

Article

# Performance Enhancement of IEEE 802.15.6 Using Collision Avoidance Technique

Muhammad Adnan <sup>1,†</sup>, Farag Sallabi <sup>2,\*,†</sup>, Khaled Shuaib <sup>3</sup> and Mohammed Abdul-Hafez <sup>4</sup>

<sup>1</sup> Division of Computer and Information Sciences, Higher Colleges of Technology, Al Ain, UAE; madnan@hct.ac.ae

<sup>2</sup> Department of Computer and Network Engineering, College of Information Technology, United Arab Emirates University, Al Ain, UAE

<sup>3</sup> Department of Information Systems and Security, College of Information Technology, United Arab Emirates University, Al Ain, UAE; k.shuaib@uaeu.ac.ae

<sup>4</sup> Department of Electrical Engineering, College of Engineering, United Arab Emirates University, Al Ain, UAE; mhafez@uaeu.ac.ae

\* Correspondence: f.sallabi@uaeu.ac.ae; Tel.: +971-3-713-5549

† These authors contributed equally to this work.

Received: 28 May 2020; Accepted: 13 July 2020; Published: 17 July 2020



**Abstract:** Research related to Wireless Body Area Networks (WBAN) has recently gained more attention due to its application in enabling smart healthcare systems. A WBAN consists of several sensing nodes and a dedicated coordinator. The distributed nodes communicate with the coordinator by accessing the physical communication channel in a randomly distributed fashion. Random channel access may cause frame re-transmission of corrupted frames due to frame collisions. As a result of that, there will be degradation in the WBAN throughput, an increase in delay, and a waste of node energy. Nodes within a WBAN can be classified using specific user priorities allowing for prioritized communication to reduce possible frame collisions. To improve the performance and energy efficiency, this work aims to reduce collisions among nodes that belong to the same users' priority (homogeneous collisions) and collisions among nodes of different users' priorities (heterogeneous collisions). Homogeneous collisions can be reduced by scaling the minimum Contention Window (CW) among nodes within the same user priority, whereas heterogeneous collisions can be reduced by allowing higher user priority nodes to transmit while lower user priority nodes enter into a backoff state. This paper presents an analytical model and extensive simulations to show the enhanced performance of the proposed collision avoidance mechanism. The results show that the throughput and node energy efficiency is improved by a factor of three and two times, respectively.

**Keywords:** Internet of Things (IoT); smart healthcare; network delay; IEEE 802.15.6; energy efficiency

## 1. Introduction

Internet of Things (IoT) is an architecture in which physical objects, i.e., sensors, actuators, and devices, work together to share information in a distributed manner [1]. IoT enables these physical objects to work seamlessly by using various technologies such as sensor networks, communication protocols, and applications [2]. IoT application areas include healthcare, smart cities, smart homes, environment monitoring, vehicular networks, and other industries. However, IoT-based healthcare has 41% of the potential market shares among IoT-based applications [3]. The number of patients with chronic health conditions is increasing. In 2008, non-communicable diseases, for example, diabetes, accounted for 63% of all deaths in the world [4]. The management of chronic diseases puts significant strain on patients, healthcare systems, and communities around the world. The treatment of these diseases is

usually lengthy and costly and requires frequent medical consultations. Because of community aging and an increase in the number of patients with chronic conditions, more people will need long-term personal medical care. IoT can be used in healthcare for the diagnosis of diseases, therapy, medications, healthcare monitoring, etc. Wireless networks are required to ease communication of application data among wireless devices within IoT-based healthcare systems. Due to the mature development of Wireless Sensor Networks (WSN), Wireless Body Area Network (WBAN) has become an area of great interest for developers and researchers. WBAN consists of sensing nodes and a hub or a coordinator. Sensor nodes collect vital data signs such as body temperature, electrocardiography, sugar level, SpO<sub>2</sub>, and blood pressure (BP) from the human body and send them to a hub or a coordinator via wireless channels [5]. After receiving the data, the coordinator pre-processes the received data, e.g., compression and filtration, and then sends the data to the healthcare center.

IEEE 802.15.6 standard [6] is used for WBAN, which employs Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). In IEEE 802.15.6, the node initializes its Backoff Counter (BC) based on the Contention Window (CW). Each node chooses a random integer uniformly distributed between interval 1 and CW, Where  $CW \in [CW_{min}, CW_{max}]$ . The value of CW is double on alternative collisions and reset to  $CW_{min}$  on successful transmission. Nodes are assigned user priority (UP) based on traffic type and select its  $CW_{min}$  and  $CW_{max}$  according to these UPs, as shown later in Table 1. Nodes are assigned different minimum and maximum CW to provide differential services based on requirements. However, the minimum and maximum CW of the highest UP has small values, and if few nodes are belonging to the highest UP or nodes in other UPs, they result in high collision probability and re-transmission. The high collision probability decreases throughput, increases energy consumption, and under uses the channel. Another issue is the under-saturation condition, where there exist nodes belonging to all available UPs in which the node belonging to a lower UP faces starvation [7]. The reason behind starvation is the difference between the minimum CW of lowest and highest UPs, which is very high, and the node with lower UP does not receive a chance to access the channel. Given that WBANs consist of battery-operated wearable devices with a limited life span makes it a more challenging problem to address [8,9]. The issue of re-transmission and starvation degrades the performance of the IEEE 802.15.6 standard. The performance of the CSMA/CA of the IEEE 802.15.6 is also affected by the hidden node problem. The hidden node effect results in degraded throughput and poor link reliability [10].

In this paper, we propose a novel mechanism that reduces the re-transmissions of a data frame due to collisions. The proposed mechanism reduces collisions among nodes belonging to a similar UP (homogeneous collisions) and decreases collision probability among nodes belonging to different UPs (heterogeneous collisions). The homogeneous collision is reduced by scaling the minimum CW of any UP node with several nodes in that UP category. However, heterogeneous collisions are minimized by introducing different Clear Channel Assessment (CCA) times for different UPs. When the backoff counter of two or more nodes belongs to different UPs becomes zero, the one with low CCA time (highest UP) will transmit while other nodes belonging to lower UP adjust the backoff time. As a result, this reduces higher collision probability without affecting the differentiated channel access among UPs and resolves the starvation issue that occurs among nodes of high and low UPs. The following are the main features and contributions of this study.

- Propose a mechanism to avoid homogeneous and heterogeneous collisions by controlling CW and prioritize channel access without collisions.
- Improve the energy efficiency, the throughput, and use of the channel.
- Develop an analytical model for both the IEEE 802.15.6 standard and the proposed mechanism.
- Implement a simulation model to test the effectiveness of the analytical model and compare the analytical results in terms of throughput, energy per bit, and normalized delay.

The rest of the paper is organized as follows: Section 2 reviews the IEEE 802.15.6 standard, issues in IEEE 802.15.6, and solutions available in the literature. Section 3 presents details of the proposed

mechanism. In Section 4, we develop a detailed analytical model for both IEEE 802.15.6 standard and proposed mechanism. The results and discussion are presented in Section 5 and finally, Section 6 concludes the paper.

## 2. Background and Related Work

The IEEE 802.15.6 standard supports three different physical layers, namely Narrowband (NB), Ultra-Wide Band (UWB), and Human Body Communication (HBC). The detailed description and functionality of these layers are presented in [11]. Furthermore, the IEEE 802.15.6 standard MAC layer provides three types of channel access mechanisms, i.e., Beacon mode with superframe boundaries, Nonbeacon mode with superframe boundaries, and Nonbeacon mode without superframe boundaries. Since the development of the IEEE 802.15.6 standard, more research has been conducted to improve its performance. An efficient MAC protocol is one of the most crucial components in the WBAN to provide quality of service and reliable communication. MAC protocols are classified based on channel access and scheduling techniques. Marinkovic et al. [12] proposed a Time Division Multiple Access (TDMA) protocol for WBAN. The protocol has little overhead, long sleep time to sense and transmit, and it is robust to communication errors. In [13], the authors proposed an energy-efficiency and delay-sensitivity TDMA-based MAC protocol for WBAN to monitor physiological signals such as ECG and EEG remotely. TDMA-based protocols assign an equal time slot to each sensor in the WBAN. This is useful if all sensors use the same resources and have equal priorities. On the other hand, Frequency Division Multiple Access (FDMA) assigns different frequency channels to different WBAN devices [14,15]. In scheduling-based schemes, i.e., TDMA and FDMA, the channel resources are underused in many cases. The contention-based scheme, i.e., CSMA/CA, is used both in IEEE 802.15.4 and IEEE 802.15.6 standards. In both standards, the CSMA/CA is quite similar, but in IEEE 802.15.6, after a transmission failure of the frame, CSMA/CA increases its contention window [16]. Moulik et al., [17] proposed a MAC-frame payload tuning mechanism based on priority and energy efficiency for the healthcare system. The goal of the study was to consider different properties of nodes, i.e., radio status, frame length, and transmission time, to have an optimization solution for improving energy efficiency. A MAC protocol is developed in [18] to improve the energy efficiency and quality of service for WBANs. This mechanism achieves lower energy efficiency by waking sleeping nodes to receive the polling message. Otherwise, they are in a sleeping mode to conserve energy. Furthermore, the authors in [19] developed a game-theoretic approach based on intelligent management of WBANs. The work attempts to combine the contention channel access and contention-free channel access of the MAC layer. In their work, a network has different adaptive mechanisms based on application requirements and the status of the channel to use energy resources efficiently. The work in [20] presents an analytical model of the IEEE 802.15.6 CSMA/CA protocol under non-saturated traffic conditions. They computed throughput, energy consumption, and mean frame service time and optimized phase lengths to attain a higher throughput and the minimum delay. The work in [21] determines the optimum allocation intervals for the IEEE 802.15.6 nodes to maximize the network capacity and maintain a frame delay within limits. They also obtain the payload sizes that extend the battery life of the nodes. An analytical model is presented in [22] for scheduled access mechanisms that provide throughput analysis and closed-form expressions for different performance parameters, e.g., reliable data transfer, throughput, delay, and energy consumption for a variety of applications with medium to high data rates. Sultana et al. [23] developed a new IEEE 802.15.6 MAC superframe structure to accommodate different data types with different priorities, which reduced the delivery delay as compared to other schemes. To improve the use of the IEEE 802.15.6 superframe, the work in [24] presents a dynamic slot allocation scheme using non-overlapping contention windows. Another work [25] proposed a general analytical model for performance evaluation of the IEEE 802.15.6 with different traffic priorities. The proposed model is composed of two complementary sub-models, namely a renewal reward-based analytical sub-model and an M/G/1 queuing model with non-preemptive priority. The work in [26]

presents a comprehensive review of the major components of the IEEE 802.15.6 standard and modeling strategies for implementing IEEE 802.15.6 MAC on NS-3 simulator.

The motivation of our mechanism has several benefits as compared to previous approaches, which are as follows:

- Reduce collision probability by categorizing collisions into collisions among nodes of the same UP and collisions among/between different UPs.
- The mechanisms based on time scheduling [12,13] require changes to the current IEEE 802.15.6 standard channel access approach, whereas our mechanism does not require significant changes and can be practically realized.
- Previously developed mechanisms [16–19] do not deal with collisions and re-transmissions. Our proposed mechanism reduces collisions to improve energy efficiency and the overall performance.

### 3. Proposed Mechanism

Our proposed mechanism improves energy efficiency by avoiding homogeneous and heterogeneous collisions. The mechanism adaptively scales the minimum CW to the number of nodes in the UP to prevent homogeneous collisions. However, heterogeneous collisions are avoided by sequential transmissions of frames based on UPs when the backoff counter of two or more different UP nodes becomes zero without affecting the importance of UPs. Furthermore, the proposed mechanism does not make significant changes in the IEEE 802.15.6 standard. The following subsections explain how the proposed mechanism avoids homogeneous and heterogeneous collisions.

#### 3.1. Heterogeneous Collisions

In IEEE 802.15.6, nodes decrement their backoff counter by one if they detect an idle slot for the duration of  $\rho\text{CSMASlot}$ . More specifically, the  $\rho\text{CSMASlot}$  is divided into two durations,  $\rho\text{CCATime}$ , and  $\rho\text{CSMAMACPHYTime}$ . The  $\rho\text{CCATime}$  is used to determine the status of  $\rho\text{CSMASlot}$ . Nodes assume the CSMA slot idle if they find the channel idle from the start of the CSMA slot to the  $\rho\text{CCATime}$ . The  $\rho\text{CSMAMACPHYTime}$  is the time required to transmit a frame to the channel at the end of the CSMA slot when the backoff counter reaches zero. In the proposed mechanism, we introduce two slots, one that is used to decrement the backoff counter called backoff slot, and the other used to transmit frames when the backoff counter reaches zero. Assume that  $\psi$  represents the  $\rho\text{CCATime}$  in the IEEE 802.15.6 standard, and  $\Gamma$  represents several user priorities in the network. Then we define the unit  $\rho\text{CCATime}$  of the proposed mechanism as:

$$\psi' = \frac{\psi \times \beta}{\Gamma} \tag{1}$$

Also, when  $\alpha$  represents the  $\rho\text{CSMAMACPHYTime}$  of the standard, then we define the  $\rho\text{CSMAMACPHYTime}$  of proposed mechanism as:

$$\alpha' = \frac{\alpha \times \beta}{\Gamma} \tag{2}$$

Here,  $\beta$  is a scaling parameter which means the scaling of  $\psi$  and  $\alpha$  with the number of priorities. Now, we define the backoff slot of the proposed mechanism as:

$$T_{\text{slot,prop}} = \psi' + \alpha'e. \tag{3}$$

Finally, we define the differentiated  $\rho\text{CCATime}$  of UP  $k$  ( $\rho\text{CCATime}_{UP,k}$ ) as:

$$\rho\text{CCATime}_{UP,k} = ((UP_{max} - UP_k) + 1) \times \psi' + (UP_{max} - UP_k) \times \alpha'e. \tag{4}$$

We can observe from Equation (4) that a higher UP has smaller  $\rho CCATime$ , i.e., a higher priority, whereas a low UP has a long  $\rho CCATime$ . Equation (4) leads to a situation in which we avoid a collision between two or more different UPs while maintaining the significance of each UP. Next, we define how a successful transmission, backoff, and collision happen in the proposed mechanism.

- Successful transmission: When the backoff counter of a node becomes zero, the node waits some time as specified in equation 4, then it starts transmission. In addition, when the backoff counter of two or more nodes with different UPs becomes zero, the node with a higher UP starts transmission after waiting for its  $\rho CCATime$ , as shown in Figure 1. In Figure 1, three nodes have UP 6, 5, and 0, along with a coordinator. Initially, the backoff counter of a node belongs to UP 6, 5, and 0 is set to 2, 3, and 3, respectively. After two backoff slots, the UP 6 backoff counter becomes zero. Thus, it starts transmission after waiting for its  $\rho CCATime$  as given in Equation (4). The  $\rho CCATime$  of any node is smaller than the backoff slot. After successful transmission by a node of UP 6, all the nodes resumes the process of backoff and decrements its backoff counter. Subsequently, the nodes with UPs 5 and 0 backoff counter becomes zero. Both the nodes must wait for their  $\rho CCATime$ , but based on equation UPs have lower  $\rho CCATime$  and start transmission. Node with UP 0 found the channel busy as it has bigger  $\rho CCATime$  as compared to UP 5, so it does not transmit and choose its backoff counter again based on its current CW.
- Collision: Collision happens between nodes with similar UPs and zero backoff counter. In this mechanism, the collision is prevented by allowing transmission of the high priority node, whereas the low priority node enters the backoff stage.
- Backoff: The backoff counter is decremented if the channel is idle for the duration of a time, as given in Equation (3).

The proposed mechanism introduced a design parameter  $\beta$ , which plays a significant role in its performance. Here, we discuss how the value of  $\beta$  affects the performance and provides guidelines for setting its value. Value of  $\beta = 1$  means only one slot of the IEEE 802.15.6 has been used to have differentiated channel access that leads to shorter time wastage in the backoff process. However, every node has a short time for sensing the channel state (idle or not). On the other hand, a large value of  $\beta (> 1)$  results in more time being spent in the backoff procedure with more time for sensing the channel. The effect of  $\beta$  on the performance is further investigated in Section 5.

### 3.2. Homogeneous Collisions

The number of competing nodes in a UP greatly affects the collision probability, and size adjustment of the CW can manage that. The IEEE 802.15.6 standard suggests a fixed CW for each UP, as shown in Table 1, which is not adaptable to the number of competing nodes. To compensate for this fixed size of the CW, the IEEE 802.15.6 standard proposes the Alternative Binary Exponential Backoff (ABEB) mechanism that enables nodes to double the value of the CW when facing a collision to avoid the possible failure in the re-transmission of a frame. However, the value of  $CW_{min}$  of a UP, which is used for medical data (as shown in Table 1), is minimal even if there are few nodes belonging to UP 6 and UP 7 (which may face collisions). In addition, the ABEB is not useful in avoiding a collision as the number of nodes increases due to its reactive nature.

Furthermore, the work in [27,28] suggests that to reduce the re-transmission, the CW needs to be proportional to the number of competing nodes. Based on these reasons, we proposed a proactive scaling of the CW with several nodes as follows; linear scaling for CW and node adjusts it based on the number of nodes in the corresponding UP. We denote adjusted minimum CW by  $CW'_{min,k}$  and define it as follows.

$$CW'_{min,k} = CW_{min,k} + n_k, \tag{5}$$

where  $CW_{min,k}$  and  $n_k$  are the minimum CW given by the IEEE 802.15.6 standard, and the number of nodes belonging to  $k$ th UP, respectively. We assume that each node keeps track of the number of nodes in each UP as known that in the IEEE 802.15.6, the number of nodes is small and the coordinator has

the information, which can be periodically broadcasted using beacon frames. It is also worthwhile to note that nodes also maintain the backoff mechanism implemented in the IEEE 802.15.6 standard, which is doubling the CW on alternative collisions and has a subsidiary role in dealing with collisions.

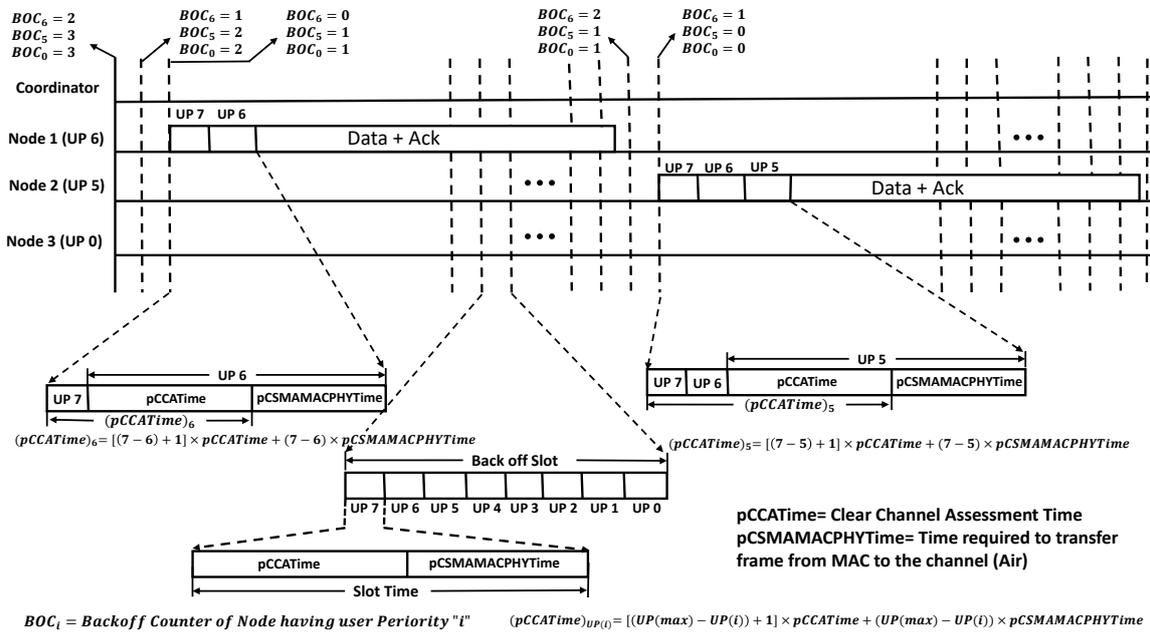


Figure 1. Channel access method of the proposed mechanism.

Table 1. Maximum and Minimum CW for IEEE 802.15.6 CSMA/CA.

Traffic Type	User Priority	$CW_{min}$	$CW_{max}$
Background	0	16	64
Best effort	1	16	32
Excellent effort	2	8	32
Video	3	8	16
Voice	4	4	16
Network Control or medical data	5	4	8
High priority medical data	6	2	8
Emergency or medical implant event report	7	1	4

#### 4. Performance Analysis

To analyze the performance of IEEE 802.15.6, we consider discrete-time Markov chain (DTMC), as shown in Figure 2 by following the well-known models given in [7,20,29,30]. We compare the analytical model that depicts the mechanism of IEEE 802.15.6 CSMA/CA under steady-state conditions. The nodes are divided into classes based on user priorities denoted by  $i$ , where  $i \in \{0, 1, 2, 3, 4, 5, 6, 7\}$  and classes are differentiated by  $CW_{min}$  and  $CW_{max}$ . The IEEE 802.15.6 MAC superframe structure consists of different access phases. For simplicity, we only assume mechanism in the Random Accesses Phase 1 (RAP1) and neglect other optional access phases. Furthermore, we assume an ideal channel in which packets subject to collisions only.

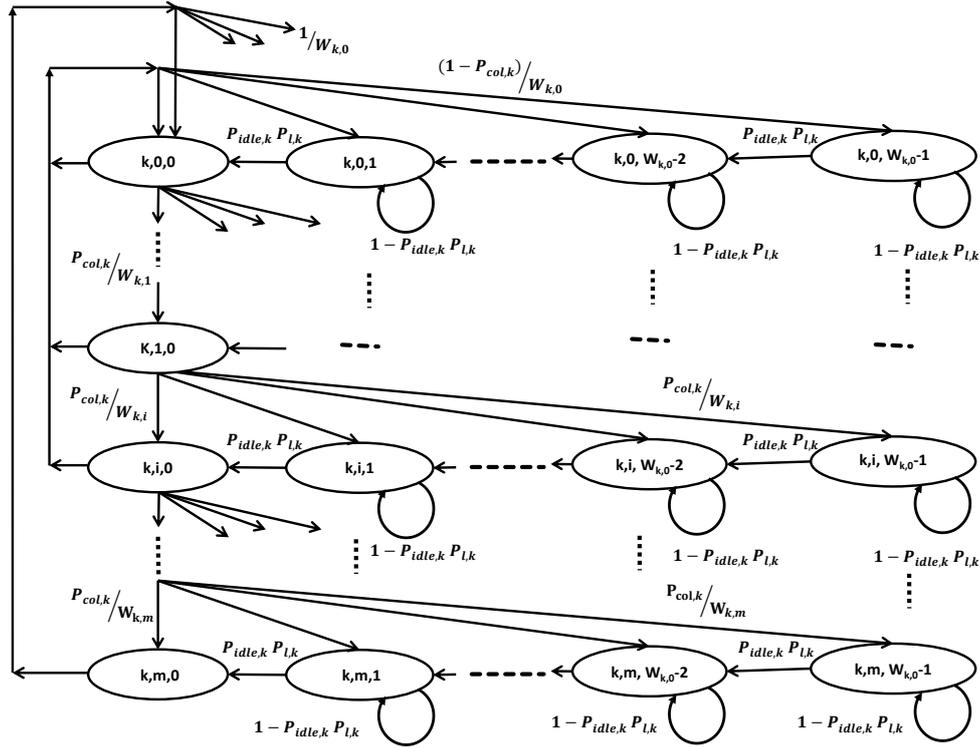


Figure 2. Markov chain model for IEEE 802.15.6 and Proposed mechanism.

The state transition probabilities of DTMC is given by:

$$\begin{aligned}
 (S1): P\{k, i, j | k, i, j + 1\} &= P_{idle,k} P_{l,k}, \\
 &0 \leq i \leq m, 0 \leq j \leq W_{k,i} - 2, \\
 (S2): P\{k, i, j | k, i - 1, 0\} &= \frac{P_{col,k}}{W_{k,i}}, \\
 &1 \leq i \leq m, 0 \leq j \leq W_{k,i} - 1, \\
 (S3): P\{k, 0, j | k, i, 0\} &= \frac{1 - P_{col,k}}{W_{k,0}}, \\
 &0 \leq i \leq m - 1, 0 \leq j \leq W_{k,i} - 1, \\
 (S4): P\{k, 0, j | k, m, 0\} &= \frac{1}{W_{k,0}}, \\
 &0 \leq j \leq W_{k,0} - 1, \\
 (S5): P\{k, i, j | k, i, j\} &= 1 - P_{idle,k} P_{l,k}, \\
 &0 \leq i \leq m, 1 \leq j \leq W_{k,i},
 \end{aligned} \tag{6}$$

where  $P_{idle,k}$ ,  $P_{l,k}$  and  $P_{col,k}$  are the probabilities and are defined as channel idle probability, there is enough time left for transmitting the frame probability and the probability of collision of the  $k$ th UP node, respectively.

Now by using the state transition probabilities, we derive the steady-state distribution  $b_{k,i,j}$  of DTMC using the following equations:

$$\begin{aligned}
 1 &= \sum_{i=0}^m \sum_{j=0}^{W_{k,i}-1} b_{k,i,j} \\
 &= \sum_{i=1}^m \sum_{j=1}^{W_{k,i}-1} b_{k,i,j} + \sum_{i=1}^m b_{k,i,0} + \sum_{j=0}^{W_{k,0}-1} b_{k,0,j},
 \end{aligned} \tag{7}$$

$$\sum_{i=1}^m b_{k,i,0} = \frac{P_{col,k}(1 - (P_{col,k})^m)}{(1 - P_{col,k})} b_{k,0,0}, \tag{8}$$

$$\sum_{j=0}^{W_{k,i}-1} b_{k,0,j} = \frac{W_{k,0} + 1}{2P_{l,k}P_{idle,k}} b_{k,0,0}. \quad (9)$$

It is known that  $\sum_{i=0}^m \sum_{j=0}^{W_{k,i}-1} b_{k,i,j} = 1$  and from Equations (7)–(9), we derive the  $b_{k,0,0}$  as:

$$b_{k,0,0} = \frac{2P_{idle,k}P_{l,k}(1-P_{col,k})}{\left\{ 2 \sum_{i=1}^m P_{col,k}^i \frac{W_{k,i}-1}{2} (1-P_{idle,k}) + 2P_{idle,k}P_{l,k}P_{col,k}(1-(P_{col,k})^m) + (1-P_{col,k})(W_{k,0}+1) + 2P_{idle,k}P_{l,k}(1-P_{col,k}) \right\}} \quad (10)$$

We define  $P_{a,k}$ , which is the channel access probability of a node with UP  $k$  as:

$$P_{a,k} = \sum_{i=0}^m b_{k,i,0} = \frac{(1 - (P_{col,k})^{m+1})}{1 - P_{col,k}} b_{k,0,0}. \quad (11)$$

Now we define several probabilities  $P_{col,k}$ ,  $P_{idle,k}$ , and  $P_{l,k}$  as:

$$P_{col,k} = 1 - (1 - P_{a,k})^{n_k-1} \prod_{i \neq k} (1 - P_{a,i})^{n_i}, \quad (12)$$

$$P_{idle,k} = \frac{\prod_{i=0}^7 (1 - P_{a,i})^{n_i}}{(1 - P_{a,k})}, \quad (13)$$

and

$$P_{l,k} = 1, \quad (14)$$

where for simplicity, we set  $P_{l,k} = 1$  in this paper, which means that there is always enough time left to transmit the frame. Equations (11)–(13) are simultaneous equations and are solved numerically to find the probabilities  $P_{a,k}$ ,  $P_{col,k}$ , and  $P_{idle,k}$ .

#### 4.1. Analytical Model of the IEEE 802.15.6

In this section, we give derived analytical results for IEEE 802.15.6 in terms of throughput, energy efficiency, and normalized average delay. For this purpose, the probability of transmission  $P_t$  and probability of success  $P_{s,k}$  of UP  $k$  are defined, respectively, as:

$$P_t = 1 - \prod_{i=0}^7 (1 - P_{a,i})^{n_i}, \quad (15)$$

$$P_{s,k} = [P_{a,k}P_{idle,k}P_{l,k}(1 - P_{a,k})^{n_k-1}] \prod_{i \neq k} (1 - P_{a,i})^{n_i}. \quad (16)$$

##### 4.1.1. Throughput

Per-node throughput with UP  $k$  is defined as the amount of data successfully transmitted per fraction of time consumed. Per-node throughput is stated as:

$$T_k = \frac{P_{s,k} \cdot L_{p,k}}{(1 - P_t)T_{slot} + P_{s,k}T_s + (1 - P_s)T_c}, \quad (17)$$

where  $P_s = \sum_{k=0}^7 n_k P_{s,k}$ ,  $L_{p,k}$  is the expected frame size excluding PHY and MAC headers and  $T_{slot}$  is the idle slot time. Also  $T_s$  and  $T_c$  are the times spent in transmitting a single frame during successful transmission and collision, respectively.

#### 4.1.2. Energy Efficiency

Energy efficiency (Joules/bit) is quite demanding in the IEEE 802.15.6-based WBANs and therefore we also derive equations for  $E_{e,k}$  (i.e., the energy efficiency of UP  $k$ ) as:

$$E_{e,k} = \frac{Pr_k}{T_k}, \quad (18)$$

where  $Pr_k$  and  $T_k$  are the power consumed and throughput of UP  $k$ , respectively.  $Pr_k$  is defined as:

$$Pr_k = \frac{E_k}{(1 - P_t)T_{slot} + P_{s,k}T_s + (1 - P_s)T_c}, \quad (19)$$

where  $E_k$  is the amount of energy consumed by UP  $k$  and defined as:

$$E_k = E_{b0,k} + E_{s,k} + E_{bs,k} + E_{c,k} + E_{bc,k}, \quad (20)$$

where  $E_k$  has five types of energies, similar to [31], and are defined as:

- $E_{b0,k}$ : The amount of energy consumed when the channel is idle. All nodes decrement their backoff counters.
- $E_{s,k}$ : The energy consumed by a node with UP  $k$  during the successful transmission of a frame.
- $E_{bs,k}$ : It is the energy consumed when a node overhears (receives) another successful transmission with a coordinator.
- $E_{c,k}$ : The amount of energy consumed during collisions and the intended node is involved.
- $E_{bc,k}$ : The energy consumed during collisions between/among background nodes (unintended).

These energies are calculated using the following equations:

$$E_{b0,k} = P_{idle,k}Pr_{idle}T_{slot}, \quad (21)$$

$$E_{s,k} = P_{s,k}Pr_{tx}T_s, \quad (22)$$

$$E_{bs,k} = P_{bs,k}Pr_{rx}T_s, \quad (23)$$

$$E_{c,k} = P_{col,k}Pr_{tx}T_c, \quad (24)$$

$$E_{bc,k} = P_{bc,col,k}Pr_{rx}T_c, \quad (25)$$

where  $Pr_{idle}$ ,  $Pr_{tx}$ , and  $Pr_{rx}$  are the powers consumed by a node during the backoff, transmission, and reception, respectively. However,  $P_{bs,k}$  and  $P_{bc,col,k}$  used in Equations (23) and (25) are probabilities of successful transmission and collisions of non-intended (background) nodes, respectively. Both probabilities are defined as:

$$P_{bs,k} = (n_k - 1) [P_{a,k}P_{idle,k}P_{l,k}(1 - P_{a,k})^{n_k - 1}] \prod_{i \neq k} (1 - P_{a,i})^{n_i}, \quad (26)$$

$$P_{bc,col,k} = (1 - P_s)P_t - P_{col,k}. \quad (27)$$

#### 4.1.3. Normalized Average Delay

The normalized average delay is defined as the fraction of time a node spent in decrementing the backoff counter, waiting for a channel to be idle, and time spent in collisions. Thus, we define the normalized average delay as:

$$D_k = 1 - U_k, \quad (28)$$

where  $U_k$  is the use of the channel by a node with UP  $k$  defined as:

$$U_k = \frac{P_{s,k} \cdot T_s}{(1 - P_t) T_{slot} + P_{s,k} T_s + (1 - P_s) T_c} \quad (29)$$

#### 4.2. Analytical Model for the Proposed Mechanism

To develop the analytical model for the proposed mechanism, we assume that nodes belong to the highest UP( $h$ ) only compete in contention with nodes with the highest priority. However, the node of second highest UP ( $s$ ) competes with nodes belong to that UP and with nodes belong to UP  $h$ . If two nodes win the contention (backoff counter reaches zero at the same backoff slot), then the node with higher UP is allowed to transmit due to lower CCA time. In addition, the node with lower UP makes the channel busy due to higher CCA time and goes to the backoff procedure following the ABEB. Hence, the channel access probability defined by Equation (11) remains the same. However, the probability of collision and channel idle probability is given by:

$$P_{col,k,prop} = 1 - (1 - P_{a,k})^{n_k - 1} \prod_{i \neq k, i > k} (1 - P_{a,i})^{n_i}, \quad (30)$$

$$P_{idle,k,prop} = \frac{\prod_{i=k}^7 (1 - P_{a,i})^{n_i}}{(1 - P_{a,k})}, \quad (31)$$

As Equations (11) and (14) remain the same for the proposed mechanism. Now, one can solve Equations (11), (14), (30) and (31) simultaneously using numerical methods for the proposed mechanism.

Similarly, the probability of backoff  $P_{b,k}$  and the probability of success  $P_{s,k,prop}$  of each UP are given by:

$$P_{b,k} = \prod_{i=k}^7 (1 - P_{a,i})^{n_i}, \quad (32)$$

$$P_{s,k,prop} = [P_{a,k} P_{idle,k,prop} P_{l,k} (1 - P_{a,k})^{n_k - 1}] \prod_{i > k} (1 - P_{a,i})^{n_i}. \quad (33)$$

##### 4.2.1. Throughput

Throughput for the proposed mechanism is defined as the number of bits sent within a time unit spent in success, collision, or backoff for transmitting a single frame. The proposed mechanism's throughput ( $T_{k,prop}$ ) is given as:

$$T_{k,prop} = \frac{P_{s,k} \cdot L_{p,k}}{P_{b,k} T_{slot} + \sum_{i=k}^7 n_i P_{s,i,prop} T_s + \sum_{i=k}^7 n_i P_{coll,i,prop} T_c} \quad (34)$$

##### 4.2.2. Energy Efficiency

$$E_{e,k,prop} = \frac{Pr_{k,prop}}{T_{k,prop}}, \quad (35)$$

where  $Pr_{k,prop}$  and  $T_{k,prop}$  are the power consumed and throughput of UP  $k$  in the proposed mechanism, respectively.  $Pr_{k,prop}$  is defined as

$$Pr_{k,prop} = \frac{E_{k,prop}}{P_{b,k} T_{slot} + \sum_{i=k}^7 n_i P_{s,i,prop} T_s + \sum_{i=k}^7 n_i P_{coll,i,prop} T_c}, \quad (36)$$

where  $E_{k,prop}$  is the amount of energy consumed by UP  $k$  in the proposed mechanism and defined as:

$$E_{k,prop} = E_{bo,k,prop} + E_{s,k,prop} + E_{bs,k,prop} + E_{c,k,prop} + E_{bcoll,k,prop}, \quad (37)$$

where  $E_{k,prop}$  has five types of energies, as defined in Section 4.1.2. Hence, these energies are calculated using the following equations:

$$E_{bo,k,prop} = P_{b,k}Pr_{idle}T_{slot}, \quad (38)$$

$$E_{s,k,prop} = P_{s,k,prop}Pr_{tx}T_s, \quad (39)$$

$$E_{bs,k,prop} = P_{bs,k,prop}Pr_{rx}T_s, \quad (40)$$

$$E_{c,k,prop} = P_{col,k,prop}Pr_{tx}T_c, \quad (41)$$

$$E_{bcoll,k,prop} = P_{bcoll,k,prop}Pr_{rx}T_c, \quad (42)$$

whereas  $P_{bs,k,prop}$  and  $P_{bcoll,k,prop}$  used in Equations (40) and (42) are the probabilities of successful transmission and collisions of non-intended (background) nodes, respectively. Both probabilities are defined as:

$$P_{bs,k,prop} = (n_k - 1) [P_{a,k}P_{idle,k,prop}P_{l,k}(1 - P_{a,k})^{n_k-1}] \prod_{i>k} (1 - P_{a,i})^{n_i}, \quad (43)$$

$$P_{bc,k,prop} = (1 - P_{s,prop}) - P_{col,k,prop}, \quad (44)$$

where  $P_{s,prop} = \sum_{k=0}^7 n_k P_{s,k,prop}$ .

## 5. Results and Discussion

In this section, we present the validation of the proposed analytical model given in Section 4 compared to the simulation results presented in this section. In addition, we evaluated and compared the performance of the proposed mechanism with the IEEE 802.15.6 in terms of throughput, energy efficiency, and normalized average delay via extensive simulations.

### 5.1. Simulation Configuration

We developed simulations in MATLAB, considering the IEEE 802.15.6 MAC/PHY layers evaluation methodology. The simulation parameters that are used in this study are listed in Table 2. In the evaluation, we assumed the steady-state condition, i.e., every node always had data to send and every node had the same and fixed transmission rate.

**Table 2.** Parameters used in performance evaluation and comparison.

Parameters	Values	Parameter	Values
Payload size ( $L_{p,k}$ )	100 bytes	Data Rate	151.8 kbps
$T_s$	0.0069 s	$T_c$	0.0064 s
$Pr_{idle}$	267 $\mu$ W	$Pr_{tx}$	414 $\mu$ W
$Pr_{rx}$	393 $\mu$ W	$T_{SIFS}$	75 $\mu$ s
$\rho CCATime(\psi)$	252 $\mu$ s	$\rho CSMAMACPHYTime(\alpha)$	40 $\mu$ s
Slot time ( $T_{slot}$ )	292 $\mu$ s		

We considered the following scenarios for performance analysis.

- **Scenario 1:** There are three UPs (UP0, UP6, and UP7) and each UP has varying number of nodes, i.e.,  $n = 2, 3,$  and  $4$ . The value of performance factor  $\beta = 1$ .
- **Scenario 2:** There are 8 UP nodes and each UP has a single node and  $\beta = 1$ .

- **Scenario 3:** There are 8 UP nodes and each UP has a single node; however, we vary the performance factor  $\beta$  from 1 to 8.

Furthermore, we examine the performance in terms of throughput, energy efficiency, and normalized average delay with validation of the analytical model and comparisons averaged for 30 instances of simulations.

### 5.2. Analysis Validation

To validate the analytical model, we match the simulation results with the analytical results for both IEEE 802.15.6 and the proposed mechanism. Table 3 presents the analytical and simulation results of the IEEE 802.15.6 for Scenario 1. The analytical results are compared with simulation results using three parameters: throughput, energy efficiency, and normalized average delay, where all parameters are computed using Equations (17), (18) and (28), respectively. We also compute the relative difference between the analysis and simulation results given by:

$$\epsilon = \frac{| \text{AnalyticalResults} - \text{SimulationResults} |}{\text{AnalyticalResults}} \tag{45}$$

Table 3 shows the precision of analytical models, i.e., throughput, energy efficiency, and normalized average delay, obtained from simulations closely match with that attained from the analysis. For UP 0 and  $n = 2$ , throughput, energy efficiency, and normalized average delay for simulations and analysis results are equal to 2.532 kbps, 0.155  $\mu$  J/bit, 0.978, 2.502 kbps, 0.138  $\mu$  J/bit, and 0.978, respectively. Their  $\epsilon$  is equal to 0.012, 0.109, and 0.001, which is a small value. Hence, these results affirm the rationality of the analytical model for the IEEE 802.15.6 as there is a trivial difference between the values of simulations and analysis results.

Table 4 compares the analytical and simulation results of the proposed mechanism. We validate the analysis model of the proposed mechanism by observing the throughput, energy efficiency, and normalized average delay is given in Equations (34), (35) and (28) respectively. Similar to IEEE 802.15.6’s analysis results, the validation results are computed for Scenario 1. For UP 7 and  $n = 4$ , throughput, energy efficiency, and normalized average delay for simulation results are equal to 13.866 kbps, 0.028  $\mu$  J/bit, and 0.880, respectively. These results closely match the analysis results with  $\epsilon$  equal to 0.061, 0.026, and 0.009 for the three performance matrices. These results confirm the accuracy of the analytical model as there is a negligible difference between the simulation and analysis results.

**Table 3.** Comparison of simulation and analytical results for IEEE 802.15.6.

		IEEE 802.15.6 MAC								
		Throughput (Kbits/s)			Energy Efficiency ( $\mu$ J/bit)			Delay (Fraction)		
No. of nodes		n = 2	n = 3	n = 4	n = 2	n = 3	n = 4	n = 2	n = 3	n = 4
UP 0	Simulation	2.532	1.370	0.856	0.155	0.287	0.459	0.978	0.988	0.992
	Analysis	2.502	1.393	0.926	0.138	0.267	0.412	0.978	0.988	0.992
	$\epsilon$	0.012	0.017	0.082	0.109	0.070	0.103	0.001	0.000	0.000
UP 6	Simulation	10.207	5.461	3.382	0.039	0.073	0.117	0.910	0.952	0.970
	Analysis	10.143	5.588	3.674	0.037	0.070	0.107	0.913	0.952	0.968
	$\epsilon$	0.006	0.023	0.086	0.047	0.040	0.084	0.002	0.000	0.002
UP 7	Simulation	20.381	10.917	6.653	0.020	0.037	0.060	0.822	0.905	0.941
	Analysis	19.845	11.000	7.184	0.021	0.037	0.057	0.829	0.905	0.938
	$\epsilon$	0.026	0.008	0.080	0.061	0.025	0.046	0.008	0.000	0.004

**Table 4.** Comparison of simulation and analytical results for the proposed mechanism.

		Proposed Mechanism								
		Throughput (Kbits/s)			Energy Efficiency ( $\mu$ J/bit)			Delay (Fraction)		
No. of nodes		n = 2	n = 3	n = 4	n = 2	n = 3	n = 4	n = 2	n = 3	n = 4
UP 0	Simulation	2.025	1.350	1.000	0.193	0.288	0.388	0.983	0.988	0.991
	Analysis	2.302	1.266	0.882	0.198	0.302	0.406	0.980	0.989	0.992
$\epsilon$		0.137	0.062	0.117	0.030	0.048	0.048	0.002	0.001	0.001
UP 6	Simulation	9.179	5.782	4.105	0.043	0.067	0.095	0.921	0.950	0.965
	Analysis	9.344	4.889	3.256	0.040	0.062	0.085	0.919	0.958	0.972
$\epsilon$		0.018	0.154	0.207	0.061	0.082	0.099	0.001	0.008	0.008
UP 7	Simulation	33.927	20.003	13.866	0.012	0.020	0.028	0.707	0.827	0.880
	Analysis	33.136	18.856	13.017	0.014	0.021	0.029	0.714	0.837	0.888
$\epsilon$		0.023	0.057	0.061	0.209	0.082	0.026	0.011	0.012	0.009

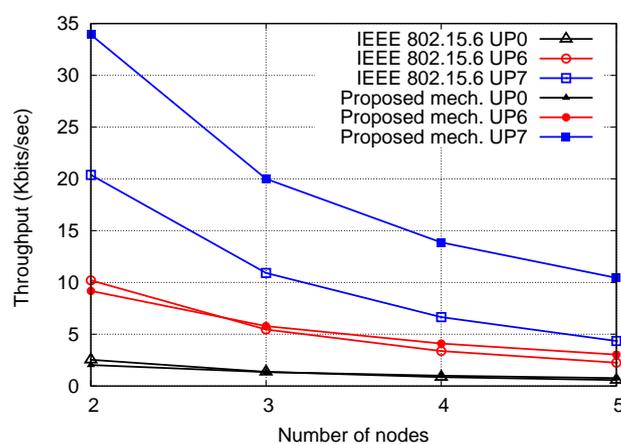
Tables 3 and 4 confirms the validity of our analytical model for both IEEE 802.15.6 standard and proposed mechanism. The analysis results of three performance parameters throughput, energy efficiency, and delay closely match with simulation results.

### 5.3. Performance Comparison

In this section, we compare the performance of the proposed mechanism with IEEE 802.15.6 for different scenarios via simulations.

#### 5.3.1. Throughput

Figures 3 and 4 show the throughput of IEEE 802.15.6 and proposed mechanism for Scenario 1 and Scenario 2, respectively. In Figure 3, the throughput of all mechanisms decreases with the number of nodes due to the increase in contention and channel shared among the increasing number of nodes. For UP 7, the throughput of the proposed mechanism is improved by 1.66 to 2.08 times for varying the number of nodes. The outstanding performance of the proposed mechanism is due to avoiding retransmissions for higher priority nodes. The proposed mechanism avoids collisions among different UPs by employing a differentiated  $\rho CCATime$  and a proactive approach to reduce contention between nodes with a similar UP. However, for the lower priority nodes, the proposed mechanism performs similar to the IEEE 802.15.6 standard. The rationale behind this performance is when the backoff counter of two different priority nodes become zero at the same time, the node with higher priority has a better chance to access the channel while the lower priority one follows the backoff process using ABEB.



**Figure 3.** Throughput comparison of IEEE 802.15.6 and proposed mechanism for different UP.

Figure 4 shows the throughput of IEEE 802.15.6 and the proposed scheme for Scenario 2. It is obvious from Figure 4 that a higher priority node has higher throughput as compared to a lower priority one. For the proposed mechanism, nodes with different UPs with the same minimum CW achieve similar throughput, which confirms that there is no collision between nodes with different UPs. It is important to note that the throughput of UP 0 for IEEE 802.15.6 is 0.70 kbps, which means that the node with UP 0 almost starves in the presence of all other UP nodes. However, for the proposed mechanism, the UP 0 node has throughput 4.16 kbps. The percentage increase in the proposed mechanism as compared to IEEE 802.15.6 for UP 0 and UP 7 is 492% and 41%, respectively. Hence, the throughput is improved due to collision reductions among UPs and within the same UP.

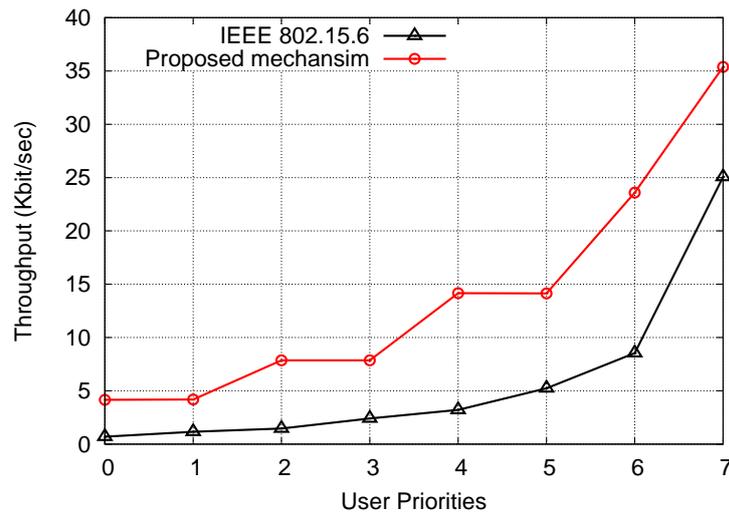


Figure 4. Throughput comparison of IEEE 802.15.6 and proposed mechanism for different UP (Scenario 2).

### 5.3.2. Energy Efficiency

In this section, we compare the energy efficiency (J/bit) of the proposed mechanism with that of the IEEE 802.15.6 for different scenarios. Figure 5 shows the energy efficiency of the proposed mechanism and IEEE 802.15 for Scenario 1. For both mechanisms, when increasing the number of nodes, the energy efficiency increases as throughput decreases. The throughput decreases due to the increase in the collision probability. In addition, the energy efficiency of lower UP is greater than that of higher priority as a lower priority node receives less channel access and hence lower throughput resulting in an increase in energy efficiency. The energy efficiency for UP 0 of IEEE 802.15.6 standard when  $n = 2, 3,$  and  $4$  is equal to  $0.155 \mu\text{ J/bit}, 0.287 \mu\text{ J/bit},$  and  $0.459 \mu\text{ J/bit}$ , respectively. However, the same for the proposed mechanism is  $0.193 \mu\text{ J/bit}, 0.288 \mu\text{ J/bit},$  and  $0.388 \mu\text{ J/bit}$ . Except for  $n = 4$ , IEEE 802.15.6 has slightly better energy efficiency. Furthermore, for UP 6 and 7, the proposed mechanism has lower energy efficiency as compared to IEEE 802.15.6. This is the case as the proposed mechanism reduces heterogeneous and homogeneous collisions.

Figure 6 shows the energy efficiency for the proposed mechanism and IEEE 802.15.6 standard for Scenario 2. We can see from the figure that a lower priority node has higher energy efficiency, and a higher priority node has lower energy efficiency. This is due to the fact that a lower priority node sends fewer bits and due to the contention process. Also, we can see that the energy efficiency of every UP in the case of the proposed mechanism is decreased as compared to the IEEE 802.15.6 standard. For all UPs, on average, the energy efficiency decreases by 3.75 times due to collision avoidance in the proposed mechanism.

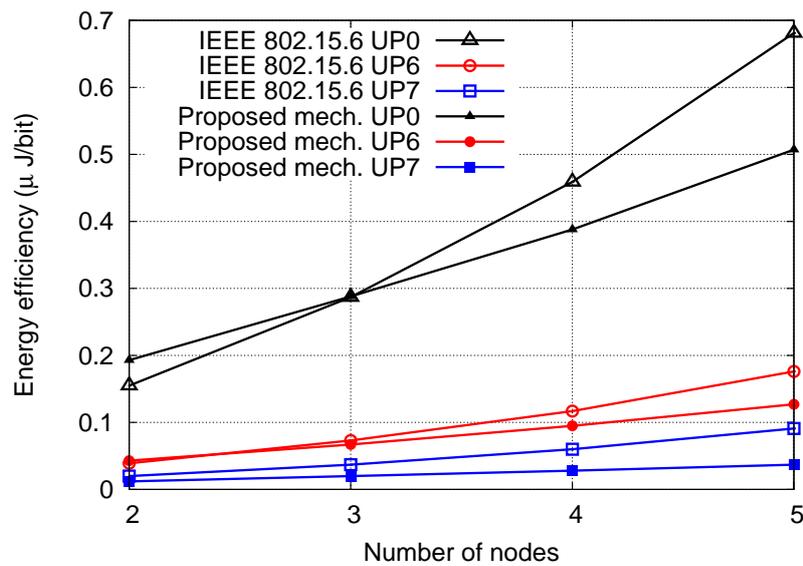


Figure 5. Energy efficiency comparison of IEEE 802.15.6 and proposed mechanism for different UP.

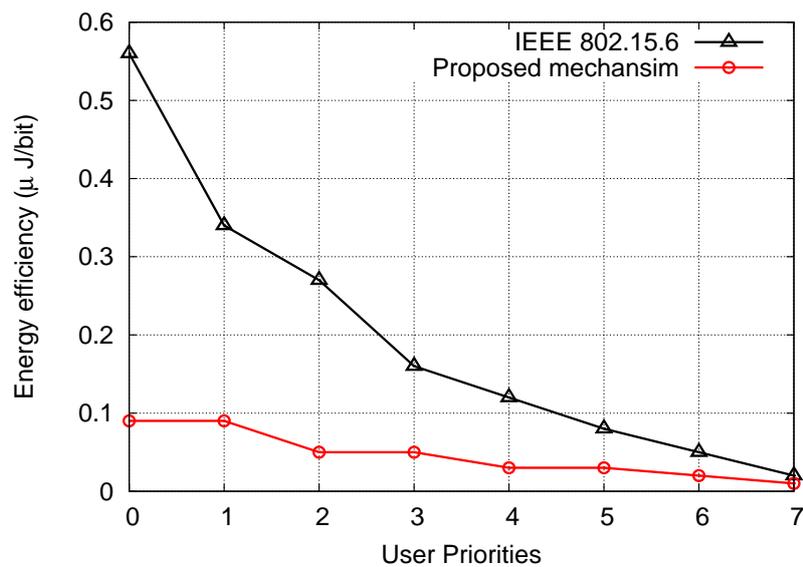


Figure 6. Energy efficiency comparison of IEEE 802.15.6 and proposed mechanism for different UP (Scenario 2).

### 5.3.3. Normalized Average Delay

In this section, we discuss results obtained for normalized average delay. Normalized average delay is the fraction of time spent in the backoff procedure, collision, and waiting for channel to be idle.

Figure 7 shows the normalized average delay for Scenario 1. It is obvious from the figure that with the increase in the number of nodes, the normalized average delay increases, which is due to an increase in the contention. For UP 0 and 6, the proposed mechanism is almost similar to the IEEE 802.15.6. However, for UP 7, the normalized average delay is decreased by 0.05 to 0.1. We give more chances to high UP nodes in the proposed mechanism to avoid collisions. Secondly, we also increase the value of minimum CW with the number of nodes.

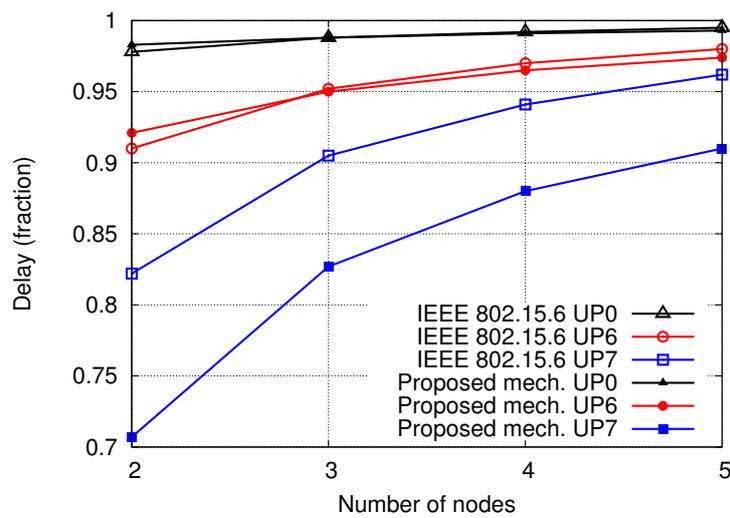


Figure 7. Delay comparison of IEEE 802.15.6 and proposed mechanism for different UP.

Figure 8 shows the normalized average delay for the proposed mechanism and IEEE 802.15.6 following Scenario 2. It is important to note that for the proposed mechanism, some UPs have the same normalized average delay because they have similar minimum CW. In addition, in the proposed mechanism, there is no collision among/between nodes of different UPs. Also, for all UPs, the proposed mechanism has better performance than the IEEE 802.15.6 standard.

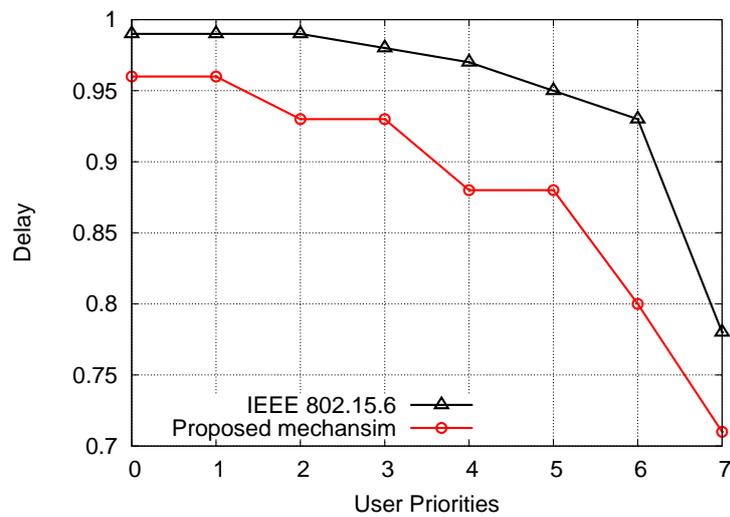


Figure 8. Delay comparison of IEEE 802.15.6 and proposed mechanism for different UP (Scenario 2).

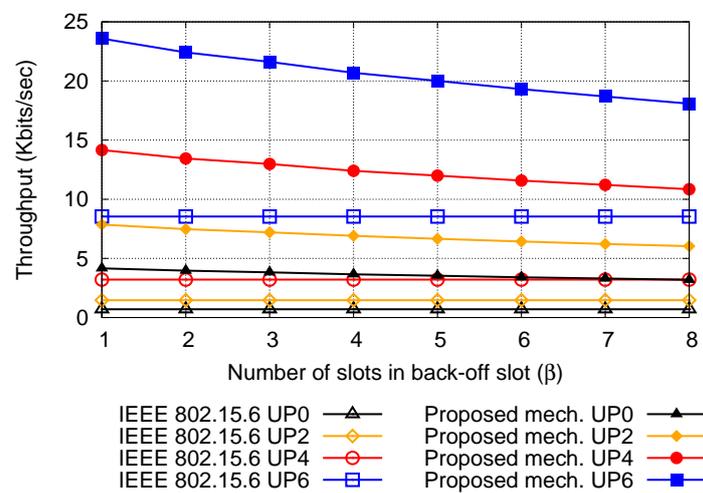
The proposed mechanism outperforms the IEEE 802.15.6 standard in terms of throughput, energy efficiency, and delay. The outstanding performance stems from the fact that the proposed mechanism avoids collision between/among nodes with different UPs by assigning different  $\rho CCATime$ . Also, the collision between/among nodes with the same UPs is reduced by scaling minimum CW with the number of nodes in that UP.

#### 5.4. Effects of $\beta$ on the Performance

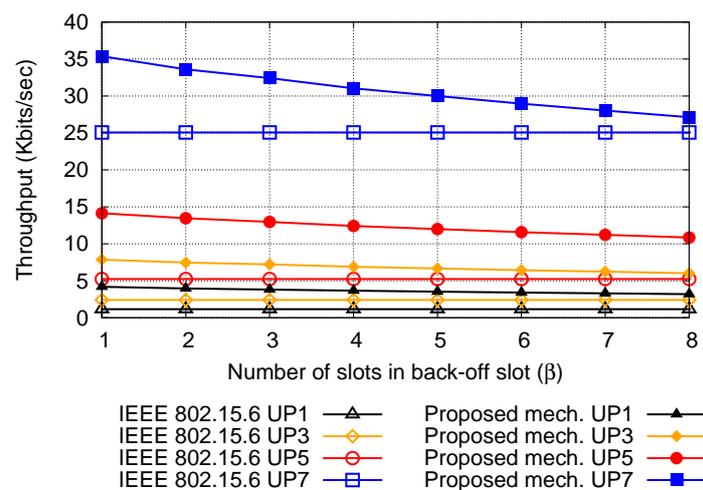
As given in Equations (1) and (2),  $\beta \geq 1$  is a scaling factor of the backoff slots. As the value of  $\beta$  increases, the performance gain decreases because more time will be wasted in the backoff. However,

smaller values of  $\beta$  reduce  $\rho_{CCATime}$  and  $\rho_{CSMAMACPHYTime}$ , which may lead to a failure in sensing the state of the channel. Thus,  $\beta$  can be used to tune the trade-off between performance gain and time for sensing the state of the channel. In this research work, we did not address the trade-off between the performance and sensing time, which will be considered part of our future work. Due to the available facts, we suggest setting the value of  $\beta$  between one and three. To further investigate this fact, we present the results in terms of throughput, energy efficiency, and normalized average delay for different values of  $\beta$ .

Figure 9 shows the throughput for the value of  $\beta$  ranges from 1 to 8 for 3. As we know in Scenario 3, we have a node from every UP; however, for a better presentation of the results, we show the results in two figures. As we can see, the performance gain of the proposed scheme decreases as we increase the value of  $\beta$ , but still, it is better than the IEEE 802.15.6 standard. For UP 6 and UP 7, the throughput is equal to 8.54 kbps and 25.07 kbps for IEEE 802.15.6, and on the other hand, for these two UPs, the throughput of the proposed mechanism for  $\beta = 1$  is 23.59 kbps and 35.38 kbps, respectively, and for  $\beta = 8$  is equal to 18.08 kbps and 27.13 kbps, respectively. We can see that there is a significant gain for both small and large values of  $\beta$ .



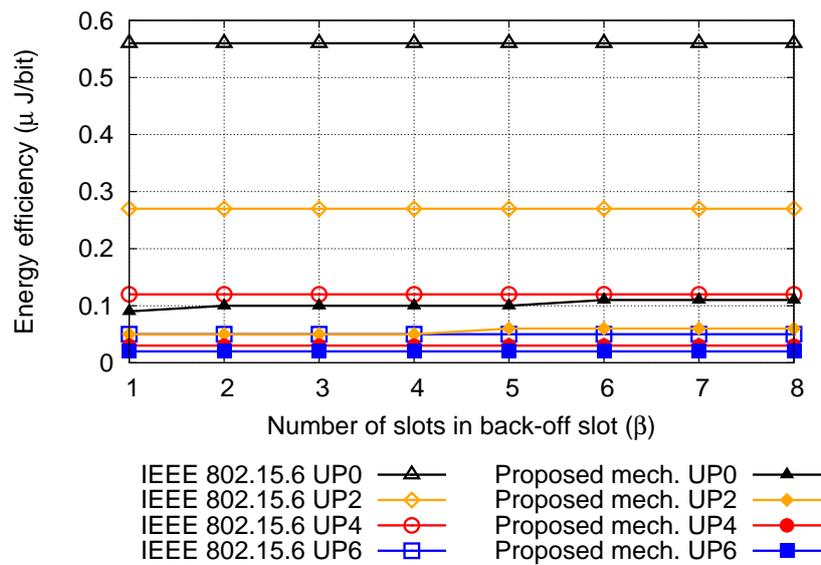
(a)



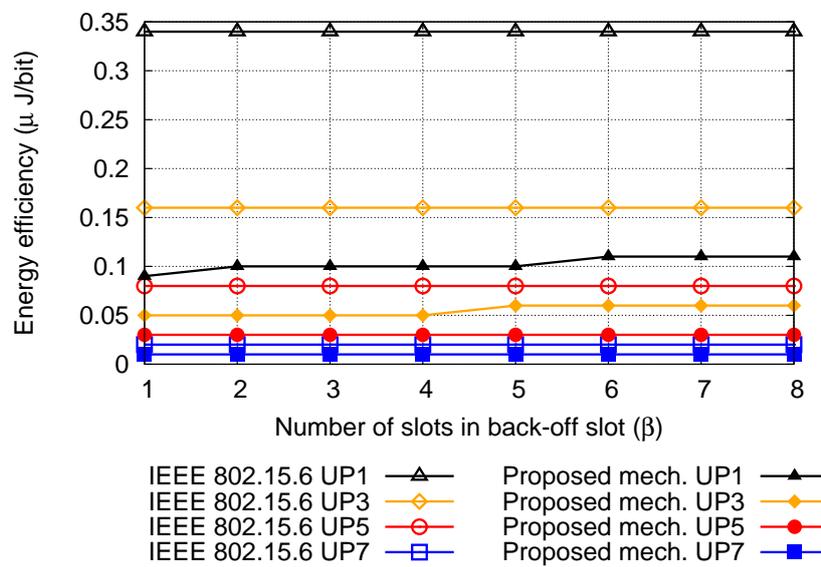
(b)

**Figure 9.** Throughput comparison of IEEE 802.15.6 and proposed mechanism for different UP (Scenario 2). (a) Throughput comparison for UP 0, 2, 4, and 6; (b) throughput comparison for UP 1, 3, 5, and 7.

Figure 10 shows the energy efficiency of the proposed mechanism and IEEE 802.15.6 by varying the performance parameter  $\beta$ . There are 8 UP nodes, thus, we split the results into two figures (i.e., Figure 10a,b). The relative gain decreases as we increase  $\beta$ . However, for all UPs and smaller values of  $\beta$ , the proposed mechanism has better performance. For UP 6, 7, and  $\beta = 2$ , the energy efficiency of the proposed mechanism is  $0.02 \mu\text{ J/bit}$  and  $0.01 \mu\text{ J/bit}$ , respectively. However, IEEE 802.15.6 has the energy efficiency  $0.05 \mu\text{ J/bit}$  and  $0.02 \mu\text{ J/bit}$ , which is at least 2 times greater than the proposed mechanism. Hence, similar to the throughput, in case of energy efficiency, the proposed mechanism outperforms IEEE 802.15.6 because in the proposed mechanism, we vary the minimum CW with the number of nodes and avoid inter UP nodes' collisions.



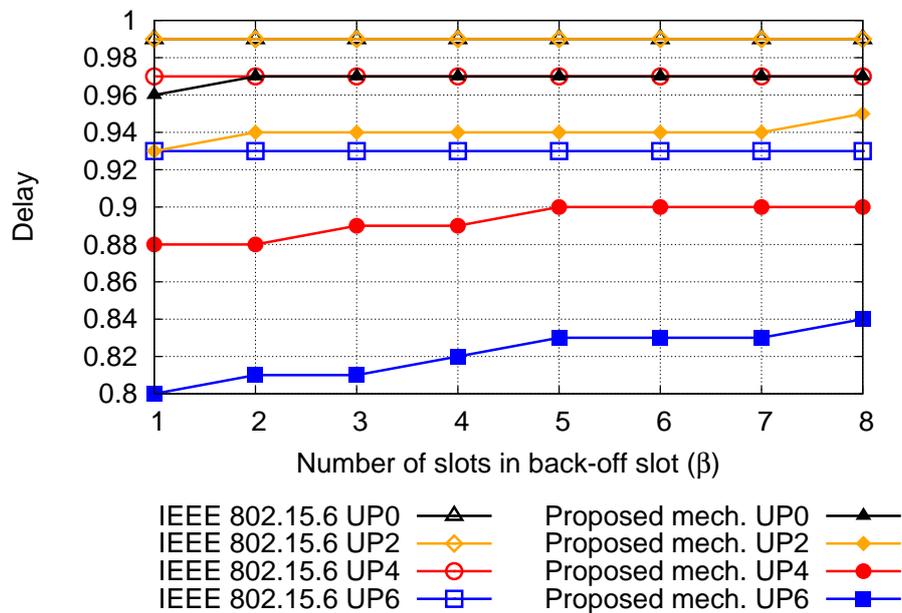
(a)



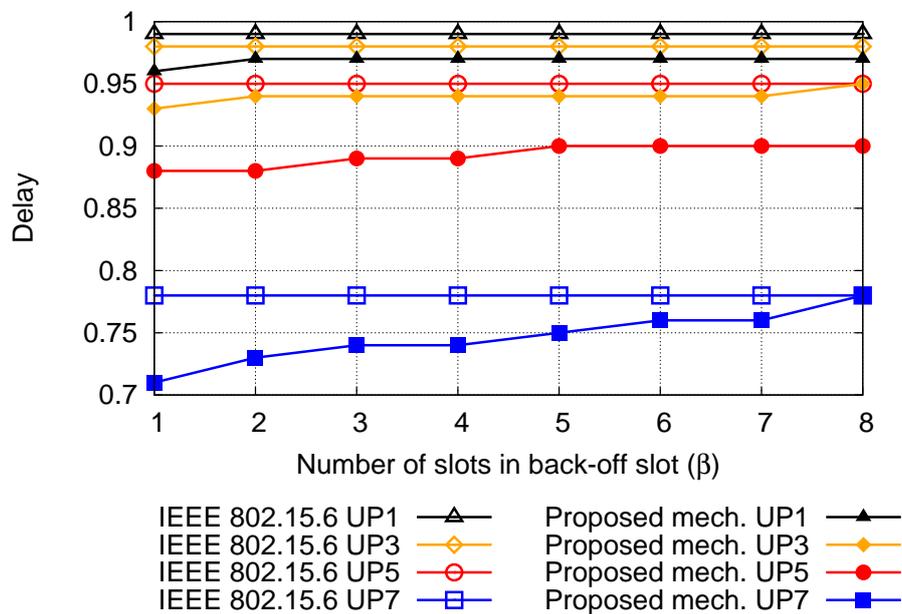
(b)

**Figure 10.** Energy efficiency comparison of IEEE 802.15.6 and proposed mechanism for different UP (Scenario 3). (a) Energy efficiency comparison for UP 0, 2, 4, and 6; (b) energy efficiency comparison for UP 1, 3, 5, and 7.

Figure 11 depicts the delay of the proposed mechanism and IEEE 802.15.6 standard by varying performance parameter  $\beta$ . It is evident from the results that the proposed mechanism has better performance as compared to the IEEE 802.15.6 standard in terms of delay. Figures 9–11 shows the effect of  $\beta$  on throughput, energy efficiency and delay, respectively. Based on these results we recommend  $\beta$  value ranges from one to three.



(a)



(b)

**Figure 11.** Delay comparison of IEEE 802.15.6 and proposed mechanism for different UP (Scenario 3). (a) Delay comparison for UP 0, 2, 4, and 6; (b) delay comparison for UP 1, 3, 5, and 7.

## 6. Conclusions

In this paper, we focused on the issue of energy efficiency, throughput degradation, and network delay due to collisions in IEEE 802.15.6-based WBAN. We categorize collisions into two categories: collision among the same UP and collisions between different UPs. To resolve the problem, we suggested a novel mechanism, which consists of two parts. First, we presented differentiated channel access mechanisms by introducing different  $\rho CCATime$  for different UPs, which reduce collisions between the nodes with different UPs. Secondly, to reduce the collision between nodes of the same UP, we scaled the minimum CW with varying number of nodes in that UP. Therefore, the proposed mechanism improves energy efficiency, increases throughput, and reduce delay. An analytical model was derived, and to validate its results, we compared them with simulations results. We compared the proposed mechanism with the IEEE 802.15.6 standard to confirm its outstanding performance in terms of energy per bit, throughput, and delay.

**Author Contributions:** This work was analyzed, designed, and implemented by M.A. F.S. supervised and validated the work, and as the principal investigator, provided technical guidance and funding acquisition. K.S., co-investigator, validated the work and provided technical guidance. M.A.-H. reviewed the analytical work and performance evaluations. M.A. wrote the original draft of the paper, F.S. and K.S. proofread, and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the United Arab Emirates University grant number 31T078.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Ray, P.P. A survey on Internet of Things architectures. *J. King Saud Univ. Comput. Inf. Sci.* **2016**, *30*, 291–319. [[CrossRef](#)]
2. Lee, S.K.; Bae, M.; Kim, H. Future of IoT networks: A survey. *Appl. Sci.* **2017**, *7*, 1072. [[CrossRef](#)]
3. Al-Fuqaha, A.; Guizani, M.; Mohammadi, M.; Aledhari, M.; Ayyash, M. Internet of things: A survey on enabling technologies, protocols, and applications. *IEEE Commun. Surv. Tutor.* **2015**, *17*, 2347–2376. [[CrossRef](#)]
4. Alwan, A. *Global Status Report on Noncommunicable Diseases 2010*; World Health Organization: Geneva, Switzerland, 2011.
5. Movassaghi, S.; Abolhasan, M.; Lipman, J.; Smith, D.; Jamalipour, A. Wireless body area networks: A survey. *IEEE Commun. Surv. Tutor.* **2014**, *16*, 1658–1686. [[CrossRef](#)]
6. Association, I.S. IEEE Standard for Local and Metropolitan Area Networks—Part 15.6: Wireless Body Area Networks. *IEEE Stand. Inf. Technol.* **2012**, *802*, 1–271. Available online: <https://ieeexplore.ieee.org/document/6161600/> (accessed on 24 August 2018).
7. Rashwand, S.; Mišić, J.; Khazaei, H. IEEE 802.15.6 under saturation: Some problems to be expected. *J. Commun. Netw.* **2011**, *13*, 142–148. [[CrossRef](#)]
8. Fang, G.; Dutkiewicz, E. BodyMAC: Energy efficient TDMA-based MAC protocol for wireless body area networks. In Proceedings of the 2009 9th International Symposium on Communications and Information Technology, Icheon, Korea, 28–30 September 2009; pp. 1455–1459.
9. Khan, P.; Ullah, N.; Alam, M.N.; Kwak, K.S. Performance analysis of WBAN MAC protocol under different access periods. *Int. J. Distrib. Sens. Netw.* **2015**, *11*, 102052. [[CrossRef](#)]
10. Ullah, S.; Hassan, M.M.; Hossain, M.S.; Alelaiwi, A. Performance Evaluation of RTS/CTS Scheme in Beacon-Enabled IEEE 802.15.6 MAC Protocol for Wireless Body Area Networks. *Sensors* **2020**, *20*, 2368. [[CrossRef](#)]
11. Ullah, S.; Mohaisen, M.; Alnuem, M.A. A review of IEEE 802.15.6 MAC, PHY, and security specifications. *Int. J. Distrib. Sens. Netw.* **2013**, *9*, 950704. [[CrossRef](#)]
12. Marinkovic, S.; Spagnol, C.; Popovici, E. Energy-efficient TDMA-based MAC protocol for wireless body area networks. In Proceedings of the 2009 IEEE Third International Conference on Sensor Technologies and Applications, Athens, Greece, 18–23 June 2009; pp. 604–609.
13. Goyal, R.; Bhadauria, H.; Patel, R.; Prasad, D. TDMA based delay sensitive and energy efficient protocol for WBAN. *J. Eng. Sci. Technol.* **2017**, *12*, 1067–1080.

14. Ullah, F.; Abdullah, A.H.; Kaiwartya, O.; Kumar, S.; Arshad, M.M. Medium Access Control (MAC) for Wireless Body Area Network (WBAN): Superframe structure, multiple access technique, taxonomy, and challenges. *Human-Centric Comput. Inf. Sci.* **2017**, *7*, 34. [[CrossRef](#)]
15. Wang, R.; Wang, H.; Roman, H.E.; Wang, Y.; Xu, D. A cooperative medium access control protocol for mobile clusters in wireless body area networks. In Proceedings of the 2013 First International Symposium on Future Information and Communication Technologies for Ubiquitous HealthCare (Ubi-HealthTech), Jinhua, China, 1–3 July 2013; pp. 1–4.
16. Shakir, M.; Rehman, O.U.; Rahim, M.; Alrajeh, N.; Khan, Z.A.; Khan, M.A.; Niaz, I.A.; Javaid, N. Performance Optimization of Priority Assisted CSMA/CA Mechanism of 802.15.6 under Saturation Regime. *Sensors* **2016**, *16*, 1421. [[CrossRef](#)] [[PubMed](#)]
17. Moulik, S.; Misra, S.; Chakraborty, C.; Obaidat, M.S. Prioritized payload tuning mechanism for wireless body area network-based healthcare systems. In Proceedings of the 2014 IEEE Global Communications Conference (GLOBECOM), Austin, TX, USA, 8–12 December 2014; pp. 2393–2398.
18. Jacob, A.K.; Jacob, L. Energy efficient MAC for QoS traffic in wireless body area network. *Int. J. Distrib. Sens. Netw.* **2015**, *11*, 404182. [[CrossRef](#)]
19. Zhou, J.; Guo, A.; T Nguyen, H.; Su, S. Intelligent management of multiple access schemes in wireless body area network. *J. Netw.* **2015**, *10*, 108–116. [[CrossRef](#)]
20. Khan, P.; Ullah, N.; Ali, F.; Ullah, S.; Hong, Y.S.; Lee, K.Y.; Kim, H. Performance analysis of different backoff algorithms for WBAN-based emerging sensor networks. *Sensors* **2017**, *17*, 492. [[CrossRef](#)]
21. Manna, T.; Misra, I.S. Implementation of energy efficient WBAN using IEEE 802.15.6 scheduled access MAC for e-healthcare. In Proceedings of the 2018 IEEE 10th International Conference on Communication Systems & Networks (COMSNETS), Bengaluru, India, 3–7 January 2018; pp. 267–274.
22. Manna, T.; Misra, I.S. Performance analysis of scheduled access mode of the IEEE 802.15.6 MAC protocol under non-ideal channel conditions. *IEEE Trans. Mob. Comput.* **2019**, *19*, 935–953. [[CrossRef](#)]
23. Sultana, N.; Huq, F.; Razzaque, M.A.; Rahman, M.M. Prioritized IEEE 802.15.6 MAC Protocol for Wireless Body Area Network. In Proceedings of the IEEE 2019 International Conference on Sustainable Technologies for Industry 4.0 (STI), Dhaka, Bangladesh, 24–25 December 2019; pp. 1–5.
24. Saboor, A.; Ahmad, R.; Ahmed, W.; Kiani, A.K.; Alam, M.M.; Kuusik, A.; Le Moullec, Y. Dynamic Slot Allocation using Non Overlapping Backoff Algorithm in IEEE 802.15.6 WBAN. *IEEE Sens. J.* **2020**. [[CrossRef](#)]
25. Benmansour, T.; Ahmed, T.; Moussaoui, S.; Doukha, Z. Performance analyses of the IEEE 802.15.6 wireless body area network with heterogeneous traffic. *J. Netw. Comput. Appl.* **2020**, *163*, 102651. [[CrossRef](#)]
26. Kim, B.S.; Sung, T.E.; Kim, K.I. An NS-3 Implementation and Experimental Performance Analysis of IEEE 802.15.6 Standard under Different Deployment Scenarios. *Int. J. Environ. Res. Public Health* **2020**, *17*, 4007. [[CrossRef](#)]
27. Cali, F.; Conti, M.; Gregori, E. Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit. *IEEE/ACM Trans. Netw.* **2000**, *8*, 785–799. [[CrossRef](#)]
28. Syed, I.; Shin, S.H.; Roh, B.H.; Adnan, M. Performance Improvement of QoS-Enabled WLANs Using Adaptive Contention Window Backoff Algorithm. *IEEE Syst. J.* **2017**, *12*, 3260–3270. [[CrossRef](#)]
29. Jung, B.H.; Akbar, R.U.; Sung, D.K. Throughput, energy consumption, and energy efficiency of IEEE 802.15.6 body area network (BAN) MAC protocol. In Proceedings of the 2012 IEEE 23rd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), Sydney, NSW, Australia, 9–12 September 2012; pp. 584–589.
30. Adnan, M.; Park, E.C. Hybrid control of contention window and frame aggregation for performance enhancement in multirate WLANs. *Mob. Inf. Syst.* **2015**, *2015*, 383081. [[CrossRef](#)]
31. Adnan, M.; Park, E.C. Improving Energy Efficiency in Idle Listening of IEEE 802.11 WLANs. *Mob. Inf. Syst.* **2016**, *2016*, 6520631. [[CrossRef](#)]

