# Experimental Characterisation of an IEEE 802.15.6-Based Body Area Network

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## ABSTRACT

This paper presents the implementation of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) Medium Access Control (MAC) protocol based on the IEEE 802.15.6 standard on a hardware platform developed for Wireless Body Area Network (WBAN) applications. The CSMA/CA allows each node to detect an ongoing transmission and consequently wait until the channel is idle. A testing campaign has been conducted in order to evaluate the performance of the protocol in terms of packet loss rate, average packet delay and network throughput.

## Categories and Subject Descriptors

C.2 [**Computer-Communications networks**]: Network Architecture and Design, Network Protocols—*wireless communication, network communications, network protocols.*

## General Terms

Wireless Body Area Networks, Medium Access Control, CSMA/CA.

## Keywords

CSMA/CA, IEEE 802.15.6, WBAN, Packet Loss Rate, Delay, Throughput.

## 1. INTRODUCTION

The evolution of wireless communications toward the increase of connectivity and the advances in miniaturization allow for increased mobility and accessibility and decrease in size and cost in terms of power consumption. This has empowered the development of Wireless Body Area Network (WBAN): networks of sensors placed on or implanted in the human body capable of establishing wireless communication links to improve different lifestyle facets. Although the range of applications for WBAN is huge, the healthcare field is the most suitable to be investigated: WBAN can monitor physiological signals collected from the body and perform a continuous and remote monitoring on the human body. These applications impose stringent requirements in terms of energy efficiency, delay and reliability [3].

This paper focuses on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) Medium Access Control (MAC) protocol defined in the IEEE 802.15.6 standard [1]. In particular, it has been implemented on a real platform developed for WBAN applications, as described in the Section 3 and tested in the field by performing a measurement campaign. Numerical results in terms of packet loss rate (PLR), average packet delay and throughput are presented.

In the literature it is possible to find an estimation of the performance of the protocol, in terms of the same metrics as the ones considered in this paper, based on analytical models or simulations. In [6] a mathematical model is presented in order to determine the theoretical throughput and delay limits of WBAN using the IEEE 802.15.6 CSMA/CA for an ideal channel with no transmission errors. In [5] Bit Error Rate (BER) is measured as a function of channel quality, diversity order, and Signal to Noise Ratio (SNR) values for all User Priorities (UPs). MAC performance is evaluated by means of analytical modelling and simulation considering a Rician fading channel as a reference model. In [2] a novel MAC protocol, inspired by those defined in the IEEE 802.15.4 and 802.15.6 standards, is presented and implemented on the Texas Instruments CC2530 platform, and a data aggregation strategy is proposed to reduce packets losses and energy consumption.

To the authors' knowledge, there is no experimental performance characterisation of the CSMA/CA MAC protocol based on the IEEE 802.15.6 standard.

## 2. THE MAC PROTOCOL

This research has been performed as a part of the WiserBAN project, which aims at creating an ultra-miniature and ultra-low power RF microsystem for WBAN.

In this paper we focus on a superframe (SF)-based MAC layer: the coordinator periodically broadcasts beacon packets for synchronization and maintenance of the entire network. The period of time between two consecutive beacons is known as SF. This period is divided into several smaller periods, each dedicated to different operations. The SF structure implemented in the experiments is depicted in Fig. 1: the Contention Access Period (CAP) begins immediately after the reception of the beacon, then there is an inactive period during which the device switches to sleep mode to save energy. Packets are transmitted during the CAP using the IEEE 802.15.6 CSMA/CA protocol.

According to the CSMA/CA algorithm defined in the IEEE

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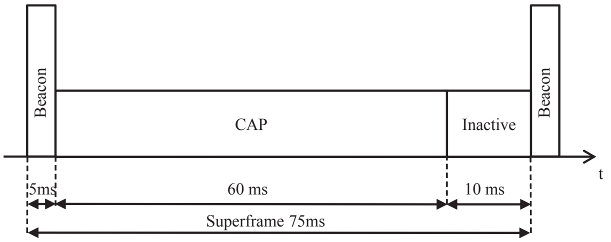

**Figure 1: Superframe structure**

**Table 1: User Priority and CW values used in the experiments.**

| UP | $CW_{min}$ | $CW_{max}$ |
|---|---|---|
| 3 | 8 | 16 |
| 5 | 4 | 8 |
| 6 | 2 | 8 |
| 7 | 1 | 4 |

802.15.6 standard [1], when a node of the WBAN has data to be transmitted, it chooses a random number uniformly distributed over the interval [1; CW], where CW is the contention window value initialized to the $CW_{min}$, which depends on the UP (Table 1 shows the reference UPs used in this paper; refer to [1, Table 20] for the full table). The node decreases the backoff counter by one at the end of each CSMA/CA slot if the channel is idle, meaning that no transmissions from other nodes are detected. Data is transmitted when the backoff counter reaches zero and there is enough time in the current CAP to complete the entire transmission (data packet transmission and acknowledgement (ACK) reception). If the channel is found busy because of other nodes' transmission, the node locks its backoff counter until the channel is found idle. The CW is doubled at even number of consecutive failures, that is when the node fails to receive an acknowledgement, until it reaches $CW_{max}$, which depends on the UP. The flow chart in Fig. 2 illustrates the CSMA/CA algorithm.

## 3. EXPERIMENTAL SETUP

The CSMA/CA protocol has been developed for the IcyCom platform [4]. This System-on-Chip (SoC) embeds on a single die a radio transceiver with a 32-bit low-power DSP core running at 3.2 MHz and a comprehensive set of analog/digital peripherals, with a supply as low as 1 V. The radio operates in the 863-928 MHz ISM band with a Minimum Shift Keying (MSK) modulation at a bitrate of 200 kbps.

The measurement campaign has been conducted considering a network composed by a maximum number of three nodes managed by one coordinator. Devices were located on a plane surface at the same distance from the coordinator, appositely chosen larger than the wavelength (approximatively 37 cm) in order to avoid near field propagation problem. Nodes transmit the packets toward the coordinator according to two traffic schemes: i)*Periodic traffic*: one packet per SF is generated for a total of 5000 packets per node; ii)*Random traffic*: packets are randomly generated within a period of time $T$ such that the packet generation rate is known. Devices are kept in the same location throughout the measurements.

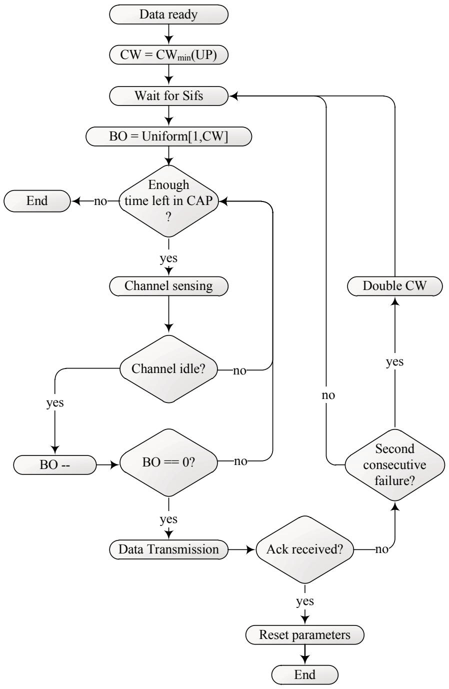

**Figure 2: IEEE 802.15.6 CSMA/CA flow chart**

Performance is evaluated in terms of: i)*Average Delay*: the interval of time elapsed between the data packet generation and its reception from the coordinator. The latter means that the packet delay incorporates the time needed for accessing the channel, for transmitting the packet and the acknowledgement, for processing and for the turn-around times. The average delay is obtained by averaging over all the successfully received packet delays in the measurement. Delay evaluation has been performed using timestamping functionality. ii)*PLR*: the ratio between the number of packets which are not successfully received by the coordinator and the total number of transmitted packets, averaged among the different nodes; iii)*Network Throughput*: average amount of useful information received by the coordinator (averaged among the different transmissions) per unit of time.

An important parameter in the measurement is the SF duration which is set to 75 ms. It is composed of beacon period (5 ms), CAP period (60 ms) and inactive period (10 ms) as depicted in Fig. 1.

## 4. EXPERIMENTAL RESULTS

In this section we will first discuss the average packet delay followed by the PLR and network throughput. The periodic traffic generation is considered in Fig. 3,4,5 and 6, while the random traffic generation is considered in Fig. 7, showing the network throughput.

Fig. 3 shows the average packet delay per node as a function of the payload size of the transmitted packets[1]. Delay

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[1] We refer to payload as the useful and non-redundant information contained in a data packet.

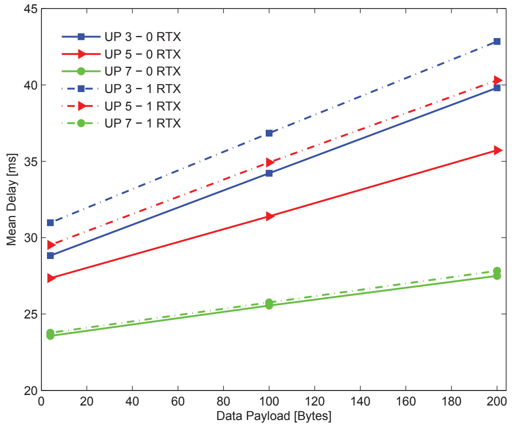

**Figure 3: Mean delay for a three nodes-network, each one with different UP values: node 1-UP 3; node 2-UP 5; node 3-UP 7.**

is defined as the time elapsed from the packet generation at the source and the correct packet reception at the destination node, failed transmissions are not taken into account. The three nodes forming the network have different UPs. Two sets of curve are shown for different values of retransmissions allowed. Node 3, being the one with UP 7, experiences the lowest mean delay since its $CW_{min}$ is 1 so it is always the first node to start the transmission. On the other hand Node 1 and Node 2 have higher $CW_{min}$ values, which leads to higher delay since the backoff time is longer. When the number of retransmissions increases from zero to one, in order to decrease the PLR, the average packet delay increases.

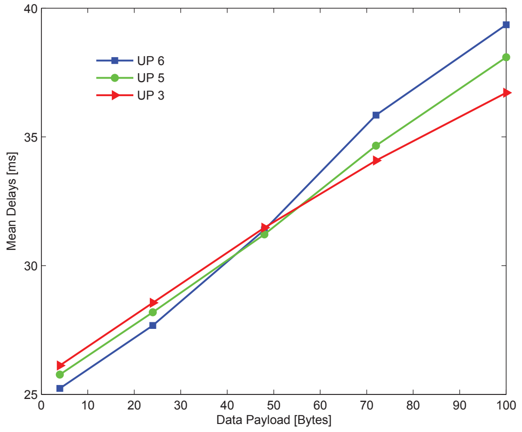

**Figure 4: Mean delay for a three nodes-network, each one with the same UP value.**

Fig. 4 presents the average packet delay for a three-nodes network as function of the payload size and for different values of UP, in this case the three nodes have the same UP value. Each point represents the delay averaged over the total number of packets correctly received by the coordinator. The maximum number of retransmissions is set to three. It can be seen that for low values of payload size, the average delay is mainly due to the the backoff period, therefore it decreases by increasing UP. Conversely, when the payload size is large and UP increases, more packets are retransmitted since collisions are more likely to happen. This has greater impact on the average delay than the backoff period.

The value of UP has a major impact on the performance: a small value will decrease the number of collisions but each node will on average wait longer to access the channel. This effect is presented in Fig. 5 where the mean packet delay is shown as a function of the payload size in a network composed of a different number of nodes. The mean delay increases with the number of devices since the probability that the channel is found busy increases due to higher network traffic. There is an offset between curves belonging to the same network topology, but characterised by different priorities, since lower UP values, introduce longer backoff periods. In the case of three nodes topology, there is an intersection between the curves, since, for large payload size and higher generated traffic, retransmissions affect the delay more that the backoff time, as explained before.

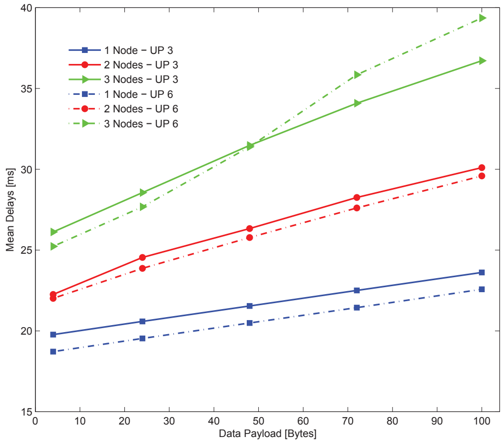

**Figure 5: Mean delay for different network sizes, all nodes have the same UP.**

For what concerns the PLR analysis, it is interesting to observe the impact of UP on this metric. Fig. 6 shows PLR as a function of the payload size for different priorities. When the number of retransmissions is larger then two the PLR gets much better, which happens because the value of CW is doubled after an even number of failures (see Section 2). Moreover the PLR has an almost flat behaviour because CAP lasts enough to fit the transmissions and retransmissions of all the nodes in the network. Therefore, the PLR is determined by the probability that at least two devices choose the same random number of backoff periods, and this is clearly independent from the payload size.

Network throughput can be defined as the average amount of successfully transmitted data per unit time. Therefore it is a measure of the efficiency of a network expressed as the data transfer rate of useful and non-redundant information.

The offered load is defined as the overall amount of data generated by the network. Apart from payload it includes also redundant information contained in the header of each packet. The throughput is evaluated as $S = \frac{N_{RX} \cdot L_P}{T}$ $[bit/s]$ and the offered load as $G = \frac{N \cdot (L_P + L_H)}{T}$ $[bit/s]$. Where N is the number of devices in the network. It is used to evaluate the amount of traffic generated in the period of time T by all the devices in the network. T is the packet generation rate. It is set to [200, 100, 50, 30, 20] ms. $N_{RX}$ is the average number of successfully received packets in the period T. $L_P$ and $L_H$ are the payload and the header size and are equal to 200 and 23 Bytes respectively.

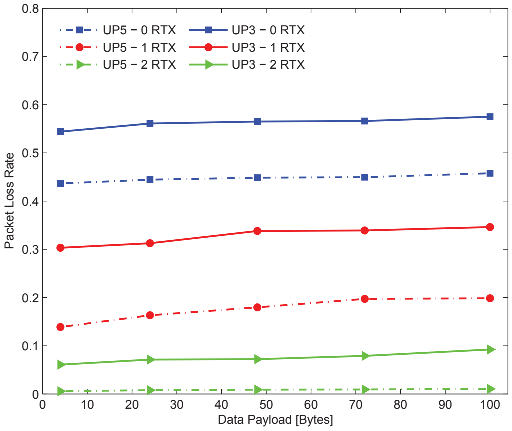

**Figure 6: PLR for a three nodes-network with the same UP and different number of retransmissions.**

Fig. 7 shows the throughput S as function of the offered load G. Increasing the offered load makes the throughput deviate significantly from the ideal case (dashed line), where the network throughput is equal to the offered load. The inability of the network to deliver a certain amount of traffic and is caused by several aspects: i) The header (only 200 out of 223 transmitted Bytes represent useful information). ii) Collisions: time is wasted in transmitting a packet that will not be properly received. Moreover, they make the node retransmit the packet. iii) Hardware limitations (e.g. limited packet queue size, variable processing and turn-around time).

As expected the curves present a maximum: for low values of the offered load, the network throughput increases by increasing the offered load. When the offered load becomes too large (this is obtained by decreasing $T$), more collisions occur and the network throughput starts decreasing. Note that the maximum is reached for larger values of the offered load when no retransmissions are considered. The latter is due to the fact that, since retransmissions prolong the time a packet resides in the queue, for a high offered load the packet queue fills up faster and new packets are prevented to be put in the queue.

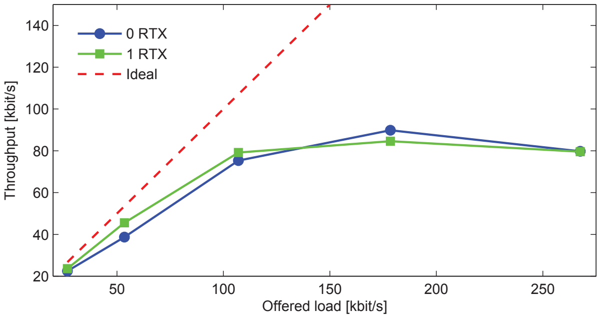

**Figure 7: Network throughput vs offered load.**

## 5. CONCLUSION

This paper presents the results of an experimental campaign performed to evaluate the performance of a IEEE 802.15.6-based CSMA/CA MAC protocol. The protocol has been implemented on a low power platform designed for WBAN applications. The impact of different MAC parameters such as the UP values, number of retransmissions and network size, on the considered performance metrics is experimentally characterised. This work corroborates the analytical and simulation results presented in the literature. Furthermore it unveils the effects of a real WBAN deployment, including real hardware and real environment etc., on the performance of the whole WBAN.

The results of this work can be used as a set of reliable guidelines by the WBAN designer.

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