Performance Analysis of IEEE 802.15.6 MAC Protocol in Beacon Mode with Superframes

Changle Li [1,2*], Xiaoyan Geng [1], Jingjing Yuan [1], and Tingting Sun [1]
[1] State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an, Shaanxi, 710071 China
[2] National Mobile Communications Research Laboratory, Southeast University, Nanjing, Jiangsu 210096, China
[*e-mail: clli@mail.xidian.edu.cn]

Received October 16, 2012; revised February 3, 2013; accepted February 5, 2013; published May 31, 2013

Abstract

Wireless Body Area Networks (WBANs) are becoming increasingly important to solve the issue of health care. IEEE 802.15.6 is a wireless communication standard for WBANs, aiming to provide a real-time and continuous monitoring. In this paper, we present our development of a modified Markov Chain model and a backoff model, in which most features such as user priorities, contention windows, modulation and coding schemes (MCSs), and frozen states are taken into account. Then we calculate the normalized throughput and average access delay of IEEE 802.15.6 networks under saturation and ideal channel conditions. We make an evaluation of network performances by comparing with IEEE 802.15.4 and the results validate that IEEE 802.15.6 networks can provide high quality of service (QoS) for nodes with high priorities.

Keywords: WBAN, IEEE 802.15.6, MAC, Markov chain

This work was supported by National Natural Science Foundation of China under Grant No. 61271176, National Science and Technology Major Project under Grant No. 2011ZX03001-007-01 and 2013ZX03004007-003, Special Research Fund of State Key Laboratory under Grant No. ISN1102003, Open Research Fund of National Mobile Communications Research Laboratory, Southeast University under Grant No. 2012D01, and the 111 Project (B08038).

http://dx.doi.org/10.3837/tiis.2013.05.010

1. Introduction

The aging society, limited health care resources, the miniaturization of biomedical sensors, and a wide application market have triggered the concept of Wireless Body Area Networks (WBANs) and received considerable attentions in academy and industry. The WBANs applications contain medical applications, entertainment applications, and disability assistance applications. The medical applications contain periodic traffic of different duty cycles and unexpected traffic while the traffic of the entertainment application is mainly burst traffic. Moreover, due to potentially life-threatening situation, the reliable and timely delivery of vital body parameters is more critical requirement of patient monitoring. Due to heterogeneous service requirements from different applications and the time-varying channel characters owing to body motions, Wireless Personal Networks (WPANs) can’t satisfy the major medical requirements, for example, the timely and reliable emergency delivery, for WBANs. The IEEE 802.15 has established Task Group 6 (TG6) for an appropriate communication standard for WBANs, called IEEE 802.15.6. The first version of the standard had been issued in February 2012 [1] and has overcome limitations of IEEE 802.15.4 [2]. For example, IEEE 802.15.4 reckons without the priorities of different traffics, the adaptive adjustment of access phases and the timely and reliable delivery of emergency traffic. The IEEE 802.15.4 protocol describes three different physical layers (PHYs) and medium access control (MAC) specifications based on these PHYs for WBANs.

There are also many works about MAC protocols design. Literatures [3] and [4] proposed an efficient MAC protocol to improve energy consumption. A comprehensive investigation of WBAN was presented in [5] and [6]. Literatures also described the network layer communication and wireless radio technologies. As for the in-body communication, RF technology and MAC protocol were introduced in [7] and [8]. An efficient MAC protocol is very important to guarantee the timely delivery of emergency traffic. Therefore, the analysis of IEEE 802.15.6 is necessary and there have been a few works on its performance.

In the IEEE 802.15.6 protocol, there are eight user priorities (UPs) for different applications. A node may initiate frame transaction in different contended-based access phases using carrier sense multiple access with collision avoidance (CSMA/CA) and Slotted Aloha. A hub of body area network (BAN) has the ability of arranging committed scheduled allocation intervals, unscheduled bilink allocation intervals on a best-effort basis, and improvised polled and posted allocation intervals in contention free access phases. The detailed overview of MAC and PHY functionalities in IEEE 802.15.6 was presented in [9] and [10], which also provided important features and requirements for WBANs. References [11] and [12] investigated the medical sensor lifetime for real application requirements using scheduled access schemes.

Many literatures about performance analysis paid attention to CSMA/CA access schemes of IEEE 802.15.6. The theoretical maximum throughput and minimum delay limits of IEEE 802.15.6 were presented for different frequency bands and data rates in [13] and [14]. For a better network performance, the delay and throughput may not be meet simultaneously, which needs a compromise, and the method in [15] and [16] can be referred. IEEE 802.15.6 was analyzed using probability generation functions (PGFs) and the evaluation of network performances is provided, focusing on the impact of different access phases lengths on network performances in [17]-[20]. The author evaluated the network performance compared with IEEE 802.15.4 in terms of packet loss rate (PLR), delay, and throughput, by means of simulations in [21]. The applicability of IEEE 802.15.4 over WBANs was introduced using different access schemes in [22]. Reference [23] proposed an analytical model based on Markov chain and studied the throughput performance of IEEE 802.11 [24]. In [26], the author presented the network performance of different access categories in IEEE 802.11e [25], while an effective analysis of slotted IEEE 802.15.4 on delay is presented in [27].

The previous works of IEEE 802.15.6 focused on the length of access phases or the limit of delay and throughput, and didn't investigate the comprehensive effect of the traffic load, modulation and coding mode, and user priority on the performance of IEEE 802.15.6. In our work, we consider the comprehensive performance in the aspect of the normalized throughput and average access delay compared with IEEE 802.15.4.

In our work, in order to model the procedure of CSMA/CA, a modified Markov chain model is proposed to evaluate performances by comparing with theoretical results of IEEE 802.15.4 in terms of normalized throughput and average access delay. We model all eight UPs $(UP_i,\ i=0,...,7)$ under saturation conditions, i.e. there is always a packet waiting to transmit. The approximation that enables our model is the assumption of the constant and independent collision probability of a packet transmission by each node.

This paper is outlined as follows. Section 2 briefly reviews the standard. Section 3 employs a modified Markov model to analyze the node's behavior of access channel, and then drives the expressions of the normalized throughput and average access delay. Section 4 describes the analytical results under different scenarios and gets the conclusion that IEEE 802.15.6 can supply high QoS and low delay for nodes of high UPs by comparing with IEEE 802.15.4. Section 5 simply concludes the paper.

2. IEEE802.15.6 Standard

This is a standard for short-range, low power consumption wireless communication in the vicinity of, or inside, a human body. It supports QoS, extremely low power, and data rates up to 10 Mbps. In addition, it considers the body effect on the channel and the safety due to the specific absorption rate into the body. The following section presents relevant content in our work.

2.1 Physical Layer

IEEE 802.15.6 defines Narrowband (NB), Ultra wideband (UWB) and Human body communications (HBC) PHY specifications. Our analysis is based on NB physical layer. NB physical layer protocol data unit (PPDU) is composed of three components: the physical layer convergence protocol (PLCP) preamble, the PLCP header, and the physical-layer service data unit (PSDU). The PLCP preamble is to help nodes in packet detection, timing synchronization and carrier offset recovery. The PLCP header contains the information of data rate and length of MAC frame, and is transmitted using the given data rata after the PLCP preamble. The PSDU is formed with the MAC frame header, the MAC frame body and Frame Check Sequence (FCS) and is transmitted after PLCP header using one of four different data rates.

Table 1. Modulation parameter for PLCP header and PSDU

Packet Component	Modulation	Code Rate（k/n）	Spreading Factor(S)	Data Rate（kbps）	MCS
PLCP Header	π/2-DBPSK（M=2）	19/31	4	91.9	
PSDU	π/2-DBPSK（M=2）	51/63	4	121.4	0
PSDU	π/2-DBPSK（M=2）	51/63	2	242.9	1
PSDU	π/2-DBPSK（M=2）	51/63	1	485.7	2
PSDU	π/2-DQPSK（M=4）	51/63	1	971.4	3

NB physical layer operates in seven different frequency bands. Each frequency band offers four Modulation and Coding Schemes (MCSs), four data rates and different number of channels. The analysis focuses on the widely used industrial, scientific and medical (ISM) frequency bands and these bands operate at a symbol rate of 600 ksps. On the same frequency bands of IEEE 802.15.4, the data rate is 250 kbps. **Table 1** presents the value of date rates, modulation, code rate and spreading factor. The different MCSs and spreading factor determine different data rates of the PSDU.

2.2 Medium Access Control Layer

All nodes are organized intoBANs, and coordinated by their respective hubs for medium access. There is only one hub and at most mMaxBANSize (64) nodes constituting the BAN. There are eight UPs that indicate the priorities for access to the medium. The values of UPs are determined based on the traffic designation. The UP mapping and the corresponding value of the contention window (CW) in CSMA/CA are shown in **Table 2**.

Table 2. User priority mapping

Priority	User Priority	Traffic designation	CWmin	CWmax
Lowest	0	Background (BK)	16	64
	1	Best effort (BE)	16	32
	2	Excellent effort (EE)	8	32
	3	Video (VI)	8	16
	4	Voice (VO)	4	16
	5	Medical data or network control	4	8
	6	High priority medical data or network control	2	8
Highest	7	Emergency or medical	1	4

		implanted event report		

In order to support time reference allocations in BAN, a hub should establish a time base. The time axis is divided into superframes of equal length in order to support time reference allocations in the BAN. Each superframe consists of allocations slots of equal length and it is necessary for the hub to choose the boundary of the superframe and then of the allocation slots. A hub can operate in three modes: the beacon mode with superframes, the non-beacon mode with superframes and the non-beacon without superframes. Here we focus on the introduction to the beacon mode with superframes.

2.2.1 beacon mode with superframes

In our work, all the nodes and the hub operate in beacon mode with superframes and one-hop star network, in the assumption of all nodes supporting the CSMA/CA access. In this mode, after an active superframe there may be several continuous inactive superframes in which a hub doesn't transmit any beacon and also doesn't provide any access phase. **Fig. 1** shows the superframe structure of the beacon mode with superframes, which is divided into seven access phases: exclusive access phase 1 (EAP1), random access phase 1 (RAP1), managed access phase (MAP), exclusive access phase 2 (EAP2), random access phase 2 (RAP2), managed access phase (MAP), and contention access phase (CAP).

- Beacon: A hub transmits a beacon at the start of each superframe, except for inactive superframes, or other especial location due to the coexistence of the neighbor BAN. It is used to facilitate clock synchronization and network management.
- EAP1 and EAP2: Nodes or a hub that have the data of the highest UP such as emergency can obtain contend allocations by using CSMA/CA or slotted Aloha in EAP1 and EAP2. In order to improve channel utilization, nodes can treat the continuous EAP and RAP as the single EAP and are allowed continuous invocation of CSMA/CA.
- RAP1, RAP2 and CAP: Only nodes can compete for contended allocations to send management or data type frame using CSMA/CA access or slotted Aloha. These kinds of access phases are used for general of unexpected traffic. To provide a non-zero length CAP, the hub must transmit a preceding B2 frame and if the length of CAP is zero, there is unnecessary to transmit a B2 frame. The detailed algorithm procedure of CSMA/CA will be illustrated in the following context.
- MAP: Nodes or a hub can use a committed scheduled access, a best-effort unscheduled access and improvised access to the medium via connection request and connection assignment frame. Scheduled access and unscheduled access are both based on advance reservation for high or low duty cycle periodic and quasi-periodic traffics. Improvised access can be use as independent access, a supplemental access, or an enabling access to send polls or post to obtain improvised allocations.

According to the real requirement, the hub can set any of the access phases to zero, but RAP1 cannot end before the time that is defined by the connection assignment frame. The hub informs nodes of the end time of CAP by broadcasting a B2 frame.

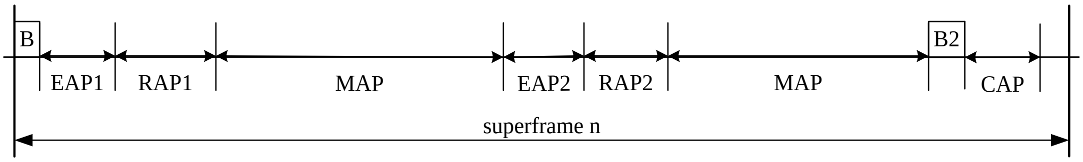

Fig. 1. Superframe structure of the beacon mode with superframes

2.3 CSMA/CA

There are many kinds of accesses in different access phases in the beacon mode with superframe. Here we focus on the CSMA/CA description on the RAP or CAP. All the nodes support the CSMA/CA access to obtain the channel. At a certain time, a packet arrives. Node sets the value of CW depending on the priority and the following regulations. Then node uniformly selects a random integer from the interval [1 CW] as the backoff counter value. The backoff counter is decreased by one once the CSMA/CA slot is idle, and begins to transmit a packet once the backoff counter reaches zero. Due to the sharing medium, the packet may collide with other nodes' transmitting packets and later the node retransmits the packet. The procedure of access the medium by using CSMA/CA is shown in **Fig. 2**. Each CSMA/CA slot has fixed duration and the hub considers the CSMA/CA slot to be idle if the channel is monitored idle for a period of time equal to 63 symbol duration time.

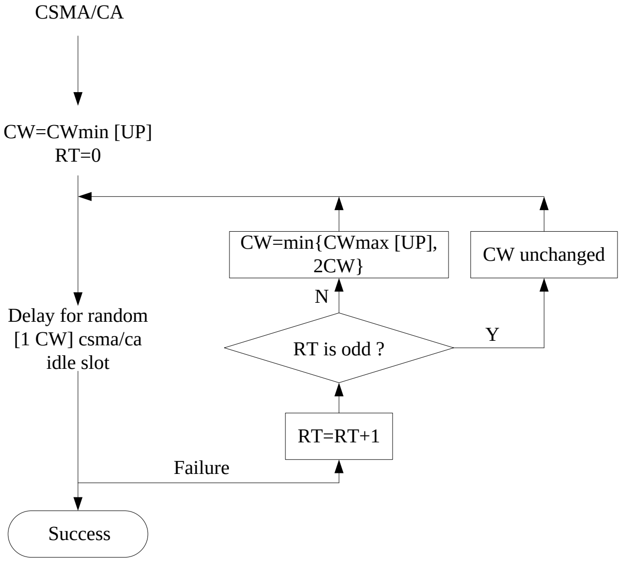

Fig. 2. Procedure of CSMA/CA algorithm

At a moment there is a packet waiting to transmit on the channel, but the current moment is outside its contention phase or there is not long enough to complete a packet transaction during the remaining time. The backoff counter is locked and waits the right time to be restarted at the moment that the channel has been sensed idle for SIFS and it is long enough to complete a packet transaction during the remaining time. When the backoff counter is decreased to zero, the node starts to transmit data. Because all the nodes share the channel, the packet may collide with packets being transmitted by other nodes and then the node retransmits the packet. Assume j represents the number of retransmission, the CW is set according to the regulation below and the maximums of CW cannot be larger than the corresponding CWmax[*UP*]. **Table 3** shows the CW value of the jth retransmission of different priority nodes and from the fifth retransmission nodes employ the CWmax as the CW value to obtain contended allocation intervals.

Table 3. CW value of retransmission

User Priority	CW		CW value of the jth retransmission					
	CWmax	CWmin	0	first	second	third	forth	fifth
0	16	64	16	16	32	32	64	64
1	16	32	16	16	32	32	32	32
2	8	32	8	8	16	16	32	32
3	8	16	8	8	16	16	16	16
4	4	16	4	4	8	8	16	16
5	4	8	4	4	8	8	8	8
6	2	8	2	2	4	4	8	8
7	1	4	1	1	2	2	4	4

According the user priority and the number of retransmission, nodes set the CW as follows:

1) If the node contends for allocation for the first time, it set the CW to CWmin[*UP*].
2) If a node transmits a packet successfully in the last contended allocation it has obtained, it sets the CW to CWmin[*UP*].
3) At the end of the last contended allocation, the packet being transmitted does not require an acknowledgement to the packet, it remains CW unchanged.
4) The node fails in the last contended allocation. If this is an odd number of failures, it remains CW unchanged, or if this is even number of failures, it doubles the CW, that the doubled CW cannot be exceed the CWmax[*UP*].

The backoff counter is reduced by one for each idle CSMA/CA slot and the node obtains the contended allocation and begins to transmit a packet once the backoff counter reaches zero. The obtained allocations span from the end of current CSMA/CA slot to the end of the access phase. As long as the node obtains the allocations and succeeds in transmitting a packet, the node will be able to transmit a new packet or retransmit an old packet with a UP not lower than the UP to obtain the current contended allocations. In our work, we assume the node transmits only one packet in the current contended allocation whether success or failure.

3. Analytical model

In this section, all eight UPs are considered and only one UP has packets to send in each node. That is, the UP in a node may be different with that of another one. The number of UP_i is n_i, and i represents the user priority. We analyze the network in the consumption of ideal channel, saturation condition, and assume that it always has enough time to complete a packet transaction in the access phases. If the packet is transmitted successfully, we consider that the ACK frame for the packet is successfully received by the sending node. Therefore, the failure of a packet is only due to the collision with packets being sent by other nodes and the backoff counter is frozen just because of the packet transmission of other nodes, instead of the reason that it hasn’t enough time to complete a packet transaction.

The analysis is divided into three parts. First, we analyze a node behavior of accessing medium using a Markov chain model, and the frozen states of a node during backoff stages using a backoff model. Then we get the access probability τ that a node sends a packet in a CSMA/CA slot. Second, based on the proposed models, we derive the expressions of normalized throughput of all UPs. At the last, the formula of average access delay for a successful packet is derived.

3.1 Markov Chain Model

In our work, we assume that a node has data to send at the moment t. Let $i(t)$ be the priority of a node at the moment t. Let $s(t)$ be stochastic process representing the backoff stage, i.e. the number of retransmission. Let $b(t)$ be stochastic process representing the backoff counter. Let s and c represent the success and failure of other nodes during the node's attempt to access the medium, respectively. Let $v(t)$ be stochastic process representing the remaining time during the successful transmission time or collision time. It is easy to model the process $\{i(t), s(t), b(t)\}$ with discrete-time Markov chain in the assumption that p_i (collision probability) and d_n (the channel busy probability during its backoff stage) are independent. The discrete-time Markov chain model is shown in **Fig. 3**.

At the beginning of each backoff stage, a random number is drawn from the range $[1\ W_{i,j}]$, where $CW_i = W_{i,j}$, j=0,…,m_i, and m_i is the backoff stage number in which the CW_i reaches the CWmax for the first time. The CW_i of a node during the jth backoff stage is got as follows:

$W_{i,0} = CW_{\min}[up]$
$W_{i,j} = W_{i,j-1}$ if j is an odd number
$W_{i,j} = \min\{W_{i,\max}, 2W_{i,j-1}\}$ if j is an even number

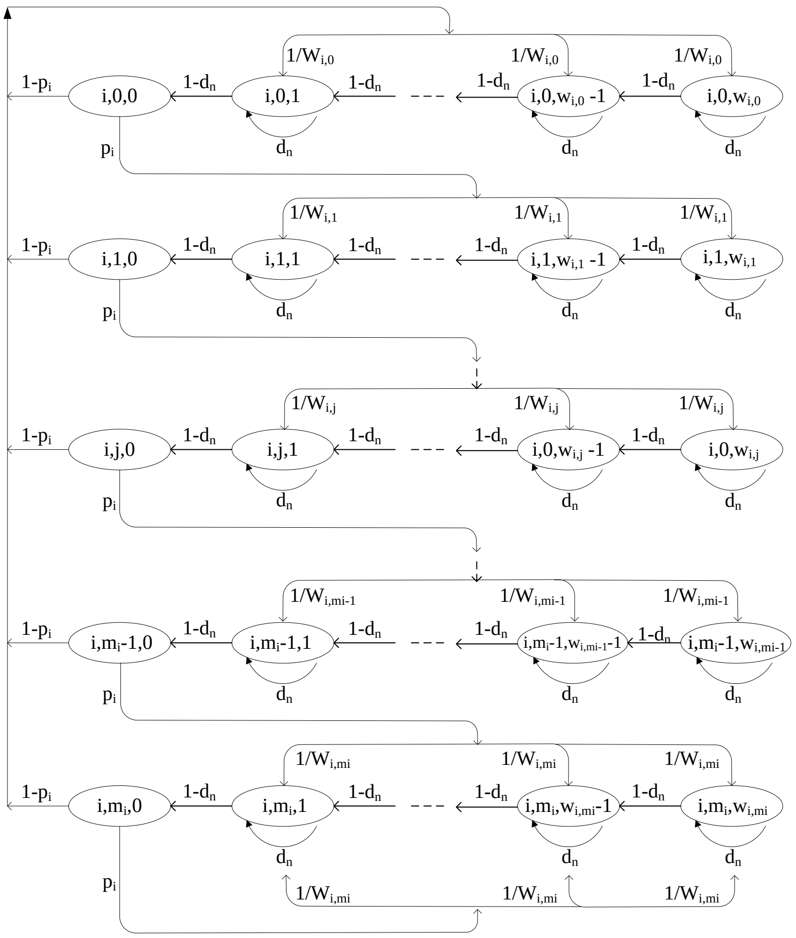

Fig. 3. Markov chain model for a node

In order to compute the performance exactly, we extend the Markov chain model that includes all the slots when the backoff counter is frozen. Due to the assumption that it has enough time to complete packet transaction, there are two cases that result in the channel busy status. One is the packet successful transmission and the other is the packet unsuccessful transmission. Considering that the backoff counter is locked, the node's current state in Markov chain model remains unchanged and is referred to as the frozen state. For accurate calculation, we concrete this frozen state from these two cases and the detailed frozen procedures of a state is shown in **Fig. 4**. Therefore, the state of node enters the corresponding states of the backoff model as a result of different reasons.

During the backoff stage of a node, if the channel is monitored busy, the backoff counter is locked and the node enters the frozen state. State $\{i, j, k, s, d\}$ and state $\{i, j, k, c, d\}$ represent the frozen states due to successful transmission of other nodes and due to failure of other nodes, respectively. Moreover, s and c represent the successful and the failing transmission respectively, and d represents the number of remaining slots during the collision or successful transmission periods. D_s is the total slot number that successful transmission needs, where $D_s = \lceil T_s / \sigma \rceil$ (T_s Ts is the successful transmission time) and D_c is the total slot number of the collision time, where $D_c = \lceil T_c / \sigma \rceil$.

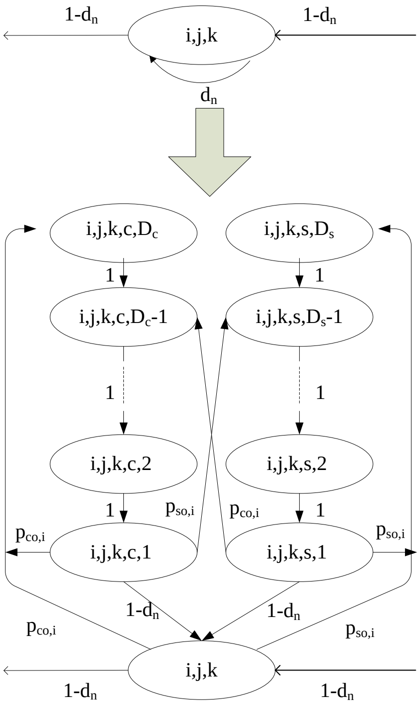

Fig. 4. Backoff model

All the transition probabilities in the model of **Figs. 3** and **4** are shown as follows.

1) For states $(i, j, 0)$, $i = 0,...,7$, when the backoff counter is zero, if there are other nodes to send a packet at the same time, the transmission is failed.

$$\begin{aligned} &P\{i, j+1, 0 | i, j, 0\} = p_i \qquad j \in (0, m_i) \\ &P\{i, \mathrm{m}_i, 0 | i, \mathrm{m}_i, 0\} = p_i \end{aligned} \tag{1}$$

2) For states (i, j, k), $k = 1,...,W_{i,j}$, the backoff counter decreases by one if the node senses the channel idle.

$$P\{i, j, k | i, j, k+1\} = 1 - d_n \qquad k \in (0, W_{i,j} - 1) \quad j \in (0, m_i) \tag{2}$$

3) For states $(i, j-1, 0)$ and (i, j, k) ,once the packet collides, the node sets the CW value according the regulation above, selects a random integer from [1,CW] and enter the next backoff stage.

$$P\{i, j, k | i, j-1, 0\} = p_i / W_{i,j} \qquad k \in (1, W_{i,j}) \quad j \in (1, m_i) \tag{3}$$

4) For states (i, j, k, s, d), $d = 1,...,D_s$, during the successful transmission of other nodes, the remaining slot number is reduced by one for each CSMA/CA slot.

$$P\{i, j, k, s, d | i, j, k, s, d+1\} = 1 \qquad d \in (1, D_s\text{ -}1),\ j \in (0, m_i),\ k \in (1, W_{i,j}) \tag{4}$$

5) For states (i, j, k, c, d), $d = 1,...,D_c$, during the failed transmission of other nodes, the remaining slot number is reduced by one for each CSMA/CA slot.

$$P\{i, j, k, c, d | i, j, k, c, d+1\} = 1 \qquad d \in (1, D_c\text{ -}1), j \in (0, m_i),\ k \in (1, W_{i,j}) \tag{5}$$

6) For states $(i,j,k,s,1)$ and $(i,j,k,c,1)$, if the channel is idle, the node unlocks the backoff counter.

$$\begin{aligned} &P\{i,j,k \mid i,j,k,s,1\} = 1-d_n \qquad j\in(0,m_i),\ k\in(1,W_{i,j}) \\ &P\{i,j,k \mid i,j,k,c,1\} = 1-d_n \qquad j\in(0,m_i),\ k\in(1,W_{i,j}) \end{aligned} \tag{6}$$

If the channel is detected busy, the node continues the frozen states and enters different frozen procedures.

$$\begin{aligned} &P\{i,j,k,s,D_s \mid i,j,k,s,1\} = p_{so,i} \qquad j\in(0,m_i),\ k\in(1,W_{i,j}) \\ &P\{i,j,k,s,D_s \mid i,j,k,c,1\} = p_{co,i} \qquad j\in(0,m_i),\ k\in(1,W_{i,j}) \\ &P\{i,j,k,c,D_c \mid i,j,k,c,1\} = p_{co,i} \qquad j\in(0,m_i),\ k\in(1,W_{i,j}) \\ &P\{i,j,k,c,D_c \mid i,j,k,s,1\} = p_{co,i} \qquad j\in(0,m_i),\ k\in(1,W_{i,j}) \end{aligned} \tag{7}$$

Let $b_{i,j,k}$, $b_{i,j,k,s,d}$ and $b_{i,j,k,c,d}$ be stationary probabilities of states (i,j,k), (i,j,k,s,d) and (i,j,k,c,d), respectively. We can get these relations according to the equilibrium states regularities of Markov chain. First, we have

$$b_{i,j,0} = \begin{cases} p_i^j b_{i,0,0} & j\in(0,m_i\text{ -}1) \\ \dfrac{p_i^{m_i}}{1-p_i} b_{i,0,0} & j=m_i \end{cases} \tag{8}$$

and

$$b_{i,j,k} = \begin{cases} b_{i,j,0} & k=0 \\ \dfrac{W_{i,j}+1-k}{W_{i,j}\left(1-d_n\right)} b_{i,j,0} & k\in(1,W_{i,j}) \end{cases} \tag{9}$$

For the backoff duration model, we can obtain the relations below:

$$b_{i,j,k,s,d} = \frac{p_{so,i}}{1-d_n} b_{i,j,k} \qquad d\in(1,D_s) \tag{10}$$

and

$$b_{i,j,k,c,d} = \frac{p_{co,i}}{1-d_n} b_{i,j,k} \qquad d\in(1,D_c) \tag{11}$$

Thus, by Eqs. (8), (9), (10), (11), all the states probability can be expressed as a function of the variable τ_i and of the conditional collision probability p_i. Based on the normalization condition of discrete-time Markov chains, summation of all the sates probabilities is equal to 1, which leads to the set of eight equations:

$$\begin{aligned} 1 &= \sum_{j=0}^{m_i} b_{i,j,0} + \sum_{j=0}^{m_i}\sum_{k=1}^{W_{i,j}} b_{i,j,k} + \sum_{j=0}^{m_i}\sum_{k=0}^{W_{i,j}}\sum_{d=1}^{D_c} b_{i,j,k,c,d} + \sum_{j=0}^{m_i}\sum_{k=0}^{W_{i,j}}\sum_{d=1}^{D_s} b_{i,j,k,s,d} \\ &= \tau_i + \left(1+\frac{D_s p_{so,i}}{1-d_n}+\frac{D_c p_{co,i}}{1-d_n}\right)\left[\frac{\tau_i}{2(1-d_n)}+\frac{\tau_i W_{i,0}}{2(1-d_n)}\left(\frac{(1-p_i^2)(1-(2p_i^2)^{m_i/2})}{1-2p_i^2}+(2p_i^2)^{m_i/2}\right)\right] \end{aligned} \tag{12}$$

Thus, we get eight equations as a function of the variables τ_i , p_i , d_n , $p_{so,i}$ and $p_{co,i}$. We can express the probability τ_i that a UP_i node attempts to access the medium in randomly chosen CSMA/CA slot, and it is the sum of all the steady states probabilities of states $(i, j, 0)$ .Then

$$\tau_i = \sum_{j=0}^{m_i} b_{i,j,0} = \frac{b_{i,0,0}}{1-p_i} \tag{13}$$

From the viewpoint of a UP_i node, during the backoff counter countdown, the collision probability p_i that there is at least one of the remaining nodes sending packets in the chosen CSMA/CA slot. The probability that the packet of the node is collided and enters the next backoff stage is

$$p_i = 1 - \frac{\prod_{i=0}^{7} (1-\tau_i)^{n_i}}{1-\tau_i} \tag{14}$$

Similarly, the probability d_n that the backoff counter is locked is

$$d_n = 1 - \frac{\prod_{i=0}^{7} (1-\tau_i)^{n_i}}{1-\tau_i} \tag{15}$$

During the backoff procedure, the probabilities $p_{so,i}$ and $p_{co,i}$ that the backoff counter is frozen due to the successful transmission or the failing transmission of other nodes is

$$\begin{aligned} p_{so,i} &= \sum_{k=0}^{7} \frac{n_k \tau_k \prod (1-\tau_i)^{n_k}}{(1-\tau_i)(1-\tau_k)} - \frac{\tau_i \prod (1-\tau_i)^{n_k}}{(1-\tau_i)^2} \\ p_{co,i} &= d_n - p_{so,i} \end{aligned} \tag{16}$$

By substituting Eqs. (13), (14), (15), (16) into Eq. 12, we can obtain eight expressions as a function of the variable τ_i . By solving the set of equations, we can calculate the access probabilities of all priorities. And then all the transition probabilities and steady-state probabilities can be obtained.

3.2 Normalized Throughput

Let S_i be the normalized throughput of a UP_i node, calculated as the ratio of average time occupied by the successful transmission information to the interval between two consecutive transmissions. The channel is sensed busy, that is, there is at least one node sending packets. The probability that the channel is busy is

$$p_b = 1 - \prod_{\mathrm{i}=0}^{7} (1-\tau_i)^{n_i} \tag{17}$$

The probability $p_{s,i}$ that a transmission of a UP_i node is successful is the probability that only one node is transmitting on the medium, conditioned on the fact that channel is busy,

$$p_{s,i} = n_i \tau_i \frac{\prod_{h=0}^{7} (1-\tau_h)^{n_h}}{(1-\tau_i)\, p_b} \tag{18}$$

The normalized throughput of a UP_i node is defined as the ratio of average time occupied by the successful transmission to the interval between two consecutive transmissions. Then we can express the throughput S_i as

$$S_i = \frac{p_b p_{s,i} T_{payload}}{\left(1-p_b\right)\sigma + p_b \sum_{i=0}^{7} p_{s,i} T_s + p_b (1-\sum_{i=0}^{7} p_{s,i}) T_c} \tag{19}$$

Here, T_s is the mean time of successful transmission, and T_c is the mean time that the channel is occupied because of the collision. $T_{payload}$ is the time of payload and σ is the duration of CSMA/CA slot. T_s and T_c can be written, respectively.

$$\begin{cases} T_s = T_{pack} + T_{ack} + 2SIFS \\ T_c = T_{pack} + SIFS + T_{preamble} + Timeout \end{cases} \tag{20}$$

And the packet duration is calculated as

$$T_{pack} = \frac{N_{preamble} + N_{header} \times S_{header} + \frac{N_{total}}{\log_2\left(M\right)} \times S_{PSDU}}{R_s} \tag{21}$$

By substituting Eqs. (17), (18), (20), (21) into Eq. (19), we can obtain the normalized throughput of all UPs and the overall throughput of the network is the sum of S_i.

3.3 Average Access Delay

We define the average access delay of a successful packet as the time interval from the moment that the packet is in front of the waiting queue until the instant that the ACK frame for this packet is received. Here, we don't consider the waiting time in the node queue. In our hypothetic model, the packet is retransmitted until success and isn't dropped due to the unlimited retry number. Let A_l be the event that the packet is transmitted successfully at time l+1 and the packet has failed for l times. When the node obtains the contended allocations and is ready to send data, the transmission is collided with the probability p_i. The average access delay D_i of a UP_i node is

$$D_i = \sum_{l=0}^{\infty} Pr(A_l) D_{i,l} \tag{22}$$

where $D_{i,l}$ is the delay that a packet of a UP_i node is needed to successfully transmit at time l+1. The probability that the packet is successful at time l+1 is

$$Pr(A_l) = p_i^l (1-p_i) \tag{23}$$

And the $D_{i,l}$ expression is

$$D_{i,l} = \begin{cases} T_s + lT_c + \sum_{h=0}^{l} \frac{W_{i,h}+1}{2}\sigma & l \in (0, m_i\text{-}1) \\ T_s + lT_c + \sum_{h=0}^{m_i-1} \frac{W_{i,h}+1}{2}\sigma + (l\text{-}m_i+1)\frac{W_{i,m_i}+1}{2}\ \sigma & l \in (m_i, \infty) \end{cases} \tag{24}$$

where $(W_{i,j}+1)\sigma/2$ is the mean backoff time of the stage j.

By substituting Eqs. (23), (24) into Eq. (22), the average access delay can be rewritten as follows.

$$\begin{aligned} D_i &= \sum_{l=0}^{\infty} p_i^l(1-p_i)D_{il} \\ &= \sum_{l=0}^{m_i-1} p_i^l(1-p_i)(T_s + lT_c + \sum_{h=0}^{l}\frac{W_{i,h}+1}{2}\sigma) \\ &+ \sum_{m_i}^{\infty} p_i^l(1-p_i)(T_s + lT_c + \sum_{h=0}^{m_i-1}\frac{W_{i,h}+1}{2}\sigma + (l+1-m_i)\frac{W_{i,m_i}+1}{2}\sigma) \\ &= T_s + T_c\frac{p_i}{1-p_i} + \sum_{l=0}^{m_i-1} p_i^l(1-p_i)\sum_{h=0}^{l}\frac{W_{i,h}+1}{2}\sigma + p_i^{m_i}\sum_{h=0}^{m_i}\frac{W_{i,h}+1}{2}\sigma - m_i\frac{W_{i,m_i}+1}{2}\sigma p_i^{m_i} \\ &+ \frac{W_{i,m_i}+1}{2}\sigma\frac{m_i p_i^{m_i} - (m_i-1)p_i^{m_i}}{1-p_i} \end{aligned} \tag{25}$$

Then, we can get eight equations as a function of the variable p_i, which can be calculated using Eq. 14. The average access delay in IEEE 802.15.6 is determined by the collision probability, packet transmission time and the value of m_i.

4. Performance Evaluation

In our analysis, the hub operates in the beacon mode with superframes and nodes use the CSMA/CA to obtain contended allocations. We assume the number of the UP_i nodes is equal and that there is always a packet waiting to send in the node's queue. We analyze the performance for IEEE 802.15.6 with the increasing traffic load, different payload of MAC frame and data rate. All the achieved results are compared with IEEE 802.15.4. **Table 4** lists the parameter value in our analysis between IEEE 802.15.6 and IEEE 802.15.4.

Table 4. Analytical parameter value

802.15.6	
MAC Header	9B
PLCP Header	31 bits
PLCP Preamble	90 symbols
ACK	9B+ PLCP Header + PLCP Preamble
Symbol rate	600 ksps
SIFS	75 μs
CSMA/CA Slot Time	145 μs
Timeout	30 μs
802.15.4	
MAC Header(including FCS bits)	9B
PHY Header	6B
ACK	5B+PHY Header
Data Rate	250 kbps

Unit Backoff Period	20 symbols
LIFS	40 symbols

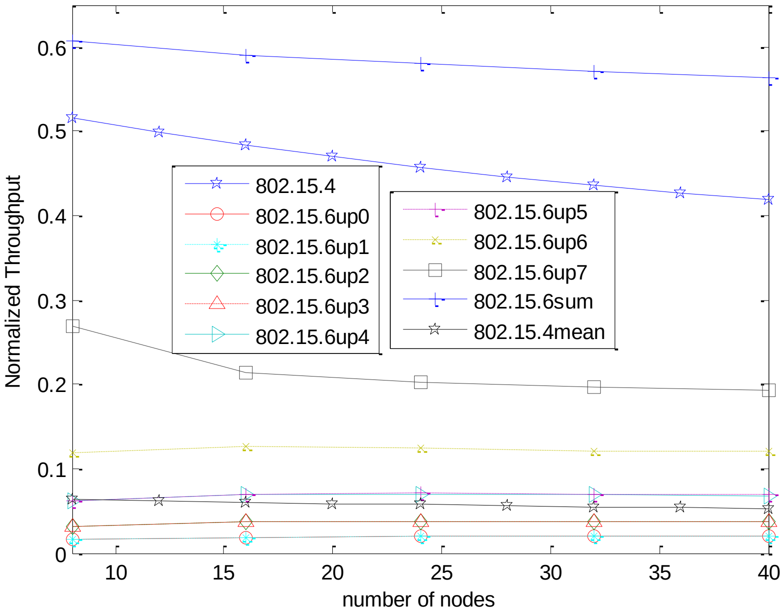

Fig. 5. Comparison of normalized throughput for all UPs in IEEE 802.15.6 and IEEE 802.15.4, MCS 1

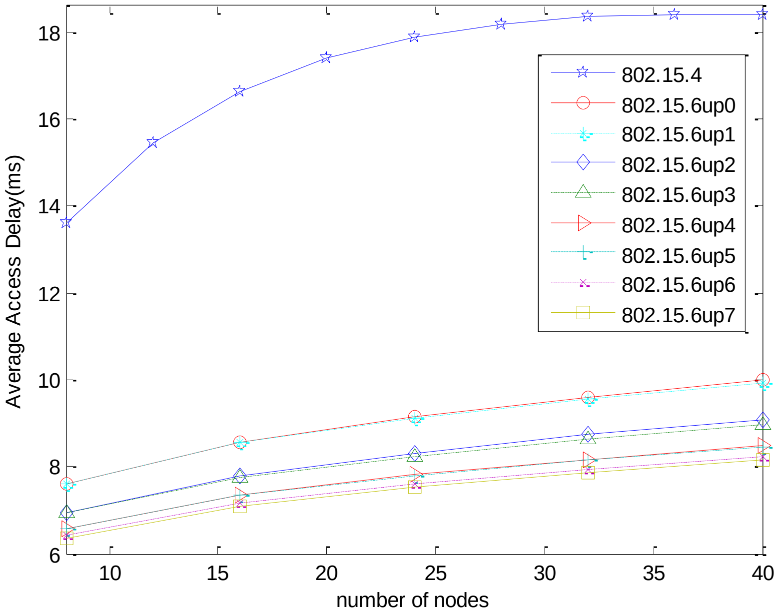

Fig. 6. Comparison of mean access delay for all UPs in IEEE 802.15.6 and IEEE 802.15.4, MCS 1

For comparison, we give mean normalized throughput of IEEE 802.15.4 distributed on each of eight UPs, and the overall normalized throughput of the network in IEEE 802.15.6, which is noted as IEEE 802.15.4 mean and IEEE 802.15.6 sum, respectively. **Fig. 5** shows the normalized throughout versus the number of nodes with a payload of 118 bytes and the model MCS1. From the curves of 802.15.6 sum and 802.15.4, the overall normalized throughput of IEEE 802.15.6 is better than that of IEEE 802.15.4. Though the normalized throughput decreases as the network traffic load increases, the degree of deterioration for 802.15.6 sum is relatively small compared to that of 802.15.4. When the number of nodes is from 8 to 40, the normalized throughput respectively decreases by 0.04 and 0.1 for 802.15.6 sum and 802.15.4. For different UPs, the higher the user priority, the larger the normalized throughput is. From the viewpoint of the trend of curves, all the Ups except UP7 remain about the same and there is no reduction on the normalized throughput when the number of nodes increases. But the nodes of UP7 suffer a reduction of 0.05 when number of nodes increases from 8 to 40, while other UPs are nearly unchanged. The reason is that the increasing traffic load has an influence on the access probability and the reduction of access probability is large for UP7, leading that the growing tendency of collision probability in UP7 becomes relatively apparent compared with other Ups. Therefore, there is a little deterioration on the normalized throughput of UP7. Moreover, the nodes of UP7, UP6, UP5, and UP4 can obtain higher normalized throughput than the mean normalized throughput of IEEE 802.15.4. For the nodes of UPs lower than 3, the maximum normalized throughput is 0.0377 and nodes obtain a relatively poor performance. So the nodes of low UPs are always starved and the nodes of high UPs have more chance to access the medium.

We show the average access delay for successfully transmission one packet with a payload of 118 bytes and the mode MCS1 in **Fig. 6**. Average access delay increases as the number of nodes increases. Relatively, IEEE 802.15.4 has the longest average access delay. The maximum average access delay of IEEE802.15.6 is 10 ms with 40 nodes, whereas the minimum value of IEEE 802.15.4 is 13.8 ms with 8 nodes. There is deterioration in IEEE 802.15.4 with the increasing nodes, due to the collision probability, the different bakeoff unit, the different date rate, and the difference of minimum contention window. For different UPs, the higher the user priority, the lower the average access delay is. The difference of average access delay of UP7 and 6 is not apparent, as well as UP5 and UP4, UP3 and UP2, UP1 and UP0. We will explain the phenomenon later.

In a word, from **Figs. 5** and **6**, it is noted that IEEE 802.15.6 provides higher normalized throughput and lower average access delay to the nodes of high UPs. Thus, the highest user priority such medical information can obtain the highest reliability and lowest delay.

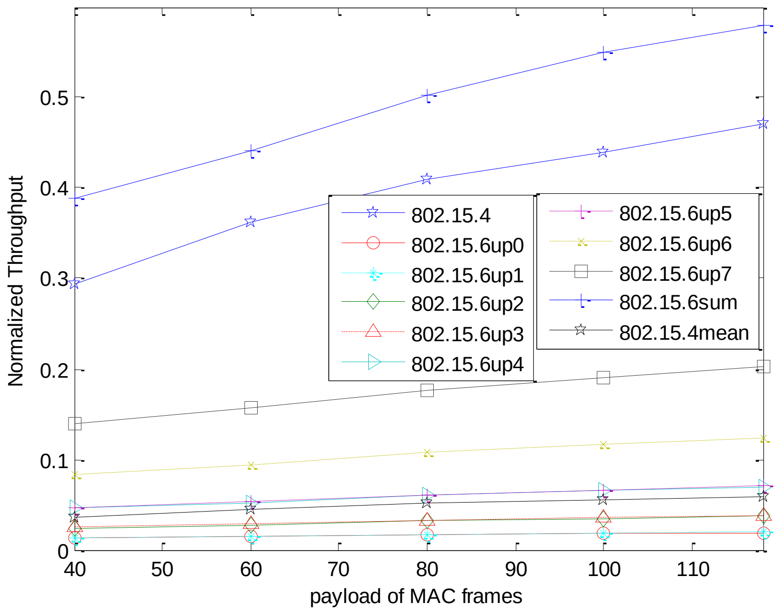

Fig. 7. Comparison of normalized throughput for all UPs in IEEE 802.15.6 and IEEE 802.15.4, MCS1

Fig. 7 indicates the normalized throughput increases as the payload of MAC frames increases that is achieved under the MCS1 mode and 24 nodes. For comparison, the overall normalized throughput of IEEE 802.15.6 is larger than that of IEEE 802.15.4. When the number of nodes is 8 and 40, normalized throughput increases from 0.38 to 0.6 and 0.29 to 0.48 for IEEE 802.15.6 and IEEE 802.15.4, respectively. For different UPs, the increasing tendency of high UPs is larger than that of low UPs. When the payload of MAC frame increases from 40 bytes to 100 bytes, the increase of normalized throughput is 0.06, 0.04, 0.023, 0.023 for UP7, UP6, UP5, and UP4 respectively, but the normalized throughput nearly remains unchanged for UP3, UP2, UP1, and UP0 respectively. **Fig. 8** plots the average access delay as a function of the payload with the same conditions. The average access delay of different UPs increases with the increase of the payload. IEEE 802.15.4 has the longest average access delay, increased by 8 ms compared to the maximum average access delay in IEEE 802.15.6. The payload of MAC frame has a relatively big influence on nodes of high UPs in terms of normalized throughput and average access delay.

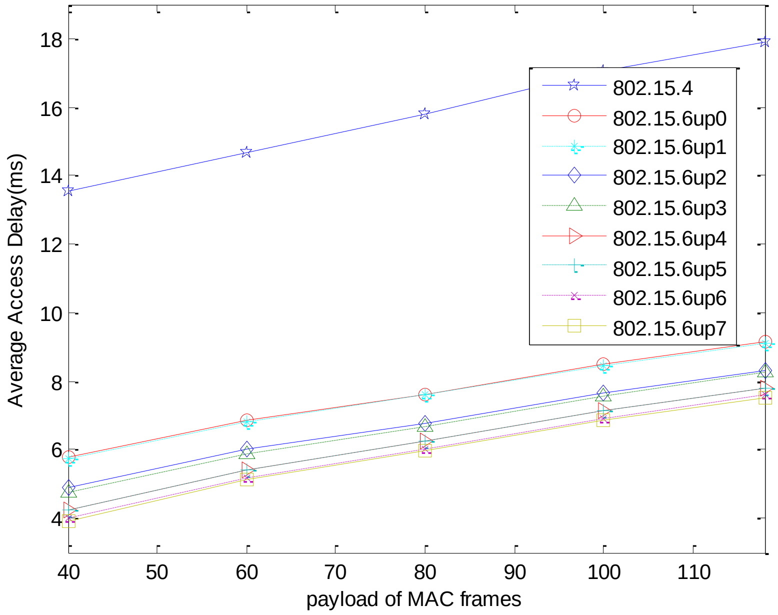

Fig. 8. Comparison of average access delay for all UPs in IEEE 802.15.6 and IEEE 802.15.4, MCS 1

From **Figs. 5** and **7**, it can be seen that the normalized throughput of the UP5 and UP4 is nearly equal, as well as UP3 and UP2, UP1 and UP0. The reason is that the equal of the minimums CW value and the very similar equations of UP5 and UP4 lead the nearly equal access probability and collision probability. So the lines of normalized throughput of UP5 and UP4 are nearly coincident. The reason is similar to other UPs. **Figs. 6** and **8** show the same phenomenon for UP7 and UP6. Another reason for the average access delay is that the difference of the mean backoff time is very small for UP7 and UP6. As is shown in figures above, under the varying traffic load and the payloads of MAC frames, the better performance of the normalized throughput and average access delay is provided for the medical applications.

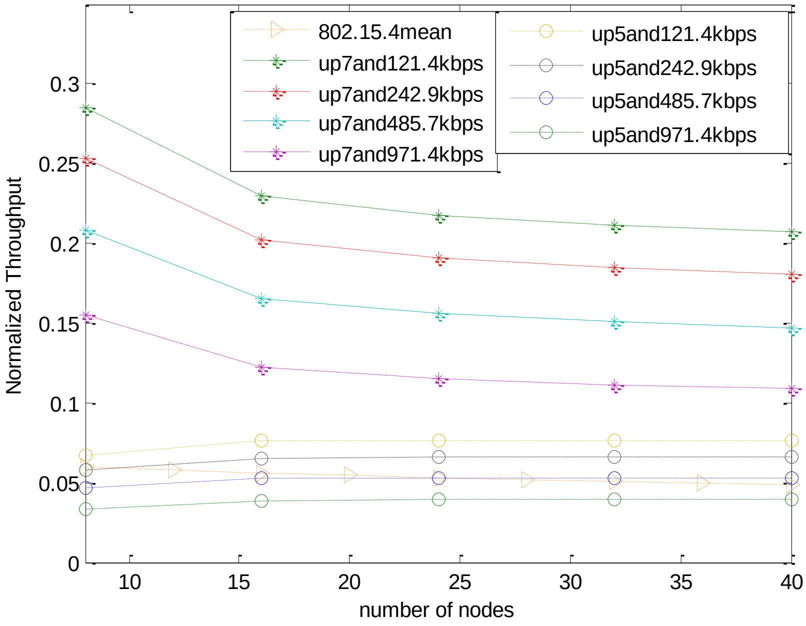

Fig. 9. Comparison of normalized throughput for UP 7 and UP5 and IEEE 802.15.4 under all the MCSs

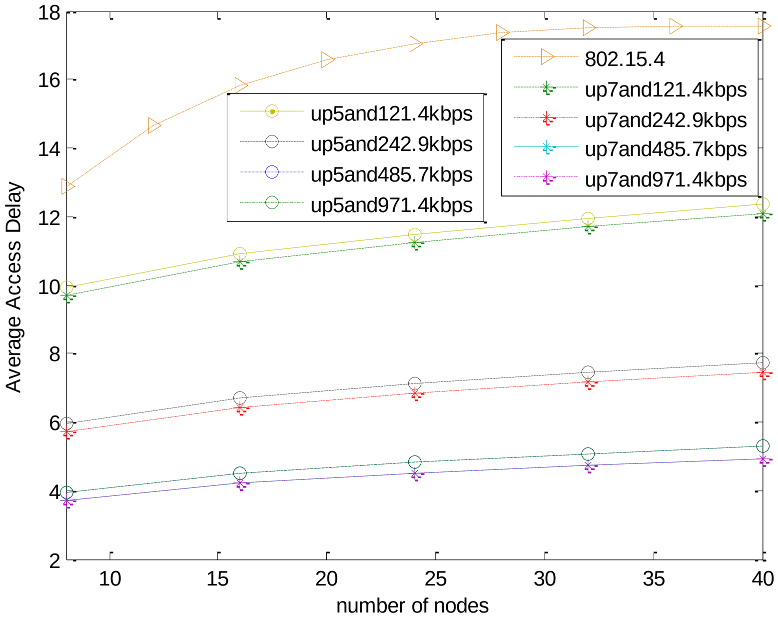

Fig. 10. Comparison of average access delay for UP7 and UP5 and IEEE 802.15.4 under all the MCSs

Figs. 9 and **10** illustrate the normalized throughput and average access delay with a payload of 100 bytes and the four data rates. When the traffic load increases under all date rates, the normalized throughput reduces for UP7, however the values are almost unchanged for UP5. When the number of nodes is 8 and 40, the normalized throughputs of UP7 reduces by 0.08, 0.07, 0.05, and 0.03 with the date rates of 121.4 kbps, 242.9 kbps, 485.7 kbps, and 971.4 kbps respectively. For different data rates, the normalized throughput of UP7 and UP5 reduce when the date rate increases. The higher data rate, the less the transmission time is. But the corresponding access probabilities and the collision probability become large and then the normalized throughput become small. We can see the usage of different MCSs has a big influence on the normalized throughput.

Fig. 9 depicts the average access delay with the same conditions. The average access delay increases with the reducing date rate. The maximum average access delay of UP7 is 12 ms, 7.8 ms, 4.5 ms and 4.5 ms for 121.4 kbps, 242.9 kbps, 485.7 kbps, and 971.4 kbps, respectively. Since the more time is needed to send a packet with the low data rate. The data rates correspond to the MCS as shown in **Table 1**. The results show that different MCSs have a great influence on the average access delay, and that MCS 2 and MCS3 get the nearly average access delay. Modulation mode, code rate and the spreading factor determine different data rates. Due to the even number of payload, the number of pad bits is zero under MCS2 and MCS 3. Therefore, the packet duration is equal with the same spreading factor. So the average access delay under MCS 2 and MCS3 is equal. Hence, it is important to choose modulation and coding mode for each scenario so as to get a realistic evaluation of the network performance.

In short, IEEE 802.15.6 can provide high reliability, low delay and high QoS for the nodes of high UPs in medical applications than IEEE 802.15.4.

5. Conclusion

In the paper we proposed a Markov chain model and a backoff model to analyze the performance of IEEE 802.15.6 with the assumption of ideal channel and saturation conditions. With fixed frame payload, we calculated the normalized throughput and average access delay of all UPs with the varying network traffic and payloads of MAC frames. All the four MCSs were taken into account for comparison in evaluation of network performances. In all the cases, the performance achieved at the ISM frequency bands was analyzed and compared with the same scenarios in IEEE 802.15.4.

By taking into account the effect of the traffic load, payload of MAC frames, modulation and coding modes, and priorities on the network performance, the results show that IEEE 802.15.6 supplies nodes of high UPs with better performance, but it starves nodes of lower UPs such as non-medical traffics. And by comparing the two protocols, the results achieved point out that IEEE 802.15.6 outperforms IEEE 802.15.4 in the performance of guaranteeing reliable and timely medical information delivery.

References

[1] IEEE Standard 802.15.6, Wireless Body Area Networks, Feb. 2012. Article (CrossRef Link).

[2] IEEE Standard 802.15.4, Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs), Sep. 2011. Article (CrossRef Link).

[3] S. Rezvani, A. Ghorashi, "A Novel WBAN MAC Protocol With Improved Energy Consumption and Data Rate," *KSII transactions on internet and information system*, vol. 6, no. 9, pp. 2302-2322, Sep. 2012. Article(CrossRef Link)

[4] Y. Kang, S. Lim, C. Kim, “Design, analysis and implementation of energy-efficient broadcast MAC protocols for wireless sensor networks,” *KSII transactions on internet and information system*, vol. 5, no. 6, pp. 1113-1132, Jun. 2011. Article (CrossRef Link).

[5] S. Ullah, H. Higgins, B. Braem del, et al, “A Comprehensive Survey of Wireless Body Area Networks,” *Journal of Medical Systems*, vol. 36, no. 3, pp. 1065-1094, Jun. 2012. http://dx.doi.org/10.1007/s10916-010-9571-3

[6] M. Chen, S. Gonzalez, A. Vasilakos, et al. “Body Area Networks: A Survey,” *Journal of Mobile Networks and Applications*, vol. 16, no. 2, pp. 171-193, Apr. 2011. Article (CrossRef Link).

[7] S. Ullah, H . Higgins, B. Shen, K. S. Kwak, “On the implant communication and MAC protocols forWBAN,” *Journal of Communication Systems*, vol. 23, no. 8, pp. 982-999, Jan. 2010. Article (CrossRef Link).

[8] S. Ullah, X. An, K. Kwak, “Towards Power Efficient MAC Protocol for In-Body and On-Body Senseor Networks,” *Agent and Multi-Agent System: Technologies and Application*, pp. 335-345, Jun. 2009. Article (CrossRef Link).

[9] K. S. Kwak, S. Ullah, N. Ullah, “An Overview of IEEE 802.15.6 Standard,” in *Proc. of 3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL)*, pp. 1-6, Rome, Italy, Nov. 2010. Article (CrossRef Link).

[10] N. Bradai, S. Belhaj, L. Chaari, L. Kamoun, “Study of Medium Access Mechanisms under IEEE 802.15.6 Standard,” in *Proc. of 4th Joint IFIP Wireless and Mobile Networking Conference (WMNC)*, pp. 1-6, Toulouse, France, Oct. 2011. Article (CrossRef Link).

[11] C. Tachtatzis, F. Di Franco, D. C. Tracey, N. F. Timmons, J. Morrison, “An Energy Analysis of IEEE 802.15.6 Scheduled Access Modes,” *IEEE Globecom Workshops*, pp. 1270-1275, Miami, USA, Dec. 2010. Article (CrossRef Link).

[12] C. Tachtatzis, F. Di Franco, D. C. Tracey, N. F. Timmons, J. Morrison, “An Energy Analysis of IEEE 802.15.6 Scheduled Access Modes for Medical Applications,” *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering*, pp. 209-222, Paris, France, Sep. 2011. Article (CrossRef Link).

[13] S. Ullah, M. Chen, K. S. Kwak, “Throughput and Delay Analysis of IEEE 802.15.6-based CSMA/CA Protocol,” *Journal of Medical Systems*, vol. 36, pp. 3875-3891, Jul. 2012. Article (CrossRef Link).

[14] S. Ullah, K. S. Kwak, “Throughput and Delay Limits of IEEE 802.15.6,” *IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 174-178, Cancun, Quintana Roo, Mexico, Mar. 2011. Article (CrossRef Link).

[15] X. Wang, L. Fu, C. Hu, “Multicast Performance with Hierarchical Cooperation,” *IEEE Transactions on Networking*, vol. 20, no. 3, pp. 917-930, Jun. 2012. Article (CrossRef Link).

[16] X. Wang, W. Huang, S. Wang, et al, “Delay and Capacity Tradeoff Analysis for MotionCast,” *IEEE Transactions on Networking*, vol.19, no. 5, pp. 1354-1367, Oct. 2011. Article (CrossRef Link).

[17] S. Rashwand, J. Misic, H. Khazaei, “Performance Analysis of IEEE 802.15.6 under Saturation Condition and Error-prone Channel,” in *Proc. of IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1167-1172, Cancun, Quintana Roo, Mexico, Mar. 2011. Article (CrossRef Link).

[18] S. Rashwand, J. Misic, H. Khazaei, "IEEE 802.15.6 under Saturation: Some Problems to be Expected," *Journal of Communications and Networks*, vol. 13, no. 2, pp. 142-148, Apr. 2011. Article (CrossRef Link).

[19] S. Rashwand, J. Misic, "Performance Evaluation of IEEE 802.15.6 under Non-Saturation Condition," in *Proc. of IEEE Global Telecommunications Conference (GLOBECOM)*, pp. 1-6, Kathmandu, Nepal, Dec. 2011. Article (CrossRef Link).

[20] S. Rashwand, J. Misic, "Effects of Access Phases Lengths on Performance of IEEE 802.15.6 CSMA/CA," *Journal of Computer Networks*, vol. 56, pp. 2832-2846, Aug. 2012. Article (CrossRef Link).

[21] F. Martelli, C. Buratti, R. Verdone, "On the Performance of an IEEE 802.15.6 Wireless Body Area Network," in *Proc. of 11th European Wireless Conference (EW)*, pp. 1-6, Vienna, Austria, Apr. 2011. Article (CrossRef Link).

[22] C. Li, H. Li, R. Kohno, "Performance Evaluation of IEEE 802.15.4 for Wireless Body Area Network (WBAN)," in *Proc. of IEEE International Conference on Communications Workshops*, pp. 1-5, Dresden, Germany, Jun. 2009. Article (CrossRef Link).

[23] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *Journal of Selected Areas in Communications*, vol. 18, no. 3, pp. 535-547, Mar. 2000. Article (CrossRef Link).

[24] IEEE Standard 802.11, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Nov. 1997. Article (CrossRef Link).

[25] IEEE Standard 802.11e, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Medium Access Control (MAC) Quality of Service Enhancements, Sep. 2005. Article (CrossRef Link).

[26] Z. Kong, D. H. K. Tsang, B. Bensaou, D. Gao, "Performance Analysis of IEEE 802.11e Contention-Based Channel Access," *Journal of Selected Areas in Communications*, vol. 22, no.10, pp. 2095- 2106, Dec. 2004. Article (CrossRef Link).

[27] P. Park, P. Di Marco, P. Soldati, C. Fischione, K. H. Johansson, "A Generalized Markov Chain Model for Effective Analysis of Slotted IEEE 802.15.4," in *Proc. of IEEE 6th international Conference on Mobile Adhoc and Sensor Systems*, pp. 130-139, Macau, China, Oct. 2009. Article (CrossRef Link).

Changle Li received the B.Eng. degree in Microwave Telecommunication Engineering, M.Eng. and Ph.D. degrees in Communication and Information System, all from Xidian University, China, in 1998, 2001 and 2005, respectively. From 2006 to 2007, he was with Computer Science Department at University of Moncton, Canada as a postdoctoral researcher. From 2007 to 2009, he was an expert researcher at National Institute of Information and Communications Technology (NICT), Japan. He is currently a professor in State Key Laboratory of Integrated Service Networks at Xidian University, China. His research interests include cross-layer design and communication protocols for cellular network, mobile ad hoc network, wireless sensor network, vehicular network and wireless body area network (WBAN).

Xiaoyan Geng received the B. Eng. Degree in communication engineering in 2011 from PLA Information Engineering University, Zhengzhou, Henan, China. Since September 2011, she has been Xidian University for her M. Eng with researches including cognitive radio networks and medium access control for wireless body area networks.

Jingjing Yuan received her B. Eng. degree in 2010, from PLA Information Engineering University, Zhengzhou, Henan, China. Since September 2010, she has been Xidian University for her M. Eng. Her major research includes medium access control for wireless body area networks.

Tingting Sun received the B. Eng. degree in Communications Engineering from Hefei University of Technology, Hefei, Anhui, China in 2011. She is currently pursuing for the M. Eng. degree in Communication and Information System from Xidian University, Xi’an, Shaanxi, China. Her current research interests include wireless network capacity and medium access control for wireless personal area networks.