



# Effect of Channel Slot Time on Performance of IEEE 802.15.6-Based Medical Body Area Network

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**Abstract.** The IEEE 802.15.6 standard is an emerging technology that supports low data rate, short-range wireless communication. Medical Body Area Networks (MBAN) are a special type of wireless communication where multiple sensor nodes are deployed on the human body to measure vital parameters. The data is sent by the nodes to a coordinator, the latter aggregates the data and sends it to a central server using standard protocols. The coordinator allows the nodes to access the channel using different access modes-beacon mode with the super frame, non-beacon mode with super frame and non-beacon mode without super frame. The standard allows different user priorities to be assigned to the nodes. The nodes may access the channel using scheduling done by the coordinator (scheduled access) or may randomly access the channel using the CSMA/CA (for narrowband PHY) or Slotted Aloha for UltraWideBand (UWB PHY) protocols. In this work we have conducted an analytical study to understand the performance parameters of different user priority nodes using CSMA/CA protocol and operating in the Beacon access mode with super frame boundaries. Parameters like the probability of successful transmission (reliability) which in turn depend on the probability of packet drop due to channel access failure and the probability of failure due to insufficient time slot available have been studied. This study reveals that once a channel is assessed by a node, then the probability of sufficient time slot of 60% yields the best packet transmission probability. The successful delivery of the packet also depends on back off counter. Markov chain models for nodes with different priorities have been developed using backoff stage and backoff counter as parameters.

**Keywords:** Markov chain · MAC layer · Medical body area network · Time Slot · User Priority

## 1 Introduction

Remote health monitoring has become an emerging technology and many health parameters are measured using sensor nodes on human body. These sensor nodes send the measured data to coordinator using IEEE 802.15.6 standard. The nodes along with the coordinator form network which follow the standard and are known as Medical Body Area Networks (MBAN). The rules defined for the PHY and MAC layers of MBAN have

non-optimized parameters and there is scope for improving the QoS by varying these parameters. The channel available time slot has a significant impact on the performance of the MBAN, specially with understanding that the standard keeps the Super-frame length fixed but allows slot lengths to be varied. Several research groups are working on optimizing the slots and achieving better traffic management.

A research group has recommended mini slots for emergency packet communication [1]. Each slot in the super-frame is split into two sections ordinary slots and mini slots. Mini slots are used to facilitate emergency packet transfer without the CSMA/CA access procedure. The MAC protocol controls vital traffic in the beacon-enabled super-frame using mini slots and regular traffic using a predefined slots allocation technique based on data rate. The high energy consumption of nodes with high data rates is a significant disadvantage of this technology. Another group of authors have developed two Time division multiple access-based scheduling techniques to increase reliability and energy efficiency, specifically adaptive scheduling, and dynamic scheduling techniques. The first technique dynamically assigns time slots to nodes by evaluating their network and storage health in both emergency and non-emergency situations. As opposed to the first method, the second grants time slots to nodes based on their queue length. Nonetheless, node prioritizing is not considered in these slot allocation algorithms [2]. Dynamic Slot Scheduling (DSS) technique for optimizing slot scheduling in the super-frame by utilizing a temporal autocorrelation model has been developed by researchers [3]. Actual on-body data is examined to ascertain the unpredictability of communication networks obtained from certain wireless transceivers. The disadvantage of this system is that each node has the same signal strength. In another work it has been suggested that a non-overlapping contention window-based dynamic slots allocation approach. This technique introduces two algorithms: the Non-Overlapping Backoff Algorithm (NOBA) and the Dynamic Slot Allocation (DSA) scheme. The NOBA removes backoff-induced inter-priority conflicts, whereas the DSA distributes dynamic slots to decrease waste caused by the fixed slot size of the super-frame structure. However, this system has not been evaluated in several healthcare event [4]. Author in [5] have suggested the 'varyschedslots' approach, which allows the number of slots assigned to a node to be varied depending upon the packet arrival rate from the node.

Various analytical models have been developed using Markov chain and analysis done for saturated and non-saturated regimes. Researchers [6, 7] have proposed models that use queueing sub model for buffers and have analyzed the mean waiting time and transmission success probability for all the eight user priorities. Performance enhancement have been recommended by a new model where collision avoidance between nodes assigned same user priority has been suggested by another group [8]. Monte Carlo simulations have been done so as to study the reliability and throughput for the different user priority for different payloads and the simulations have been compared with analytical model [9]. Backoff counter regulation has been done based on random parameter generator and a model for Back off counter has been developed to study the effect on reliability of data transmission [10].

From the state of art study, it may be summarized that some of the algorithms work by assuming that there are no default user priorities assigned to the nodes. The nodes are assigned priority dynamically, according to data rate or data buffer size. Super-frame

utilization is kept flexible in some methods so that the various phase lengths are varied according to emergency or normal data [11]. In some cases back off counter values are varied, so that there is minimum collision and delay between the data transmitted by different nodes. In this work, we plan to explore the effect of channel slot length for preassigned priority nodes so as to study its effect on probability of data transmission and successful packet delivery.

Optimization of throughput, packet delivery, latency, energy consumption, lifetime, relay mechanism, and channel utilization are done using analytical models. Markov chain model have been used for developing relation between performance metrics. In this study we have identified the following objectives:

- (a) To develop an analytical model to study stationary state transitions and develop an understanding of how packets are transmitted and successfully delivered by a node under test.
- (b) Develop equations for state transition probabilities using the mathematical model
- (c) Studying the effect of variation in channel slot length on the probability of packet transmission and the probability of successful delivery.

The model has been implemented using MATLAB for nodes with different user priorities.

The paper has been organized as follows: Sect. 2 contains an overview of IEEE 802.15.6 standard where CSMA/CA used graphs in MAC layer have been discussed. Section 3 deals with the mathematical model and the expression for three probabilities used as performance metric. Results have been presented in Sect. 4 where the graphs have been plotted and analyzed. The outcomes of the study have been summarized in the conclusion.

## 2 Overview of IEEE 802.15.6 MAC Protocol

In the access phase Beacon mode with super frame, the different access periods for nodes are: Exclusive Access Periods (EAP1, EAP2), Random Access Periods (RAP1 and RAP2), Managed Access Periods (MAP1, MAP2) and optional Contention Access Period (CAP). To manage network congestion, eight user priorities (UP0–UP7) are assigned to nodes depending upon the data traffic as shown in Table 1. In the standard beacon mode with Superframe, the nodes contents for EAP or RAP and CAP using CSMA/CA or slotted aloha mechanism. While the EAP periods are reserved for emergency data, the RAP and CAP periods are available for all nodes. The CAP period is preceded by beacon B2 so as to synchronize with the node. MAP is used by coordinator to allocate resources using polling mechanisms.

In CSMA/CA protocol the data transmission process is controlled by two parameters: the back-off counter and Contention Window (CW). Table 1 shows that the CW is variable and depends on node's priority. The CW size is large for low priority nodes (UP 0) and smallest for the high priority nodes at UP7. The back-off counter plays a vital role in the case of MAC layer of MBAN as it is loaded with  $CW_{min}$  value which depends on priority of node as per Table 1. The goal of incorporating a backoff counter in the CSMA/CA

**Table 1.** Node priorities as per traffic classification and contention window bounds as per IEEE 802.15.6 standard

| User priority | Traffic designation               | Contention window minimum ( $CW_{min}$ ) | Contention window maximum ( $CW_{max}$ ) |
|---------------|-----------------------------------|------------------------------------------|------------------------------------------|
| UP0           | Background                        | 16                                       | 64                                       |
| UP1           | Best effort                       | 16                                       | 32                                       |
| UP2           | Excellent effort                  | 8                                        | 32                                       |
| UP3           | Video                             | 8                                        | 16                                       |
| UP4           | Voice                             | 4                                        | 16                                       |
| UP5           | Network control                   | 4                                        | 8                                        |
| UP6           | High priority data                | 2                                        | 8                                        |
| UP7           | Emergency or medical implant data | 1                                        | 4                                        |

method is to create different time delay between nodes contesting to transmit data so that the hub can regulate node collisions.

At the start of CSMA/CA procedure, the node loads its backoff counter to a random value between 1 to  $CW_{min}$  and remains in its idle state till the channel is busy. When the channel is found to be free, the node begins to decrease the back-off counter by 1. After every decrement of the back-off counter, the channel is sensed and if found busy or if the current slot time is insufficient for the transmission, the back-off counter is made to freeze. The node stays in that state till the channel is sensed-free and has sufficient time length available for the data packet. After the backoff counter becomes zero, the node starts transmitting data. If the data is transmitted successfully to the node, the transmission is continued till completion or till collision is sensed. However, if the transmission is a failure, then the back-off stage is increased by 1, and the process is repeated, till maximum back-off stages are reached. The back-off counter gets updated with  $CW$  depending on the number of failures, using the following algorithm as shown in Eq. 1.

$$CW = \begin{cases} CW_{min} & \text{successful transmission} \\ CW & \text{same as the previous value for odd number of failures} \\ 2 * CW_{min} & \text{for even number of failures} \end{cases} \quad (1)$$

### 3 Mathematical Model

Markov chain model has been developed for different user priorities, as an example, Markov model for UP6 is shown in Fig. 1. The Markov model shows three parameters: user priority (UP), backoff stage (s), and backoff counter (j). The user priorities in this model vary from 0 to 7, the backoff stage (s) runs from 1 to m, the value of m is calculated by the formula  $2^m * CW_{min} = CW_{max}$  [12] these value of  $CW_{max}$  and  $CW_{min}$  have been

taken from the Table 1 and the backoff counter ( $j$ ) varies from 1 to  $CW_{min}$  [12] The probabilities of transition between different states of the model have been shown in Table 2.

**Table 2.** Probabilities definition for Markov model

| Notation   | Description                                              |
|------------|----------------------------------------------------------|
| $P_{busy}$ | Probability of channel is busy                           |
| $P_{idle}$ | Probability for start carrier sensing by nodes           |
| $P_L$      | Probability for insufficient time slot length            |
| $P_s$      | Probability of successfully packet deliver               |
| $P_t$      | Probability of transmission                              |
| $P_f$      | Probability of collision                                 |
| $P_{cf}$   | Probability of packet drop due to channel access failure |
| $N$        | Number of sensor nodes in MBAN                           |

In Fig. 1, the process begins with the idle state  $(0, 0, 0)$ , which occurs when all nodes are in the queue or idle state. Probability  $1 - P_{idle}$  is computed when nodes are unable to get access and remain in the same condition. The  $P_{idle}$  defines the likelihood of node starting carrier sensing to see if the channel is free. After gaining access, the node updates all index values and begins decrementing the backoff counter number by one for every time slot. If the channel is not free, then the node continues in the same state with probability  $P_{busy}$ . If the channel is free then the node moves to the next stationary state with probability determined in terms of  $P_{busy}$  and  $P_L$ , as per Eqs. 6 and 8. The Eq. 6 shows that probability that the channel is free and Eq. 8 shows the probability of sufficient length time slot availability. This process is continued vertically down within a back off stage as shown by arrows in Fig. 1, till the stationary state where the back off counter decrements to zero. The node now attempts to transmit the data packet and if not successful then enters the next Back off stage, where again the back off counter is reloaded and the procedure is repeated until it does not exceed its maximum limit.

The stationary states of the Markov chain are represented by the equation

$$S_{s,j} = \lim_{t \rightarrow \infty} p((a(t) = s, \quad b(t) = j)) \quad (2)$$

where backoff stage  $s \in [1, m]$ , backoff counter  $j \in [0, CW_{min}]$

From Fig. 1, we arrive at the following transition probabilities between the various stationary states of the Markov chain which are also proposed in ref [9] for evaluating reliability or probability of successful packet transmission.

The probability that the node stays in the idle state is given by Eq. 3.

$$P(0, 0, 0|0, 0, 0) = 1 - P_{idle} \quad (3)$$

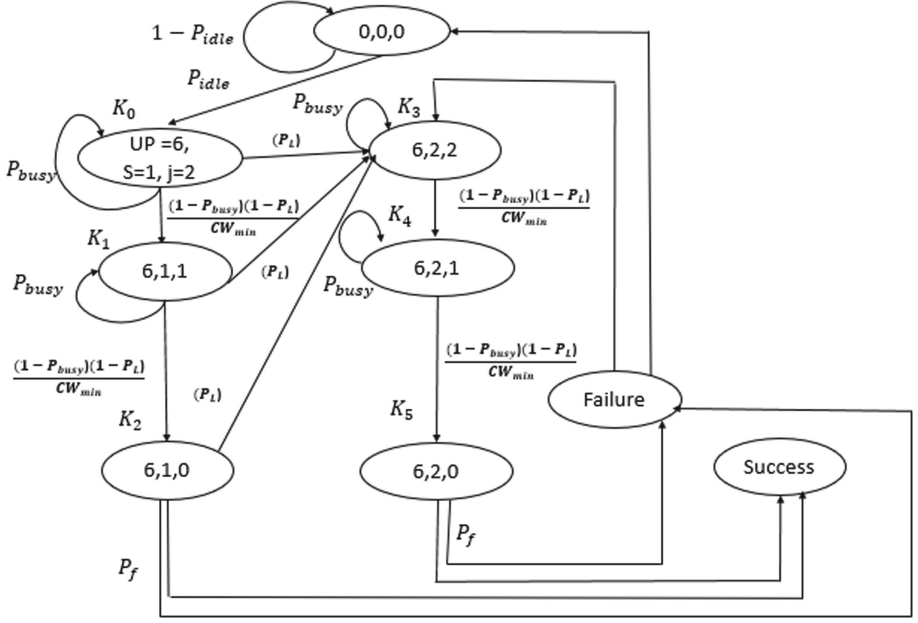


Fig. 1. Markov model for UP6

The probability that the node moves to the state where it loads the indices is determined by Eq. 4.

$$P(UP, m, CW_{min} | 0, 0, 0) = P_{idle} \quad (4)$$

The probability that the node senses that the channel is busy while decrementing its backoff counter is illustrated in Eq. 5.

$$P(UP, m, CW_{min} | UP, m, CW_{min}) = P_{busy} \quad (5)$$

When the channel is free, the probability of moving the node to the next state is given by Eq. 6.

$$P(UP, m, CW_{min} - 1 | UP, m, j) = \frac{(1 - P_{busy})}{CW_{min}} \quad \text{for } j \in [1, CW_{min}] \quad (6)$$

Equation 7 depicts the likelihood of a node going to the next backoff stage owing to a lack of time slots.

$$P(UP, s + 1, j | UP, s, j) = P_L \quad \text{for } s \in [1, m] \quad (7)$$

Equation 8 illustrates the likelihood of decreasing the backoff counter if the channel has an enough time slot.

$$P(UP, s, j - 1 | UP, s, j) = 1 - P_L \quad \text{for } j \in [1, CW_{min}], s \in [1, m] \quad (8)$$

The probability of successful packet transmission is given by Eq. 9.

$$P(\text{Success}|UP, s, 0) = 1 - P_f \quad (9)$$

When a data packet is not reached at the receiver end owing to a collision, the failure probability is represented in the Eq. 10.

$$P(\text{Failure}|UP, s, 0) = P_f \quad (10)$$

The likelihood that a node will reach the last backoff stage and fail to deliver packets is provided in Eq. 11.

$$P(\text{PacketDrop}|UP, s, 0) = P_f \quad (11)$$

Equation 12 depicts the likelihood of a node moving into the packet drop state owing to inadequate time slot length on a node that is already in the final state.

$$P(\text{PacketDrop}|UP, s, j) = P_L \quad (12)$$

As shown in Eq. 13, once the node reaches the packet drop state, the chance of going to the idle state is equal to one.

$$P(0, 0, 0|\text{PacketDrop}) = 1 \quad (13)$$

Using these equations and the Markov chain model, the transition matrix for UP6 has been developed as shown in Fig. 2. The stages of Markov model shown in Fig. 1, for UP6 are used for developing this matrix.

$$\begin{bmatrix} P_{\text{busy}} & (1 - P_{\text{busy}})(1 - P_L)/CW_{\text{min}} & 0 & P_L & 0 & 0 \\ 0 & P_L & (1 - P_{\text{busy}})(1 - P_L)/CW_{\text{min}} & P_L & 0 & 0 \\ 0 & 0 & 0 & P_t P_L & 0 & 0 \\ 0 & 0 & 0 & P_{\text{busy}} & (1 - P_{\text{busy}})(1 - P_L)/CW_{\text{min}} & 0 \\ 0 & 0 & 0 & 0 & P_{\text{busy}} & (1 - P_{\text{busy}})(1 - P_L)/CW_{\text{min}} \\ 0 & 0 & 0 & 0 & 0 & P_t P_L \end{bmatrix}$$

**Fig. 2.** Transition matrix for stationary states in Markov model for UP6

We investigate the impact of a channel time slot transmission probability  $P_t$ , and probability of successful packet delivery  $P_s$ .

The intermediate transmission Probability is defined as probability where the node is able to reach the zero value for backoff counter and start transmission in any backoff stage. From the Markov chain,  $P_t$  is calculated as follows

$$P_t = \sum_{j=1}^{CW_{\text{min}}} \sum_{s=1}^m \frac{(1 - P_{\text{busy}})}{CW_{\text{min}}} P_L^{s-1} (1 - P_L)^j \quad (14)$$

The probability of unsuccessful packet transmission  $P_f$  can be expressed in terms of transmission probability  $P_t$

$$P_f = 1 - P_t^{N-1} \quad (15)$$

Reliability, also known as Probability of successful transmission  $P_s$ , is given by

$$P_s = 1 - P_{cf} \quad (16)$$

where  $P_{cf}$  is the probability of packet loss as a result of channel access failure. Channel access failure occurs when either the time slot length is insufficient or data transmission through other nodes collides. The Markov chain can now be used to calculate the probability of packet loss due to channel access failure.

$$P_{cf} = \sum_{j=1}^{CW_{min}} \sum_{s=1}^m P_L^{s-1} (1 - P_L)^j P_f P_L^m (1 - P_L)^{j-1} \quad (17)$$

## 4 Results Analysis

Using the transition matrix and Eqs. 14–17, the two probabilities reflecting the performance of network are calculated and plotted for varying probability of sufficient channel time slot ( $1 - P_L$ ) for UP 6, 4, 2, 0.

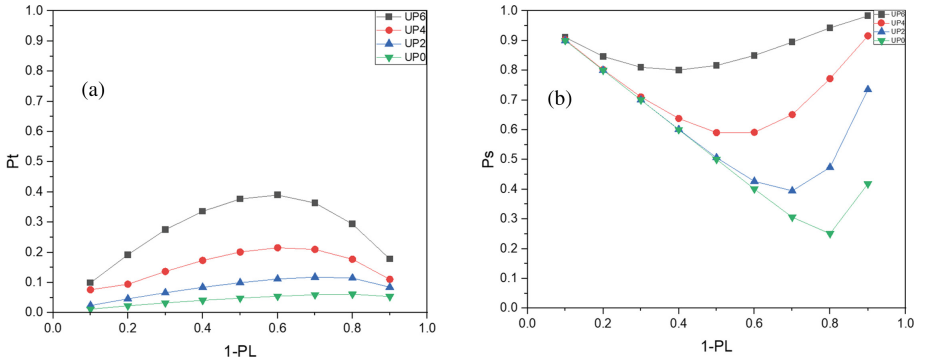


**Fig. 3.** Graphs for probability of transmission, probability of packet drops due to channel access failure, probability of successful packet delivery.

Figure 3(a) depicts the transmission probability of nodes for UP 6, 4, 2, 0. The graph shows that the  $P_t$  is higher for UP6 as compared to other nodes lower user priorities. The value of  $P_t$  increases as the probability of sufficient time slot increases and reaches a peak value when the probability of sufficient channel time slot is nearly 60%. As the probability of sufficient time slot increase, more nodes are now ready for transmission and as soon as their back off counters are zero, these nodes transmit data and collisions may occur. This reduces the transmission probability for node under test.

The graph in Fig. 3(b) depicts the likelihood of successful packet delivery for UP 6, 4, 2, 0. We notice that the UP6 has a higher probability of successful packet delivery than the other nodes of lesser priority. As previously stated, all nodes have different back counter values depending on their user priority; higher user priority nodes have a low value for the counter, whereas lower user priority nodes have a high value for the

counter. Therefore, higher user priority nodes have a better chance of occupying a good fraction of channel time slot for data transmission, while lower priority nodes face the possibility of channel access failure. This increases the probability of successful packet delivery.

## 5 Conclusion

The study is a generalized approach for understanding the roles of back off counter and channel time slot in successful packet delivery when nodes with different user priority are ready for data transmission. It is seen that the higher user priority nodes have better probability of packet delivery as compared to lower user priority nodes when sufficient time slot of channel is available. The backoff counter also plays an important role in the transmission probability as nodes with higher user priority have a smaller contention window, which causes lower backoff counts as well as lower number of backoff stages. As a future scope of work, we plan to study the complete performance analysis including parameter- through-put by modifying the Markov chain to include retransmission.

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