

Performance Analysis of IEEE 802.15.6 MAC Protocol in WBAN with Energy Harvesting Nodes

Fan Yun
cloudfan@mail.ustc.edu.cn

Bin Liu
flowice@ustc.edu.cn

Lei Zou
zoulei@mail.ustc.edu.cn

Key Laboratory of Electromagnetic Space Information, Chinese Academy of Sciences
School of Information Science and Technology
University of Science and Technology of China

Chang Wen Chen
Dept. of Computer Science &
Engineering,
State University of New York,
University at Buffalo,
chencw@buffalo.edu

ABSTRACT

Wireless Body Area Network (WBAN) have been widely used in many fields. With the development of energy harvesting technologies, applying energy harvesting (EH) nodes to WBAN becomes more practical. In this paper, a Discrete-Time Markov Chain (DTMC) model is built to analyze the IEEE 802.15.6 Medium Access Control (MAC) protocol under saturation condition in the WBAN with energy harvesting devices. The long term performance including throughput and energy consumption is then derived based on the statistical characteristics of the analytical model. The simulation results demonstrate the accuracy of the analytical model. A conclusion has been drawn from the results that a better energy harvesting state will make the system perform better, and the influence of the energy harvesting state will be different for different priority nodes.

CCS Concepts

•Networks → Network performance analysis; *Network performance modeling*; Network simulations;

Keywords

IEEE 802.15.6; Energy Harvesting; Markov Chain; MAC Protocol; Wireless Body Area Network

1. INTRODUCTION

With the development of the emerging Wireless Body Area Network (WBAN) technology, a solid foundation has been laid for pervasive healthcare monitoring system. WBAN has drawn increased attentions from healthcare community and engineering industry, due to its ability to improve health care efficiency and service quality of Electronic Health (eHealth) [7]. The WBAN usually contains one coordinator and several power-constraint sensor nodes in, on, or around human body, and physiological signals are collected by the sensor nodes and then transmitted to the coordinator for further analysis and observation [8]. However, the battery capacity of these sensor nodes is very limited, even replacing batteries periodically is not always available.

Fortunately, energy harvesting technology, which exploits supercapacitors to collect energy from ambient sources, such as electromagnetic source, solar source [11], has become an essential technology for low-power WBAN to prolong the system lifetime. Recently, energy harvesting technology has been adopted in many healthcare applications, especially for those where battery replacement is difficult or even impossible. Although energy from harvesting nodes is limited and stochastic, energy harvesting network can still work continuously via advanced technologies [6].

IEEE 802.15.6 task group (TG6) has published the IEEE 802.15.6 standard [1] to support the highly reliable and low-power wireless communication in WBAN. Quality of Service (QoS), extremely low power and high data rate are the main aims of IEEE 802.15.6 standard, and the MAC protocol is the key section of the standard. To better analyze the performance of IEEE 802.15.6 MAC protocol, an analytical Markov Chain model has been constructed by many researchers to model the process of CSMA/CA-based MAC protocol as the state transition. Analyses under saturated condition, i.e., always having data to send, and unsaturated condition in an ideal channel have been carried out in [10] and [4], respectively. It was shown in [10] that as the length of payload increases, the reliability of a node decreases, while the throughput increases. As the number of nodes in the network increases, the energy efficiency and throughput tends to decrease [4]. The different access phase employed on system degrades the throughput performance of IEEE 802.15.6 network under unsaturated condition in ideal channels [5]. However, none of the above analyses involved energy harvesting technologies. In [12], an analytical model for IEEE 802.11 network with energy harvesting devices was proposed, but the analysis for IEEE 802.11 standard cannot be directly applied to IEEE 802.15.6 standard due to the difference in MAC protocol design.

In this paper, we propose a Markov Chain analytical model for IEEE 802.15.6 MAC protocol in the WBAN with energy harvesting nodes. As the average energy harvesting rate is usually very small such that the harvested energy is not enough for the nodes with common data arrival rate to transmit their data in real time, here we assume the nodes

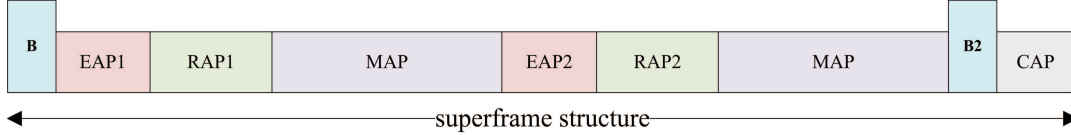


Figure 1 Structure of superframe for beacon mode [1].

in the WBAN are under saturation condition, i.e., the nodes always have data to send. Our contributions can be summarized as follows: 1) A four-dimensional DTMC model is built to analyze the system performance. Both MAC property and energy harvesting property are involved in the model. From what we know, it is the first time to build the analytical model for IEEE 802.15.6 MAC protocol in the WBAN with energy harvesting devices. 2) The long term performance including throughput and energy consumption is derived based on the statistical characteristics of the analytical model.

The rest of the paper is organized as follows. In Section 2, we give a brief introduction of IEEE 802.15.6 Standard, and present the MAC specification. The analytical models including energy harvesting model and Markov Chain model are described in Section 3. Numerical results are presented in section 4. Conclusions are drawn in Section 5.

Table 1 UP and Contention Windows (CW) of data [1].

UP	Traffic designation	CW
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 and network control	[4,8]
6	High-priority medical data and network control	[2,8]
7	Emergency and medical implant event report	[1,4]

2. IEEE 802.15.6 STANDARD

IEEE 802.15.6 Standard specifies short-range (human body range) wireless communications in WBAN [1]. To provide diverse service for various data, especially for emergency data, the standard defines different User Priorities (UPs) to ensure the QoS of data transmission in the proximity of human body.

2.1 An overview of IEEE 802.15.6 MAC protocol

IEEE 802.15.6 specifies three operation modes in MAC protocol and beacon mode with superframes is generally used. In the mode, the transmission period in WBAN is divided into multiple equal-length superframes starting with a beacon frame. Each superframe is comprised of seven phases which are 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) [1]. Structure of the superframe is illustrated in Figure. 1. EAP can only be accessed by highest priority exclusively. If the length of CAP is greater than zero, B2 frame should be transmitted firstly as a flag after

MAP. In addition, resources are usually allocated through polling mechanism in MAP. And nodes in EAP, RAP or CAP access the channel by contention. Contention mechanism in these access phases is either CSMA/CA or slotted ALOHA. In this paper, we focus on the performance analysis of CSMA/CA mechanism in IEEE 802.15.6 Standard. Thus, our analysis is based on beacon mode with superframes in which random access phase exists.

2.1.1 CSMA/CA mechanism

IEEE 802.15.6 Standard defines eight User Priorities (UP-) according to traffic designation, as shown in Table 1. Nodes transmit data with different user priorities and may access channel using CSMA/CA mechanism. A node in CSMA/CA mechanism maintains a backoff counter depending on W_k , which is the window value of backoff counter in UP_k . The value of backoff counter is set to a random integer ranging from 1 to W_k . The value of W_k changes with the number of retries r and can be formulated as follows,

$$W_k(r) = \begin{cases} CW_{k,min} & r = 0 \\ W_k(r-1) & r = odd, r \leq m \\ \min\{CW_{k,max}, 2W_k(r-1)\} & r = even, r \leq m \end{cases} \quad (1)$$

where k is the UP of data processed by nodes. Besides, $CW_{k,min}$ and $CW_{k,max}$ are the minimum and maximum value of CW in priority k . And m is the maximum number of retries.

Backoff counter of a node is locked or unlocked under several conditions. Backoff counter is locked in the following situations: 1) System resets the backoff counter or the counter decreases to zero. 2) Channel is occupied by other nodes when the node is listening. 3) The current time is not in RAP, CAP or EAP. 4) The current time is inside the period of RAP, CAP or EAP, but the length between the current time and the end of the phase is too short to send a frame. On the other hand, the backoff counter is unlocked when the channel has been idle for a Short Interframe Space (SIFS) period. At the same time, there is plenty of time for completing frame transmission until the end of the phase. In fact, nodes transmit packet when the value of backoff counter decreases to zero. If the packet is sent successfully, the value of r returns to zero. Otherwise, r is increased by one. However, value of r will never exceed m .

3. ANALYTICAL MODEL AND PERFORMANCE ANALYSIS

In this section, we first describe the energy harvesting model for sensor nodes and then develop a DTMC model for the CSMA/CA-based MAC protocol of IEEE 802.15.6 Standard in the EH-based WBAN. Based on the analysis of the DTMC model, we derive the close form formulations for the system performance of the WBAN with energy harvest-

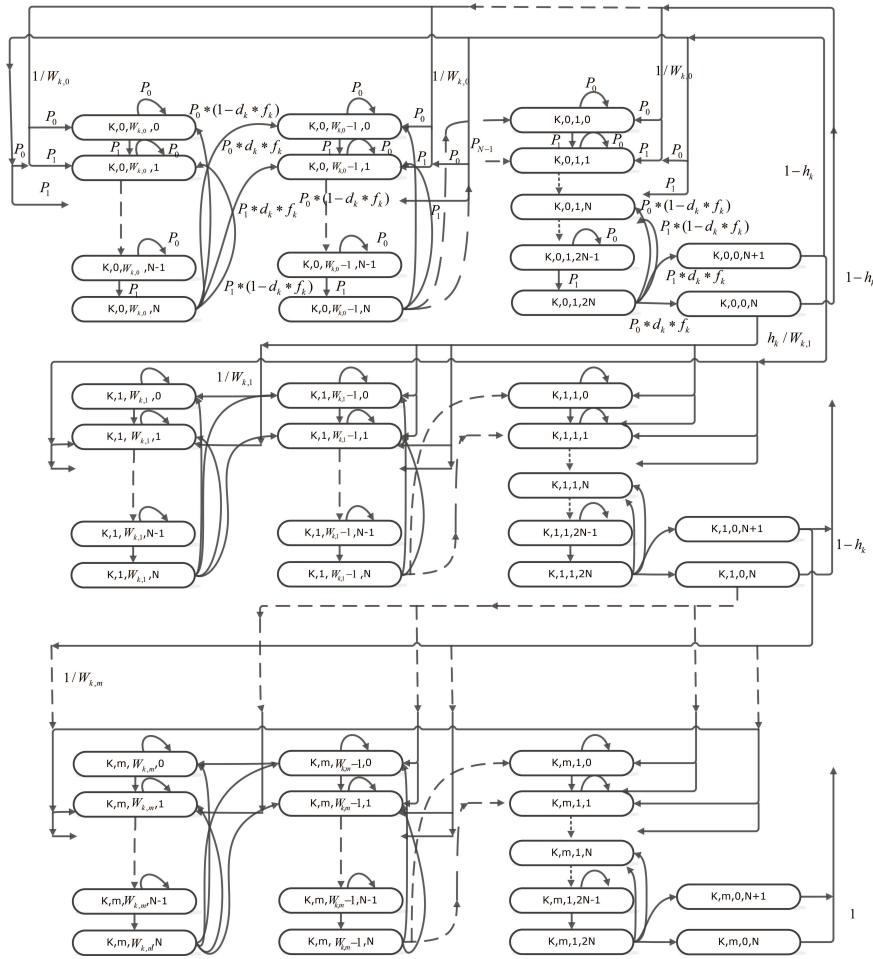


Figure 2 State transition diagram of DTMC model.

ing nodes. Here we assume that the WBAN is in saturation condition.

3.1 Energy harvesting model

Here we adopt a Poisson Distributed energy harvesting model for each node [2], i.e., the amount of energy arriving at the energy buffer of each node follows a Poisson Distribution. Here the energy buffer of each node is assumed to be unlimited. To simplify the analysis, we further transfer the EH model from the Poisson process to a Bernoulli process [12]. In this model, energy arriving at the buffer is packetized into some units and E_{unit} is used to denote the amount of one unit energy. If the quantity of energy arrival in a time slot exceed E_{unit} , we ignore the residual energy and regard the arrival energy as one unit. Otherwise, we regard the arrival energy as zero. Furthermore, it is assumed that when a node is sensing the channel or transmitting a packet, it can be charged simultaneously. Therefore, the energy model can be expressed as follows,

$$E(t) = \begin{cases} E(t-1) & P_1 \\ E(t)+1 & P_0 = 1 - P_1 \end{cases} \quad (2)$$

where t is the index of time slot and $E(t)$ is the state of the energy buffer.

3.2 Discrete-Time Markov Chain model

A Discrete-Time Markov Chain (DTMC) model is used to describe the process of CSMA/CA MAC protocol of IEEE 802.15.6 Standard. As stated in [3] that the power consumption in Clear Channel Assessment (CCA) period is approximately equivalent to the power consumption of transmission. Therefore, the energy consumption of channel sensing and packet transmission can be assumed to be an equal value E_{th} and is denoted as N energy units. The DTMC model for CSMA/CA MAC protocol is then depicted in Figure. 2. Notations used in this model analysis are defined in Table 2.

The contention process in the MAC protocol is modeled as different state transition. Some identical state transition probabilities in Figure. 2 are omitted [4]. System states in the model are all observed at the end of each time slot. Every state is a tuple with four elements, which is denoted by $\{k, i(t), j(t), q(t)\}$. The first element denotes the user priority and the second element denotes the number of retries. The third element is the value of backoff counter. The last one is state of energy buffer q . When q reaches to N , it will be immediately used up by the node for CCA or transmitting if backoff counter greater than one. However, when the backoff counter decreases to one, the node will send the packet immediately in next state where the backoff counter equals to zero, so there need more energy in this state, i.e., $2N$ units of energy for both listening and transmission. The transition probability from state A to state B is denoted

Table 2 Notation Definitions.

Notations	Definitions
k	user priority $k, k \in (0, \dots, 7)$
i	number of retries, $i \in (0, \dots, m)$
j	value of backoff counter, $j \in (0, \dots, W_{k,i})$
q	energy quantity of energy buffer, $q \in (0, \dots, 2N)$
m	maximum number of retries
d_k	probability of the idle channel
n_k	number of nodes in UP_k
n	number of nodes in WBAN
h_k	collision probability after frame transmitting
τ_k	transmission probability for the node in UP_k
f_k	probability of leaving sufficient time for frame transmission
$b_{k,i,j,q}$	steady-state probability in certain state
P_0	probability that no energy arrives in a slot
P_1	probability that one unit energy arrives in a slot
N	energy needed in CCA or transmission in units
$W_{i,k}$	window value of backoff counter in the i th retry of UP_k

by $P(A|B)$ and the probabilities of some important state transitions in DTMC are given as follows,

$$P(k, i, j, q|k, i, j, q) = P_0,$$

$$j \geq 2, q \leq N - 1 \text{ or } j = 1, q \neq 2N$$

$$P(k, i, j, q + 1|k, i, j, q) = P_1,$$

$$j \geq 2, q \leq N - 1 \text{ or } j = 1, q \neq 2N$$

$$P(k, i, j, q|k, i - 1, 0, N) = P_q h_k / W_{k,i},$$

$$i \neq 0, j \neq 0, q \in (0, 1)$$

$$P(k, i, j, q|k, i - 1, 0, N + 1) = P_{q-1} h_k / W_{k,i},$$

$$i \neq 0, j \neq 0, q \in (1, 2)$$

$$P(k, 0, j, q|k, i, 0, N) = P_q (1 - h_k) / W_{k,0},$$

$$i \neq m, j \neq 0, q \in (0, 1)$$

$$P(k, 0, j, q|k, i, 0, N + 1) = P_{q-1} (1 - h_k) / W_{k,0},$$

$$i \neq m, j \neq 0, q \in (1, 2)$$

$$P(k, 0, j, q|k, m, 0, N) = P_q / W_{k,0}, j \neq 0, q \in (0, 1)$$

$$P(k, 0, j, q|k, m, 0, N + 1) = P_{q-1} / W_{k,0}, j \neq 0, q \in (1, 2)$$

$$P(k, i, j - 1, q|k, i, j, N) = P_q (d_k f_k), j \geq 2, q \in (0, 1)$$

$$P(k, i, j, q|k, i, j, N) = P_q (1 - d_k f_k), j \geq 2, q \in (0, 1)$$

$$P(k, i, 0, q|k, i, 1, 2N) = P_{q-N} (d_k f_k), q \in (N, N + 1)$$

$$P(k, i, 1, q|k, i, 1, 2N) = P_{q-N} (1 - d_k f_k), q \in (N, N + 1)$$

Based on the above transition probabilities, we could obtain the steady-state probabilities of DTMC using property that sum of all steady-state probabilities is equal to one,

$$\begin{aligned} & \sum_{i=0}^m \sum_{q=N}^{N+1} b_{k,i,0,q} + \sum_{i=0}^m \sum_{q=N}^{2N} b_{k,i,1,q} \\ & + \sum_{i=0}^m \sum_{j=2}^{W_{k,i}} b_{k,i,j,N} + \sum_{q=0}^{N-1} \sum_{i=0}^m \sum_{j=1}^{W_{k,i}} b_{k,i,j,q} = 1 \end{aligned}$$

The probability of packet transmission τ_k and the probability of CCA $P_{cca,k}$ can then be respectively calculated by

$$\begin{aligned} \tau_k &= \sum_{i=0}^m \sum_{q=N}^{N+1} b_{k,i,0,q} \\ &= \frac{d_k f_k P_1}{N \left[d_k f_k \sum_{i=0}^m h_k^i + \sum_{i=0}^m \frac{(W_{k,i+1})}{2} h_k^i \right]} \sum_{i=0}^m h_k^i \\ P_{cca,k} &= \frac{P_1 \sum_{i=0}^m \frac{(W_{k,i+1})}{2} h_k^i}{N \left[d_k f_k \sum_{i=0}^m h_k^i + \sum_{i=0}^m \frac{(W_{k,i+1})}{2} h_k^i \right]} \end{aligned}$$

where the collision probability after transmitting h_k and the probability of the idle channel d_k are formulated as follows,

$$h_k = 1 - (1 - \tau_k)^{n_k - 1} \prod_{i \neq k, i=0}^7 (1 - \tau_i)^{n_i}$$

$$d_k = (1 - \tau_k)^{n_k - 1} \prod_{i \neq k, i=0}^7 (1 - \tau_i)^{n_i}$$

The corresponding transmission probability P_{tr} , the probability of successful transmission of one node in UP_k $P_{su,k}$, and the probability of successful transmission in the WBAN P_{su} can then be derived as follows respectively,

$$P_{tr} = 1 - \prod_{i=0}^7 (1 - \tau_i)^{n_i} \quad (3)$$

$$P_{su,k} = \tau_k d_k f_k = \tau_k f_k (1 - \tau_k)^{n_k - 1} \prod_{i \neq k, i=0}^7 (1 - \tau_i)^{n_i} \quad (4)$$

$$P_{su} = \sum_{i=0}^7 C_{n_i}^1 P_{su,i} = \sum_{i=0}^7 n_i \tau_i d_i f_i \quad (5)$$

3.3 Throughput

In this work, we assume that a failed transmission can only be caused by collision. The throughput S_k is defined as bits of packet transmitted successfully per second in UP_k and is formulated as

$$S_k = \frac{P_{su,k} L_p}{(1 - P_{tr}) t_{idle} + P_{tr} P_{su} t_{su} + P_{tr} (1 - P_{su}) t_{col}} \quad (6)$$

where t_{idle} is the time duration of no transmission and L_p is the average packet length in bits. t_{su} and t_{col} are used to represent the time duration for successful transmission and collision, respectively,

$$t_{su} = t_{packet} + t_{ACK} + t_{SIFS} \quad (7)$$

$$t_{col} = t_{packet} + t_{ACKtimeout} \quad (8)$$

where t_{packet} and t_{ACK} are the time periods to transmit a data packet and an ACK packet, respectively. t_{SIFS} is the time duration of SIFS. $t_{ACKtimeout}$ is the ACK timeout.

Table 3 Values of simulation parameters.

Simulation parameters	Values
Symbol Rate	187.5ksp/s
Slot length	376μs
Average packet length	114bits
Data rate	303.6kbp/s
SIFS	75μs
P_{TX}	401μW
P_{RX}	405μW
P_{CCA}	405μW

3.4 Energy consumption

Due to the much smaller energy consumption in sleep mode than channel listening or data transmission [3], we ignore energy consumption in sleep mode in which CCA and transmission are not performed. Energy consumption per unit time of a node with UP_k is denoted as

$$E_k = \frac{P_{su,k}E_{su,k} + (\tau_k - P_{su,k})E_{col,k} + P_{cca,k}E_{cca,k}}{(1 - P_{tr})t_{idle} + P_{tr}P_{su}t_{su} + P_{tr}(1 - P_{su})t_{col}} \quad (9)$$

where $E_{su,k}$ is the energy consumption for successful transmission, which is comprised of energy consumption of packet transmission and ACK reception. $E_{col,k}$ is the energy consumption for a failed transmission. $E_{cca,k}$ is the energy consumption in CCA.

$$E_{su,k} = t_{packet}P_{TX} + t_{ACK}P_{RX} \quad (10)$$

$$E_{col,k} = t_{packet}P_{TX} \quad (11)$$

$$E_{cca,k} = t_{cca}P_{CCA} \quad (12)$$

where P_{TX} and P_{RX} are the power consumption of transmission and receiving, respectively, P_{CCA} is the power consumption of CCA, and t_{cca} represents the time duration for CCA.

4. NUMERICAL RESULTS

In this section, some simulation results are obtained to demonstrate the effectiveness of the proposed analytical model for IEEE 802.15.6 MAC protocol. Here we only focus on the random access mechanism in IEEE 802.15.6, thus the manage access phases are left out in each superframe [1]. Parameters used in the simulations are summarized in Table 3. Although eight UPs are defined in IEEE 802.15.6 standard, we only use four UPs, i.e., UP_0 , UP_2 , UP_4 , UP_6 in the simulations as four UPs are enough for performance analysis in WBAN [9]. The number of energy units required for packet transmission N can be determined in terms of different harvesting technologies [11] and here we alter it in some simulations to see its effect for system performance.

In Figure 3, by fixing $P_1 = 0.6$ and $N = 25$, the performance curves are plotted for different user priorities as n varies. As shown in Figure 3a and Figure 3b, the transmission probability and the throughput decrease monotonically as n increases. It is due to the fact that more collisions happen if there are more number of nodes involved in the WBAN, which results in lower transmission probability and throughput. We could also find that higher priority nodes tend to achieve higher throughput since they access channel more frequently. As shown in Figure 3c, the power consumption of different UPs increase as n increases since there

are more nodes consuming energy. Although the lower priority nodes have higher power consumption, the difference of power consumption among different UPs is very small. It is because that lower UP nodes have larger CW and they need to sense channel more frequently, and the higher UP nodes transmit packet more often. The power required in CCA and transmission is equally considerable.

In Figure 4, we test the impact of N and P_1 to the system performance. As shown in Figure 4a, by setting $P_1 = 0.6$ and $N = 1000$, the probability of packet transmission almost remains unchanged with increasing n , which indicates that the number of nodes almost has no impact on throughput. This is because a large N implies a long energy-waiting period for transmission or CCA, and thus low packet transmission probability. Therefore, increasing n in the WBAN does not result in more collision, and certainly has little impact on system throughput. By setting $n = 12$ and $P_1 = 0.6$, the influence of varying N to the system performance is shown in Figure 4b, where the packet transmission probability decreases as N increases due to the longer energy-waiting period. We can also find that the gap of packet transmission probability between each UP becomes smaller as N increases. It is because higher UP nodes have larger probability to transmit and thus need more energy. Therefore, a weak energy harvesting ability affects their performance more.

Figure 4c plots the packet transmission probability versus the energy arrival probability with $n = 12$ and $N = 25$. We can find that, as P_1 increases, the probability of packet transmission also increases. With higher energy arrival rate, nodes recharge more quickly and sense channel more frequently. Consequently, the access probability of nodes tends to increase. Furthermore, the higher priority nodes achieve higher increasing rate compared to the nodes with lower priority. The result can be explained as follows. Despite the smaller CW of the higher priority nodes, if the higher priority nodes lack of energy, they are not able to sense the channel or transmit the packet. Thus, the performance of the higher priority nodes approach to that of the lower priority nodes for small energy arrival rate. However, if there are more energy arriving to the nodes, the superiority of higher priority nodes would reveal and they will achieve more opportunities to transmit packets.

5. CONCLUSIONS

In this paper, we develop a DTMC model for IEEE 802.15.6 MAC protocol in the WBAN with energy harvesting nodes. The long term performance of the WBAN in terms of throughput and energy consumption is analyzed. The effectiveness of the analytical model is demonstrated by the simulation results. This work is the first step to evaluate the performance of IEEE 802.15.6 MAC protocol in the WBAN with energy harvesting nodes. In the future work, we will consider a more practical energy arrival model. We will also consider the unsaturated case, i.e., the packets are arrived in each node based on some data arrival model, e.g., Poission arrival model.

6. ACKNOWLEDGMENTS

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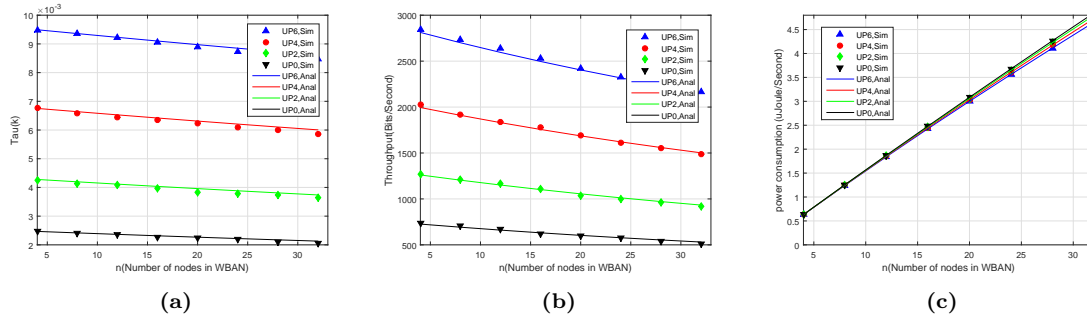


Figure 3 System performance curves for different user priorities

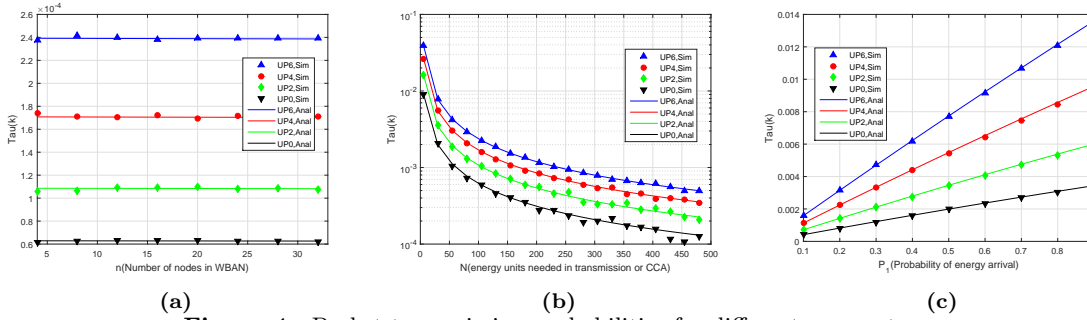


Figure 4 Packet transmission probabilities for different parameters.

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