Wireless Personal Communications (2021) 119:1499–1513
https://doi.org/10.1007/s11277-021-08292-8

Energy Efficiency Solutions for IEEE 802.15.6 Based Wireless Body Sensor Networks

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Accepted: 11 February 2021 / Published online: 26 February 2021

Abstract
IEEE 802.15.6 standard has been designed for wireless body sensor networks (WBSNs) that consist of several sensors and a coordinator node in, on or around the human body. In WBSNs, the body sensors continuously send their data to the coordinator node for remote healthcare applications. Continuously sensing body signals is a requirement for vital signs but continuously sending these signals to a destination over coordinator node is not necessary. Measured signs may be in a normal range for a healthy person, so these measurements may not be transmitted to a destination. In this study, the event-driven approach in an IEEE 802.15.6 based WBSN architecture are examined. If a vital sign exceeds the normal range in the proposed architecture, the corresponding sensor must send the sign to the coordinator node. In addition, a WBSN architecture is designed with the energy harvesting capabilities for purposing energy efficiency in a different way. Comparative performance analysis of three WBSN; traditional WBSN, event-driven WBSN, and energy harvesting aware WBSN is given in this study to show the impacts of energy efficiency methods to WBSNs. The event-driven scheme outperforms traditional WBSN, with a delay of 21% and energy consumption of 67% and the proposed energy harvesting aware scheme provides 5% additional energy to the traditional WBSN. Simulation results show that our proposed methods yield much better performance than the traditional approach.

Keywords Energy efficiency · Wireless body sensor networks · IEEE 802.15.6 · Event-driven · Network performance

1 Introduction

Wireless Body Sensor Networks (WBSNs) generally have tiny, lightweight, wireless sensor nodes that are located in, on, or surround of human bodies. These sensor nodes are able to monitor the functions of the human body and surrounding features [1]. Recent developments in the Internet of Things (IoT) and remote health monitoring (eHealth) applications have increased interest in WBSN. The diversity of applications (health, military,

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entertainment, etc.) reveals the need for more flexible architectures and protocols to better performance. In this context, it has been proposed in the literature to use new medium access control protocols (MAC) such as Bluetooth, IEEE 802.15.4 and IEEE 802.15.6, which will meet the quality of service (QoS) requirements of WBSN architecture [2, 3].

The IEEE 802.15.6 standard has been proposed for specified service requirements in short-range communications among sensor nodes in, on or around the human body. This standard suggests one hop and two-hop star topology in physical and data link layers. In addition, the IEEE 802.15.6 based WBSN scheme consists of one coordinator node (HUB) and several sensor nodes. The coordinator node uses beacon mode with superframe structure and duty cycle mechanism to reduce energy consumption [4, 5].

One of the most important problems of WBSN is energy consumption because of heterogeneous architecture and limited resources. Nowadays, many researchers are working on the improvement of energy sensitive MAC protocols for WBSNs [2, 6, 7]. In contrast to many studies in the literature, the IEEE 802.15.6, which has become the current and standardized method, has been used instead of developing a new MAC protocol [8]. This standard describes the communication methods between a HUB and several sensor nodes connected to it. In this communication, it is an important problem in terms of energy consumption that the sensor nodes continuously send their routine data to the HUB. This situation causes unnecessary energy consumption and increase of network traffic. As a solution to this problem, the event-driven approach is integrated into the IEEE 802.15.6 based WBSN for ensuring energy efficiency and reducing network traffic in this study. This approach provides that only important data be sent to the HUB. In addition, energy harvesting methods are applied to WBSN to give a comparative performance analysis.

The event-driven approach is proposed on energy-sensitive MAC protocols [9–12]. In this study, a sensor node with a specific task definition is continuously following an event. If an event occurs, it is expected to send the obtained data to the relevant units. Various normal range sign values are defined for each sensor node and it is aimed to transmit the obtained data to the destination if these normal range sign values are exceeded. For example, the body temperature measured from the ear of a human is normally 37.5 °C. If the value measured is not around this value, the related sensor has to send this abnormal value to the coordinator.

The remainder of the paper is organized as is follows: The related works are given in detail in Sect. 2. The energy-efficient methods in the literature are discussed in Sect. 3. The proposed architectures (event-driven approach and energy harvesting) are explained in Sect. 4. The simulation results are given in Sect. 5 and Sect. 6 presents the conclusions.

2 Related Works

The wide explosion in usage of WBSN applications for health care has triggered many investigators to study WBSNs' performance. Few studies have been conducted to examine the effect of an event-driven and energy harvesting approach on the human body.

Huang et al. [10] propose a new receiver-centric MAC protocol called RC-MAC, which integrates the duty cycle and receiver-centric scheduling, ensuring high efficiency without sacrificing energy efficiency. To handle the bursty traffic triggered by an event, the RC-MAC utilizes the tree structure and the multichannel technique supported by existing IEEE 802.15.4 RF transceivers to assist scheduling of medium access. The main difference of this study from our study is that IEEE 802.15.16 protocol is not used.

Singh et al. [11] develop a low-latency, cross-layer contention-based synchronous MAC (LDCMAC) protocol for event-driven wireless sensor networks (WSNs). The proposed protocol compares to the cross layer (CL-MAC) [13] protocol using the NS-2.35 simulation. The proposed protocol has been found to perform significantly better than CL-MAC in terms of end-to-end latency and packet transmission rate (PDR). The IEEE standard used in this study is not given.

Hang et al. [14] propose a new solution that combines energy-sensitive, event-driven routing protocol, and dynamic distribution plan to support multi-stage WSN requirements. It shows that the proposed approach reduces the packet loss rate for high-reliability requirement events and extends the network lifetime of the multi-stage WSN. In addition, sharing the load along multiple paths in high traffic conditions will reduce the delay for emergency events in multiple events network.

Mansano et al. [15] have developed an asynchronous event-driven transmitter for wireless ECG sensor nodes. Unlike existing solutions for autonomous wireless sensors such as ECG monitoring, an asynchronous method that transmits data from the ECG front end, designed with a 2-bit level-crossing analog-to-digital converter, has been proposed. Crepaldi et al. [16] propose a quasi-digital radio system for muscle force transmission based on event-driven Impulse-Radio Ultra-Wide Band technology.

Zhang et al. [17] propose an ultra-low-power, event-driven analog-to-digital converter with real-time QRS detection for wearable electrocardiogram sensors in WBSN applications. It has been emphasized that the event-driven approach is a suitable method for energy efficiency. When the studies in the literature are examined, there is no study that recommends an event- driven approach for IEEE 802.15.6 based WBSN.

The contributions of our study can be summarized as follows:

(i) Energy efficiency solutions are suggested with CSMA/CA-based IEEE 802.15.6 standard for WBSN.
(ii) Energy efficiency methods (IEEE 802.15.6, event-driven and energy harvesting) are compared for comparative performance analysis.
(iii) Example case studies are given for further investigations.
(iv) Various scenarios are simulated with Riverbed Modeler.

3 The Energy Efficiency Methods for WBSNs

Energy efficiency in WBSNs [18] is a crucial issue due to the heterogeneous structure, different data rates, limited energy, and complex channel conditions of WBSNs. There are several energy efficiency methods in the literature such as radio optimization [19, 20], data optimization [21], routing protocols [22, 23], MAC protocol schemes, etc. In addition, alternative energy generation methods like energy harvesting [24–26] and charging can be used for WBSNs.

Radio optimization is defined as controlling the antenna power. WBSN as a wireless network has transmitter and receiver antennas for communications. An important part of the energy consumption of wireless networks has happened at the antennas. In WBSNs, the wireless sensor nodes can be placed in, on, or around the body. Therefore, the coverage area, interference, and absorption of the signals in WBSNs are very complicated issues for designing antennas. The optimization of the WBSN antenna radio capabilities is very difficult for general use of WBSNs because of the aforementioned problems.

Data optimization is defined as reducing the amount and sample rate of the sending and transmitting the data when the data are changed in wireless networks. The quality and quantity of the data are very important usually, but to transmit the same data continuously is not necessary for WBSNs. The sensed data in WBSNs can be sent in changing data situations like exceeding the threshold value.

Routing protocol design is another important issue for large-scale wireless networks. In WBSNs, the communication is set up on star topology in Intra-WBSN. However, in some cases, several WBSNs can communicate with each other as inter-WBSN communication. In the literature, WSN routing protocols have been used for WBSNs mostly.

MAC protocols are necessarily utilized for sharing frequency channels in wireless networks with sleep/wake-up scheme, duty cycling, traffic control, etc. mechanisms. The authors modify the standard MAC protocols for various wireless networks [27]. IEEE 802.15.6 standard is completed with the aforementioned properties of the WBSNs.

Consequently, the energy efficiency methods to be applied to the WBSN must be chosen considering the IEEE 802.15.6 standard. In this study, we have considered energy harvesting and event-driven methods with the IEEE 802.15.6 for energy efficiency analysis of the WBSNs.

4 The Proposed Architectures

In this section, the proposed architectures are described in detail. First, event-driven IEEE 802.15.6 based WBSN is expressed, then, some case studies are explained in event-driven WBSN, and then the energy harvesting approach is given comprehensively.

4.1 Event-Driven IEEE 802.15.6 Based WBSN

WBSN is mainly composed of a HUB and many sensor nodes connected to the HUB. HUBs are expressed as a node that coordinates and manages the sensor nodes. HUBs are expected to receive various packets from the sensor nodes and to transmit these packets to the destination (gateway or sink). Sensor nodes with different tasks, data rates, and priorities send the data to the HUB. Communication between HUB and sensor nodes is defined as intra-WBSN communication. Communication among HUBs is called as inter-WBSN communication.

Table 1 presents the different priorities and contention window (CW) values defined by IEEE 80,215.6 standard. The CW variable decides the number of backoff periods that the channel must be idle before starting to transmit. For example, if CW is equal to 2, the device begins to transmit only after two consecutive backoffs resulted in an available channel.

The UP7 sensor node is highly prioritized by the small CW size and the UP0 sensor node is lowest prioritized by the large CW size. The detailed information about IEEE 802.15.6 can be found in [4]. Briefly, the CW is set to CWmin for each priority class and remains the same for each successful data transmission for the backoff process in the beginning. If the contention fails, the sensor node doubles the CW for an even number of failures and keeps it unchanged for an odd number of failures. If doubling the CW exceeds the CWmax, the node sets the CW to CWmax. If the data transmission is successful and then CW is reset to CWmin.

Table 1 Contention window bounds and priority mapping

Priority	CSMA/CA		Slotted Aloha	
	CWmin	CWmax	CPmax	CPmin
0	16	64	1/8	1/16
1	16	32	1/8	3/32
2	8	32	1/4	3/32
3	8	16	1/4	1/8
4	4	16	3/8	1/8
5	4	8	3/8	3/16
6	2	8	1/2	3/16
7	1	4	1	1/4

To meet the QoS requirements of WBSNs is very important depending on where they are used. When IEEE 802.15.6 standard is used for wireless communication between the sensor nodes on, in, or near the human body, delays and packet loss rates are expected to be at the lowest level. When the IEEE 802.15.6 standard, which is used frequently in WBSN architecture, is examined, it is seen that the sensor nodes continuously send the data to the HUB. This traditional approach causes to send the ordinary vital data to the HUB and the related units constantly. After a while, the data obtained is continuously transformed into large amounts of data. In order to obtain a result, it is necessary to analyse these large data with various techniques. At the HUBs, the continuous packet receiving and processing of these packets in order of priority and sending them to the destination also causes a negative situation in terms of both network traffic and energy consumption. So, new approaches are needed to examine the IEEE 802.15.6 based WBSN architecture and solve the aforementioned problems. In this study, the event-driven approach with 802.15.6 based WBSN is discussed and a new approach is proposed.

Figure 1 shows the star topology used for intra-WBSN communication in the IEEE 802.15.6 standard. Each sensor node has different tasks, data rates, and priorities. In addition, these sensor nodes sense body sign values according to their tasks. These signs and their values are detailed in Table 2. This table determines the normal range sign values for the sensor nodes in our scenario.

In Fig. 2, the state transitions of the traditional sensor node and proposed event-driven sensor node are drawn. As can be seen in Fig. 2 (left), energy consumption is happened in sensing and sending processes usually in a classic manner. In Fig. 2 (right), the data measured must exceed the threshold for the sending process.

In Fig. 3, a flow diagram of the proposed approach is given. As can be seen in the figure, a sensor identifies the CW values given in Table 1 as a function of the priority of the node. It then begins to obtain relevant vital data. HUB starts to manage the environment with the beacon packet, which is an indication of the beginning of the superframe period. In the IEEE 802.15.6 standard, the sensor node uses the wireless communication environment according to the CW value and sends the data to the HUB. In this study, each sensor node performs this process by comparing the sensed data with the threshold values assigned to it. If the sensed data are in normal ranges, it continues to measure the new data. However, if the sensed data is below or above the threshold, it is immediately forwarded to the HUB. HUB sends an acknowledgement (ACK) packet to the relevant

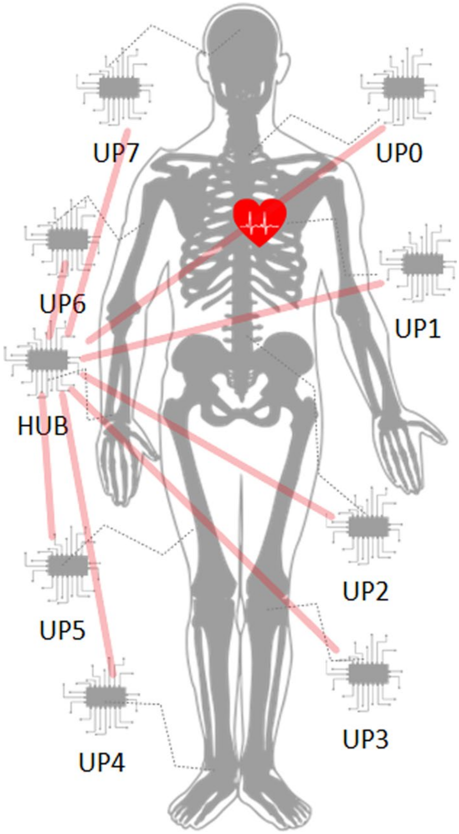


Fig. 1 The proposed IEEE 802.15.6 intra-WBSN communication

Table 2 Human body signs

Body sign	Values	Description
Temperature	37.5	Threshold (anus, vagina, ear) (℃)
Temperature	36.8	Threshold (oral) (℃)
Temperature	36.5	Threshold (armpit) (℃)
Pulse rhythm	70–80	Interval (adult)
Pulse rhythm	80–100	Interval (child)
Pulse rhythm	100–120	Interval (baby)
Respiration	12–20	Respiratory rate per minute (adult)
Respiration	16–22	Respiratory rate per minute (child)
Respiration	18–24	Respiratory rate per minute (baby)
Blood Pressure	90–120	Systolic pressure (mmHg)
Blood Pressure	60–80	Diastolic pressure (mmHg)
SPO2	95–100%	Percentage
Glucometer	70–99	Normal (mg/dl)
Glucometer	100–125	Latent diabetes (mg/dl)

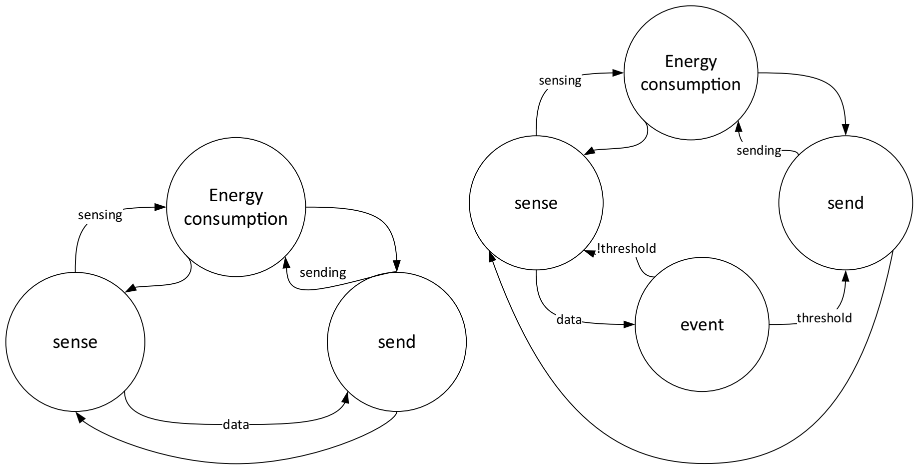
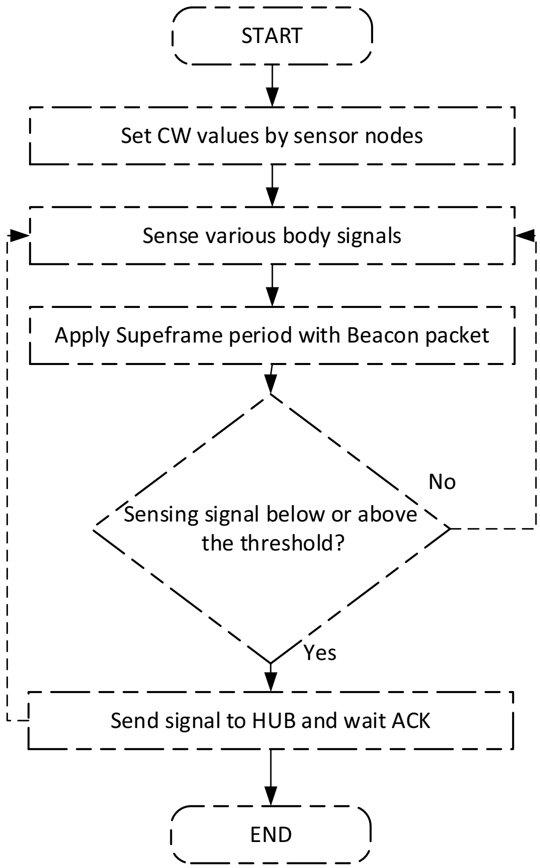


Fig. 2 State transitions for a traditional (left) and an event-driven sensor nodes (right)

Fig. 3 The proposed event-driven WBSN approach flow diagram



sensor indicating that it has received this packet. Furthermore, the data from the sensor node are queued according to its priority and transmitted to the gateway in its order.

Using the CSMA/CA protocol for medium access creates a contention situation between the HUB and the sensor nodes connected to the HUB. These contentions vary according to the priority values assigned to the nodes. While the “Binary Exponential Backoff” algorithm is used in the traditional CSMA/CA protocol, the “Alternative Binary Exponential Backoff” algorithm is used in the CSMA/CA used in the IEEE 802.15.6 standard. CW ranges are given in Table 1. The detailed MAC parameters used in the simulation are given in Table 4. More detailed information is available in [4].

4.2 Event-Driven WBSN Case Studies

4.2.1 Hyperthermia and Hypothermia

Body temperature can fall or rise due to some reasons and is an indicator of the amount of heat contained in a human body. Body temperature may vary depending on many external factors. Some of them can be stress, poor nutrition, or even aging and mood swings. However, the average normal temperature is between 35 and 37.7 degrees. It may also vary depending on what time of day you are on or from which part of the body you are measuring the temperature. Hypothermia happens when the body’s temperature drops to dangerously low levels. When the body temperature rises too high and threatens the health, it’s known as hyperthermia. The aforementioned changes in body temperature must be taken into consideration as soon as possible. The body temperature sensor in WBSN assumes the task in an event-driven approach.

4.2.2 Hypertension and Hypotension

High blood pressure, also known as hypertension has happened when too much blood is being pumped into the arteries that can cause life-threatening conditions like heart disease and stroke. Hypotension, or low blood pressure, means blood is not fully flowing to the brain, arteries, and organs. Hypertension is defined as systolic blood pressure of 140 mm Hg or greater. Moreover, it happens when diastolic blood pressure of 90 mm Hg or greater. Hypotension occurs when the systolic blood pressure falls to 90 mm Hg or below. The blood pressure sensor in WBSN undertakes the task in an event-driven approach.

4.2.3 Hyperglycemia and Hypoglycemia

Hyperglycemia refers to chronically high blood glucose levels. Hypoglycemia sets in when blood sugar levels are too low. Between around 60 and 140 mg of sugar per deciliter of blood (mg/dL) is considered to be healthy. The glucose sensor in WBSN undertakes the task in an event-driven approach.

As can be seen in the explanations above, the data intervals vary in individuals with different diseases. For example, systolic blood pressure is seen as 140 mmHg and above for hypertensive patients, while this value is in the range of 90–120 mmHg for healthy individuals [28]. This leads to ambiguity in the range of data to be used for event-driven approach. For this reason, in our study, the data ranges given in Table 2 have been taken as reference, especially for healthy individuals without a history of disease. Different scenarios should be developed for individuals with known disease history or with different diseases.

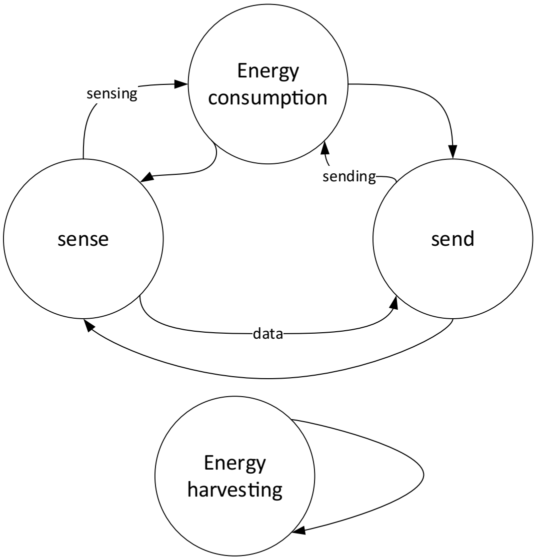


Fig. 4 State transitions with energy harvesting

Table 3 Human body energy sources

Energy harvesting unit	Energy type	Generated energy for 1 s (mJ)
Enzymatic biofuel cell (glucose)	Biochemical	1.8
Enzymatic biofuel cell (lactate)	Biochemical	0.44
Piezoelectric (blood pressure)	Biomechanical	0.03
Piezoelectric (heartbeat)	Biomechanical	0.012
Thermoelectricity (heat)	Ambient	1.35

4.2.4 Energy Harvesting Aware WBSN

Power from non-electric renewable energy sources can be harnessed with suitable hardware. Then the obtained power can be converted to electrical form to satisfy the energy requirements of WBSNs. The aforementioned method is referred to as energy harvesting. The human body holds ample energy sources that can be used to power both implanted and on-body sensors. Its sources can be classified into biochemical and biomechanical energy depending on the nature of the energy. In Fig. 4, the state transitions with energy harvesting is drawn for energy harvesting aware WBSN.

In this study, a WBSN structure with energy harvesting methods is designed. The energy harvesting units, energy types, and obtained energy for one second in this study are categorized in Table 3 [29]. We only deal with energy sources from human organs.

5 Simulation Results

The most important aim of our study is to develop and analysis effective and efficient models for IEEE 802.15.6 based WBSN. For this purpose, IEEE 802.15.6 based WBSN with the event-driven approach (ED-802.15.6) is designed and analysed in the Riverbed Modeler [30] simulation software. The proposed approach is examined with two different scenarios and its performance is evaluated.

In these scenarios, there are eight sensor nodes and one HUB as shown in Fig. 1. HUB is responsible for the control and management of eight sensor nodes. These nodes are named UP7, UP6, UP5, UP4, UP3, UP2, UP1, and UP0, with the highest priority to the lowest priority. UP7 has 5 packets/second, UP6 has 3 packets/second, UP5 has 2 packets/second, UP4 has 1 packet/second, UP3 has 0.5 packet/second, UP2 has 0.1 packet/second, UP1 and UP0 have 0.05 packet/second packet rates. Since WBSN has a heterogeneous network structure, each node has different packet rates and different tasks. These sensor nodes have different CWs and priorities as shown in Table 1.

All nodes are designed and simulated in the Riverbed Modeler. The simulation parameters used for the performance analysis of both scenarios are given in Table 4. MicaZ values are used to calculate energy consumption with default values [31].

In the first scenario, the traditional approach of the IEEE 802.15.6 based WBSN is used to analyse and all nodes attempt to send data to the HUB as in Fig. 1. The detailed analysis of this scenario is also available in other studies [32, 33]. In this study, delay and energy consumption results of the HUB node are obtained. In order to compare the traditional approach with the proposed approach (ED-802.15.6), the delay results of UP7, UP5, and UP3 nodes are discussed. There is no particular reason for choosing these nodes; they have been selected to illustrate the results.

In the second scenario, simulation is performed in the same environment using the ED-802.15.6. It is assumed that UP7, UP5 and UP3 nodes sense data above the threshold value and only those nodes send packet to HUB. In this scenario, the energy consumption values of the HUB and the delay results of UP7, UP5, and UP3, which are different priority nodes, are examined and two scenarios are compared.

Table 4 Simulation parameters

Parameters		Value	Parameters	Value
Simulation time		1200 s	Slot time	145 µs
Frequency		2400 to 2483.5 GHz	SIFS	75 µs
Number of nodes		8 nodes 1 HUB	pCCA	105 µs (63/symbol rate)
Random access		CSMA/CA	pCSMA-MACPHY-Time	40 µs
Bandwidth		1 MHz	ACK time	468.4 µs
Data rate		971.4 kb/s	Extra IFS	10 µs
Payload		1020 bits	Timeout	30 µs
MicaZ	Initial node energy	50 J	P_{TX}	0 dBm = 17.4 mA
			P_{RX}	27.7 mA
	Battery	2 AA (3 V)	P_{Sleep}	16 µA
			P_{Idle}	35 µA

Figure 5 shows the delay results of UP7, UP5, and UP3 for both scenarios. The delay results expressed as IEEE 802.15.6 are the results obtained without the event-driven approach in the first scenario. Here, all sensor nodes send their packets to the HUB. On the other hand, ED-802.15.6 delay results are the results obtained when the event-driven approach is used in the second scenario. When these results are compared, it is seen that for ED-802.15.6, UP7, UP5, and UP3 sensor nodes have lower delays than traditional IEEE 802.15.6. This delay difference is caused by continuous unnecessary packet sending, which causes increased network traffic. The delay differences between these different priority nodes seen in both approaches are related to the CW values given in Table 1. For example, the CW value of the UP7 node with a high priority is lower than the other nodes. Thus, UP7 has the opportunity to access the wireless communication environment earlier than others. Therefore, it sends packets with less delay. According to the results, ED-802.15.6 can decrease unnecessary network traffic with the help of an event-driven approach. In this way, only nodes that sense data below or above the threshold value are trying to transmit the packet and use the medium. The second scenario using ED-802.15.6 performs approximately 21% better performance than traditional IEEE 802.15.6.

Figure 6 shows the energy consumption rates in both scenarios. The energy consumption rates here are calculated at the HUB with MicaZ parameters. When the results are examined, it is seen that ED-802.15.6 is more successful than the traditional approach. The most important reason for this is that the routine (ordinary vital) data of the human body are continuously sent to the HUB in the traditional approach. The HUB receives the data in its queue according to its priorities and sends it to the destination (gateway or sink) respectively. Therefore, the energy consumption is increased certainly. However, in the second scenario where ED-802.15.6 is used, only the operations that exceed the threshold values are performed. In this way, only the critical packets are sent. When energy consumption results are analysed, ED-802.15.6 shows that it is 67% more successful. In addition, the proposed ED-802.15.6 is also compared with the developed energy harvesting

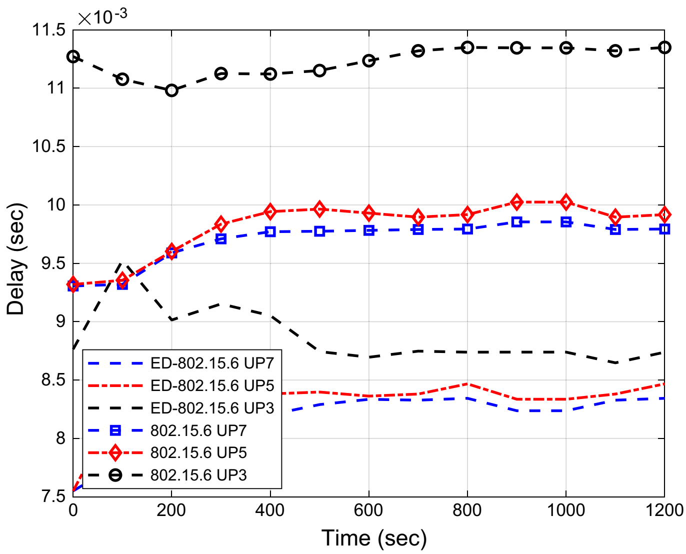


Fig. 5 Delay results for ED-802.15.6 and IEEE 802.15.6 with different priorities

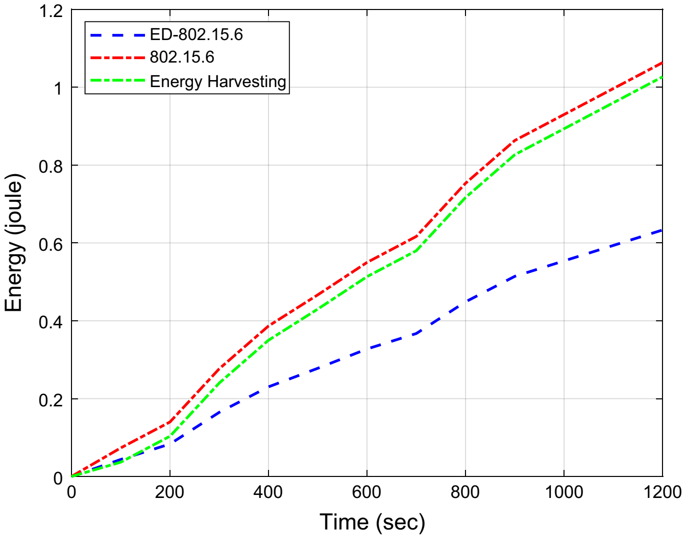


Fig. 6 Energy consumption results for IEEE 802.15.6, ED-802.15.6 and Energy Harvesting

WBSN system with the values in Table 3. As can be seen from Fig. 6, the energy harvesting aware scheme provides 5% additional energy to the traditional WBSN. These results can be changed according to the scenarios and the energy source types.

6 Conclusions

WBSN technology is still attracting great attention from researchers in terms of many benefits for future technologies. The IEEE 802.15.6 is an important standard contributing to the use and diversity of WBSN technologies. However, this standard also has some shortcomings, especially in terms of energy efficiency. Therefore, we propose various energy efficiency methods for the IEEE 802.15.6 standard in this study. First, we develop the IEEE 802.15.6 based event-driven WBSN scheme to provide a more energy-efficient structure. The proposed scheme is compared to traditional IEEE 802.15.6 in terms of delay and energy consumption. In addition, energy harvesting aware WBSN architecture is also developed for comparative performance analysis. The results show that the event-driven approach gives much more effective results than the other approach. The proposed approach provides 21% better performance in latency and 67% better performance in energy consumption. For future works, the event-driven approach will be proposed for inter-WBSN communications. In addition, various energy harvesting methods and specific sensors can be added to the WBSN applications.

Authors' Contributions M.C. and A.Ç. designed the model and the computational framework and analysed the data, carried out the implementation, performed the calculations, wrote the manuscript, conceived the study and were in charge of overall direction and planning.

Funding The author(s) received no financial support for the research, authorship, and/or publication of this article.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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