

Markov chain based analysis of IEEE 802.15.6 MAC protocol in real life scenario

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ABSTRACT

In this article, a generalized analytical model for the evaluation of different performance parameters of IEEE 802.15.6 standard is proposed. The standard is specifically designed for the purpose of supporting body-sensors, e-health monitoring and human body communication. The analytical framework of this standard is modelled using a three dimensional Markov chain with backoff stage, backoff counter and retransmission counter, as the stochastic parameters. To model the mechanism of backoff freezing, which occurs due to insufficient time period for data packet transmission in the allotted access period and the packet is dropped after certain recurrences of this incident, allocating the access period for the next data packet. Unlike previous analytical models, a dynamic or time-variant variable is incorporated in our proposed analytical model to support this mechanism. From the analytical model, we obtain the expressions for different performance metrics such as reliability or the probability of successful packet delivery, throughput and energy consumption. Using Monte-Carlo simulation we obtain the analytical results of reliability, throughput and energy consumption for varying offered load and payload, and the simulation results are obtained using Castalia simulator. The simulation results are compared with the analytical results of our proposed analytical model and an existing analytical model from present literature.

Categories and Subject Descriptors

C.2.1 [Network Architecture and Design]: Wireless communication; C.4 [PERFORMANCE OF SYSTEMS]: Performance attributes, Reliability, availability, and service-

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ability, Modeling techniques

General Terms

Performance

Keywords

IEEE 802.15.6, Backoff freezing, Throughput, Energy consumption, WBAN.

1. INTRODUCTION

In the aeon of embedded systems and wireless communication, our daily lives are redefined by new technologies. In distant future, traditional concept of healthcare systems and health monitoring will be outshined by the e-health systems. Body-sensor or body area network (BAN) is the stepping stone towards this giant leap [1, 2]. Distant health monitoring is newly defined by wireless body area networks (WBAN). A WBAN comprises of multiple body-sensors and a hub or logical data processing unit (LDPU). The sensed data is transmitted to the hub or LDPU by the sensor and using multi-tier communication it reaches the physician [3, 4]. Using the multi-tier architecture WBAN provides healthcare even to the patients in the rural or remote areas, workplace or home and thus offering cost savings, moreover improving the quality of life of the patient [5, 6]. Thus, WBAN is introducing the epoch of e-health care, a way to look beyond the traditional health care systems.

Initially communication in a WBAN followed the IEEE 802.15.4 standard [7]. However, 802.15.4 standard could not support all the necessary requirements of a WBAN. The main shortfalls of the 802.15.4 standard are not supporting high data rate and performance degradation for high offered load. To support WBAN applications IEEE has designed a new standard, 802.15.6 [8]. This standard has immense possibility to redefine our social scenario in many aspects and calls for large scale practical implementations. So, it is very important to provide a analytical model for IEEE 802.15.6 to evaluate the important parameters, such as reliability,

throughput and energy consumption to find the possible improvements of the standard.

In the present literature, there are very few papers to provide a generalized analytical model for the performance evaluation of this standard. In one of the major works, Rashwand et al. had considered a three dimensional Markov chain using user priority, backoff stage and backoff counter as the parameters [9, 10]. This model seems inconsistent as the retransmission counter is ignored in the analytical model. To solve this problem, Byoung et al. considered a variable denoting the frame transmission probability in a randomly chosen time slot [11]. However, this model triggers few doubts in our minds with the assumption of always having enough time for frame transmission. This assumption bypasses the required dynamic property from the Markov chain for analyzing the backoff freezing mechanism. Moreover, the problem of buffer overflow and channel congestion due to the backoff freezing remains unaddressed. In another work Sana et al. gave an overview of the highest limit of throughput for different user priorities and different data rates [12]. However, several assumptions like zero bit error rate (BER), ideal channel, saturated traffic, no packet losses due to buffer overflow, and consideration of only one receiver and one sender is not applicable in real life scenario. To our best knowledge, the dynamic property of the CSMA/CA mechanism, reflecting the incident of backoff freezing due to insufficient remaining time for data packet transmission in the present access period and discarding the present data packet after repeated incident of backoff freezing due to insufficient remaining time for data packet transmission, is not considered in any of the existing works. In this article, we have addressed and overcome these shortcomings using the proposed analytical model.

1.1 Contribution

Precisely, the main contributions of this article can be summarized as follows:

- In the proposed analytical model we redefine the definition of backoff stage and use it to model the packet drop due to several channel access failure for insufficient remaining time to transmit the data packet. The proposed analytical model also incorporates the mentioned dynamic behaviour, to model the backoff freezing mechanism.
- For performance evaluation we take account of non-ideal channel by introducing BER, multipath effect, shadowing standard deviation, and error probability due to the modulation schemes, making our simulation results more comprehensive and similar with the practical performances.

1.2 Paper Organization

The rest of the paper is organized as follows. The IEEE 802.15.6 standard is described briefly in section II. Section III provides the three dimensional Markov chain based analytical model and derivation of analytical expressions for the considered performance metrics. Simulation results, obtained from Monte-Carlo simulation, validating the analytical expressions are presented in section IV. Analytical results

are compared with the results obtained using the analytical expressions of [11]. Section V describes the scope of the future work and concludes the paper.

2. OVERVIEW OF IEEE 802.15.6 STANDARD

This section provides a brief outline of the physical layer (PHY) and MAC layer specifications of the IEEE 802.15.6 standard.

2.1 PHY Layer Specifications

The 802.15.6 standard supports three PHY, Narrowband (NB), Ultra Wideband (UWB) and Human Body Communications (HBC). The main features of the different PHY are mentioned below:

2.1.1 Narrowband PHY

The NB PHY is an optional physical layer, which is responsible for the following tasks:

- Activation and deactivation of the radio transceiver.
- Clear channel assessment (CCA).
- Data transmission and reception. [8]

This PHY supports different frequency bands, 402-405 MHz, 420-450 MHz, 863-870 MHz, 902-928 MHz, 950-958 MHz, 2360 to 2400 MHz, and 2400-2483.5 MHz [13].

2.1.2 Ultra Wideband PHY

The Ultra Wideband PHY is used to provide a data interface to the MAC layer under the control of physical layer convergence protocol (PLCP). It's main functions are:

- Activation and deactivation of the radio transceiver.
- The PLCP constructs the PHY layer protocol data unit (PPDU) by concatenating the synchronization header (SHR), physical layer header (PHR) and physical layer service data unit (PSDU), respectively.
- It may provide CCA indication to the MAC [8].

2.1.3 Human Body Communications PHY

Human Body Communication (HBC) PHY supports two modes of operation, default mode and high quality of service (QoS) mode, which are depending upon the application. HBC PHY operates in two frequency bands centred 16 MHz and 27 MHz with the bandwidth of 4 MHz. The main operation of HBC is to provide electrostatic field communication (EFC) specification for the whole WBAN.

2.2 MAC Layer Specifications

IEEE 802.15.6 is a standard specially designed for WBANs, modifying various MAC parameters from IEEE 802.15.4 for supporting different user priorities. The value of the contention window is selected according to the user priority. The utilities of different user priorities are given in Table 3. The user priorities are expressed by $UP(s)$ where $s \in [0, 7]$

The WBAN supported by IEEE 802.15.6 can operate in one of the following three modes:

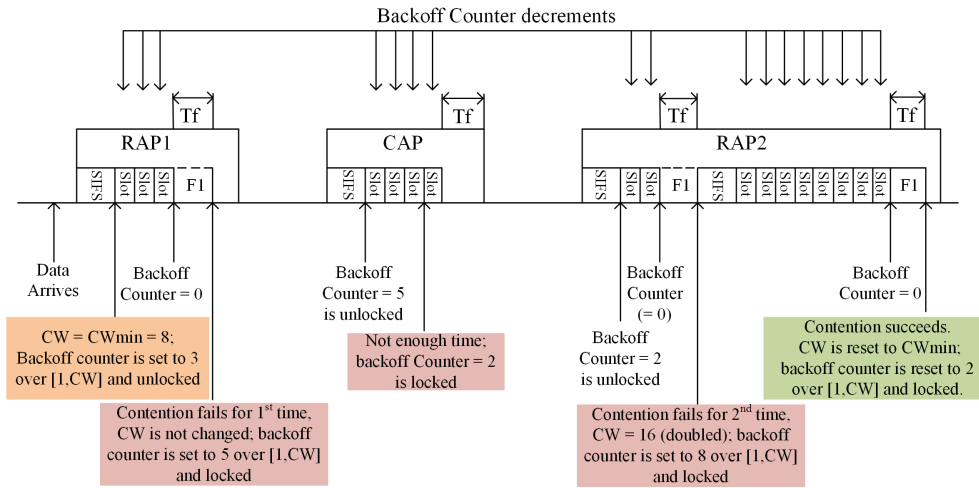


Figure 1: Modes of Backoff counter in CSMA/CA

Table 1: 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

2.2.1 Access Mode 0

- *Beacon Mode:* In this mode the body-sensors are synchronized by periodic transmission of the beacon from the hub, and every sensor follow the superframe structure given in the standard.
- *Non-Beacon Mode:* In this access mode the whole superframe duration is allocated to either Type I/II phases, not both of them.

2.2.2 Access Mode I

Access Mode I is the non-beacon mode without the superframe. In this mode the hub grants unscheduled Type II polled allocation which allows the sensor to transmit only a limited number of frames.

At initial stage, the value of contention window (CW) is selected to CW_{min} and according to the value of retransmission counter it is increased. For odd number of retry the value of CW remains in the previous value of contention window CW_{prev}, and for even number of retry the value becomes 2CW_{prev}, and the increment continues till the value reaches CW_{max}. The value of the backoff counter is set randomly in the [1, CW] interval. Different modes of the backoff counter is shown in Fig. 1 [8].

3. ANALYTICAL MODEL

In this section, an analytical model of the IEEE 802.15.6 standard with slotted CSMA/CA mechanism is proposed, using Markov chain. The tuple of the three dimensional Markov chain has been formed using backoff stage, backoff counter and retransmission limit, as given in Fig. 2. The stochastic processes, namely backoff stage, state of the backoff counter and the retransmission limit are represented by $B(t)$, $b(t)$ and $r(t)$. The analytical model is independent of any specific UPs and takes account of all possible modes of the backoff counter. For modelling the Markov chain, we assume a probability τ for which the chosen sensor starts carrier sensing in a randomly selected time slot. For probability $(1 - \tau)$ the sensor remains in the idle state. For the probability Ω the channel is busy after the carrier sensing, with probability $(1 - \alpha)$, sensor finds that there is enough time for the data packet transmission. Now the sensor starts decrementing its backoff counter, when it reaches zero, the data packet is transmitted. Probability α is considered for the backoff freezing mechanism, it defines that the remaining time in that is not enough for transmitting the data packet and the sensor. If the sensor could not access the channel till the maximum backoff limit, the data packet is dropped. The symbols or notations used throughout the mathematical model is given in Table 2. Using the Markov chain we derive the analytical expressions for reliability, throughput and energy consumption and compare them with the simulation results for the validation of analysis.

3.1 Mathematical Analysis

The stationary distribution of the Markov chain is given by

$$S_{i,j,k} = \lim_{t \rightarrow \infty} P((B(t) = i, b(t) = j, r(t) = k) \quad (1)$$

where $i \in [1, B_m]$, $j \in [0, CW_{max}]$, $k \in [0, R_{max}]$.

According to IEEE 802.15.6 standard the size of the contention window CW changes according to the number of

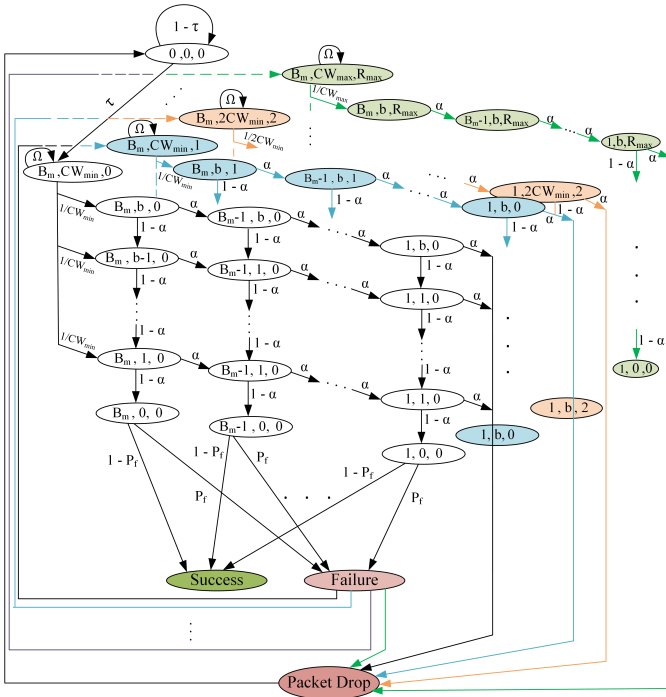


Figure 2: Markov chain model for any $UP(s)$

Table 2: Notations and Descriptions

Notation	Descriptions
P_c	Probability of collision of a transmitted packet
L_p	Slot length of the transmitted packet
L_s	Slot length for determining successful packet delivery
L_c	Slot length for determining collision probability
L_{Ack}	Slot length of the Acknowledgement frame
B_m	Maximum CSMA Backoffs
R_{max}	Maximum frame retransmission limit
N	Number of sensors in WBAN
E_T	Total Energy consumption
E_i	Energy consumption in idle state
E_{tx}	Energy consumption during data packet transmission
E_{rx}	Energy consumption during packet reception

retransmission, which can be expressed as

$$CW = \begin{cases} CW_{min} & k = 0, \\ CW_{prev} & k \geq 1 \text{ and } k \text{ is odd,} \\ \min(2CW_{prev}, CW_{max}) & k \geq 2 \text{ and } k \text{ is even.} \end{cases} \quad (2)$$

where CW_{prev} is the size of contention window during previous attempt of transmission. From the Markov chain, we obtain the following state transitions:

$$P(0, 0, 0 | 0, 0, 0) = 1 - \tau \quad (3)$$

$$P(B_m, CW_{min}, 0 | 0, 0, 0) = \tau \quad (4)$$

$$P(B_m, CW_{min}, 0 | B_m, CW_{min}, 0) = \Omega, \text{ for } k \in [0, R_{max}] \quad (5)$$

$$P(B_m, CW_{min}, 0 | B_m, j, 0) = \frac{1 - \Omega}{CW_{min}}, \text{ for } j \in [1, b] \quad (6)$$

$$P(i - 1, j, k | i, j, k) = \alpha, \text{ for } i \in [2, B_m], k \in [0, R_{max}] \quad (7)$$

$$P(i, j - 1, k | i, j, k) = (1 - \alpha), \text{ for } j \in [1, b], i \in [1, B_m] \quad (8)$$

$$P(\text{Success} | i, 0, k) = 1 - P_c \quad (9)$$

$$P(\text{Failure} | i, 0, k) = P_c, \text{ for } k \in [0, R_{max} - 1] \quad (10)$$

$$P(B_m, CW(r), r | \text{Failure}) = 1, \text{ Failure in } k = r - 1 \quad (11)$$

$$P(\text{Packet Drop} | i, 0, R_{max}) = P_c \quad (12)$$

$$P(\text{Packet Drop} | 1, j, k) = \alpha, \text{ for } k \in [0, R_{max}] \quad (13)$$

$$P(0, 0, 0 | \text{Packet Drop}) = 1 \quad (14)$$

The collision probability P_c can be expressed as,

$$P_c = 1 - \xi^{N-1} \quad (15)$$

where ξ is the transmission probability of a sensor. The calculated transmission probability from the Markov chain is,

$$\xi = \sum_{k=0}^{R_{max}} \sum_{j=1}^{CW} \sum_{i=1}^{B_m} \left(\frac{1 - \Omega}{CW} (\alpha^{i-1}) (1 - \alpha)^j \right)^k \quad (16)$$

Using Eqn. 2 we can further express transmission probability ξ as,

$$\xi = \begin{cases} \frac{1 - \Omega}{CW_{min}} \left(\frac{1 - \alpha^{B_m-1}}{1 - \alpha} \right) \left(\frac{1 - (1 - \alpha)^{CW_{min}-1}}{\alpha} \right) & \text{for } k = 0, \\ \frac{1 - \Omega}{CW_{prev}} \left(\frac{1 - \alpha^{B_m-1}}{1 - \alpha} \right) \left(\frac{1 - (1 - \alpha)^{CW_{prev}-1}}{\alpha} \right) & \text{for } k \geq 1 \text{ and } k \text{ is odd,} \\ \frac{1 - \Omega}{2CW_{prev}} \left(\frac{1 - \alpha^{B_m-1}}{1 - \alpha} \right) \left(\frac{1 - (1 - \alpha)^{2CW_{prev}-1}}{\alpha} \right) & \text{for } k \geq 2 \text{ and } k \text{ is even.} \end{cases} \quad (17)$$

Replacing ξ in Eqn. 15 we obtain the collision probability. Now reliability can be defined as the probability of successful packet delivery, which can be expressed as,

$$R = 1 - P_{cf} - P_{cr} \quad (18)$$

where P_{cf} is the probability of packet drop due to channel access failure and P_{cr} is the probability of packet drop due to retry limits [14].

Now, from the Markov chain the probability of packet drop

due to channel access failure can be defined as,

$$\begin{aligned}
P_{cf} &= \sum_{i=1}^{B_m} \sum_{j=1}^{CW} \sum_{k=0}^{R_{max}} (\alpha^{i-1} (1-\alpha)^j P_c)^{k-1} \alpha^{B_m} (1-\alpha)^{j-1} \\
&= \frac{1 - \left(\frac{1 - (1-\alpha)^{CW-1}}{\alpha} P_c \frac{1 - \alpha^{B_m-1}}{1-\alpha} \right)^{R_{max}-1}}{1 - \frac{1 - (1-\alpha)^{CW-1}}{\alpha} P_c \frac{1 - \alpha^{B_m-1}}{1-\alpha}} \\
&\quad \times \frac{1 - (1-\alpha)^{CW-1}}{\alpha} \alpha^{B_m} \quad (19)
\end{aligned}$$

Similarly the probability of packet drop due to retry limits is found to be,

$$\begin{aligned}
P_{cr} &= \sum_{i=1}^{B_m} \sum_{j=1}^{CW} \sum_{k=0}^{R_{max}} (\alpha^{i-1} (1-\alpha)^j P_c)^k \\
&= \frac{1 - \left(\frac{1 - (1-\alpha)^{CW-1}}{\alpha} P_c \frac{1 - \alpha^{B_m-1}}{1-\alpha} \right)^{R_{max}}}{1 - \left(\frac{1 - (1-\alpha)^{CW-1}}{\alpha} P_c \frac{1 - \alpha^{B_m-1}}{1-\alpha} \right)} \quad (20)
\end{aligned}$$

Replacing Eqn. 19 and 20 in Eqn. 18

$$\begin{aligned}
R &= 1 - \left(\frac{1}{1 - \frac{1 - (1-\alpha)^{CW-1}}{\alpha} P_c \frac{1 - \alpha^{B_m-1}}{1-\alpha}} \right) \\
&\quad \times \left[\left(1 - \left(\frac{1 - (1-\alpha)^{CW-1}}{\alpha} P_c \frac{1 - \alpha^{B_m-1}}{1-\alpha} \right)^{R_{max}-1} \right) \right. \\
&\quad \times \frac{1 - (1-\alpha)^{CW-1}}{\alpha} \alpha^{B_m} + \left. \left(P_c \frac{1 - \alpha^{B_m-1}}{1-\alpha} \right)^{R_{max}} \right. \\
&\quad \times \left. \left(1 - \left(\frac{1 - (1-\alpha)^{CW-1}}{\alpha} \right)^{R_{max}} \right) \right] \quad (21)
\end{aligned}$$

Throughput of the WBAN can be expressed analytically as,

$$\begin{aligned}
S &= R \times L_{payload} \\
&= \left[1 - \left(\frac{1}{1 - \frac{1 - (1-\alpha)^{CW-1}}{\alpha} P_c \frac{1 - \alpha^{B_m-1}}{1-\alpha}} \right) \right. \\
&\quad \times \left. \left(\left(1 - \left(\frac{1 - (1-\alpha)^{CW-1}}{\alpha} P_c \frac{1 - \alpha^{B_m-1}}{1-\alpha} \right)^{R_{max}-1} \right) \right. \right. \\
&\quad \times \left. \left. \frac{1 - (1-\alpha)^{CW-1}}{\alpha} \alpha^{B_m} + \left(P_c \frac{1 - \alpha^{B_m-1}}{1-\alpha} \right)^{R_{max}} \right) \right. \\
&\quad \times \left. \left(1 - \left(\frac{1 - (1-\alpha)^{CW-1}}{\alpha} \right)^{R_{max}} \right) \right] \times L_{payload} \quad (22)
\end{aligned}$$

Here CW is used for simpler expression, the complete expression can be obtained by replacing Eqn. 2 in place of CW .

Now the average energy consumption of a sensor for a single data packet transmission can be obtained from the following expression,

$$\begin{aligned}
E_T &= \sum_{k=0}^{R_{max}} \left(\sum_{i=1}^{B_m} \sum_{j=1}^{CW} (\alpha^i (1-\alpha)^j P_c E_i)^k + ((P_c(L_c - L_p) \right. \\
&\quad \left. + (1 - P_c)(L_s - L_p - L_{Ack})) E_i)^k + (L_p E_{tx})^k \right. \\
&\quad \left. + (L_{Ack} E_{rx})^k \right) \quad (23)
\end{aligned}$$

4. SIMULATION RESULTS

The simulation results are provided for a sample WBAN architecture, shown in Fig. 3, consisting of 6 different body-sensors and a LDPU. The sensors are using different user priorities UP for the health monitoring. The distribution of the sensors and their respective UP s, payload size and information data-rate are mentioned in Table 3.

Table 3: Distribution of body-sensors

Body-sensor	UP	Payload (bytes)	Data-rate (kbps)
Motion sensor	0	50	91.9
Ear sensor	2	100	242.9
Blood Pressure	4	150	485.7
EMG	6	200	971.4
EEG, ECG	7	255	971.4

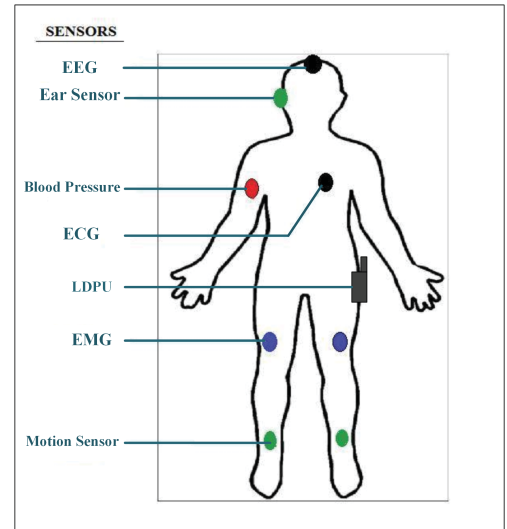


Figure 3: Considered WBAN Architecture

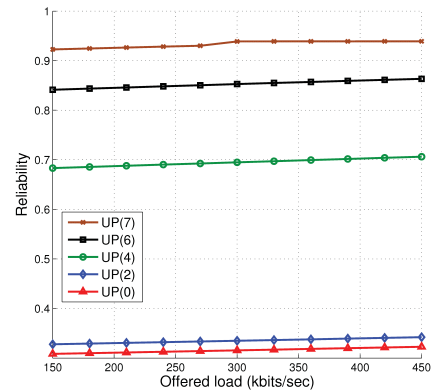


Figure 4: Reliability vs Offered load

Using the considered WBAN architecture, we have simulated the successful packet delivery ratio or reliability, throughput and energy consumption using Monte-Carlo simulation. The simulation results, reliability, throughput and energy consumption for varying offered load and payload are presented in Fig. 4 - 9 respectively, where the parameter offered

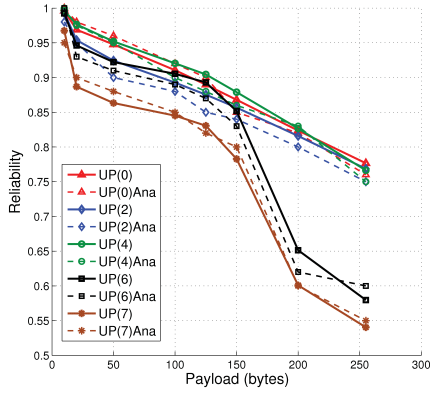


Figure 5: Reliability vs Payload

load denotes the amount of data operation (transmission or reception of data packet) in the network at a randomly chosen time slot. Simulation results, obtained using Castalia simulator, are compared with the analytical results for the validation of our analytical model. In Fig. 7 we have also compared the analytical results obtained using the expressions given by Byoung et. al in [11]. From the figures, we observe that our analytical model approximate the real-time performance of this standard more intently.

- **Figures for reliability (Fig. 4-5):** Reliability for varying offered load and payload are given in Fig. 4, 5 respectively. From Fig. 4 we observe that the reliability of the sensor is almost independent of the offered load of the network and reliability is less for higher UPs . For higher UPs the chosen payload size is greater and hence the probability of collision is much greater, hence reliability highly degrading compared with other user priorities. Similar observation is also reflected in Fig. 5, where we observe that reliability decreases for increase in the payload size. A nominal margin of error is obtained by comparing the analytical results and simulation results.

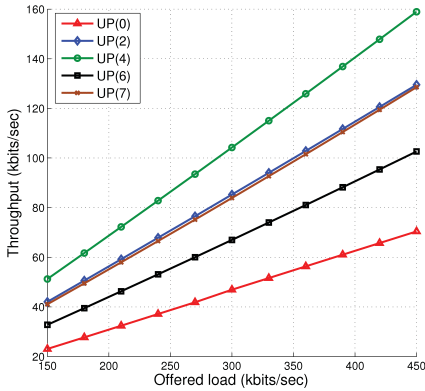


Figure 6: Throughput vs Offered load

- **Figures for Throughput (Fig. 6-7):** Throughput for varying offered load and payload are given in Fig. 6, 7 respectively. From Fig. 6 we observe that for greater

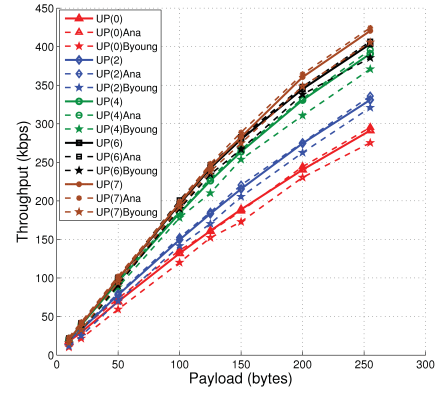


Figure 7: Throughput vs Payload

amount of data operation or offered load, throughput increases proportionally. This observation can be persuaded using the fact that more offered load characterizes more data transmission and reception and hence the amount of data operation over the network and throughput of different body-sensors increase simultaneously.

From the expression for throughput in Eqn. 22, we observe that throughput is directly proportional with the packet length, hence, for increasing payload the throughput increases too. From the Fig. 7 we also observe that critical throughput is not reached till payload size of 255 bytes.

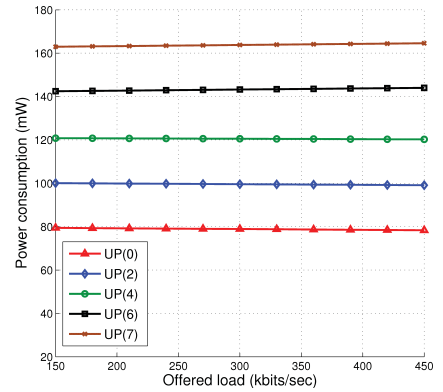


Figure 8: Power consumption vs Offered load

- **Figures for Power consumption (Fig 8-9):** Power consumption for varying offered load and payload is outlined in Fig. 8, 9. From Fig. 8 we observe that for variation in offered load, Power consumption of the sensors remain almost unchanged. Moreover, power consumption is greater for higher UPs , as data transmission takes place more frequently.

For varying payload the power consumption of a sensor show an unusual characteristics, as observed in Fig. 9. For $UP(0)$ and $UP(2)$ the power consumption decreases for increasing payload, however for $UP(4)$ to $UP(7)$ the energy consumption increases till the pay-

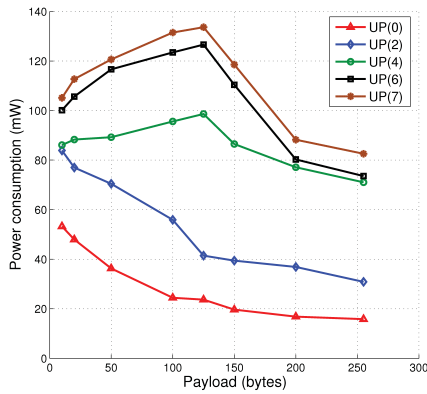


Figure 9: Power consumption vs Payload

load size of 150 bytes and then suddenly starts decreasing. This observation can be explained as, $UP(4)$ to $UP(7)$ can support payload size till 150 bytes, without network congestion. Although once the payload size is greater than 150 bytes, the energy consumption starts decreasing as less packet transmission takes place and sensors remain in idle state for most of the time, unable to find the channel idle. For $UP(0)$ and $UP(2)$ the energy consumption decreases for increase in payload size. Moreover for lower UPs the size of contention window is more, therefore the backoff counter is initially set to a much higher value and therefore spend more time in the idle state before transmission, than higher UPs .

5. CONCLUSION

In this work, we have presented a generalized approach towards the performance evaluation of the slotted CSMA/CA mechanism in the IEEE 802.15.6 standard. Our mathematical framework is based on a Markov chain that considers the stochastic variables backoff stage, backoff counter and retransmission limits, supporting the acknowledgement mechanism. We derive the expressions for reliability, throughput and energy consumption from the analytical model, and use Monte-Carlo simulation to obtain the simulation results. We observe that the analytical results obtained using the analytical expressions approximate the simulation results with a very narrow margin of error.

For complete evaluation of this standard, we also need to evaluate several other parameters, such as delay, collision due hidden terminals, mobility robustness. Using the proposed analytical model, we can extend our analysis by calculating the above-mentioned variables.

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