Performance Study of the IEEE 802.15.6 Slotted Aloha Mechanism with Power Control in a Multiuser Environment

Luis Orozco-Barbosa(✉)

Albacete Research Institute of Informatics,
Universidad de Castilla La Mancha, 02071 Albacete, Spain
luis.orozco@uclm.es

Abstract. Recent developments in wireless systems and sensor technologies have spurred the interest on the design and development of Wireless Body Area Networks (WBANs). The performance of such systems will very much rely on protocols capable of dealing with the stringent QoS requirements of the end applications. Towards this end, numerous studies are being carried out aiming to evaluate the IEEE 802.15.6 MAC protocol. In this paper, we undertake the development of a simulation tool enabling the study of the IEEE 802.15.6 slotted-Aloha MAC with power control. Our study particularly focuses on a multiuser environment where the monitoring devices of a number of users will communicate with a central hub. Such scenario will typically describe the operating conditions of a nursing unit.

Keywords: Wireless Body Area Networks · Performance evaluation · IEEE 802.15.6 · Simulation

1 Introduction

Recent developments in the area of wireless communications and sensors have enabled the design and deployment of applications in a wide variety of fields: entertainment, industry, agriculture, medicine, healthcare, among others [1]. Due to the increasing cost of healthcare and ageing population, the use of Wireless Body Area Networks (WBANs) should enable ambulatory care and continuous monitoring of patients.

Even though many Wireless Personal Area Networks (WPANs) technologies are already available in the market, such as Bluetooth, Zigbee and Wi-Fi, it has been recognized that they do not meet the requirements of WBANs. In particular, major challenges to wireless communications designers are (1) the definition of the proper protocol architecture addressing the Quality of Service (QoS) requirements of the various medical parameters, (2) an adequate characterization of the wireless channel temporal variations providing a better insight on the major challenges facing the design of effective protocol mechanisms and (3) energy-efficient protocol mechanisms [2]. The first issue is being addressed by the IEEE 802.15.6 Standard developed by the Task Group 6 (TG6) of the IEEE 802.15 Working Group [3]. The IEEE 802.15.6 standard defines the MAC layer mechanisms supporting three different physical layers, namely,

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Narrowband (NB), Ultra-Wideband (UWB), and Human Body Communications (HBC) layers [4]. Among its main features, the IEEE 802.15.6 MAC protocol incorporates eight different user priorities for accessing the medium in an aim to meet the QoS requirements of the various medical applications and vital signals communications to be supported.

Regarding the characterization of the wireless channels within the context of WBANs, experimental efforts are being carried out on the operating conditions of WBANs [5]. It is clear that the fact of placing the wireless nodes in and around the human body, see Fig. 1, requires an analysis of the impact over the channel behavior introduced by the human body and the relative displacement of the various wireless nodes.

Nowadays BSN research still faces many key technical challenges. One of the ultimate goals of many current studies is the development of wireless channel models to be used in the performance analysis of the proposed protocol mechanisms of the IEEE 802.15.6 MAC protocol [6].

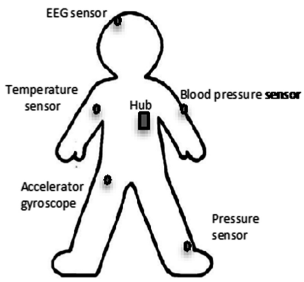

Fig. 1. Body Area Network

In this paper, we undertake the study of the IEEE 802.15.6 slotted-Aloha MAC protocol. First, we examine the priority mechanism and conflict access resolution algorithm implemented by the MAC protocol. Taking as a baseline, a simple Markov Chain model recently reported in the literature, we then evaluate the performance of the proposed mechanisms having an enhanced capture effect. We evaluate the impact of using a simple power control scheme over the performance of the IEEE 802.15.6. Our study and simulator development efforts set the basis for further studies using power control, wireless channel models and experimental traces reported in the literature and/or gathered in our labs.

In the following this document is organized as follows. Section 2 overviews some recent works in the area of channel modeling and power control. Section 3 describes the IEEE 802.15.6 slotted-Aloha mechanism. Section 4 reviews a simple model of the IEEE 802.15.6 slotted-Aloha MAC protocol, the use of power control mechanism and major efforts towards the development of representative channel wireless models within the scope of WBANs. We also provide some results under different scenarios. Section 5 draws some conclusions and outlines our future research plans.

2 WBANs Power Control and Channel Modelling for MAC Performance

Numerous research initiatives around the world are actively working on the characterization of the wireless channel for WBANs. It is widely accepted that WBANs introduce a very different environment with respect to the ones characterizing other wireless technologies. Many studies are then conducting field trials with the main goal of developing channel models from the data being obtained [5]. Within these efforts, the study of the stability and or temporal variation WBANs are particular relevant to the development of tools for evaluating MAC protocols. In [5], the authors have investigated the wireless channel temporal variations. In a first set of simulations, they vary the transmission power while fixing the average path loss to the coordinator. As expected, their findings report that the number of unacknowledged frames increases exponentially increases as the transmission power is decreased. Their results further confirm that the retransmissions do not prove effective on improving the frame transmission success rate.

In [9], the authors characterize the stability of a WBAN narrowband based on real-time measurements of the time domain channel impulse response (CIR) at frequencies near the 900- and 2400-MHz industrial, scientific, and medical (ISM) bands. Their findings confirm that body movement has considerable impact on the stability of the channel. This is numerically confirmed by the length of the coherence time. Furthermore, they conclude that there is a greater temporal stability at the lower frequency, namely 900 MHz.

Based on the results reported in [5, 9], it is clear that a power control strategy may play a major role on improving the performance of the MAC protocol. In fact, several efforts on evaluating the use of transmission power control in the context of contention-based MAC protocols have been reported in the literature [10–13]. Most of these studies focus on the slotted Aloha mechanism aiming to improve its performance through the capture effect. In [10], the capture event success probability is improved by controlling the probability of choosing the high power transmission level. In [12], the authors develop a wireless random access protocol with multiple power levels. Under the proposed protocol, each node contends following a random access mechanism incorporating a random transmission power value selected among a given set. Following a game theory approach, the channel throughput is optimized taking into account the network load. In [13], the authors develop a three-state discrete-time Markov chain model of a contention-based MAC protocol including the conditional capture probability. Their work included the development of an experimental platform validating their results. In [14], a model and experimental evaluation of the capture effect in an IEEE 802.15.4 is also presented. All these studies show the great benefits of incorporating the use of multiple power levels into the operation of contention-based mechanism.

3 IEEE 802.15.16 Slotted Aloha Mechanism

In this section, we briefly describe the slotted-Aloha MAC mechanism of the IEEE 802.15.6 standard. The IEEE 802.15.6 slotted-Aloha MAC mechanism defines eight different User Priorities; UPi, i = 0, . . ., 7. A parameter, Contention Probability (CP) is used to implement the prioritized access of differing users, where CP $\in$ [CP_{max}, CP_{min}]. The values of CP_{max} and CP_{min} are set differently for each UP_i as shown in Table 1.

Table 1. Contention probability thresholds for slotted Aloha access

Priority	Traffic type	CP_{max}	CP_{min}
0	Background (BK)	1/8	1/16
1	Best effort (BE)	1/8	3/32
2	Excellent effort (EE)	1/4	3/32
3	Video (VI)	1/4	1/8
4	Voice (VO)	3/8	1/8
5	Medical data or network control	3/8	3/16
6	High-priority medical data	1/2	3/16
7	Emergency	1	1/4

A sensor node contends to transmit its packet as follows:

1. A node generates a random number z from the interval [0, 1].
2. The CP value is set to CP_{max} for a new packet.
3. A node obtains a contended allocation by the current Aloha slot if $z \leq$ CP.
4. If the transmission fails, the CP value is halved for an even number of retransmissions, and is fixed to the previous value for an odd number of retransmissions. If halving CP makes the new CP smaller than CP_{min}, the CP value is set to CP_{min}.

The CP value does not change when it gets settled with CP_{min} at the m-th retransmission. The value of m is given by:

$$m = 2\left\lceil \log_2\left(\frac{CP_{max}}{CP_{min}}\right)\right\rceil. \tag{1}$$

4 Protocol Models and Simulation

4.1 The IEEE 802.15.6 Slotted-Aloha MAC Protocol

In this section, we first follow the work reported in [7]. The authors introduce an analytical model to evaluate the saturation throughput of the IEEE 802.15.6 slotted Aloha mechanism. In their analysis, the authors assume a single hop star topology consisting of a central hub and a fixed number of nodes. Each and every node always has a packet available for transmission under an ideal channel scenario. The nodes implement the IEEE 802.15.6 slotted-Aloha MAC protocol described in Sect. 3.

The authors introduce a simple Discrete Time Markov Chain (DTMC) model. The DTMC is obtained from the state transition of the IEEE 802.15.6 slotted-Aloha MAC protocol. The key element of the model is that it captures the decreasing probability of transmission stated in the IEEE 802.15.6 standard and the division of the time into sequence of well-defined packets of fixed length.

In the DTMC, $\{0, 1, 2, \ldots, m\}$ are the states through which a node goes based on the contention probability. For the tagged node being in state k, the slot-wise event probabilities are denoted as follows:

- p(k, i): remains idle in the current slot without attempting to transmit
- p(k, s): transmits successfully in the current slot
- p(k, c): transmits in the current slot that ends up in collision

The one-state transition probabilities in the DTMC are:

$$\begin{cases} Pr(0|0) = p(0,s) + p(0,i) & \\ Pr(k+1|k) = p(k,c) & k \in [0, m-1] \\ Pr(0|k) = P(k,s) & k \in [1, m] \\ Pr(k|k) = p(k,i) & k \in [1, m-1] \\ Pr(m|m) = p(m,c) + p(m,i) & \end{cases} \tag{2}$$

Under the saturation case scenario, the collision probability for the node i is:

$$\gamma_i = 1 - (1 - \tau_i)^{(n_i - 1)} \prod_{j=0, j \neq i}^{7} (1 - \tau_j)^{n_j}. \tag{3}$$

From the analysis reported in [7], the probability that node i transmits in a slot is given by:

$$\tau_i = \frac{CP_{\max(i)}(1 - 2\gamma_i^2)}{(1 - \gamma_i^2)\{1 - (\sqrt{2}\gamma_i)^{m_i}\} + (1 - 2\gamma_i^2)(\sqrt{2}\gamma_i)^{m_i}}. \tag{4}$$

The pair of non-linear Eqs. (3) and (4) are solved by means of Equilibrium Point Analysis (EPA) [8]. Taking this model as a starting point, and as a first step to evaluate the priority and backoff mechanisms of the IEEE 802.15.6 MAC protocol, we have developed a simulation tool. This first set of results complement the finding reported in [7]. In an aim to gain insight into the effectiveness of the priority mechanism, we consider a network consisting of one Class 5 sensor node while increasing the number of Class 0 nodes.

Figure 2 shows the normalized saturation throughput for the two different priority classes, Class 0 and Class 5 and the channel. The figure depicts both the results derived from the model and simulation results. Each simulation run was set for 106 slots. There is a good match between the results obtained from the model and simulation. As already stated, the purpose of this first part of the study has been centered on the development and validation of a simulation tool allowing us to further explore the performance of the MAC protocol: identify the impact/use of the priority mechanism

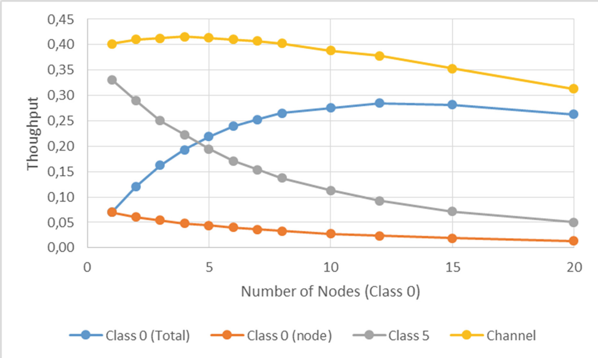

Fig. 2. Throughput – IEEE 802.15.6 Standards

and back-off mechanism. Furthermore, in order to get a more accurate evaluation tool reflecting the control mechanisms of the IEEE 802.15.6 slotted Aloha mechanism, we have set the maximum retransmission parameters to 10 as specified in the standard. In this case, a frame exceeding this threshold is discarded.

Figure 3 shows the frame loss probability for both classes being considered. From the results depicted in Figs. 2 and 3, it is clear that the higher-priority traffic, Class 5 is heavily penalized as the load generated by the low-priority class increases. Figure 2 shows that the throughput of a Class 5 node decreases at a much faster pace than the throughput of a Class 0 node as the number of nodes of Class 0 increases. The results clearly show that the priority mechanism does not provide QoS guarantees to the high-priority traffic.

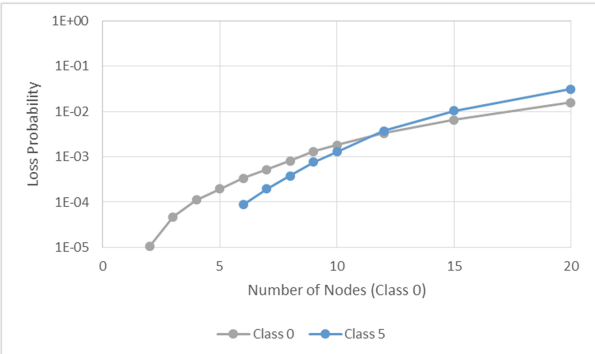

Fig. 3. Frame loss probability

In order to gain further insight into the performance of the backoff mechanism of the IEEE 802.15.6 MAC standard, we consider the case of halving the CP value as soon as a transmission fails.

Figure 4 depicts the throughput for both classes and the channel. The results show a slight degradation when a reduced number of Class 0 nodes, up to five, are present. This clearly shows that the backoff over reacts in this case. However for a network configuration between five and 10 nodes, the throughput improves: in this case the backoff proves effective. Figures 1 and 3 show very similar results, as the number of Class 0 nodes increases. This is due to the fact that as the number of active nodes increases, the backoff mechanism quickly fixes the CP parameters to its minimum value.

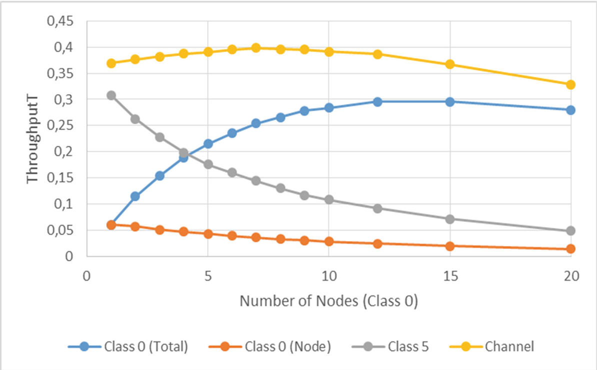

Fig. 4. Throughput – modified

4.2 Simulation Scenarios and Results

Following the results reported in Sect. 3A and the literature review, we propose to supplement the IEEE 802.15.6 MAC protocol by incorporating into it the use of multiple power levels selected randomly by the nodes. Under the proposed scheme, a node being ready to transmit will randomly select its transmission power. The proposed mechanism should not only prove effective on limiting the adverse condition of the channel, but it will also be effective in producing a capture effect in the presence of a limited number of simultaneous transmissions. The latter effect has lately attracted the attention of researchers due to the increasing number of wireless devices and emerging wireless technologies [11, 12]. Remember that our main aim is to explore the performance of the IEEE 802.15.6 in scenarios where a large number of devices are collocated, such as in a nursing home.

We undertake the study of the proposed scheme under two main scenarios. In order to get a better insight on the impact of the retransmission probability used by the different priorities, we study two classes: Class 0 and Class 5. We assume that a node can transmit using one of two power levels selected randomly. Similar to the study reported in [11], we assume that all nodes experience the same channel gain. The transmission of the target node i will be successful in the presence of simultaneous transmission if the following three conditions are met.

1. *Node i* transmits with the highest power level, denoted by P_i.
2. All other nodes transmit with power levels lower than P_i.
3. The instantaneous SINR of tagged *Node i* is higher than the target SINR at the hub (receiver).

The number and values of the power levels to use will very much depend on the actual technology being used. As for the actual random selection scheme of the power level, the results in [12] have shown that uniform random scheme proves to be effective. Condition c is derived from the channel model. From the results reported in [5, 12, 14], the actual values will depend very much on the end-user environment.

In our simulations, we explore the performance of the two classes of traffic. Since our main aim is to explore the role of the contention probability defined by the IEEE 802.15.6 and the power control mechanism, we consider two scenarios: a network exclusively comprising only Class 0 (Class 5) nodes and a network consisting of one Class 5 and one or more Class 0 nodes. For both scenarios, we consider the use of two power levels, p_{high} and p_{low}, randomly selected following a uniform random distribution. A transmission is successful in a given slot if (1) the aforementioned conditions are met or (2) in the case that only one node transmits.

Figures 5 and 6 show the results obtained for both classes and the two MAC protocols, namely, the IEEE 802.15.6 standard MAC and the proposed power-enhanced MAC protocol. Besides the fact that the capture effect considerable improves the network performance, it is evident that the use of a higher retransmission probability, Class 5, has a negative impact as the number of competing nodes increases. In fact, in one of our previous works using game theory principles, we have shown that the nodes should reduce their retransmission probability as the load increases [12].

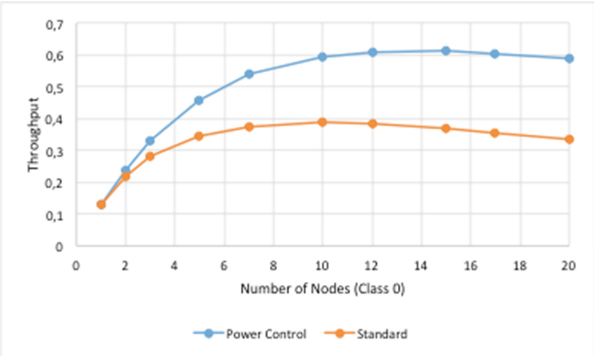

Fig. 5. Throughput - Class 0

Figures 7 and 8 depict the results for a network consisting of a single high-priority node (Class 5) and a given number of low-priority nodes (Class 0). In the first case, Fig. 7, the nodes of both classes randomly select one of the two available transmission powers with equal probability, i.e., $p_{high} = p_{low} = 0.5$. The results clearly show an improvement on the throughput of both classes. However, similar to the results

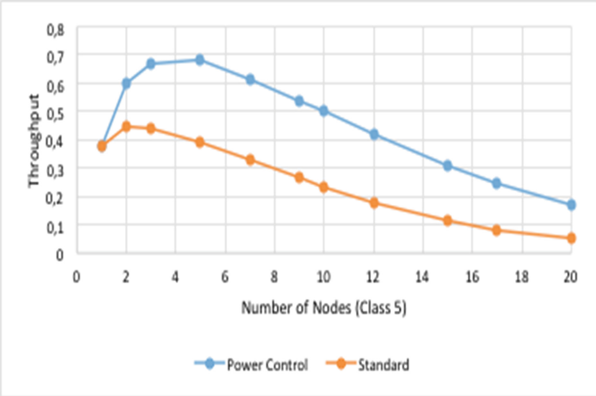

Fig. 6. Throughput - Class 5

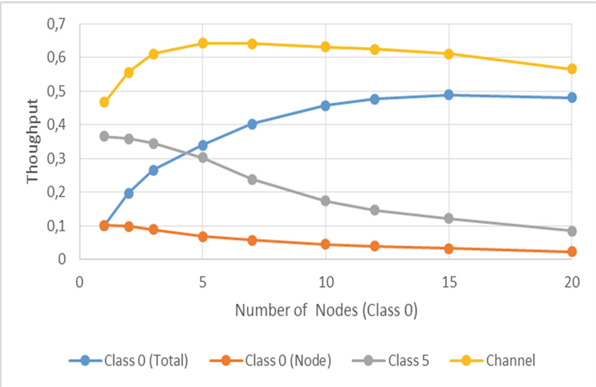

Fig. 7. Throughput – symmetric

depicted in Fig. 1, the throughput of Class 5 gets penalized as the number of Class 0 nodes increases.

Figure 8 show the results for both classes when the probability of selecting the high power transmission level has been set to 0.9 for the Class 5 and 0.1 for Class 0. In this case, the Class 5 throughput exhibits better results. However, the overall throughput degrades as the network load increases. The results also show that for a typical WBANs consisting of five to seven nodes with one high-priority node, the setting of the power levels is rather straightforward, i.e., $p_{high} = p_{low} = 0.5$ for all classes.

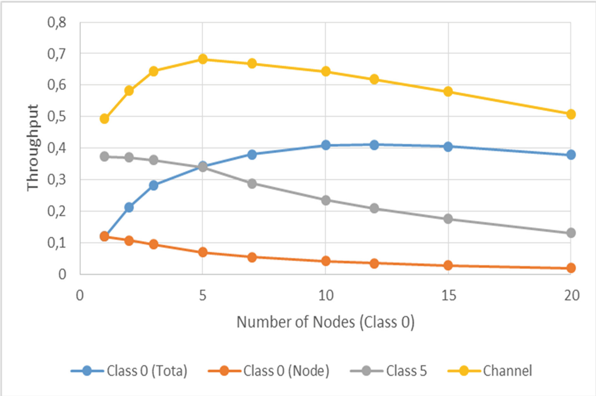

Fig. 8. Throughput – asymmetric

5 Conclusions and Future Work

In this work, we have first reviewed the principles of operation of the IEEE 802.15.6 slotted-Aloha MAC protocol. Taking as a basis the model recently reported in [7], we have validated our simulation tool. We have then explored the performance of the MAC protocol making use of a simple power control scheme. Some preliminary results have been reported focusing on the network parameters. Our future work plans comprise: the inclusion of channel models, the evaluation of a multiple-class network, and the QoS guarantees as perceived by the end-user application.

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