CISTER
Research Centre in
Real-Time & Embedded
Computing Systems

Journal Paper

Performance Analysis of Priority-Based IEEE 802.15.6 Protocol in Saturated Traffic Conditions

Sana Ullah

Eduardo Tovar

Ki-Il Kim

Kyong Hoon Kim

Muhammad Imran

CISTER-TR-181117

Performance Analysis of Priority-Based IEEE 802.15.6 Protocol in Saturated Traffic Conditions

Sana Ullah, Eduardo Tovar, Ki-Il Kim, Kyong Hoon Kim, Muhammad Imran

*CISTER Research Centre

Polytechnic Institute of Porto (ISEP-IPP)

Rua Dr. António Bernardino de Almeida, 431

4200-072 Porto

Portugal

Tel.: +351.22.8340509, Fax: +351.22.8321159

E-mail:

http://www.cister.isep.ipp.pt

Abstract

Recent advancement in internet of medical things (IoMT) has enabled deployment of miniaturized, intelligent, and low-power medical devices in, on, or around a human body for unobtrusive and remote health monitoring. The IEEE 802.15.6 standard facilitates such monitoring by enabling low-power and reliable wireless communication between the medical devices. The IEEE 802.15.6 standard employs a carrier sense multiple access with collision avoidance (CSMA/CA) protocol for resource allocation. It utilizes a priority-based backoff procedure by adjusting the contention window bounds of devices according to user requirements. As the performance of this protocol is considerably affected when the number of devices increases, we propose an accurate analytical model to estimate the saturation throughput, mean energy consumption, and mean delay over the number of devices. We assume an error-prone channel with saturated traffic conditions. We determine the optimal performance bounds for a fixed number of devices in different priority classes with different values of bit error ratio. We conclude that high-priority devices obtain quick and reliable access to the error-prone channel compared to low-priority devices. The proposed model is validated through extensive simulations. The performance bounds obtained in our analysis can be used to understand the tradeoffs between different priority levels and network performance.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2878315, IEEE Access

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.DOI

Performance Analysis of Priority-Based IEEE 802.15.6 Protocol in Saturated Traffic Conditions

SANA ULLAH[1,2] EDUARDO TOVAR [3], KI-IL KIM [4], KYONG HOON KIM [1], MUHAMMAD IMRAN [5]

[1]Department of Informatics, Gyeongsang National University, Jinju, South Korea (e-mail: sanajcs@gmail.com, khkim@gnu.ac.kr)
[2]Department of Computer and Software Technology, University of Swat, Pakistan
[3]CISTER Research Unit, ISEP, Porto, Portugal (e-mail: emt@isep.ipp.pt)
[4]Department of Computer Science and Engineering, Chungnam National University, Daejeon, South Korea (e-mail: kikim@cnu.ac.kr)
[5]College of Applied Computer Science, King Saud University, Riyadh, Saudi Arabia (e-mail: dr.m.imran@ieee.org)

Corresponding author: Ki-Il Kim (e-mail: kikim@cnu.ac.kr).

This work was supported by Human Resources Program in Energy Technology of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry and Energy, Republic of Korea. (No. 20174030201440).This work was also partially supported by National Funds through FCT/MCTES (Portuguese Foundation for Science and Technology), within the CISTER Research Unit (CEC/04234).

ABSTRACT Recent advancement in internet of medical things (IoMT) has enabled deployment of miniaturized, intelligent, and low-power medical devices in, on, or around a human body for unobtrusive and remote health monitoring. The IEEE 802.15.6 standard facilitates such monitoring by enabling low-power and reliable wireless communication between the medical devices. The IEEE 802.15.6 standard employs a carrier sense multiple access with collision avoidance (CSMA/CA) protocol for resource allocation. It utilizes a priority-based backoff procedure by adjusting the contention window bounds of devices according to user requirements. As the performance of this protocol is considerably affected when the number of devices increases, we propose an accurate analytical model to estimate the saturation throughput, mean energy consumption, and mean delay over the number of devices. We assume an error-prone channel with saturated traffic conditions. We determine the optimal performance bounds for a fixed number of devices in different priority classes with different values of bit error ratio. We conclude that high-priority devices obtain quick and reliable access to the error-prone channel compared to low-priority devices. The proposed model is validated through extensive simulations. The performance bounds obtained in our analysis can be used to understand the tradeoffs between different priority levels and network performance.

INDEX TERMS IEEE 802.15.6, Health, BAN, Pervasive, MAC

I. INTRODUCTION

INTERNET of medical things (IoMT) has widely adapted pervasive computing to provide smart healthcare services to end users. Over the years, medical industries have been developing smart healthcare systems that allow for the seamless integration of wireless communication, low-power computing, and network technologies to enable the real-time and unobtrusive health monitoring of indoor and outdoor patients. These efforts have introduced the concept of body area networks (BANs) where miniaturized, low-power and intelligent devices are deployed in, on, or around a human body to serve a wide range of healthcare applications [1]–[4]. BANs are becoming increasingly important to monitor the health status of millions of people who die due to serious chronic health conditions such as asthma, gastrointestinal, diabetes, hypertension, parkinson, and cardiovascular diseases. Research shows that most of the afore-mentioned diseases can be detected and treated in the early stages. BANs have the potential to monitor, detect and prevent the occurrence of abnormal health conditions. For example, BANs may continuously monitor the hear beat of a patient suffering from a cardiovascular disease regardless of any constraint on his routine daily activities [5], and may quickly report any abnormal health conditions to the physician. Furthermore, BANs may also be used to predict the occurrence of abnormal health conditions such as predicting the occurrence of

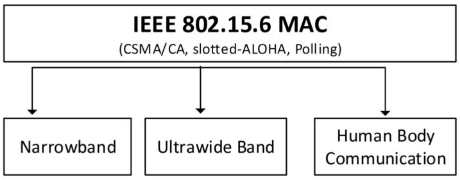

Figure 1: IEEE 802.15.6 MAC over multiple physical layers

epileptic seizure or panic attacks.

BANs are usually comprised of 1) wearable devices, which are deployed on the human body, and 2) implantable devices, which are deployed under the human skin. For example, wearable devices such as electrocardiograms monitor and detect the electric potential of body muscles. The implantable devices, on the other hand, may include infusion pumps that are used to inject insulin to diabetic patients. The wearable and implantable devices in BANs are connected to a central device creating a star topology network. The central device called the hub is responsible for gathering patients' information from the devices over a long period of time. The collected data is then forwarded to a remote medical server or a base station for diagnosis and treatment of life-threatening diseases. [6], [7].

The earlier research work on BANs focused on studying the conventional protocols and standards including IEEE 802.15.4 and IEEE 802.15.1. These conventional protocols could not satisfy the BAN requirements owing to heavy energy consumption, unreliability, and complexity. Because of the limitations in the existing standards, the IEEE 802 has established a task group called IEEE 802.15.6. The IEEE 802.15.6 is a communication standard optimized for low-power devices that are placed on, inside, or around a human body to serve various applications. It defines a medium access control (MAC) layer supporting three physical layers, i.e., narrow band, ultra wideband, and human body communication, as shown in Figure 1. The devices are organized in a one-hop or two-hop star BANs. In one-hop BANs, data communication occurs between devices and the hub without using any relay-capable device. In two-hop BANs, a relay-capable device is used to connect the devices and the hub.

The IEEE 802.15.6 operates in three access modes. In the beacon access mode, periodic beacons are transmitted by a hub at the beginning of each superframe. As shown in Figure 2, each superframe includes two phases of the exclusive access phases (EAP1 and EAP2), two phases of random access phases (RAP1 and RAP2), two phases of managed access phases (MAP1 and MAP2-either of these phases may also include Type I/II access phase) , and one contention access phase (CAP). Depending on the physical layer, the EAPs, RAPs, and CAP use either a carrier sense multiple access with collision avoidance (CSMA/CA) or a slotted ALOHA protocol to obtain access to a channel. The EAPs are used for urgent data, while the remaining contention access phases are used for routine data. The MAP is used for scheduled uplink and downlink allocations, and may also allow scheduled and unscheduled bi-link allocation intervals. In a nonbeacon access mode with superframe boundaries, the entire superframe is comprised of a MAP for resource allocations. Finally, a nonbeacon access mode without superframe boundaries provide unscheduled Type-II polled allocation used for transmitting a few number of data packets.

The priority-based IEEE 802.15.6 CSMA/CA protocol has the capability to accommodate a wide range of health applications. The prioritized access used in this protocol allows BANs to report emergency health conditions to the physicians in real-time resulting in the prevention of fatal accidents. This protocol has the potential to transform the integration of BANs and IoMT technologies improving delivery and affordability of healthcare services. Such integration may also promote personalized healthcare with reliable and remote access to the physician anywhere anytime. To achieve the afore-mentioned benefits, it is important to analyze the performance of the priority-based IEEE 802.15.6 CSMA/CA protocol in terms of different quality of service parameters that are important for reliable delivery of healthcare data. In this study, we develop an accurate analytical model to analyze the performance of this protocol used in the beacon communication mode by extending our previous work [8]. We consider a fixed number of devices under saturated traffic conditions, and concentrate on estimating different qualities of the service parameters, such as the saturation throughput, mean energy consumption, and mean delay for various priority classes. Unlike the previous work that considers ideal channel characteristics, we consider an error-prone channel and study the effects of bit errors on the performance. The key approximation in our model is the consideration of independent probabilities of busy and error-prone channels. Our evaluation considers a single access phase in a star topology network. We consider a probabilistic approach to derive a closed-form expression for the priority-based IEEE 802.15.6 CSMA/CA protocol. The results are presented for three priority classes, i.e., device priority 0, device priority 2, and device priority 3, with different bit error ratio (BER) values. The analytical results are validated by simulations using an independent C++ simulator. The analysis of the proposed analytical model facilitates protocol designers to understand the key approximations and performance analysis for various priority levels.

The remainder of this paper is organized into five sections. Section 2 presents the related work in this area. Section 3 briefly overviews the IEEE 802.15.6 random access mechanisms including the priority-based IEEE 802.15.6 CSMA/CA protocol. Sections 4 and 5 present the proposed model and results, respectively. Section 6 presents our final conclusion.

II. RELATED WORK

Several researchers have attempted to study the IEEE 802.15.6 standard, and most of them have focused on random access protocols, such as the CSMA/CA and slotted ALOHA protocols, for saturated and ideal traffic conditions. Inspired from [9], these studies used the Markov chain to determine

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2878315, IEEE Access

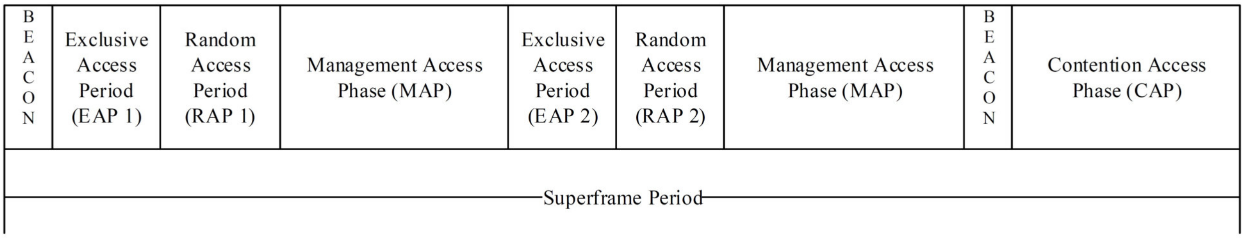

Figure 2: IEEE 802.15.6 superframe structure

the saturation throughput of the IEEE 802.15.6 CSMA/CA protocol, and have recommended useful conclusions. In [10], the authors evaluated and predicted the throughput, energy consumption, and mean frame service time of the IEEE 802.15.6 CSMA/CA protocol for nonsaturated traffic scenarios, and concluded that optimized phase lengths may be recommended for certain applications to achieve a higher throughput and the minimum delay. Another analytical model presented in [11] used a Markov chain to study the IEEE 802.15.6 CSMA/CA protocol for saturated traffic scenarios, and showed that the channel was always utilized by high-priority devices because of smaller backoff durations. The same authors also analyzed the impact of access periods on the quality of service, and concluded that smaller and larger access periods affected the resource utilization [12]. They further concluded that the IEEE 802.15.6 CSMA/CA protocol did not utilize the channel efficiently under heavy traffic conditions. The authors of [13] proposed a discrete-time Markov chain to analyze the IEEE 802.15.6 CSMA/CA protocol for non-ideal channel characteristics and saturated traffic conditions. Unlike the previous work, this study considered the time spent by a device in waiting for the acknowledgment after packet transmission. The authors recommended that five priority parameters are sufficient to achieve the desirable network performance in terms of throughput, average delay, reliability, and power consumption. In another recent study [14], the authors conducted a Markov-chain-based study to enhance the transmission and packet drop algorithm of the IEEE 802.15.6 CSMA/CA protocol, and defined a novel algorithm to assign dynamic backoff boundaries based on user priorities. They concluded that the proposed enhancement provided a high quality of service in terms of throughput, reliability, and energy consumption. In [15], the authors proposed a hybrid prioritization scheme in the IEEE 802.15.6 CSMA/CA protocol to reduce the average energy consumption and extended the network lifetime. The authors of [16] introduced a hybrid and secured MAC protocol called PMAC which allows all devices to get prioritized access to the channel. The simulation results concluded that the PMAC protocol achieves better performance in terms of throughput, delay and power consumption.

In [17], [18], the authors studied the IEEE 802.15.6 slotted ALOHA throughput for different network scenarios. The authors of [19] studied the same protocol and recommended the use of several spreading code lengths. They suggested that by using various code lengths, the protocol would achieve better quality of service for different channel models. In [20], the authors extended the IEEE 802.15.6 slotted ALOHA protocol by exploiting contention probabilities that considered the length of queues. They concluded that this scheme is better than the traditional IEEE 802.15.6 slotted ALOHA protocol in terms of throughput, packet dropping rate, and average delay. The authors of [21] studied the theoretical throughput and delay limits of IEEE 802.15.6 for an error-free channel, and defined several guidelines for protocol designers to determine the optimal bounds for heterogeneous applications. The authors of [22] analyzed the impact of several priority classes for various kinds of traffic. They concluded that, for high-priority medical data, the performance of priority backoff and traditional backoff procedures remained the same. However, for low-priority medical and nonmedical traffic, using different user priorities yields better performance in terms of throughput and packet delivery ratio. In [23], [24], the authors provided an analytical model to determine the device lifetime for scheduled access protocols defined in the standard. Further work on the energy efficiency of IEEE 802.15.6 can be found in [25], [26].

The work above primarily considered the ideal channel characteristics for either saturation or nonsaturation traffic conditions. In our analysis, we consider devices in different priority classes over an error-prone channel with saturated traffic conditions.

III. OVERVIEW OF IEEE 802.15.6 RANDOM ACCESS MECHANISMS

The IEEE 802.15.6 employs the following two random access mechanisms.

A. SLOTTED ALOHA PROTOCOL

The IEEE 802.15.6 slotted ALOHA protocol allows access to a channel based on predefined device priorities, as mentioned in Table 1. Unlike the conventional slotted ALOHA, this protocol resolves contention by reducing retransmission probabilities. The devices are assigned different collision probabilities (CPs) based on their priorities. Initially, the CP is set to CP_{max} for a new arrival of a packet. The contented allocation is granted to the device when z is less than or equal to CP, where z is randomly selected from $[0, 1]$. If the allocation is not granted or if the device fails to transmit, the CP is halved when the device fails for an even number of attempts, and remains the same when the device fails for an odd number of attempts.

TABLE 1. IEEE 802.15.6 Slotted ALOHA. Different thresholds of CP

Device Priorities	CP_{max}	CP_{min}
0	0.125	0.0625
1	0.125	0.0937
2	0.25	0.0937
3	0.25	0.125
4	0.375	0.125
5	0.375	0.1875
6	0.5	0.1875
7	1	0.25

B. PRIORITY-BASED CSMA/CA PROTOCOL

This protocol allows the devices to set their backoff counters to random integers uniformly distributed over the interval $[1, W]$, where W is called the contention window and is chosen in the range $[W_{min}, W_{max}]$.The values W_{min} and W_{max} are the minimum and maximum contention windows, respectively. The value of W depends on the number of failed attempts to transmit data. The device having high priority will have a small contention window, thus increases the chances of channel accessibility in the presence of low priority devices. The device having low priority will have higher backoff periods owing to larger contention window size. The reason for using different device priorities is to accommodate a wide range of traffic services including the best effort and time-critical traffic services.

At the first transmission attempt, W is set to W_{min} for each device and is unchanged for each successful transmission. The device decreases the backoff counter by one for each idle CSMA slot. According to the standard, the CSMA slot is considered idle if the device verifies that the channel is free between the start of the CSMA slot and the clear channel assessment (CCA) duration called pCCATime in the standard. The counter is decremented with pCCATime after the start of the CSMA slot. The data packet is transmitted on the channel when the value of the backoff counter is zero. The backoff counter is unlocked when the device senses the channel for an idle short interframe space (pSIFS) period or when the current time in the EAP, CAP, and RAP is sufficient to accommodate the entire transmission. The backoff counter is frozen when the channel is busy owing to an ongoing transmission. It is also frozen when the current phase length of the EAP, RAP, and CAP is insufficient for the transmission, or when the current time is outside the aforementioned phases. Collision occurs when two or more devices send data simultaneously. Unlike the conventional CSMA/CA protocol where W is doubled for each collision until it reaches the maximum value, the value of W, according to the IEEE 802.15.6 standard, doubles for an even number of failures until it reaches W_{max}, and remains the same for an odd number of failures. Figure 3 shows an example of a device contenting for the channel using the priority-based IEEE 802.15.6 CSMA/CA protocol. Initially, the device selects a random backoff counter over the contention window $[1, W]$ and starts decrementing it for each idle pSIFS. When the backoff counter reaches zero, the data is transmitted. When the transmission fails for the first time, the contention window is not changed. The new backoff counter is selected again from the same contention window; however, this time the transmission fails for the second time (an even number of time), and the value of the contention window is doubled. The backoff counter is now selected over the new contention window, and the data are transmitted once the counter reaches zero.

IV. PROPOSED MODEL FOR SATURATED TRAFFIC CONDITIONS

In this section, we provide an analytical evaluation of the saturation throughput, mean energy consumption, and mean delay under the assumption of an error-prone channel. We consider a fixed number of devices n_i in the priority class $i = 1, 2, 3......$ The queues of each device always contain a packet waiting for transmission, and each device always contains a packet available for transmission on the channel; in other words, a saturation traffic scenario is considered in our analysis. We consider a star topology network where all devices communicate with a central hub. Our assumption further considers a single access phase in the super frame, i.e., the existence of all other access phases is not considered. Let β_i denote the probability of a busy channel in the priority class i, i.e., when the channel is sensed busy by a device for an ideal channel. For example, the channel may be busy owing to ongoing transmissions by another tagged device. Let σ_r denote the probability of error on the channel. It is obvious that both β_i and σ_r contribute to the increment of the backoff stage of each tagged device [27]; therefore, the union of these probabilities, under the assumption that both probabilities are independent, is denoted by α_i and is obtained as

$$\alpha_i = \beta_i + (1 - \beta_i)\sigma_r. \tag{1}$$

where the expression for σ_r can be obtained as

$$\sigma_r = 1 - (1 - e)^{P+PH+MH+E(P)+ACK}, \tag{2}$$

where P and PH represent the physical layer convergence protocol (PCLP) preamble and header, respectively. The MH represents the MAC header and footer, and the $E(P)$ and ACK indicate the average payload information and acknowledgment, respectively. The term e is the probability of errors in the bits and is calculated as the mean value of the BER. The calculation of e requires a complete analysis of many parameters such as noise and interference, multipath fading, and attenuation, and is not in the scope of this analysis. Therefore, we consider that the value of e is constant in the whole analysis.

The values of β_i can be derived as [28]

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2878315, IEEE Access

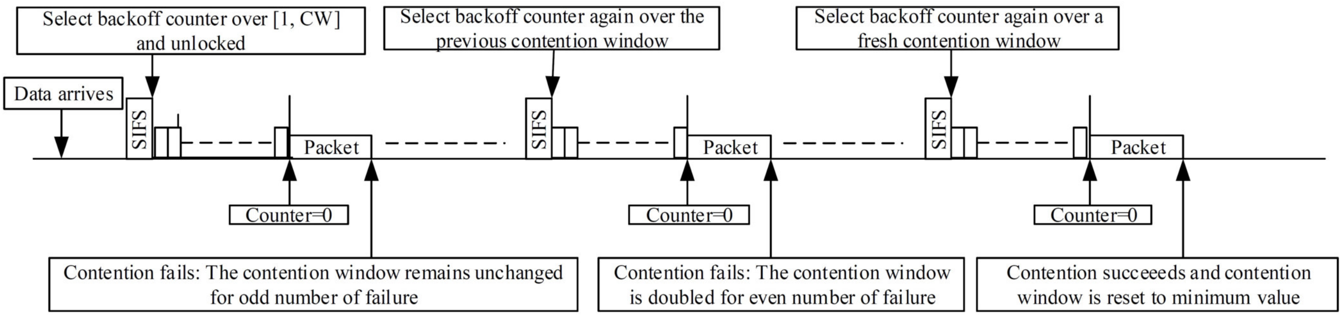

Figure 3: Priority-based IEEE 802.15.6 CSMA/CA Protocol: Channel access procedure where the device wins contention at a third attempt.

$$\beta_i = 1 - \left\{1 - \left(\frac{E[X_i]}{E[Y_i] + E[X_i]}\right)\right\}^{n_i - 1} \prod_{j=0, j\neq i}^{7} \left\{(1 - \left(\frac{E[X_j]}{E[Y_j] + E[X_j]}\right)\right\}^{n_j}, \tag{3}$$

where the term $\frac{E[X_i]}{E[Y_i]+E[X_i]}$ denotes the transmission probability of a tagged device in the priority class i. This term is derived by referring to [29], and the renewal reward theorem stating that the value of $\frac{E[X_i]}{E[Y_i]+E[X_i]}$ can be obtained as the mean reward during the renewable cycle. The term $E[X_i]$ represents the mean number of attempts by a tagged device to send data, while the term $E[Y_i]$ represents the mean backoff time required by the same device. The term $E[X_i]$ may be considered as a geometrical random variable and its average value for the backoff stage M can be obtained as

$$E[X_i] = \sum_{x=0}^{M-1} \alpha_i^x (1 - \alpha_i)(x + 1) + \alpha_i^M (M + 1). \tag{4}$$

Furthermore, the backoff process of the priority-based IEEE 802.15.6 CSMA/CA protocol can also be modeled as a geometric random variable [30], [31] where the contention window is doubled only when the transmission fails for an even number of attempts. For a minimum $W_{i,0}$ in the priority class i, the mean of $E[Y_i]$ can be obtained as

$$E[Y_i] = \sum_{x=0}^{M-1} \alpha_i^x (1 - \alpha_i) \sum_{j=0}^{x} \frac{2^{\lfloor \frac{j}{2} \rfloor} W_{i,0} - 1}{2} + \alpha_i^M \sum_{j=0}^{M} \frac{2^{\lfloor \frac{j}{2} \rfloor} W_{i,0} - 1}{2}, \tag{5}$$

where the term $\frac{2^{\lfloor \frac{j}{2} \rfloor} W_{i,0}-1}{2}$ represents the mean contention window of a device; in other words, this indicates that the contention window is doubled for an even number of failures. The term $\sum_{x=0}^{M-1} \alpha_i^x (1 - \alpha_i) \sum_{j=0}^{x} \frac{2^{\lfloor \frac{j}{2} \rfloor} W_{i,0}-1}{2}$ represents the successful transmission of data packets after the backoff procedure, and the second term $\alpha_i^M \sum_{j=0}^{M} \frac{2^{\lfloor \frac{j}{2} \rfloor} W_{i,0}-1}{2}$ represents that the data packet is not transmitted after several backoff attempts and is discarded. Multiple studies have considered backoff triggering owing to collision. As shown in our analysis, the conditional probability α_i used in Equation 5 is different from that of [30], [31]. Unlike [30], [31], we assume that the backoff is triggered owing to channel error and collision. The values obtained from Equation 4 and 5 are finally substituted in $\frac{E[X_i]}{E[Y_i]+E[X_i]}$, and is subsequently used to derive the value of α_i from Equation 1. The same values may also be used to derive the idle channel probability, represented by P_I, in a given slot time from the following equation.

$$p_I = \prod_{i=0}^{7} \left(1 - \frac{E[X_i]}{E[Y_i] + E[X_i]}\right)^{n_i} \tag{6}$$

Let π_i denote the probability that exactly one device in the priority class i sends data. The expression for π_i can be obtained as

$$\pi_i = n_i \frac{E[X_i]}{E[Y_i] + E[X_i]} \left\{1 - \left(\frac{E[X_i]}{E[Y_i] + E[X_i]}\right)\right\}^{n_i - 1} \prod_{j=0, j\neq i}^{7} \left(1 - \frac{E[X_j]}{E[Y_j] + E[X_j]}\right)^{n_j}. \tag{7}$$

A. SATURATION THROUGHPUT

The saturation throughput denoted by S_i is calculated by the fraction of transmission duration of a payload to the total duration of a slot time. As we considered an error-prone channel in our analysis, the effects of σ_r on the saturation throughput cannot be ignored. By following [9], the expression for S_i can be obtained as

$$S_i = \frac{\pi_i E(P)(1 - \sigma_r)}{p_I \delta + \pi_s (1 - \sigma_r) T_s + \pi_s \sigma_r T_e + (1 - p_I - \pi_s) T_c}, \tag{8}$$

where $\pi_s = \sum_{i=0}^{7} \pi_i$ represents the successful transmission probability in a given slot time. The terms T_s and T_c represent the mean time of a busy channel owing to a successful transmission and collision, respectively. The term T_e represents the mean time of a busy channel owing to an error on the channel. The term δ represents the backoff slot time and is equal to $\Phi + 40\mu s$, where Φ is the CCA slot time. The values of T_s and T_c=T_e can be obtained as

$$T_s = T_P + T_{PH} + T_{MH} + T_{E(P)} + T_{ACK} + 2pSIFS + 2\theta \tag{9}$$

and

$$T_c = T_P + T_{PH} + T_{MH} + T_{E(P)} + pSIFS + \theta \tag{10}$$

where T_P, T_{PH} represent the transmission time of the PCLP preamble and header, respectively. The term T_{MH} represents the time to transmit the MAC header and footer. The terms $T_{E(P)}$ and T_{ACK} represent the time to transmit the mean payload and acknowledgment frame, respectively. Finally, the term θ indicates the propagation time.

B. MEAN ENERGY CONSUMPTION

The mean energy consumed by a tagged device is affected by several stages: 1) backoff stage, when the tagged device attempts to access the channel, 2) sensing stage, when the tagged device senses the channel after a successful backoff, 3) collision stage, when the tagged device experiences a collision on the channel, 4) error stage, when error occurs on the channel, and 5) transmission stage, when the tagged device transmits data on the channel. Let P_{TX}, P_{RX}, and P_{IDLE} indicate the power consumed in the transmit, receive, and idle states, respectively. The expression for the mean energy consumption, denoted by $E[M_i]$ in the priority class i can be obtained as

$$E[M_i] = E[BO_i]+E[S_i]+E[SUCC_i]+E[COL_i]+E[ER_i], \tag{11}$$

where $E[BO_i]$ is the mean energy consumption of a tagged device by performing the backoff procedure in the priority class i. The terms $E[S_i]$ and $E[SUCC_i]$ represent the mean energy consumption of a tagged device owing to the CCA procedure and successful transmission in the priority class i, respectively. Furthermore, the terms $E[COL_i]$ and $E[ER_i]$ represent the mean energy consumption owing to collision and error on the channel in the priority class i, respectively.

The expression for $E[BO_i]$ is given by

$$E[BO_i] = P_{IDLE}E[Y_i]\delta \tag{12}$$

Furthermore, the expression for $E[S_i]$ is given by

$$E[S_i] = P_{RX}\Big(\sum_{x=0}^{M-1} \alpha_i^x(1-\alpha_i)(x+1) + \alpha_i^M(M+1)\Big)\Phi, \tag{13}$$

The term $\sum_{x=0}^{M-1} \alpha_i^x(1-\alpha_i)(x+1) + \alpha_i^M(M+1)$ represents the mean number of CCAs on the channel. In other words, the device performs CCA before the transmission of data packet; hence, the mean number of attempts is considered as equal to the mean number of CCAs.

The expression for $E[SUCC_i]$ is given by

$$E[SUCC_i] = P_{TX}(1-\alpha_i^{m+1})(T_P + T_{PH} + T_{MH} + T_{E(P)}) + P_{RX}(2pSIFS + T_{ACK}), \tag{14}$$

where the term $(1-\alpha_i^{m+1})$ represents that the packet is successfully sent after $M+1$ attempts [32].

To calculate $E[COL_i]$, we need to obtain the mean number of slots during which the channel remains busy. Let $E[L_i]$ represent the mean time when the tagged device locks the backoff counter in the priority class i. The backoff counter is typically locked owing to many reasons; in our calculation, we assume that the backoff counter is locked only when the channel is busy. The expression for $E[L_i]$ can be obtained as [33]

$$E[L_i] = \frac{\beta_i E[Y_i]}{1-\beta_i}. \tag{15}$$

It is pertinent to mention that the tagged device experiences extra energy consumption owing to the ongoing transmissions of other devices. Such ongoing transmissions may either be successful or failed; however, in both situations, the energy of the tagged device is consumed [32]. Considering the aforementioned scenario, the expression for $E[COL_i]$ can now be obtained as

$$E[COL_i] = P_{RX}\left[\frac{\pi_s(1-\sigma_r)}{p_{tr}}T_s + (1-\frac{\pi_s(1-\sigma_r)}{p_{tr}})T_c\right]E[L_i], \tag{16}$$

where the term $\frac{\pi_s(1-\sigma_r)}{p_{tr}}$ indicates that the tagged device listens to a transmission that is successful, and the term $1-\frac{\pi_s(1-\sigma_r)}{p_{tr}}$ indicates that the tagged device listens to a collision on the channel. The term p_{tr} indicates that at least a single transmission exists in a given slot, and is derived as $p_{tr} = 1 - p_I$.

As discussed above, we assume that the tagged device consumes extra energy owing to errors on the channel. The expression for $E[ER_i]$ is given by

$$E[ER_i] = P_{RX}\frac{\pi_s\sigma_r}{p_{tr}}T_e. \tag{17}$$

The above mentioned analysis does not consider extra energy consumption owing to the retransmission of data packets caused by errors on the channel.

C. MEAN SATURATION DELAY

The mean saturation delay includes the channel access delay caused by backoff and collision, the delay caused by locking the backoff counter owing to data transmission, or collisions on the channel, and the delay to transmit the data packet. The mean delay is also affected by: 1) queuing delay, when packets wait in the queue before transmission, and 2)

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2878315, IEEE Access

retransmission, when packets are collided or did not reach the destination owing to errors on the channel; in this case, the delay may include the time to retransmit a packet. The consideration of queuing delay is important for application scenarios with high traffic rate. For example, the traffic rate may be high when the BAN monitors patients' health status during a surgical activity that requires all devices to transmit data in real-time. However, the two reasons above are omitted in our analysis. By referring to [33], the expression for the mean delay $E[D_i]$ for priority class i can be obtained as

$$E[D_i] = E[Y_i]\delta + \left[\frac{\pi_s(1-\sigma_r)}{p_{tr}}T_s + (1 - \frac{\pi_s(1-\sigma_r)}{p_{tr}})T_c\right] E[L_i] + T_s. \quad (18)$$

TABLE 2. IEEE 802.15.6 parameters (2360 MHz to 2400 MHz)

Symbol	Value	Symbol	Value
P	90 bits	R_S	600 ksps
PH	31 bits	R_H	91.9 kbps
MH	56 bits + 16 bits	θ	$1\mu s$
T_P	P/R_S	T_{PH}	PH/R_H
T_{MH}	MH/R_D	$T_{E(P)}$	$E(P)/R_D$
pSIFS	$75\mu s$	$E(P)$	1920 bits
Φ	$63/R_S$	δ	$\Phi + 40\mu s$
ACK	193 bits	P_{IDLE}	$5\mu W$
P_{TX}	$27mW$	P_{RX}	$1.8mW$
R_D	485.7 kbps		

V. ANALYSIS AND RESULTS

We evaluate the performance of the priority-based IEEE 802.15.6 protocol for saturated traffic conditions, where devices always contain a packet available for transmission, under the assumption of an error-prone channel. Because the implementation of the IEEE 802.15.6 protocol stack is not available in well-known simulation tools, we developed an independent C++ simulator for evaluation. The simulator implements the analytical model and protocol operations above, such as the backoff procedure and priority classes, for a narrow band physical layer; the ultrawide and human body communication bands are not considered in our analysis. We consider a star topology network where all devices communicate with a central hub over an error-prone channel with different values of the BER. Initially, we consider three priority classes, i.e., device priority 0, device priority 2, and device priority 3. However, the proposed model is valid for all priority classes. We assume that all devices in the aforementioned priority classes are not independent of each other and are coexisting in one network. The standard defines several narrow band physical layer; however, we consider 2360 MHz to 2400 MHz. Furthermore, the headers P and PH are sent at symbol R_S and header R_H rates, respectively. The payload $E(P)$ is transmitted at the information data rate R_D. According to the standard, the value of Φ is calculated as $63/R_S$. In our analysis, the R_D is set to $485.7kbps$, while the values of R_S and R_H are set to $600ksps$ and $91.9kbps$, respectively. The value of $E(P)$ is set to 1920 bits. Both numerical and simulation results are presented for different levels of priorities and BER values. All other parameters considered in our analysis are given in Table 2. The values of W_{min} and W_{max} are set according to the levels of priority classes, as mentioned in Table 3

TABLE 3. Contention bounds for IEEE 802.15.6 CSMA/CA

Traffic type	Device Priorities	W_{min}	W_{max}
Background	0	16	64
Best effort	1	16	32
Excellent effort	2	8	32
Video	3	8	16
Voice	4	4	16
Medical data	5	4	8
High-priority data	6	2	8
Emergency event report	7	1	4

Figure 4 shows the saturation throughput over a number of devices for three different priority classes. This figure considers an error-prone channel with $BER = 10^{-6}$. The figure shows that the throughput depends on the number of devices and their relative priority classes; in other words, it depends on the values of the contention window. Generally, the saturation throughput decreases as a function of number of devices owing to heavy contention and collisions on the channel. For 20 devices, the normalized throughputs for priority class 3 and class 0 are 0.62 and 0.24, respectively. Similarly, for the same number of devices, the normalized throughput is 0.51 for priority class 2. This means that high-priority devices efficiently utilize the bandwidth in the presence of low-priority devices. One reason is that high-priority devices typically obtain quick access to the channel owing to the smaller backoff periods compared to that of low-priority devices, thus decreasing the saturation throughput of the latter.

Figure 5 shows the saturation throughput of devices for priority class 3 with different BER values. We observed that errors on the channel cause diverse effects on the saturation throughput. For a higher BER value, the saturation throughput is lower in the same priority class compared to that of a lower BER value. We observed that the saturation throughput for 19 devices is 0.61 and 0.39 for $BER = 10^{-6}$ and $BER = 10^{-3}$, respectively. We conclude that in the case of minimum error on the channel, high-priority devices could communicate critical data directly to the central hub by penalizing low-priority devices.

Figure 6 shows the mean energy consumption as a function of number of devices for three different priority classes with $BER = 10^{-6}$. As shown in the figure, the mean energy consumption for 16 devices in priority class 3 is $68mJ$ compared to that of $20mJ$ in the priority class 0. We observed that the mean energy consumption increases over the number of devices owing to heavy contention and backoff delay. However, compared to high-priority devices, the mean energy consumption of low-priority devices is low because they remain in the backoff or idle stage most of the time

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2878315, IEEE Access

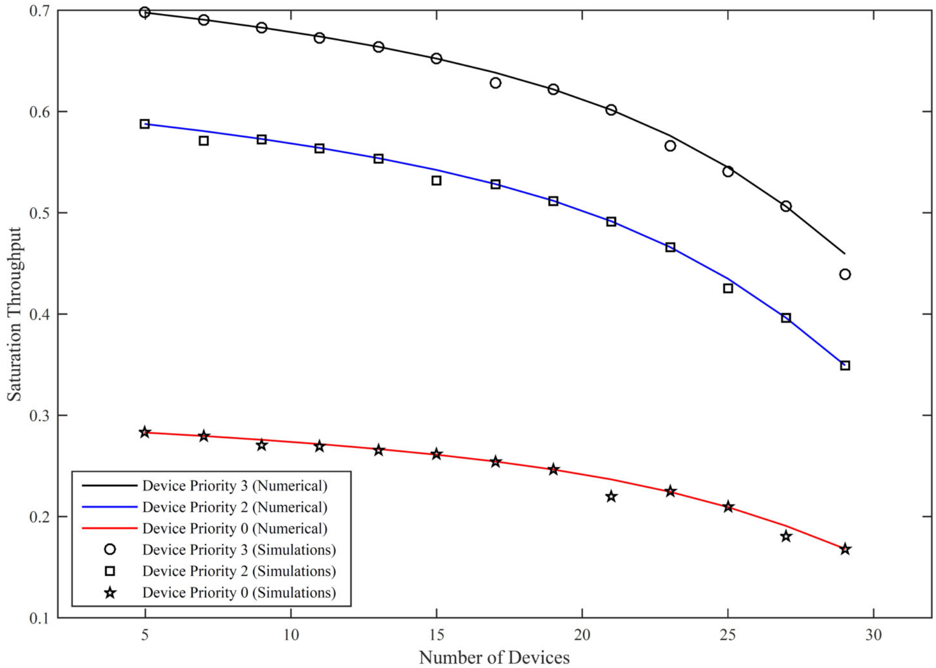

Figure 4: Saturation throughput vs. number of devices ($BER = 10^{-6}$)

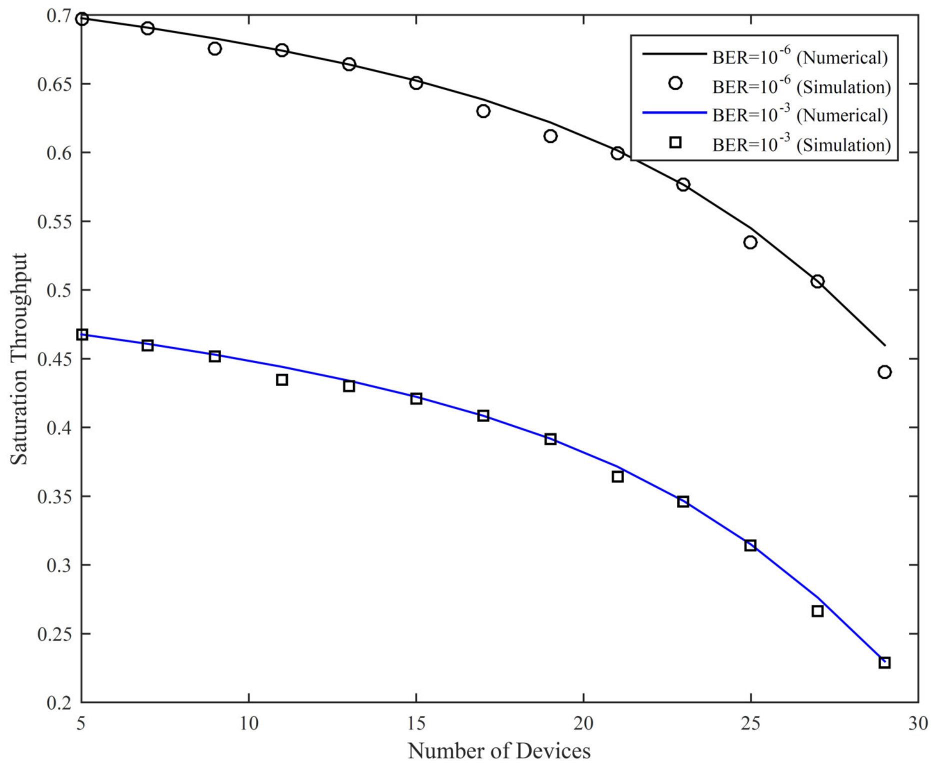

Figure 5: Saturation throughput for device priority 3 vs. number of devices

owing to the presence of high-priority devices. Meanwhile, high-priority devices consume more energy owing to the high channel utilization and high saturation throughput.

The effects of the BER on the mean energy consumption of the devices for priority class 3 are shown in Figure 7. The figure shows that for a lower BER value, the mean energy consumption is lower compared to that of a higher BER value. We observed that the mean energy consumption primarily depends on the BER values; in other words, the packets are typically not transmitted owing to a high BER

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2878315, IEEE Access

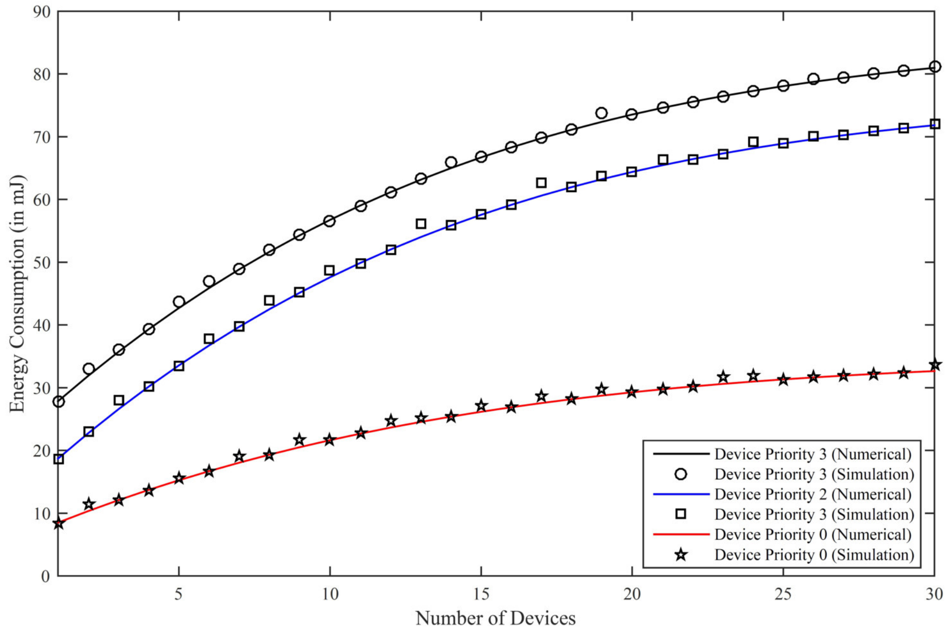

Figure 6: Mean energy consumption vs. number of devices ($BER = 10^{-6}$)

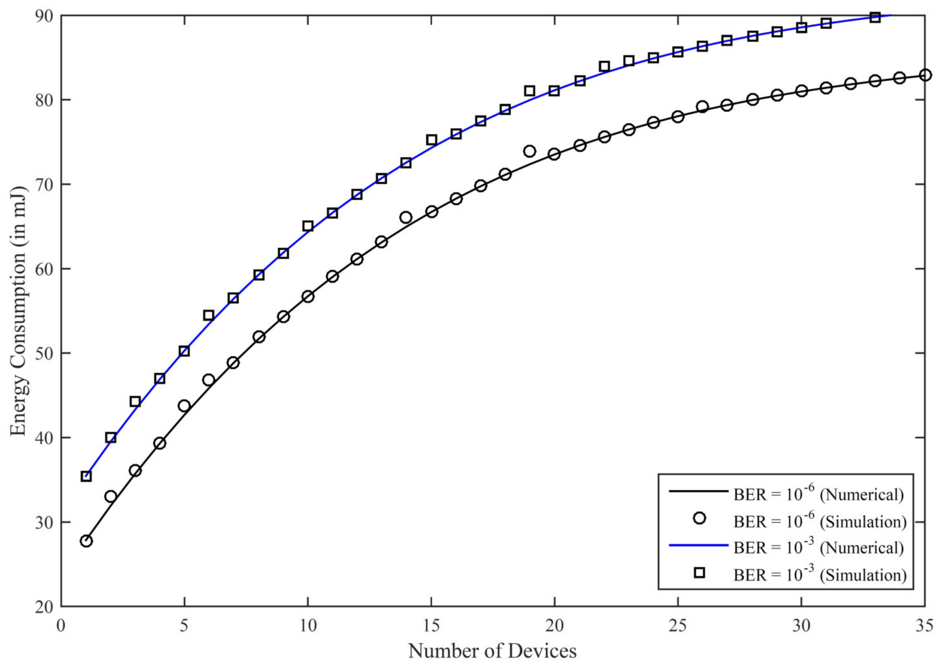

Figure 7: Mean energy consumption for device priority 3 vs. number of devices

on the channel. A primary reason is that higher BER values trigger multiple backoffs, thus increasing the mean energy consumption.

The mean saturation delay for three different priority classes with $BER = 10^{-6}$ is shown in Figure 8. As low-priority devices have larger contention windows, their mean saturation delay is also higher compared to that of high-priority devices. The latter typically obtains quick access to the channel. As observed in Figure 4 and 8, high-priority devices steal bandwidth from low-priority devices, thus affecting the mean saturation delay of the latter by increasing their backoff delay. Figure 9 shows the mean saturation delay for devices in priority class 0 with different BER values. For 16 devices, the mean delay is 160 ms and 100 ms for $BER = 10^{-3}$ and $BER = 10^{-6}$, respectively.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2878315, IEEE Access

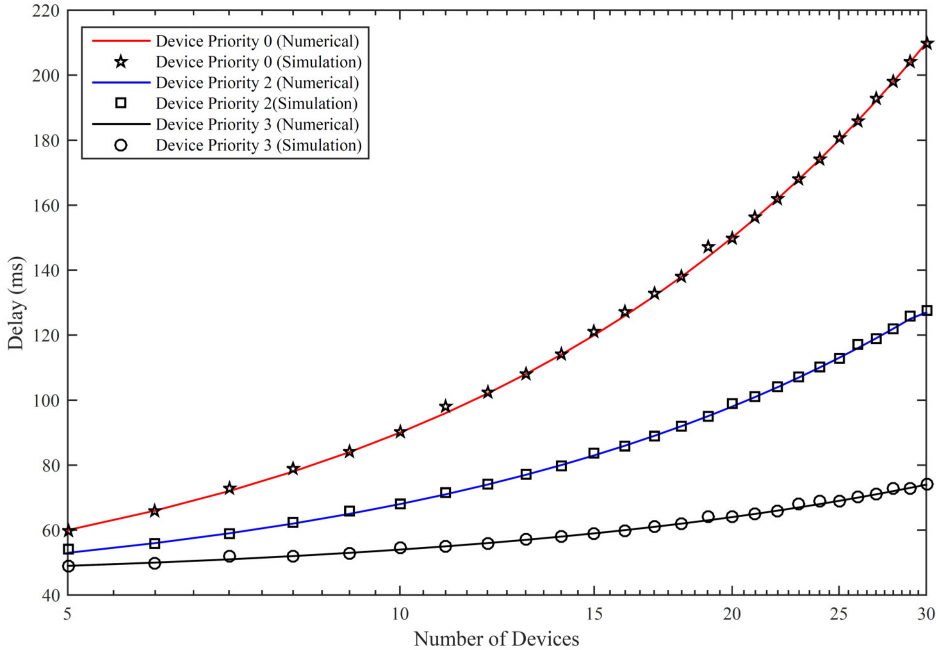

Figure 8: Mean delay vs. number of devices ($BER = 10^{-6}$)

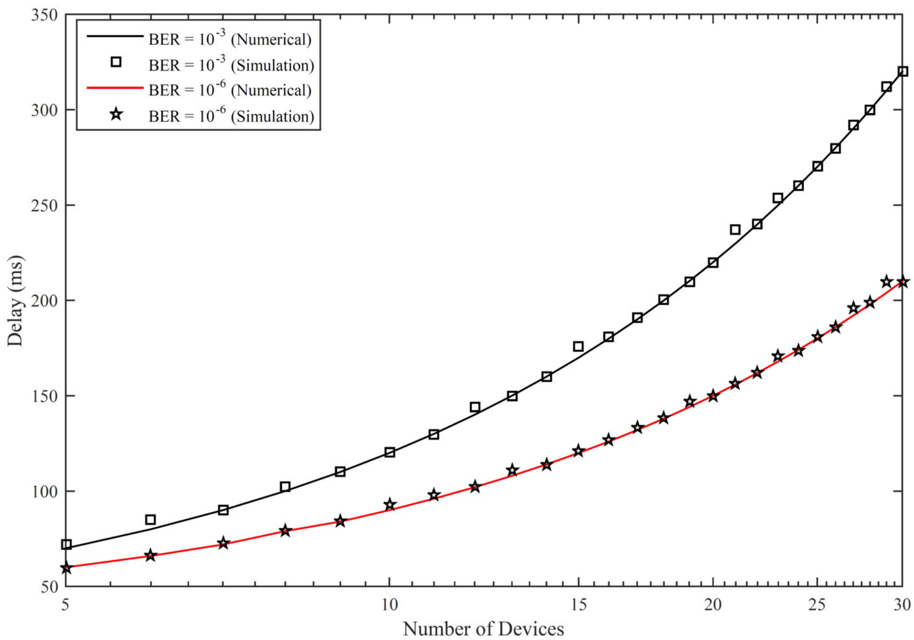

Figure 9: Mean delay for device priority 0 vs. number of devices

VI. CONCLUSION

We studied the performance of the priority-based IEEE 802.15.6 CSMA/CA protocol employed in the beacon communication mode. We proposed an accurate analytical model to analyze the backoff priority schemes of the priority-based IEEE 802.15.6 CSMA/CA protocol in terms of the saturation throughput, mean energy consumption, and mean delay, and derived the optimal bounds for saturated and error-prone channel conditions. We obtained the aforementioned bounds for the devices in three priority classes, ranging from device priority 0 to 3. Our study concluded that high-priority devices typically steal bandwidth from low-priority devices owing to their smaller backoff periods and contention windows, thus affecting the quality of service of the latter. We also observed that high-priority devices consume more energy compared to low-priority devices owing to the high saturation throughput and channel utilization. Our model assumed three priority classes; however, it could also be used to evaluate other

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2878315, IEEE Access

priority classes.

In the future, this model can be extended to evaluate the effects of queuing delay and retransmission on quality of service for high BER values. This model can also be extended towards nonsaturation traffic conditions.

LIST OF ABBREVIATIONS

CSMA/CA: carrier sense multiple access with collision avoidance, BER: bit error ratio, MAC: medium access control, BAN: body area networks, EAP: exclusive access phase, RAP: random access phase, MAP: managed access phase, CP: collision probability, CCA: clear channel assessment, pSIFS: idle short interframe Space, PLCP: physical layer convergence protocol, ACK: acknowledgment.

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHORS CONTRIBUTIONS

SU is the lead author and proposed the entire study including the analytical approximations. ET helped in correcting and revising the analytical model. KI.K designed the simulation environment and helped in providing the results. KH.K and M.I verified and revised the whole manuscript for validity and consistency. All authors read and approved the manuscript.

REFERENCES

[1] Chen, M., Gonzalez, S., Vasilakos, A., Cao, H., Leung, V.C.M.: Body area networks: A survey. Mobile Networks and Applications 16(2), pp. 171-193 (2011). doi:10.1007/s11036-010-0260-8

[2] Fortino, G., Fatta, G.D., Pathan, M., Vasilakos, A.V., Cloud-assisted body area networks: state-of-the-art and future challenges, Springer Wireless Networks, 20(7), pp. 1925âĂŞ1938, 2017.

[3] Cavallari, R., Martelli, F., Rosini, R., Buratti, C., Verdone, R.: A survey on wireless body area networks: Technologies and design challenges. IEEE Communications Surveys Tutorials 16(3), pp. 1635-1657 (2014). doi:10.1109/SURV.2014.012214.00007

[4] Gravina, R., Alinia, P., Ghasemzadeh, H., Fortino, G., Multi-sensor fusion in body sensor networks: State-of-the-art and research challenges. Information Fusion 35, pp. 68-80 (2017).

[5] Andreoli A., Gravina R., Giannantonio R., Pierleoni P., Fortino G. (2010) SPINE-HRV: A BSN-Based Toolkit for Heart Rate Variability Analysis in the Time-Domain. In: Lay-Ekuakille A., Mukhopadhyay S.C. (eds) Wearable and Autonomous Biomedical Devices and Systems for Smart Environment. Lecture Notes in Electrical Engineering, vol 75, pp. 369-389, Springer, Berlin, Heidelberg, 2010.

[6] Movassaghi, S., Abolhasan, M., Lipman, J., Smith, D., Jamalipour, A.: Wireless body area networks: A survey. IEEE Communications Surveys Tutorials 16(3), pp. 1658-1686 (2014). doi:10.1109/SURV.2013.121313.00064

[7] Latre, B., Braem, B., Moerman, I., Blondia, C., Demeester, P.: A survey on wireless body area networks. Wireless Networks 17(1), pp. 1-18 (2011). doi:10.1007/s11276-010-0252-4

[8] Ullah, S., and Tovar, E., Performance analysis of IEEE 802.15.6 contention-based MAC protocol," 2015 IEEE International Conference on Communications (ICC), London, pp. 6146-6151, 2015.

[9] Bianchi, G.: Performance analysis of the ieee 802.11 distributed coordination function. IEEE Journal on Selected Areas in Communications 18(3), 535-547 (2000). doi:10.1109/49.840210

[10] 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 17(3) (2017). doi:10.3390/s17030492

[11] Rashwand, S., Misc, J., Khazaei, H.: Ieee 802.15.6 under saturation: Some problems to be expected. Journal of Communications and Networks 13(2), 142-148 (2011). doi:10.1109/JCN.2011.6157413

[12] Rashwand, S., Misc, J.: Effects of access phases lengths on performance of ieee 802.15.6 csma/ca. Comput. Netw. 56(12), 2832-2846 (2012). doi:10.1016/j.comnet.2012.04.023

[13] Sarkar, S., Misra, S., Bandyopadhyay, B., Chakraborty, C., Obaidat, M.S.: Performance analysis of ieee 802.15.6 mac protocol under non-ideal channel conditions and saturated traffic regime. IEEE Transactions on Computers 64(10), 2912-2925 (2015). doi:10.1109/TC.2015.2389806

[14] Hend Fourati, L.A.S. Hanen Idoudi: Intelligent slots allocation for dynamic differentiation in ieee 802.15.6 csma/ca. Ad Hoc Networks 72(27-43) (2018). doi:10.1016/j.adhoc.2018.01.007

[15] 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 16(9) (2016). doi:10.3390/s16091421

[16] Ullah, S., Imran, M., Alnuem, M., A Hybrid and Secure Priority-Guaranteed MAC Protocol for Wireless Body Area Network, IJDSN, 10(2), 2014.

[17] Chowdhury, M.S., Ashrafuzzaman, K., Kwak, K.S.: Modelling ieee 802.15.6 slotted aloha in heterogeneous condition. Electronics Letters 50(5), 415-416 (2014). doi:10.1049/el.2013.2802

[18] Chowdhury, M.S., Ashrafuzzaman, K., Kwak, K.S.: Saturation throughput analysis of ieee 802.15.6 slotted aloha in heterogeneous conditions. IEEE Wireless Communications Letters 3(3), 257-260 (2014). doi:10.1109/WCL.2014.021714.140008

[19] Fatehy, M., Kohno, R.: Variable spread slotted aloha simulation analysis over ieee 802.15.6 using ir-uwb for wireless body area networks. In: 2013 European Modelling Symposium, pp. 572-577 (2013). doi:10.1109/EMS.2013.95

[20] Fatehy, M., Kohno, R.: A novel contention probability dynamism for ieee 802.15.6 standard. EURASIP Journal on Wireless Communications and Networking 2014(1), 92 (2014). doi:10.1186/1687-1499-2014-92

[21] Ullah, S., Chen, M., Kwak, K.S.: Throughput and delay analysis of ieee 802.15.6-based csma/ca protocol. Journal of Medical Systems 36(6), 3875-3891 (2012). doi:10.1007/s10916-012-9860-0

[22] Kahsay, L.Z., Paso, T., Iinatti, J.: Evaluation of ieee 802.15.6 mac user priorities with uwb phy for medical applications. In: 2013 7th International Symposium on Medical Information and Communication Technology (ISMICT), pp. 18-22 (2013). doi:10.1109/ISMICT.2013.6521691

[23] Tachtatzis, C., Franco, F.D., Tracey, D.C., Timmons, N.F., Morrison, J.: An energy analysis of ieee 802.15.6 scheduled access modes. In: 2010 IEEE Globecom Workshops, pp. 1270-1275 (2010). doi:10.1109/GLOCOMW.2010.5700142

[24] Tachtatzis, C., Di Franco, F., Tracey, D.C., Timmons, N.F., Morrison, J.: An energy analysis of ieee 802.15.6 scheduled access modes for medical applications. In: Simplot-Ryl, D., Dias de Amorim, M., Giordano, S., Helmy, A. (eds.) Ad Hoc Networks, pp. 209-222. Springer, Berlin, Heidelberg (2012)

[25] Kartsakli, E., Antonopoulos, A., Alonso, L., Verikoukis, C.: A cloud-assisted random linear network coding medium access control protocol for healthcare applications. Sensors 14(3), 4806-4830 (2014). doi:10.3390/s140304806

[26] Ibarra, E., Antonopoulos, A., Kartsakli, E., Rodrigues, J.J.P.C., Verikoukis, C.: Joint power-qos control scheme for energy harvesting body sensor nodes. In: 2014 IEEE International Conference on Communications (ICC), pp. 3511-3516 (2014). doi:10.1109/ICC.2014.6883865

[27] Dong, X.J., Varaiya, P.: Saturation throughput analysis of ieee 802.11 wireless lans for a lossy channel. IEEE Communications Letters 9(2), 100-102 (2005). doi:10.1109/LCOMM.2005.02011

[28] Li, B., Battiti, R.: Performance analysis of an enhanced ieee 802.11 distributed coordination function supporting service differentiation. In: Karlsson, G., Smirnov, M.I. (eds.) Quality for All, pp. 152-161. Springer, Berlin, Heidelberg (2003)

[29] Ling, X., Liu, K.H., Cheng, Y., Shen, X.S., Mark, J.W.: A novel performance model for distributed prioritized mac protocols. In: IEEE GLOBECOM 2007 - IEEE Global Telecommunications Conference, pp. 4692-4696 (2007). doi:10.1109/GLOCOM.2007.890

[30] Cai, L.X., Mark, J.W., Shen, X., Liu, K.H., Rutagemwa, H.: Performance analysis of hybrid medium access protocol in ieee 802.15.3 wpan. In: 2007 4th IEEE Consumer Communications and Networking Conference, pp. 445-449 (2007). doi:10.1109/CCNC.2007.94

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2878315, IEEE Access

[31] Cai, L.X., Shen, X., Mark, J.W., Cai, L., Xiao, Y.: Voice capacity analysis of wlan with unbalanced traffic. IEEE Transactions on Vehicular Technology 55(3), 752-761 (2006). doi:10.1109/TVT.2006.874145

[32] Maskooki, A., Soh, C.B., Gunawan, E., Low, K.S.: Adaptive routing for dynamic on-body wireless sensor networks. IEEE Journal of Biomedical and Health Informatics 19(2), 549-558 (2015). doi:10.1109/JBHI.2014.2313343

[33] Xiao, Y.: Performance analysis of priority schemes for ieee 802.11 and ieee 802.11e wireless lans. IEEE Transactions on Wireless Communications 4(4), 1506-1515 (2005). doi:10.1109/TWC.2005.850328