Proposal Methods for Performance Analysis of WBANs Based on CSMA/CA

Do Thanh Quan[1,2], Pham Thanh Hiep[2], Takumi Kobayashi[1], Kento Takabayashi[1], Ryuji Kohno[1]
1. Graduate School of Engineering, Yokohama National University
Yokohama, Japan
2. Faculty of Electronic and Radio Engineering, Le Quy Don Technical University
Hanoi, Vietnam

***Abstract*— There have been burning issues on Wireless Body Area Networks (WBANs) in which performance analysis for media access layer (MAC) protocol is essential and has been discussed in many literatures. By using Markov chain model, saturation and non-saturation conditions, many works can calculate access probability and throughput of system. However, previous works usually assumed that channel is ideal and with both saturation and non-saturation conditions effect of remained packets, which were transmitted unsuccessfully due to collision or busy channel, was not considered adequately. The target of this paper is to evaluate system performance more accurately and flexibly, considering channel is non-ideal, taking into account the remained packets and using statistical mathematics instead of saturation and non-saturation condition and then to optimize parameters to achieve higher performance.**

Keywords*— *WBANs; BER/PER; Performance analysis; CSMA/CA; Saturation condition; Non-saturation condition; IEEE 802.15.6.

I. INTRODUCTION

In 2012, IEEE set up the standard for WBANs, IEEE.802.15.6, that has been considered as a breakthrough in development process of e-health care and information communications technology in general. To develop better technologies, protocols and to realize WBANs in commercial area are continuous works of researchers and engineers. A dependable and efficient MAC protocol is really important with WBANs when they are applied for medicine or even though for non-medicine. Better MAC protocol can produce low energy consumption or at least can guarantee the timely delivery of emergency traffic. Therefore, beside of improving MAC protocol, correctly analyzing it is necessary. There have been many works on performance analysis of IEEE 802.15.6, especially based on carrier sense multiple access with collision avoidance (CSMA/CA) scheme. The theoretical maximum throughput and minimum delay limit of IEEE 802.15.6 were clarified for different frequency bands and data rates in [2,3]. In addition, there have been many performance analyses for WBANs MAC protocol by using Markov chain model as in [4,5,6]. In the previous works on IEEE 802.15.6 MAC layer, the Markov chain model was usually proposed in order to calculate the access probability in saturation or non-saturation conditions.

However, the channel was frequently assumed to be ideal or all effect of noise and interference was solved or mitigated totally at physical (PHY) layer and the effect of remained packets, which are not transmitted because of busy channel or collision, was not considered adequately. These could make previous works meeting with limitations. These limitations will be solved in Section II and Section III of this paper, respectively.

II. PERFORMANCE ANALYSIS FOR WBANS WITH NON-IDEAL CHANNEL

A. Markov chain Monte Carlo (MCMC) method

In order to calculate throughput of system we developed discrete time Markov chain (DTMC) model to simulate the state of sensors in WBANs in non-saturation condition. The access probability of all sensor nodes can be obtained by solving the set of following equations.

$$\tau_i = \sum_{k=0}^{m} b_{i,k,0} = \frac{1-P_{i,fail}^{m+1}}{1-P_{i,fail}} b_{i,0,0} \qquad (1)$$

Here $b_{i,j,k}$ is the stationary distribution probability, τ_i is the access probability of sensor i and other parameters have the same meaning in previous works [4,5,6].

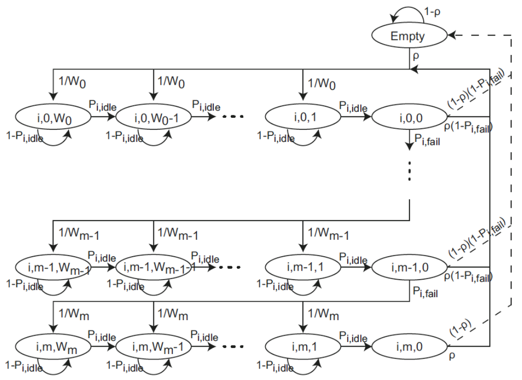

Fig. 1. DTMC model.

However, the access probability of all sensor nodes relates to each other. In this paper, the channel is non-ideal and then bit error rate (BER) and packet error rate (PER) are taken into account. It is clear that the PER of each sensor node affects the access probability of all sensor nodes, including itself. As a result, solving equations of access probability by mathematical method is considerably complicated. We proposed the MCMC method to easily obtain all access probabilities, considering variant PER in each sensor node for each superframe.

Let

$$f\left(\tau_i\right)=\tau_i-\frac{1-P_{i,fail}^{m+1}}{1-P_{i,fail}}b_{i,0,0} \qquad (2)$$

The access probability τ_i is obtained by solving $f\left(\tau_i\right)=0$. We developed the MCMC method to find all access probabilities with which all functions $f\left(\tau_i\right)$ are close to zero. The proposal method can be considered as a development or adjustment of DTMC method with key issue is to solve equations (1) approximately.

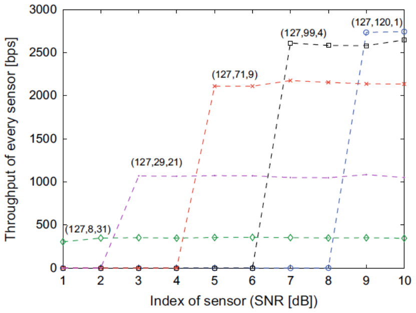

Fig. 3. Throughput of each sensor.

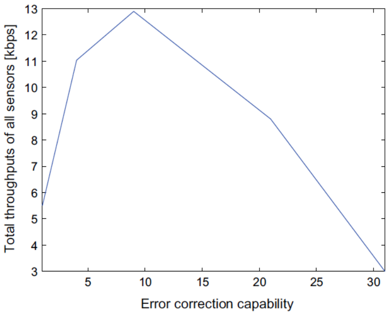

Fig. 2. Throughput of all sensors.

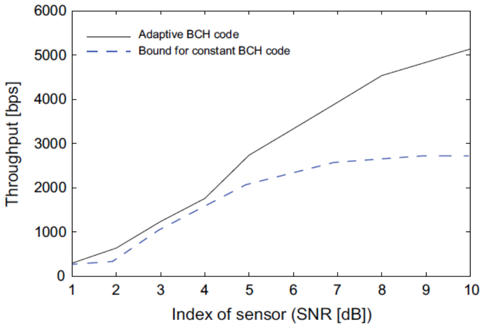

Fig. 4. Adaptive BCH code rates.

B. *Proposal adaptive BCH code rates for WBANs*

In this paper we use Bose–Chaudhuri–Hocquenghem (BCH) code as an example. With differential binary phase shift keying (DBPSK) modulation scheme, the BER and PER after demodulation can be obtained as follow.

$$BER_i=\sum_{j=t+1}^{m}\binom{m}{j}p_i^j(1-p_i)^{m-j} \qquad (3)$$

$$PER_i=1-(1-BER_i)^x \qquad (4)$$

Where m and t denote block length and error correction capability of BCH code and x is payload size.

C. *Numerical evaluation*

We developed simulation program for a star WBAN with one coordinator and 10 sensor nodes. We assumed that the received signal to noise ratio (SNR) of coordinator from every sensor node is different and varies within [1dB, 10dB]. Let the received SNR from sensor i be set as idB, for i=1,…,10. The retry limit and the packet generation rate are fixed to be 5 times and 5 packets/second, respectively. The other parameters are taken from Std.IEEE.802.15.6 [1].

As can be seen from Fig.2 the throughput is high when code rate and SRN are high, however, if code rate is low or correction capability is high, the throughput is likely to be stable even SNR is increased. With the Fig.3, it is clear that the total throughput reaches the highest value when error correction capability is at about 10, meaning that throughput will lower when error correction capability is high or low, on the other hand, code rate is low or high. As result, with each SNR value we can find optimal value of code rate. With this key point, this paper proposed adaptive BCH code rates depending on SNR values. The final result is showed in Fig.4 in which adaptive code rate produces significantly higher throughput than constant code rate.

III. TIME-VARYING STATISTICAL METHOD FOR PERFORMANCE ANALYSIS OF WBANS

In this paper, we developed mathematical statistical method to calculate the throughput of system in order to overcome the limitations of conventional methods, taking into account effect of remained packet. The probability that there is a packet to transmit after T_m duration time of a m^{th} UP sensor is described by follow.

$$\rho_m=1-e^{-\lambda_m T_m} \qquad (5)$$

Here m is the user priority index, λ_m denotes the packet generation rate and T_m is service time.

The service time (T_m) is defined as total time to transmit a packet of m^{th} UP sensors included the *backoff* time (T_W), time to transmit a data packet (T_{data}), short interframe spacing (T_{pSIFS}), time of acknowledgement packet (T_{ACK}) and delay time (α) which is defined as the sum of propagation and signal processing delay.

$$T_m = T_W + T_{data} + T_{ACK} + 2T_{pSIFS} + 2\alpha \tag{6}$$

Let's T_s denote a CSMA slot length, the value of the average backoff time can be calculated as follow.

$$T_W = \overline{W_m} T_s \tag{7}$$

Here, $\overline{W_m}$ is average backoff counter defined more detail below, in formula (14).

Since a data packet consists of a preamble, physical header, MAC header, MAC frame body and frame check sequence, the time to transmit a data packet is represented as follow.

$$T_{data} = T_P + T_{PHY} + T_{MAC} + T_{BODY} + T_{FCS} \tag{8}$$

Here, T_P, T_{PHY}, T_{BODY}, T_{FCS} represent the time to transmit a preamble, physical header, MAC header, MAC frame body and frame check sequence, respectively. Since an immediate acknowledgement carries no payload, its transmission time is given by follow.

$$T_{ACK} = T_P + T_{PHY} + T_{MAC} + T_{FCS} \tag{9}$$

In IEEE 802.15.6 based on CSMA/CA, the packet is discarded after the retry limit. According to application, the time-out data is deleted even the number of retransmission does not reach the retry limit. The time-out of data is set as k times of T_m, meaning that at the time $t=k+1$ packets generated at time $t=1$ are discarded. As a result, because of remained packet, the probability that a m^{th} UP sensor has a packet to send after t times of T_m will be changed as follow.

$$\rho_m(t) = \begin{cases} = \rho_m;\ for\ t=1 \\ = \rho_m + \rho_m(t-1) - \dfrac{P_{sucm}(t-1)}{N_m};\ for\ 1<t\le k \\ = \rho_m + \rho_m(t-1) - \dfrac{P_{sucm}(t-1)}{N_m} \\ \quad -\rho_m(t-k)\displaystyle\prod_{l=t-k}^{t-1}\dfrac{P_{failm}(l)}{N_m};\ for\ t>k \end{cases} \tag{10}$$

Here, $P_{failm}(t)$ is the fail transmission probability at time t of the m^{th} UP sensors due to the q^{th} UP ($q\neq m$) sensors accessing the channel or the m^{th} UP sensors transmitting packet unsuccessfully because of collision or error. The probability $P_{failm}(t)$ can be calculated as follow.

$$P_{failm} = 1 - P_{sucm}(t) - P_{idle} \tag{11}$$

Here, P_{idle} is the probability that all the sensors of system do not have a packet to send, $P_{idle} = \prod_{m=0}^{7}\left(1-\rho_m\right)^{N_m}$.

In some scenarios, a sensor may have more than one packet to send and then $\rho_m(t)$ may be more than one. In these scenarios, the data in the newest packet is updated and the data in other packets is outdated. Consequently, only the newest packet is kept to send and others are deleted as the time-out packets. Therefore, $\rho_m(t)$ is defined as $\rho_m(t) = \min(\rho_m(t), 1)$ for all t.

A packet of the m^{th} UP sensors is successfully transmitted if both two following conditions are satisfied. The first condition is that one or more than one m^{th} UP sensors have packet to send but only one m^{th} UP sensor accesses the channel. The second condition is that all other q^{th} UP sensors ($q\neq m$) do not have packet to send or if they have packet to send, their backoff counters must be higher than backoff counter of the m^{th} UP sensor accessing the channel. Let p_{sucm}, p_{suc_1m} and p_{suc_2m} denote successful probability that a packet of the m^{th} UP sensors is successfully transmitted, probability of the first condition and probability of the second condition, respectively. As a result, the successful transmission probability of the m^{th} UP sensors, p_{sucm}, can be calculated as follow.

$$P_{sucm} = P_{suc_1m} P_{suc_2m} \tag{12}$$

In the first condition, we assume that the total number of the m^{th} UP sensors is N_m and the number of the m^{th} UP sensors having a packet to send is i_m, $i_m \in \left[1, N_m\right]$. The probability that the m^{th} UP sensors have i_m sensors having a packet to send can be obtained as follow.

$$P_{suc_1m_1} = \binom{N_m}{i_m} \rho_m^{i_m}(1-\rho_m)^{N_m - i_m} \tag{13}$$

Only one sensor of m^{th} UP sensor successfully transmits when its backoff counter is smallest and there is not other sensors have the same backoff counter or other sensors do not have packet to send. The average backoff counter of the m^{th} UP sensors can be calculated as follow.

$$\overline{W_m} = \begin{cases} \dfrac{W_{\min}}{2} + P_{fail_m}^2 W_{\min} + P_{fail_m}^4 \dfrac{W_{\max}}{2} & for\, even\, UPs \\ \dfrac{W_{\min}}{2} + P_{fail_m}^2 \dfrac{W_{\max}}{2} & for\, odd\, UPs \end{cases} \tag{14}$$

The smallest backoff counter of the m^{th} UP sensor having smallest backoff counter is assumed as W_m, $W_m \in \left[1, \overline{W_m} - 1\right]$. The backoff counter of other m^{th} UP sensors must be higher than W_m meaning it must be within $\left[W_m+1,\overline{W_m}\right]$. The probability that the backoff counter of a m^{th} UP sensor is set as W_m is represented as $\binom{i_m}{1}\frac{1}{\overline{W_m}}$, and the probability that the backoff counter of the other m^{th} UP sensors are within $\left[W_m+1,\overline{W_m}\right]$ is represented as $\left(\frac{\overline{W_m}-W_m}{\overline{W_m}}\right)^{i_m-1}$. Consequently, the probability that in i_m m^{th} UP sensors having a packet to send there is one sensor takes the smallest backoff counter and others take higher backoff counter can be obtained as follow.

$$P_{suc_1m_2}=\sum_{W_m=1}^{\overline{W_m}-1}\binom{i_m}{1}\frac{1}{\overline{W_m}}\left(\frac{\overline{W_m}-W_m}{\overline{W_m}}\right)^{i_m-1} \qquad (15)$$

As a result, the probability of the first condition, p_{suc_1m}, is calculated as follow.

$$\begin{aligned}P_{suc_1m}&=\sum_{i_m=1}^{N_m}P_{suc_1m_1}P_{suc_1m_2}\\&=\sum_{i_m=1}^{N_m}\binom{N_m}{i_m}\rho_m^{i_m}(1-\rho_m)^{N_m-i_m}\sum_{W_m=1}^{\overline{W_m}-1}\binom{i_m}{1}\frac{1}{\overline{W_m}}\left(\frac{\overline{W_m}-W_m}{\overline{W_m}}\right)^{i_m-1}\end{aligned} \qquad (16)$$

Here $\binom{N_m}{i_m}$ denotes the binomial coefficient indexed by N_m and i_m.

In the second condition, we assume that the total number of the q^{th} UP ($q\neq m$) sensors is N_q and the number of the q^{th} UP sensors having a packet to send is i_q, $i_q\in\left[0,N_q\right]$. Probability that the q^{th} UP sensors have i_q sensors having a packet to send can be obtained as $\binom{N_q}{i_q}\rho_q^{i_q}(1-\rho_q)^{N_q-i_q}$, the same with formula (13). If any q^{th} UP sensor has packet to send, its backoff counter should be higher than W_m. The probability that all i_q q^{th} UP sensors having packet to send but their backoff counter are higher than W_m is $\left(\frac{\overline{W_q}-W_m}{\overline{W_q}}\right)^{i_q}$ in which if $\overline{W_q}\leq W_m$, $\frac{\overline{W_q}-W_m}{\overline{W_q}}$ is assumed to be zero. Therefore, The probability of the second condition, P_{suc_2m}, can be calculated as follow.

$$P_{suc_2m}=\prod_{\substack{q=0\\q\neq m}}^{7}\sum_{i_q=0}^{N_q}\binom{N_q}{i_q}\rho_q^{i_q}\left(1-\rho_q\right)^{N_q-i_q}\left(\frac{\overline{W_q}-W_m}{\overline{W_q}}\right)^{i_q} \qquad (17)$$

Finally, the successful transmission probability of the m^{th} UP sensors in formula (12), p_{sucm}, can be rewritten as follow.

$$\begin{aligned}p_{sucm}&=p_{suc_1m}\times p_{suc_2m}\\&=\sum_{i_m=1}^{N_m}\binom{N_m}{i_m}\rho_m^{i_m}(1-\rho_m)^{N_m-i_m}\sum_{W_m=1}^{\overline{W_m}-1}\binom{i_m}{1}\frac{1}{\overline{W_m}}\left(\frac{\overline{W_m}-W_m}{\overline{W_m}}\right)^{i_m-1}\\&\times\prod_{\substack{q=0\\q\neq m}}^{7}\sum_{i_q=0}^{N_q}\binom{N_q}{i_q}\rho_q^{i_q}\left(1-\rho_q\right)^{N_q-i_q}\left(\frac{\overline{W_q}-W_m}{\overline{W_q}}\right)^{i_q}\end{aligned} \qquad (18)$$

The throughput of m^{th} UP sensors can be calculated as follow.

$$S_{T_m}(t)=P_{sucm}(t)E\left[x\right] \qquad (19)$$

Here *E[x]* is the payload size of packet.

IV. CONCLUSION

In this paper we had developed the MCMC method for performance analysis for WBANs on MAC layer with non-ideal channel and then proposed adaptive BCH code rates for WBANs. The proposal adaptive coding scheme can improve the throughput of system, however, it may cause system become more complex and this problem is not solved in this paper yet. We also developed algorithm for time-varying statistical method to overcome limitation of conventional method. For future work, we hope to extend this result for other coding schemes and develop simulation program for the time-varying statistical method in order to compare our results with previous work results and prove the proposal method.

REFERENCES

[1] Group, W.P.A.N.W.: Ieee standard 802.15.6, wireless body area networks. IEEE standards **2**, 1{271 (2012)

[2] Li, C., Geng, X., Yuan, J., Sun, T.: Performance analysis of ieee 802.15.6 mac protocol in beacon mode with superframes. KSII transaction on internet and information systems **7**, 1108{1130 (2013)

[3] Ullah, S., Chen, M., Kwak, K.S.: Throughput and delay analysis of ieee 802.15.6-based csma/ca protocol. Journal of Medical Systems **36**, 3875{3891 (2012)

[4] Li, C., Geng, X., Yuan, J., & Sun, T. (2013). Performance analysis of IEEE 802.15.6 MAC protocol in Beacon mode with superframes. KSII Transaction on Internet and Information Systems, 7, 1108–1130.

[5] Rashwand, S., & Misic, J. (2012). Effects of access phases lengths on performance of IEEE 802.15.6 CSMA/CA. Journal of Computer Networks, 56, 2832–2846.

[6] Sarkar, S., Misra, S., Bandyopadhyay, B., Chakraborty, C., & Obaidat, M. S. (2015). Performance analysis of IEEE 802.15.6 MAC protocol under non-ideal channel conditions and saturated traffic regime. IEEE Transactions on Computers, 64(10), 2912–2925.