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Research Article

Performance Analysis of WBAN MAC Protocol under Different Access Periods

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The IEEE 802.15.6 is a new standard on wireless body area network (WBAN) for short-range, extremely low power wireless communication with high data rates in the vicinity of, or inside, a human body. The standard defines two contention-based channel access schemes: slotted ALOHA and carrier sense multiple access with collision avoidance (CSMA/CA) using an alternative binary exponential backoff procedure. The standard supports quality of service (QoS) differentiation through user priorities and access phases. In this study, we develop an analytical model for the estimation of performance metrics such as energy consumption, normalized throughput, and mean frame service time, employing a Markov chain model under nonsaturated heterogeneous traffic scenarios including different access phases specified in the standard for different user priorities and access methods. We conclude that the deployment of exclusive access phase (EAP) is not necessary in a typical WBAN using CSMA/CA because it degrades the overall system throughput, consumes more energy per packet, and results in higher delay for nonemergency nodes.

1. Introduction

A WBAN is a logical set comprised of small and intelligent wireless medical sensors (which are worn or implanted into the tissues) and a common hub. These medical sensors are capable of measuring, processing, and forwarding important physiological parameters such as the heart rate, blood pressure, glucose level, body and skin temperature, oxygen saturation, and respiration rate, as well as records such as electrocardiograms and electromyograms. This enables health professionals to predict, diagnose, and react to adverse events earlier than ever. A conceptual view of medical WBAN is shown in Figure 1. The depicted WBAN includes a few sensors to monitor vital bodywide health information and send it to a remote server using a personal digital assistant (PDA) [1]. The IEEE 802.15 Working Group formed Task Group 6 (TG6) in November 2007 to develop a communication standard known as IEEE 802.15.6. The purpose of the group is to establish a communication standard optimized for low-power and short-range in-body/on-body nodes to serve a variety of medical, consumer electronics, and entertainment applications. WBANs must support a combination of reliability, quality of service (QoS), low power, high data rate, and noninterference to address the gamut of WBAN applications. The IEEE 802.15.6 standard was approved in 2012 for wireless communications in WBANs. The standard provides efficient communication solutions to ubiquitous healthcare and telemedicine systems, interactive gaming, military services, and portable audio/video systems.

The medium access control (MAC) protocol provides a control mechanism to allow packet transmission through a shared wireless channel. The IEEE 802.15.6 supports two communication modes: (1) beacon communication mode, where the hub transmits beacons for resource allocation and synchronization, and (2) nonbeacon communication mode, where the scheduled/unscheduled allocations and polling are used [2]. In the beacon communication mode, the beacons are transmitted in the beginning of each superframe. As illustrated in Figure 2, in a beacon communication mode each superframe is divided into different access phases (APs).

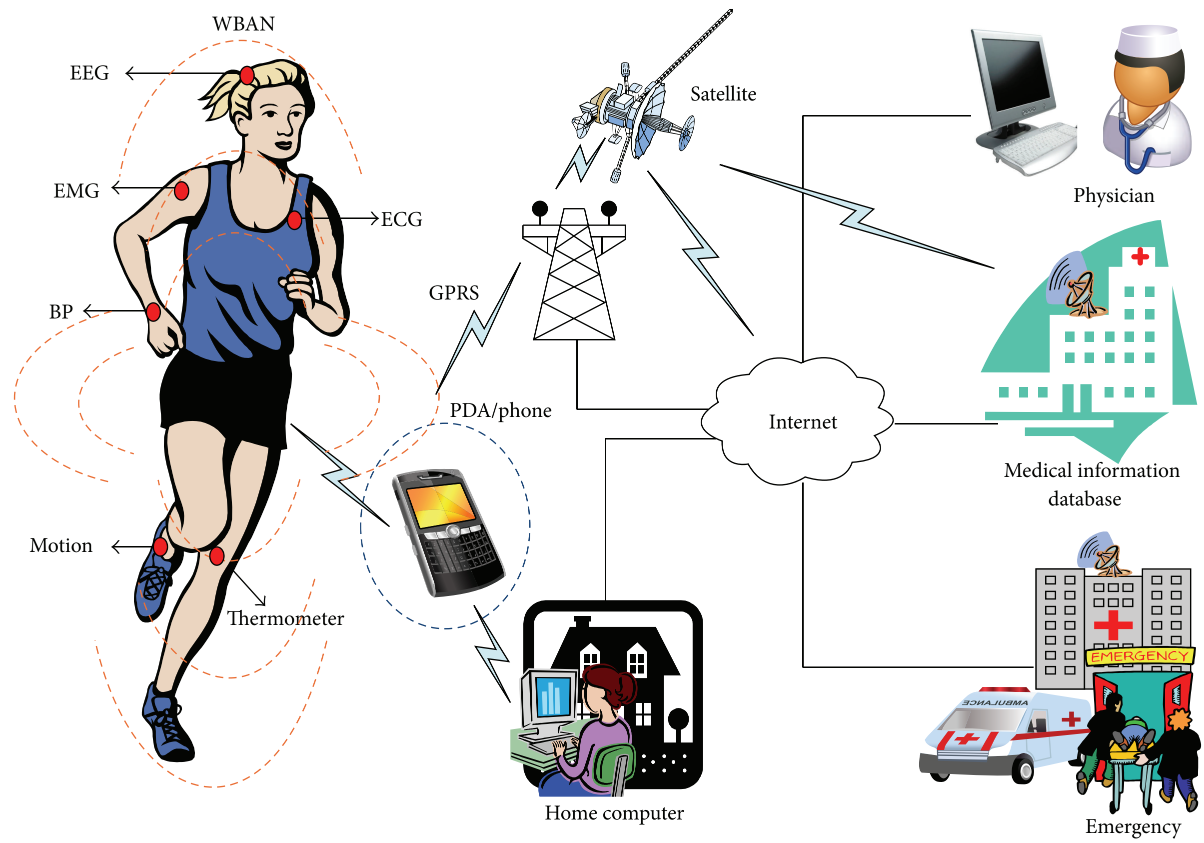

Figure 1: Abstract view of WBAN and its framework.

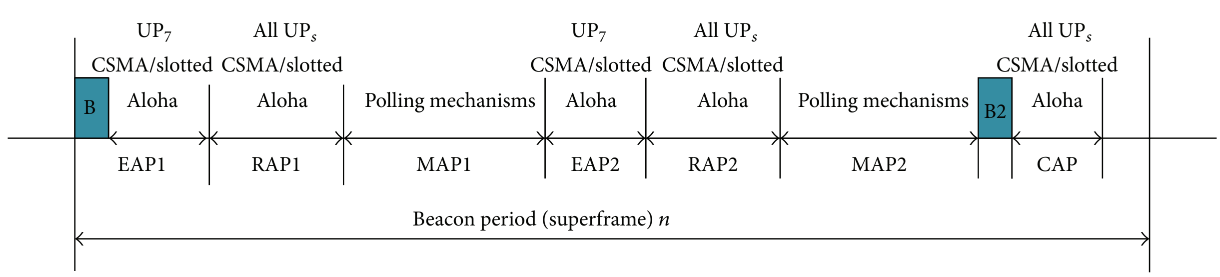

Figure 2: Layout of access phases with superframe boundaries [15].

A superframe includes exclusive access phase 1 (EAP1), random access phase 1 (RAP1), management access phase 1 (MAP1), exclusive access phase 2 (EAP2), random access phase 2 (RAP2), management access phase 2 (MAP2), and an optional B2 frame followed by a contention access phase (CAP). The EAPs are used for life-critical traffic while the RAPs and CAP are used for regular traffic. Each AP, except RAP1, may have zero length [3].

In IEEE 802.15.6, the contention-based access methods for obtaining allocations are either carrier sense multiple access/collision avoidance (CSMA/CA) if a narrowband physical layer (PHY)/ultra-wideband (UWB) PHY is chosen or slotted ALOHA if UWB PHY is used [3]. The IEEE 802.15.6 CSMA/CA mechanism is different in important aspects from the CSMA/CA mechanism of other wireless standards. The backoff mechanism is not binary exponential, and the contention window doubles only when the retry counter is an even number. In addition to busy channel the node will also lock the backoff counter if it is not allowed to access the medium during the current AP or the current AP length is not long enough for a frame transmission. These differences require changes in the typical discrete time markov chains (DTMCs) adopted for the CSMA/CA mechanism of previous standards presented in [4–7] for IEEE 802.11; in [8–11] for IEEE 802.11e; in [12, 13] for IEEE 802.15.4; and in [14] for IEEE 802.15.3c.

To employ the CSMA/CA mechanism, as shown in Figure 4 the contending node i belonging to a user class UP_i where $i = 0, \ldots, 7$ shall set its backoff counter to a random integer over the interval $[1, CW_i]$. The contention window (CW) is chosen as follows: (a) If the node does not obtain any contended allocation previously, or if it succeeds in a data frame transmission, it will set the CW to CW_{min}. (b) If the node fails to transmit, it will keep the CW unchanged if this is the mth time the node has failed consecutively, where m is an odd number; otherwise, the CW is doubled. (c) If doubling the CW results in a value that exceeds CW_{max} for a UP_i node, the node will set the CW to CW_{max}. After choosing the contention window, the node will decrement its backoff counter by one for each idle pCCATime. Further, the node will lock the backoff counter whenever it detects any transmission on the channel during pCCATime and will unlock it when the channel has been idle for pSIFS. The node will also lock the backoff counter if it is not allowed to access the medium during the current AP or the current AP length is not long enough for a frame transmission. The node transmits when the backoff counter reaches zero [3].

In this study, we develop analytical and simulation models to evaluate the CSMA/CA mechanism of IEEE 802.15.6 media access control (MAC), by considering a portion of the APs that can easily be extended to the entire superframe. We have not considered the deployment of EAP2 and RAP2 access phases. Given that the objective is to investigate the performance of the CSMA/CA mechanism, we ignore activities in the contention-free access phases (i.e., MAP1 and MAP2). Our analysis is validated with accurate computer simulation.

The rest of this paper is structured as follows: Section 2 reviews the related studies available in the literature. Section 3 describes the framework of the analytical model and performance measures. The experimental results are presented in Section 4, and finally, Section 5 concludes our study.

Table 1: Contention window bounds for CSMA/CA.

User priority	Traffic designation	CW_{min}	CW_{max}
7	Emergency or medical implant event report	1	4
6	High-priority medical data or network control	2	8
5	Medical data or network control	4	8
4	Voice (VO)	4	16
3	Video (VI)	8	16
2	Excellent effort (EE)	8	32
1	Best effort (BE)	16	32
0	Background (BK)	16	64

2. Related Studies

Since the IEEE 802.15.6 standard has recently been released, there have been very few probabilistic works in the literature that analyze the CSMA/CA mechanism of the IEEE 802.15.6 standard. However, many researchers have analyzed the CSMA/CA protocol of various other communication standards in their articles. Performance analyses of the CSMA/CA mechanism for various IEEE wireless communication standards were presented in [4–7] for IEEE 802.11; in [8–11] for IEEE 802.11e; in [12, 13] for IEEE 802.15.4; and in [14] for IEEE 802.15.3c. Because the IEEE 802.15.6 CSMA/CA mechanism is different from the mechanisms of other wireless technologies, these analytical models are not appropriate for the IEEE 802.15.6 standard. In [16, 17], the authors study the performance of IEEE 802.15.6 CSMA/CA only under saturation conditions. The results indicate that the medium is accessed widely by the high-user-priority nodes, while the other nodes starve. In [18], the authors present numerical formulas to determine the theoretical throughput and delay limits of IEEE 802.15.6-based networks. They aim to optimize the packet size and to determine the upper bounds of IEEE 802.15.6 networks for different WBAN applications. They assume a collision-free network with no user priorities (UPs). The authors in [15] propose an analytical model to evaluate the performance of a contention-based IEEE 802.15.6 CSMA/CA mechanism under saturated conditions for heterogeneous WBAN scenarios. However, in most real-world IEEE 802.15.6 networks, the saturation assumption is not likely to hold, and the traffic is mostly nonsaturated. In [19] the authors study the normalized throughput performance of IEEE 802.15.6 slotted ALOHA protocol in nonsaturation conditions. In [20] the authors develop an analytical model for performance evaluation of the IEEE 802.15.6 standard under nonsaturation regime. They only calculated the mean response time of the data frames in the network. In [21] the authors develop a DTMC model for the analysis of reliability and throughput of an IEEE 802.15.6 CSMA/CA-based WBAN under saturation condition. A generalized three-dimensional Markov chain with backoff stage, backoff counter, and retransmission counter, as the stochastic parameters, is proposed in [22].

3. Performance Analysis

In order to analyze the CSMA/CA performance of the IEEE 802.15.6 MAC protocol, we introduce a DTMC model under nonsaturation modes, as shown in Figure 3. We adopt the same analytic model as presented in [23]. We consider Poisson packet arrival at the rate of λ packets/microsecond. We assume that a sensor node can have only one packet at a time so that if it has a packet to transmit, then no other packets are generated. Eight user priorities in the WBAN, UP_i where $i \in \{0, 1, 2, 3, 4, 5, 6, 7\}$ are differentiated by CW_{min} and CW_{max}, as depicted in Table 1. UP_7 has been given an aggressive priority as compared to the other UPs. Moreover, UP_7 nodes also have a separate AP for transmission. The contention window size for a UP_i node during the jth backoff stage is calculated as $W_{i,j} = 2^{\lfloor j/2 \rfloor} CW_{i,\min}$. We assume a star-topology single-hop WBAN with N heterogeneous nodes. The total number of nodes in the network can be obtained as $N = \sum_{i=0}^{7} n_i$, where n_i is the number of nodes in a class. We consider two nodes in each class. In the proposed analytical model, we consider that the lengths of EAP2, RAP2, and CAP are set to 0. We assume that transmissions errors are only due to collisions. We do not consider any retry limit in our model. We consider that the nodes access the medium without any RTS/CTS mechanism.

Let P_{tr} be the probability that there is at least one transmission in the time slot under consideration and let β_i

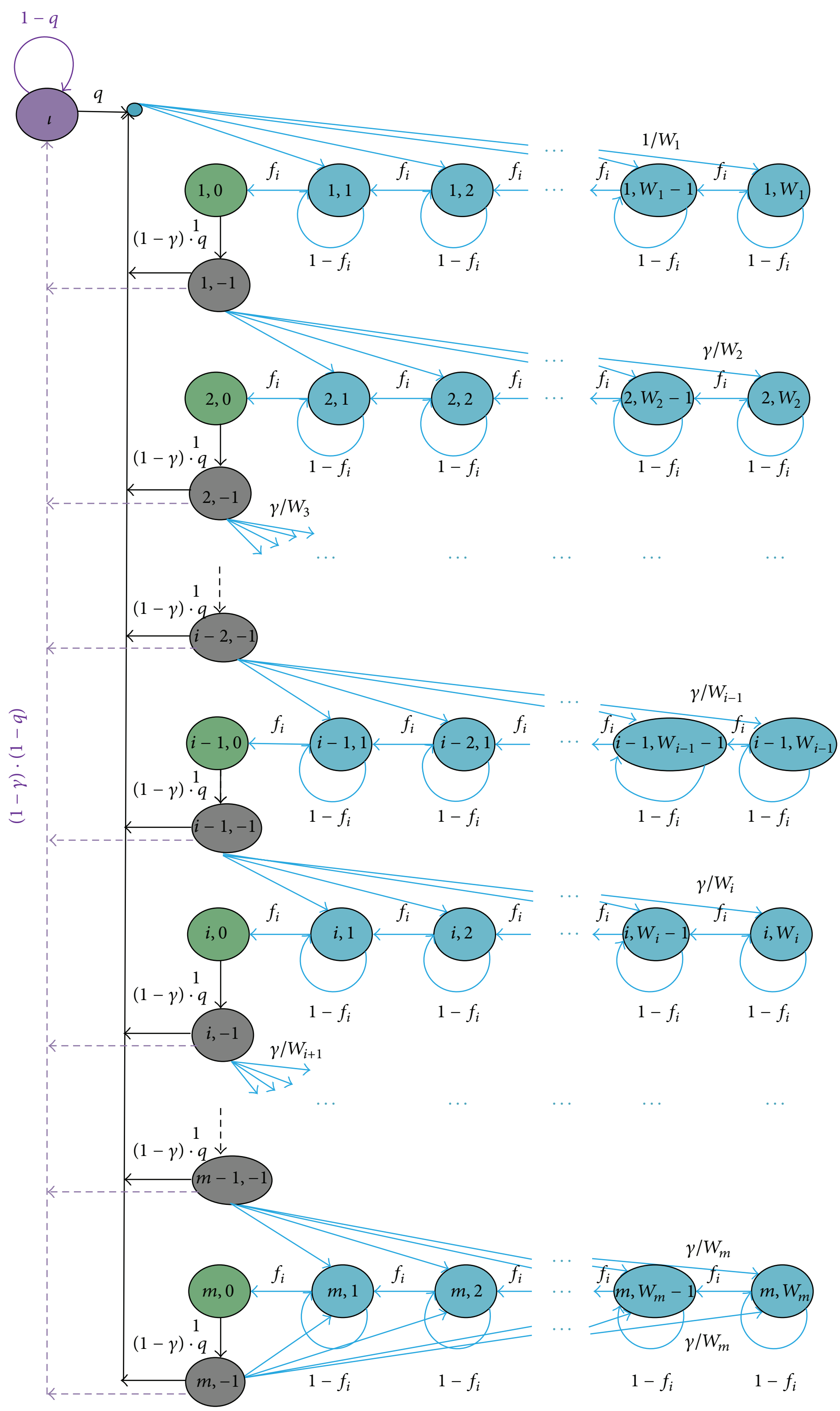

Figure 3: DTMC model for the CSMA/CA behavior in nonsaturated traffic conditions.

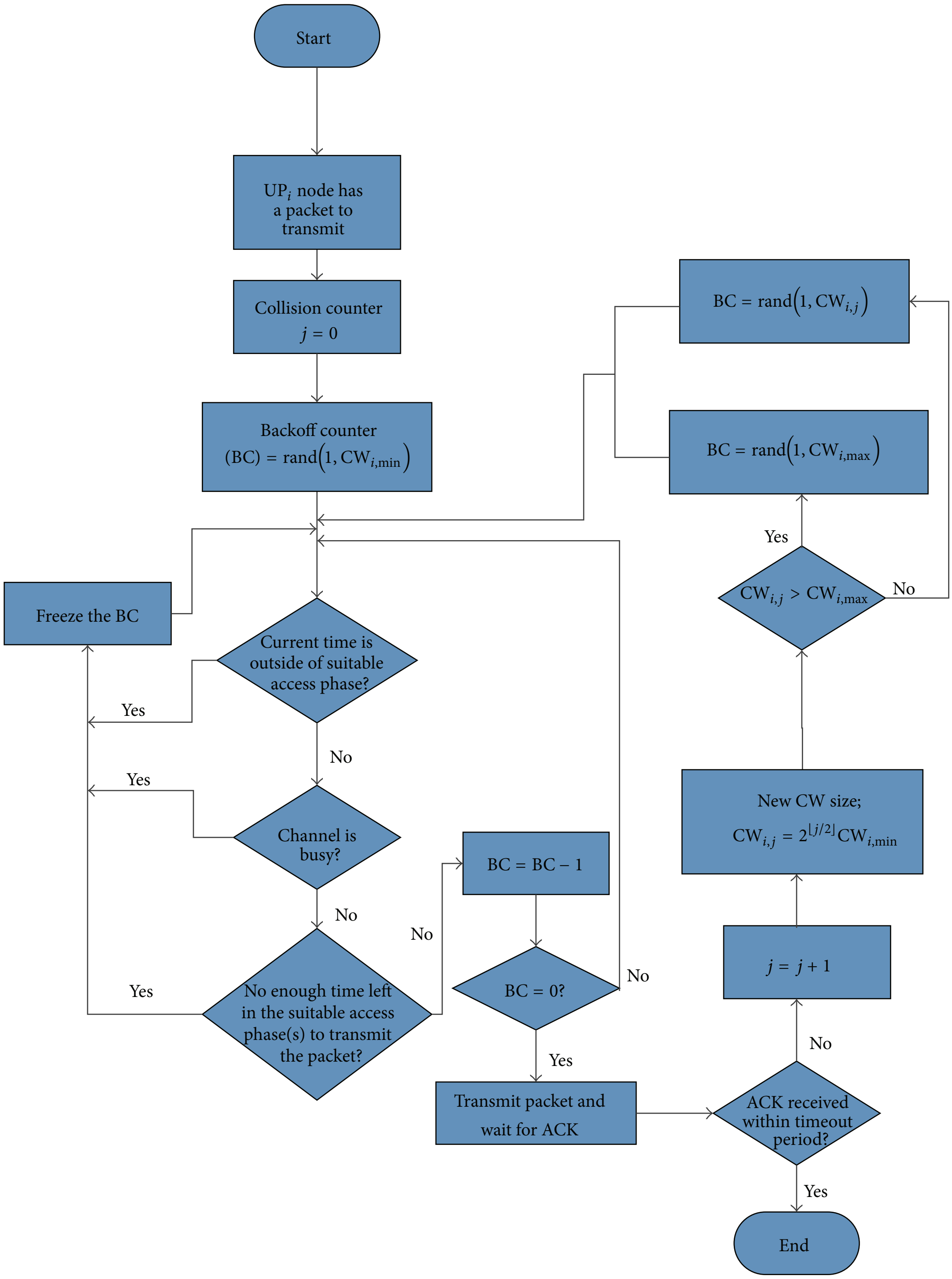

FIGURE 4: IEEE 802.15.6 CSMA/CA flowchart.

be the probability that a node of class i transmits in a generic slot; P_{tr} is given by

$$P_{tr} = 1 - \prod_{i=0}^{7} (1 - \beta_i)^{n_i}. \qquad (1)$$

The collision probability for a class i node can be obtained as follows:

$$\gamma_i = 1 - (1 - \beta_i)^{(n_i - 1)} \prod_{j=0, j \neq i}^{7} (1 - \beta_j)^{n_j}. \qquad (2)$$

Let T_s and T_c be the average durations for which the medium is sensed to be busy owing to a successful and a collision transmission, respectively. T_s and T_c can be computed as

$$T_s = T_c = T_{(\text{MAC+PHY})\text{overhead}} + T_{\text{Payload}}. \quad (3)$$

Let $E_{\text{state},i}$ be the expected time spent per state of the Markov chain by a tagged node of class i. We compute $E_{\text{state},i}$ as follows:

$$E_{\text{state},i} = (1 - P_{\text{tr}}) \cdot \delta + \sum_{i=0}^{7} P_{s,i} \cdot T_s + T_c \left(1 - \sum_{i=0}^{7} P_{s,i}\right) + P_{\text{tr}} \cdot (1 - \gamma) T_{\text{ack}}. \quad (4)$$

δ is the length of a pCSMAslot mentioned in the standard.

Let q be the probability that a packet is available to the MAC of a node in a given slot and let λ be the packet arrival rate. q is determined by

$$q = 1 - e^{-\lambda E_{\text{state},i}}. \quad (5)$$

$P_{s,i}$ be the probability that a transmission occurring on the medium by a class i node is successful and can be computed as

$$P_{s,i} = n_i \beta_i (1 - \beta_i)^{n_i - 1} \prod_{j=0, j \neq i}^{7} (1 - \beta_j)^{n_j}. \quad (6)$$

Let X_{eap} and X_{rap} be the mean number of slots in EAP1 and RAP1, respectively, and let them be computed as follows:

$$X_{\text{eap}} = \frac{\text{eap}}{E_{\text{state},i}}, \qquad X_{\text{rap}} = \frac{\text{rap}}{E_{\text{state},i}}, \quad (7)$$

where eap and rap are the duration of the access phases EAP1 and RAP1, respectively.

In a given pCSMA slot the backoff counter of a node should be locked till the beginning of the next eligible AP if there is no enough time for a packet transmission during the current AP. This probability is represented as

$$\widehat{e}_i = \begin{cases} \dfrac{1}{\text{rap} - T_s}, & 0 \le i \le 6, \\ \dfrac{1}{\text{eap} + \text{rap} - T_s}, & i = 7. \end{cases} \quad (8)$$

Therefore, for a UP_i node the probability to decrement the backoff counter during RAP1 is given by

$$f_i = \frac{\prod_{j=0}^{7} (1 - \beta_j)^{n_j} * (1 - \widehat{e}_i)}{(1 - \beta_i)}, \quad i = 0, \ldots, 6. \quad (9)$$

The probability that a UP_7 node decrements the backoff counter during EAP1 or RAP1 is given by

$$f_7 = \frac{X_{\text{rap}} \prod_{j=0}^{7} (1 - \beta_j)^{n_j} (1 - \widehat{e}_7)}{(X_{\text{eap}} + X_{\text{rap}})(1 - \beta_7)} + \frac{X_{\text{eap}} (1 - \beta_7)^{n_7} (1 - \widehat{e}_7)}{(X_{\text{eap}} + X_{\text{rap}})(1 - \beta_7)} \quad (10)$$

Let η_i be the normalized per class throughput, defined as the fraction of time for which the medium is used to successfully transmit payload bits. It can be computed as

$$\eta_i = \begin{cases} \dfrac{P_{s,i} * T_{\text{payload}} * X_{\text{rap}}}{\text{eap} + \text{rap}}, & 0 \le i \le 6, \\ \dfrac{P_{s,i} * (X_{\text{rap}} + X_{\text{eap}}) * T_{\text{payload}}}{\text{eap} + \text{rap}}, & i = 7. \end{cases} \quad (11)$$

T_{payload} is the mean payload duration.

Thus, normalized system throughput can be obtained as

$$\eta = \sum_{i=0}^{7} \eta_i. \quad (12)$$

Let T_i be the duration between the instant that the packet arrives at the head of the queue of a class i node and the time when the packet is successfully acknowledged by the receiver. The mean frame service time can be expressed as

$$T_i = \begin{cases} \dfrac{\left(\delta \cdot \gamma_i / (1 - \gamma_i) + T_s + E_{\text{state},i} \sum_{j=0}^{m_i - 1} \gamma_i^j \cdot W_{i,j+1}/2 + E_{\text{state},i} \left(\gamma_i^{m_i} W_{i,m} / 2 (1 - \gamma_i)\right)\right) * X_{\text{eap}}}{\text{eap} + \text{rap}}, & 0 \le i \le 6, \\ \delta \cdot \dfrac{\gamma_i}{1 - \gamma_i} + T_s + E_{\text{state},i} \displaystyle\sum_{j=0}^{m_i - 1} \gamma_i^j \cdot \frac{W_{i,j+1}}{2} + E_{\text{state},i} \frac{\gamma_i^{m_i} W_{i,m}}{2 (1 - \gamma_i)}, & i = 7. \end{cases} \quad (13)$$

Energy is quite critical in WBANs, and therefore, in addition to the throughput and the mean frame service time, we are also interested in calculating the energy consumption. We estimate the energy consumption on a per-node per-packet basis. The expression for the mean frame service time T_i in (13) represents the time elapsed from the arrival of the packet until its successful delivery. The service time of the packet might contain a number of unsuccessful transmissions, with the associated backoff intervals. Denoting by P_{tx}, P_{rx}, P_{bo}, and P_{sleep} the power consumed by the transceiver of a node during transmission, reception, backoff, and sleep, respectively, we derive an estimate of the energy consumption $E_{\text{AVG},i}$ for a class of UP_i node on a per-node per-packet basis as follows:

$$E_{AVG,i} = \begin{cases} \dfrac{\left(1/\lambda * P_{sleep} + \delta \cdot (\gamma_i/(1-\gamma_i)) * P_{rx} + T_s * P_{tx} + P_{bo} * E_{state,i} \sum_{j=0}^{m_i-1} \gamma_i^j \cdot W_{i,j+1}/2 + P_{bo} * E_{state,i} (\gamma_i^{m_i} W_{i,m}/2(1-\gamma_i))\right) * X_{eap}}{eap + rap}, & 0 \le i \le 6, \\ \dfrac{1}{\lambda} * P_{sleep} + \delta \cdot \dfrac{\gamma_i}{1-\gamma_i} * P_{rx} + T_s * P_{tx} + P_{bo} * E_{state,i} \sum_{j=0}^{m_i-1} \gamma_i^j \cdot \dfrac{W_{i,j+1}}{2} + P_{bo} * E_{state,i} \dfrac{\gamma_i^{m_i} W_{i,m}}{2(1-\gamma_i)}, & i = 7. \end{cases} \quad (14)$$

A sensor node deployed with a CSMA/CA mechanism needs to wait for a random backoff time before transmission. Let $b(t)$ be the stochastic process representing the backoff time counter for a given sensor node. The backoff time counter of each contending node decrements after each successful pCCAtime, and the counter is stopped when the medium is sensed busy. Given that the value of the backoff counter of each contending node also depends on its transmission attempts, each transmission attempt leads the node to a new backoff window called the backoff stage. Let $s(t)$ be the stochastic process representing the backoff stage of the node at time t. It is possible to model the two-dimensional stochastic processes $s(t)$ and $b(t)$ depicted in Figure 3 with a discrete time Markov chain having the following one-step transition probabilities among them:

$$\begin{aligned} &\Pr((i,k-1) \mid (i,k)) = f_i, \quad 1 \le k \le W_i, \\ &\Pr((i,-1) \mid (i,0)) = 1, \quad 1 \le i \le m, \\ &\Pr(i+1,k) \mid (i,-1) = \frac{\gamma}{W_{i+1}}, \\ &\qquad 1 \le i \le m-1, \ 1 \le k \le W_{i+1}, \\ &\Pr(1,k) \mid (i,-1) = q \cdot (1-\gamma) \cdot \frac{1}{W_1}, \\ &\qquad 1 \le i \le m, \ 1 \le k \le W_1, \\ &\Pr(l \mid (i,-1)) = (1-\gamma)(1-q), \quad 1 \le i \le m, \\ &\Pr(l \mid l) = 1-q, \\ &\Pr((1,k) \mid l) = q \cdot \frac{1}{W_1}, \quad 1 \le k \le W_1, \\ &\Pr((m,k) \mid (m,-1)) = \frac{\gamma}{W_m}, \quad 1 \le k \le W_m, \\ &\Pr((i,k) \mid (i,k)) = 1-f_i, \quad 1 \le k \le W_i. \end{aligned} \quad (15)$$

The first equation in (15) reflects the fact that, after each successful pCCAtime, the backoff counter is decremented. The second equation reflects the fact that, after a transmission, the nodes involved in the current transmission (at a state $(i,0)$) wait for an $ACK_{timeout}$ period to know the status (success/collision) of their transmitted packet. Upon an unsuccessful transmission, the node chooses another random backoff value uniformly distributed in the range $1,\ldots,W_{i+1}$, and this is shown in the third transition probability of (15). The fourth case deals with the situation that, after a successful transmission, another packet is generated, and the node takes a new backoff for the new packet. The fifth case models the fact that, after a successful transmission, the node has no packet to transmit and so enters the idle state. The node remains in the idle state until a new packet arrives, when the node takes a new random backoff value in the range $1,\ldots,W_1$ (first backoff stage); these are depicted in the sixth and seventh expressions. The second last case models the fact that once the backoff stage reaches value m, it is not increased in a subsequent packet retransmission. Finally, the last case reveals that the backoff counter is locked whenever a node detects any transmission on the channel during pCCATime, or if it is not allowed to access the medium during the current access phase, or the current AP length is not long enough for a frame transmission.

For mathematical convenience, the abbreviated notations (i,k) are used to represent the random processes $s(t)$ and $b(t)$, respectively. The backoff stage i starts at 1 and can reach a maximum value of m. Once the backoff stage reaches the maximum value m, it is not increased for a packet retransmissions. A contending node, after reaching a maximum backoff stage m will continue to try in that backoff stage until the packet is successfully transmitted. Counter k is initially chosen uniformly between $[1,W]$, where W is initially set to CW_{min}, and then its value increases in a nonbinary exponential manner, as explained in Section 1. The state $(i,0)$ in our Markov chain is the state of transmission (at backoff stage i), which can be either successful or colliding. With $b(i,k)$ and $b(l)$ we now show how to obtain a closed-form solution for the Markov chain depicted in Figure 3. The main quantity of interest is the probability that a node transmits in a generic slot, regardless of the backoff stage. We denote $\beta_i : i \in \{0,1,2,3,4,5,6,7\}$ as the transmission probability by a UP_i node. This probability can be expressed as

$$\beta_i = \sum_{i=1}^{m} b(i,0). \quad (16)$$

The stationary probability of being in the $ACK_{timeout}$ state $(i,-1)$ can be expressed as

$$b(i,-1) = 1b(i,0) \quad 1 \le i \le m. \quad (17)$$

Therefore (1) can be written as

$$\beta_i = \sum_{i=1}^{m} b(i, -1). \tag{18}$$

The stationary distributions $\sum_{k=1}^{W_1-1} b(1,k) + b(1,W_1)$ represent the topmost row of the Markov chain and is simplified as

$$\begin{aligned}&\sum_{k=1}^{W_1-1} b(1,k) + b(1,W_1)\\ &\quad = \frac{1}{f_i}(1-\gamma_i)\sum_{j=1}^{m}\gamma_i^j(1-\gamma_i)\beta_i\frac{W_1+1}{2}.\end{aligned} \tag{19}$$

Similarly, The stationary distribution $\sum_{k=1}^{W_m-1} b(m,k) + b(m,W_m)$ represents the lowermost row of the Markov chain and can be expressed as

$$\begin{aligned}&\sum_{k=1}^{W_1-1} b(m,k) + b(m,W_m)\\ &\quad = \frac{1}{f_i}\gamma_i\{b(m-1,-1) + b(m,-1)\}\frac{W_m+1}{2}.\end{aligned} \tag{20}$$

The stationary distribution $\sum_{i=2}^{m-1}\sum_{k=1}^{W_i-1} b(i,k) + \sum_{i=2}^{m-1} b(i, W_i)$ can be expressed as

$$\begin{aligned}&\sum_{i=2}^{m-1}\sum_{k=1}^{W_i-1} b(i,k) + \sum_{i=2}^{m-1} b(i,W_i)\\ &\quad = \frac{1}{f_i}\gamma_i\sum_{i=2}^{m-1}\left\{b(i-1,-1)\frac{W_i+1}{2}\right\}.\end{aligned} \tag{21}$$

Similarly, sum of the remaining stationary distributions of the Markov chain is given by

$$\begin{aligned}&\sum_{i=1}^{m} b(i,0) + \sum_{i=1}^{m} b(i,-1) + b(l)\\ &\quad = \beta_i\left\{2 + \frac{1}{q}(1-q)(1-\gamma_i)\right\}.\end{aligned} \tag{22}$$

The stationary distribution $b(l)$ takes into consideration the situation where the queue of the node is empty and is waiting for a packet to arrive.

To find the normalized equation,

$$\sum_{i=1}^{m}\sum_{k=-1}^{W_i} b(i,k) + b(l) = 1. \tag{23}$$

Let us sum the stationary distributions of (19), (20), (21), and (22) that give

$$\sum_{k=1}^{W_1-1} b(1,k) + b(1,W_1) + \sum_{k=1}^{W_1-1} b(m,k) + b(m,W_m) + \sum_{i=2}^{m-1}\sum_{k=1}^{W_i-1} b(i,k) + \sum_{i=2}^{m-1} b(i,W_i) + \sum_{i=1}^{m} b(i,0) + \sum_{i=1}^{m} b(i,-1) + b(l) = 1 \tag{24}$$

$$\begin{aligned}&\Longrightarrow \frac{1}{f_i}(1-\gamma_i)\beta_i\cdot\frac{(W_1+1)}{2} + \frac{1}{f_i}\cdot\gamma_i\cdot\frac{(1-\gamma_i)\beta_i}{2}\left\{\sum_{j=1}^{m-1}\gamma_i^j\left(W_{i,j+1}+1\right) + \gamma_i^m\left(W_{i,m}+1\right)\right\} + \beta_i\left\{2 + \frac{1}{q}(1-q)(1-\gamma_i)\right\}\\ &\quad = 1\end{aligned} \tag{25}$$

$$\Longrightarrow \beta_i = \frac{1}{2 + (1/q)(1-q)(1-\gamma_i) + (1/f_i)(1-\gamma_i)^2\sum_{j=0}^{m}\gamma_i{}^j\cdot\left(W_{i,j+1}+1\right)/2 + (1/f_i)(1-\gamma_i)\cdot\gamma_i^{m+1}\cdot\left(W_{i,m}+1\right)/2}. \tag{26}$$

Equations (2) and (26) represent a nonlinear coupled system with 16 unknown variables of γ_i and β_i, which can be solved by using a contraction-mapping method in MATLAB. Here we use MATLAB's fsolve function to solve the problem. The values of γ_i and β_i can then be used to estimate the desired performance metrics such as normalized throughput, mean frame service time, and energy consumption by using (11), (13), and (14), respectively.

4. Results and Discussion

To validate the accuracy of the developed analytical model, we have compared its results with an event-driven custom-made simulation program written in the C++ programming language. The simulator closely follows the behavior of the CSMA/CA mechanism of the IEEE 802.15.6 standard. The simulations are performed for a WBAN with five user priorities by considering two nodes in each class and a hub. Here, we consider the CSMA/CA MAC mechanism running in the narrowband (NB) PHY, as described by the standard. The NB PHY operates in seven different frequency bands and offers a variable number of channels, bit rates, and modulation schemes. One of these seven frequency bands is used for an implantable WBAN, whereas the other six are used for a wearable WBAN. The focus of this analysis is on the seventh band (or the sixth band of a wearable WBAN) of the NB PHY layer of 2400~2483.5 MHz, because it is a commonly used, free Industrial, Scientific, and Medical (ISM) band. The

Table 2: Narrowband "channel seventh" parameters and energy descriptions.

Slot time	145 μs
pSIFS	75 μs
pCCA	105 μs
pCSMAMACPHYTime	40 μs
MAC header	56 bits
MAC footer	16 bits
PHY header	31 bits
Payload	1020 bits
PLCP Header (data rate)	91.9 (kb/s)
PSDU (data rate)	971.4 (kb/s)
P_{tx}	29.9 mW
P_{rx}	24.5 mW
P_{bo}	24.5 mW
P_{sleep}	37 μW

values of the parameters used to obtain our results, for both the analytical model and the simulation, are summarized in Table 2. These parameters are specified for a narrowband PHY in the IEEE 802.15.6 standard. The packet payload has been assumed to be constant and is equal to 1020 bits, which is the average value of the largest allowed payload size for the NB PHY. For estimating energy, we used the parameters considered in [24]. In all the plots in this section, we used standard markers to represent the data obtained from the simulations and different type of lines to refer to the analytical results.

For a given number of nodes, we see that the throughput for lower-priority nodes decreases drastically as λ increases. This is because with a low arrival rate, very few nodes have packets to transmit, but when the arrival rate increases, the number of attempts decreases more for the lower-priority nodes. All these curves show that classes with smaller CW_{min} and CW_{max} have a higher priority in accessing the channel and hence higher throughput performance because of the smaller values of CW_{min} and CW_{max} reduces the average backoff time before a transmission attempt. From Figures 5 and 6 it is clear that the IEEE 802.15.6 CSMA/CA employing different access phases degrades the normalized throughput performance of the nodes other than UP_7 nodes. This is because nodes other than UP_7 are unable to transmit in the EAP period and hence their performance degrades. While UP_7 has the same number of nodes for all the results so its performance is the same even with the use of an EAP period. The duration of EAP is 0.3 seconds and the duration of RAP is 0.6 seconds in case when EAP is half in length of RAP period.

Figures 7 and 8 show the overall network throughput for the two different scenarios, that is, without access phases and with access phases, respectively. The network consists of five different user priority classes, where each class has the same number of nodes but has different combination of CW_{min} and CW_{max} values. These results show that IEEE 802.15.6 CSMA/CA employing access phases degrades the overall system throughput performance.

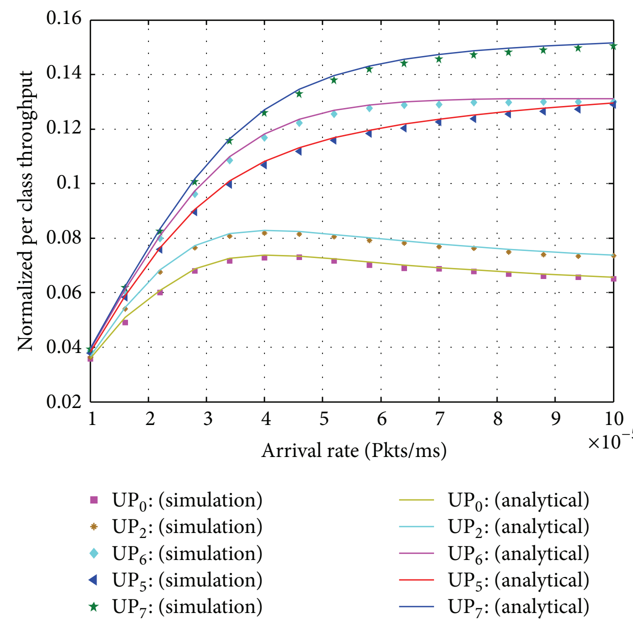

Figure 5: Normalised per class throughput by considering both EAP and RAP as one RAP.

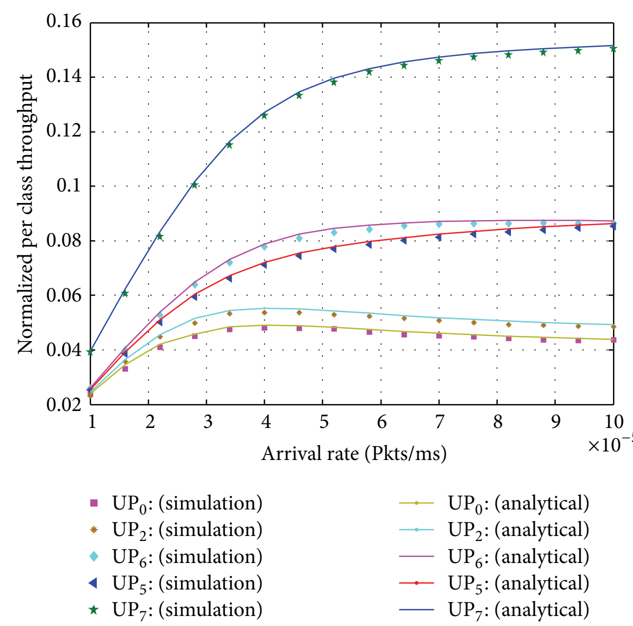

Figure 6: Normalised per class throughput, when EAP length is half of RAP.

The mean frame service time performance in a nonsaturated heterogeneous scenario is illustrated in Figures 9 and 10 as a function of the arrival rates. For a given UP_i, we see that the mean frame service time increases with an increase in the arrival rate. The mean frame service time increases quickly for low-priority classes compared with high-priority classes as λ increases, because smaller values of CW_{min} and CW_{max} reduce the average backoff time. From Figures 9 and 10, it is clear that the IEEE 802.15.6 CSMA/CA employing different

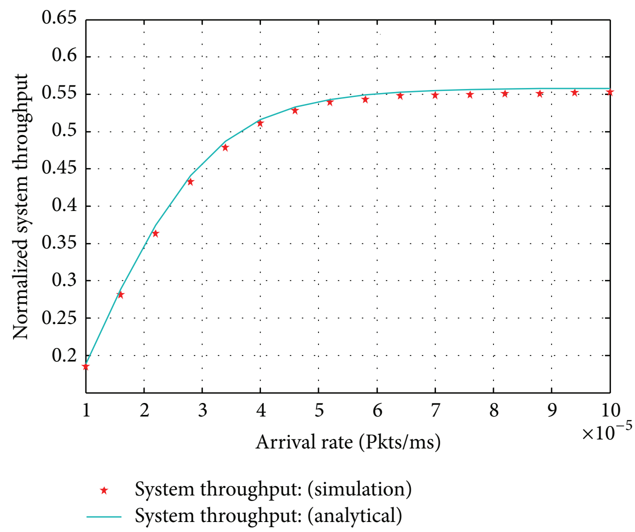

Figure 7: Normalised system throughput by considering both EAP and RAP as one RAP.

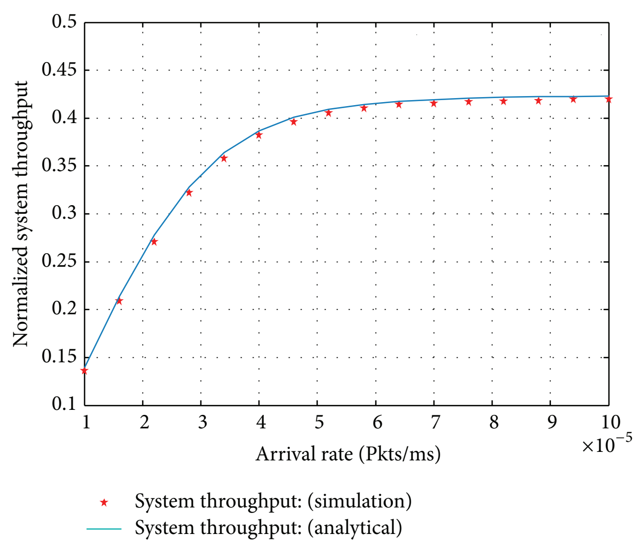

Figure 8: Normalised system throughput, when EAP length is half of RAP.

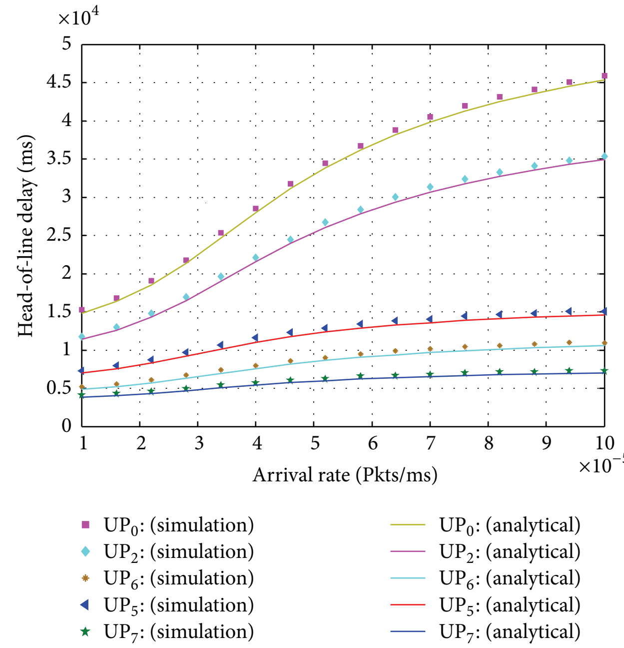

Figure 9: Head-of-line delay by considering both EAP and RAP as one RAP.

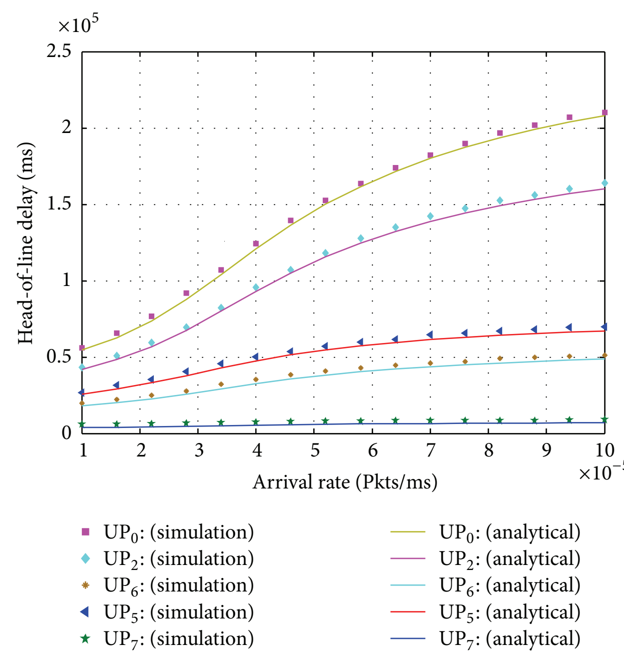

Figure 10: Head-of-line delay, when EAP length is half of RAP.

access phases maximizes the mean frame service time of the nodes other than UP_7. This is because nodes other than UP_7 are unable to transmit in the EAP period and hence their mean frame service time increases. While UP_7 has almost the same performance for all the results even with the use of an EAP period. From these results, we can optimize the length of the access phases and number of nodes to achieve a reasonable delay.

Figures 11 and 12 show the average energy consumption of a UP_i node on a per-node per-packet basis for the two different scenarios against the arrival rate (packets/microsecond). It is clear that the energy consumption for a higher user priority is very low as compared to that for a low user priority, as is the case for the mean frame service time in Figures 9 and 10. This is understandable in light of the fact that the longer frame service time is attributed to the longer periods of backoff and unsuccessful transmissions, and thus, the associated energy consumption also increases until a successful transmission occurs. The more energy consumption for lower user priority classes in the case of different access phases happens due to the higher mean frame service time of the nodes.

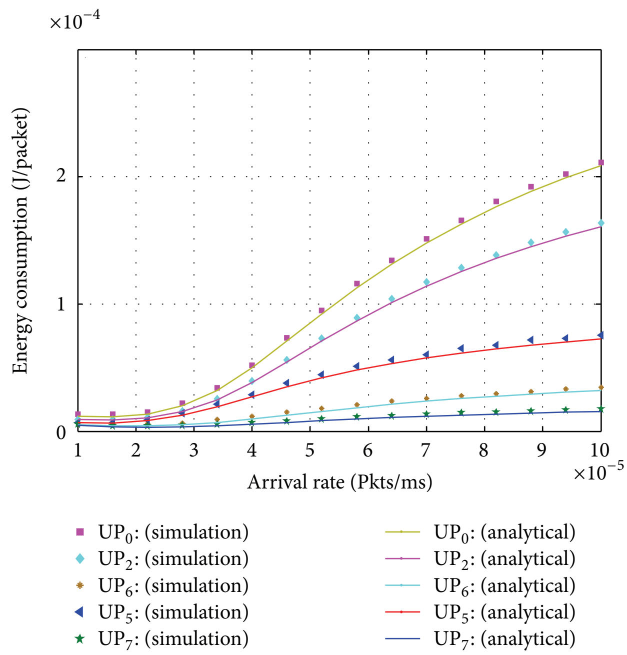

Figure 11: Energy consumption by considering both EAP and RAP as one RAP.

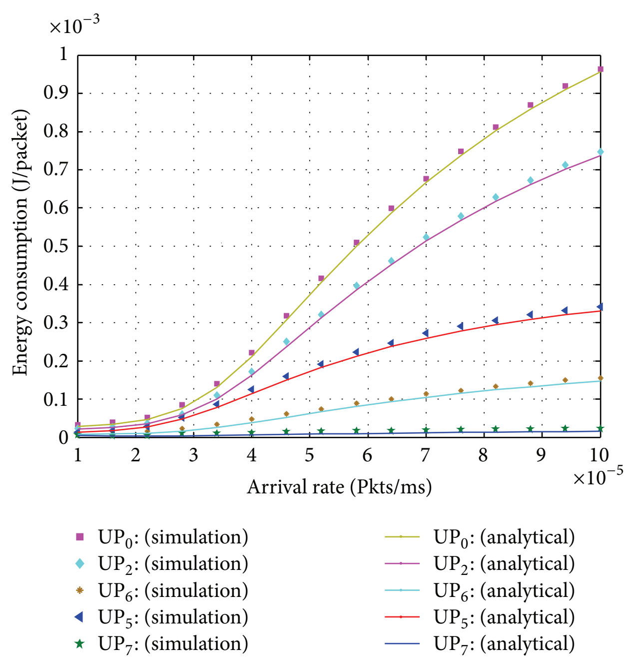

Figure 12: Energy consumption, when EAP length is half of RAP.

5. Conclusions

In this study, we developed a discrete time Markov chain to model the backoff procedure of IEEE 802.15.6 CSMA/CA under nonsaturated conditions, by considering different access phases lenghts. We evaluated the performance of the IEEE 802.15.6 CSMA/CA mechanism to predict energy consumption, normalized throughput, and mean frame service time of the network by employing the proposed Markov chain model. The performance measures obtained by the analytical model were validated against accurate simulation results. Our results show that the IEEE 802.15.6 CSMA/CA mechanism utilizes the medium poorly for low priority users. In addition, the use of different access phases degrades the overall system throughput performance, resulting in higher delay for nonemergency nodes and hence more energy per packet consumed. We can optimize the length of the access phases to achieve better throughput and reasonable delay. This model will be extended in our future work, considering all the APs, error-prone channel, and multi-user environments. We also intend to fine-tune the length of the access phases and number of nodes for different user priorities, which will lead to comparatively better system throughput and minimum delay.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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