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WBAN MAC Protocols— Non-Saturation Modeling and Performance Analysis

Pervez Khan[1], Niamat Ullah[2] and Hoon Kim[1]
[1]Department of Electronics Engineering, Incheon National University,
Incheon, South Korea
[e-mail: pervaizkanju@hotmail.com, hoon@inu.ac.kr]
[2]Department of Computer Science, Govt. Postgraduate Jahanzeb College, Saidu Sharif, Swat, Khyber Pakhtunkhwa, Pakistan
[e-mail : niamatnaz@gmail.com]
*Corresponding author: Hoon Kim

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Abstract

The current literature on discrete-time Markov chain (DTMC) based analysis of IEEE 802.15.6 MAC protocols for wireless body area networks (WBANs), do not consider the ACK timeout state, wherein the colliding nodes check the ill fate of their transmissions, while other contending nodes perform backoff check that slot as usual. In this paper, our DTMC model accurately captures the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism of IEEE 802.15.6 medium access control (MAC) and allows the contending nodes performing backoff to utilize the ACK timeout slot during collisions. The compared rigorous results are obtained by considering a non-ideal channel in non-saturation conditions, and CSMA/CA parameters pertaining to UWB PHY of IEEE 802.15.6 MAC protocols.

Keywords: Wireless Body Area Network, IEEE 802.15.6, MAC Protocols, CSMA/CA, Analytical Modeling

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1. Introduction

The carrier sense multiple access with collision avoidance (CSMA/CA) procedure of IEEE 802.15.6 medium access control (MAC) protocols for wireless body area network (WBAN) is varying in key features from the conventional CSMA/CA procedures. In IEEE 802.15.6 CSMA/CA procedure, a transmitting node takes an entire CSMA slot right after the end of immediate past transmission to hear the status of its transmission. Therefore, we append a supplementary state in the DTMC model to represent that inspection slot. In our proposed Markov chain, from the transmitting state (i,0), there is a transition with probability γ to that additional slot (i,-1). We consider two cases of our Markov model, case1 considers the special state (i,-1), while case2 does not consider this state. Also, the CSMA/CA backoff procedure of WBAN MAC protocol is not binary increasing. To employ the CSMA/CA mechanism, a contending node shall maintain a backoff counter $\in [1, \mathrm{CW}]$ and a contention window (CW) to detect a new contended allocation. The contending node having a packet for transmission shall set its backoff counter over the interval [1,CW] to minimize the probability of collision. To initiate the CSMA/CA operation of IEEE 802.15.6 MAC protocol, a CW is picked as: a) the node shall set CW to $\mathrm{CW}_{\mathrm{min}}$ for each newly arrived packet. b) An even number of failure for a same packet can only double the CW. c) If the new CW value exceeds $\mathrm{CW}_{\mathrm{max}}$ the node will keep the CW to $\mathrm{CW}_{\mathrm{max}}$. After a CW is chosen, the node starts its carrier sensing at the beginning of the next pCSMAslot to determine the current state of the channel. Each pCSMAslot has a fixed duration specified by pCSMASlotLength. The very first portion of pCSMAslot, which is equal to 63/symbol-rate in time length, corresponds to pCCATime (physical CCA), while the latter portion of pCSMAslot is used by the contending node to transmit its frame to the transport medium when its backoff counter reaches zero. Each idle pCCATime will lead the contending nodes to decrement its backoff counter by one. Moreover, any transmission on the channel during pCCATime will lead the contending nodes to lock their backoff counters until it has been idle for pSIFS. Other locking/unlocking mechanisms are beyond the scope of this study, as we only consider activity in the random access phase1 (RAP1). Upon reaching the backoff counter to 0, the contending node starts transmission [1].

Fig. 1 shows an example that how the situation of collision is treated by the nodes involved in collision and by the other contending nodes performing backoff. In **Fig. 1**, nodes A and B involved in collision are yet to realize (in the immediate next slot following that colliding transmission) that there is a collision, but node C is doing backoff check that slot as usual. Node C finds that slot idle and decreases its backoff counter. Colliding nodes A and B see off that slot as $\mathrm{ACK}_{\mathrm{timeout}}$ and extract a new backoff value. Due to the these differences, the typical CSMA/CA discrete time markov chains (DTMCs) models need to be modified. The current literature witnesses few probabilistic works on analyzing the contention-based access schemes of IEEE 802.15.6 MAC protocols, such as [2][3][4][5][6][7][8][9] and [10]. However, none of these works consider the supplementary state where the colliding nodes check the ill fate of their transmissions, while other contending nodes performing backoff check that slot as usual. The supplementary state in the DTMC model of [9][10][11] and [12], also do not allow the contending nodes to decrement their backoff counters during collisions because from the transmission state to waiting timeout state the transition probability is 1 and hence all the nodes (contending and colliding) will observe this state in the same manner.

In this paper, we focus on the comparative study by considering case1 (with special state (i,-1)) and case2 (without special state (i,-1)) of the proposed DTMC model. Our DTMC model accurately captures the CSMA/CA mechanism of IEEE 802.15.6 MAC and allows the contending nodes performing backoff to utilize the $\mathrm{ACK}_{\mathrm{timeout}}$ slot during collisions. The compared rigorous results are obtained by considering a non-ideal channel in non-saturation conditions, and CSMA/CA parameters pertaining to UWB PHY of IEEE 802.15.6 MAC protocols.

The rest of this paper is structured as follows: Section 2 presents the related studies available in the literature. Section 3 describes the framework of the analytical model and performance measures. The numerical results are provided in Section 4, and eventually, Section 5 concludes our research findings.

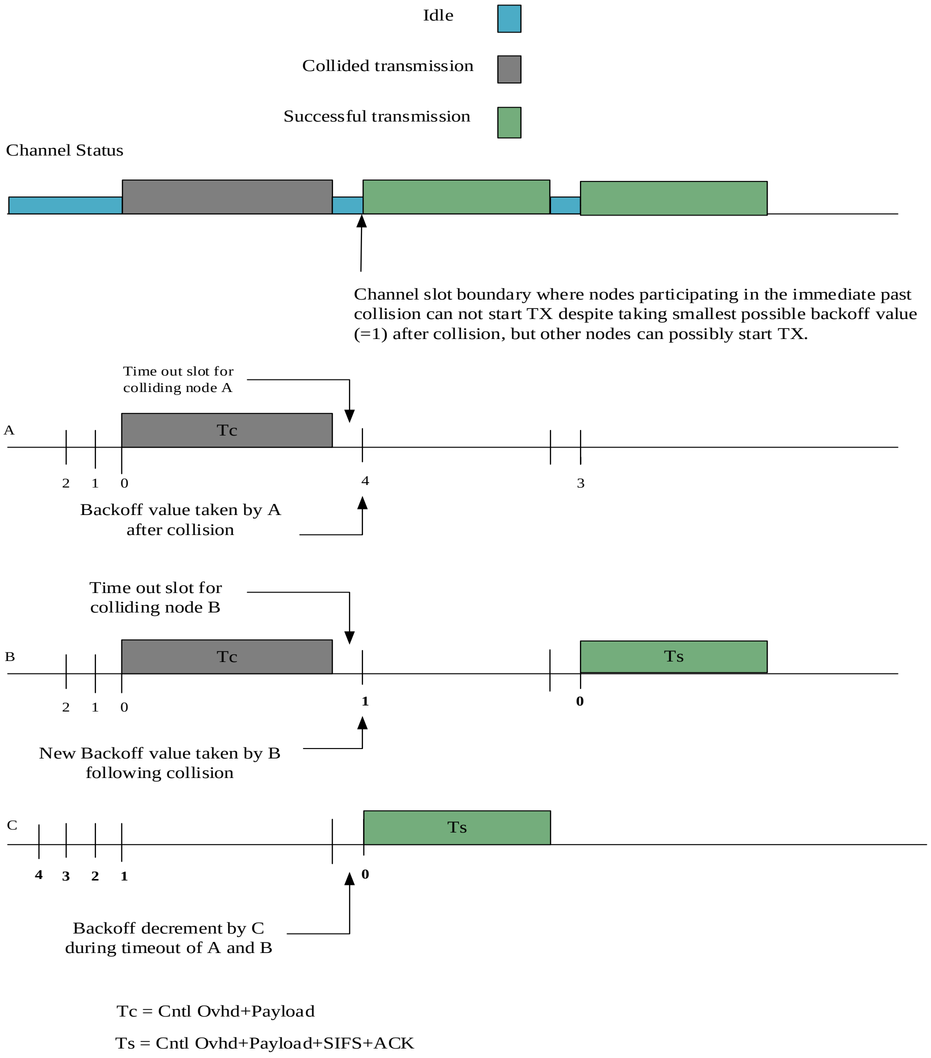

Fig. 1. IEEE 802.15.6 CSMA channel access diagram

2. THE SYSTEM MODEL AND ASSUMPTIONS

We develop a DTMC model to analyze the behavior of IEEE 802.15.6 CSMA/CA procedure under non-saturation conditions, as shown in **Fig. 2**. We presume that no other packet is generated by a sensor node if it has a packet in service. There are eight different user classes defined by the IEEE 802.15.6 standard. The user classes, also called user priority of class i (UP_i) nodes, where $i \in \{0,1,2,3,4,5,6,7\}$, are differentiated by CW_{min} and CW_{max} as depicted in **Table 1**. The CW bounds for a node of UP_i during the bth backoff stage can be determined as $W_{i,b} = 2^{\lfloor b/2 \rfloor} CW_{i,min}$We consider a single-hop star-network WBAN with N

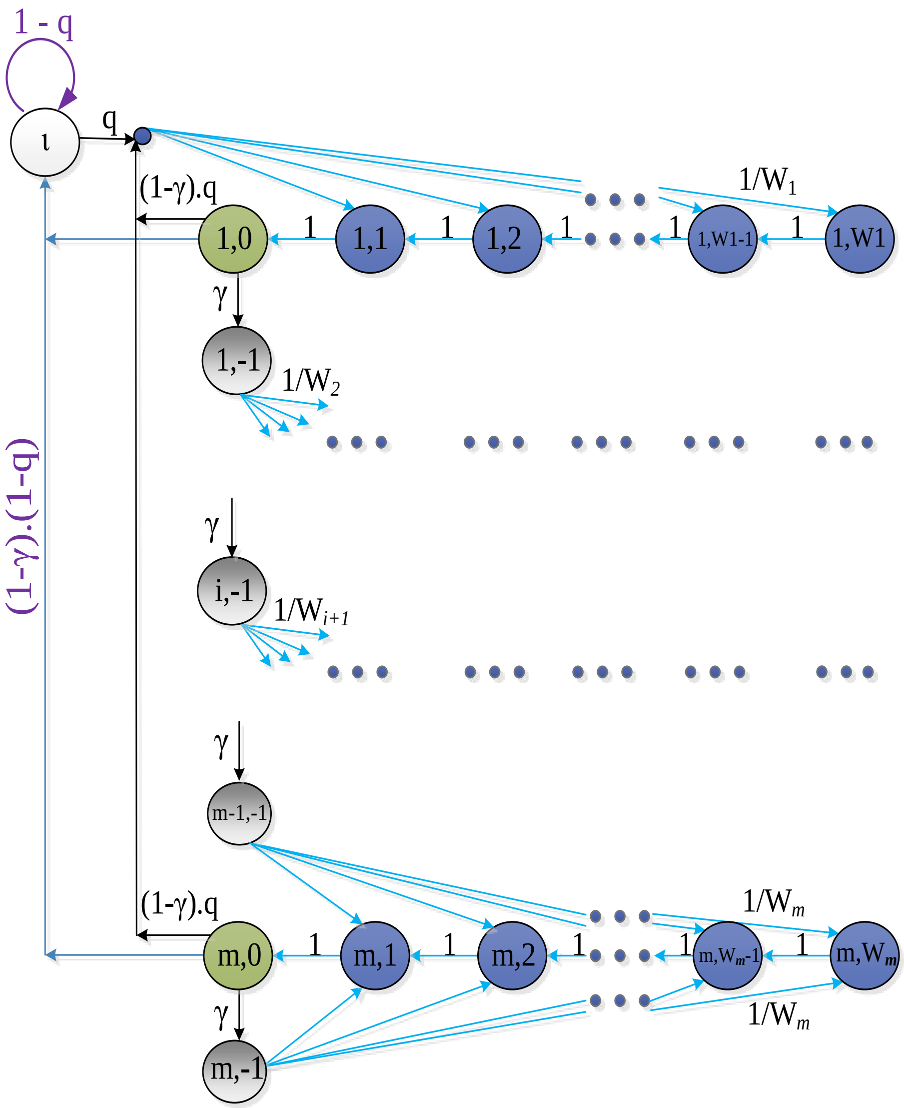

Fig. 2. DTMC for the non-saturation behavior of WBAN CSMA/CA

UP_i sensor nodes. The size of WBAN in terms of nodes can be computed as $N = \sum_{i=0}^{7} n_i$, where n_i is the number of nodes in a UP_i. For our results, we examine three different $UP_i's$

with three nodes in each $\mathrm{UP_i}$. The superframe structure of WBAN MAC comprises different access phases (AP's) as shown in **Fig 3**. However, to validate our model, we only consider activity in the random AP1 (RAP1) (accecibale by all the $\mathrm{UP_i}$), and assumed other optional AP's to be null. We assume a noisy channel and besides collisions, a packet may not be received correctly if at least one of the bits is erroneously received. Probability of such an event can be given by $\gamma_e = 1 - (1 - \varepsilon_\theta)^L$. Where L denotes the frame size in bits and ε_θ symbolizes the bit error rate, assumed to be 10^{-5}. We consider immediate acknowledgement (I-ACK) policy of IEEE 802.15.6 CSMA/CA mechanism. Due to the fact that a medical data is of high importance and should be delivered to the remote medical server, our model considers no retry limit.

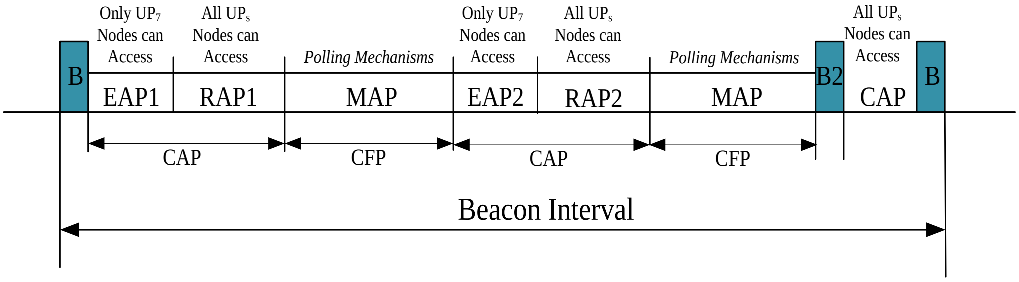

Fig. 3. Configuration of access phases with beacon intervals

Let (i, k) represents two random processes $\chi(t)$ and $\kappa(t)$ for backoff stage and backoff time counter, respectively. The two special states in our Markov chain are (i,0); the state of transmission, and (i,-1); the timeout slot to know the status (collision) of the transmitted packet. As we consider non-saturated conditions in our model, a packet may not be always available to the MAC of a node. The probability of a packet availability is given by $q=1-e^{-\lambda E_{\mathrm{state},i}}$, where $E_{\mathrm{state},i}$ is the expected waiting time of a $\mathrm{UP_i}$ node in each state of the Markov chain. λ is the Poisson packet arrival rate. We compute $E_{\mathrm{state},i}$ in order to convert the states into real time.

$$E_{\mathrm{state},i} = (1 - P_{tr}) \times \delta + \sum_{i=0}^{7} P_{s,i} \times T_s + T_c \left(1 - \sum_{i=0}^{7} P_{s,i} \right) \tag{1}$$

where δ represents the pCSMAslot duration, $P_{s,i}$ is the success probability, T_s and T_c are the mean time-span of a busy channel, and P_{tr} is the probability that at a minimum one $\mathrm{UP_i}$ node transmits in a given time slot and can be obtained as

$$P_{tr} = 1 - \prod_{i=0}^{7} (1 - \beta_i)^{n_i} \tag{2}$$

$P_{s,i}$ is the success probability by a $\mathrm{UP_i}$ node and can be simplified as (case1)

$$\mathrm{P_{s,i}} = \mathrm{n_i}\upbeta_\mathrm{i}(1-\upbeta_\mathrm{i})^{\mathrm{n_i}-1} \prod_{\mathrm{b}=0,\ \mathrm{b}\neq \mathrm{i}}^{7} (1-\upbeta_\mathrm{b})^{\mathrm{n_b}} \times (1-\varepsilon_\theta)^{L} \tag{3}$$

$\mathrm{T_s}$ and $\mathrm{T_c}$ represent the mean time-span of a busy channel due to an acknowledged and failed transmission, respectively. $\mathrm{T_s}$ and $\mathrm{T_c}$ are represented as

$$\begin{gathered} \mathrm{T_s} = \mathrm{T_{(MAC+PHY)overhead}} + \mathrm{T_{Payload}} + \mathrm{T_{pSIFS}} + \mathrm{T_{ACK}} \\ \mathrm{T_c} = \mathrm{T_{(MAC+PHY)overhead}} + \mathrm{T_{Payload}} \end{gathered} \tag{4}$$

where $\mathrm{T_{(MAC+PHY)overhead}}$, $\mathrm{T_{Payload}}$, $\mathrm{T_{pSIFS}}$, and $\mathrm{T_{ACK}}$ are the MAC&PHY overhead duration, mean payload duration, transceiver turnaround time and acknowledgement frame duration, respectively.

The probability of collision for a $\mathrm{UP_i}$ node can be specified as follows (case1)

$$\gamma_\mathrm{i} = 1-(1-\upbeta_\mathrm{i})^{\mathrm{n_i}-1} \prod_{\mathrm{b}=0,\ \mathrm{b}\neq \mathrm{i}}^{7} (1-\upbeta_\mathrm{b})^{\mathrm{n}_b} \tag{5}$$

We denote $\upbeta_\mathrm{i}$ as the probability of transmission by a $\mathrm{UP_i}$ node. $\upbeta_\mathrm{i}$ can be determined as

$$\upbeta_\mathrm{i} = \sum_{\mathrm{i}=1}^{\mathrm{m}} \uppi(\mathrm{i},0) \tag{6}$$

The stationary distribution of being in the $\mathrm{ACK_{timeout}}$ state (i,-1) is given by

$$\uppi(\mathrm{i},-1) = \gamma_\mathrm{i} \times \uppi(\mathrm{i},0) \qquad 1 \le \mathrm{i} \le \mathrm{m} \tag{7}$$

The normalized equation is given by (case1)

$$\begin{gathered} \sum_{\mathrm{i}=1}^{\mathrm{m}} \sum_{\mathrm{k}=-1}^{\mathrm{W_i}} \uppi(\mathrm{i},\mathrm{k}) + \uppi(\iota) = \sum_{\mathrm{k}=1}^{\mathrm{W_1}-1} \uppi(1,\mathrm{k}) + \uppi(1,\mathrm{W_1}) + \sum_{\mathrm{k}=1}^{\mathrm{W_m}-1} \uppi(m,\mathrm{k}) + \uppi(m,\mathrm{W_m}) \\ + \sum_{\mathrm{i}=2}^{\mathrm{m}-1} \sum_{\mathrm{k}=1}^{\mathrm{W_i}-1} \uppi(i,\mathrm{k}) + \sum_{\mathrm{i}=2}^{\mathrm{m}-1} \uppi(i,\mathrm{W_i}) + \sum_{\mathrm{i}=1}^{\mathrm{m}} \uppi(i,0) + \sum_{\mathrm{i}=1}^{\mathrm{m}} \uppi(\mathrm{i},-1) + \uppi(\iota) = 1 \end{gathered} \tag{8}$$

$$\begin{gathered} \Rightarrow (1-\gamma_\mathrm{i})\upbeta_\mathrm{i}\frac{(\mathrm{W_1}+1)}{2} + \frac{(1-\gamma_\mathrm{i})\upbeta_\mathrm{i}}{2}\left\{\sum_{\mathrm{i}=1}^{\mathrm{m}-1} \gamma_\mathrm{i}{}^{\mathrm{b}}(\mathrm{W_{i+1}}+1) + \gamma_\mathrm{i}{}^{m_\mathrm{i}}(\mathrm{W_m}+1)\right\} \\ +\upbeta_\mathrm{i}\left\{1+\gamma_\mathrm{i}+\frac{1}{\mathrm{q}}(1-\mathrm{q})(1-\gamma_\mathrm{i})\right\} = 1 \end{gathered} \tag{9}$$

$$\Rightarrow \beta_i = \frac{1}{1 + \gamma_i + \frac{1}{q}(1-q).(1-\gamma_i) + (1-\gamma_i)\sum_{b=0}^{m-1} \gamma_i{}^{b}\,\frac{W_{i,b+1}}{2} + (1-\gamma_i)\gamma_i{}^{m_i}\,\frac{W_{i,m}}{2} + \frac{1-\gamma_i{}^{m_i+1}}{2}} \tag{10}$$

Similarly, the transmission probability (let's say $\widehat{\beta_i}$) for a markov chain without considering the special state (i,-1) can be obtained as (case2)

$$\widehat{\beta_i} = \frac{1}{1 + \frac{1}{q}(1-q).(1-\widehat{\gamma_i}) + (1-\widehat{\gamma_i})\sum_{b=0}^{m-1} \widehat{\gamma_i}^{\,b}\,\frac{W_{i,b+1}}{2} + (1-\widehat{\gamma_i})\widehat{\gamma_i}^{\,m_i}\,\frac{W_{i,m}}{2} + \frac{1-\widehat{\gamma_i}^{\,m_i+1}}{2}} \tag{11}$$

where $\widehat{\gamma_i}$ is the probability of collision for a UP_i node and is computed as (case2)

$$\widehat{\gamma_i} = 1 - (1-\widehat{\beta_i})^{n_i-1} \prod_{b=0,\ b\neq i}^{7} (1-\widehat{\beta_b})^{n_b} \tag{12}$$

Also, let $\widehat{P_{s,\imath}}$ be the success probability of a UP_i node and can be obtained as (case2)

$$\widehat{P_{s,i}} = n_i\widehat{\beta_i}(1-\widehat{\beta_i})^{n_i-1} \prod_{b=0,\ b\neq i}^{7} (1-\widehat{\beta_b})^{n_b} \times (1-\varepsilon_\theta)^{L} \tag{13}$$

The per-node throughput for a UP_i is the fraction of time being used to transmit the actual data bits successfully. The per-class normalized throughput can be stated as

$$\Theta_i = \begin{cases} \dfrac{P_{s,i} \times T_{payload}}{E_{state,i}} & \text{where } i = 0..7 \\ \dfrac{\widehat{P_{s,\imath}} \times T_{payload}}{E_{state,i}} & \text{where } i = 0..7 \end{cases} \tag{14}$$

$T_{Payload}$ is the mean payload duration.

Thus, system throughput can be acquired as

$$\Theta = \sum_{i=0}^{7} \Theta_i \times \rho_i \qquad i = 0,\dots,7 \tag{15}$$

where $\rho_i = \frac{n_i}{N}$

Table 1. CSMA/CA CW_{min} and CW_{max} bounds for UP_i

User Priority Class (UP_i)	**Traffic Class**	CW_{min}	CW_{max}
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	Media data (network control)	4	8
6	medical data or control	2	8
7	Emergency or medical event report	1	4

We are also interested in the performance assessment of mean frame service time $E[T_i]$, which is defined as the time span between the events, that the packet reaches at the head of the queue and the time when the receiver acknowledges the packet successfully. In the case of successful transmission at the first attempt, $E[T_i]$ can be estimated as $E[T_i] = \frac{W_{1,b}}{2}.E_{state,i} + (1-\gamma_i)T_s$. If the tagged node does not succeed in the first attempt then for any subsequent success, the mean frame service time $E[T_i]$ for a particular user class can be expressed as

$$\begin{aligned}
&E[T_i] = \frac{W_{1,b}}{2} \times E_{state,i} + (1-\gamma_i)T_s + \gamma_i \times T_c\{\delta + \frac{W_{2,b}}{2} E_{state,i} + (1-\gamma_i)T_s \\
&+\gamma_i \times T_c \times \{\delta + \tfrac{W_{3,b}}{2} E_{state,i} + (1-\gamma_i)T_s \\
&+\gamma_i \times T_c \times \{\delta + \tfrac{W_{4,b}}{2} E_{state,i} + (1-\gamma_i)T_s \\
&\vdots \\
&\cdots\}\}\}
\end{aligned}$$

$$\Rightarrow \qquad E[T_i] = \delta.\sum_{i=1}^{\infty} \gamma_i{}^b T_c + E_{state,i} \sum_{i=0}^{\infty} \gamma_i{}^b \frac{W_{i,b+1}}{2} + T_s(1-\gamma_i) \sum_{i=0}^{\infty} \gamma_i{}^b$$

$$= \delta.\tfrac{\gamma_i}{1-\gamma_i} T_c + T_s(1-\gamma_i)\tfrac{1}{1-\gamma_i} + E_{state,i} \textstyle\sum_{i=0}^{m-1} \gamma_i{}^b \tfrac{W_{i,b+1}}{2} + E_{state,i}.\gamma_i{}^{m_i}.\tfrac{W_{i,m}}{2}.\textstyle\sum_{i=0}^{\infty} \gamma_i{}^b$$

$$= \delta.\tfrac{\gamma_i}{1-\gamma_i} T_c + T_s + E_{state,i} \textstyle\sum_{b=0}^{m_i-1} \gamma_i{}^b \tfrac{W_{i,b+1}}{2} + E_{state,i} \tfrac{\gamma_i{}^{m_i} W_{i,m}}{2(1-\gamma_i)}$$

Now $E[T_i]$ for case1 and case2 can be expressed as

$$E[T_i] = \begin{cases} \delta . \dfrac{\gamma_i}{1-\gamma_i} T_c + T_s + E_{state,i} \displaystyle\sum_{b=0}^{m_i-1} \gamma_i{}^{b} \dfrac{W_{i,b+1}}{2} + E_{state,i} \dfrac{\gamma_i{}^{m_i} W_{i,m}}{2(1-\gamma_i)} & \text{(case1)} \\ \dfrac{\widehat{\gamma_i}}{1-\widehat{\gamma_i}} T_c + T_s + E_{state,i} \displaystyle\sum_{b=0}^{m_i-1} \widehat{\gamma_i}{}^{b} \dfrac{W_{i,b+1}}{2} + E_{state,i} \dfrac{\widehat{\gamma_i}{}^{m_i} W_{i,m}}{2(1-\widehat{\gamma_i})} & \text{(case2)} \end{cases} \qquad (16)$$

where $W_{i,b}$ represents the number of backoff slots in a particular backoff stage and i = 0,1,2,...7.

3. Performance Evaluation

We have compared the analytical results of the proposed model by taking into account case1 (considering the special state (i,-1)) and case2 (without considering the special state (i,-1)) of the Markov chain model. The PHY-dependent MAC sublayer parameters pertaining to UWB PHY, being specified in the IEEE 802.15.6 standard are used to obtain our results. These parameters are summarized in **Table 2.**

Table 2. UWB PHY-dependent MAC sublayer parameters

Parameter Timings	Slot time	292 μs
	pSIFS	75 μs
	pCCA	252 μs
	pCSMAMACPHYTime	40 μs
	Ack Time	468.4 μs
Parameter Lengths (bits)	MAC Header	56 bits
	MAC Footer	16 bits
	PHY Header	31 bits
	Payload (average)	2040/2 bits
Data Rates	PLCP Header	91.9($Kbps$)
	PSDU	3159($Kbps$)

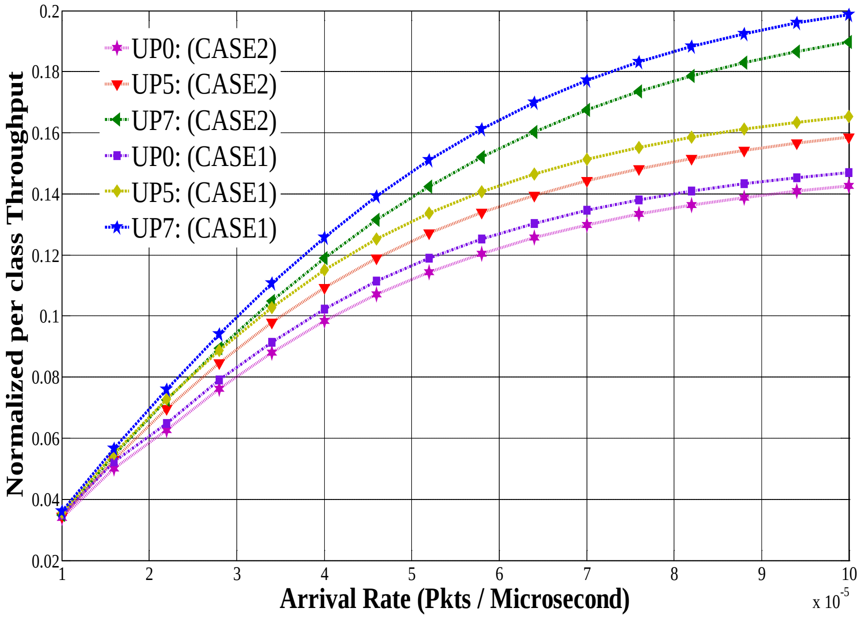

Fig. 4. Per class normalized throughput for case1 and case2

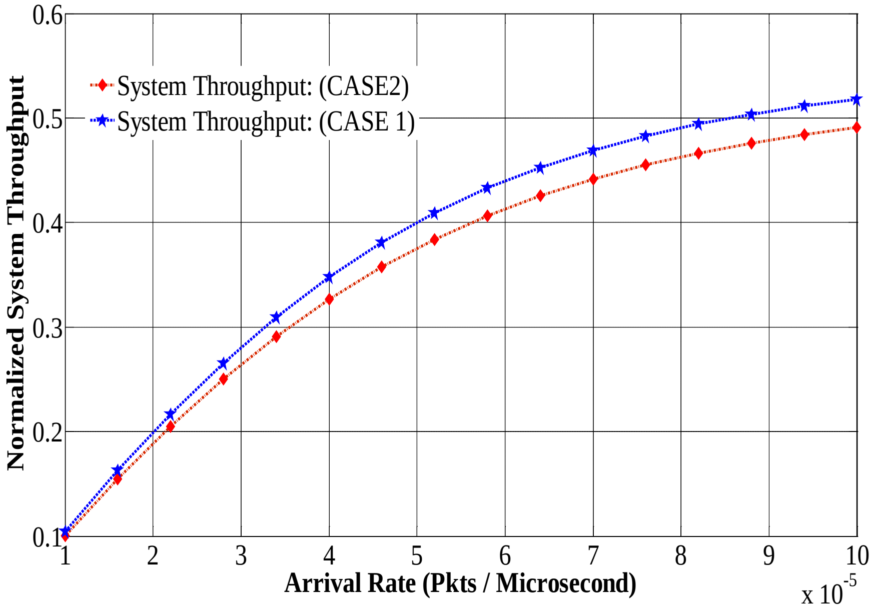

Fig. 5. Normalized system throughput for case1 and case2

Fig. 4 and **Fig. 5** show normalized per-class throughput and normalized system throughput performance as a function of traffic load in non-saturated heterogeneous scenario, respectively. To explain the results visibly, we chose three different priority classes (from lower to higher class), i.e., UP_0, UP_5 and UP_7. However, other priority classes can be easily considered in our model. All these results show that UP_i nodes with lower CW_{min} and CW_{max} values, can access the medium more frequently and hence can achieve higher per class throughput. From **Fig. 4** and **Fig. 5**, it is obvious that case1 of the proposed DTMC model shows a reasonable difference in the throughput performance over case2. This is because in case1, during collision while the colliding nodes inspect a further CSMA slot to learn the result of its packet just transmitted, all other contending nodes find this slot idle and perform a backoff countdown. On the other hand, in case2 as we have omitted the additional slot (i,-1), other contending nodes will not find this slot idle and hence cannot count-down the backoff counter and therefore, performance is degraded as shown in **Fig. 4**, and **Fig. 5**.

Fig. 6 shows the head of line delay performance as a function of traffic load in non-saturated heterogeneous scenario. We see that UP_i nodes with lower CW_{min} and CW_{max} values, can access the medium more frequently and hence the delay is low. From **Fig. 6**, it is obvious that case1 of the proposed DTMC model shows a reasonable difference in the delay performance over case2. More $ACK_{timeout}$ slots will be observed by the system with the increase in the collision rate. The head of line delay difference between case1 and case2 is negligible for low arrival rate, but as the arrival rate increases, the collision probability also increases and hence the difference in delay performance of the two cases is more visible.

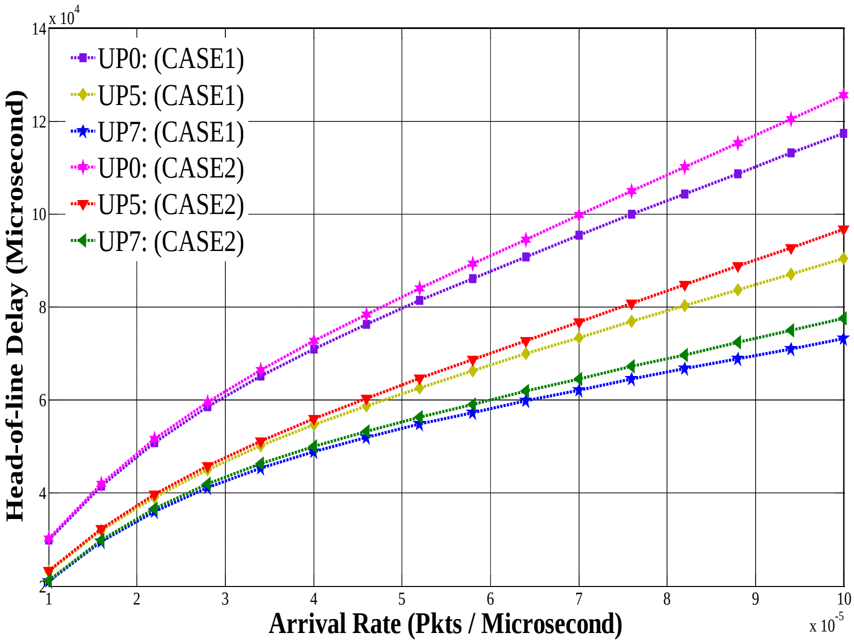

Fig. 6. Head-of-Line-Delay for and case2

Fig. 7 shows the collision probability as a function of traffic load in non-saturated heterogeneous scenario for case2 only. We only focus one case to show that how offered load will impact the collision probability. We see that for low arrival rates, the collision probabilities of transmitting nodes in each class are very close to each other. For higher loads the nodes with small CW_{min} and CW_{max} values are more likely to access the channel at the same time, and hence resulting in increased collision rates.

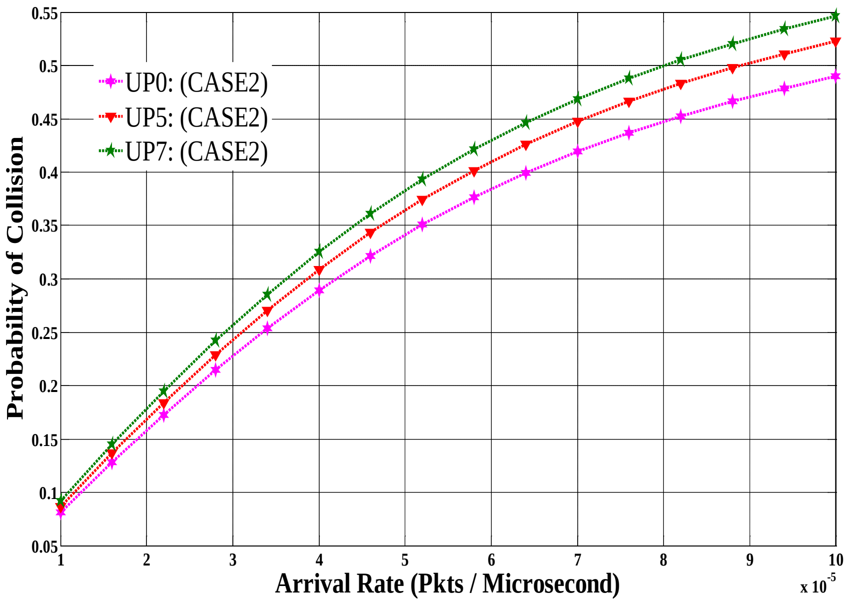

Fig. 7. Probability of Collision for case2

4. Conclusion

This study evaluates the performance of IEEE 802.15.6 CSMA/CA procedure in terms of normalized throughput and head of line delay by exploiting the proposed Markov chain model. Our results show that the proposed DTMC model has truly captured the CSMA/CA procedure of IEEE 802.15.6 MAC protocols and has allowed the contending nodes performing backoff to utilize the ACK timeout slot during collisions. We intend to extend this work by taking into account the entire superframe and other performance criterions.

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Pervez Khan received his Master and Bachelor degrees, both in Computer Science from the University of Peshawar, Pakistan, in 2006 and 2003 respectively, and a Ph.D. degree in information technology and telecommunications from the Graduate School of IT and Telecommunication Engineering Inha University, Incheon, South Korea, in 2015 with the University-President Award. He has been a Post-doctoral Fellow with the Wireless Innovative Transmission Lab, Department of Electronics Engineering, Incheon National University, Incheon, South Korea, since March 2016. His current research interests include wireless communications, wireless sensor networks, wireless ad-hoc networks, wireless body area networks, Mesh networks, performance evaluation, and MAC protocol design.

Niamat Ullah received his B.Sc. in mathematics in 1994 from Peshawar University, Pakistan, and his master in computer sciences in 1996 from Quaid-e-Azam University Islamabad, Pakistan. He then joined the Higher Education Department Khyber Pakhtunkhwa as a lecturer. He got Ph.D. degree from Graduate School of IT and Telecommunications at Inha University, Incheon, South Korea, in 2013. He is an assistant professor and chariman at department of Computer Science, Govt. Postgraduate Jahanzeb College Saidu Sharif Swat, Khyber Pakhtunkhwa, Pakistan. His research area includes wireless communications, wireless ad Hoc networks, directional and smart antenna, wireless sensor networks, and MAC protocol for wireless body area networks.

Hoon Kim received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from Korea Advanced Institute of Science and Technology (KAIST), Korea in 1998, 1999, and 2004, respectively. He had been working with Samsung Advanced Institute of Technology (SAIT) during 2004 to 2005 and served as a Senior Engineer in Communications and Networks Laboratory Division joining the project of design and performance analysis of radio transmission technology for 3G and beyond 2G mobile communication systems. He also had been working with Ministry of Information and Communications (MIC) during 2005 to 2007 and served as a Deputy Director in Broadband Communications Division promoting policies for broadband communications industry such as WiBro and NGN, etc. He joined Stanford University as a visiting scholar during 2007 to 2008 developing radio resource management algorithms and cross layer optimization schemes for 4G mobile communications systems. He is currently with the Department of Electronics Engineering at University of Incheon as a faculty. His research interests include performance evaluation of mobile communication systems, radio resource management schemes, and optimization of mobile systems operation. He is a Member of KICS, IEEE, and IEICE.