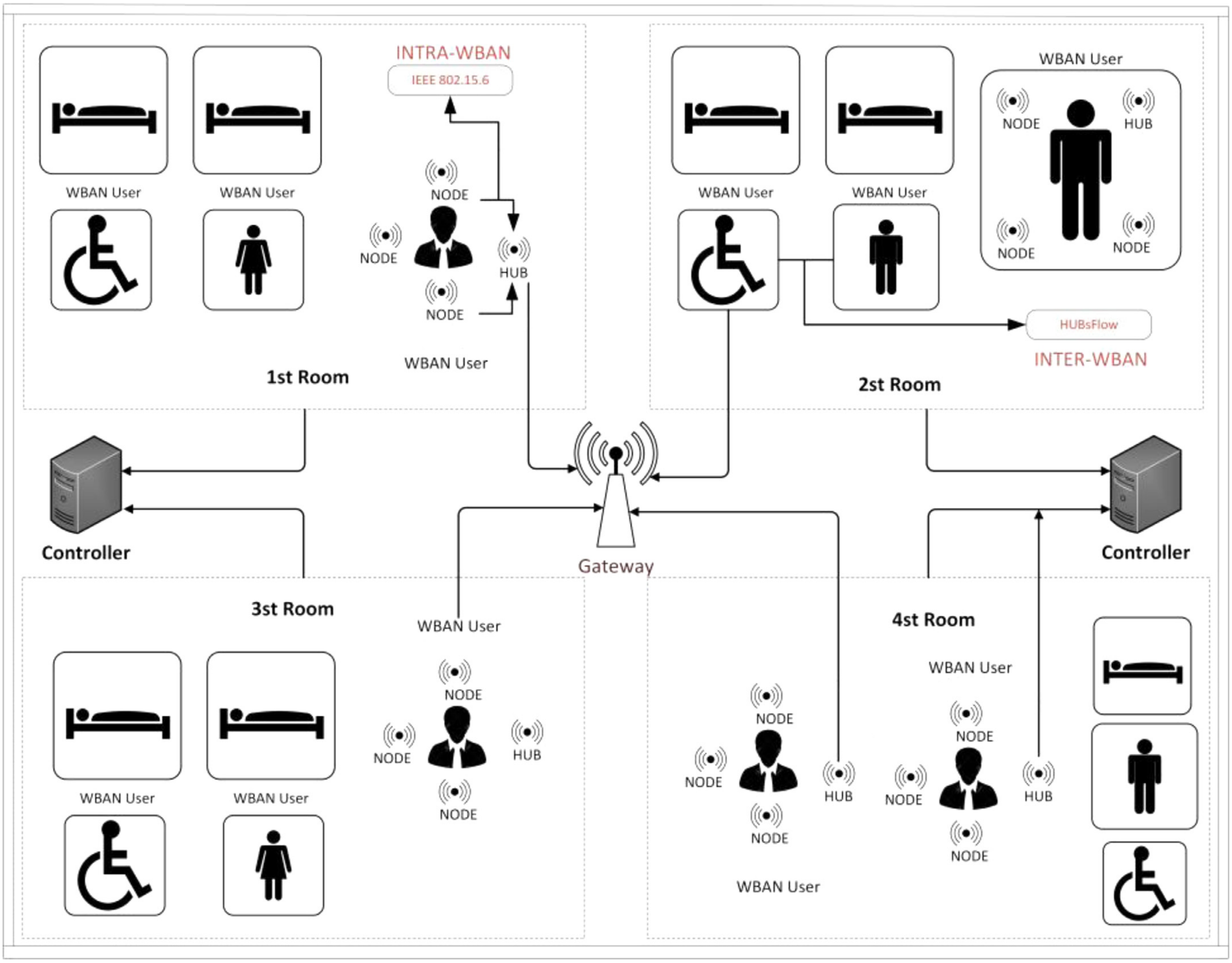


Fig. 8. SD-WBAN case scenario (a floor of the hospital).

consumption, and inter-WBAN interference problems can be minimized. Also the packet loss ratio, bit error rate are decreased, and the throughput parameter is increased in this way. The simulations results in Riverbed Modeler have supported these advantages as shown in the next section.

5. Simulation results

WBAN with various priority classes and the controller as the unit of the control plane in SD-WBAN architecture are designed with Riverbed Modeler software. Riverbed Modeler is an object-oriented and discrete time simulation program that presents a visual simulation environment. Hierarchical modeling layers, network links, data packets, wired/wireless nodes, and protocols can be developed, modeled and simulated in different editors of the Riverbed Modeler [38].

The topology in the Riverbed Modeler simulation software is given in Fig. 9. As seen in the figure, there are 3 HUBs, 8 sensor nodes connected to each HUB, 1 controller and 1 gateway.

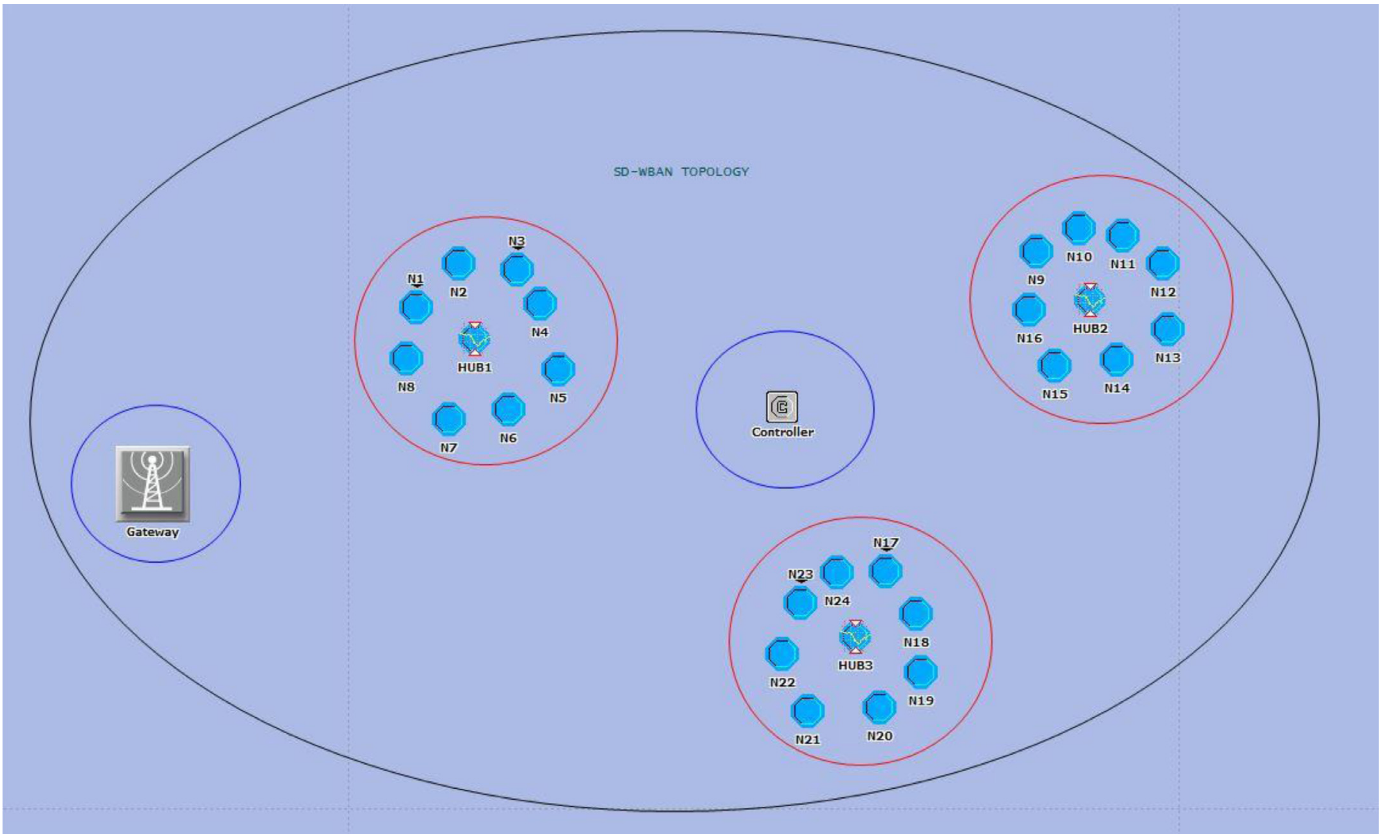


Fig. 9. SD-WBAN topology in Riverbed Modeler.

Table 4
Simulation parameters.

Parameter	Value	
Simulation time	300 s	
Network coverage area	100 m x 100 m	
Frequency	2400 to 2483.5 GHz	
Number of node and HUB devices	24 - 3	
Number of Controller	1	
Bandwidth	1 MHz	
Data rate	971.4 kbps	
Packet payload size	100 bytes	
Packet interarrival time *(Generated using the exponential distribution function)*	UP7 = 0.1 s	UP3 = 2 s
	UP6 = 0.2 s	UP2 = 10 s
	UP5 = 0.5 s	UP1 = 20 s
	UP4 = 1 s	UP0 = 20 s
Initial energy	50 Joule	
HUB status transmission period	15 s	
MicaZ parameter [39,40]		
Battery	2 AA (3 V)	
P_{TX} *(Power consumed by the node during receive state)*	−10 dBm = 11 mA −5 dBm = 14 mA 0 dBm = 17.4 mA	
P_{RX} *(Power consumed by the node during transmission 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	

The simulation parameters are given in Table 4, and two different network scenarios are considered in this paper. The first scenario is executed as traditional WBAN architecture (using IEEE 802.15.6) that consists of the HUBs, the sensor nodes, and a gateway. The SD-WBAN architecture (using HUBsFlow interface protocol) is performed in the second scenario with the controller that utilizes the control and management processes among HUBs. These scenarios are compared with each other for performance analysis. Both scenarios have 24 sensor nodes and 3 HUBs. Each HUB manages 8 sensor nodes which have different priorities and various data rates. The priority values are categorized as high to low as UP7, UP6, UP5, UP4, UP3, UP2, UP1, and UP0. UP7 has 10 packets / second, UP6 5 packets / second, UP5 2 packets / second, UP4 1 packet / second, UP3 0.5 packet / second, UP2 0.1 packet / second,

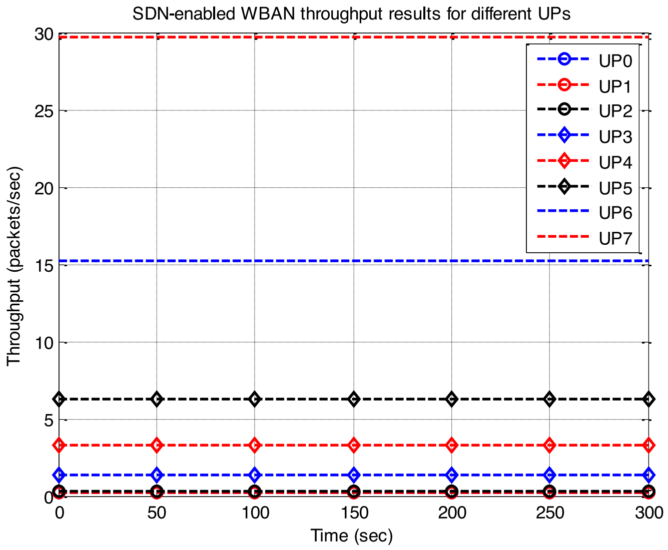


Fig. 10. The SD-WBAN nodes' throughput results.

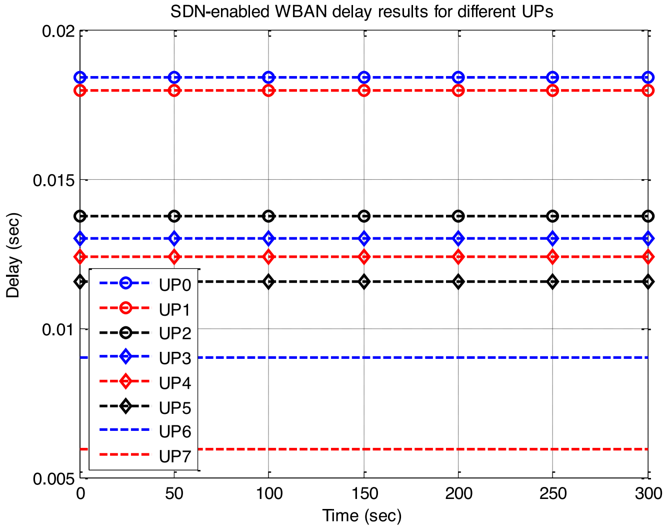


Fig. 12. SD-WBAN nodes' delay results for different user priorities.

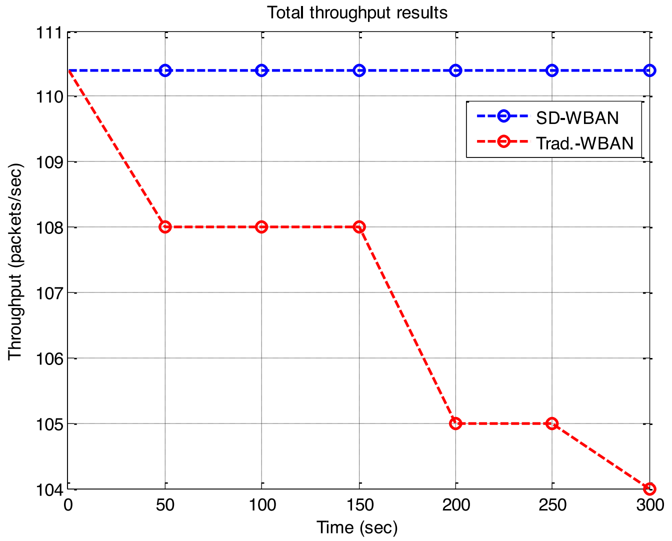


Fig. 11. Throughput results of traditional WBAN and SD-WBAN.

UP1 and UP0 0.05 packet / second data rates. Because WBAN has a heterogeneous network structure, each node has different data rates and different tasks. For example, the UP7 sensor node is assumed that it has 72,000 bps as ECG medical data. Therefore, SPO_2, accelerometer and glucose and etc. medical data are assumed similarly. The packets are generated by exponential distribution function for more realistic simulation environment.

MicaZ node operating parameters are used for realistic simulation results [39]. The energy consumption values (P_{RX}, P_{TX}, P_{Idle}, P_{Sleep}) are used on the basis of the Zigbee protocol designed in the Riverbed Modeler simulation program [40].

The SD-WBAN nodes' throughput results are given in Fig. 10. The highest priority nodes' data must be reached to the gateway without loss. In the same way, all sensor nodes' data reach to the gateway without loss as a result of SD-WBAN approach. In Inter-WBAN communication, the controller assigns time slots to the HUBs for getting the wireless environment. This approach allowed the HUBs to deliver different priority and size packets in their queues without loss. The obtained results are compared with the literature, and the throughput results are consistent [15,35,41].

In Fig. 11, throughput results are compared with the traditional WBAN and the SD-WBAN architecture. With the SD-WBAN architecture, all packets sent by the sensor nodes are transmitted without loss, whereas traditional WBAN architecture causes the data loss. The data loss is the result of using the contention based CSMA/CA in IEEE 802.15.6 standard that causes packet collisions and starvation. So, the throughput performance reduces. The network throughput performance is increased owing to the controller that manages and controls the wireless environment in inter-WBAN. The HUBs collect data from sensor nodes, and sometimes they must use the bonded channels for sending high data rates to the gateway. So, in the proposed SD-WBAN architecture the controller has channel bonding capabilities for better throughput performance.

The SD-WBAN nodes' end-to-end delay (eed) results are given in Fig. 12. As can be understood from the figure, UP7 node has the lowest eed and UP0 has the highest eed. The differences between eed values are caused by assigning different CW values to the various priority nodes in the IEEE 802.15.6 standard. The eed is occurred with calculating total delay between the sensor nodes-the HUB and the HUB-the gateway. Therefore, it is observed that the newly proposed HUBsFlow interface protocol does not increase the eed, and the eed values are fulfilled the ISO/IEEE 11073 standard QoS requirements given in Table 3. The obtained results are compared with the literature, and the delay results are consistent [15,42].

In Fig. 13, the packet loss ratios (PLR) are compared with the traditional WBAN and the SD-WBAN architecture. It is seen that the PLR is low in the SD-WBAN architecture, whereas the PLR is high in the traditional WBAN architecture as a result of the SDN approach used. The packet loss is defined as the inability of one or more packets to reach the destination and the PLR is one of the most important metrics for the WBAN architecture. In traditional WBAN architecture, the HUBs can be exposed to more collision and packet drop in the wireless environment. However, in the SD-WBAN architecture, this challenges are minimized with the help of the controller. The results show that the proposed approach is advantageous in the minimization of the PLR. In Fig. 14, the bit error rates (BER) are compared with the traditional WBAN and the SD-WBAN architecture. The BER is low in the SD-WBAN architecture, whereas the BER is high in the traditional WBAN architecture. The BER results obtained by the Riverbed Modeler simulation program show that the architecture of SD-WBAN is more successful.

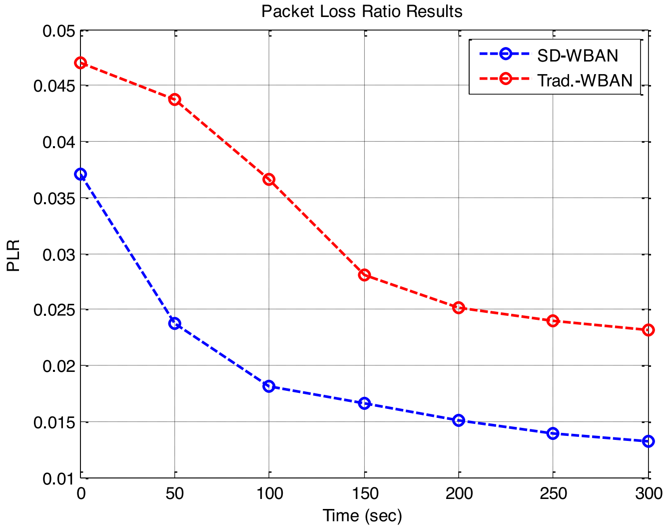


Fig. 13. Packet loss ratios of traditional WBAN and SD-WBAN.

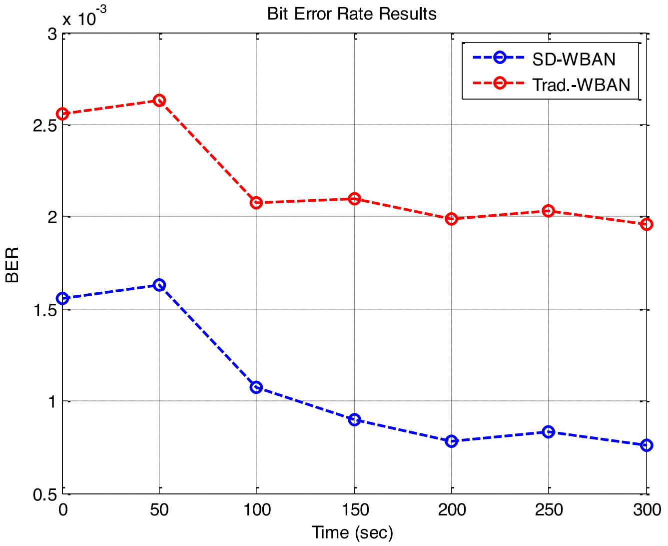


Fig. 14. Bit error rates of traditional WBAN and SD-WBAN.

The HUBs can use channels with the help of the controller and thus the BER is reduced considerably.

In Fig. 15, the average energy consumption results are compared with the traditional WBAN and the SD-WBAN architecture. In our study, energy consumption is calculated by considering packet transmission, packet receive, idle and sleep modes. These calculations are occurred with reference to the MicaZ energy module default values given in Table 4. As can be seen in the figure, the average energy consumption of the SD-WBAN architecture is better than the traditional architecture. The main reason for this is that the HUBs in the SD-WBAN architecture do not have to sense the environment to detect the appropriate channels and send the packets.

The routing, transmission, reception and idle status of HUB nodes are controlled by a central controller. Thus, SD-WBAN optimizes the tasks of HUB nodes to minimize energy consumption while taking advantage of the overall outlook of the network. Therefore, the proposed protocol is also useful for extending the network lifetime. The main reason for the higher energy consumption in traditional WBAN is that HUBs continuously sense the environment to transmit their packets. 24 sensors and 3 HUBs in a busy environment to send a continuous packets makes the environment more difficult to access. Additionally distributed MAC techniques are not energy sensitive because they are contention based. Therefore, it has been seen that a controller that manages and coordinates the HUBs in the environment is also of great importance in term of energy efficiency. Finally, it is observed that the HUBsFlow interface protocol used in the SD-WBAN architecture is energy-sensitive.

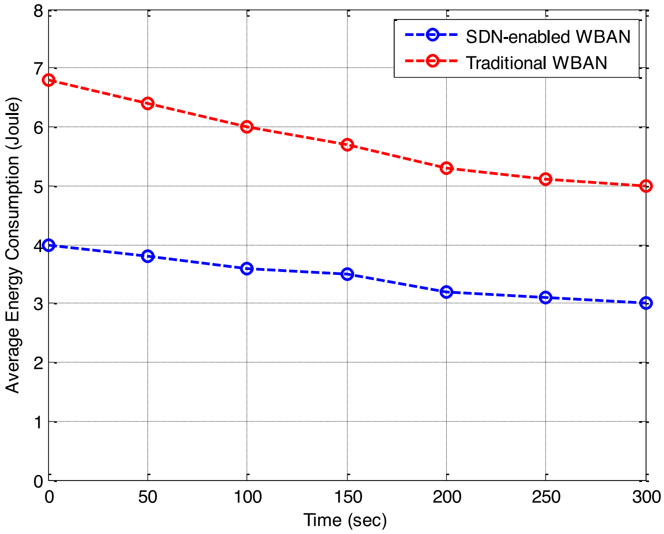


Fig. 15. Average energy consumption results of traditional WBAN and SD-WBAN.

6. Conclusions

In this paper, an SDN-enabled WBAN approach for heterogeneous and complex network infrastructures is proposed. With this approach, a new WBAN architecture (SD-WBAN) is designed with a manageable, dynamic, energy sensitive and more flexible structure. A new interface protocol called HUBsFlow, which is responsible for all communication processes between the HUBs and the controller, is also developed to increase the WBAN performance results based on SDN approach. The network performance parameters such as throughput, end-to-end delay, packet loss ratios, bit error rates, and average energy consumption are examined with the Riverbed Modeler simulation software and the results are compared with the traditional WBAN architecture. According to the results obtained, it has been found that the overall performance of the WBAN architecture increases, and according to the various priorities, ISO/IEEE 11073 standard meets the QoS requirements and gives positive results in all network performance parameters compared to the traditional WBAN architecture. This paper also shows that the SDN approach plays a key role in the control and management processes of the WBAN architecture with a complex network infrastructure. Future studies are planned to develop the controller using various artificial intelligence techniques with different scenarios.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.comnet.2019.06.007.

References

[1] M. Salayma, A. Al-Dubai, I. Romdhani, Y. Nasser, Wireless body area network (WBAN), ACM Comput. Surv. (2017), doi:10.1145/3041956.

[2] P. Khan, N. Ullah, F. Ali, S. Ullah, Y.S. Hong, K.Y. Lee, H. Kim, Performance analysis of different backoff algorithms for WBAN-based emerging sensor networks, Sens. (Switz.) (2017), doi:10.3390/s17030492.

[3] R. Cavallari, F. Martelli, R. Rosini, C. Buratti, R. Verdone, A survey on wireless body area networks: technologies and design challenges, IEEE Commun. Surv. Tutor. (2014), doi:10.1109/SURV.2014.012214.00007.

[4] P.-J. Chuang, C.-S. Lin, Energy-efficient two-hop extension protocol for wireless body area networks, IET Wirel. Sens. Syst. 3 (2013) 37–56, doi:10.1049/iet-wss.2012.0070.

[5] N. Feamster, J. Rexford, E. Zegura, The road to SDN: an intellectual history of programmable networks, ACM SIGCOMM Comput. Commun. (2014), doi:10.1145/2602204.2602219.

[6] D. Kreutz, F.M.V. Ramos, P. Esteves Verissimo, C. Esteve Rothenberg, S. Azodolmolky, S. Uhlig, Software-defined networking: a comprehensive survey, Proc. IEEE (2015), doi:10.1109/JPROC.2014.2371999.

[7] I.F. Akyildiz, A. Lee, P. Wang, M. Luo, W. Chou, A roadmap for traffic engineering in SDN-OpenFlow networks, Comput. Netw. (2014), doi:10.1016/j.comnet.2014.06.002.

[8] S. Namal, I. Ahmad, S. Saud, M. Jokinen, A. Gurtov, Implementation of OpenFlow based cognitive radio network architecture: SDN&R, Wirel. Netw. (2016), doi:10.1007/s11276-015-0973-5.

[9] M. Cicioğlu, A. Çalhan, SDN-enabled wireless body area networks, in: Proceedings of the Sixth International Conference on Control Engineering & Information Technology, IEEE, İstanbul, 2018, pp. 1–6.

[10] F. Silva, J. Castillo-Lema, A. Neto, F. Silva, P. Rosa, Software defined eHealth networking towards a truly mobile and reliable system, in: Proceedings of the IEEE Sixteenth International Conference on e-Health Networking, Application and Services Health 2014, 2015, doi:10.1109/HealthCom.2014.7001903.

[11] M. Al Shayokh, A. Abeshu, G.B. Satrya, M.A. Nugroho, Efficient and secure data delivery in software defined WBAN for virtual hospital, in: Proceedings of the ICCEREC 2016 International Conference on Control, Electronics, Renewable Energy, and Communications, 2017, doi:10.1109/ICCEREC.2016.7814973.

[12] H.C. Keong, M.R. Yuce, Analysis of a multi-access scheme and asynchronous transmit-only UWB for wireless body area networks, in: Proceedings of the Thirty-First Annual International Conference of the IEEE Engineering in Medicine and Biology Society: Engineering the Future of Biomedicine, EMBC 2009, 2009, doi:10.1109/IEMBS.2009.5333616.

[13] M.R. Yuce, Implementation of wireless body area networks for healthcare systems, Sensors Actuators, A Phys. (2010), doi:10.1016/j.sna.2010.06.004.

[14] D. Malan, T. Fulford-Jones, M. Welsh, S. Moulton, Codeblue: an ad hoc sensor network infrastructure for emergency medical care, in: Proceedings of the International Workshop on Wearable and Implantable Body Sensor Networks, Boston, MA, 2004.

[15] S. Ullah, M. Chen, K.S. Kwak, Throughput and delay analysis of IEEE 802.15.6-based CSMA/CA protocol, J. Med. Syst. 36 (2012) 3875–3891.

[16] S. Rashwand, J. Mišić, H. Khazaei, Performance analysis of IEEE 802.15.6 under saturation condition and error-prone channel, in: Proceedings of the IEEE Wireless Communications and Networking Conference WCNC 2011, 2011, doi:10.1109/WCNC.2011.5779296.

[17] S. Sarkar, S. Misra, C. Chakraborty, M.S. Obaidat, Analysis of reliability and throughput under saturation condition of IEEE 802.15.6 CSMA/CA for wireless body area networks, in: Proceedings of the IEEE Global Communications Conference, 2014, pp. 2405–2410, doi:10.1109/GLOCOM.2014.7037168.

[18] S. Ullah, E. Tovar, Performance analysis of IEEE 802.15.6 contention-based MAC protocol, in: Proceedings of the IEEE International Conference on Communications, 2015, doi:10.1109/ICC.2015.7249302.

[19] A.B. Al-Shaikhli, C. Çeken, M. Al-Hubaishi, WSANFlow: an interface protocol between SDN controller and end devices for SDN-oriented WSAN, Wirel. Pers. Commun. (2018) 1–19, doi:10.1007/s11277-018-5714-5.

[20] M. Al-Hubaishi, C. Çeken, A. Al-Shaikhli, A novel energy-aware routing mechanism for SDN-enabled WSAN, Int. J. Commun. Syst. (2018) e3724, doi:10.1002/dac.3724.

[21] T. Chen, M. Matinmikko, X. Chen, X. Zhou, P. Ahokangas, Software defined mobile networks: concept, survey, and research directions, IEEE Commun. Mag. (2015), doi:10.1109/MCOM.2015.7321981.

[22] N.A. Jagadeesan, B. Krishnamachari, Software-defined networking paradigms in wireless networks: a survey, ACM Comput. Surv. (2014), doi:10.1145/2655690.

[23] D. Kreutz, F.M.V. Ramos, P. Verissimo, Towards secure and dependable software-defined networks, in: Proceedings of the Second ACM SIGCOMM Workshop on Hot Topics in Software Defined Networking HotSDN '13, 2013, doi:10.1145/2491185.2491199.

[24] T. Galinac Grbac, C.M. Caba, J. Soler, Software Defined Networking demands on software technologies, in: Proceedings of the Thirty-Eighth International Convention on Information and Communication Technology, Electronics and Microelectronics MIPRO 2015, 2015, doi:10.1109/MIPRO.2015.7160315.

[25] M. Cicioğlu, A. Çalhan, Yazılım Tanımlı Ağlar - Software Defined Networks, Karaelmas Fen ve Mühendislik Derg. 7 (2017) 684–695 doi:10.7212%2Fzkufbd.v7i2.835.

[26] M. Cicioglu, S. Cicioglu, A. Calhan, Performance analysis of software-defined network approach for wireless cognitive radio networks, in: Proceedings of the Twenty-Sixth Signal Processing and Communication Application Conference, 2018, pp. 1–4, doi:10.1109/SIU.2018.8404691.

[27] T. Luo, H.P. Tan, T.Q.S. Quek, Sensor openflow: enabling software-defined wireless sensor networks, IEEE Commun. Lett. (2012), doi:10.1109/LCOMM.2012.092812.121712.

[28] S. Bera, S. Misra, S.K. Roy, M.S. Obaidat, Soft-WSN: software-defined WSN management system for IoT applications, IEEE Syst. J. 12 (2018) 2074–2081, doi:10.1109/JSYST.2016.2615761.

[29] L. Galluccio, S. Milardo, G. Morabito, S. Palazzo, SDN-WISE: design, prototyping and experimentation of a stateful SDN solution for WIreless SEnsor networks, in: Proceedings of the IEEE INFOCOM, 2015, doi:10.1109/INFOCOM.2015.7218418.

[30] S. Costanzo, L. Galluccio, G. Morabito, S. Palazzo, Software defined wireless networks: unbridling SDNs, in: Proceedings of the European Workshop on Software-Defined Networking, EWSDN 2012, 2012, doi:10.1109/EWSDN.2012.12.

[31] T.M.C. Nguyen, D.B. Hoang, Z. Chaczko, Can SDN technology be transported to software-defined WSN/IoT? in: 2016 IEEE Int. Conf. Internet Things IEEE Green Comput. Commun. IEEE Cyber, Phys. Soc. Comput. IEEE Smart Data, IEEE, 2016, pp. 234–239, doi:10.1109/iThings-GreenCom-CPSCom-SmartData.2016.63.

[32] C. Yu, C. Lumezanu, A. Sharma, Q. Xu, G. Jiang, H.V. Madhyastha, Software-defined latency monitoring data center networks, in: Lect. Notes Comput. Sci. (Including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics), 2015, doi:10.1007/978-3-319-15509-8_27.

[33] K. He, J. Khalid, S. Das, A. Gember-Jacobson, C. Prakash, A. Akella, L.E. Li, M. Thottan, Latency in software defined networks, in: Proceedings of the ACM SIGMETRICS International Conference on Measurement and Modeling of Computer Systems SIGMETRICS '15, New York, New York, USA, ACM Press, 2015, pp. 435–436, doi:10.1145/2745844.2745880.

[34] IEEE Standards Association, IEEE Standard for Local and metropolitan area networks - Part 15.6: wireless Body Area Networks, 2012. doi:10.1109/IEEESTD.2012.6161600.

[35] M. Cicioğlu, A. Çalhan, IoT based wireless body area networks for disaster cases, Int. J. Commun. Syst. (2018), doi:10.1002/dac.3864.

[36] C. Tachtatzis, F. Di Franco, D.C. Tracey, N.F. Timmons, J. Morrison, An energy analysis of IEEE 802.15.6 scheduled access modes for medical applications, in: Lect. Notes Inst. Comput. Sci. Soc. Telecommun. Eng., 2012, doi:10.1007/978-3-642-29096-1_15.

[37] NEC Corporation, Kanazawa University Hospital, NEC Corp. (2016) 1–2. https://www.necam.com/docs/?id=d90ff012-ff0b-4ece-9cb5-e19972161d93 (Accessed 5 February 2017).

[38] SteelCentral, Riverbed, Riverbed Model. Softw. (2018). https://www.riverbed.com/gb/products/steelcentral/steelcentral-riverbed-modeler.html (accessed March 13, 2018).

[39] Crossbow Technology, MICAz: Wireless Measurement System, Productive Datasheet, 2008 http://www.openautomation.net/uploadsproductos/micaz_datasheet.pdf (accessed March 20, 2018).

[40] Zigbee Alliance, Zigbee Specification, Zigbee Alliance Website. (2015). doi:http://people.ece.cornell.edu/land/courses/ece4760/FinalProjects/s2011/kjb79_ajm232/pmeter/ZigBee%20Specification.pdf.

[41] G. Chen, W. Chen, S. Shen, 2L-MAC: a MAC protocol with two-layer interference mitigation in wireless body area networks for medical applications, in: Proceedings of the IEEE International Conference on Communications, 2014, doi:10.1109/ICC.2014.6883867.

[42] S. Sarkar, S. Misra, B. Bandyopadhyay, C. Chakraborty, M.S. Obaidat, Performance analysis of IEEE 802.15.6 mac protocol under non-ideal channel conditions and saturated traffic regime, IEEE Trans. Comput. (2015), doi:10.1109/TC.2015.2389806.

Murtaza Cicioğlu was born in 1987. He is a Ph.D. student at the Electrical-Electronics and Computer Engineering Department of Duzce University, Turkey. He currently serves as a reviewer in Wireless Personal Communications (WPC), the Computer Journal (COMPJ), Ad Hoc & Sensor Wireless Networks (AHSWN). Her research interests include wireless body area networks, Software-Defined Networks and Riverbed Modeler simulation software.

Ali Çalhan received his M.Sc. and Ph.D. degrees from the University of Kocaeli, Turkey in 2006 and 2011. Since 2011, he has been a member of the Computer Engineering Department of Duzce University. His research interests are wireless communications, cognitive radio networks, body area networks, and software-defined networks.