A QoS-Based Medium Access Control Protocol for WBANs and Its Performance Evaluation

Abdullah Sevin and Cuneyt Bayilmis
Department of Computer Engineering, Sakarya University, Turkey

Abstract: *Nowadays, Wireless Body Area Networks (WBANs) are used in many fields. WBANs are described as small sensor nodes that communicate wirelessly and provide services to the personal area. Quality of Service (QoS) is an essential issue for WBANs due to the importance of human life. QoS problems can only be solved with a robust Medium Access Control (MAC) protocol in WBANs. To find a solution to this problem, developers performed many MAC protocols for WBANs. ISO/IEEE 11073 health informatics defines the standard of personal health information and purposes to provide interoperability between medical technologies. This paper presents a MAC protocol that provides ISO/IEEE 11073 communication standards with QoS support, bases on cross-layer architecture. We designed a slot assignment scheme, prioritization mechanism, admission control mechanism to provide QoS. The performance evaluation of the proposed MAC protocol is compared with IEEE 802.15.4 and IEEE 802.15.6 protocols by considering end-to-end delay, packet loss ratio, and throughput parameters, and it has achieved out performance. It is observed that the proposed protocol doesn't exceed 45 ms delay, reached 81% traffic load, and a maximum error rate of 0.162%.*

Keywords: *Wireless body area networks, quality of service, ISO/IEEE 11073, medium access control protocol, cross-layer.*

Received March 28, 2020; accepted January 19, 2021
https://doi.org/10.34028/iajit/18/6/3

1. Introduction

Benefiting from innovation provides quality and efficient service facilities for the field of health technology in recent years. Nowadays, wireless technology has been used in many areas of healthcare" because of these developments. Wireless Body Area Networks (WBANs) communicate with the wireless environment that is consists of tiny sensor nodes. WBANs provide more comfortable, efficient, and reliable healthcare applications to enable remote monitoring of health information [8].

Data reliability and Quality of Service (QoS) in healthcaretechnologies have vital importance. Therefore, ensuring the QoS has precedence in WBANs. Many studies aim to resolve this problem. However, these studies have different operating parameters due to the absence of any standardization. ISO/IEEE 11073 [9] standard addresses the interoperability of medical devices and the issue of defining the required QoS parameters (bandwidth, latency) in medical applications [17]. Table 1 demonstrates medical application categories and requirements for ISO/IEEE 11073 standard.

In the literature, many studies were performed to provide QoS for WBANs in [1, 2, 3, 4, 5, 6, 7, 10, 11, 12, 13, 16, 18, 19, 20, 21]. These studies seem to consider latency, redundancy rate, reliability, and efficiency (energy, bandwidth, etc.) to support QoS. These studies can be categorized into four parts according to the access mechanism; Time Division Multiple Access (TDMA), contention-based, polling-based, and hybrid studies. Also, particular methods have been developed to ensure QoS in WBANs.

Table 1. Classification of ISO/IEEE 11073.

Category: Data Type	Acceptable Delay	Bandwidth
A: Alarms and alerts (Real-time)	A1: <200 msand A2:<3 sec	64 bytes per alarm
B: Patient condition	<3 sec	64 bytes per alarm
C: Heartbeat, Sensor heartbeat	<60 sec	64 bytes per hour
D: Remainder	<3 sec	1632 bytes per alarm
E: Physiologic parameters (Real-time)	<3 sec	E1: 10 bytes, E2: 100 bytes
F: Remote measuring waveforms (Real-time)	<300 ms	ECG: [F1: 2.4 kbps, F2: 10 kbps, F3: 72 kbps], F4: Ventilator: 50-60 bps, F5: Oxygen Saturation: 50-120 bps

The previous Medium Access Control (MAC) protocols utilize one or more access mechanisms as a hybrid according to the application area. Most of the studies in the literature used the priority assignment mechanism to serve different traffic loads. The scalability of the network is provided by admission control mechanisms in some of the works.

We designed a new MAC protocol to ensure the QoS in WBANs that is based on ISO/IEEE 11073 standard in [15] in the literature. This paper clarifies the detailed structure of the QoS-based cross-layer MAC protocol with a sequence diagram. Also, we analyzed the limitation of the study and compared with standard protocols. The proposed MAC protocol describes a new superframe structure including a slot assignment scheme and prioritization, channel allocation and Bit Error Rate (BER) reduction, admission control mechanisms with cross-layer architecture to provide QoS requirements. The main contributions of the paper are; provides an international communication standard and realizes a protocol design with a higher performance than other standard protocols.

The remainder of the paper is structured as follows. Section 2 describes the system model of the proposed cross-layer QoS-based MAC protocol. In section 3, a performance evaluation of the proposed MAC protocol is presented, and the last section discusses the conclusions.

2. Design of the Proposed MAC Protocol

2.1. Network Model and Frame Structure

WBANs have different features from the wireless sensor network. In general, there are three layers (application layer, MAC layer, physical layer) in WBANs regarding the OSI reference model. The proposed protocol is designed according to a cross-layered architecture (Figure 1). These three layers interact with each other to improve the QoS. The application layer considers the user requests to serve, and the physical layer sends data to decrease Bit Error Rate (BER).

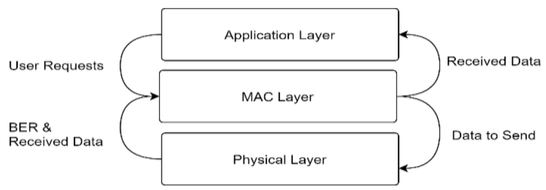

Figure 1. Cross-layered architecture and interaction between layers.

A new superframe structure is developed for the proposed QoS-based MAC protocol. The superframe structure consists of three kinds of phases and two periods of these phases (Figure 2). The first phase is Allocated Time Slots (ATS) which are based on the TDMA mechanism. The second phase is Contention Access Periods (CAPs) and that support random access. A Carrier Sense Multiple Access With Collision Avoidance (CSMA/CA) scheme is implemented in these phases, and emergency alarm, non-periodic, retransmission, and different data packets can be transmitted. The final stage is Improvised Communication (IC) that supports user requests and control packets.

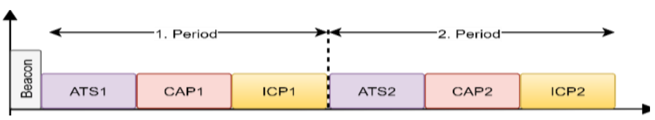

Figure 2. The Superframe of the proposed MAC protocol.

The sequence diagram and methodology of the proposed MAC protocol is presented in Figure 3 to explain the communication of the proposed MAC protocol. The diagram describes the communication between the nodes after the installation of the network infrastructure. In the setup phase, sensor nodes send application parameters to a base node (data rate, latency, etc.) and the time slots required for communication assigned to the nodes according to the slot assignment scheme. In the ATSs phases, all nodes send data in their allocated slots based on the TDMA mechanism. In the CAPs phases, CSMA/CA mechanism is utilized. In the IC phases, control packets and user request packets are transmitted.

Thus, periodic communication is provided in constant time slots in ATS which constitutes most traffic load. Also, non-periodic messages can be transmitted in CAPs. When there is a change on the user or system side, the adaptation process and control packet transmission or user requests ensured from Improvised Communication Phase (ICP).

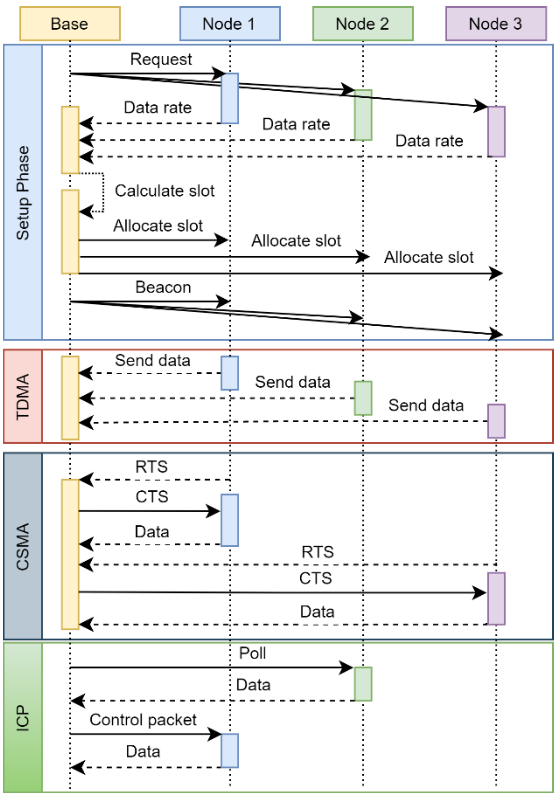

Figure 3. Sequence diagram of the superframe.

2.2. Slot Assignment Scheme

The involved time slots must be assigned to client nodes in WBAN to provide QoS support. Therefore, the number of slots to be allocated to the node is determined by the base. The sensor nodes send the required service parameters to the base node in the setup phase. Based on this information, the central node calculates the needed number of slots to the sensor nodes according to Equations (1) and (2) with the m value. The m value represents the superframe period required for the sensor node to provide the data rate it needs. For example, nodes with low data rates do not need to send every superframe. It will be sufficient to transmit data at determined periodic superframes. Then the number of slots required in each superframe is calculated according to the *m* value.

$$no.\ ATS = \left\lceil \frac{App.\ rate\ \ x\, T_{superframe}}{Data\ rate \times T_{slot}}\ \times\ m \right\rceil \qquad (1)$$

$$m = \begin{cases} 1 & If\ (\frac{Data\ rate \times T_{slot}}{T_{superframe}} \geq 1) \\ \left\lfloor \frac{Latency}{T_{superframe}} \right\rfloor & If\ (\frac{Data\ rate \times T_{slot}}{T_{superframe}} \leq 1) \end{cases} \qquad (2)$$

2.3. Prioritization

Two types of priority are defined in the classification for the proposed MAC protocol; reliability priority and delay priority. User priorities are described for contention-based traffic according to the application scenario. The Contention Window (CW) value varies according to the kinds of traffic (Table 2). Thus, the backoff time is determined, and the priority mechanism defines the medium access possibility. This will increase the probability of nodes transmitting data in order of importance. Furthermore, it regulates the sending of non-periodic data, especially in emergencies. Data reliability is provided in the second priority mechanism.

Table 2. Delay priorities.

User Priority	Type	Samples	CSMA	
			CW_{min}	CW_{max}
0	Urgent alarm	Urgent alerts	1	4
1	Health (Critical Sign)	Cardiac out put	2	4
2	Health	Temperature, CO_2 level	2	8
3	Non-health	Voice	4	8

The second prioritization is relevant to reliability. When the sensor nodes exceed the threshold value, the priority is updated, and the sensor node should send ACK information. Otherwise, ACK information is not required.

2.4. Channel Allocation and BER Reduction Mechanism

Channel allocation and BER reduction mechanisms support the reliability of the proposed MAC protocol by storing low-reliability packets and changing the channel when the BER increased (Figure 4). Thus, when the decrease in BER is achieved, and the unsent messages will be sent later. Additionally, a base node can change the communication channel to avoid collisions when the coexistence of other WBANs.

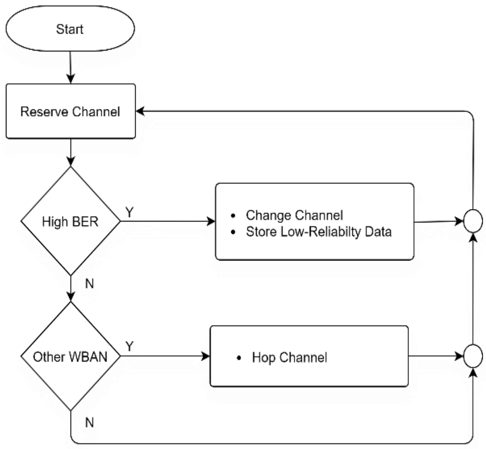

Figure 4. The proposed channel allocation scheme and BER reduction mechanism.

2.5. Admission Control Mechanism

The admission control mechanism is designed supports to QoS by managing traffic flows effectively (Figure 5). When an admission request is received and if there is enough bandwidth available to service, the admission request is admitted. In other cases, the admission request will be rejected. The same condition is applied when the admission request comes from another WBAN.

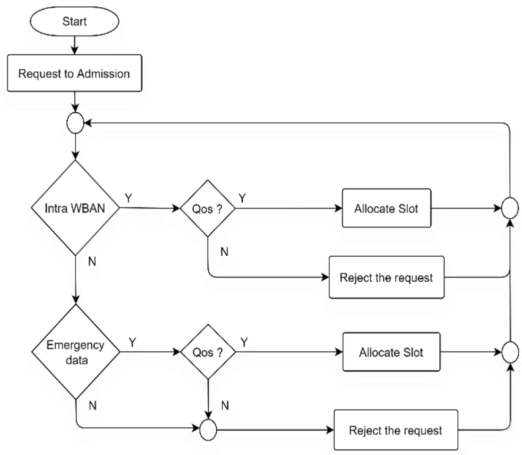

Figure 5. The proposed admission control mechanism.

3. Simulation Implementation and Performance Analysis

The modeling and simulation of the proposed QoS-based MAC protocol are carried out by Riverbed Modeler [14]. To evaluate the performance of the proposed MAC protocol, we compared it with IEEE 802.15.4 and IEEE 802.15.6 protocols. To this end, simulation results of the proposed MAC, IEEE 802.15.4, and IEEE 802.15.6 protocols are analyzed by considering end-to-end delay, packet loss ratio, and throughput parameters.

3.1. Simulation Environment

The simulation parameters used are given in Table 3.

The superframe consists of 128 slots, and each slot is 1.92 ms, and the length of the superframe is about 245.76 ms in the scenario. The packet size is 50 bytes for each packet, and the data rate is 250 Kbps because of using narrow-band communication in WBAN. The frequency of the nodes is 2.4 GHz to adapt Industrial Scientific Medical Band. The simulation time is 100 seconds to see about 400 super frames.The different number of nodes are used to obtain several traffic loads. Also, we used the free space channel propagation model in the simulation environment.

Five sensor nodes have been selected as; temperature, Oxygen Saturation, Electrocardiograms (ECG), glucose, and movement sensor in the simulation scenarios. The sensor nodes and characteristics are given in Table 4.

Table 3. Simulation parameters.

Parameters	Value	Parameters	Value
Data rate	250 Kbps	Simulation time	100 sec
T_{slot}	1.92 ms	Packet size	50 byte
nSlots	128	Number of nodes	5,6,7,8
$T_{superframe}$	245.76 ms	Wireless channel model	Free space
Area	100m x 100m	Packet Inter-Arrival time	Constant

Table 4. The sensors used in the sample application.

Sensor	App. Class	Application Rate (Bits/Sec)	Delay	*N* Slots	m
Temperature	E1	80	3	1	12
Oxygen Saturation	F5	120	0.3	1	1
ECG	F3	72000	0.3	37	1
Movement sensor	F6	43200	0.3	23	1
Glucose	E3	1600	0.3	1	1

3.2. Simulation Results

The Riverbed Modeler hasbeen used to simulate the proposed MAC protocol. The Riverbed Modeler is a development environment to analyze, design, and model communication networks, devices, and protocols. The software provides a comprehensive environment with a network project layer, node model, process model, packet model designs, and graphical analysis tools, etc.

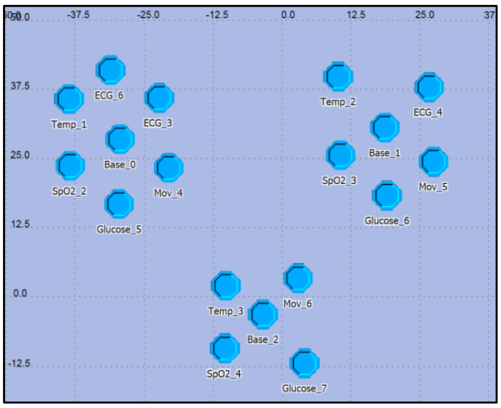

Figure 6. The networkmodel.

The performance of the proposed MAC protocol is evaluated with five different scenarios shown in Figure 6. The scenarios have several traffic loads

- Scenario-1: 45 kbps
- Scenario-2: 117 kbps
- Scenario-3: 160 kbps
- Scenario-4: 190 kbps
- Scenario-5: 233 kbps

By using various selected sensor nodes. For example, the temperature, oxygen saturation, glucose, ECG, and two units of movement sensors are used in scenario-3.

Figure 7 depicts the end-to-end delay for a variable data rate for the proposed MAC, IEEE 802.15.6, and IEEE 802.15.4 protocols. The end-to-end delay of the proposed MAC protocol varies between 16 ms and 45 ms. The other protocols have a very high delay value as a level of seconds because of a buffer overflow. However, the proposed MAC protocol achieves tolerable delay due to the prioritization mechanism and robust slot assignment scheme.The primary reason for low latency is that the time slots needed by the nodes have already been allocated to them. Furthermore, the superframe is divided into two parts. Half of the allocated slots are in the 1. period, and the other half is in the 2. period, wherefore latency is even lower. Non-periodic and improvised communication can be achieved with a rapid response in CAPs and ICPs. Thus, the necessary communication is carried out without waiting for the other superframe. The delay priority mechanism provides fast transmission of urgent or critical data.

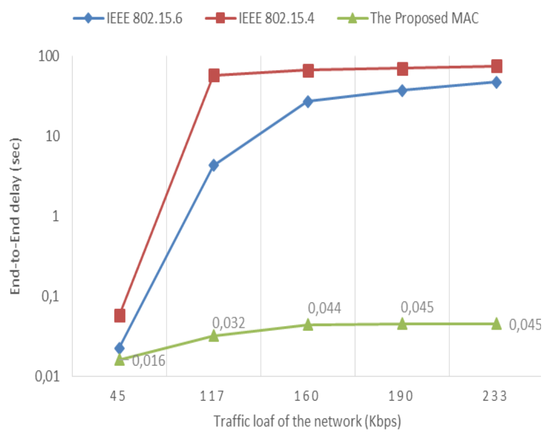

Figure 7. End-to-end delay comparison of protocols.

Figure 8 represents the comparison of each protocol according to the throughput of different traffic loads. The Zigbee protocol reaches a transmission capacity limit at 45 kbps, and also the IEEE 802.15.6 protocol reaches its limit at 56 kbps. The proposed MAC protocol continues data transmission until 190 kbps on narrow-band communication in WBAN. The throughput performance of the proposed MAC protocol has noticeable better results owing to the superframe structure and slot assignment scheme. Each node has a sufficient number of time slots for periodic data transmission determined at the setup phase. Since the superframe is divided into two periods, the generated packets are sent with fewer delays in a buffer. The throughput is managed through the admission control mechanism, enabling new nodes to access the network when necessary and preventing extra entries that may adversely affect the network traffic.

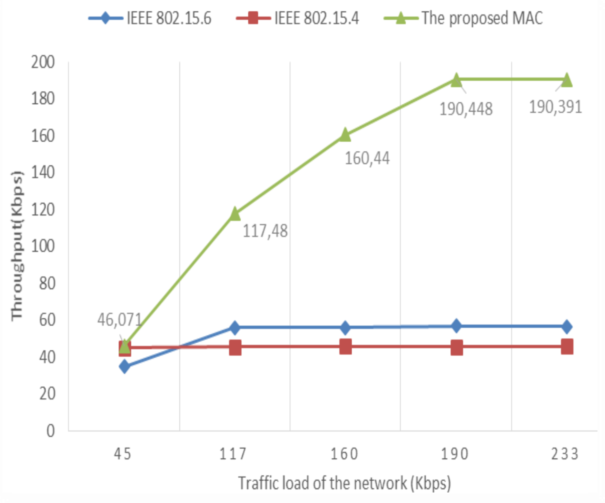

Figure 8. Performance comparison of the protocol throughputs.

The packet loss ratio concerning traffic loads for each MAC protocol is given in Figure 9. These results indicate that the proposed MAC protocol has reliable data communication than the other protocols despite high throughput and low end-to-end delay. This achievement results from the superframe structure, robust slot assignment scheme, and channel allocation mechanism.The base node switches to another channel when the signal quality decreases, and storing low-reliability data will cause reducing packet loss. Channel change can also be performed when encountered with another WBAN because of mobility.

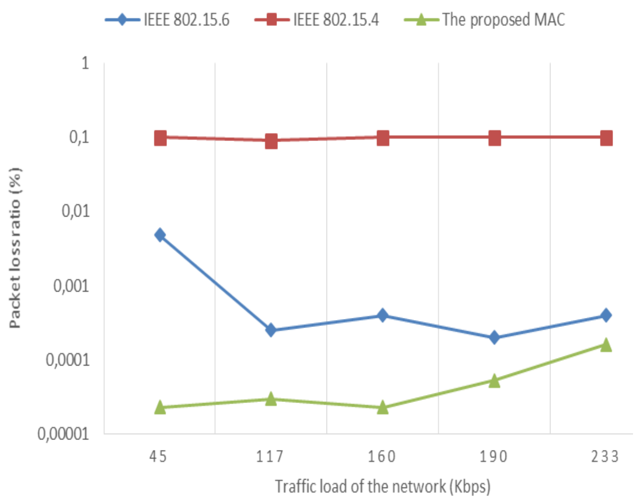

Figure 9. Packet loss ratio comparison of the protocols.

4. Conclusions

This paper has analyzed a new QoS-based cross-layer MAC protocol that provides ISO/IEEE 11073 communication standards. A cross-layer structure is adapted to co-operate betweenthe application layer, MAC layer, and the physical layer. In this way, we serve user requests in the application layer, and the BER is reduced by interacting with the physical layer. It can provide services to different traffic loads and reliability byutilizing latency and reliability priority mechanisms. The hybrid access mechanism and slot assignment scheme in the superframe structure improve throughput and latency performance. The Riverbed Modeler hasbeen used to model the proposed MAC protocol and evaluate the system performance. The proposed MAC protocol is compared with standard technologies as; IEEE 802.15.4 and IEEE 802.15.6. We consider the end-to-end delay, packet loss ratio, and throughput parameters. The proposed MAC protocol demonstrates noticeable better simulation results as; a 36 ms average end-to-end delay for different traffic loads and a mean percentage of 0,0058packet loss ratio, and 2-3 times better through putt han other protocols. The proposed MAC protocol requires a setup phase, but this will provide an advantage in communication phases. The protocol will reach its limit when the allocated time slots are expended as other protocols. The performance analysis with energy consumption on the hardware platform and different comprehensive scenarios with a large number of nodes are intended for future works.

References

[1] Ali K., Sarker J., and Mouftah H., "Urgency-Based MAC Protocol for Wireless Sensor Body Area Networks," *in Proceedings of IEEE International Conference on Communications Workshops*, Cape Town, pp. 1-6, 2010.

[2] Anjum I., Alam N., Razzaque M., Hassan M., and Alamri A., "Traffic Priority and Load Adaptive MAC Protocol for QoS Provisioning in Body Sensor Networks," *International Journal of Distributed Sensor Networks*, vol. 9, no. 3, pp. 205192, 2013.

[3] Bayilmis C. and Kucuk K., *Internet of Things: Theory and Applications*, DaisyScience International Publishing House, 2019.

[4] Chen B. and Pompili D., "Transmission of Patient Vital Signs Using Wireless Body Area Networks," *Mobile Networks and Applications*, vol. 16, no. 6, pp. 663-682, 2011.

[5] Ferdawss D. and Braham R., "An Adaptive MAC Protocol for Wireless Body Area Networks," *in Proceedings of International Conference on Intelligent Systems Design and Applications*, Cham, pp. 764-773, 2020.

[6] Garcia J. and Falck T., "Quality of Service for IEEE 802.15.4-based Wireless Body Sensor Networks," *in Proceedings of the 3rd International Conference on Pervasive Computing Technologies for Healthcare*, London, pp. 1-6, 2009.
[7] Gouda K., Biswal S., Debnath S., and Sahu S., "Implementation of Traffic Priority Aware Medium Access Control Protocol for Wireless Body Area Networks," In Design Frameworks for Wireless Networks, pp. 379-397, 2020.
[8] Hajar M., Al-Kadri M., and Kalutarage H., "A Survey on Wireless Body Area Networks: Architecture, Security Challenges and Research Opportunities," *Computers and Security*, vol. 104, 2021.
[9] Health Informatics-Point-of-Care Medical Device Communication-Application Profiles-Base Standard: ISO/IEEE 11073 Committee; 2004.
[10] Hossam A., Salem T., Abdel-Hady A., and Abd El-Kader S., "MCA-MAC: Modified Cooperative Access MAC Protocol in Wireless Sensor Networks," *The International Arab Journal of Information Technology*, vol. 18, no. 3, pp. 326-335, 2021.
[11] Huq M., Dutkiewicz E., Fang G., Liu R., and Vesilo R., "MEB MAC: Improved Channel Access Scheme for Medical Emergency Traffic in WBAN," *in Proceedings of the International Symposium on Communications and Information Technologies*, Gold Coast, pp. 371-376, 2012.
[12] Misra S., Bishoyi P., and Sarkar S., "i-MAC: in-Body Sensor MAC in Wireless Body Area Networks for Healthcare IoT," *IEEE Systems Journal*, vol. 15, no. 3, pp. 4413-4420, 2020.
[13] Pandey A. and Gupta N., "An Energy Efficient Adaptive Wake-Up Radio MAC (EEAWuR-MAC) Protocol for IoT Wireless Body Area Networks," *Wireless Personal Communications*, pp. 1275-1299, 2021.
[14] Riverbed Modeler by Riverbed Technology, 2020.
[15] Sevin A., Bayilmis C., and Kirbas I., "Design and Implementation of A New Quality of Service-Aware Cross-Layer Medium Access Protocol for Wireless Body Area Networks," *Computers and Electrical Engineering*, vol. 56, pp. 145-156, 2016.
[16] Subramanian A., Ghosh U., Ramaswamy S., Alnumay W., and Sharma P., "PrEEMAC: Priority Based Energy Efficient MAC Protocol for Wireless Body Sensor Networks," *Sustainable Computing: Informatics and Systems*, vol. 30, 2021.
[17] Tachtatzis C., Franco F., Tracey D., Timmons N., and Morrison J., "An Energy Analysis of IEEE 802.15.6 Scheduled Access Modes for Medical Applications," *in Proceedings International Conference on Ad Hoc Networks*, Paris, pp. 209-222, 2011.
[18] Thalore R., Sharma J., Khurana M., and Jha M., "QoS Evaluation of Energy-Efficient ML-MAC Protocol for Wireless Sensor Networks," *AEU-International Journal of Electronics and Communications*, vol. 67, no. 12, pp. 1048-1053, 2013.
[19] Touijer B., Maissa Y., and Mouline S., "IEEE 802.15. 6 CSMA/CA Access Method for Wbans: Performance Evaluation and New Backoff Counter Selection Procedure," *Computer Networks*, pp. 188, pp. 107759, 2021.
[20] Yan Z., Liu B., and Chen C., "QoS-Driven Scheduling Approach Using Optimal Slot Allocation for Wireless Body Area Networks," *in Procceding of 14th International Conference on e-Health Networking, Applications and Services (Healthcom)*, Beijing, pp. 267-272, 2012.
[21] Zia Y., Bashir F., and Qureshi K., "Dynamic Superframe Adaptation Using Group-Based Media Access Control for Handling Traffic Heterogeneity in Wireless Body Area Networks," *International Journal of Distributed Sensor Networks*, vol. 16, no. 8, 2020.

Abdullah Sevin received his M.Sc. and Ph.D. degrees from Sakarya University, Turkey in 2011 and 2016. His research interests are MAC protocols, WBANs, IoT, Security and QoS.

Cuneyt Bayilmis received the M.Sc. in 2003 at Sakarya University and Ph.D. degree in 2006 at Kocaeli University, His active research interests are CAN, internetworking, IoT, WSNs, WBANs.