Analysis of Reliability and Throughput under Saturation Condition of IEEE 802.15.6 CSMA/CA for Wireless Body Area Networks

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***Abstract*—The standardization of the IEEE 802.15.6 protocol for wireless body area networks (WBANs) dictates the physical layer and medium access control layer standards from the communication perspective. The standard supports short-range, extremely low power wireless communication with high quality of service and data rates upto 10 Mbps in the vicinity of any living tissue. In this paper, we develop a discrete-time Markov model for the accurate analysis of reliability and throughput of an IEEE 802.15.6 CSMA/CA-based WBAN under saturation condition. Existing literature on Markov chain-based analysis of IEEE 802.15.6, however, do not take into consideration the time a node spends waiting for the immediate acknowledgement frame after transmission of a packet, until time-out occurs. In this work, we take into consideration the waiting time for a node after its transmission, and accordingly modified the structure of the discrete-time Markov chain (DTMC). We also show that as the payload length increases, the reliability of a node decreases; whereas its throughput sharply increases.**

***Index Terms*—IEEE 802.15.6, WBAN, Markov model, Reliability, Throughput**

I. Introduction

In recent times, healthcare systems have undergone a steep series of advancements. WBAN-based remote and ubiquitous healthcare services have proved to be a great success in this context. A WBAN comprises of multiple body sensors that are capable of measuring certain physiological attributes constantly over time. The sensed data are transmitted by the sensors to a hub, also known as local data processing unit (LDPU) [1]. The hub or LDPU, in turn, sends the data to remote hospitals or healthcare centers for real-time analysis, prediction, or diagnosis based on the data. WBAN-based remote and ubiquitous healthcare [2]–[5] has proven to be a great success in real-time monitoring of various physiological parameters, such as blood oxygen saturation level, glucose, pH, heart rate, and respiration rate. For prevention and treatment of chronic diseases, such as asthma, diabetes, and cardiac diseases, WBANs are also realized to be highly effective. The recent standardization by the IEEE 802.15.6 Task Group provides a new set of physical layer (PHY) and medium access control layer (MAC) specifications [6], particularly for wireless communications using WBANs. However, apart from healthcare applications, the IEEE 802.15.6 standard supports different non-medical applications (e.g. video streaming, file transfer, and gaming) [7] as well.

In this paper, inspired by Bianchi's works [8], [9], we develop a DTMC to analyze the performance of the IEEE 802.15.6 communication standard. Our model is constructed specifically for the CSMA/CA access mechanism under saturation regime and immediate acknowledgement (I-ACK) policy. We assume that ideal channel conditions persist for all the transmitting nodes, and there exists finite number of nodes in the system. We present the different states in which a transmitting node may be present at different instances along the time-axis. There exists few similar Markov model-based analytical works (e.g. [10]–[14]). In [10] and [11], the authors did not take into consideration the states which a node transits through after transmitting a packet while waiting for a positive I-ACK from the hub or LDPU. It is assumed that the node continues to remain in the same state while transmitting a packet for the entire duration before it is notified that the transmitted packet is either received successfully by the intended recipient, or otherwise. A similar work is done in [12] for non-saturated condition which has the same limitation. However, in practice, a node starts off a counter immediately after transmitting the last bit of a packet. It, then, increases the value of the count after every time-slot, and continues to do so until either a positive I-ACK frame is received, or the counter reaches its maximum limit (mTimeOut) (details in [6]).

A similar approach is presented in [15], [16], in which the authors have introduced two types of queues – one for successful transmission of a packet, and the other for collision of the transmitted packet. However, these works concern the IEEE 802.15.4 communication protocol [17]. Also, it is unclear how a node decides *a priori*, which of the two available

TABLE I: Parameters and Traffic designation for different user priorities

UP	CW_{min}	CW_{max}	Traffic designation
0	16	64	Background
1	16	32	Best Effort
2	8	32	Excellent effort
3	8	16	Controlled load
4	4	16	Video (VI)
5	4	8	Voice (VO)
6	2	8	High priority medical data or Network Control
7	1	4	Emergency or Medical implant event report

queues it should enter after completion of the transmission of a packet. In this work, we address these limitations by designing a DTMC that efficiently depicts the different states of a transmitting node across time. Interestingly, unlike [15], [16], we introduce only a single queue to represent the states of a node following the successful transmission of a packet. Further, we use the Markov model-based analysis to mathematically deduce the reliability and throughput of a node operating under the IEEE 802.15.6 series of protocols.

II. Overview of IEEE 802.15.6

The IEEE 802.15.6 standard [6] is especially designed for WBANs by modifying of the PHY and MAC parameters similar to the IEEE 802.15.4 standard [17] to support short range, ultra-low power, and reliable wireless communication in vicinity of living tissue. A major modification that was introduced in the standard is the introduction of 8 different user-priorities (UPs) based on the traffic designation. The value of the minimum and maximum sizes of the contention window changes along with the traffic designation is depicted in Table I.

According to the standard, a maximum of 64 nodes may be connected to a hub or LDPU simultaneously. Also, it is mentioned that a WBAN operating according to the IEEE 802.15.6 communication guidelines, can operate in one of the three access modes:

1) Beacon Enabled Access Mode 0: In this mode the nodes are synchronized by periodic transmission of the beacon (superframe) from the hub. Every superframe includes Exclusive Access Phase 1 (EAP1), Random Access Phase 1 (RAP1), Type I/II phase, Exclusive Access Phase 2 (EAP2), Random Access Phase 2 (RAP2), another Type I/II phase, Managed Access Phase (MAP), and Contention Access Phase (CAP). The EAP1 and EAP2 are used in highest user priority, and the RAP1, RAP2 and CAP are used for other traffic conditions.

2) Non-Beacon Access Mode 0: In this access mode, the whole superframe duration is allocated by either Type I/II phases, but not by both of them.

3) Non-Beacon Access Mode 1: Access Mode 1 is the non-beacon mode without superframe. In this mode the hub grants unscheduled Type II polled allocation, which allows the sensor to transmit only a limited number of frames.

In this work, we construct the DTMC that accurately depicts the performance of the beacon enabled (access mode 0) IEEE 802.15.6 CSMA/CA protocol only. Another crucial modification that is introduced in the IEEE 802.15.6 standard is in regards to the update of the value of the backoff counter for a node. For a node operating in $UP(i)$, the value of the backoff counter is initialized to a randomly chosen integer over $(1, W_0^i)$, where W_0^i denotes the minimum value of the backoff counter for a node operating in $UP(i)$. Following this, for every odd number of retry, the value of the contention window is left unaltered. On the contrary, for every even number of retry, the value is doubled. This procedure is continued until the value of the contention window reaches or surpasses its maximum value for that user priority. In such cases, the contention window value is set to W_{max}^i as per Table I. Mathematically,

$$W_k^i = \begin{cases} W_{min}^i & \text{,when } l = 0 \\ W_k^{i-1} & \text{,when } l \text{ is odd } ,1 \leq i \leq m \\ min\{2W_k^{i-1}, W_{max}\} & \text{,when } l \text{ is even } ,2 \leq i \leq m \end{cases} \quad (1)$$

where, l corresponds to the number of re-transmissions of a packet.

The IEEE 802.15.6 standard also uses backoff freezing mechanism during data transmission. The backoff counter is locked or freezed if any one of the following three phenomena occurs:

- The backoff counter is reset upon decrementing to zero.
- The channel is busy due to data packet transmission from another sensor or Ack transmission from the hub.
- The current time is outside any RAP, CAP for $UP(i)$ where $i \in (0, 6)$ or EAP, RAP, CAP for $UP(7)$.
- There is not enough time for frame transmission according to the allocated time in the superframe structure.

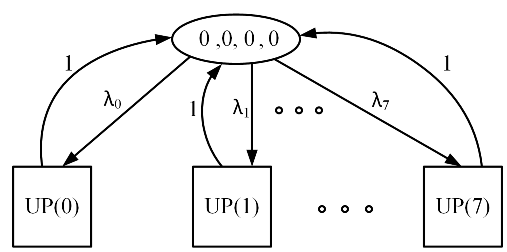


Fig. 1: Markov chain model considering all UPs in IEEE 802.15.6 CSMA/CA

III. Analytical Model

In this Section, we design a DTMC that accurately depicts the different states involved in the CSMA/CA access mechanism for beacon enabled (Access Mode 0) IEEE 802.15.6 with finite retry limits for every packet generated. We assume a single hop, star topology for the network which consists of n_i number of body sensor nodes connected to a single sink for $UP(i)$. The transmission queue for every station is always assumed to be non-empty, i.e., we refer to the *saturated traffic regime* only. The collision probability of a packet transmitted by a station is also assumed to be invariant of the number of re-transmissions [8], [9] already suffered by it.

A. Markov Chain

The DTMC is constructed as a four-tuple $u(t), s(t), b(t), r(t)$. The stochastic processes $u(t)$, $s(t)$, $b(t)$, and $r(t)$ represent the user priority to which a node belongs, the backoff stage, the backoff counter, and the re-transmission counter at time t, respectively. Fig. 1 shows the Markov model for the IEEE 802.15.6 CSMA/CA access mechanism that considers all the eight user priorities into account. The states within, and the corresponding transitions are kept abstracted, and the UPs are represented as blocks in this figure.

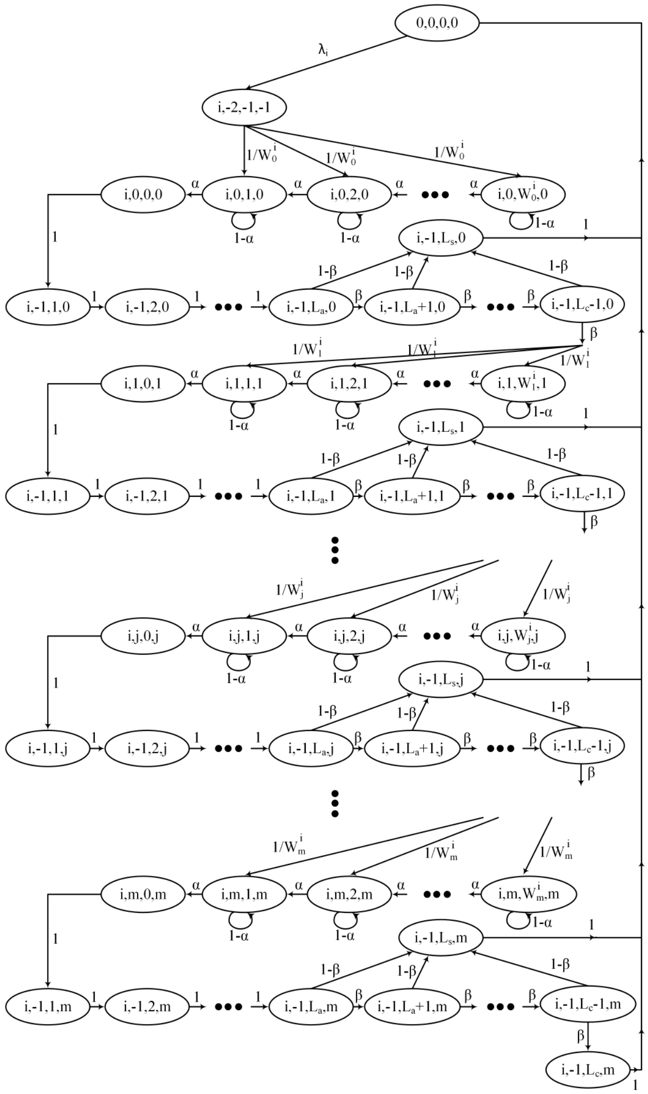


Fig. 2: Markov chain model for $UP(i)$ in IEEE 802.15.6 CSMA/CA

In Fig. 2, the internal structure of one of these blocks ($UP(i)$) is shown in detail. The analysis is divided into two parts. First, we obtain the expressions for all the states in the Markov chain in terms of $b_{0,0,0,0}$ using chain regularities, and finally, compute the value of $b_{0,0,0,0}$ using the normalization condition. In the second part, we compute the expressions for reliability and throughput, and show through simulations the variation of these parameters against payload.

For any transmitting node, whenever it has a packet to send, it chooses $UP(i)$ with probability λ_i, as shown in Fig. 1. Clearly, $\sum_{i=0}^{7} \lambda_i = 1$. The node, then, chooses a random value over the interval $(1, W_0^i)$ against its backoff counter. W_0^i denotes the value of CW_{min} for a node operating in $UP(i)$. The values for the backoff stage and the re-transmission counter are set to zero at this stage. The backoff counter is decremented by 1 if the channel is sensed idle, and there is enough time in the current superframe for the node to transmit the frame in its entirety. However, if any one of the two conditions is sensed to be false, the backoff counter is freezed. A node transmits a packet immediately after its backoff counter reaches zero.

After transmitting a packet, the backoff stage of the node is set to -1 (now the re-transmission counter acts as representative of the backoff stage), and a counter is started by the node. The value of this counter is incremented by unity after every timeslot, until the timeout for the I-ACK reception (L_c) is exhausted. L_a denotes the minimum time required for the I-ACK frame to be received. After this time interval, the node may reach the $(i, -1, L_s, l)$ state which is indicative of successful packet delivery. Otherwise, the node continues to increase the re-transmission counter till its value reaches $(L_c - 1)$. At this stage, if the node still fails to transmit the packet, values of its backoff stage and re-transmission counter are incremented by 1. The value of the backoff counter is updated as per Equation (1). This procedure continues until the re-transmission limit is reached, and time-out for I-ACK occurs. At this point, the node drops the packet, and returns to its initial state. The one-step, non-null probabilities for the DTMC, as shown in Fig. 2, are:

$$P\{(i,-2,-1,-1)|(0,0,0,0)\} = \lambda_i, \text{ for } i \in (0,7) \quad (2)$$

$$P\{(i,0,k,0)|(i,-2,-1,-1)\} = \frac{1}{W_0^i}, \text{ for } k \in (0, W_0^i) \quad (3)$$

$$P\{(i,j,k,l)|(i,j,k+1,l)\} = \alpha, \quad \text{for } j \in (0,m), k \in (0, W_l^i - 1), l = j \quad (4)$$

$$P\{(i,j,k,l)|(i,j,k,l)\} = 1 - \alpha, \quad \text{for } j \in (0,m), k \in (1, W_l^i), l = j \quad (5)$$

$$P\{(i,-1,1,l)|(i,j,0,l)\} = 1, \text{ for } j \in (0,m), l = j \quad (6)$$

$$P\{(i,-1,k+1,l)|(i,-1,k,l)\} = 1, \quad \text{for } k \in (1, L_a - 1), l \in (0,m) \quad (7)$$

$$P\{(i,-1,k+1,l)|(i,-1,k,l)\} = \beta, \quad \text{for } k \in (L_a, L_c - 2), l \in (0,m) \quad (8)$$

$$P\{(i,-1,L_s,l)|(i,-1,k,l)\} = 1 - \beta, \quad \text{for } k \in (L_a, L_c - 1), l \in (0,m) \quad (9)$$

$$P\{(i,j,k,l)|(i,-1,L_c-1,l-1)\} = \frac{\beta}{W_l^i}, \quad \text{for } j \in (1,m), k \in (1,W_l^i), l = j \tag{10}$$

$$P\{(i,-1,L_c,m)|(i,-1,L_c-1,m)\} = \beta \tag{11}$$

$$P\{(0,0,0,0)|(i,-1,L_s,l)\} = 1, l \in (0,m) \tag{12}$$

$$P\{(0,0,0,0)|(i,-1,L_c,m)\} = 1 \tag{13}$$

Our objective is to find the stationary probability for each state, and, thus, compute the expressions for reliability and throughput of a node. Let the stationary distribution of the Markov chain be, $b_{i,j,k,l} = \lim_{t\to\infty} P\{u(t) = i, s(t) = j, b(t) = k, r(t) = l\}, i \in (0,7), j \in (-2,m), k \in (-1, max(W_l^i, L_s, L_c)), l \in (-1,m)$. We now obtain the closed-form solution for this DTMC using chain regularities.

From Equations (4), (5), and (10), we get:

$$b_{i,j,k,l} = \frac{W_l^i - k + 1}{\alpha W_l^i} \beta^{(L_c-L_a)l} \times b_{i,0,0,0}, \quad \text{where } j \in (0,m), k \in (1,W_l^i), l = k \tag{14}$$

Equation (9) through (10), and (14) yield:

$$b_{i,j,0,l} = \beta^{(L_c-L_a)l} \times b_{i,0,0,0}, \text{ where } j \in (0,m), l = j \tag{15}$$

$$b_{i,0,k,0} = \frac{W_0^i - k + 1}{\alpha W_0^i} \times b_{i,0,0,0}, \text{ where } k \in (1,W_0^i) \tag{16}$$

Also, we get:

$$b_{i,-1,k,l} = \begin{cases} b_{i,j,0,l} & , j \in (0,m), k \in (1,L_a-1), j = l \\ \beta^{k-L_a} b_{i,j,0,l} & , j \in (0,m), k \in (L_a, L_c-1), j = l \end{cases} \tag{17}$$

From Equations (10), and (17), we have:

$$b_{i,-1,L_c-1,l} = \beta^{(L_c-L_a-1)+(L_c-L_a)l} \times b_{i,0,0,0}, \quad \text{where } l \in (0,m) \tag{18}$$

Finally, from Equation (12), we get:

$$b_{i,-1,L_s,l} = (1-\beta^{L_c-L_a}) \times b_{i,j,0,l}, \text{ where } l \in (0,m), j = l \tag{19}$$

Applying the normalization condition on the above set of equations, we get:

$$1 = \sum_{i=0}^{7}\sum_{j=0}^{m}\sum_{k=0}^{W_j^i} b_{i,j,k,l} + \sum_{i=0}^{7}\sum_{k=1}^{L_c-1}\sum_{l=0}^{m} b_{i,-1,k,l} + \sum_{i=0}^{7}\sum_{l=0}^{m} b_{i,-1,L_s,l} + \sum_{i=0}^{7} b_{i,-1,L_c,m} + \sum_{i=0}^{7} b_{i,-2,-1,-1} + b_{0,0,0,0} \tag{20}$$

We now derive each of the terms in Equation (20) separately.

$$\sum_{i=0}^{7}\sum_{j=0}^{m}\sum_{k=0}^{W_j^i} b_{i,j,k,l} = \sum_{i=0}^{7}\sum_{j=1}^{m}\sum_{k=1}^{W_j^i} b_{i,j,k,l} + \sum_{i=0}^{7}\sum_{j=1}^{m} b_{i,j,0,l} + \sum_{i=0}^{7}\sum_{k=1}^{W_0^i} b_{i,0,k,0} + \sum_{i=0}^{7} b_{i,0,0,0} \tag{21}$$

The first part of Equation (21) is computed as expressed in Equation (22), where

$$\Psi = W_0^1\lambda_1 + W_0^2\lambda_2 + ... + W_0^7\lambda_7$$

The remaining terms of Equation (21) are computed as following:

$$\sum_{i=0}^{7}\sum_{j=1}^{m} b_{i,j,0,l} = \beta^{L_c-L_a}\frac{1-\beta^{m(L_c-L_a)}}{1-\beta^{L_c-L_a}} \times b_{0,0,0,0} \tag{23}$$

$$\sum_{i=0}^{7}\sum_{k=1}^{W_0^i} b_{i,0,k,0} = \frac{1+\Psi}{2\alpha} \times b_{0,0,0,0} \tag{24}$$

$$\sum_{i=0}^{7} b_{i,0,0,0} = \sum_{i=0}^{7} \lambda_i b_{0,0,0,0} = b_{0,0,0,0} \tag{25}$$

By substituting the values obtained from Equations (22), (23), (24), and (25) in (21), we get the expression for $\sum_{j=0}^{m}\sum_{k=0}^{W_j^i} b_{i,j,k,l}$.

$$\sum_{i=0}^{7}\sum_{k=1}^{L_c-1}\sum_{l=0}^{m} b_{i,-1,k,l} = (1-\beta^{(m+1)(L_c-L_a)})\Big[\frac{(L_a-1)}{1-\beta^{L_c-L_a}} + \frac{1}{1-\beta}\Big] \times b_{0,0,0,0} \tag{26}$$

$$\sum_{i=0}^{7}\sum_{l=0}^{m} b_{i,-1,L_s,l} = \Big[1-\beta^{(m-1)(L_c-L_a)}\Big] \times b_{0,0,0,0} \tag{27}$$

$$\sum_{i=0}^{7} b_{i,-1,L_c,m} = \beta^{(m+1)(L_c-L_a)} \times b_{0,0,0,0} \tag{28}$$

$$\sum_{i=0}^{7} b_{i,-2,-1,-1} = b_{0,0,0,0} \tag{29}$$

Equations (21), and (26)-(28) yield the values of the states as a function of $b_{0,0,0,0}$. By replacing these Equations in the normalized condition in Equation (20), we get the expression for $b_{0,0,0,0}$.

B. Collision Probability

We now compute the collision probability (ρ_i) of a packet transmitted by a node that is operating in $UP(i)$. It might be reiterated that ρ_i is independent of the number of re-transmissions the packet has already undergone. For this, we first compute τ_i, the transmission probability for a node operating in $UP(i)$, given that the channel is idle at the time of the transmission. Clearly,

$$\tau_i = \sum_{l=0}^{m} b_{i,j,0,l}, \qquad \text{where } j = l$$
$$= \frac{1-\beta^{(m+1)(L_c-L_a)}}{1-\beta^{L_c-L_a}} \times b_{i,0,0,0} \tag{30}$$

$$\sum_{i=0}^{7}\sum_{j=1}^{m}\sum_{k=1}^{W_j^i} b_{i,j,k,l} = \begin{cases} \frac{\beta^x}{2\alpha}\left[\left(\frac{1-\beta^{mx}}{1-\beta^x}\right) + \frac{2\beta^x}{1-2\beta^{2x}}(2-(2\beta^{2x})^{(m-1/2)}(1+2\beta^{2x}))\Psi\right] \times b_{0,0,0,0} & \text{if m is odd} \\ \frac{\beta^x}{2\alpha}\left[\left(\frac{1-\beta^{mx}}{1-\beta^x}\right) + \frac{1}{1-2\beta^{2x}}(1-(2\beta^{2x})^{m/2})(1+2\beta^x)\Psi\right] \times b_{0,0,0,0} & \text{otherwise} \end{cases} \tag{22}$$

Therefore, ρ_i can be mathematically expressed as:

$$\rho_i = 1 - \left[\prod_{j=0}^{7}(1-\tau_j)^{n_j} + (1-\tau_i)^{n_i-1}\prod_{j=0,j\neq i}^{7}(1-\tau_j)^{n_j}\right] \tag{31}$$

where, n_i is the number of nodes operating under $UP(i)$, and are connected to the hub or LDPU. Clearly, for a system with a total of n number of nodes, $\sum_{i=0}^{7} n_i = n$.

C. Reliability

We define *reliability* ($\mathcal{R}$) of a node as the probability of successful delivery of a transmitted packet. In other words, it is the complementary probability with which a transmitted packet is dropped due to finite retry limits. The frame payload for each packet is considered to be equal. In may be noted that, unlike most wireless communication protocols (as in [17]), in IEEE 802.15.6, a packet is not dropped due to channel access failure. Therefore, $\mathcal{R}$ is symbolically represented as:

$$\mathcal{R} = 1 - P_r = 1 - \sum_{i=0}^{7}\sum_{l=0}^{m} b_{i,-1,L_s,l}$$

$$\Rightarrow \mathcal{R} = 1 - \beta^{(m+1)(L_c-L_a)} \times b_{0,0,0,0} \tag{32}$$

where, P_r is the probability that a packet is dropped due to finite retry limits.

D. Throughput

The *throughput* $\mathcal{S}_i$ of a node operating in $UP(i)$ (in bits/second) is defined as the number of bits successfully transmitted over the channel in unit time. Mathematically, for a node operating in $UP(i)$, throughput is defined as the product of the average length of the packets transmitted ($\mathcal{L}$) (in bits), the reliability of the system ($\mathcal{R}$), and the transmission probability (τ_i) of the node. $\mathcal{S}$ can be defined as:

$$\mathcal{S}_i = \mathcal{L} \times \mathcal{R} \times \tau_i \tag{33}$$

where, $\mathcal{L}$ denotes the average length of the transmitted packets (header length + payload) in bits. Substituting the values of $\mathcal{R}$, and τ_i from Equations (32) and (30) in Equation (33), we obtain the expression for $\mathcal{S}_i$.

IV. Performance Analysis

In this Section, we analyze the performance of the IEEE 802.15.6 CSMA/CA protocol under saturated traffic regime in terms of reliability and throughput based on the DTMC. In Section III, we have derived the expressions for reliability and throughput for ideal channel conditions, by accurate analysis of the model. However, in a practical environment, it may be required for a sensor node to compute internally its reliability and throughput values as a part of some optimization problem.

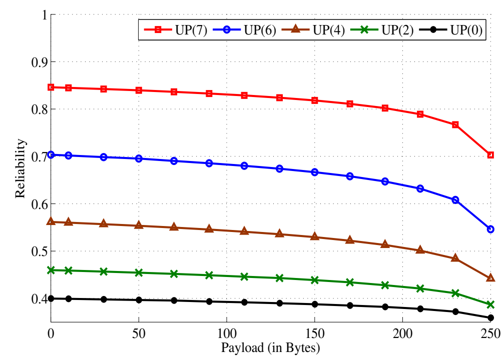


Fig. 3: Reliability vs Payload for different UPs

Therefore, there persists a need to simplify the complex non-linear equations to a set of approximated equations.

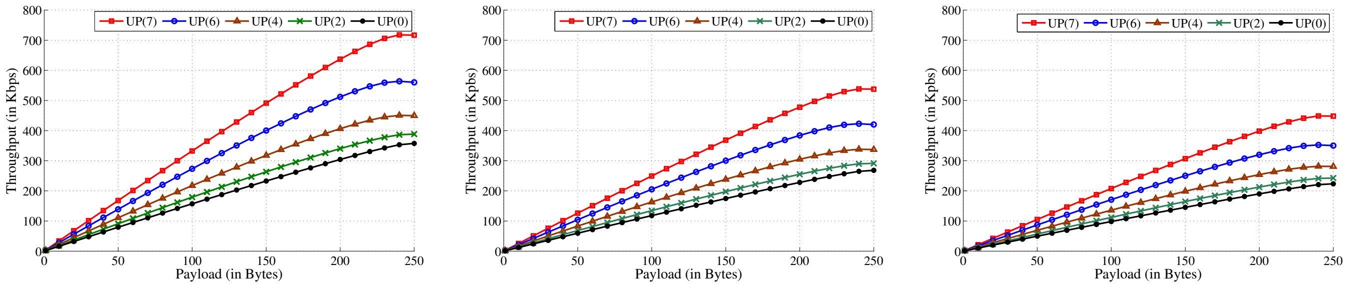
In order to approximate the expressions for reliability and throughput (as given in Equations (32) and (33), respectively), we approximate the expression for $b_{0,0,0,0}$. Firstly, we consider the value of β to be considerably small, and, thus, we approximate it as:

$$\frac{1-\beta^m}{1-\beta} \approx 1-\beta, \text{ where } \beta > 0 \tag{34}$$

Also, as per the IEEE 802.15.6 standard, the maximum retry limit for a packet, $m = 7$. Therefore, considering the small magnitude of β, the higher order terms are neglected.

In Fig. 3, the variation of reliability with the change of the frame payload is shown for different user priorities. However, due to the same value of the W^i_{min}, the pair-wise results for priorities 0 and 1, 2 and 3, and 4 and 5, respectively, do not show any significant change, rather these priorities are noticed to be pair-wise overlapping to one another. Therefore, it can be fairly concluded instead of having eight user priorities, four priorities would have been adequate.

Also, it is noted that with the increase in the frame payload the reliability of the frame transmission decreases for all the user priorities. The result is straightforward, as with the increase in the payload length, the packet drop rate also increases. It is also noted that for constant payload, the reliability of a node operating in $UP(0)$ is lowest, and this value increases linearly till $UP(7)$. The inference for this variation can be explained from the contention window size perspective. The minimum and maximum size (as well as the range) of the contention window gradually increases from $UP(0)$ to $UP(7)$. Therefore, the value of the backoff counter chosen by a node is large in case of lower UPs, resulting in higher delay and unsuccessful packet delivery.



(a) Data rate = 971.4 Kbps

(b) Data rate = 728.6 Kbps

(c) Data rate = 607.1 Kbps

Fig. 4: Throughput vs Payload for different data rates

The variation of throughput with the frame payload for three different data rates (971.4 Kbps (2360 − 2400 MHz), 728.6 Kbps (950 − 958 MHz), and 607.1 Kbps (950 − 958 MHz)) under the I-ACK policy increases is shown in Fig. 4. It is observed that higher the user priority, more the throughput is. Also, comparing the three graphs, we observe that for any given user priority, with the increase of the data rate, throughput also increases. Therefore, we conclude that, both reliability and throughput of a node operating under the IEEE 802.15.6 CSMA/CA protocol, are functions of the frame payload, and both of these parameters increase as the user priority increases. The bandwidth efficiency is found to be maximum for $UP(7)$, increasing gradually from that of $UP(0)$. In other words, reliability and throughput are noted to be maximum in cases of medical data transmission and emergency medical reporting, which explicitly illustrate the importance of this protocol from a medical point of view.

V. Conclusion

In this paper we constructed a DTMC to accurately model the operation of the IEEE 802.15.6 CSMA/CA protocol under saturated traffic regime and ideal channel conditions. We took into consideration the state of a node following the transmission of a packet, and considered the node to enter a queue of states while waiting for a positive I-ACK frame. This aspect depicts the state of a node precisely, and the subsequent analyses based on the DTMC is found to be significantly accurate. We also shown the variation of reliability and throughput of a node with the of user priorities and frame payloads. It is observed that reliability and throughput for a node in $UP(7)$ is distinctly high as compared to the other user priorities. Finally, our future works involve the performance analysis of the IEEE 802.15.6 slotted CSMA/CA protocol under saturated and unsaturated traffic regime, and for non-ideal channel conditions. We also propose to extend our work for the IEEE 802.15.6 slotted ALOHA protocol.

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