Modeling and Performance Analysis of MAC Protocol for WBAN with Finite Buffer

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Abstract

The IEEE 802.15.6 standard is introduced to satisfy all the requirements for monitoring systems operating in, on, or around the human body. In this paper, analytical models are developed for evaluating the performance of the IEEE 802.15.6 CSMA/CA-based medium access control protocol for wireless body area networks (WBAN) under unsaturation condition. We employ a three-dimensional Markov chain to model the backoff procedure, and an M/G/1/K queuing system to describe the packet queues in the buffer. The throughput and delay performances of WBAN operating in the beacon mode are analyzed in heterogeneous network comprised of different user priorities. Simulation results are included to demonstrate the accuracy of the proposed analytical model.

Keywords: Wireless body area networks, IEEE 802.15.6, medium access control (MAC), carrier-sense multiple access with collision avoidance (CSMA/CA), Markov chain, M/G/1/K queuing system.

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1. Introduction

Wireless body area network (WBAN) is a novel wireless technology-driven human body monitoring network which aims to predict, diagnose, and monitor the response of the body to treatments[1]-[3]. The network typically consists of a collection of low-power, miniaturized, invasive or non-invasive, lightweight devices with wireless communication capabilities [4]-[6]. The collected data is transmitted to a medical center to be further processed, stored and applied. WBANs must satisfy the various requirements of application scenarios, such as reliability, quality of service (QoS), low power, high data rate and noninterference [7]-[10]. Hence, the IEEE 802.15 working group developed the IEEE 802.15.6 standard optimized for low power devices operating in the vicinity of, or inside a human body (but not limited to humans) [11].

Performance of the CSMA/CA mechanism in IEEE standards has been studied in [12]-[14] for IEEE 802.11, [15], [16] for IEEE 802.11e and [17]-[22] for IEEE 802.15.4. However, there is not much work in the reported literature, which investigates the IEEE 802.15.6-based network performance. In [23], [24], analytical models are presented to estimate the saturation throughput based on a slotted Aloha protocol. In [25], a simple model is proposed to evaluate the theoretical throughput and delay limits of the IEEE 802.15.6-based networks. However, the user priorities and the backoff stages are not taken into account. In [26], [27], analytical models are developed to evaluate performance of the IEEE 802.15.6 CSMA/CA mechanism with respect to exclusive access phase (EAP) and random access phase (RAP), and contention access phase (CAP), but the packet arrival process is not considered, i.e., it is assumed that there is at least one data frame in the queue waiting to be served at all times. Performance of the CSMA/CA mechanism under unsaturation condition is studied in [22] for IEEE 802.15.4, but the developed models are not appropriate for the IEEE 802.15.6 due to the different characteristics of the CSMA mechanisms.

In this paper, we evaluate the performance of the IEEE 802.15.6 CSMA/CA based MAC protocol, and the activities in the contention-free access phases are ignored. We develop a three-dimensional Markov chain to model the backoff procedure of the CSMA/CA mechanism during the exclusive and random access phases of IEEE 802.15.6 under unsaturated condition. The discrete-time Markov chains are solved to calculate the medium access probabilities of all user priorities. Afterwards, we develop an M/G/1/K queuing model to analyze the queue length in the buffer [28]. Using probability generating functions (PGFs), we compute the average packet service time, and furthermore, the average packet delay and throughput are derived. The analytical results are validated by using simulations.

The paper is organized as follows: Section 2 specifies the IEEE 802.15.6 CSMA/CA medium access control, and Section 3 provides a discrete-time Markov chain model for the analysis of the IEEE 802.15.6 CSMA/CA-based MAC for all user priorities. In Section 4, a finite-length first-in-first-out (FIFO) buffer is modeled as an M/G/1/K queue and analyzed by using an embedded Markov chain approach. Section 5 presents the performance analysis, including throughput and average packet delay. Section 6 validates the analytical results by numerical simulations. Finally, we conclude our results in Section 7.

2. IEEE 802.15.6 CSMA/CA MAC Specification

In this paper, we assume that the hub in a CSMA/CA-based WBAN operates in beacon mode with superframe boundaries. Each superframe is divide into different access phases as shown in **Fig. 1.** A hub or any node may obtain contended allocations in RAP if it requires the transmission of data frames for all eight user priorities UP_k , $k = 0,\ldots,7$, in the WBAN. UP_7 has an aggressive priority compared to the other user priorities. During the EAP periods, the medium is only accessible by UP_7 with very small contention window sizes. The hub or a node with the highest user priority (UP) frames may treat the combined EAP and RAP as a single EAP to allow continual invocation of CSMA/CA and improve channel utilization.

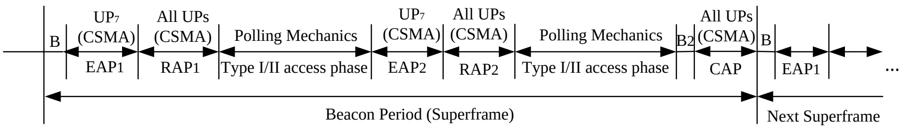

Fig. 1. IEEE 802.15.6 superframe period for beacon mode

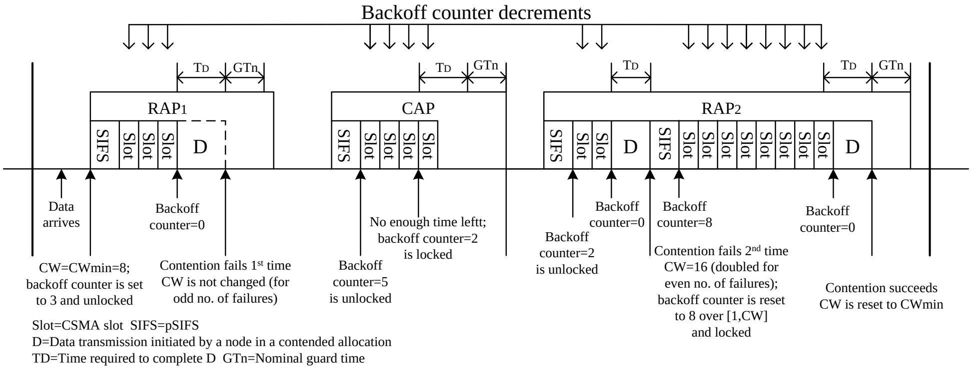

Fig. 2. CSMA/CA procedure used in IEEE 802.15.6

The user priorities, as shown in **Table 1**, are differentiated by the values of the minimum and maximum contention windows ($CW_{k,min}$ and $CW_{k,max}$), respectively. **Fig. 2** shows the CSMA/CA procedure defined in the IEEE 802.15.6 standard. Based on the CSMA/CA mechanism, a node shall maintain a backoff counter and a contention window to determine when it obtains a new contended allocation. The node sets its backoff counter to a sample of an integer random variable uniformly distributed over the interval $[1, CW_k]$. The node is allowed to transmit one frame of UP over the medium if the backoff counter reaches 0. The contention windows CW_k , $k = 0,\ldots,7$, are chosen as follows:

Table 1. WBAN user priorities

User priority	CW_{min}	CW_{max}	Traffic
0	16	64	Background (BK)
1	16	32	Best effort (BE)
2	8	32	Excellent effort
3	8	16	Controlled load (CL)
4	4	16	Video (VI)
5	4	8	Voice (VO)
6	2	8	Medical data/network control
7	1	4	Emergency/medical report

- If the node succeeds a data frame transmission, or requires no acknowledgement, but it does not obtain any contended allocation previously, it sets CW_k to $CW_{k,min}$.
- If the node fails, i.e., if the node does not receive an expected acknowledgement to its last frame transmission in the last contended allocation it has obtained, and if this is the *m*th time the node has failed consecutively, where *m* is an odd number, it keeps CW_k unchanged. Otherwise, CW_k is doubled.
- If doubling CW_k makes new CW_k exceed $CW_{k,max}$, the node shall set CW_k to $CW_{k,max}$.

The node locks the backoff counter when any of the following events occurs:

- The backoff counter is reset upon decreasing to 0.
- The channel is busy. If the channel is busy because the node detects a frame transmission, the channel remains busy until at least the end of the frame transmission without having to resense the channel.
- The current time is at the start of a CSMA slot within an EAP, RAP, or CAP, but the time between the end of the slot and the end of the EAP, RAP, or CAP is not long enough to complete a frame transaction and setting aside a nominal guard time.

3. Markov Chain Model

In this section, we provide a discrete-time Markov chain model for the analysis of the CSMA/CA-based IEEE 802.15.6 MAC. All eight *UPs* are considered, and each node has one *UP*. A node belongs to UP_k if it has a queue of user priority *k*. We consider a single hop WBAN with n_k nodes of UP_k and lengths of EAP2, RAP2, and CAP are set to 0. Finally, it is assumed that packets arrive at the nodes for transmission according to a Poisson arrival rate of λ packets per packet duration.

The backoff counter for a node of UP_k is an integer uniformly drawn over the interval $[1, CW_k]$, where $CW_k = W_{k,i}$, for $i = 0,\ldots,m$; *m* is the transmission retry limit and CW_k has minimum value of $CW_{k,min} = W_{k,0}$, and maximum value of $CW_{k,max} = W_{k,m_k}$. CW_k is set to $CW_{k,min}$ when the backoff procedure is started. The contention window size during the *i*th backoff stage for a node of UP_k, $CW_k = W_{k,i}$, is calculated as follows:

- $W_{k,0} = W_{k,min} = CW_{k,min}$.
- $W_{k,i} = \min\{2W_{k,i-1}, CW_{k,max}\}$ for $2 \le i \le m$ if i is an even number.
- $W_{k,i} = W_{k,i-1}$ for $1 \le i \le m$ if i is an odd number.

Figs. 3 shows the proposed discrete-time Markov chain model of the IEEE 802.15.6 MAC protocol in the unsaturated condition. Let $s_k(t)$ and $b_k(t)$ represent the backoff stage and the backoff counter corresponding to UP_k, respectively. We define p_k as the conditional collision probability regardless of the number of retransmission. Let $b_{k,i,j} = \lim_{t\to\infty} P\{s_k(t) = i, b_k(t) = j\}$, $i = 0,\ldots,m$, $j = 1,\ldots,W_{k,i}$ be the stationary distribution of the chain. In this Markov model, the one-step state transition probabilities are:

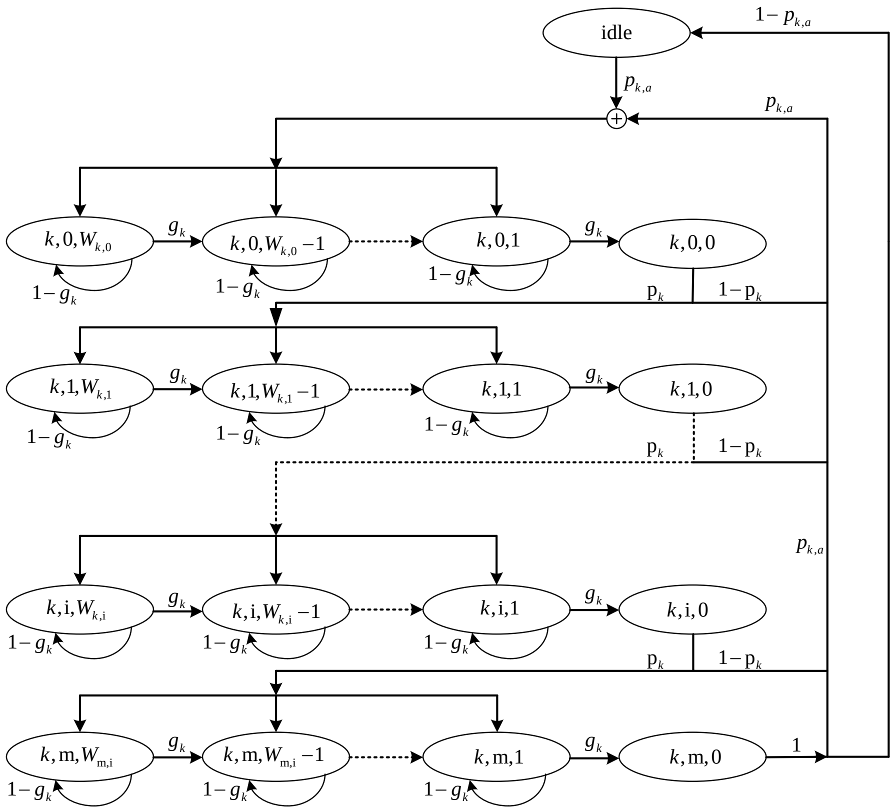

Fig. 3. Markov chain of IEEE 802.15.6 for UP_k

$$\begin{aligned}
&Pr\{k,i,j\,|\,k,i,j+1\} = g_k && i\in[0,m], \quad j\in[1,W_{k,i}-1]\\
&Pr\{k,i,j\,|\,k,i-1,0\} = p_k / W_{k,i} && i\in[1,m], \quad j\in[1,W_{k,i}]\\
&Pr\{k,0,j\,|\,k,i,0\} = (1-p_k)p_{k,a}/W_{k,0} && i\in[0,m], \quad j\in[1,W_{k,0}]\\
&Pr\{k,0,j\,|\,k,m,0\} = p_{k,a}/W_{k,0} && j\in[1,W_{k,0}]\\
&Pr\{k,0,j\,|\,e\} = p_{k,a}/W_{k,0} && j\in[1,W_{k,0}]\\
&Pr\{e\,|\,k,i,0\} = (1-p_k)(1-p_{k,a}) && i\in[0,m-1]\\
&Pr\{e\,|\,k,m,0\} = 1-p_{k,a}\\
&Pr\{e\,|\,e\} = 1-p_{k,a}
\end{aligned} \tag{1}$$

where g_k, $k=0,\ldots,7$ are the probabilities that the backoff counter of a node with UP_k decreases. Assume that there is sufficient time left for packet transmission, so g_k is equal to the probability q_k that the medium is idle during backoff countdown, for a node of UP_k, $k=0,\ldots,6$, which can be approximated as

$$q_k = \prod_{i\neq k}(1-\tau_i)^{n_i}(1-\tau_k)^{n_k-1} \tag{2}$$

For a node of UP_7, the probability that the medium is idle during backoff countdown can be described by

$$q_7 = \delta_1 \prod_{i \neq 7} (1-\tau_i)^{n_i} (1-\tau_7)^{n_7 - 1} + \delta_2 (1-\tau_7)^{n_7 - 1} \tag{3}$$

where τ_k is the probability of transmission for a node of UP_k assuming that the medium is not busy, $p_{k,a}$ is the probability that a node of UP_k has at least one packet to send in a time slot. δ_1 and δ_2 are expressed as $\delta_1 = l_R / (l_R + l_E)$, $\delta_2 = l_E / (l_R + l_E)$, where l_R and l_E are the lengths of RAP and EAP in slots, respectively. We define Y_k, $k = 0, \ldots, 7$ as the input probability to the zero-th backoff phase. Hence, we have

$$Y_k = \sum_{i=0}^{m-1} (1-p_k) p_{k,a} b_{k,i,0} + b_{k,m,0} p_{k,a} + p_{k,a} b_{idle} \tag{4}$$

where b_{idle} is the stationary probability of the idle state. By means of relations in (1), and the fact that $b_{k,i,0} = Y_k$, which can be derived by solving the Markov chain, all the stationary probabilities $b_{k,i,j}$ can be expressed as functions of the values $b_{k,0,0}$, p_k and $p_{k,a}$

$$\begin{aligned} b_{k,i,0} &= p_k^i b_{k,0,0} & i \in [1, m] \\ b_{k,0,j} &= \frac{W_{k,0} + 1 - j}{g_k W_{k,0}} b_{k,0,0} & j \in [1, W_{k,0}] \\ b_{k,i,j} &= \frac{W_{k,i} + 1 - j}{g_k W_{k,i}} p_k^i b_{k,0,0} & i \in [1, m],\ \ j \in [1, W_{k,i}] \end{aligned} \tag{5}$$

In view of the fact that $b_{idle} = (1-p_{k,a})(1-p_k) \sum_{i=0}^{m-1} b_{k,i,0} + b_{k,m,0}(1-p_{k,a}) b_{k,0,0} + (1-p_{k,a}) b_{idle}$, we obtain

$$b_{idle} = \frac{1-p_{k,a}}{p_{k,a}} b_{k,0,0} \tag{6}$$

Use the normalization condition of Markov chain, which means the sum of the stationary probabilities is equal to 1 for $k = 0, \ldots, 7$, we have

$$\begin{aligned} 1 &= \sum_{i=0}^{m} \sum_{j=0}^{W_{k,i}} b_{k,i,j} + b_{idle} \\ &= \frac{2g_k + 1}{g_k} \frac{1-p_k^{m+1}}{1-p_k} b_{k,0,0} + \frac{\bar{S}}{2g_k} b_{k,0,0} \end{aligned} \tag{7}$$

where

$$\begin{cases} \bar{S} = \dfrac{(1+p_k)(1-(2p_k^2)^{\lceil \frac{m}{2} \rceil +1})}{1-2p_k^2} & m \ \ is \ \ odd \\ \bar{S} = \dfrac{1-(2p_k^2)^{\lceil \frac{m}{2} \rceil +1} + p_k(1-(2p_k^2)^{\lceil \frac{m}{2} \rceil})}{1-2p_k^2} & m \ \ is \ \ even \end{cases} \tag{8}$$

where $\lceil m/2 \rceil$ denotes the ceiling function, which is the smallest integer not less than $m/2$.
Solving (7) results in the stationary probability of $b_{k,0,0}$ as the function of p_k and $p_{k,a}$, i.e.,

$$\begin{cases} b_{k,0,0} = \dfrac{2g_k(1-p_k)(1-2p_k^2)p_{k,a}}{(1+p_k)(1-(2p_k^2)^{\lceil \frac{m}{2} \rceil +1})p_{k,a}CW_{k,min} + \Gamma_1} & m \ \ is \ \ odd \\ b_{k,0,0} = \dfrac{2g_k(1-p_k)(1-2p_k^2)p_{k,a}}{(1-(2p_k^2)^{\lceil \frac{m}{2} \rceil +1} + p_k(1-(2p_k^2)^{\lceil \frac{m}{2} \rceil}))(1+p_k)p_{k,a}CW_{k,min} + \Gamma_1} & m \ \ is \ \ even \end{cases} \tag{9}$$

where

$$\Gamma_1 = (2g_k + 1)(1-p_k^{m+1})(1-2p_k^2)p_{k,a} + 2g_k(1-p_k)(1-2p_k^2)(1-p_{k,a}) \tag{10}$$

As any transmission starts when the backoff counter is equal to zero, regardless of the backoff stage, the probability τ_k that a node transmits in a randomly chosen slot can be expressed as

$$\tau_k = \sum_{i=0}^{m} b_{k,i,0} = \frac{1-p_k^{m+1}}{1-p_k} b_{k,0,0} \tag{11}$$

Note that the conditional collision p_k is the probability that a transmitted packet encounters a collision, which means, in a time slot, at least one of the remaining nodes transmits. In addition, nodes that do not have the highest priority cannot access the medium during EAP. Thus, for a node of priority UP_k, $k = 0,\ldots,6$, the conditional collision probability p_k during RAP can be expressed as

$$p_k = 1 - \sum_{i \neq k} (1-\tau_i)^{n_i} (1-\tau_k)^{n_k - 1} \tag{12}$$

The conditional collision probability for a node of UP_7 is given by

$$p_7 = 1 - \left(\delta_1 \sum_{i=0}^{6} (1-\tau_i)^{n_i} (1-\tau_7)^{n_7 - 1} + \delta_2 (1-\tau_7)^{n_7 - 1} \right) \tag{13}$$

Once $p_{k,a}$ is known, we can obtain the values of τ_k and p_k, $k = 0,1,\ldots,7$, from (11)-(13), where $p_{k,a}$ is derived from the following queuing model.

4. Markov Queuing Model

A finite-length FIFO buffer is employed at each node, which can be described by the Markov model with a queue capacity K. Note that K means $K-1$ packets wait in the queue and one is served, so the buffer length is $K-1$. If the buffer is full, the new arriving packets will be dropped. Since the packet generation follows a Poisson distribution and the service time general distribution, thus, it can be modeled as an M/G/1/K queue and analyzed by using an embedded Markov chain approach. The state space of the embedded Markov chain is $S = \{X_0, X_1, \ldots, X_K\}$, where X_j, $j = 1,\ldots,K$, denotes that there are *j* packets waiting in the queue and that one is served. Particularly, X_0 is the state that the queue is empty and no packets are served. Let B_n and Q_n be the queue length of the buffer at the beginning and at the end of the *n*th packet period. **Fig. 4** illustrates the Markov model with a queue capacity K. The transition probabilities from one state to another in the transmission process can be expressed as

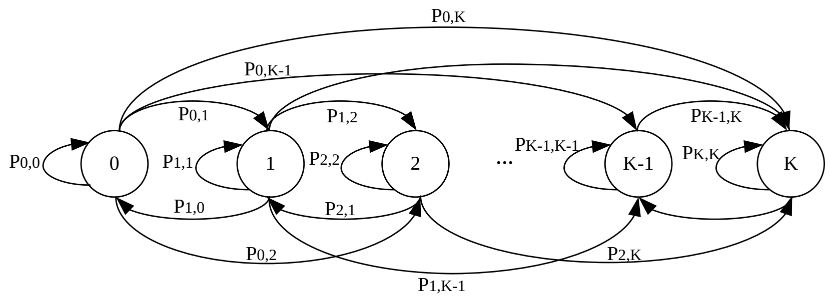

Fig. 4. Markov model with a queue capacity K

$$\begin{cases} Pr\{B_{n+1} = 0 \mid Q_n = 0\} = 1 \\ P_r\{B_{n+1} = r-1 \mid Q_n = r\} = p_{ac} \\ P_r\{B_{n+1} = r \mid Q_n = r\} = 1 - p_{ac} \end{cases} \tag{14}$$

where p_{ac} is the probability that the tagged node can catch the medium, which means that either a data packet is successfully transmitted, or a data packet is dropped as the transmission retry limit is reached. Suppose there are N nodes in a fully connected WBAN network. When a tagged node has a data packet to send, the probability that *n* nodes out of the other $N-1$ nodes competing for the medium can be described by

$$S_n = \begin{bmatrix} N-1 \\ n \end{bmatrix} (1-\pi_0)^n \pi_0^{N-n-1} \quad n = 0,1,\ldots,N-1 \tag{15}$$

where π_0 is the probability that a node have an empty queue in the buffer. Suppose the tagged node randomly choose time slot *s* to start backoff process, then the probability that it can catch the medium can be written as

$$p_{wn} = \sum_{i=0}^{m} \left(\prod_{j=0}^{i-1} p_{c,j} \right) p_{s,i} + \prod_{j=0}^{m} p_{c,j} \tag{16}$$

where $p_{c,j}$ is the probability that the tagged node suffers a collision during backoff stage *j*, which means that at least one of the remaining nodes chooses time slot $s, s+1, ..., W_{k,j}$ to start backoff procedure, i.e.,

$$p_{c,j} = \sum_{s=1}^{W_{k,j}} \left(\frac{W_{k,j} - s + 1}{W_{k,j}} \right)^n \left(1 - \left(\frac{W_{k,j} - s}{W_{k,j} - s + 1} \right)^n \right) \tag{17}$$

And $p_{s,j}$ is the probability that the tagged node transmits successfully during backoff stage *j*, which means that the other nodes randomly choose time slots from $s+1, s+2, ..., W_{k,j}$ to start backoff procedure, i.e.,

$$p_{s,i} = \sum_{s=1}^{W_{k,i}} \frac{1}{W_{k,i}} \left(\frac{W_{k,i} - s}{W_{k,i}} \right)^n \tag{18}$$

Using (16)-(18), we obtain

$$p_{ac} = \sum_{n=0}^{N-1} S_n p_{wn} \tag{19}$$

The state transition probabilities of the arrival process are given by:

$$\begin{aligned}
&Pr\{Q_{n+1} = i \mid B_{n+1} = 0\} = A_i, && i = 0,1,\ldots,K-1 \\
&P_r\{Q_{n+1} = K \mid B_{n+1} = 0\} = A_{\geq K} && \\
&P_r\{Q_{n+1} = j \mid B_{n+1} = i\} = A_{j-i}, && i = 1,2,\ldots,K-1, j = i,\ldots,K-1 \\
&P_r\{Q_{n+1} = K \mid B_{n+1} = i\} = A_{\geq K-i}, && i = 1,2,\ldots,K \\
&P_r\{Q_{n+1} = j \mid B_{n+1} = i\} = 0, && i = 2,\ldots,K, j = 0,\ldots,i-2
\end{aligned} \tag{20}$$

where A_i is the probability of i packets arriving during $(n+1)$-th packet period T_s, i.e., $A_i = e^{-\lambda T_s} (\lambda T_s)^i / i!$, and $A_{\geq i}$ is the probability of no less than i packets arriving in a packet period, i.e., $A_{\geq i} = 1 - \sum_{v=0}^{i-1} A_v$. For simplicity, we define the following probabilities

$$\begin{aligned}\alpha_{l,s} &= Pr\{Q_{n+1} = l \mid B_{n+1} = s\} \\ \beta_{s,r} &= Pr\{B_{n+1} = s \mid Q_n = r\}\end{aligned} \tag{21}$$

Given that the queue length is r in the previous packet period, the transition probability that there are l packets in the buffer is denoted by $p_{l,r}$. By use the fact that $Pr\{Q_{n+1} = l \mid Q_n = r\} = \sum_{s=0}^{K} Pr\{Q_{n+1} = l \mid B_{n+1} = s\} Pr\{B_{n+1} = s \mid Q_n\}$, we can obtain the transition probability matrix $P = [p_{l,r}]_{(K+1)\times(K+1)}$ as follows:

$$P = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1,K+1} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2,K+1} \\ \cdots & \cdots & \cdots & \cdots \\ \alpha_{K+1,1} & \alpha_{K+1,2} & \cdots & \alpha_{K+1,K+1} \end{bmatrix} \begin{bmatrix} \beta_{11} & \beta_{12} & \cdots & \beta_{1,K+1} \\ \beta_{21} & \beta_{22} & \cdots & \beta_{2,K+1} \\ \cdots & \cdots & \cdots & \cdots \\ \beta_{K+1,1} & \beta_{K+1,2} & \cdots & \beta_{K+1,K+1} \end{bmatrix} \tag{22}$$

The stationary probability of the number of packets in the buffer at the end of a packet period, denoted by π_n , can be expressed as

$$\pi_n =_{r\to\infty} Pr\{Q_r = n\} \tag{23}$$

where $0 \le n \le K$. The stationary probability π_n satisfies the following equations

$$\begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1,K+1} \\ p_{21} & p_{22} & \cdots & p_{2,K+1} \\ \cdots & \cdots & \cdots & \cdots \\ p_{K+1,1} & p_{K+1,2} & \cdots & p_{K+1,K+1} \end{bmatrix} \begin{bmatrix} \pi_0 \\ \pi_1 \\ \vdots \\ \pi_K \end{bmatrix} = \begin{bmatrix} \pi_0 \\ \pi_1 \\ \vdots \\ \pi_K \end{bmatrix} \tag{24}$$

In addition, according to the normalization condition, it follows that

$$\sum_{n=0}^{K} \pi_n = 1 \tag{25}$$

where Π is the vector of π_n , i.e., $\Pi = [\pi_0, \pi_1, \cdots, \pi_K]$. Assume that packet arrival information λ , A_i , $A_{\ge K}$ are known, solve (19), (24) and (25), we can obtain π_j , $j = 0,1,\ldots,K$. Since π_0 is the probability that a node has an empty queue in the buffer, $p_{k,a}$ is derived by

$$p_{k,a} = 1 - \pi_0 \tag{26}$$

5. Performance Analysis

Service time is the time interval from the time instant when a packet becomes the head of the MAC queue to the time instant when the packet is either successfully transmitted or dropped. Consider a system in which each packet is transmitted by means of the *RTS-CTS-data-ACK* access mechanism. Let $S_t(z)$ be the PGF of the packet transmission time, and $C_t(z)$ be the PGF of transmission time due to an RTS collision, which are described by

$$\begin{aligned} S_t(z) &= z^{rts+cts+l_d+ack+3sifs} \\ C_t(z) &= z^{rts+cts+sifs} \end{aligned} \tag{27}$$

where *rts/cts* denotes the length of RTS/CTS packet, and *ack* the length of ACK packet. *sifs* is the time duration of inter-frame space (SIFS), and l_d is the average packet length. We assume that all values of length are in time slots.

The PGF of the time that the backoff counter decrements by one during the backoff stage *i* can be expressed as

$$H_{k,i}(z) = g_k z + (1 - p_k) S_t(z) + p_k C_t(z) \tag{28}$$

Further, we can obtain the PGF of the time consumed in the backoff stage *i*, i.e.,

$$B_{k,i}(z) = \frac{1}{W_{k,i}} \sum_{j=1}^{W_{k,i}} H_{k,i}^{j}(z) \tag{29}$$

Since the service time is composed of the backoff time and the transmission time, and the probability that the packet is successfully transmitted at the *u*th backoff stage is $p_{s,u} = p_k^u(1 - p_k)$, we can obtain the PGF of the service time

$$P_{sv}(z) = \sum_{u=0}^{m} p_k^u (1 - p_k) \prod_{v=0}^{u} B_{k,v}(C_t(z))^u S_t(z) + p_k^{m+1} \prod_{i=0}^{m} B_{k,i}(C_t(z))^{m+1} \tag{30}$$

Thus, the average service time can be calculated by

$$T_{sv} = \left. \frac{dP_{sv}(z)}{dz} \right|_{z=1} \tag{31}$$

The packet delay is composed of two parts. One is the service time computed in the above, and the other is the queuing time from the time instant when a packet arrives in the queue to the time instant when it becomes the head of the queue. Let π_j^* be the steady-state probability that there are *j* packets found by an arbitrary arrival, which can be evaluated in terms of the steady probability that a departure customer leaves behind *j* customers, i.e., π_j. This leads to the expressions for the values of

$$\begin{cases} \pi_j^* = \dfrac{\pi_j}{\pi_0 + \lambda T_s} & 0 \le j \le K-1 \\ \pi_K^* = 1 - \dfrac{1}{\pi_0 + \lambda T_s} \end{cases} \tag{32}$$

The mean packet number in the buffer is straight forward

$$E[L_q] = \sum_{j=1}^{K} j\pi_j^* = \frac{\sum_{j=1}^{K-1} j\pi_j}{\pi_0 + \lambda T_s} + K\left(1 - \frac{1}{\pi_0 + \lambda T_s}\right) \tag{33}$$

Based on Little's law, the mean queuing delay is derived by

$$T_q = \frac{1}{\lambda}\left(\sum_{j=1}^{K-1} j\pi_j + K(\pi_0 + \lambda T_s - 1)\right) \tag{34}$$

Since the average packet delay is the sum of the average service time and average queuing delay, it follows that

$$T_{de} = T_{sv} + T_q \tag{35}$$

Based on the backoff algorithm and queuing model, per class throughput is computed by

$$\eta_k = \lambda(1 - X_K)(1 - p_k^{m+1})E[P_{ck}] \tag{36}$$

where $E[P_{ck}]$ is the average packet payload size. The system throughput can be obtained as

$$\eta = \sum_{k=0}^{7} \eta_k \rho_k \tag{37}$$

where $\rho_k = n_k / N$ is the probability of UP_k in the system.

6. Simulations

To validate the analytical model, simulation results are obtained by a significant amount of iterations. In this section, we investigate the performance analysis of the throughput and packet delay for different user priorities under the unsaturation and saturation conditions. We choose three classes of user priorities, i.e., a lower priority class UP_0, a medium priority class UP_3, and a higher priority class UP_5 to explain the results. And three pairs for (τ_k, p_k) in numerical values are obtained from the associated system of non-linear equations. The throughput and packet delay results are produced considering equal numbers of nodes for each user class.

Table 2. Simulation parameters

Parameters	Value
K	51 frames
Payload Size	800bits
Symbol Rate	187.5 kbps
Slot Time	63/Symbol Rate + 20e-6
MAC Header	56bits
$T_{Preamble}$	90/Symbol Rate
$T_{PLCPheader}$	31/Symbol Rate
ACK Length	88bits
Propagation Delay	2e-8s
pSIFS	50e-6s
MacACKWaitDuration	960e-6s
MaxFrameRetries	3
MaxCSMABackoffs	4

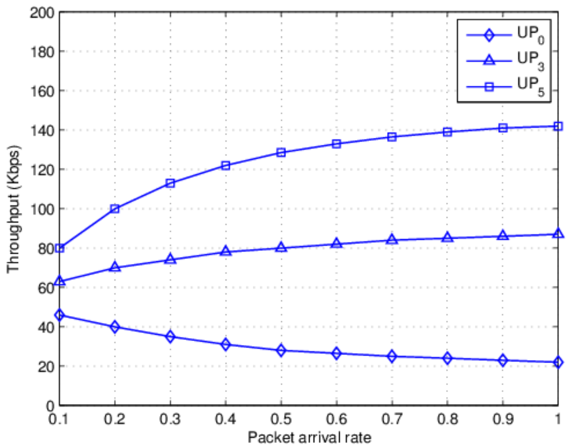

Fig. 5. Average throughput under the unsaturation condition

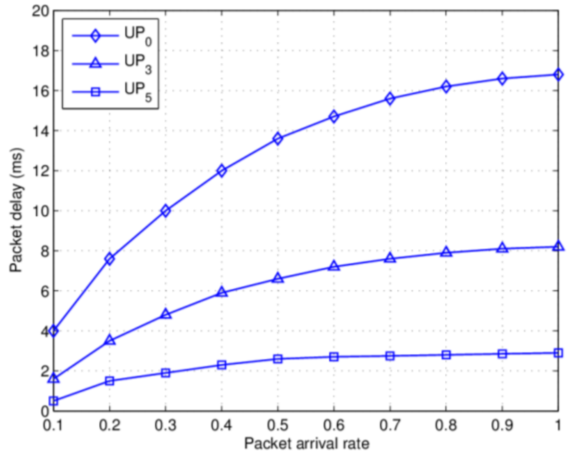

Fig. 6. Average packet delay under the unsaturation condition\

Figs. 5 and **Figs. 6** show the average throughput and packet delay of WBAN nodes with varying packet arrival rates λ for different user priorities, respectively. It can be seen that the higher priority nodes achieve higher throughput compared to the lower priority nodes. As the packet arrival rate in the network increases, the higher priority nodes access channel more frequently due to the lower $CW_{\min}$ and CW_{max} values, compared to the lower priority ones. In addition, given λ, the packet delay with the lower priority nodes is longer than the nodes with relative high priorities. With the arrival rate rising, the packet delay increases, and arrives at the peak value when the network approaches the saturated condition.

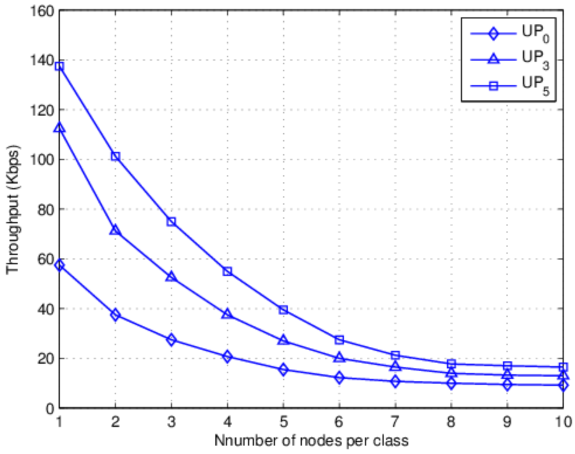

Fig. 7. Average throughput under the saturation condition

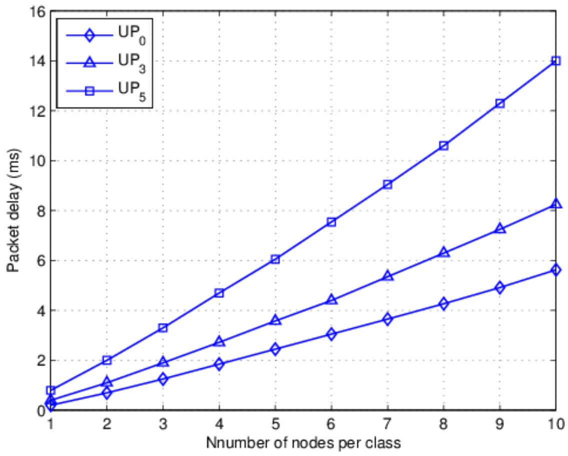

Fig. 8. Average packet delay under the saturation condition

Figs. 7 and **Figs. 8** illustrate the average throughput and packet delay of WBAN nodes for different user priorities in the saturation condition. As shown in **Fig. 7**, for the nodes with the same priority, the throughput decreases with the increasing of the number of nodes in the network because contentions will occur more frequently. When different priorities are assigned to the nodes, the higher priority class (UP_5) with lower contention window values can obtain a contended allocation more frequently than the lower priority class, UP_0. Hence, the nodes with the higher priority class achieve higher throughput with respect to the lower priority nodes. The performance of the average packet delay is shown in **Fig. 8**, obviously, as the use priority decreases, the packet delay becomes much longer. In addition, the packet delay increases with the number of the nodes, and the differences between different priority classes are greater for the larger amount of nodes.

7. Conclusions

In this paper, we evaluate the performance of the CSMA/CA based medium access mechanism of IEEE 802.15.6 under the unsaturation condition. The discrete-time Markov chains are used to solve the random medium access probabilities of all user priorities. A finite-length FIFO buffer is modeled as an M/G/1/K queue and analyzed by using an embedded Markov chain approach. Further, the throughput and average packet delay of WBANs are derived in heterogeneous networks. Simulations are carried out for different user priorities under the unsaturation and saturation conditions. Simulation results indicate that both the packet arrival rate and the user priorities have a great influence on the average throughput and packet delay of WBANs.

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