



**HAL**  
open science

## Performance analyses of the IEEE 802.15.6 wireless body area network with heterogeneous traffic

Tariq Benmansour, Toufik Ahmed, Samira Moussaoui, Zouina Doukha

### ► To cite this version:

Tariq Benmansour, Toufik Ahmed, Samira Moussaoui, Zouina Doukha. Performance analyses of the IEEE 802.15.6 wireless body area network with heterogeneous traffic. *Journal of Network and Computer Applications (JNCA)*, 2020, pp.102651. 10.1016/j.jnca.2020.102651 . hal-02546913

**HAL Id: hal-02546913**

**<https://hal.science/hal-02546913>**

Submitted on 22 Aug 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License



Contents lists available at ScienceDirect

Journal of Network and Computer Applications

journal homepage: [www.elsevier.com/locate/jnca](http://www.elsevier.com/locate/jnca)

# Performance Analyses of the IEEE 802.15.6 Wireless Body Area Network with Heterogeneous Traffic

Tariq Benmansour<sup>a,b,\*</sup>, Toufik Ahmed<sup>b</sup>, Samira Moussaoui<sup>a</sup>, Zouina Doukha<sup>a</sup>

<sup>a</sup>Computer Science Department, University of Science and Technology (USTHB) P.O. Box 32 USTHB, El-Alia, Bab Ezzouar, Algiers, Algeria

<sup>b</sup>CNRS-LaBRI, University of Bordeaux / Bordeaux INP P.O. Box 99, Talence Cedex, 33400, France

## ARTICLE INFO

### Keywords:

WBAN

IEEE 802.15.6

CSMA/CA

Quality of Service

Priority Queuing

Renewal Reward Process.

## ABSTRACT

Recent advance in wireless communication and electronics industry has allowed the development of a wide range of biosensors to be used for Wireless Body Area Networks (WBANs) and Internet of Medical Things (IoMTs) which are emerging technologies for health monitoring. IEEE 802.15.6 is the first international WBANs' standard, developed by the IEEE Task Group-6 to fulfill WBANs requirements for wireless communication around the human body, by supporting short range communications, high quality of service and extremely low power consumption. In many WBANs applications, sensor nodes must manage various types of traffic due to the fact that the monitored vital signs have different requirements in terms of reliability and latency. Many analytical models were proposed in the literature to study and assess the standard performances. However, taking into consideration heterogeneous traffic in the proposed models is overlooked in most, if not all, of existing work. For this aim, we propose in this paper, a general analytical model for performance evaluation of the IEEE 802.15.6 based WBANs with heterogeneous traffic in terms of priority. The proposed model is composed of two complementary sub-models. The first is a renewal reward based analytical sub-model that efficiently describes the IEEE 802.15.6 CSMA/CA Backoff process. The second sub-model is an M/G/1 queuing model with non-preemptive priority. To the best of our knowledge, this is the first analytical analysis of the IEEE 802.15.6 standard with heterogeneous traffic in terms of priority. Using Matlab and Maple, we conducted an analysis of the proposed analytical model under ideal channel conditions and saturated network traffic regime. Besides, to validate the proposed model, we performed simulations of the IEEE 802.15.6 standard using Castalia Simulator based on OMNeT++. Results showed the accuracy of the proposed model for managing WBANs with heterogeneous traffic.

© 2019xxxxxxx. Hosting by ElsevierB.V. All rights reserved.

## 1. Introduction

WBANs are a sub-class of Wireless Sensor Networks (WSNs), construing of a reduced number of heterogeneous nodes, characterized by limited energy resource, no redundancy and extremely low transmission range to minimize negative effects of interferences on the human body. A typical WBAN incorporates various sensor nodes, deployed on or inside the human body to monitor the surrounding body environment as well as human physiological signs such as body temperature, heart rate, and glucose level, etc. WBAN nodes forward the sensed data to a central

device called the Body Network Coordinator (BNC) (Latre et al., 2011), which, in turn, sends this data to external medical servers for further analysis.

Actually, many wireless standards such as IEEE 802.11(IEEE, 1997), IEEE 802.15.1(IEEE, 2002) and IEEE 802.15.4 (IEEE, 2006) are used for ensuring WBANs' communications. However, these standards are designed for environments having different characteristics (Ad-Hoc, WSN, and WPAN) compared to WBANs. Therefore, they cannot meet all WBANs' constraints; The power consumption of the IEEE 802.11 and IEEE 802.15.1, which can reach up to 800 mW and 100 mW respectively, is too high to respond to WBANs' low power nodes (Alam and Hamida,

\* Corresponding author. Computer Science Department, University of Science and Technology (USTHB) P.O. Box 32 USTHB, El-Alia, Bab Ezzouar, Algiers, Algeria.

E-mail address: [tbenmansour@usthb.dz](mailto:tbenmansour@usthb.dz)

2014). The IEEE 802.15.4 standard is the most used in WBANs. However, this standard cannot support high data rate applications either ensure data transmission of more than 250 Kbps (Alam and Hamida, 2014) (Li and Zhuang, 2012). Therefore, the IEEE Task Group 6 has been formed to standardize the MAC layer of WBANs operating in short-range wireless communications within the vicinity of, or inside, a human body (IEEE Standards Association, 2012). The group provided the IEEE 802.15.6 standard, which supports QoS and allows devices to operate on very low transmission power ensuring human safety by minimizing the Specific Absorption Rate (SAR) into the body and increasing the battery lifetime (IEEE Standards Association, 2012). The IEEE 802.15.6 standard offers up to 10 Mbps data rate and it includes three different Physical Layers: Human Body Communications (HBC), Narrowband (NB) PHY and Ultra-wideband (UWB) PHY in order to cover the broad range of monitoring applications. In addition, the standard presents a more flexible frame structure at the MAC layer that supports multiple channel access modes (Huang et al., 2015). According to several studies such as (Benmansour et al., 2016), (Bradai et al., 2014) and (Nabila and Mohamed, 2019), the IEEE 802.15.6 standard is the more suitable for WBAN communications than other standards, especially for latency and reliability sensitive applications.

In many WBANs applications, sensor nodes generate different types of traffic with different QoS requirements in terms of latency and reliability according to their nature and their impact on human health. For example, the electrocardiogram (ECG) traffic, which is critical emergency traffic, requires high reliability and low transmission delay, while normal traffic concerning regular vital signs such as body temperature and blood pressure are usually delay-tolerant. Nevertheless, normal traffic may be in some medical situations considered as emergency traffic and delay sensitive if it exceeds critical thresholds. To differentiate the traffic, the IEEE 802.15.6 standard offers QoS differentiation by dedicating Exclusive Access Phases for emergency traffic and by using a priority-aware CSMA/CA Backoff process, in which nodes adjust the contention window bounds according to the traffic priority, which allows quick delivery of the emergency traffic.

Recently, there is a considerable focus on performances evaluation of the IEEE 802.15.6 based WBANs, as well as WBANs deployment, their security, energy efficiency, and many other related research axes. Various research studies such as (Rashwand et al., 2016), (Sarkar et al., 2015), (Chowdhury et al., 2014b), (Khan et al., 2017b), (Mukherjee et al., 2014), (Jacob et al., n.d.), (Quan et al., 2017) and (Ullah et al., 2018), based mainly on the Bianchi's work (Bianchi, 1998) (Bianchi, 2000), have attempted to provide generalized analytical models for performance evaluations of the IEEE 802.15.6 standard. To model the Backoff process behavior of the CSMA/CA access scheme, the aforementioned studies have used mainly Discrete-Time Markov Chain (DTMC) and the renewal reward process. Most of these analytical models handle heterogeneous traffic in a global manner while assuming that each WBAN's node can generate and process only one user priority type of packets. This assumption does not meet the IEEE 802.15.6 standard features that allow generating heterogeneous traffic with different user priorities (Medical traffic, Network control traffic, sensor nodes event reports...) by the same node. Therefore, these analytical models are not suitable to study all possible WBANs applications supported by the IEEE 802.15.6 standard,

in particular, WBANs with heterogeneous traffic. For that, in this paper, we aim to address WBANs performance analysis with heterogeneous traffic in terms of priority. Our main contributions are as follows:

- We develop an analytical model that efficiently describes the IEEE 802.15.6 CSMA/CA-based WBANs. Based on the renewal reward process, we model the different steps of the Backoff process of a sensor node executing the IEEE 802.15.6 CSMA/CA access scheme, and we calculate the channel access probabilities.
- In addition to supporting heterogeneous traffic in terms of priority, the proposed model allows calculating performance metrics of the overall WBAN or of each WBAN's node separately, which was not handled in previous works.
- We propose an M/G/1 queuing model with non-preemptive priority, in order to improve the IEEE 802.15.6 standard with QoS differentiation. Indeed, having heterogeneous traffic in terms of priority at MAC layer leads to the necessity to model the way the traffic is buffered and scheduled.
- We calculate the performance metrics of the proposed analytical model by using Maple and Matlab. Extensive simulations using Castalia Simulator are conducted to validate the proposed model.

The remainder of this paper is organized as follows. In section II, we present the related work. In Section III, we give an overview of the IEEE 802.15.6 MAC layer focusing on the related CSMA/CA access scheme. In section IV, we present the analytical model. In section V, performance evaluation and results are described and analyzed. We conclude the paper and present future scope in Section VI.

## 2. Related work

Several simulation studies have been conducted in the literature to analyze the IEEE 802.15.6 performances. In addition, efforts have been made in analytical modeling, which allowed better analysis of the overall characteristics of the standard without being limited to predefined scenarios like in simulation studies. As was the case for the earliest IEEE standards modeling, the proposed analytical models for the IEEE 802.15.6 analyses were based mainly on Markov chains approaches and renewal reward processes and most of them have focused on random access protocols, such as the CSMA/CA and slotted ALOHA protocols. In order to cover the whole related work to better situate our contribution, we divide our state of the art into two parts.

In the first one, we classify the analytical models to provide the IEEE 802.15.6 CSMA/CA performances according to the theoretical basis, using Markov chain or renewal reward processes. In the second part, we present studies aimed to perform QoS differentiation in WBANs by involving queuing models.

### 2.1.1. Markov Chain Based Analysis

Markovian based analyses were widely used for performance evaluation of earlier IEEE standards, such as the IEEE 802.11 and the IEEE

802.15.4. These analyses were inspired by Bianchi's proposed model, which used the DTMC to analyze the throughput of the IEEE 802.11 Distributed Coordination Function (DCF) (Bianchi, 1998), (Bianchi, 2000). S. Rashwand and al presented the first analytical models for performance analysis of the IEEE 802.15.6 CSMA/CA access scheme under different traffic regimes and channel states. They developed 4-dimensional DTMC combined with Probability Generating Functions (PGFs) for calculating the WBAN's metrics such as the mean Backoff duration and the normalized throughput for all user priority nodes; (Rashwand et al., 2011a) and (Rashwand et al., 2011b) limited their studies to the EAP1 and the RAP1 access phases without presenting any queuing analysis of the node buffer. In (Rashwand and Mišić, 2012), the authors extended their work to take into account EAP1, RAP1, EAP2, RAP2, and type-I/II access phases while in (Rashwand et al., 2016), the authors included to the proposed model a Geo/G/1 queuing sub-model of the node buffer. They showed that the channel was always utilized by high-priority sensor nodes due to their small Backoff durations and concluded that smaller and larger access periods affects the medium utilization. (Sarkar et al., 2015) constructed a DTMC that efficiently depicts the states of an IEEE 802.15.6 CSMA/CA. Unlike the previous proposed analytical models, the time spent by a node while waiting for an acknowledgment (Ack) frame after sending a packet is taken into consideration in this model. In (Mukherjee et al., 2014), a generalized analytical model for performance evaluation of the IEEE 802.15.6 CSMA/CA is proposed using a 3-dimensional DTMC with Backoff stage, Backoff counter and retransmission counter as stochastic parameters. The authors modelled the Backoff locking mechanism, which occurs due to insufficient remaining time in the Random Access Phase (RAP), by incorporating a dynamic time-variant variable into the proposed analytical model. To make simulation results similar to the practical performances, the authors considered a non-ideal channel by introducing Bit Error Rate (BER), multipath effect, shadowing standard deviation and an error probability in the evaluation of the reliability, throughput, and energy consumption. Unlike the previous models that analyzed the CSMA/CA access scheme, the authors of (Chowdhury et al., 2014b) and (Chowdhury et al., 2014a) presented an analytical model to estimate the saturation throughput of the IEEE 802.15.6 prioritized Slotted Aloha access scheme under saturation regime and an ideal channel condition. The Markov chain based model was also used to analyze many improvements of the IEEE 802.15.6 standard. In (Khan et al., 2017a) and (Khan et al., 2017b), a DTMC is used to model a new Backoff procedure called Prioritized Fibonacci Backoff (PFB) for the IEEE 802.15.6 CSMA/CA under non-saturated conditions to predict the normalized throughput and the mean service time of the network. In (Fourati et al., 2018), authors proposed a new access mechanism by defining a new algorithm for dynamic Backoff bounds assignment, which takes into consideration the traffic state of the network after that they investigated the performance of an enhanced IEEE 802.15.6 CSMA/CA access mechanism by using the DTMC model. In (Deepak and Babu, 2018), the authors proposed an adaptive superframe structure-based scheme for improving the reliability of emergency data. Based on DTMC, an analytical model has been developed to compute the reliability and the average delay experienced by emergency data frames. In (Jacob et al., n.d.), the authors proposed a sleep mechanism for the IEEE 802.15.6

CSMA/CA access scheme in a typical WBAN deployed in a hospital environment. In order to analyze lifetime and delay requirements, the authors developed an analytical model based on PGFs and Markovian techniques. In (Quan et al., 2017), the authors proposed a new method to calculate the BER and Packet Error Rate (PER) and then analyzed the performance of WBANs while assuming a fluctuation of received Signal to Noise Ratio (SNR) of the BNC. They showed that the DTMC method used in previous work to calculate the access probability of all sensor nodes was not effective and complicated while considering the BER/PER. For this aim, they proposed the use of Markov Chain Monte Carlo (MCMC) method to calculate the access probability.

### Renewal Reward Process based Analysis

The renewal reward process has been used for IEEE standards analyses with the same way as Markov based models. Initial work in this axis was made to provide analytical models for IEEE 802.11 based WLANs analysis, where the authors of (Yu et al., 2012) extended the analysis of Bianchi's proposed Backoff model for the IEEE 802.11 DCF to unsaturated conditions by using the renewal reward theorem. From the fixed point analysis, the authors provided explicit formulas for the collision probability, the mean attempt rate, and the mean throughput. In (Xinhua Ling et al., 2008), the authors provided an analytical model for the IEEE 802.15.4 MAC protocol. They modeled the IEEE 802.15.4 CSMA/CA behavior by three-level renewal reward process and they used fixed-point techniques for solving the proposed model in order to obtain MAC layer metrics such as the throughput and the mean access delay. The authors in (Ullah et al., 2018) presented a simple and accurate model to predict throughput, energy consumption and transmission delay for different nodes priorities with the assumption of a finite number of nodes under the saturated regime and lossy channel conditions. The accuracy of the proposed model was validated by simulations. In Table 1, we summarize the main related work to our proposed approach.

We notice from the review that all the proposed analytical models supposed that IEEE 802.15.6 based WBANs are composed of sensor nodes that generate only one user priority type of traffic. As we mentioned in the introduction, this assumption cannot allow analyzing the standard performances in all possible scenarios, especially when sensor nodes have to generate at least two types of traffic with different user priorities. To cover such applications' scenarios, heterogeneous networks in terms of traffic's priority must be taken into account in the proposed analytical models of the IEEE 802.15.6 CSMA/CA access scheme.

### 2.2. QoS Differentiation

Due to transmission's constraints and limits caused by high use of the medium, the traffic has to wait at sensor and relay nodes until its transmission. This leads to the necessity of the use of efficient scheduling and queuing strategy. Improving the QoS of IEEE 802.15.6 based WBANs, particularly, ensuring reliable and instantaneous delivery for emergency packets; requires the use of service differentiation techniques. Several works were presented in the literature to take over this research area, including studies involving queuing strategies to perform the service differentiation in the WBANs. According to the level in which the traffic

is buffered, we classify the related work into two major sub-classes namely: the queuing in intra-WBAN and the queuing beyond the WBAN.

The first class includes all literature studies that treat how packets are buffered at WBANs' sensor nodes before their transmission to the coordinator.

### 2.2.1. Queuing based models in intra-WBANs

**Table 1. Comparison of analytical models proposed for IEEE 802.15.6 based WBANs.**

	Access scheme	Assumptions	Analytical approach	Queuing	Access phases	Traffic
(Rashwand et al., 2011a)	CSMA/CA	- Saturation condition - Noisy channel	DTMC	No	EAP1, RAP1	Each node has one UP traffic
(Rashwand et al., 2011b)	CSMA/CA	- Saturation condition - Error-Prone Channel	DTMC	No	EAP1, RAP1	Each node has one UP traffic
(Rashwand and Mišić, 2012)	CSMA/CA	- Saturation regime - Error prone channel	DTMC	No	EAP1, RAP1, EAP2, RAP2, and type-I/II	Each node has one UP traffic
(Rashwand et al., 2016)	CSMA/CA	- Non-saturated - Error-Prone Channel	DTMC	Geo/G/1	EAP1, RAP1, EAP2, RAP2, and type-I/II	Each node has one UP traffic
(Sarkar et al., 2015)	CSMA/CA	- Saturated - Non-ideal channel conditions	DTMC	No	RAP	Each node has one UP traffic
(Chowdhury et al., 2014b)	Slotted Aloha	- Non-Saturated - Ideal channel condition	DTMC	No	RAP	Each node has one UP traffic
(Ullah et al., 2018)	CSMA/CA	- Saturated traffic conditions - Error-prone channel with	Renewal Reward approach	No	RAP	Each node has one UP traffic
Proposed approach	CSMA/CA	- <b>Saturation regime</b> - <b>Ideal channel condition</b>	<b>Renewal Reward approach</b>	<b>M/G/1 with non preemptive priority</b>	<b>EAP1, RAP1</b>	<b>Heterogeneous traffic in term of priority</b>

In (Salam et al., 2014), the authors proposed a class-based QoS framework in order to provide low delay and maximum throughput for critical nodes in medical applications. The proposed framework performs service differentiation by categorizing packets by a classifier into three service classes namely (Guaranteed service, Real-time service, and Best effort service). Packets are enqueued in an adequate position of priority queue according to their assigned classes. In (Kateretse et al., 2013), the authors proposed a traffic differentiation and a scheduling scheme based on data prioritization. Through queues scheduling and path choice issues, emergency packets are delivered timely to the coordinator in order to provide a guarantee QoS for WBANs. After the classification phase, packets are enqueued in three queues (M/M/1) according to their priority class. Packets are scheduled from a tagged queue only if there is no data in the higher priority queues. In (Iftikhar et al., 2014), the authors developed an analytical framework to support low power body area networks. They defined three kinds of traffic coming to sensor nodes namely: critical traffic, streaming traffic, and non-critical traffic. To support WBANs QoS, they considered three queues based on a G/M/1 model. In (Jacob et al., n.d.), the authors developed an analytical model for the IEEE 802.15.6 CSMA/CA Backoff process by using Markovian techniques and they used an M/G/1 queue with repeated inhomogeneous vacations. In (Rashwand et al., 2016), (Rashwand and Mišić, 2012) and (Li et al., 2013), the authors provided several performance evaluations of the IEEE 802.15.6 standard under various channel conditions and traffic

regimes. The authors proposed formal models for the CSMA/CA access scheme, based on the 3-dimensional DTMC, assuming that each node generates only one type of traffic, buffered in local MAC queue with infinite capacity. In (Fatehy and Kohno, 2014), the authors proposed to use queues' lengths to provide a novel contention probability dynamism for the aim of improving the IEEE 802.15.6 slotted-ALOHA scheme. They assumed that each node treats only one type of traffic, buffered in its local queue. The authors in (Muthulakshmi and Shyamala, 2016) provided a prioritized queuing mechanism for the IEEE 802.15.6 standard by defining three priority queues at the MAC layer. The goal of this prioritization is to guarantee minimum delay and more reliability. The authors showed by simulations that the latency of the emergency packets is improved. To minimize QoS degradations in multiple adjacent BANs scenarios, the authors of (Marbukh et al., 2016) assumed that each node buffers the traffic in local queues and exploited previous work on Q-CSMA/CA (Ghaderi and Srikant, 2013) to propose a queue-size and channel quality based adaptation of the Energy Detection Threshold (EDT) at the receiver nodes. In (Benmansour et al., 2017), the authors studied the impact of queuing strategies on the IEEE 802.15.6 based WBANs. Simulation results showed that Priority Queuing (PQ) and Low Latency Queuing (LLQ) improve clearly the latency and packets delivery rate of those networks.

### 2.2.2. Queuing based models beyond the WBANs

The second class focuses on the queuing beyond the WBANs, where the

traffic is buffered at the BNC or at gateways before its transmission to external centers for further processing. In (Yi et al., 2016) and (Yi and Cai, 2017), the authors designed a priority aware architecture for health monitoring networks. Medical packets are divided into several priority classes according to their delay sensitivity and buffered at intermediate gateways until their transmission beyond the WBAN to external servers. The authors have used an M/D/K queuing model with priorities, with a Poisson arrival, a deterministic service time and K servers (i.e., K channels). The proposed differentiation permits a priority transmission of critical packets over ordinary ones. In (Rashwand and Mistic, 2012), the authors defined a bridging between the IEEE 802.15.6 based WBANs and the IEEE 802.11e Enhanced Distributed Channel Access (EDCA) based WLAN. The proposed bridge operates as a BNC in collecting medical data from WBAN nodes and as an ordinary station in the WLAN network. At bridges, the eight different user priorities defined by the IEEE 802.15.6 are mapped to 4 different Access Categories (AC). Packets are differentiated according to the Arbitrary Inter-Frame Space (AIFS) and the Contention Window (CW) to be affected to the adequate AC. Packets of each AC are buffered at a dedicated MAC queue.

In saturation condition, where each node has at least one packet at its MAC layer buffer, an adequate queuing and scheduling strategy is needed to fulfill the IEEE 802.15.6 objectives in ensuring timely and reliable delivery of emergency traffic. However, from our literature analysis, we recorded only two works that analyzed over simulations the impact of queuing models on heterogeneous IEEE 802.15.6 based WBANs. They showed that queuing strategies taking into account traffic priority have an important impact in improving the overall WBANs performances.

To overcome the drawbacks of previous work, we propose in this paper a general and accurate analytical model to take into account heterogeneous WBANs in terms of priority. Based on renewal reward theorem, which involves a small amount of complicated formula derivation and significantly simplifies the mathematical analysis (Xinhua Ling et al., 2008), an analytical sub-model is designed for the IEEE 802.15.6 CSMA/CA Backoff process. As a complement for this proposed sub-model, an M/G/1 with non-preemptive priority queuing model is presented.

### 3. Overview OF IEEE 802.15.6 MAC

The IEEE 802.15.6 standard was developed by the IEEE association 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 WBANs each of them is expected to have only one BNC and multiple nodes. The standard offers one hop and two hop topologies. In the one hop topology, data is exchanged between nodes and the BNC directly, while in the two-hop topology, the BNC and nodes may use relay nodes to exchange data (IEEE Standards Association, 2012).

A BNC may operate in a beacon mode with superframe, non-beacon mode with superframe or non-beacon mode without superframe. The first mode offers synchronization between the BNC and all WBAN nodes and a

broad range of access modes. As shown in Fig. 1, the frame structure in beacon mode with superframe is divided into 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 B frame at the start of the superframe specifying the start and end times of these access phases and another optional beacon B2 before the start of the CAP to provide group acknowledgment. By receiving the beacon frame, WBAN's nodes and the BNC will establish reference time ensuring synchronization between them. In the EAP, RAP, and CAP access phases, sensor nodes use a priority-aware CSMA/CA or S-ALOHA access scheme to gain contended allocation. EAP is used only for high priority traffic (emergency packets and/ or medical event report), while the RAP is used for all traffic whatever the priority. To allow continual invocation of CSMA/CA or S-ALOHA and improve channel utilization, a node starting the Backoff process for an emergency packet may consider the combined EAP1 and RAP1 as a single EAP1, and the combined EAP2 and RAP2 as a single EAP2. During the MAP, the BNC may arrange scheduled uplink/downlink/bilink allocation interval, may provide unscheduled bilink allocation intervals, and may improvise Type-I immediate polled allocation intervals and posted allocation intervals (IEEE Standards Association, 2012).

#### 3.1. IEEE 802.15.6 CSMA/CA

In the IEEE 802.15.6 CSMA/CA access scheme, all nodes having a priority-class- $k$  dequeued packet to send set its Backoff Counters ( $BC$ ) to random integers uniformly distributed over the interval  $[1, W_{k,s}]$ , while  $W_{k,s}$  represents the Contention Window at the  $s^{th}$  transmission attempt (Backoff stage). To send a priority-class- $k$  packet, the node starts the Backoff process by setting the contention window  $W_{k,s}$  to  $CW_{k,min}$ . The node decrements its  $BC$  by one for each idle CSMA/CA slot. Once the  $BC$  reaches zero, the packet is transmitted over the medium. As described in the following equation, if the packet transmission fails, the node doubles its  $W_{k,s}$  for even number of failures, and keeps it unchanged for an odd number. If doubling the  $W_{k,i}$  exceeds  $CW_{k,max}$ , the node sets its  $W_{k,s}$  to  $CW_{k,max}$ .

$$W_{k,s} = \begin{cases} CW_{k,min} & s = 0 \\ \text{Min}(2W_{k,s-1}, CW_{k,max}) & 2 \leq s \leq m_k, s \text{ even} \\ W_{k,s-1} & 2 \leq s \leq m_k, s \text{ odd} \\ CW_{k,max} & m_k < s \leq R. \end{cases} \quad (1)$$

Where  $R$  stands for the maximum authorized transmission try and  $m_k$  represents the Backoff stage after which the contention window reaches its maximal value.

The values of  $CW_{k,min}$  and  $CW_{k,max}$  are defined by the standard according to data classes as presented in Table 2. The traffic is differentiated according to its type, ranging from Background traffic to the most critical emergency traffic. By assigning the highest user priority for emergency traffic and medical implant event report, and low user priorities for the normal traffic, the proposed traffic differentiation leads to allow a timely transmission for high emergency traffic.

The IEEE 802.15.6 standard allows sensor nodes to lock and unlock their  $BC$  to avoid collisions and ensure the non-overlapping between

superframe phases (IEEE Standards Association, 2012). Nodes lock their BCs in the following cases:

- The channel is busy because of a packet transmission of another node.
- The current time is outside any *EAP*, *RAP* or *CAP* phases.
- The current time is at the start of a CSMA slot within an *EAP*, *RAP*, or *CAP*, but the time between the end of the slot and the end of the *EAP*, *RAP*, or *CAP* is not long enough for completing the packet transmission.

**Table 2. Contention Window bounds and UP mapping for CSMA/CA.**

Priority	UP (k)	Traffic designation	$CW_{k,min}$	$CW_{k,max}$
Lowest	0	Background	16	64
	1	Best effort	16	32
	2	Excellent effort	8	32
	3	Video	8	16
	4	Voice	4	16
	5	Medical data or network control	4	8
	6	High-priority data or network control	2	8
Highest	7	Emergency or medical implant event report	1	4

The node keeps locking its *BC* until both of the following conditions are met:

- The channel has been idle for *SIFS* (Short InterFrame Spacing) within a *EAP*, *RAP*, or *CAP*.
- The time duration between the current time plus a CSMA/CA slot and the end of the *EAP*, *RAP*, or *CAP* is long enough for completing a packet transmission.

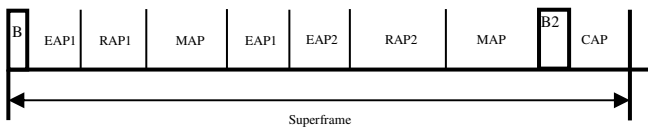


Fig. 1 Superframe structure in beacon mode with superframe

#### 4. THE PROPOSED ANALYTICAL MODEL

In order to provide a general analytical model allowing the study of the IEEE 802.15.6 CSMA/CA access scheme, in terms of latency and packets breakdown at the MAC layer, we propose two complementary sub-models as shown in Fig. 4. Firstly, we investigate an analytical sub-model depicting the Backoff process of the IEEE 802.15.6 based CSMA/CA while assuming that sensor nodes can generate heterogeneous traffic in term of priority. In the saturation regime, where each node has at least one packet waiting for transmission and with the assumption that the sensor nodes generate heterogeneous traffic, it's becoming necessary to define the scheduling strategy at the MAC layer. We have adopted the M/G/1 with non-preemptive priority to meet the QoS differentiation (traffic

prioritization) provided by the IEEE 802.15.6 standard. Among the calculated metrics from the first model; the mean delay experienced by nodes to execute the CSMA/CA Backoff process, which is carried out from the instant when the packet leaves the queue until its successful transmission or its dropping. This delay will serve as the service time of our queuing model. In Fig. 2 and Fig. 3, we illustrate the difference between the manner in which the heterogeneous traffic is handled in previous models and in our analytical model. In Fig. 2, the WBAN is formed by many sensor nodes; each of them generates only one type of traffic (temperature or Blood pressure...). However, in Fig.3, each node can generate many types of traffic with different user priorities such as periodic temperature, critical temperature and medical implant event report (Mechanical or material failure, software deficiencies, power failure ...). In both scenarios, our proposed analytical model can be used to evaluate WBAN performances. However, previously proposed models can only be used in the scenario showed in Fig. 2.

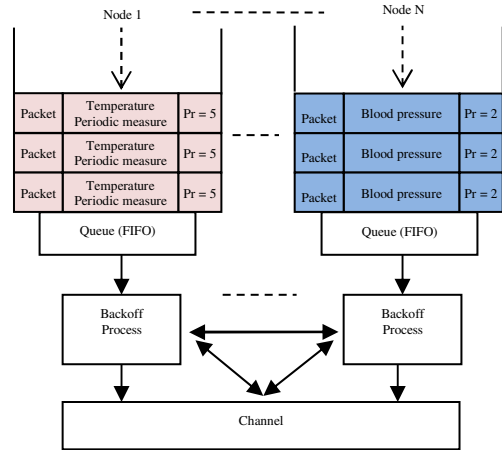


Fig. 2. Heterogeneous traffic at WBANs level

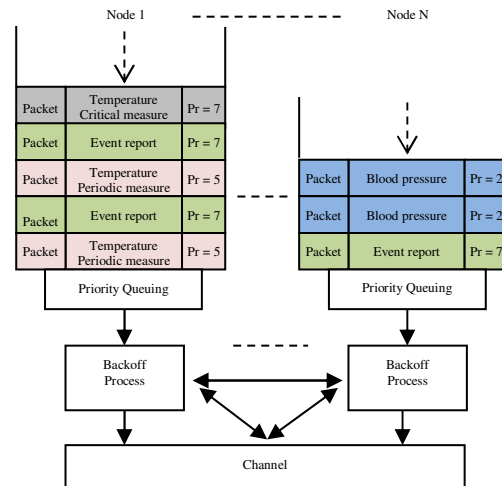
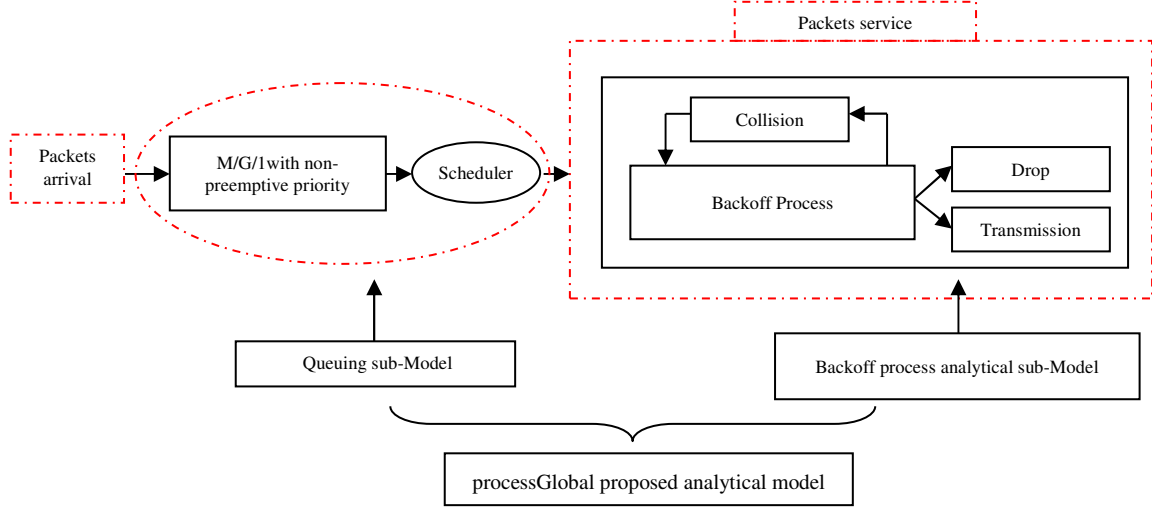


Fig. 3. Heterogeneous traffic at sensor nodes level



**Fig. 4. The architecture of proposed analytical model**

To carry out the proposed model, we consider a WBAN with one hop star topology and consisting of a BNC and up to  $m_{\text{MaxBANSize}}$  heterogeneous sensor nodes. All sensor nodes including the BNC are assumed within the transmission range of each other, so there is no hidden node problem. The network operates with the IEEE 802.15.6 in a beacon mode with superframes in which all sensor nodes are synchronized. Only EAP and RAP phases are considered with CSMA/CA access scheme and immediate Ack policy. We assume that there are neither sensing nor transmission errors, so that transmitted packets are lost only due to collisions occurred by simultaneous transmissions. We also assume that all sensor nodes transmit packets with the same length and that all sensor nodes generate heterogeneous traffic in terms of user priority and store it in a local queue if it cannot be immediately transmitted. We finally, assume that sensor nodes operate in a saturated traffic regime in which it is supposed that nodes have at least one packet in their queue at any time.

#### 4.1. Renewal-reward theorem based contention process analytical model

From the description of the IEEE 802.15.6 CSMA/CA access scheme in section II, we notice that the evolution of the Backoff process activities at the MAC layer over a large period of time can be viewed as a renewal reward process (Kulkarni, 2011). As depicted in Fig. 5, WBANs' nodes reset their Backoff parameters to the default values for each new packet. During each Backoff stage, the tagged node  $i$  decrements its  $BC$  only if the channel is sensed idle and it remains enough time in the RAP phase to complete the packet transmission. At the end of each Backoff stage  $BS_{i,k}^j$ , the node performs a transmission attempt, if a collision occurs, the node regenerates its  $BC$  and starts the next Backoff stage. The node repeats this process until the successful transmission of the packet or its dropping due to exceeding the retry limit  $R$ . Thus, we consider in our model that the renewal cycle starts from the first stage of the Backoff process until the successful transmission of the packet or its dropping, where the end of each Backoff stage is considered as the earned reward associated with the

renewal cycle.

To carry out our model, we define  $\tau_{i,k}$  as the probability of access to the channel (transmission) by a tagged node  $i$  executing a priority-class- $k$  packet Backoff process. This probability depends on the number of nodes contending the access to the channel and the priorities of their packets. From the renewal reward theorem, we can derive the access probabilities as follows:

$$\tau_{i,k} = \frac{E(N_{\text{Attempt}_{i,k}})}{E(BC_{i,k})} \quad (2)$$

Where  $E(N_{\text{Attempt}_{i,k}})$  represents the mean number of performed attempts by a tagged node  $i$  in order to send a priority-class- $k$  packet and  $E(BC_{i,k})$  depicts the mean Backoff duration experienced by this node until the successful transmission or the drop of the packet. We calculate at each node  $i$  the access probabilities for all packets' priority classes. Thus, our model allows calculating performance metrics for each node separately as well as for the overall WBAN, the aspect that was not handled in previous works, in which they provided performances for each priority class regardless the type of the node and its physical characteristics.

In order to derive the values of  $E(N_{\text{Attempt}_{i,k}})$  and  $E(BC_{i,k})$ , we define  $q_{i,k}$  as the probability that the medium is sensed idle by a tagged node  $i$  during the Backoff countdown of a priority-class- $k$  packet and remains idle until the transmission of the packet (no simultaneous transmissions) and  $P_{k,Idle}$  as the probability that the channel is sensed idle during a contended slot of the Backoff process of a priority-class- $k$  packet.



**Table 3. Summary of the used notations**

SYMBOL	MEANING
$W_{k,s}$	Contention Window of priority-class- $k$ packet at the Backoff stage $s$
$E(W_{pr})$	Mean waiting time in the queue of priority-class- $pr$ packets
$E(S_{pr})$	Mean waiting time in the system of priority-class- $pr$ packets
$E(R)$	Mean remaining time to finish packets service.
$E(X_{pr})$	Mean service time of priority-class- $pr$ packets
$\lambda_{pr}$	Priority-class- $pr$ arrival rate
$\rho_{pr}$	Priority-class- $pr$ Traffic load
$E(L_{pr}^q)$	Mean number of priority-class- $pr$ packets waiting in the queue
$E(L_{pr})$	Mean number of priority-class- $k$ packets waiting in the system
$\tau_{i,k}$	Channel Access (transmission) probability of priority-class- $k$ packet at a tagged node $i$
$q_{i,k}$	Probability that the medium remains idle during the Backoff countdown of priority-class- $k$ packet at a tagged node $i$ (transmission without collision)
$P_{k,Idle}$	Probability of sensing an idle slot during the Backoff process of priority-class- $k$ packets
$P_{k,(Idle/Busy)}$	Probability of sensing an idle slot after a busy one during the Backoff process of priority-class- $k$ packets
$P_{k,(Idle/Idle)}$	Probability of sensing an idle slot after an idle one during the Backoff process of priority-class- $k$ packets
$E(N\_Attempt_{i,k})$	Mean number of attempts until the success or the drop of priority-class- $k$ packet at a tagged node $i$
$E(BC_{i,k})$	Average Backoff time experienced by a priority-class- $k$ packet at a tagged node $i$
$E(\text{decrement}_{k,Nbr_k})$	Mean duration time between two successive $BC$ decrements
$p_{k,Nbr_k}$	Probability of insufficiency time in the RAP phase to complete the transmission of $Nbr_k$ priority-class- $k$ packets
$E(CD_{i,k})$	Mean contention delay (service time) of priority-class- $k$ packets at a tagged node $i$
$E(CD\_Succ_{i,k})$	Mean contention delay (service time) of priority-class- $k$ successfully transmitted packets at a tagged node $i$
$E(CD\_Drop_{i,k})$	Mean contention delay (service time) of priority-class- $k$ dropped packets at a tagged node $i$
$p\_Succ_{i,k}$	Probability of successful transmission of priority-class- $k$ packet at a tagged node $i$
$p\_Drop_{i,k}$	Probability of dropping a priority-class- $k$ packet at a tagged node $i$
$T_{Trans}$	Mean transmission duration of packets
$T_{Col}$	Mean collision duration of packets
$T_{pSIFS}$	Short InterFrame Spacing
$T_{I-Ack}$	Immediate Acknowledgment Time
$Rap$	Random Access Phase length
$Eap$	Exclusive Access Phase length
$R$	Retry limit

The probability  $q_{i,k}$  that other nodes do not access the channel during the contended slot in which the  $BC$  reaches zero is given by the following expression:

$$q_{i,k} = \begin{cases} \prod_{n=i}^N \prod_{p=0}^7 (1 - \tau_{n,p}) & k = 0 \text{ to } 6 \\ \prod_{n=i}^N \prod_{p=0}^7 (1 - \tau_{n,p}) \frac{Rap}{Eap+Rap} + \prod_{n=i}^N (1 - \tau_{n,7}) \frac{Eap}{Eap+Rap} & k = 7 \end{cases} \quad (3)$$

In WBANs operating with the IEEE 802.15.6 MAC protocol, nodes can

transmit all types of packets during the RAP phase and send only emergency ones during the EAP phase. Toward this aim, the probability  $q_{i,k}$  is bounded to the priority-class  $k$  of the packet as mentioned in the above equation.

To calculate  $P_{k,Idle}$ , we consider the channel state for two consecutive contended slots. By the Law of Total Probability in classical probability theory [24] and by assuming that the idle probability is constant over the Backoff process, we derive the probability that the channel is idle in the next slot according to the probability of being idle  $P_{k,Idle}$  or busy  $1 - P_{k,Idle}$  in the current slot as follows:

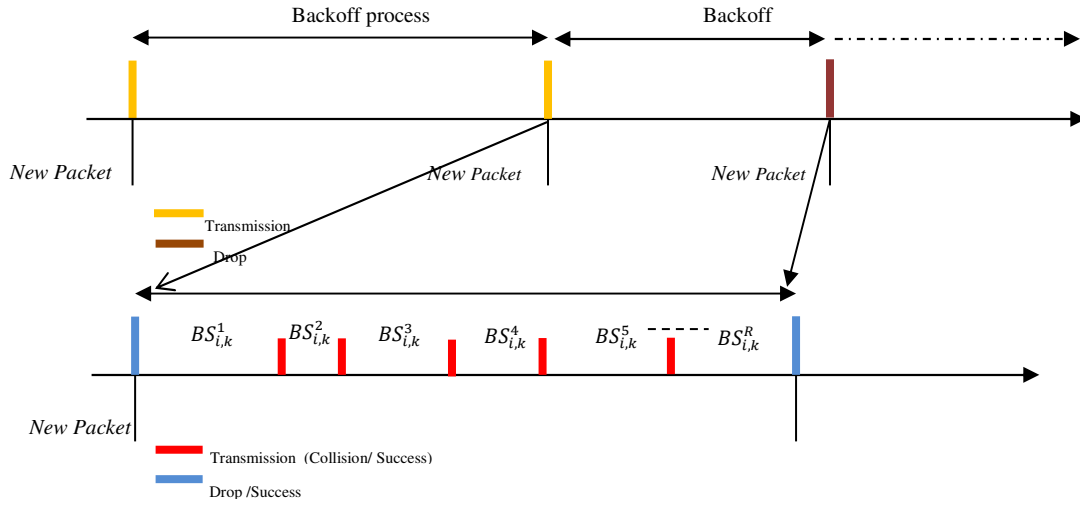


Fig. 5 IEEE 802.15.6 Backoff process as a Renewal reward process

$$P_{k,Idle} = P_{k,(Idle/Idle)} P_{k,Idle} + P_{k,(Idle/busy)}(1 - P_{k,Idle}) \quad (4)$$

$P_{k,(Idle/busy)}$  is the conditional probability that the channel is busy in the current contended slot and becomes idle in the next one and  $P_{k,(Idle/Idle)}$  is the conditional probability that the channel is idle in the current contended slot and remains idle in the next contended slot.

$P_{k,(Idle/busy)}$  may also represent the probability that the node which already gained the contended allocation finishes the transmission of at most  $Nbr$  packets at the previous slot. Hence, the probability  $P_{k,(Idle/busy)}$  can be expressed as follows:

$$P_{k,(Idle/busy)} = \begin{cases} \sum_{b=2}^{Nbr \times T_{Trans} \frac{1}{b}} & k = 0 \text{ to } 6 \\ \sum_{b=2}^{Nbr \times T_{Trans} \frac{1}{b}} \times \frac{Rap}{Eap+Rap} + \sum_{b=2}^{Nbr_7 \times T_{Trans} \frac{1}{b}} \times \frac{Eap}{Eap+Rap} & k = 7 \end{cases} \quad (5)$$

Where  $Nbr_7$  and  $Nbr$  represent the mean number of packets that can be sent by nodes having gained the contended allocation with the priority-class- 7 and priority-class-  $k$  packets ( $k = 0..7$ ), respectively. And  $T_{Trans}$  represents the mean transmission time of packets.

The channel will remain idle in the next contended slot only if none of WBAN's nodes access to the channel during this next slot, as a result,  $P_{k,(Idle/Idle)}$  is given as follows:

$$P_{k,(Idle/Idle)} = \begin{cases} \prod_{n=1}^N \prod_{p=0}^7 (1 - \tau_{n,p}) & k = 0 \text{ to } 6 \\ \prod_{n=1}^N \prod_{p=0}^7 (1 - \tau_{n,p}) \frac{Rap}{Eap+Rap} + \prod_{n=1}^N (1 - \tau_{n,7}) \frac{Eap}{Eap+Rap} & k = 7 \end{cases} \quad (6)$$

Using the probability defined in equation (3), we can derive  $E(N\_Attempt_{i,k})$  and  $E(BC_{i,k})$  as follows:

$$E(N\_Attempt_{i,k}) = \left( \sum_{l=0}^R (1 - q_{i,k})^l \times q_{i,k} \times (l + 1) \right) + \left( (1 - q_{i,k})^{R+1} \times (R + 1) \right) \quad (7)$$

$$E(BC_{i,k}) = \left( \left( \sum_{l=0}^R (1 - q_{i,k})^l \times q_{i,k} \times \sum_{s=0}^l AvgCW_{k,s} \right) + \left( (1 - q_{i,k})^{R+1} \times \sum_{s=0}^R AvgCW_{k,s} \right) \right) \times E(decrement_{i,k,Nbr_k}) \quad (8)$$

$$AvgCW_{k,s} = \frac{W_{k,s}+1}{2} \quad (9)$$

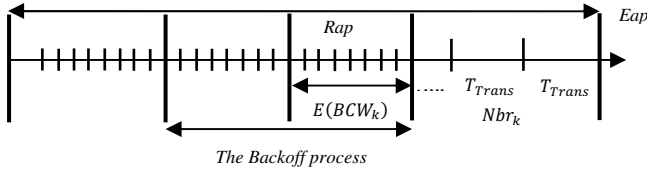
Where, the entity  $AvgCW_{k,s}$  represents the average value of the  $BC$  of priority-class- $k$  packets at the  $s^{th}$  Backoff stage and  $(1 - q_{i,k})^l q_{i,k}$  depicts the probability that the frame is successfully transmitted after the  $l^{th}$  attempt. The first terms in (7) and (8) represent the case where the packet is successfully transmitted after  $l^{th}$  attempt, while the second terms indicate that the packet is dropped after exceeding the retry limit  $R$ .

$E(decrement_{i,k,Nbr_k})$  represents the mean delay on a number of slots between two successive decrements of the  $BC$  of a priority-class- $k$  packet in a node  $i$ . As we explained previously, nodes decrement their  $BC$  only if the channel is sensed idle and there is enough time to complete the transmission in the current  $Rap$  phase. Otherwise, the  $BC$  is locked. So,  $E(decrement_{i,k,Nbr_k})$  will depend on the mean number of occupied slots by others nodes and the mean number of slots while the  $BC$  is locked due to the insufficient time remaining in the  $RAP$  phase to complete the transmission. We consider that the average channel occupation time by WBAN's nodes can be presented by the mean required time to complete the transmission of at least one packet by the node that obtains the contended allocation. According to the IEEE 802.15.6 standard, nodes can send at most four packets during an obtained contended allocation with an emergency packet and can send only one or two packets if they obtain it

with low priority packet. Thus,  $E(\text{decrement}_{i,k,Nbr_k})$  can be expressed for each node  $i$  by the following equation:

$$E(\text{decrement}_{k,Nbr_k}) = \begin{cases} \sum_{j=0}^{Nbr_k} (1 - P_{k,Idle})^{j \times T_{Trans}} P_{k,Idle} (1 + j \times T_{Trans}) & k = 7 \\ p_{k,Nbr_k} \times Eap + \sum_{j=0}^{Nbr_k} (1 - P_{k,Idle})^{j \times T_{Trans}} P_{k,Idle} (1 + j \times T_{Trans}) & k = 0..6 \end{cases} \quad (10)$$

Where,  $p_{k,Nbr_k}$  represents the probability that the remaining time in the *Rap* phase is not enough to complete the transmission of  $Nbr_k$  non-emergency packets during an obtained contended allocation.



**Fig. 5 Non-emergency packets Backoff process during the RAP phase**

As described in Fig. 6 the probability  $p_{k,Nbr_k}$  can be expressed as follows:

$$p_{k,Nbr_k} = 1 / (Rap - E(BCW_k) - Nbr_k \times T_{Trans}) \quad (11)$$

$E(BCW)_k$  depicts the mean required time to finish the Backoff stage, which depends on the mean contention window length  $W_{k,s}$  as illustrated in the following equation:

$$1 < E(BCW_k) < \sum_{s=0}^R AvgCW_{k,s} / R \quad (12)$$

By supposing that the probability that a node detects that it has not enough time to complete the Backoff process is uniformly distributed over the previous interval, we can derive  $E(BCW)_k$  as follows:

$$E(BCW_k) = (\sum_{s=0}^R AvgCW_{k,s} / R) + 1/2 \quad (13)$$

#### 4.2. Mean contention delay of the IEEE 802.15.6 CSMA/CA Backoff process

We define the mean contention delay of priority-class- $k$  packets  $E(CD_{i,k})$  as the average duration elapsed from the instant a packet becomes the head-of-line at the MAC queue until its successful transmission or its dropping, it can be expressed as follows:

$$E(CD_{i,k}) = p_{Succ_{i,k}} \times E(CD_{Succ_{i,k}}) + p_{Drop_{i,k}} \times E(CD_{Drop_{i,k}}) \quad (14)$$

$$p_{Drop_{i,k}} = (1 - q_{i,k})^{R+1} \quad (15)$$

$$p_{Succ_{i,k}} = 1 - p_{Drop_{i,k}} \quad (16)$$

Where,

- $p_{Succ_{i,k}}$  is the probability that a priority-class- $k$  packet is successfully delivered
- $p_{Drop_{i,k}}$  is the probability that it is dropped after exceeding the retry limit  $R$ .
- $E(CD_{Succ_{i,k}})$  is the mean contention delay of successfully transmitted priority-class- $k$  packets
- $E(CD_{Drop_{i,k}})$  is the mean contention delay of the dropped priority-class- $k$  packets.

**Fig. 6 Backoff process evolution for successfully transmitted packets**

As shown in Fig. 7, the mean contention delay of successfully transmitted priority-class- $k$  packets  $E(CD_{Succ_{i,k}})$  is the sum of:

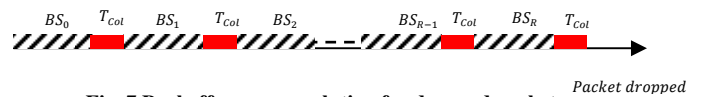
- The mean Backoff duration experienced by a tagged node before the successful transmission  $E(B_{Succ_{i,k}})$ , which represents the sum of all Backoff stages  $BS_i$ ;
- The average time wasted in possible collisions before the successful transmission  $E(Col_{Succ_{i,k}})$ ;
- The transmission time  $T_{trans}$ .

$$E(CD_{Succ_{i,k}}) = E(Col_{Succ_{i,k}}) + E(B_{Succ_{i,k}}) + T_{trans} \quad (17)$$

Where,

$$E(B_{Succ_{i,k}}) = (\sum_{l=0}^R (1 - q_{i,k})^l \times q_{i,k} \times \sum_{s=0}^l AvgCW_{k,s}) \times E(\text{decrement}_{i,k}) \quad (18)$$

$$E(Col_{Succ_{i,k}}) = (\sum_{l=0}^R (1 - q_{i,k})^l \times q_{i,k} \times (l + 1)) \times T_{col} \quad (19)$$



**Fig. 7 Backoff process evolution for dropped packets**

On the other hand, as shown in Fig. 8, the mean contention delay experienced by dropped priority-class- $k$  packets  $E(CD_{Drop_{i,k}})$  is the sum of:

- The mean Backoff duration experienced by packets before their dropping after exceeding the retry limit  $R$   $E(B_{Drop_{i,k}})$ .
- The average time wasted in possible collisions before packets dropping  $E(Col_{Drop_{i,k}})$ .

$$E(CD_{Drop_{i,k}}) = E(B_{Drop_{i,k}}) + E(Col_{Drop_{i,k}}) \quad (20)$$

Where,

$$E(B_{Drop_{i,k}}) = (\sum_{s=0}^R AvgCW_{k,s}) \times E(\text{decrement}_{i,k}) \quad (21)$$

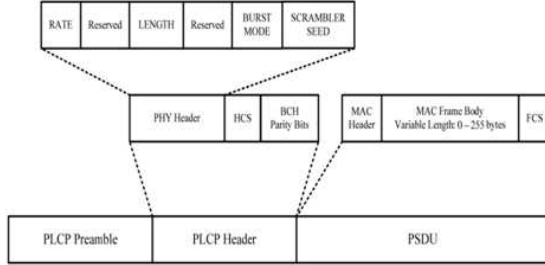
$$E(Col_{Drop_{i,k}}) = (R + 1) \times T_{col} \quad (22)$$

The transmission time  $T_{Trans}$  and the collision time  $T_{Col}$  are given by the following equations (IEEE Standards Association, 2012), (Ullah et al.,

2012):

$$T_{Trans} = T_{data} + T_{pSIFS} + T_{I-Ack} \quad (23)$$

$$T_{Col} = T_{data} + T_{pSIFS} + T_{timeout} \quad (24)$$



**Fig. 8 IEEE 802.15.6 PPDU structure for NB Physical Layer (IEEE Standards Association, 2012)**

As shown in Fig. 9, the transmission duration of a packet (PPDU) in the narrow band is defined as the transmission of the concatenation of the PLCP preamble, the PLCP header, and the PSDU. According to the IEEE 802.15.6 standard the value of this duration is given as follows:

$$T_{data} = T_s \left( N_{preamble} + N_{header} \times S_{header} + \frac{N_{PSDU}}{\log_2(M)} \times S_{PSDU} \right) \quad (25)$$

$$N_{PSDU} = (N_{MACheader} + N_{MACFrameBody} + N_{FCS}) \times 8 \quad (26)$$

Where, the physical parameters:  $T_s$ ,  $N_{preamble}$ ,  $N_{header}$ ,  $S_{header}$ ,  $S_{PSDU}$ ,  $N_{PSDU}$ ,  $N_{MACheader}$ ,  $N_{MACFrameBody}$  and  $N_{FCS}$  are given in the IEEE 802.15.6 standard according to the frequency band used for the communication between the BNC and nodes.

### 4.3. Queuing model

Without adequate queuing and scheduling strategies to promote the transmission of high emergency packets, WBANs operating the IEEE 802.15.6 standard may not be able to ensure an efficient QoS for high emergency traffic. Among a wide range of proposed queuing strategies in the literature, priority queues form an important class that fulfills QoS requirements of wireless networks. In such queuing models, arrival packets are divided according to their priorities into many priority classes and the scheduler serves packets with high priority before those with lower priority (Papir, 2005).

According to the generated traffic behavior (arrival process) and the manner by which packets are served after their dequeuing (service time distribution), many probability distributions (Markovian, General distribution, Erlang distribution ...) were used to characterize queuing models. As in most of the work dealing with queues in wireless networks, we consider in our proposed analytical model an M/G/1 priority queue with K priority classes of packets (Adan, 2001), where arrivals are Markovian (exponential inter-arrival times), service times have a General distribution (independent arrivals) and there is a single server (wireless medium). The choice of this model is justified by the fact that the service time (Backoff process duration) does not follow any universal

probability law. On the other hand, the generated traffic can be modeled by Poisson process, which makes the queue performances analysis less complicated than with the general distribution.

We denoted by:  $\lambda_{pr}$  the priority-class-pr arrival rates,  $E(X_{pr})$  the mean service time (Backoff process) and  $\lambda_{pr} \times E(X_{pr})$  the utilization of the service by priority-class-pr packets. In our model, we assume that emergency packets have an absolute priority over non-emergency packets but are not allowed to interrupt their transmissions. This priority rule is therefore called non-preemptive (Veeraraghavan, 2004).

The analytical study of the proposed queuing model allows measuring many performances metrics such as the mean waiting time and the mean number of packets in the queue and in the whole system.

We define the traffic load of a priority-class-pr as:

$$\rho_{pr} = \sum_{j=pr}^7 \rho_j \quad (27)$$

$$\text{Where, } \rho_j = \lambda_j E(X_j) \quad (28)$$

In this paper, we do not consider the packets' dropping due to the buffer overflow. Thus, for the stability of the proposed queuing system, the total traffic load must satisfy the following condition:

$$\sum_{pr=0}^{K-1} \rho_{pr} \leq 1 \quad (29)$$

According to the mean value approach (Doremalen, 1983), we can compute for a queuing model the mean number of packets and the mean sojourn time, without knowing stationery probabilities. This approach is based on Little's formula (Little, 1961) and the Poisson Arrivals See Time Averages (PASTA) property (Wolff, 1982). By assuming that the queue service discipline is non-preemptive and that within each priority class the discipline is: First In, First Out, the arrival of a new packet finds  $E(L_{pr}^q)$  packets of each class-pr, waiting in the queue and a priority-class-pr packet in the service with a probability  $\rho_{pr}$ . The waiting time in the queue  $E(W_k)$  of a new arrived packet depends on its priority k and ca, be expressed ass follows:

- For the higher priority class ( $pr = 7$ ), the new arrived packet has to wait for packets of its own class that arrived before and for the required time to finish the transmission of the packet in service. Thus, the mean waiting time is given as follows:

$$E(W_7) = E(R) + E(L_7^q)E(X_7) \quad (30)$$

By Little's law we have:

$$E(L_{pr}^q) = \lambda_{pr} E(W_{pr}) \quad (31)$$

Combining equations (30) and (31) we obtain:

$$E(W_7) = E(R) + E(W_7)\rho_7 \quad (32)$$

$$E(W_7) = \frac{E(R)}{(1-\rho_7)} \quad (33)$$

- For the lower priority classes ( $pr = 0 \dots 6$ ), a new arrived packet has to wait for packets of its own class that arrived before and all for all packets with higher priority already in the queue. The packet has to wait also to all higher priority packets arrived while it waits for the service. The mean waiting time in the queue can be expressed as follows:

$$E(W_{pr}) = E(R) + \sum_{j=pr}^7 E(L_j^q)E(X_j) + E(W_{pr}) \quad (34)$$

Substituting  $E(L_{pr}^q)$  from equation (31) into the second term in equation (34), we obtain:

$$E(W_{pr}) - E(W_{pr}) \sum_{j=pr+1}^7 \lambda_j E(X_j) = E(R) + \sum_{j=pr+1}^7 \lambda_j E(W_j) E(X_j) \quad (35)$$

Using the traffic load defined in (27) we obtain:

$$E(W_{pr})(1 - \rho_k - \rho_{pr+1}) = E(R) + \sum_{j=pr+1}^7 \rho_j E(W_j) \quad (36)$$

$$E(W_{pr}) = \frac{E(R) + \sum_{j=pr+1}^7 \rho_j E(W_j)}{(1 - \rho_{pr} - \rho_{k+1})} \quad (37)$$

From equations (33) and (38) we obtain the mean waiting time in the queue of the second priority class packets ( $pr = 6$ ) as follows:

$$(W_6) = \frac{E(R)}{(1 - \rho_7)(1 - \rho_6 - \rho_7)} \quad (38)$$

Where,  $E(R)$  represents the mean required time to finish the transmission of a packet in service. The value of  $E(R)$  is developed in (Veeraraghavan, 2004) and given as follows:

$$E(R) = \sum_{j=pr}^7 \frac{\lambda_j E(X_j^2)}{2} \quad (39)$$

Using the Little's law, we derive the mean number of packets in the queue for two packets classes as follows:

$$E(L_7^q) = \lambda_7 \frac{E(R)}{(1 - \rho_7)} \quad (40)$$

$$E(L_6^q) = \lambda_6 \frac{E(R)}{(1 - \rho_7)(1 - \rho_6 - \rho_7)} \quad (41)$$

By considering a system formed by the queue and the service (Backoff process), we can drive the mean waiting time in the system  $E(S_{pr})$  and the mean number of priority-class- $pr$  packets in the system  $E(L_{pr})$  as follows:

$$E(S_{pr}) = E(W_{pr}) + E(X_{pr}) \quad (42)$$

$$E(L_{pr}) = \lambda_{pr} E(S_{pr}) = E(L_{pr}^q) + \rho_{pr} \quad (43)$$

At a tagged node  $i$ , the mean contention delay  $E(CD_{i,pr})$  of priority-class- $pr$  traffic, calculated in the first model represents the service time  $E(X_{pr})$  of priority-class- $pr$  packets of the proposed queuing model.

## 5. Performances EVALUATION

As detailed in the previous section, we propose in this paper an accurate and general analytical model for heterogeneous WBANs. By proposing in a first part, an analytical model for the CSMA/CA Backoff process and in the second part, an adapted priority queue to meet the QoS differentiation offered by the IEEE 802.15.6 standard. By the substitution of equations (7) (8) and (2) in the equation (2) in the first model, we obtain a non-linear, multivariable system of equations. Inspired by previous work such as [11] and (Ling et al., 2008), we have used the fixed point iterative technique in order to solve the obtained system. We selected the probability to transmit the packet over the medium  $\tau_{i,k}$  as the fixed point and we used Matlab to solve our system. After that, we used the calculated mean Backoff delay from the first model to compute the performance metrics of the proposed queuing model by using Maple. To perform simulations, we chose the Castalia open source simulator (NICTA, 2011) designed for networks of low-power embedded devices, which offers a node behavior simulation in realistic wireless channels and radio models. In our simulation, sensor nodes generate all types of packets in term of priority (eight (8) priorities). The percentage of each user priority is given in each set of simulation. We used in our simulations the Narrowband Physical Layer (frequency band: 2400 to 2483.5 MHz). The parameters as defined in the IEEE 802.15.6 draft are summarized in Table 4 (IEEE Standards Association, 2012).

**Table 4. IEEE 802.15.6 parameters**

Parameter	Value
Frequency Band	2400 MHz to 2483.5MHz
$pSIFS$	75 $\mu s$
$p$ (propagation delay)	1 $\mu s$
$1/T_s$	600 $ksps$
$S_{header}$	4
$S_{PSDU}$	1
$M$	4 ( $\pi/4 - DQPSK$ )
$N_{header}$	31 bits
$N_{preamble}$	90 bits
$N_{MACheader}$	7 octets
$N_{FCS}$	2 octets
$N_{MACFrameBody}$	100 Octets < $pMaxFrameBodyLength$
$T_{I-Ack}$	468.4 $\mu s$
$mCSMATxLimit$	1
$mMaxBANSize$	< 64 nodes
$Superframe\ size$	255 Slots
$Buffer\ size$	Infinite (10000 packets)
$Simulation\ time$	1000 $s$ (50 iterations)

We consider in our assessment a simple mapping between the two sub-models by specifying only two classes as shown in Table 5. The first class relates to high emergency traffic, while the second class joins the other classes of traffic together. The first class will have an absolute priority

over the second class in which the traffic is served according to its order of arrival. Through this mapping, we try to highlight the impact of the proposed analytical model on handling the emergency traffic for the aim to meet the IEEE 802.15.6 traffic differentiation, in which the emergency traffic is promoted by reserving a dedicated access phase in the superframe and by assigning small contention windows in the CSMA/CA access scheme.

**Table 5. User priorities mapping between the proposed sub-models**

User priority (k) Backoff process model	Priority class (pr) Queuing model
7	7
0,1,2,3,4,5,6	6

In order to study the IEEE 802.15.6 based WBANs, we consider two performance metrics; the mean latency and the delivery rates of packets:

- a- Delivery rate:** In order to measure the reliability of the network and packets breakdown at MAC layer, we define  $p_{Drop_{i,k}}$  as the probability of dropping a priority-class- $k$  packet by a tagged node  $i$  after exceeding the retry limit  $R$  (no reception of the Ack frame after the last Backoff stage) and  $p_{success\_transmit_{i,k,s}}$  as the probability of successful transmission after the  $s^{th}$  Backoff stage as follows:

$$p_{Drop_{i,k}} = (1 - q_{i,k})^{R+1} \quad (44)$$

$$p_{success\_transmit_{i,k,s}} = q_{i,k} \times (1 - q_{i,k})^{s-1} \quad (45)$$

- b- Latency:** We define the mean latency of priority-class- $k$  packets as the average duration elapsed from the instant a packet arrives at the MAC queue until its successful transmission or its dropping. It can be expressed according to the packet priority as follows:

$$Latency_{i,k} = \begin{cases} \frac{E(R)}{(1-\lambda_7 E(CD_{i,7}))} + E(CD_{i,7}) & k = 7 \\ \frac{E(R)}{(1-\lambda_7 E(CD_{i,7}))(1-\lambda_k E(CD_{i,6})-\lambda_7 E(CD_{i,7}))} + E(CD_{i,6}) & k = 0 \dots 6 \end{cases} \quad (46)$$

$$\text{With: } E(CD_{i,6}) = \frac{\sum_{z=0}^6 E(CD_{i,z})}{7} \quad (47)$$

### 5.1. Measurement and result analysis

In this section, we carry out several performances' analyses of the IEEE 802.15.6 standard while varying one or more parameters in each set of simulation. Many parameters may influence the behavior of the standard; we quote the number of nodes, the percentage of emergency packets among the total packets, the EAP length, the packets arrival rate and the number of attempts. For each parameter, we calculate:

- The mean latency of both emergency and non-emergency traffic.
- The analytical traffic load for each type of packets, which represents in the queuing theory the utilization of the service by each class of traffic; it is the result of the multiplication of the arrival rate by the mean service time.

- The ratios of the successful transmissions after the 1<sup>st</sup> attempt, 2<sup>nd</sup> attempt ...  $R^{th}$  attempt and the ratio of dropped packets due to an unreceived Ack frame after the  $R^{th}$  attempt.

We evaluate the most of aforementioned parameters with several arrival rates, ranging from 10 p/s to 150 p/s (packet/ second), in order to show the behavior of the standard under many traffic's regimes. In order to avoid the overloading of results' analysis, we show for each parameter only the graphs corresponding to arrival rates which afford the most effect on this parameter. In the end, we present a performance analysis of the overall WBAN as well as the nodes that compose it separately in order to show if it is necessary to provide an analytical model, which allows analyzing nodes' performance.

#### 5.1.1. Impact of traffic Arrival rate

As shown in Fig. 10, 11 and 12, we evaluated the IEEE 802.15.6 based WBANs performances while varying the packets' arrival rate from 1 p/s to 200 p/s. We set the retry limit to two (2) (the default value of Castalia simulator), the percentage of emergency packets to 15%, the EAP length to zero (0) and the number of nodes to 12 nodes.

We notice from Fig. 11 that the mean latency increases with the increase in the arrival rate. This is explained by the longer time spent during nodes' Backoff processes caused mainly by the extensive use of the medium; The more WBAN's nodes generate traffic, the more collisions occur in the medium, which leads packets to experience more Backoff stages before their successful transmission or their drop. Moreover, by queuing theory, buffered packets in queues have to wait longer before being served, due to the longer time spent in service (Backoff process). Fig. 10 shows that while raising the packets' arrival rate, the number of transmitted packets after the first Backoff stage (without collision) decreases while the number of transmitted packets after the second Backoff stage (success after one collision) and the number of dropped packets (after two collisions) increase. This behavior is explained by the high traffic intensity, which leads to high use of the medium, resulting in an increase of the number of collisions. Indeed, as we mentioned above, each node executes the Backoff process to transmit packets. If a collision occurs at the end of a Backoff stage, the node regenerates its BC and starts another Backoff stage. This process is repeated until a successful transmission of the packet or until reaching the maximum number of authorized attempts. Fig. 12 shows that after exceeding 125 p/s, the total traffic load exceeds the stability condition of the queuing system as illustrated in equation (29). For this aim, we present only latency and packets breakdown results with arrival rates less than 125 p/s.

#### 5.1.2. Impact of number of nodes

To analyze the impact of the number of nodes on WBANs' performances, we vary the number of nodes from 1 to 12 while setting the retry limit to two (2), the percentage of emergency packets to 15% and the EAP length to zero (0). In this evaluation, we present results with the arrival rates 50 p/s, 75 p/s, and 100 p/s. We notice from Fig. 13 that in contrast to successful transmissions the amount of failed ones increases while increasing the number of nodes, and it further increases with high data arrival rate. In addition, the number of attempts before the successful transmission of packets is also influenced by both the arrival rate and the number of nodes.

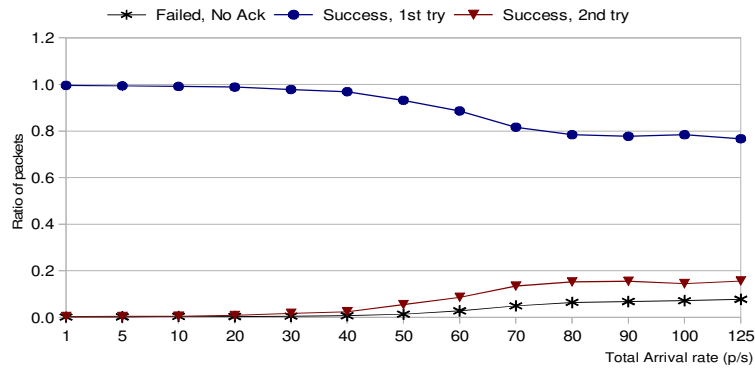


Fig. 9 the effect of arrival rate on packets breakdown at MAC Layer

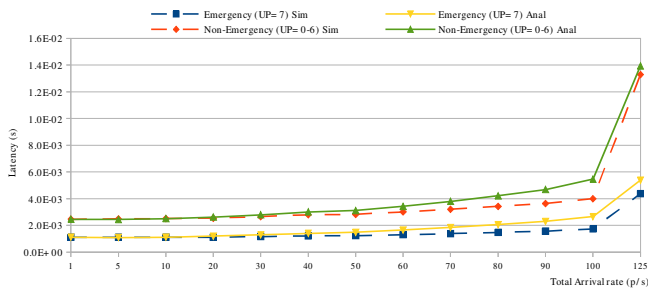


Fig. 10 the effect of arrival rate on the average latency

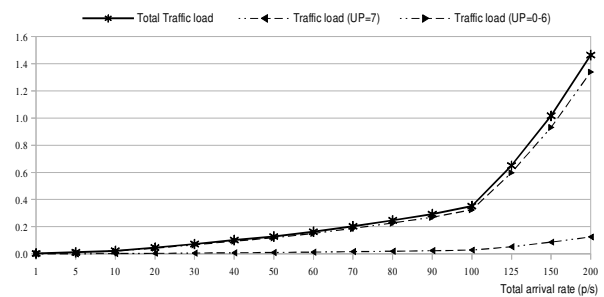


Fig. 11 the effect of arrival rate on queuing traffic load

The more the number of nodes and the arrival rate increases, the more the number of transmitted packets after the second Backoff stage increases at the expense of the transmitted packets after the first Backoff stage. This is mainly due to the rise of contending nodes to access the channel, which results in high channel occupation that leads to high packets' collisions. From Fig. 15, 17 and 19 depicting the traffic load of WBAN's nodes, we notice that the number of nodes and the arrival rate have an important impact on the traffic load of emergency and non-emergency traffic. In contrast to non-emergency traffic load, the emergency traffic load varies slightly. This difference can be explained by the fact that the Backoff process of emergency traffic is smaller than the non-emergency ones due to the gap between related contention windows. Equations (27) and (28) show how the Backoff process can influence the traffic load. Increasing of the number of nodes in the network raises the number of collisions due to

high use of the medium, thus resulting in a high amount of experienced time in Backoff processes, which leads to the increase of the latency. In addition, as depicted in Fig. 14, 16 and 18, we notice that the behavior of the latency differs according to the type of traffic. For the emergency traffic, the latency increase rate is slightly smaller than for the non-emergency traffic. This is explained by the fact that emergency packets have to wait in the queue only for previously arrived emergency packets. However, non-emergency packets have to wait for all previously arrived packets regardless of their priority. In the figures illustrating the latency, we didn't show the latency when the number of nodes goes over ten (10) nodes on Fig. 16 and seven (7) nodes on Fig. 18 because of the fact that the value of the traffic load after these numbers of nodes does not satisfy the queuing system stability condition (total traffic load < 1) as shown in Fig. 17 and 19, respectively.

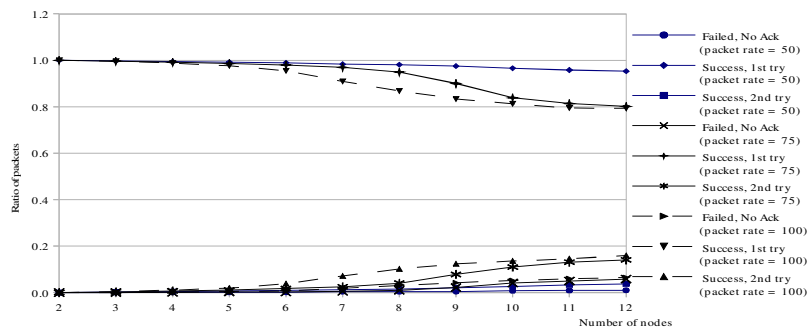


Fig. 12 the effect of number of nodes on packets breakdown at MAC Layer

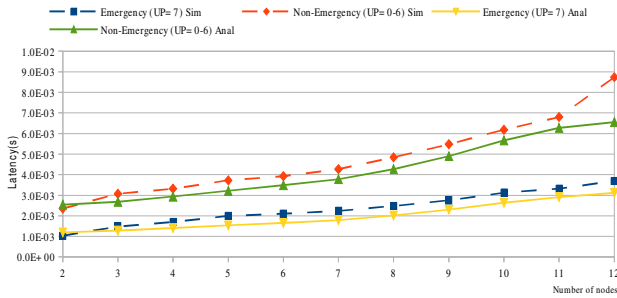


Fig. 13 the effect of number of nodes on the average latency (arrival rate = 50 p/s)

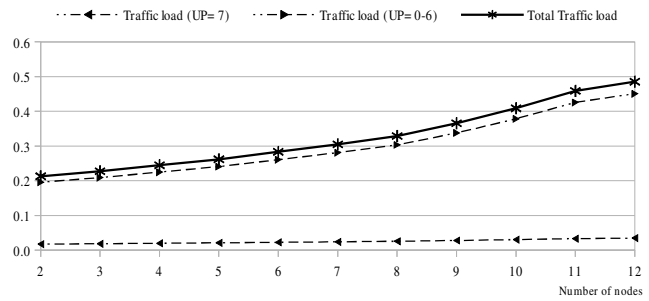


Fig. 14 the effect of number of nodes on queuing traffic load (arrival rate = 50 p/s)

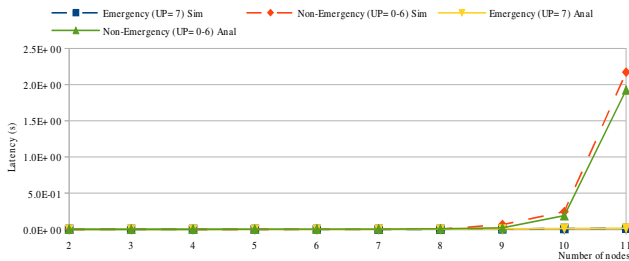


Fig. 15 the effect of number of nodes on the average latency (arrival rate = 75 p/s)

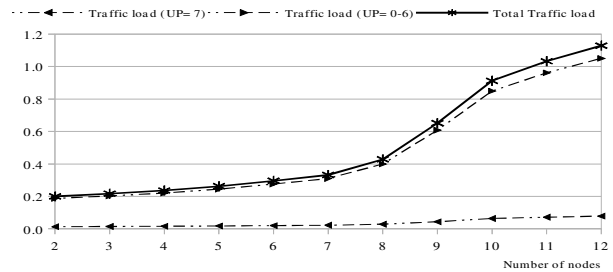


Fig. 16 the effect of number of nodes on queuing traffic load (arrival rate = 75 p/s)

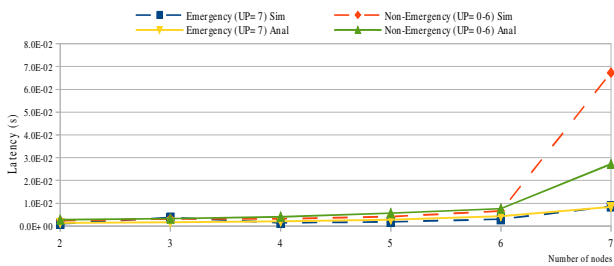


Fig. 17 the effect of number of nodes on the average latency (arrival rate = 100 p/s)

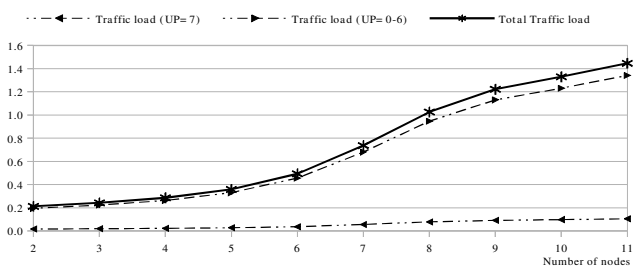


Fig. 18 the effect of number of nodes on queuing traffic load (arrival rate = 100 p/s)

### 5.1.3. Impact of EAP phase's length

In this set of simulations, we perform several assessments to study the effect of the EAP phase's length on the standard performances, we set the retry limit to two (2), the percentage of emergency packets to 15%, the number of nodes to five (5) and we present analysis results with the arrival rates 10 p/s, 50 p/s, and 100 p/s.

We notice from Fig. 22, 24 and 26 that, as we increase the arrival rate and the EAP length, the non-emergency traffic load increases while the emergency traffic load decreases. As explained in previous analyses, the more we increase packets arrival rate, the more the communication medium is saturated by WBAN's nodes transmissions, resulting in the increasing the time spent in the Backoff process. In addition to that, all non-emergency packets have to wait for more in queues by increasing the

EAP length, because only emergency packets can be served in this phase. Therefore, the medium saturation and the waiting time in queues justify the variation of the latency in Fig. 21, 23 and 25. We notice also, that there are some differences between analytical and simulation recorded latencies. This is explained by the fact that in our analytical model, we do not take into consideration communication errors for during beacon frames transmission and during WBAN setup phase, in which nodes send requests to join the BAN. The same analysis can explain the results of the packets' delivery rate presented in Fig. 20. With the increase of the arrival rate, the amount of dropped packets and the transmitted packets after the second Backoff stage decreases to the detriment of the transmitted packets after only the first Backoff stage.



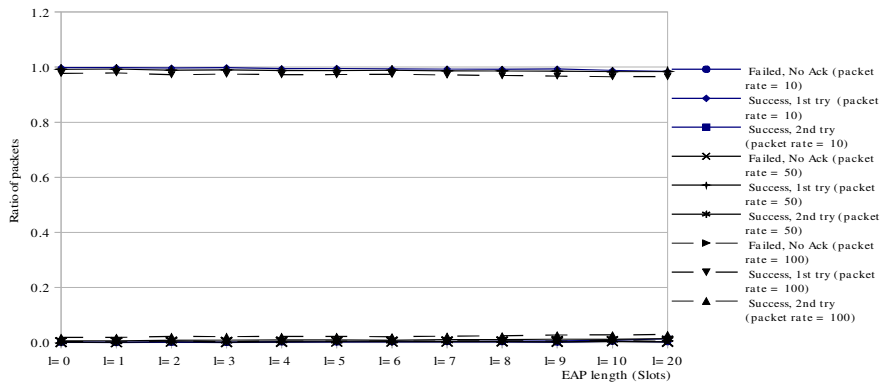


Fig. 19 the effect of the EAP length on packets breakdown at MAC Layer

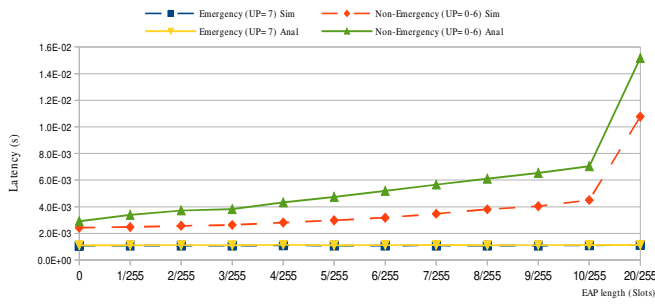


Fig. 20 the effect of the EAP length on the average latency (arrival rate = 10 p/s)

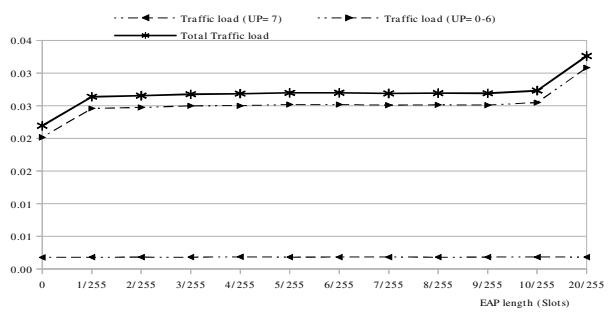


Fig. 21 the effect of the EAP length on queuing traffic load (arrival rate = 10 p/s)

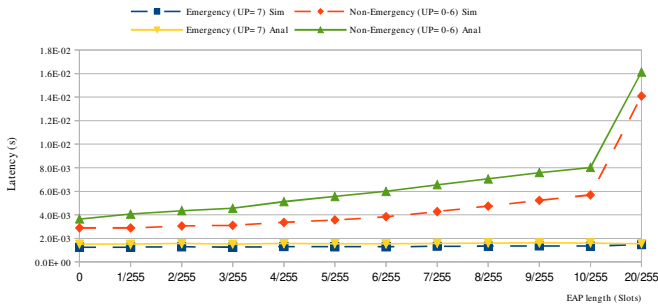


Fig. 22 the effect of the EAP length on the average latency (arrival rate = 50 p/s)

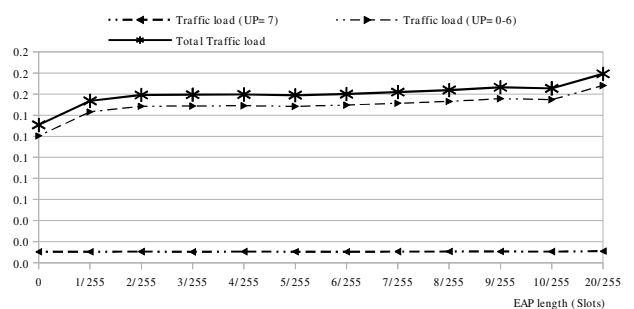


Fig. 23 the effect of the EAP length on queuing traffic load (arrival rate = 50 p/s)

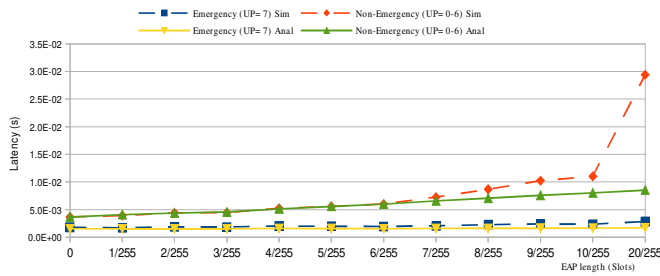


Fig. 24 the effect of the EAP length on the average latency (arrival rate = 100 p/s)

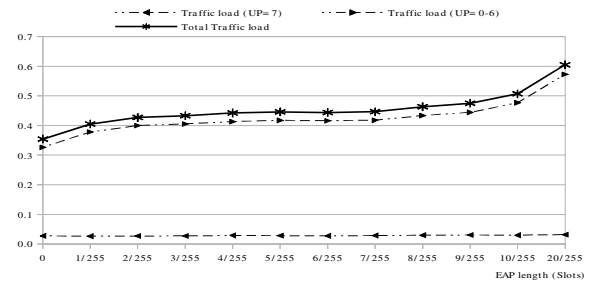


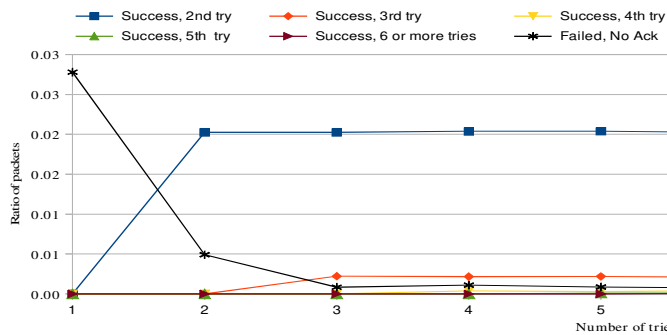
Fig. 25 the effect of the EAP length on queuing traffic load (arrival rate = 100 p/s)

**5.1.4. Impact of Retry limit**

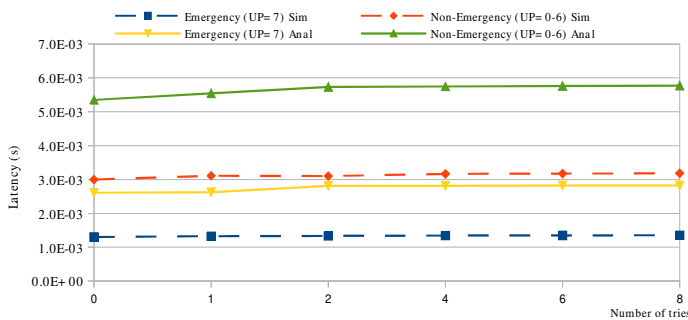
We analyze in this part, the impact of the retry limit on the mean latency and packets delivery. We set the EAP length to zero (0), the percentage of emergency packets to 15% and the number of nodes to five (5). We present analysis results for two arrival rates (100 p/s and 150 p/s), For each of them, we provide the packets breakdown at MAC layer, the latency for emergency and non-emergency traffic as shown in Fig. 27, 28, 30, and 31. To consolidate the latency results, we present in Fig. 29 and 29 the traffic load for both emergency and non-emergency traffic.

We notice from Fig. 27 and Fig. 30 depicting the failed and successful transmissions that, as the maximum number of authorized transmission tries raises, the ratio of failed packets decreases and the ratios of successful transmissions after the  $i^{th}$  attempt ( $i= 1..6$ ) increases. To make

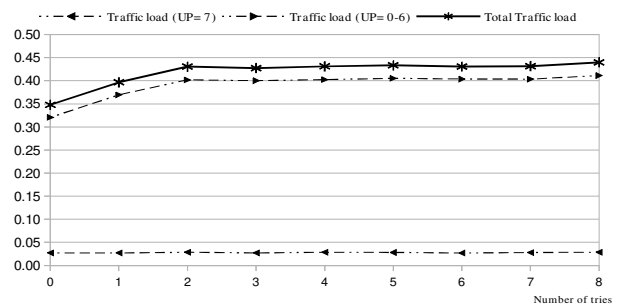
clearer the recorded results, we do not illustrate in these figures the packets breakdown after the first try, because it has extra higher values compared to other types. In fact, the more the maximum authorized attempts raises, the more the packets have the chance to be successfully transmitted in the following Backoff stage, instead of being dropped in the current one due to collisions. We also notice that the two figures Fig. 27 and Fig. 30 have the same shape, except that the ratio of failed packets is greater with the highest data rate, due to the high collision rate. We remark the same fact in Fig. 28 and 31, in which the latency increases considerably when the packet arrival rate increases. In addition to that, in we only showed Fig. 31 the latency results with 0, 1 and 2 as retry limit due to the instability of the queuing system for the values above three (3), with which the total traffic load exceeds one (1) as shown in Fig. 32



**Fig. 26 the effect of the maximum number of tries on packets breakdown at MAC Layer (arrival rate = 100 p/s)**



**Fig. 27 the effect of the maximum number of tries on the average latency (arrival rate = 100 p/s)**



**Fig. 28 the effect of the maximum number of tries on queuing traffic load (arrival rate = 100 p/s)**

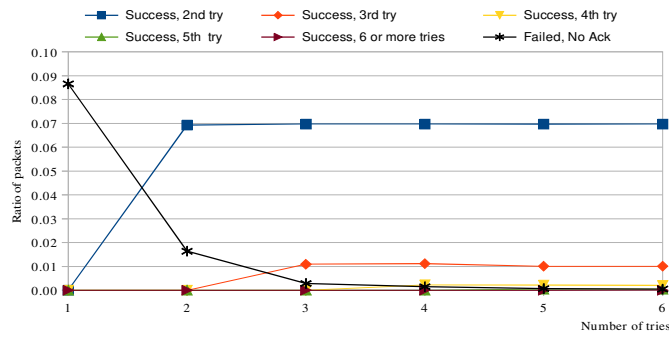


Fig. 29 the effect of the maximum number of tries on packets breakdown at MAC Layer (arrival rate = 150 p/s)

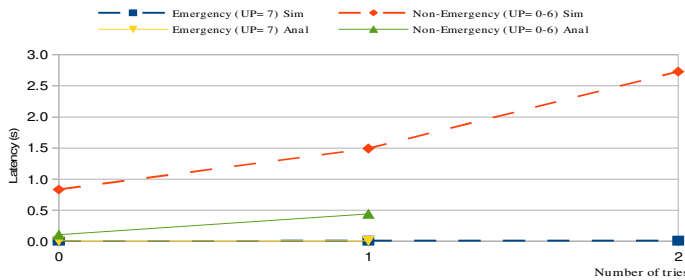


Fig. 30 the effect of the maximum number of tries on the average latency (arrival rate = 150 p/s)

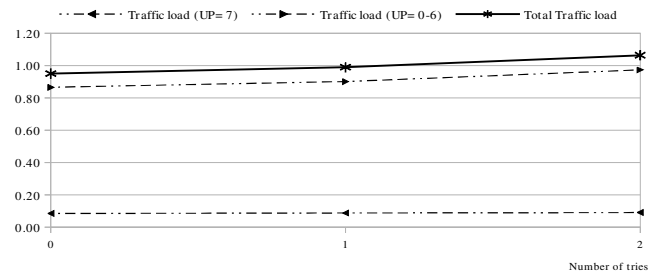


Fig. 31 the effect of the maximum number of tries on queuing traffic load (arrival rate = 150 p/s)

5.1.5. Impact of Emergency packet arrival rate

We perform in this part, analyses on the impact of varying the amount of emergency packet on the IEEE 802.15.6 based WBANs while setting the EAP length to zero (0), the retry limit to two (2) and the number of nodes to five (5). We notice from Fig. 33 that the amount of successfully transmitted packets after the first Backoff stage represents the major part compared to those transmitted after the second Backoff stage and the failed ones after exceeding the retry limit. Moreover, we notice a gap between the recorded results for each arrival rate, which is explained by the extensive use of the medium with high arrival rates.

In Fig. 34 and 36, we show the recorded latency for the two arrival rates, while varying the rate of emergency packets. We notice that the mean

latency increases while decreasing the amount of generated emergency traffic. This is mainly explained by the difference of the Backoff process experienced time by the two types of traffic; as illustrated in the IEEE 802.15.6 CSMA/CA access scheme description, the more the packet's priority decreases, the more the contention window increases, and vice versa. In addition, the adopted queuing strategy allows for high emergency packets to be served before those with low priority. As a result, the more we increase the rate of emergency packets, the more the non-emergency packets have to wait longer in the queue. Fig. 35 and 37 consolidate the obtained results in the latency graphs. Indeed, the increase of the ratio of emergency packets increases the traffic load of non-emergency traffic to the detriment of the emergency one.

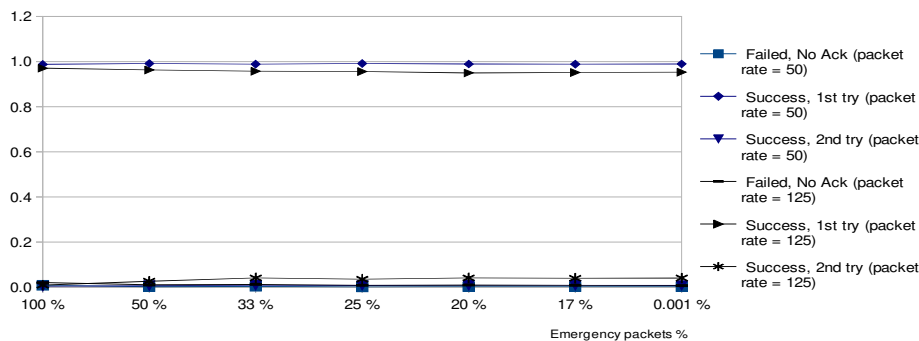


Fig. 32 the effect of percentage of emergency packets on packets breakdown at MAC Layer

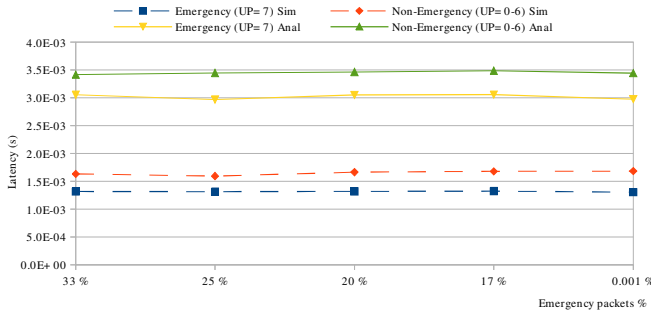


Fig. 33 the effect of percentage of emergency packets on the average latency (arrival rate = 50 p/s)

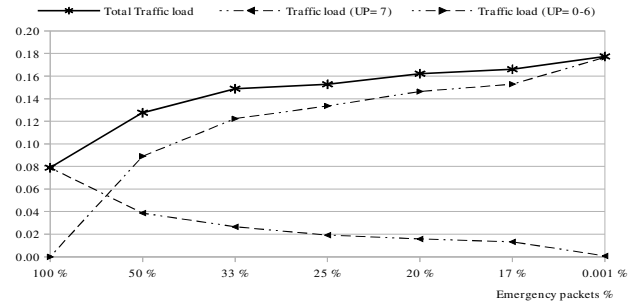


Fig. 34 the effect of percentage of emergency packets on queuing traffic load (arrival rate = 50 p/s)

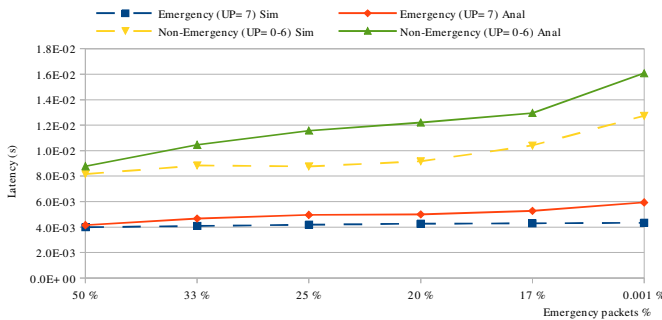


Fig. 35 the effect of percentage of emergency packets on the average latency (arrival rate = 125 p/s)

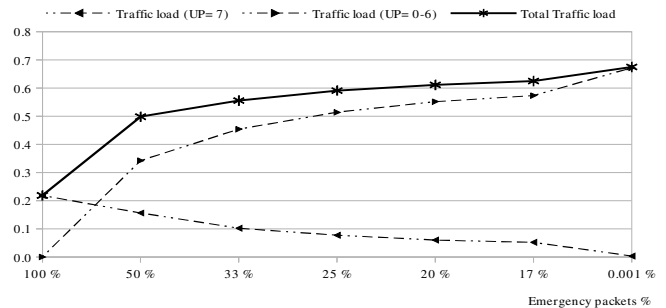


Fig. 36 the effect of percentage of emergency packets on queuing traffic load (arrival rate = 125 p/s)

5.1.6. WBAN vs. WBAN’s nodes performances

As mentioned previously, the proposed analytical model allows performances’ study of the overall WBAN’s or individual WBAN’s nodes. To make the difference clearer between results’ analysis for the overall WBAN and for individual nodes, we consider in our simulations a WBAN describing a home monitoring of an individual cardiac patient. As described in the ISO/IEEE 11073 Draft standard for Point-of-Care (PoC) medical devices (Engineers et al., 2005), this WBAN incorporates five (5) sensor nodes; to ensure the 3-lead ECG supervision, three (3) electrodes are deployed on the rib cage of the patient. The two other sensors are placed on the left and right arms to measure the SpO2 and blood pressure respectively. We carry out the analysis of the latency and the number of received packets at the BNC. The description of the considered WBAN is given in Table 6.

Fig. 38 shows the recorded mean latency for the overall WBAN and for each WBAN’s node separately. We observe that the latency differs for each node according to the traffic arrival rate and to the priority. For the non-emergency traffic, we notice that the recorded mean latency for nodes 2 and 3 is equal to zero and the recorded for the nodes 1, 4 and 5 is higher than that recorded for the overall WBAN. This is explained by the fact that nodes 2 and 3 do not generate non-emergency traffic unlike nodes 1, 4 and 5, which generate all types of traffic. In addition, we notice that the node 4 has the highest non-emergency latency compared to the other nodes. This is due to that node 4 generates traffic with higher data rate than nodes 1 and 5, which leads to an increase in the waiting time in the queue for this type of traffic, thereby increasing the global latency.

On the other hand, we notice that the recorded latency for emergency traffic is different from one node to another; the latency in nodes generating only emergency traffic is lower than in nodes generating both, emergency and non-emergency traffic. This is due to the used queuing strategy, in which we adopted a non-preemptive priority. This strategy does not allow emergency packets to interrupt the already started Backoff process by a packet even if it is a non-emergency one. Therefore, it leads to an increase in the whole latency by increasing the waiting time of emergency packets in the queue. As it was the case for non-emergency traffic, we notice that the latency for emergency traffic in node 4 is higher than that of the nodes 1 and 5. This is due to the fact that nodes 1 and 5 generate emergency traffic with a low rate compared the node 4, which results in increasing the waiting time in the queue. The results in Fig. 39.a and 39.b illustrate packets breakdown. The first noticeable characteristic is that the mean number of failed packets for the overall WBAN is different from those calculated for each node, separately. As explained for the latency analysis, the traffic arrival rate and its priority have an important impact on the nodes’ performances. In fact, the traffic with a high arrival rate increases the number of both, received and failed packets, and the opposite is true.

Table 6. Home monitoring of an individual cardiac patient WBAN characteristics

WBAN Nodes	Geometric coordinates	Arrival rate (packet/s)			
		Total traffic	emergency traffic	Non-emergency traffic	
0	BNC	x= 0.12, y= 0.30	/	/	/
1	Blood pressure	x= 1.20, y= 0.30	1	0,17	0,83 (0,11 for each UP)
2	ECG	x= 1.20, y= 0.68	150	150	0
3	ECG	x= 1.50, y= 0.68	125	125	0
4	ECG	x= 1.50, y= 0.38	150	75	75 (10,71 for each UP)

Overall WBAN	87,2	70,694	16,506
--------------	------	--------	--------

From the above results, since the analyses, we notice that the results obtained by simulations are relatively equivalent to those obtained by the analytical model. Although in some cases we notice divergences in the obtained results as shown in the figures: 16, 18 which illustrate the calculated latency in a WBAN constituted by high number of nodes with a high packet arrival rate. This divergence is explained by the fact that in such case, the WBAN runs in a saturated regime with high traffic intensity, which increases the number of collisions. As a result, the I-Ack frame indicating the successful transmission of a packet can fail. This case doesn't taken into consideration in our analytical model, which assume the only cause of transmission failing is the collision between packets. We also notice in many evaluations, such as in figures 12, 17 and 19 that the

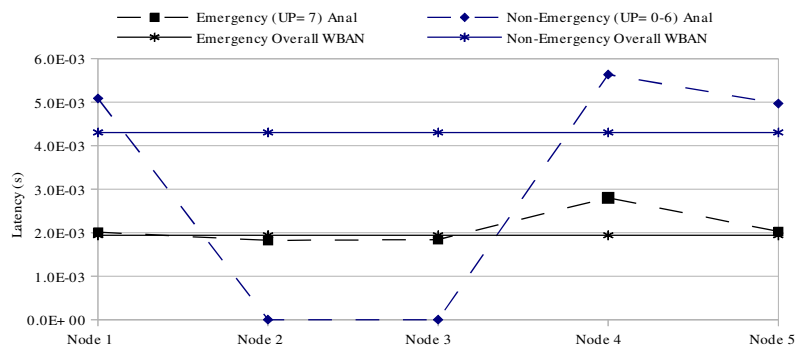


Fig. 37 the average latency per node

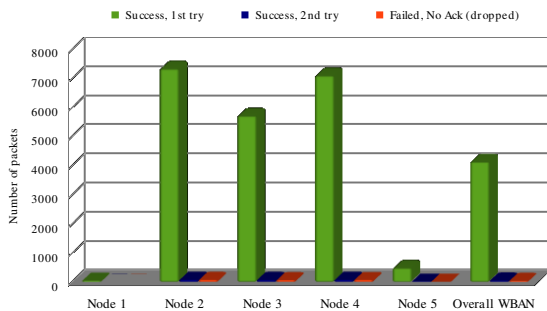


Fig. 38.a packets breakdown at MAC layer

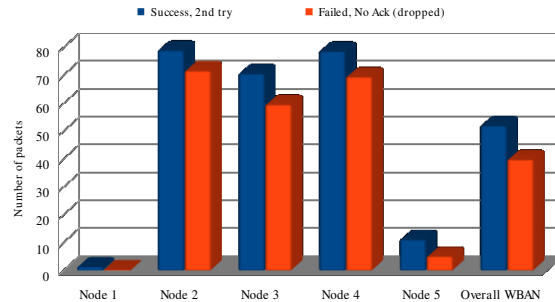


Fig. 38.b packets breakdown at MAC layer

5	Spo2	x= 1,00, y= 0.38	10	3,3	6,7 (0,95 for each UP)
---	------	------------------	----	-----	------------------------

In this situation, the analytical model cannot provide any results. However, the simulation analysis remains valid by dropping new arriving packets from the queue (Buffer overflow) and can despite this offer metrics' evaluation as it shown in Fig. 31.

On the other hand, we conclude that limiting the analyses of WBAN in the mean values of performances metrics may not reflects all WBANs performances, especially in the case where nodes do not have the same configuration and constraints such as the arrival rates and packets' priorities

total traffic load exceeds 1, which makes the queuing system unstable.

## 6. Conclusion and Future Scope

In this study, we proposed a general and accurate analytical model of the IEEE 802.15.6 based WBANs, with heterogeneous traffic in terms of priority. In the first step, based on the renewal reward process, we provided an analytical sub-model depicting the IEEE 802.15.6 based CSMA/CA Backoff process. In the second step, an M/G/1 queuing model with non-preemptive priority is proposed to handle emergency traffic at MAC queues. The performance measures obtained by the analytical

model were validated by accurate simulations using Castalia Simulator. Results showed that using a queuing model with priority improves the latency and the delivery rate of emergency traffic in detriment of non-emergency ones, which is in perfect agreement with the IEEE802.15.6 QoS targets. On the other hand, we illustrated how the proposed model can allow the computation of performances measures of individual nodes as well as the overall WBAN, which was not offered by previous analytical models. Our on-going work will analyze the IEEE 802.15.6 based WBANs with an M/G/1/k non-preemptive priority in which MAC buffers are limited in length and extend the analytical model to handle packets length variation and the Ack frame failing transmission. The renewal reward modeling approach can also be extended to analyze networks with non-saturated conditions and channel fading and shadowing caused by communication around the human body.

## References

- Adan, I., 2001. Queueing theory : Ivo Adan and Jacques Resing. Eindhoven University of Technology. Department of Mathematics and Computing Science, Eindhoven.
- Alam, M., Hamida, E., 2014. Surveying Wearable Human Assistive Technology for Life and Safety Critical Applications: Standards, Challenges and Opportunities. *Sensors* 14, 9153–9209. <https://doi.org/10.3390/s140509153>
- Benmansour, T., Ahmed, T., Moussaoui, S., 2017. Performance analyses and improvement of the IEEE 802.15.6 CSMA/CA using the low latency queuing, in: 2017 IEEE 22nd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD). IEEE, pp. 1–6. <https://doi.org/10.1109/CAMAD.2017.8031623>
- Benmansour, T., Ahmed, T., Moussaoui, S., 2016. Performance Evaluation of IEEE 802.15.6 MAC in Monitoring of a Cardiac Patient, in: 2016 IEEE 41st Conference on Local Computer Networks Workshops (LCN Workshops). IEEE, pp. 241–247. <https://doi.org/10.1109/LCN.2016.054>
- Bianchi, G., 2000. Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE J. Sel. Areas Commun.* 18, 535–547. <https://doi.org/10.1109/49.840210>
- Bianchi, G., 1998. IEEE 802.11 - Saturation throughput analysis. *IEEE Commun. Lett.* 2, 318–320. <https://doi.org/10.1109/4234.736171>
- Bradai, N., Fourati, L.C., Kamoun, L., 2014. Investigation and performance analysis of MAC protocols for WBAN networks. *J. Netw. Comput. Appl.* 46, 362–373. <https://doi.org/10.1016/j.jnca.2014.09.012>
- Chowdhury, M.S., Ashrafuzzaman, K., Kwak, K.S., 2014a. Saturation throughput analysis of IEEE 802.15.6 slotted aloha in heterogeneous conditions. *IEEE Wirel. Commun. Lett.* 3, 257–260. <https://doi.org/10.1109/WCL.2014.021714.140008>
- Chowdhury, M.S., Khan, P., Jung, J., Kwak, K.S., 2014b. Modeling Slotted Aloha of WBAN in non-saturated conditions. *KSII Trans. Internet Inf. Syst.* 8, 1901–1913. <https://doi.org/10.3837/tiis.2014.06.005>
- Deepak, K.S., Babu, A. V., 2018. Improving reliability of emergency data frame transmission in IEEE 802.15.6 wireless body area networks. *IEEE Syst. J.* 12, 2082–2093. <https://doi.org/10.1109/JSYST.2017.2717189>
- Doremalen, J.B.M., 1983. A mean-value approach for M/G/1 priority queues.
- Engineers, E., Avenue, T.P., Licensing, S., Licensing, S., 2005. Draft Standard for Health informatics - Point-of-care medical device communication - Nomenclature - Implantable device , cardiac 4.
- Fatehy, M., Kohno, R., 2014. A novel contention probability dynamism for IEEE 802.15.6 standard. *EURASIP J. Wirel. Commun. Netw.* 2014, 92. <https://doi.org/10.1186/1687-1499-2014-92>
- Fourati, H., Idoudi, H., Saidane, L.A., 2018. Intelligent slots allocation for dynamic differentiation in IEEE 802.15.6 CSMA/CA. *Ad Hoc Networks* 72, 27–43. <https://doi.org/10.1016/J.ADHOC.2018.01.007>
- Ghaderi, J., Srikant, R., 2013. The Impact of Access Probabilities on the Delay Performance of Q-CSMA Algorithms in Wireless Networks. *IEEE/ACM Trans. Netw.* 21, 1063–1075. <https://doi.org/10.1109/TNET.2012.2215964>
- Huang, R., Nie, Z., Duan, C., Liu, Y., Jia, L., Wang, L., 2015. Analysis and Comparison of the IEEE 802.15.4 and 802.15.6 Wireless Standards Based on MAC Layer, in: *Health Information Science*. Springer International Publishing, pp. 7–16. [https://doi.org/10.1007/978-3-319-19156-0\\_2](https://doi.org/10.1007/978-3-319-19156-0_2)
- IEEE, 2006. IEEE Standard for Information technology- Telecommunications and information exchange between systems- Local and metropolitan area networks-Specific requirements-Part 15.4: Wireless MAC and PHY Specifications for Low-Rate WPANs, Control. IEEE. <https://doi.org/10.1109/IEEESTD.2006.232110>
- IEEE, 2002. IEEE Standard for Telecommunications and Information Exchange Between Systems - LAN/MAN - Specific Requirements, IEEE Std 802.15.1-2002. IEEE. <https://doi.org/10.1109/IEEESTD.2002.93621>

- IEEE, 1997. IEEE Standard for Information Technology- Telecommunications and Information Exchange Between Systems-Local and Metropolitan Area Networks-Specific Requirements-Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. IEEE Std 802.11-1997 i-445. <https://doi.org/10.1109/IEEESTD.1997.85951>
- IEEE Standards Association, 2012. IEEE Standard for Local and metropolitan area networks - Part 15.6: Wireless Body Area Networks, IEEE Std. <https://doi.org/10.1109/IEEESTD.2012.6161600>
- Iftikhar, M., Elaiwi, N. Al, Aksoy, M.S., 2014. Performance Analysis of Priority Queuing Model for Low Power Wireless Body Area Networks (WBANs). *Procedia Comput. Sci.* 34, 518–525. <https://doi.org/10.1016/j.procs.2014.07.060>
- Jacob, A.K., Kishore, G.M., Jacob, L., n.d. Lifetime and latency analysis of IEEE 802.15.6 WBAN with interrupted sleep mechanism. *Sādhanā* 42, 865–878. <https://doi.org/10.1007/s12046-017-0648-2>
- Kateretse, C., Lee, G.-W., Huh, E.-N., 2013. A Practical Traffic Scheduling Scheme for Differentiated Services of Healthcare Systems on Wireless Sensor Networks. *Wirel. Pers. Commun.* 71, 909–927. <https://doi.org/10.1007/s11277-012-0851-8>
- Khan, P., Ullah, N., Ali, F., Ullah, S., Hong, Y.S., Lee, K.Y., Kim, H., 2017a. Performance analysis of different backoff algorithms for WBAN-based emerging sensor networks. *Sensors (Switzerland)* 17, 492. <https://doi.org/10.3390/s17030492>
- Khan, P., Ullah, N., Kim, H., 2017b. WBAN MAC protocols— Non-saturation modeling and performance analysis. *KSII Trans. Internet Inf. Syst.* 11, 1462–1476. <https://doi.org/10.3837/tiis.2017.03.012>
- Kulkarni, V.G., 2011. Introduction to Modeling and Analysis of Stochastic Systems. Chapman & Hall. <https://doi.org/10.1007/978-1-4419-1772-0>
- Latré, B., Braem, B., Moerman, I., Blondia, C., Demeester, P., 2011. A survey on wireless body area networks. *Wirel. Networks* 17, 1–18. <https://doi.org/10.1007/s11276-010-0252-4>
- Li, C., Geng, X., Yuan, J., Sun, T., 2013. Performance analysis of IEEE 802.15.6 MAC protocol in beacon mode with superframes. *KSII Trans. Internet Inf. Syst.* 7, 1108–1130. <https://doi.org/10.3837/tiis.2013.05.010>
- Li, M., Zhuang, M., 2012. An overview of Physical layers on wireless body area network, in: *Anti-Counterfeiting, Security, and Identification*. IEEE, pp. 1–5. <https://doi.org/10.1109/ICASID.2012.6325342>
- Ling, X., Cheng, Y., Mark, J.W., Shen, X., 2008. A renewal theory based analytical model for the contention access period of IEEE 802.15.4 MAC. *IEEE Trans. Wirel. Commun.* 7, 2340–2349. <https://doi.org/10.1109/TWC.2008.070048>
- Little, J.D.C., 1961. A Proof for the Queuing Formula:  $L = \lambda W$ . *Oper. Res.* 9, 383–387. <https://doi.org/10.1287/opre.9.3.383>
- Marbukh, V., Barbi, M., Sayrafian, K., Alasti, M., 2016. A queue-size & channel quality based adaptation of the energy detection threshold in IEEE802.15.6 CSMA/CA, in: *2016 IEEE 18th International Conference on E-Health Networking, Applications and Services (Healthcom)*. IEEE, pp. 1–6. <https://doi.org/10.1109/HealthCom.2016.7749526>
- Mukherjee, A., Bandyopadhyay, B., Das, D., Chatterjee, A., Ahmed, S.J., Naskar, M., 2014. Markov chain based analysis of IEEE 802.15.6 MAC protocol in real life scenario, in: *Proceedings of the 9th International Conference on Body Area Networks*. ICST, pp. 331–337. <https://doi.org/10.4108/icst.bodynets.2014.257202>
- Muthulakshmi, A., Shyamala, K., 2016. Queuing Based Emergency Handling in 7, 2231–2239.
- Nabila, A., Mohamed, E.B., 2019. A QoS based comparative analysis of the IEEE standards 802.15.4 & 802.15.6 in WBAN-based healthcare monitoring systems, in: *2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS)*. IEEE, pp. 1–5. <https://doi.org/10.1109/WITS.2019.8723709>
- NICTA, 2011. Castalia Simulator [WWW Document]. URL <https://castalia.forge.nicta.com.au/index.php/en/> (accessed 11.21.15).
- Papir, Z., 2005. Queuing Theory with Applications to Packet Telecommunications [Book Review]. *IEEE Commun. Mag.* 44, 2005–2006. <https://doi.org/10.1109/MCOM.2006.1637937>
- Quan, D.T., Hiep, P.T., Kohno, R., 2017. Performance Analysis Method for IEEE 802.15.6 Based WBANs with Adaptive BCH Code Rates. *Wirel. Pers. Commun.* 94, 605–619. <https://doi.org/10.1007/s11277-016-3639-4>
- Rashwand, S., Mistic, J., 2012. Two-tier WBAN/WLAN healthcare networks; Priority considerations, in: *GLOBECOM - IEEE Global Telecommunications Conference*. IEEE, pp. 5398–5403. <https://doi.org/10.1109/GLOCOM.2012.6503979>
- Rashwand, S., Mišić, J., 2012. Effects of access phases lengths on

- performance of IEEE 802.15.6 CSMA/CA. *Comput. Networks* 56, 2832–2846. <https://doi.org/10.1016/j.comnet.2012.04.023>
- Rashwand, S., Mišić, J., Khazaei, H., 2011a. IEEE 802.15.6 under saturation: Some problems to be expected. *J. Commun. Networks* 13, 142–148. <https://doi.org/10.1109/JCN.2011.6157413>
- Rashwand, S., Mišić, J., Khazaei, H., 2011b. Performance analysis of IEEE 802.15.6 under saturation condition and error-prone channel. 2011 IEEE Wirel. Commun. Netw. Conf. WCNC 2011 1167–1172. <https://doi.org/10.1109/WCNC.2011.5779296>
- Rashwand, S., Mistic, J., Mistic, V.B., 2016. Analysis of CSMA/CA Mechanism of IEEE 802.15.6 under Non-Saturation Regime. *IEEE Trans. Parallel Distrib. Syst.* 27, 1279–1288. <https://doi.org/10.1109/TPDS.2015.2447528>
- Salam, A., Nadeem, A., Ahsan, K., Sarim, M., Rizwan, K., 2014. A class based QoS model for Wireless Body Area Sensor Networks. *Res. J. Recent Sci.* 3, 69–78.
- Sarkar, S., Misra, S., Bandyopadhyay, B., Chakraborty, C., Obaidat, M.S., 2015. Performance analysis of IEEE 802.15.6 mac protocol under non-ideal channel conditions and saturated traffic regime. *IEEE Trans. Comput.* <https://doi.org/10.1109/TC.2015.2389806>
- Ullah, S., Chen, M., Kwak, K.S., 2012. Throughput and delay analysis of IEEE 802.15.6-based CSMA/CA protocol. *J. Med. Syst.* 36, 3875–3891. <https://doi.org/10.1007/s10916-012-9860-0>
- Ullah, S., Tovar, E., Kim, K.-I., Kim, K.H., Imran, M., 2018. Performance Analysis of Priority-Based IEEE 802.15.6 Protocol in Saturated Traffic Conditions. *IEEE Access* 1–1. <https://doi.org/10.1109/ACCESS.2018.2878315>
- Veeraraghavan, M., 2004. Priority queueing (nonpreemptive) 1, 1–8.
- Wolff, R.W., 1982. Poisson Arrivals See Time Averages. *Oper. Res.* 30, 223–231. <https://doi.org/10.1287/opre.30.2.223>
- Xinhua Ling, Yu Cheng, Mark, J.W., Xuemin Shen, 2008. A Renewal Theory Based Analytical Model for the Contention Access Period of IEEE 802.15.4 MAC. *IEEE Trans. Wirel. Commun.* 7, 2340–2349. <https://doi.org/10.1109/TWC.2008.070048>
- Yi, C., Alfa, A.S., Cai, J., 2016. An Incentive-Compatible Mechanism for Transmission Scheduling of Delay-Sensitive Medical Packets in E-Health Networks. *IEEE Trans. Mob. Comput.* 15, 2424–2436. <https://doi.org/10.1109/TMC.2015.2500241>
- Yi, C., Cai, J., 2017. A Priority-Aware Truthful Mechanism for Supporting Multi-Class Delay-Sensitive Medical Packet Transmissions in E-Health Networks. *IEEE Trans. Mob. Comput.* 16, 2422–2435. <https://doi.org/10.1109/TMC.2016.2628034>
- Yu, H., Fu, L., Xu, Y., 2012. Unified fixed-point analysis of IEEE 802.11 WLAN under saturated and unsaturated conditions. *Wirel. Commun. Mob. Comput.* 12, 588–597. <https://doi.org/10.1002/wcm.998>