

# Performance Evaluation of IEEE 802.15.6 MAC in monitoring of a cardiac patient

Tariq Benmansour<sup>1,2</sup>, Toufik Ahmed<sup>2</sup>, and Samira Moussaoui<sup>1</sup>

<sup>1</sup>Computer Science Department, University of Science and Technology (USTHB)

P.O. Box 32 USTHB, El-Alia, Bab Ezzouar, Algiers, Algeria

[tbenmansour@usthb.dz](mailto:tbenmansour@usthb.dz), [s\\_moussaoui@usthb.dz](mailto:s_moussaoui@usthb.dz)

<sup>2</sup>CNRS-LaBRI, University of Bordeaux

P.O. Box 99, Talence Cedex, 33400, France

[tad@labri.fr](mailto:tad@labri.fr), [tbenmans@labri.fr](mailto:tbenmans@labri.fr)

**Abstract**— Recent advances in wireless communication and electronic manufacture have allowed the creation of a variety of bio-sensors to be used for Wireless Body Area Networks (WBANs). These devices operate in close vicinity to, on or inside a human body. WBANs have gained much interest and became emerging technology in health monitoring due to its wide range of use in improving the human health. Many earlier wireless technologies were used for the transport of medical data both to and from medical devices but these standards were not appropriate for wireless communication around the human body. The first international WBANs standard was established by the Task Group 6 and called IEEE 802.15.6. The standard defines a Medium Access Control (MAC) layer that supports several Physical layers. To estimate, compare and contrast performances of different wireless technologies, many medical use-cases representing a board of typical healthcare scenarios were defined in the standard ISO/IEEE 11073 for Point-of-Care (PoC) medical devices. In this paper, we study the performances of the IEEE 802.15.6 CSMA/CA using user priority (UP) scheme in the monitoring of an individual cardiac patient while satisfying the ISO/IEEE 11073 constraints. A comparative performance analysis between the IEEE 802.15.6 based communication system using UP and the IEEE 802.15.4 based communication system has been carried. Over Castalia simulator based on OMNeT++, the results show that the IEEE 802.15.6 outperform the IEEE 802.15.4 in terms of latency, energy consumption and packets delivery rate. Expanded simulations of the IEEE 802.15.6 standard show that: the EAP and RAP phases' length and UPs values are important factors to improve WBANs performances.

**Keywords**—WBAN, IEEE 802.15.6, ISO/IEEE 11073

## I. INTRODUCTION

WBANs are a sub-class of Wireless Sensor Networks (WSNs) characterized by a limited energy resources, a reduced number of nodes with no redundancy, an extremely low transmission range (to minimize interference and health effects) and a heterogeneous nature of nodes. A typical WBAN consists of tiny sensor nodes that monitor human physiological signs such as heart rate, body temperature, glucose level, etc, and forward that information to a central device called the Body Network Coordinator (BNC) [1].

Initially, many earlier standards such as IEEE 802.11[2], IEEE 802.15.1[3] and IEEE 802.15.4 [4] were used to ensure communications in WBANs, but these standards are not suitable for WBAN applications. The power consumption of 802.11 is too high to satisfy WBANs requirements with a low power. IEEE 802.15.4 is the most used in WBANs, but it doesn't support high data rate applications (data rate > 250 Kbps). The IEEE 802.15.6 TG6 group was formed to standardize the Media Access Control (MAC) layer for WBAN, which works in short-range wireless communications within the vicinity of, or inside, a human body. This standard supports quality of service (QoS) and allows devices to operate on very low transmission power ensuring safety by minimizing the Specific Absorption Rate (SAR) into the body and increasing the battery life [5].

Compared to the IEEE 802.15.4, several improvements have been made by IEEE 802.15.6 to provide high quality of service and extreme high power efficiency. The IEEE 802.15.6 designs three different Physical Layers (PHYs) to adapt the broad range of possible applications and constructs a more flexible frame structure that supports multiple access modes. However, the main difference is that assigning different user priorities based on the traffic type, which guarantees the high priority data, for example; emergency data transmitted timely and reliably [6].

Using WBANs in healthcare has been widely studied over the last years. Most of the existing researches using the IEEE 802.15.6 standard in these networks paid attention to the MAC layer: [7], [8], [9], [10], [11], [12] and [13]. However, there are only few studies that assess the effect of user priorities (UPs) on the performance of this standard. In [14] authors studied the effect of a user UP scheme defined for different types of data for MAC layer using Slotted ALOHA channel access. A comparative performance analysis between the system using a UP scheme and a traditional random backoff scheme was presented. It was shown that the performance of the IEEE 802.15.6 UP scheme is approximately the same as the random backoff scheme in scenarios containing only high-priority medical data. However, in scenarios having both high-priority

medical and low-priority non-medical (e.g. background) data transmissions the UP scheme offers better performance in terms of throughput and packet delivery ratio for medical applications. Authors in [15] and [16] focused on the analysis of the IEEE 802.15.6 MAC layer under saturation and non-saturation conditions. It was shown that under saturation condition, nodes having the highest UP obtain unfair channel access, while nodes having lower UP will be bereft of access, in addition to a bad overall medium use. Under non-saturation condition, the mean response time of data frames with varying lengths of access phases was evaluated. According to the study, the network performance can be considerably improved, when lengths of the access phases are set according to the traffic load. In addition, results showed that the mean response time decreases when increasing UPs. Authors in [9] and [17] proposed an analytical model for a non-saturated IEEE 802.15.6 WBAN operating under an error-prone channel. They varied the access phase lengths based on traffic loads for different UPs. It was found that the deployment of Exclusive Access Phase (EAP) is not necessary in a typical WBAN. They have also found that four UPs (out of the eight available) typically suffice to achieve even the most stringent requirements for WBAN performance. In [18], authors evaluated the effect of UPs on the performance of IEEE 802.15.6 CSMA/CA channel access mechanism a narrow band. The real medical scenarios lead authors to use a periodic model for traffic arrival to cover the limits of the Bernoulli model used in [17]. Results showed that the UP mechanism has a big influence on the network's performance; it guarantees reliable and timely service for higher UPs by sacrificing the performance of lower UPs. Compared to the access mechanism without UPs, the standard is better when there is lightweight emergency traffic in the network. In this work, we will evaluate the performance of the 802.15.6 MAC layer in a real medical scenario (home monitoring of an individual cardiac patient). This scenario (description, constraints and requirements) is defined by the ISO/IEEE 11073 standard. We will evaluate the effectiveness of the CSMA/CA access scheme with UP defined in 802.15.6 by varying both EAP lengths and UP values. Then, we will compare the performances of the WBAN standard to an earlier standard (802.15.4).

The remainder of this paper is organized as follows. In Section II, we give an overview of the IEEE 802.15.6 Mac layer focusing on the CSMA/CA access scheme. In section III, we introduce the ISO/IEEE 11073 use cases. In section IV and section V the simulation parameters, performance evaluation and the results are described and analyzed. Finally, we conclude in Section VI.

## II. OVERVIEW OF IEEE 802.15.6 MAC

The IEEE 802.15.6 standard is developed by the IEEE to accommodate the growing demand for short range, wireless communication in the vicinity of, or inside a human body (but not limited to humans) and to accelerate diversified applications of WBAN worldwide. The standard organizes networks into sets of body area networks (BANs) each of them is expected to have only one BNC (Body Network Coordinator) and multiple nodes. A BNC may operate in a beamed mode with superframe, non-beamed mode with superframe or non-beamed mode without superframe. The

first mode offers synchronization between the BNC and all BAN nodes. This makes the network more reliable and more energy efficiency; nodes go to the sleep mode and wake up periodically when they have data to send. Hence it is the most used in medical applications. As shown in Fig.1, the superframe structure with beacon mode has seven (7) access phases; two Exclusive Access Phases (EAP), two Random Access Phases (RAP), two Managed Access Phases (MAP) and one Contention Access Phase (CAP). The BNC transmits a beacon at the start of the superframe to define the size of each access phase and another optional beacon before the start of the CAP. The access phases EAP 1, EAP 2, RAP 1, RAP 2, and CAP are used for contended allocation by nodes to initiate communication using CSMA/CA or S-ALOHA access scheme. EAP is used only by highest priority data, UP 7, for emergency and medical event report. During MAP, a BNC may arrange scheduled uplink/downlink/bilink allocation interval, provide unscheduled bilink allocation intervals, and improvise type-I immediate polled allocation intervals and posted allocation intervals.

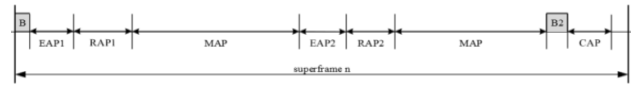


Fig.1. Superframe structure of the beacon mode with superframes.

### a. IEEE 802.15.6 CSMA/CA

In this protocol, the node sets its Backoff Counter (BC) to a random integer uniformly distributed over the interval  $[1, CW]$  where  $CW \in [CW_{min}, CW_{max}]$  is called the Contention Window, which depends on the number of failed data transmissions. The values of  $CW_{min}$  and  $CW_{max}$  are selected according to the priority classes presented in TABLE 1. These priority classes are assigned based on the type of data traffic, ranging from best-effort data traffic to the most critical emergency traffic.

TABLE 1. CW BOUNDS AND UP MAPPING FOR CSMA/CA

| Priority | User priority | Traffic designation                       | CWmin | CWmax |
|----------|---------------|-------------------------------------------|-------|-------|
| Lowest   | 0             | Background                                | 16    | 64    |
|          | 1             | Best effort                               | 16    | 32    |
|          | 2             | Excellent effort                          | 8     | 32    |
|          | 3             | Video                                     | 8     | 16    |
|          | 4             | Voice                                     | 4     | 16    |
| Highest  | 5             | Medical data or network control           | 4     | 8     |
|          | 6             | High-priority data or network control     | 2     | 8     |
|          | 7             | Emergency or medical implant event report | 1     | 4     |

Initially, the CW is set to  $CW_{min}$  for each priority class and remains the same for each successful data transmission. The node decrements the BC by one for each idle CSMA/CA slot. Once the BC reaches zero, the data is transmitted. The node locks the BC because of the following reasons:

- The channel is busy because of a frame transmission of another node,
- The current time is outside of EAP, RAP, or CAP phases,

- The current time left in the EAP, RAP, or CAP is not enough to complete the data transmission.

The node unlocks the BC when the channel is sensed idle for Short InterFrame Space (pSIFS) duration or when the current time left in the EAP, RAP, or CAP is enough to complete the data transmission. If the contention fails, the node doubles the CW for even number of failures, and keeps it unchanged for odd number of failures. If doubling the CW exceeds the  $CW_{max}$ , the node sets the CW to  $CW_{max}$ .

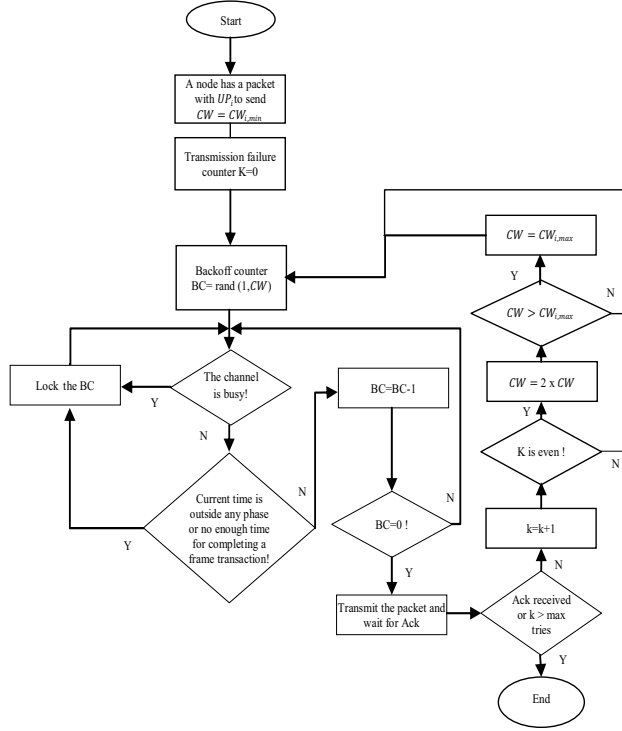


Fig.2. Data transmission flow chart for CSMA/CA in IEEE 802.15.6.

### III. ISO/IEEE 11073 APPLICATIONS

The ISO/IEEE 11073 Draft for Point-of-Care (PoC) medical devices [19] addresses the use of radio frequency wireless technology for the transport of medical data both to and from point-of-care (PoC) medical devices. This standard defines many medical use cases representing a board of typical healthcare scenarios ranging in degree of criticality and potential wireless complexity. This specifies use cases defined to estimate, compare and contrast performances of wireless technologies in terms of throughput, latency, data rate and many other parameters. For our evaluation of the standard 802.11.6, we will utilize the use case of home monitoring of an individual cardiac patient (UC1a) as a simulation scenario. This use case is defined as follows:

Un individual patient has been sent home following recovery from cardiac surgery and is ambulatory but remains within the confines of his/her home, with perimeter dimensions 17m x 9m, physiologic parameters monitored from a wireless

patient worn device (PWD) include continued 3-lead ECG (three electrodes as described in Fig.3) as well as scheduled episodic blood pressure BP and heart rate HR, SpO2 values are sent episodically from a fingertip monitor to the PWD. There is a priority real-time alarm that is transmitted one way from the PWD if an arrhythmia is detected and is directly sent to the nurse at the central surveillance station at the local hospital. TABLE 2 presents the data transport requirement for the selected scenario[20].

TABLE 2. DATA TRANSPORT REQUIREMENTS FOR HOME CARDIAC PATIENT

| Device            | Data Category   | transmission interval (ms) | Throughput (Kb/s)   | Max end-to-end latency (ms) | Min range (m) |
|-------------------|-----------------|----------------------------|---------------------|-----------------------------|---------------|
| PWD               | Uplink          | Periodic                   | 2                   | 10 000 (to the hospital)    | 17            |
| Fingertip monitor | SpO2            | 2000                       | 0.1 per sample      | < 200 (to PWD)              | 1             |
| Three Electrodes  | 1 ECG vector HR | 40                         | 1.250+0.1 for alarm | < 100 (to PWD)              | 1             |
| BP monitor        | BP              | 2000                       | 0.1 per sample      | < 100 (to PWD)              | 1             |

### IV. SIMULATION PARAMETERS

In this paper we will evaluate and compare two wireless IEEE standards; 802.15.6 and 802.15.4 over a realistic requirements and constraints of home monitoring of an individual cardiac patient. The goal of this evaluation is to show which of these two standards more fill the requirements of this type of applications. We will concentrate our studies on the EAP and RAP phases which use the CSMA/CA access schemes with priority, because it is most important contribution of the IEEE 802.15.6.

To perform simulations, we chose the Castalia open source simulator [21] designed for networks of low-power embedded devices, that offers a node behavior simulation in realistic wireless channels and radio models. All simulations described in this paper are realized with Castalia 3.2.

As described in Fig.3 the WBAN considered in our simulations incorporates five (5) sensor nodes and one BNC. To ensure the 3-lead ECG supervision, three (3) electrodes are deployed on the rib cage of the patient. The two others sensors are placed on the left and right arms to measure the SpO2 and blood pressure respectively. All these sensors communicate wirelessly with the BNC. Due the emergency aspect of the ECG electrodes data, we will assign for them the highest UP level (7) and for the others sensors we attribute a UP=6.

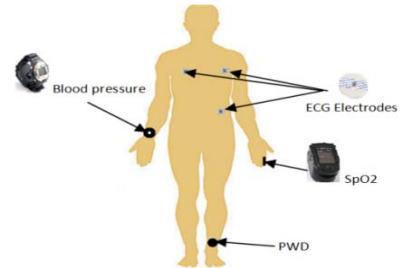


Fig.3. Simulated Network Topology

We will start our evaluation by comparing performances of the two standards; IEEE 802.15.6 and IEEE 802.15.4. Then,

we will evaluate the IEEE 802.15.6 performances by varying many parameters. First, We will vary the UP of one electrode from one (1) to seven (7) in order to show the effects of UP value on the CSMA/CA scheme used by the standard, then length of EAP and RAP phases will be varied to show its impact on the overall performances of the standard and the effectiveness of the use of EAP access phase in this type of applications.

In our evaluation, we used two different radios in order to meet the characteristics of each standard. The first radio meets with the IEEE 802.15.6 radio proposal [5] and the second one is the 2.4 GHz IEEE 802.15.4 RF Transceiver (CC2420) [22] which is used to evaluate the IEEE 802.15.4 standard. In all simulations, it is supposed that if the radio unit is not transmitting, it is either receiving or listening. TABLE 3 gives the various radio parameters defined for the two types of radios.

TABLE 3. SIMULATION RADIOS PARAMETERS

| Parameters                                                  | IEEE802.15.6 | IEEE 802.15.4 (CC2420) |
|-------------------------------------------------------------|--------------|------------------------|
| Data rate (kbps)                                            | 1024         | 250                    |
| Modulation Type                                             | DIFFQPSK     | PSK                    |
| Bits Per Symbol                                             | 2            | 4                      |
| Bandwidth (MHz)                                             | 20           | 20                     |
| Noise Bandwidth (MHz)                                       | 1000         | 194                    |
| Noise Floor (dBm)                                           | -104         | -100                   |
| Sensitivity (dBm)                                           | -87          | -95                    |
| Power Consumed on reception mode (mW)                       | 3.1          | 62                     |
| transmission power (dBm)                                    | -15          | -15                    |
| Power Consumed on transmission mode (mW)                    | 2.93         | 32.67                  |
| Power consumed on transition (transmission, reception) (mW) | 3            | 62                     |
| Time of transition (transmission, reception)                | 0.02         | 001                    |

In addition, we took some default parameters proposed by the Castalia simulator (slot length, Mac buffer size...etc). The remaining parameters used in our simulations are listed in TABLE 4.

TABLE 4. SIMULATION PARAMETERS

| Parameters                     | 802.15.6                               | 802.15.4        |
|--------------------------------|----------------------------------------|-----------------|
| Access scheme                  | CSMA/CA (with priority)                | Slotted CSMA/CA |
| Simulation time (second)       | 51 (200 repetition )                   |                 |
| Slot allocation length (ms)    | 10                                     | 15.36           |
| MAC Buffer                     | 32                                     | 32              |
| Retransmission packets tries   | 2                                      | 2               |
| Phy Layer overhead (Bytes)     | 6                                      | 6               |
| Mac frame overhead (Bytes)     | 7                                      | 14              |
| Packet header overhead (Bytes) | 05                                     | 05              |
| Data payload (Bytes)           | 100                                    | 100             |
| Packet rate (packet/s)         | Nodes (1, 5) = 0.5, Nodes (2,3,4) = 25 |                 |
| Priority                       | Nodes (1, 5) = 5, Nodes (2,3,4) = 7    |                 |
| Number of Slots allocation     | 32 (RAP length= 32- EAP length)        |                 |

## V. PERFORMANCE EVALUATION

The performance metrics considered in our work are: packet delivery rate, consumed energy and average packet latency. The packet delivery rate per node is defined as the number of successfully received packets from a node divided by the number of transmitted packets, while the average packet latency refers to the interval between the packet arrival at the local MAC layer and the successful data reception by the BNC.

### a- Energy consumption

The consumed energy histogram presented in Fig.4 shows the average consumed energy per node for the two standards where the EAP phase length is fixed to 16 slots for the IEEE 802.15.6 standard.

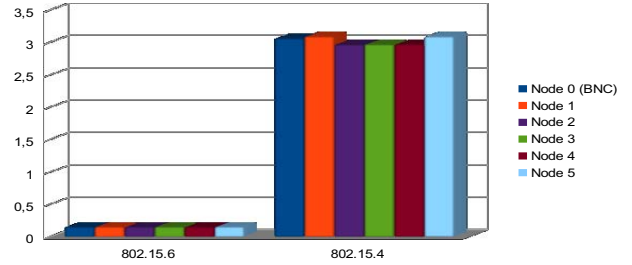


Fig.4 Consumed energy per node in joules

As shown in fig.4, we notice that the consumed energy in the IEEE 802.15.6 is less than in IEEE 802.15.4. This is mainly due to the type of radio unit used by each standard. As shown in TABLE 3 the power consumed in reception and transmission mode for the IEEE 802.15.4 radio unit is greater than the IEEE 802.15.6 radio unit. The second point to notice is that the amount of the energy consumed by ECG electrodes (2, 3 and 4) is lower than the amount consumed by SpO2 and BP nodes. This is due to the packet sending rate, where the ECG nodes send 25 packets per second while the others nodes send just one packet per two second and as known the time taken for transmitting reduces the reception / listening time which consumes more energy as shown in TABLE 3.

### b- Latency:

The Fig.5 shows the average latency of the packets received by the BNC (node 0). We notice that most of the packets are received with latency less than 25 ms in the IEEE 802.15.6 standard where in IEEE 802.15.4 most packets are received with latency superior to 200 ms. These results are explained by the access scheme used by the two standards; The ECG electrodes have the greatest packet sending rate according to the ISO/IEEE 11073 guide. Thus, by using the CSMA/CA with priority, these nodes will have the highest UP value, resulting in a small contention window. This allows ECG nodes to send their data with a minimum waiting delay. However in the slotted CSMA/CA used by the IEEE 802.15.4 standard, all nodes have the same probability to medium access, this will increase the collision probability and results a great delay. On other side, the high data rate offered by the IEEE 802.15.6 justifies more these results.

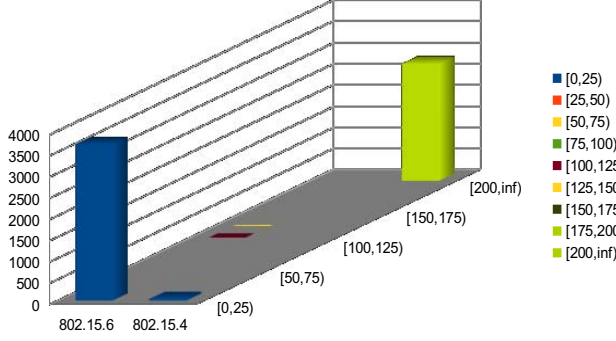


Fig.5. latency intervals (ms) of IEEE 802.15.6 and IEEE 802.15.4 standards

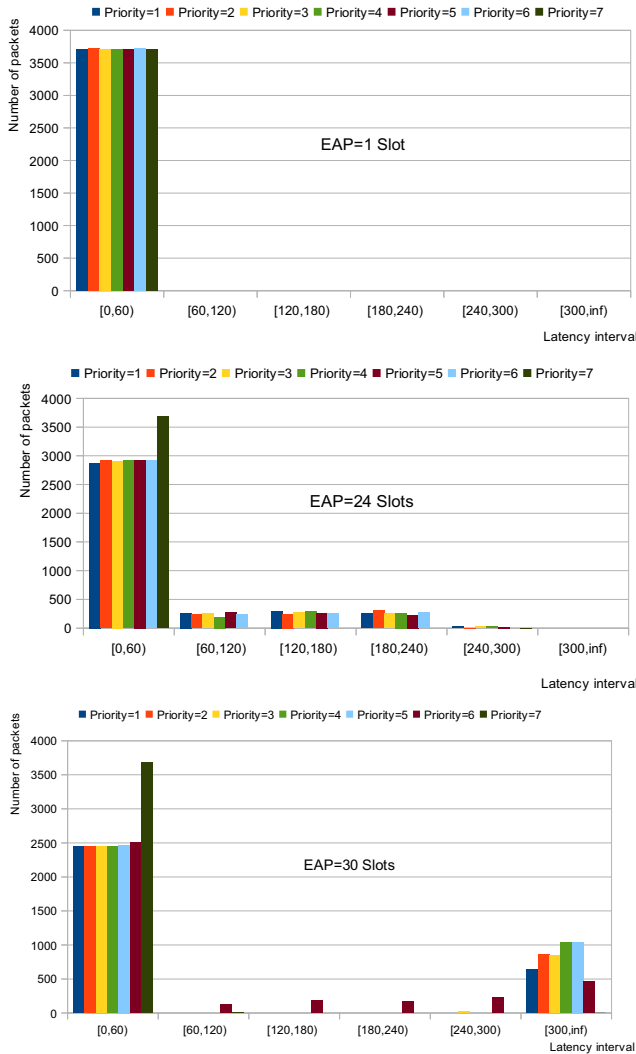


Fig.6 Latency intervals (ms) of IEEE 802.15.6 with EAP=1, 24 and 30 slots

In the second step, we evaluated the influence of Ups values on the latency while varying the EAP phase length. For this aim we varied the UP values of an ECG electrode (node 3) from one (1) to seven (7). Fig.6 shows the latency of the received packets with an EAP length equal to one (1), twenty four (24) and thirty (30) slots respectively. From fig.6, we can notice that with an EAP length equal to 1, all packets are received with a latency inferior to 60 ms. However, with an EAP length equal to 24 and 30, only packets with the highest UP (7) will be received with a latency inferior to 60 ms. While the packets with UPs different from 7 will have a higher latency. This is due essentially to the role of each access phase. The EAP is reserved only for emergency packets with high priority while the RAP is used for emergency and non emergency transfer. Accordingly, all non-emergency packets created during the EAP phase will be buffered until the start of the RAP phase. This buffering delay will increase the latency of these packets.

Latency evaluation results show that unlike the IEEE 802.15.4, the IEEE 802.15.6 satisfies the latency requirement of the ISO/IEEE 11073 standard where the maximum end-to-end latency is fixed to 100 ms from the ECG electrodes and the BP monitor to the PWD and 200 ms from the SpO2 Fingertip monitor to the PWD. The obtained results were influenced by our choice of the ECG electrodes UPs. As shown in Fig.6, if we haven't selected the highest UP for the ECG electrodes and the adequate EAP length, the IEEE 802.15.6 standard will not satisfy these requirements.

#### c- Packet delivery rate

The packet delivery rate (PDR) histogram presented in Fig.7 shows the average packet delivery rate per node for the two standards. We notice that the rate of successfully received packets by the BNC in the IEEE 802.15.6 is clearly higher than the IEEE 802.15.4 standard.

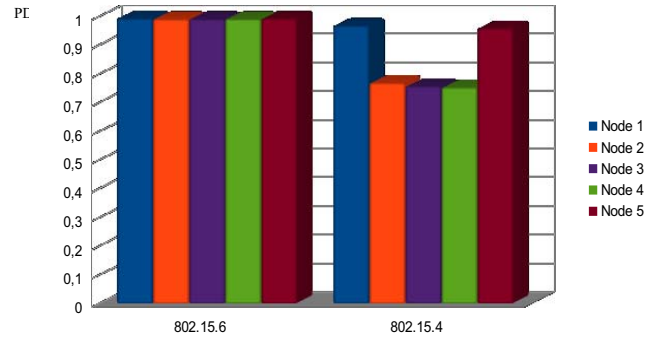


Fig.7 packet delivery rate of 802.15.6 and 802.15.4

To explain this difference, we will give details of packets failure and their causes in Fig.8 and Fig.9 corresponding to the IEEE 802.15.4 and IEEE 802.15.6 respectively. We recorded the packet breakdown at the MAC layer of the senders. Then we have classified them into five categories: a) Failed, buffer overflow (i.e., the packet was deleted because the MAC buffer was full). b) Failed, no Ack (i.e. at least one packet was transmitted to the radio without receiving the Ack), c) Failed,

channel busy (i.e., packet failed because the CSMA mechanism never found the channel free, in all transmission attempts), d) Success, first try (i.e., an Ack was received on the first transmission attempt), e) Success, 2 or more tries (i.e., an Ack was received after more than one transmission attempt).

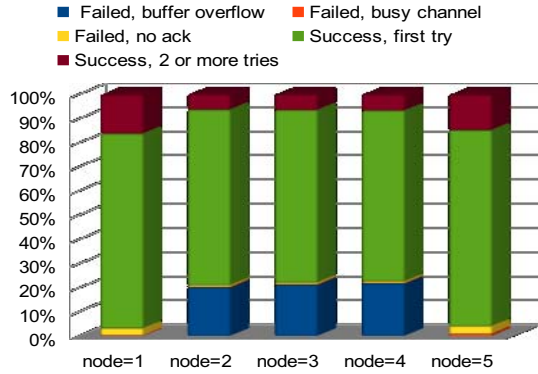


Fig.8 Data packets breakdown at the MAC layer for 802.15.4

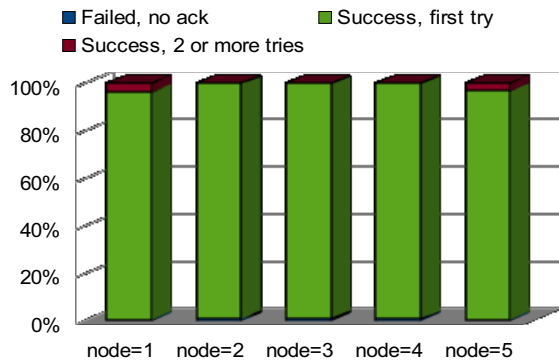


Fig.9 Data packets breakdown at the MAC layer for 802.15.6

Fig.8 and Fig.9 show the data packets breakdown per node for each standard. The results are shown in percentage. The important characteristic we notice is related to the increase of packets failure caused by the buffer overflow for the nodes 2, 3 and 4 where it is null for the other nodes. This is explained by the inability of the used radio transceiver and the Mac access scheme (CSMA/CA without priority) to satisfy the high sending data rate of the ECG electrodes (node 2, node 3 and node 4). As we know that the CC2420 radio used by the IEEE 802.15.4 can't send up to 250 kb/s unlike to the radio used by IEEE 802.15.6 which can reach the 1 Gb/s. All nodes attempt to get the access to the medium to send their packets and put all new arrival packets in the buffer waiting for their turn to be sent. When the buffer reaches its maximum size, the arrival packets will be deleted. However the same nodes do not suffer for this problem in the IEEE 802.15.6 as shown in Fig.9. This is due to the priority scheme used in the Mac layer and radio characteristics as explained above.

To evaluate the effect of UPs on packets breakdown at the MAC layer for IEEE 802.15.6, we varied the UP value of the node three (3) from one (1) to seven (7) and showed its effect on the results. The Fig.10 shows that the UP value plays an important role in the amount of packets failure. Using the highest UP increases the reception probability of the packets on the first sending attempt. However, decreasing the value of this priority of packets will increase the waiting time for their send; therefore the number of failed packets will be increased due to the buffer overflows.

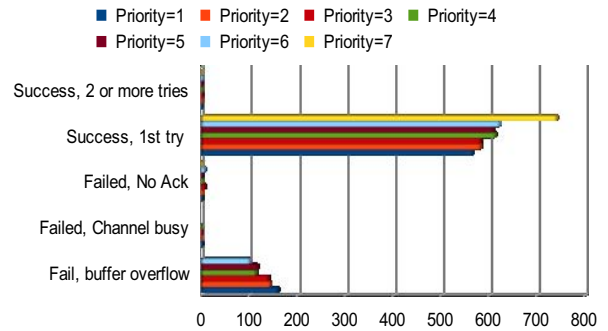


Fig.10 Data packets breakdown at the MAC layer for IEEE 802.15.6 where varying UPs

## VI. CONCLUSION

WBANs can provide real-time and reliable health monitoring. In this paper, we have evaluated the performances of the IEEE 802.15.6 in terms of energy consumption, latency, packets delivery rate and packets breakdown at the MAC layer while satisfying the ISO/IEEE 11073 requirements. In addition to the energy efficiency, we have shown the effectiveness of the IEEE 802.15.6 in home monitoring of an individual cardiac patient. Unlike the IEEE 802.15.4 standard, this standard satisfies all the requirements of the ISO/IEEE 11073 guide. We also demonstrated that the use of UPs mechanism for the IEEE 802.15.6 CSMA/CA has a big influence on the network's performance; it guarantees timely service for higher UPs while decreasing the performance of lower UPs nodes. From the obtained results, we can conclude that the use of the EAP phase with great length degrades the network performance especially with the presence of low priority nodes. As future works, we intend to implement more complicated ISO/IEEE 11073 use cases to evaluate the behavior of the standard, the coexistence of WBANs and the interferences issues, and how we can mitigate their impacts.

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