

## The Effects of Transmission Power and Modulation Schemes on the Performance of WBANs in on-Body Medical Applications

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### ARTICLE INFO

Article history:

Received: 13 July, 2020

Accepted: 02 August, 2020

Online: 28 August, 2020

Keywords:

Wireless Body Area Networks

IEEE 802.15.6

On-body medical applications

Packet Loss Rate

Throughput

Latency

### ABSTRACT

Wireless Body Area Networks support the operation within multiple frequency bands. Thus, they can be integrated in several applications, one of which is on-body medical monitoring applications, as concerned in this paper. Therefore, the purpose of this study is to present the impact of transmission power and both of Differential Binary Phase Shift Keying and Differential Quadrature Phase Shift Keying modulation schemes, on the performance of a WBAN model based on the IEEE 802.15.6 2.4 GHz narrow-band, dedicated to on-body medical applications. This involves identifying the modulation scheme(s) and transmission power level(s) to be adopted for these applications, that can be classified into three types depending on their data rate (low, medium and high data rate medical applications), in order to meet Packet Loss Rate and latency requirements. The numerical study has confirmed that the adoption of DBPSK modulation and low transmission powers provides good performance for low data rate monitoring applications. At medium data rates, a relatively increased transmit power was required. However, at high data rates, DQPSK modulation with a 0 dBm transmission power seemed to be the right choice to be made in terms of the mentioned performance indicators.

### 1. Introduction

The actual improved life expectancy all over the world has led to an increased rate of population ageing [1], which may overburden conventional healthcare infrastructures and consequently increase healthcare costs. In addition, each year millions of people die due to late diagnosis of certain fatal diseases such as cancer, cardiovascular diseases, Parkinson's disease and many others [1]. These losses could have been largely avoided if those illnesses were detected in time.

The massive growth of electronic systems [2] resulted in the appearance of small biosensors operating at the human body scale as Wireless Body Area Networks. When used in healthcare systems, WBANs can simplify the monitoring of simple parameters such as body temperature, blood pressure, ECG, etc., or be integrated in more complicated processes like changing programs for implantable pacemakers and defibrillators [3],

retrieving biokinetic information [4–6], or adjusting body limbs movements when damaged by car accidents, for example.

In medical applications [7], WBANs are considered to be the key solution to prevent a variety of cardiovascular diseases [8–9], such as myocardial infarction, which are often related to intermittent rather than permanent anomalies [10]. In addition, as the number of diabetic people worldwide is expected to reach 380 million by 2025, WBANs can also be adopted in diabetes monitoring [11–12]. Therefore, it will be necessary to integrate medical monitoring systems based on WBANs in our day to day life, in order to correctly and timely dose medicines, and thus reduce the risk of many complications. Similarly, miniaturized sensors can further be used to detect cancer cells, allowing the doctor to first diagnose tumors without the need for a biopsy [10]. As for people suffering from asthma, WBANs may also ensure the detection of allergenic agents in the environment surrounding the patient. In [13] for example, The authors proposed an alert system triggered by the detection of an environment the patient is allergic

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to. Moreover, they can be integrated into the rehabilitation process to bring patients' functional capacity back to normal [5].

For all the above mentioned medical applications, data traffic can be classified into three categories [10]: on-demand, urgent and normal traffic. For diagnostic purposes, on-demand traffic is initiated by the coordinator in order to obtain information about the patient's state of health. As for urgent traffic, it is initiated by sensor nodes when the data collected exceeds a predefined threshold. This type of data is not time-dependent and is generated in an unpredictable manner. As for normal traffic, it generally concerns normal non-critical data, that include discrete and systematic health monitoring.

In non-medical applications, WBANs take place in fitness, performance and wellness monitoring, in cognitive biometry [14] for a secure authentication to information systems, in serious gaming [15] for educational purposes, and in sport.

Given this variety of applications, the actual wireless short range technologies do not fully comply with the specific requirements and technical challenges of WBANs [16]. For this reason, IEEE 802.15.6 was created in November 2007 to deliver an international standard for highly reliable, short-range, and bodywide communications, while providing a broad range of data rates going from 75.9 Kbps (narrowband) to 15.6 Mbps (ultra-broadband); to cover a variety of applications. The standard provides an advanced MAC layer that serves three physical layers: The Narrowband (NB), the Ultra Wide Band (UWB) and the Human Body Communication (HBC) physical layers. These are chosen according to the intended application. We are interested in the narrowband physical layer, which alone offers 7 different frequency bands, one of which is the 2.4 GHz band (2400-2483.5 MHz) and is often favored over the other ones for its worldwide availability [17]. It is also the most mature band [18] which offers a larger bandwidth. Furthermore, it uses familiar PHY modules, that are already extensively applied in WiFi and Bluetooth [19], and adopts smaller antennas, which makes it ideal for the majority of on body WBAN applications. All these features contribute to make the 2.4 GHz ISM band of IEEE 802.15.6, the most widely used band.

According to the specifications of the IEEE 802.15.6 standard [20–21], The 2.4 GHz narrowband provides two modulation schemes: DQPSK and DBPSK. In addition, the nodes in a WBAN must be able to transmit their data using a power level ranging from -10 dBm (0.1 mW) to 0 dBm (1 mW) [1], so as not to exceed the specific absorption rate fixed at 1.6 W / kg in 1g of body tissue. However, the choice of one of these two modulations and the appropriate level of node transmission power, may be related to the intended application and its technical requirements, such as data rate, duty cycle, sensitivity to data loss and latency, etc.

Therefore, the aim of this paper is to study the adequacy of DBPSK and DQPSK modulations, as well as different transmission power levels in the 2.4 GHz narrowband, for a realistic WBAN model based on the IEEE 802.15.6 standard, with the requirements of normal traffic on-body medical monitoring applications, such as electrocardiogram, pulse oximetry, body temperature measurement etc., in terms of PLR, throughput and latency.

The proposed contributions of the present paper are based on two detailed numerical studies dealing with the impact of transmission power on one hand, and the two modulation schemes DBPSK and DQPSK on the other, on the performances of a WBAN model based on the IEEE 802.15.6 standard. This evaluation is done by means of three parameters: PLR, throughput and latency.

The remainder of this paper is presented as follows:

Section 2 gives an overview of the IEEE 802.15.6 standard, addressing its technical requirements for the MAC layer, with a special highlight on the beacon mode with superframe boundaries, and for the Narrow Band physical layer. Section 3 presents the PHY and MAC layer configuration of the studied WBAN model. The emphasis in this section is put on the adopted on-body channel model and the settings of MAC and radio modules. Section 4 discusses the obtained results from the performed study. and Section 5 concludes the paper.

## 2. The IEEE 802.15.6 Standard

### 2.1. Technical requirements

To implement a WBAN compliant with the IEEE 802.15.6 standard, several requirements should be considered as listed below [1] :

- Bit rate: Inter-sensor communications within WBANs should be carried out at data rates ranging from 10 kbps to 10 Mbps.
- Packet Error Rate (PER): For the majority (~95%) of the best performing links, the PER must be below 10% for a reference payload of 256 bytes.
- Easy integration and removal of nodes: Adding, removing or replacing nodes in a WBAN, should be done easily and in less than 3 seconds approximately.
- Maximum number of nodes: the size of a WBAN must not exceed 256 nodes.
- Communication reliability in case of mobility: The performance of a WBAN network must not be degraded to the point of causing data loss if the patient is mobile. Furthermore, WBANs must not cause any discomfort to the patient while moving.
- Latency and jitter: Latency and jitter are two important metrics for evaluating the performance of a WBAN. Latency should not be greater than 125 ms in medical applications and 250 ms in non-medical applications. For the jitter, it should be lower than 50 ms.
- On-body and in-body WBANs should be able of coexisting.
- Coexistence between adjacent BANs: up to 10 WBANs should be able to coexist in a space of 6m<sup>3</sup> approximately.
- Transmission power: All nodes in a WBAN must be capable of transmitting data in the range [-10 dBm, 0 dBm].
- Specific Absorption Rate (SAR): according to the Federal Communications Commissions (FCC) SAR is 1.6 W / kg in 1 g of body tissue.
- Cross-interference: WBANs must be able to provide acceptable functional performances in an environment of heterogeneous coexistence with other wireless network technologies (wifi, IEEE 802.15.14, etc.).

- Quality of Service (QoS) management must be able to provide security mechanisms, and priority features for services in a WBAN.

## 2.2. MAC layer of the standard

In order to control channel access in a WBAN, the IEEE 802.15.6 standard has defined a sophisticated MAC layer serving 3 physical layers that are designated according to the desired application.

To ensure time-referenced resources allocations in its WBAN, the coordinator (hub) must divide its transmission time axis (channel), into a series of superframes while having the choice of delimiting them or not with beacons (frames transmitted by the hub to simplify network management, such as coordination in the access to the media and power management for nodes, or to synchronize time in a WBAN, etc). However, in some cases, the coordinator may not need to time reference its allocations in the WBAN, so it can operate without using a time base, therefore, without having to transmit beacons. This means that a hub in a WBAN is able to function in one of the three access modes:

- The beacon mode with superframe boundaries.
- The non-beacon mode with superframe boundaries.
- The non-beacon mode without superframe boundaries

In this paper we only focus on Beacon mode with superframe boundaries, in which the hub sends a beacon (B) in the beginning of every active superframe to delimit it. unlike non-bacon modes, where the WBAN node can transmit its data to the coordinator using CSMA/CA or poll it to receive the data. In the beacon mode with superframe boundaries, the access phases that constitute each superframe are:

- Exclusive access phases (EAP1 and EAP2): These are time slots allocated by the hub to the rest of the WBAN nodes to transmit urgent and high-priority traffic.
- Random access phases (RAP 1 and RAP2): Dedicated to ensure random access to the medium, using CSMA/CA or Slotted ALOHA protocols (but not both at once).
- Managed Access Phases (MAP): During these access phases, the coordinator can guarantee different methods of access to the medium by the nodes of the WBAN, namely: improvised access, scheduled access and unscheduled access.
  - Improvised access: where polled (uplink allocation interval, adapted to unexpected or additional ordinary traffic service) or posted (downlink allocation interval, adapted to "unexpected" or "additional" traffic service on the downlink) allocations are generally assigned outside the planned uplink or downlink allocations.
  - Scheduled access: which is based on a pre-reservation and a validated scheduling, in such a way that nodes and the coordinator obtain scheduled recurrent time intervals to initiate frame transactions.
  - Unscheduled access: which is a combination of scheduled access and polling.

- Contention access phase (CAP): with this access phase, a time interval is defined by the coordinator and announced via a previous non-beacon frame (B2) for contention access.

## 2.3. Narrowband physical layer (NB)

As noted earlier in section I, due to the multitude of applications supported by WBANs, The IEEE 802.15.6 standard has defined three physical layers (NB, UWB and HBC). These are responsible for activating/deactivating the radio transceivers of sensor nodes, evaluating the RF channel by listening to the RF transmissions of the different sensor nodes (this mission is known as Clear Channel Assessment or CCA) and controlling the transmission/reception of data on the channel. In this work we are interested in the NarrowBand physical layer (NB), specific to medical applications like the capture of physiological signals such as temperature, blood pressure, ECG, EEG, etc.

### 2.3.1. Physical frame structure of NB-PHY

As shown in figure 1, the Physical Protocol Data Unit (PPDU) for the NB PHY layer includes:

- A PLCP (Physical Layer Convergence Procedure) preamble: 90-bit coded and used to help the receiver in time synchronization and carrier offset recovery.
- A PLCP header: it is a 31-bit coded sequence that must be inserted after the PLCP preamble to transmit information about the PHY parameters responsible for helping the receiver to decode the PSDU, essentially information about the data rate and length of the MAC frame body (data without a MAC or FCS header), and information about the following packet, whether it will be sent in BURST mode or not. These data will then be protected by a 4-bit header check sequence (HCS) (CRC-4 ITU). moreover, to improve the robustness of the PLCP header, a BCH code (31, 19, t = 2) will be applied.
- PSDU (Physical Service Data Unit): this is the last major component of the PPDU to be transmitted, it is constructed by combining the MAC header (7 bytes), the MAC frame body with a size ranging from 0 to 255 bytes, and a 2-bit Frame Check Sequence (FCS).

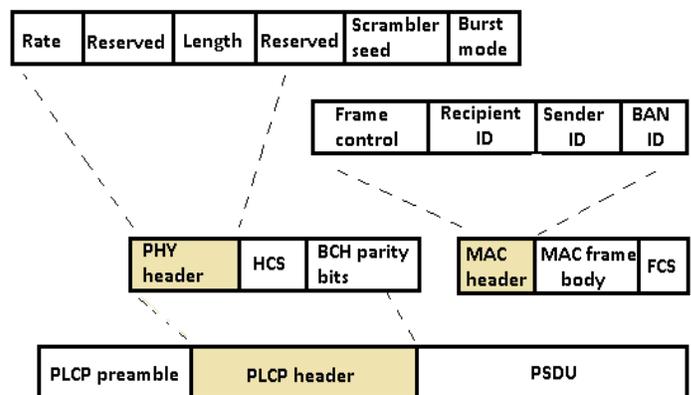


Figure1: NB PHY frame structure

### 2.3.2. NB physical layer Specifications

The IEEE 802.15.6 NB physical layer supports data transmission in a multiple frequency bands, summarized in Table 1, supporting different modulation schemes and data rates ranging from 75.9kbps to 971.4 kbps. one of the bands mentioned in the table is the 2.4 GHz band (2400-2483.5MHz) which is often the most preferred for the reasons mentioned earlier. However, several other technologies such as Wi-Fi (IEEE 802.11), Bluetooth (IEEE 802.15.1), IEEE 802.15.4 / ZigBee and others operate in this same band, and this is a real challenge due to the interference caused by the coexistence of these technologies with WBANs operating at 2.4 GHz (cross interference), and the mutual interference resulting from the coexistence of more than one WBAN in the same area [22].

### 3. Description and Settings of the Studied WBAN Model

Nodes in a WBAN can be logically arranged in different topologies, star, tree or mesh. Therefore, choosing the most suitable topology is important because of its direct impact on WBAN performances in terms of power consumption, ability to handle heterogeneity and robustness against failures [10]. As a result, most researchers assume that a one-hop star topology, where nodes send data directly to the hub without the need for relays, is the best solution [10].

The WBAN model chosen for this study operates in the NB PHY layer, at 2.45 GHz more specifically. It is composed of eleven sensor nodes, including a coordinator, which is placed at the center of the patient's belly as shown in Figure 2 [22–24]. The eleven sensors are distributed over the patient's body in a single-hop (single coordinator) star topology, where communication frames are sent directly between the coordinator and each of the other ten sensors, with no need to additional relays. Choosing these node positions is driven by the desire to monitor most of the vital signs described in the on-body medical applications of WBANS, as those proposed for IEEE 802.15.6 [25–26]. This monitoring is carried out by means of regular and programmed sampling of a number of physiological parameters such as temperature, blood pressure, pulse oximetry, ECG, EEG, etc. We have classified these applications in Table 2 into three categories: low, medium and high data rate on-body medical applications. Their technical requirements are covered and described in the references [3, 27].

#### 3.1. On-body channel model

Unlike in-body communications, where signal propagation occurs through body tissues, signals in on-body systems often propagate over body surface. Such propagation might bring up a mixture of surface, creeping, diffracted, scattered and free space waves, according to the position of the antenna [10, 28]. Furthermore, placing WBAN nodes on or around the human body, exposes them to antenna-body interaction effects, including near field coupling, distortion of the radiation pattern, and changes in the antenna impedance, which affects the functional performances of the nodes [29]. This has prompted many researchers to design on-body antennas [30–31] that take these constraints into account. In addition, patient mobility (caused by usual gestures or physiological processes such as breathing) as well as physical variations in the patient's local environment, make it difficult to model or select the appropriate on-body BAN channel, especially

since it is sensitive to temporal variations of the received signal [29]. Thus, taking into account all these issues, a good characterization of the propagation channel is required before designing any WBAN solutions.

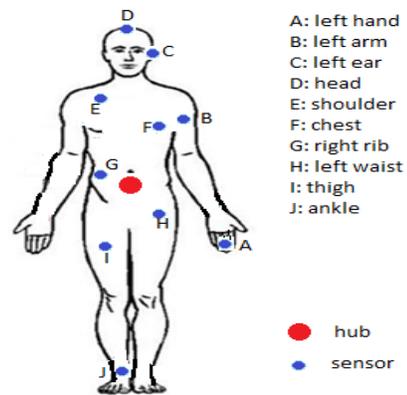


Figure 2: The proposed WBAN model

#### 3.1.1. Path loss model

To approach a realistic on-body channel modeling in our WBAN model of study, we consider that signal propagation between nodes happens on the human body surface. This brings us to distinguish two possible kinds of on-body channels:

- **The Line Of Sight channel (LOS):** characterized by the absence obstacles between sensors and the hub.
- **The Non-line Of Sight channel (NLOS)** characterized by the presence of obstacles between sensors and the hub.

Thus, for the 2.4 GHz narrow band, IEEE 802.15.6 specified two path loss models, for propagation both with and without a line-of-sight, referred to as CM3A and CM3B, respectively [32]. In this paper, the CM3B trajectory loss model is adopted, where path loss is reduced in an exponential manner around the body circumference when BAN nodes are out of line of sight. It becomes flat over longer distances due to the introduction of multipath elements from indoor conditions [32].

In this model, path loss at a distance  $d$  is defined by equation (1):

$$PL(d)[dB] = -10\log_{10} (P_0 e^{-m_0 d} + P_1) + \sigma_p n_p \quad (1)$$

Where :

- $PL(d)$  is the path loss at a distance  $d$  measured in dB
- $P_0$  represents a factor of average losses that occur close to the transmitter, and is related to the antenna design
- $P_1$  denotes the mean attenuation in indoor conditions of the elements irradiated from the body and reflected back to the receiver
- $m_0$  means the exponential mean rate of decay in dB / cm of the creeping wave diffracted around the body
- $n_p$  is a random Gaussian variable of null unit and mean
- $\sigma_p$  is the log-normal variance measured in dB

Table 1: Frequency bands and modulation parameters for the NB PHY layer

| Frequency band (MHz)     | Description   | Modulation scheme      |       | Information data rate (kbps) | Code rate (k/n) |       | Spreading factor |        | Symbol rate (Ksps) |
|--------------------------|---|------------------------|-------|------------------------------|-----------------|-------|------------------|--------|--------------------|
|                          |   | Preamble & PLCP header | PSDU  |                              | PLCP header     | PSDU  | PLCP header      | PSDU   |                    |
| 402-405                  | Medical Implant Communication Service (MICS): Communications between implants | DBPSK                  | DBPSK | 75.9                         | 19/31           | 51/63 | 2                | 2 or 1 | 187.5              |
|                          |   |                        | DQPSK | 151.8                        |                 |       |                  |        |                    |
|                          |   |                        |       | 303.6                        |                 |       |                  |        |                    |
|                          |   |                        |       | 455.4                        |                 |       |                  |        |                    |
| 420-450                  | Wireless Medical Telemetry Services (WMTS) (Japan)                            | GMSK                   | GMSK  | 75.9                         | 19/31           | 51/63 | 2                | 2 or 1 | 187.5              |
|                          |   |                        |       | 151.8                        |                 |       |                  |        |                    |
|                          |   |                        |       | 187.5                        |                 |       |                  |        |                    |
| 863-870                  | WMTS (Europe)   | DBPSK                  | DBPSK | 101.2                        | 19/31           | 51/63 | 2                | 2 or 1 | 250                |
| 902-928                  |   |                        | DQPSK | 202.4                        |                 |       |                  |        |                    |
| 950-958                  |   |                        | D8PSK | 404.8                        |                 |       |                  |        |                    |
| 2360-2400<br>2400-2483.5 | ISM worldwide   | DBPSK                  | DBPSK | 121.4                        | 19/31           | 51/63 | 4                | 4/2/1  | 600                |
|                          |   |                        | DQPSK | 242.9                        |                 |       |                  |        |                    |
|                          |   |                        |       | 485.7                        |                 |       |                  |        |                    |
|                          |   |                        |       | 971.4                        |                 |       |                  |        |                    |

Table 2: Targeted on-body medical applications

| Application category             | Sensor node               | description   | Data Rate  | Duty Cycle (per device) % per time | Power Consumption | latency | Privacy |
|----------------------------------|---------------------------|---|--|------------------------------------|-------------------|---------|---------|
| Low rate medical applications    | Temperature sensor        | Measures body temperature   | 120 bps  | <1%                                | low               | 250 ms  | high    |
|                                  | Glucose sensor (wearable) | Measures glucose level  | 1.6 kbps   | <1%                                | low               | 250 ms  | High    |
|                                  | Blood Pressure (BP)       | The pressure of circulating blood on the walls of blood vessels.  | <10 bps  | < 1%                               | High              | 250 ms  | Medium  |
| Medium rate medical applications | SpO2                      | the oxygen saturation of hemoglobin at the blood capillaries.   | 32 Kbps  | < 1%                               | Low               | 250 ms  | High    |
|                                  | EEG                       | Electroencephalogram : an electrophysiological monitoring technique to record electrical activity of the brain. | 12 leads: 43.2 kbps                                | < 10%                              | low               | 250 ms  | high    |
| High rate medical applications   | ECG                       | Electrical activity of the heart.   | -288 kbps (ECG-12 leads)<br>-71 kbps (ECG-6 leads) | < 10%                              | Low               | 250 ms  | High    |

We have measured for each node the distance separating it from the hub, and by considering that our network is under the same ambient conditions as a normal hospital room, we have calculated the values of path loss for all the links of our WBAN. We present in Table 3, the values of CM3B model parameters, under the conditions of a hospital room [32].

3.1.2. Temporal variation

Temporal variation is also another important aspect in BAN channel modeling due to the rapid changes that can occur in this type of environment. In our WBAN model of study, the mobility of body limbs is captured by a temporal variation component. To the best of our knowledge, no unique model exists in the literature describing temporal variation, but rather a general modeling of this parameter is used [33]. The description of the approach used in the majority of simulators to describe temporal variation is as follows: it is considered that the actual propagation loss may differ from the average propagation loss over time. Therefore, a probability density function (pdf) is developed to cope with this issue. The pdf is determined from the previous observed value and the time elapsed since then. This function cannot be dynamically produced from real models but must rather be derived from experimental measurements.

The actual propagation loss is calculated as the sum of the pre-calculated average propagation loss and the temporal variation.

3.2. MAC module settings

In the studied WBAN model, the beacon mode with superframe boundaries is adopted, in which a beacon is transmitted at the beginning of every active superframe. This mode allows the coordinator to divide the communication channel into multiple access phases. As a result, the MAC module configuration adopted in this work, combines both of random access based on CSMA/CA and scheduled access based on TDMA as presented in detail in our previous work [23].

3.3. Radio module settings

In the 2.4 GHz narrowband, the preamble is always modulated using  $\pi/2$ -DBPSK, and the binary information is modulated with one of the following two differential modulations:  $\pi/2$ -DBPSK or  $\pi/4$  DQPSK. For both of these, the bitstream  $b(n)$ ,  $n=0,1,\dots,N-1$  is transformed into a sequence of symbols  $s(k)$ ,  $k=0,1,\dots,(N/\text{Log}_2(M))-1$  as follows :

$$s(k) = s(k - 1)\exp(j\varphi_k) \tag{2}$$

M denotes the modulation order, and  $s(-1) = \exp(j\pi/2)$  is the reference for the first preamble symbol [20]. The transition values between the  $\varphi_k$  symbols are shown in Tables 4 and 5. for both  $\pi/2$ -DBPSK at  $\pi/4$  DQPSK. To the best of our knowledge, there is still no radio chip available in the market that has been specifically designed to meet IEEE 802.15.6 standard requirements. Therefore, our work relies on a proposed radio chip by Alan Wong et al [34], compliant with the IEEE 802.15.6 standard recommendations for the 2.4 GHz NB PHY layer. The parameters for both modulation schemes of the proposed radio are defined in Table 6.

Table 3: Values of CM3B path loss model parameters in a hospital room

| Parameter       | Value |
|-----------------|-------|
| Frequency (GHz) | 2.45  |
| $P_0$ [dB]      | -25.8 |
| $m_0$ [dB/cm]   | 2.0   |
| $P_1$ [dB]      | -71.3 |
| $\sigma_P$ [dB] | 3.6   |

Table 4: Symbols transition values of  $\pi/2$ -DBPSK

| B(K) | $\varphi_k$ |
|------|-------------|
| 0    | $+\pi/2$    |
| 1    | $-\pi/2$    |

Table 5. Symbols transition values of  $\pi/4$  DQPSK

| B(2K), B(2K+1) | $\varphi_k$ |
|----------------|-------------|
| 0 0            | $\pi/4$     |
| 0 1            | $3\pi/4$    |
| 1 0            | $7\pi/4$    |
| 1 1            | $5\pi/4$    |

4. Results and Discussion

4.1. Effects of transmission power and modulation schemes on the performance of the proposed WBAN model

To assess the impact of transmission power and modulation schemes on the studied WBAN performance, in terms of packet loss rate, throughput, and latency, we used Castalia sensor network simulator as a basis, which is based on OMNeT++ (4.6) platform and includes as standard the support of the IEEE 802.15.6 specifications, which justifies its choice in our numerical study.

In our simulations, BAN nodes send their packets at different data rates to the coordinator using a different transmission power ranging from -10 to 3 dBm, each time, and a different modulation scheme (DBPSK or DQPSK).

4.1.1. Packet Loss Rate (PLR)

Packet losses in a WBAN can be due to various possible causes such as the disconnection of a sensor from the network (no beacon reception is detected) or simply the inability to transmit data in the defined transmission tries. Therefore, The packet loss rate indicates the chance that a packet produced by a node cannot be received normally and as expected by the coordinator [35].

Nevertheless, this parameter can be impacted by different factors [36]:

- Environmental factors such as distance between sensors, activity and body posture.
- Technical factors such as transmission power, receiver

sensitivity, antenna gain or coding.

In this work, we are interested in the evaluation of two technical factors that can impact PLR in WBANs, which are modulation and transmission power. For this reason, we show in Figures 3, 4, 5, and 6, the PLR for DBPSK and DQPSK modulations as a function of different data rates when the transmission power is set to -10, -5, 0 and 3 dBm, respectively.

As expected, the analysis of the results obtained in Figures 3, 4, 5 and 6, clearly shows that packet loss rate decreases as the transmission power increases. In fact, CM3B channel model introduces relatively high path losses depending on the distance between the communicating nodes (71.3 dB for an inter-sensor distance  $d$  greater than 30cm). Therefore, to ensure a better received signal level at the coordinator (signal level higher than the minimum threshold of receiver sensitivity), corresponding to a better throughput, the transmission power of WBAN nodes must be sufficient enough. Moreover, as shown in the four figures (3, 4, 5 and 6), for low and medium data rates (below 60 kbps), DBPSK modulation shows a lower packet loss rate compared to that obtained with DQPSK. This can be explained by the difference in radio sensitivity due to the modulation scheme adopted. We can notice in table 6, that receiver sensitivity is significantly lower in DBPSK (-104 dBm) compared to DQPSK (-96.5 dBm). However, at high transmission data rates (from 60 kbps onwards), the packet reception rate appears to be better with DQPSK than with DBPSK.

We can relate the low performance of DBPSK in high data rates to the well-known problems of buffer saturation. Furthermore, DQPSK allows with 4 phases to encode two bits per symbol instead of only one in the case of DBPSK. Thus, at the same transmission data rate, DQPSK modulation allows the transmission of twice as many symbols (i.e. a multiplication of the data rate by a factor of 2) as DBPSK modulation. This explains the relatively fast saturation of the coordinator buffer at high data rate with DBPSK. This is further confirmed by the equation (3) below [10].

$$R_d = \left( \frac{R_s \cdot N}{S} * \frac{k}{n} \right) (kbps) \quad (3)$$

where  $R_d$  refers to the information data rate,  $R_s$  means the symbol rate,  $S$  is the spreading factor,  $k/n$  is the code rate BCH, and  $N$  is a variable linked to the modulation order  $M$  by  $M=2^N$ .

#### 4.1.2. Throughput

Throughput is an important metric in WBANs, it refers to the

number of packets received successfully per second (p/s). However, this parameter can be weakened due to several causes including low duty cycles, or the transmission of control packets. As demonstrated in equation (4) [35], throughput ( $S$ , expressed in bytes/s) is much higher when packet loss rate is lower.

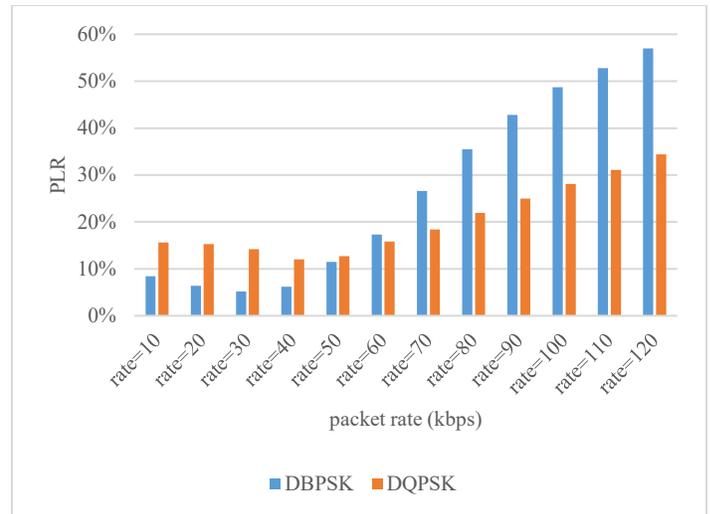


Figure 3: PLR at -10 dBm

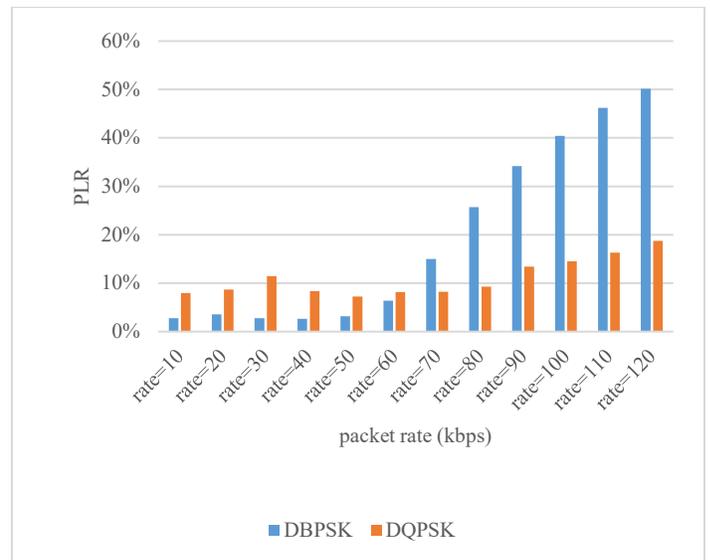


Figure 4: PLR at -5 dBm

Table 6: Settings of the modulation schemes used

| Frequency band (Ghz) | Rx sensitivity (dBm) | Channel spacing (MHz) | Symbol rate (ksps) | Tx power (dBm) | Power consumption for Tx mode |
|----------------------|----------------------|-----------------------|--------------------|----------------|-------------------------------|
| 2.4                  | -96.5(for DQPSK)     | 1                     | 600                | -10 to 3       | • 5.9 mW (for DPSK -10 dBm).  |
|                      | -104 (for DBPSK)     |                       |                    |                | • 9.5 mW (for DPSK 0 dBm).    |
|                      |                      |                       |                    |                | • 12.3 mW (for DPSK 3 dBm)    |

At constant PLR, S is proportional to the number M of nodes in the network and to the traffic payload (P) expressed in bytes, and is inversely proportional to the length of the beacon period Bp.

$$S = \frac{M \cdot P}{B_p} (1 - PLR) \quad (4)$$

Figures 7, 8, 9 and 10 illustrate the throughput of the DBPSK and DQPSK modulations as a function of various data rates at -10, -5, 0 and 3dBm respectively.

These results show, once again, as in the earlier PLR study, that the higher the transmission power the better the throughput. Furthermore, as illustrated in the four figures, for low and medium data rates (below 60 kbps), DBPSK guarantees a better throughput compared to DQPSK modulation, as the receiver sensitivity in the case of DBPSK is lower. However, at high transmission data rates (60 kbps and more) DQPSK modulation seems to be more efficient, for the same reasons (and the same high data rate context) previously formulated with the results obtained for PLR.

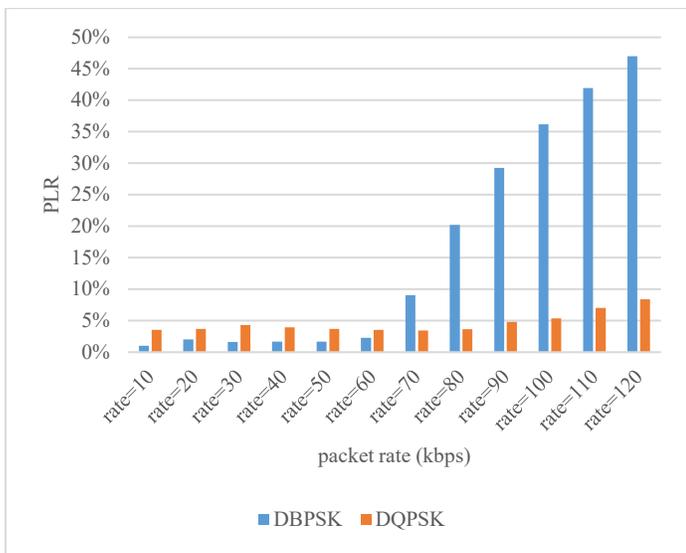


Figure 5: PLR at 0 dBm

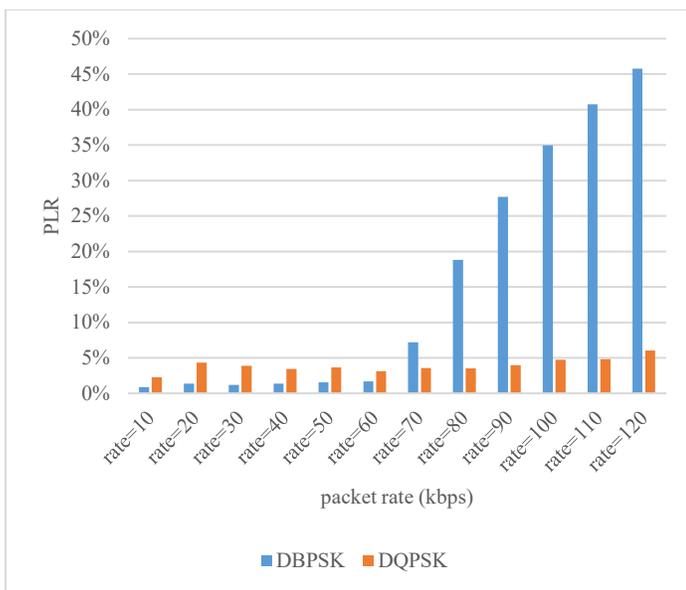


Figure 6: PLR at 3dBm

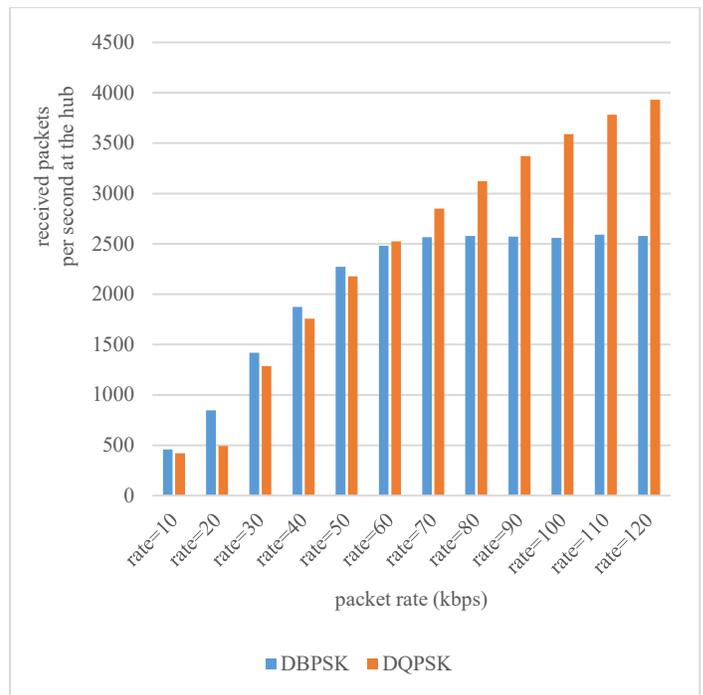


Figure 7: Throughput at -10dBm

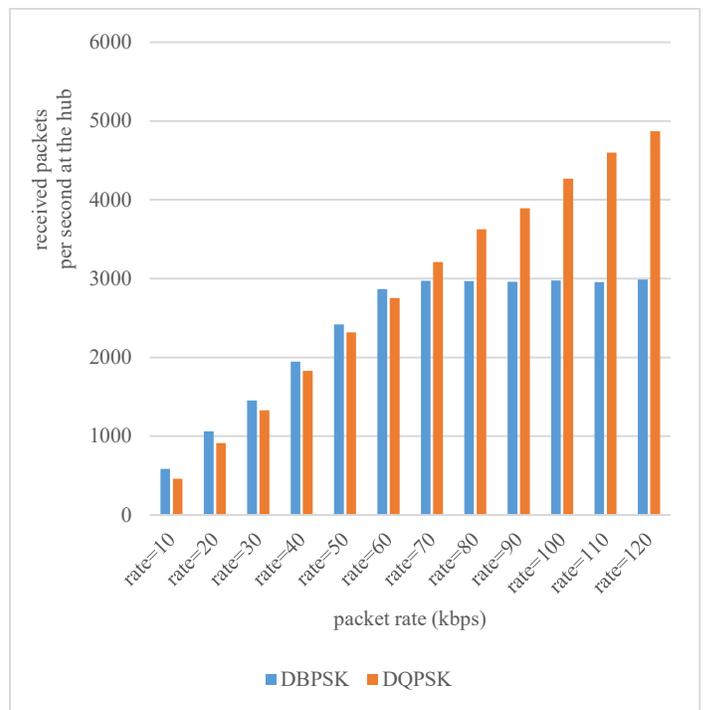


Figure 8: Throughput at -5 dBm

### 4.1.3. Latency

Latency is a metric defined, in the context of our work, as the time interval between the node receiving a beacon, and the coordinator correctly receiving the node's frame. We evaluate this metric in our WBAN model of study, at low, medium, and high data rates, for several transmission powers (-10dBm, -5dBm, 0dBm and 3dBm). For this purpose, we have considered the three following simulation scenarios:

- Transmission data rate less than 10 kbps with DBPSK modulation: to represent the case of low data rate on-body medical applications (according to the categorization in Table 2).

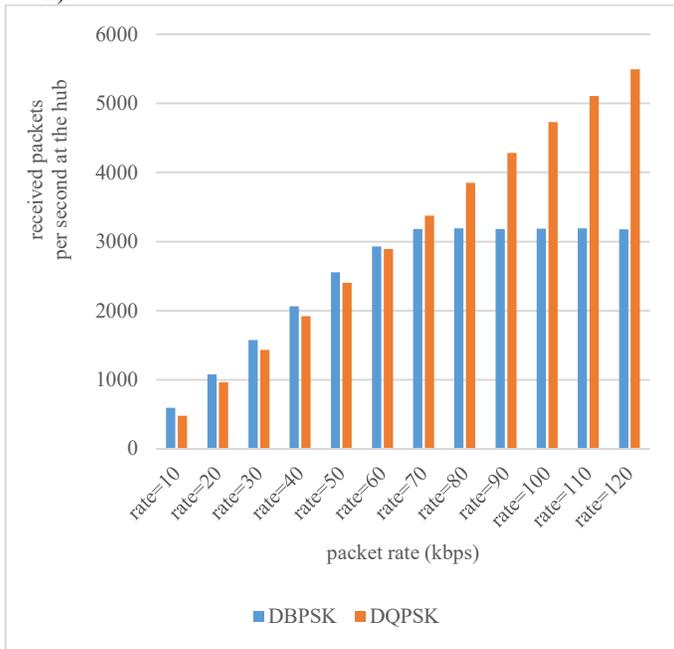


Figure 9: Throughput at 0 dBm

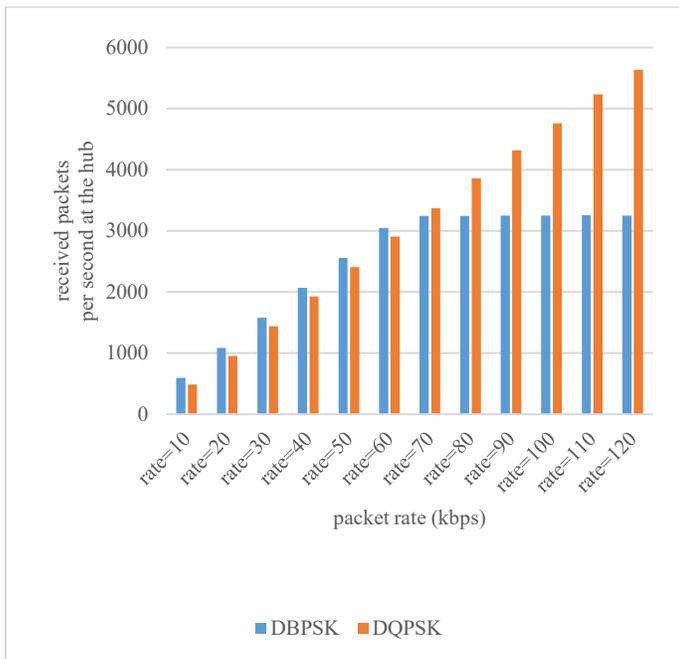


Figure 10: Throughput at 3 dBm

- Maximum transmission rate of 50 kbps with DBPSK modulation: to represent the case of medium rate on-body medical applications.
- Maximum transmission data rate of 71 kbps with DQPSK modulation: to represent the case of high data rate on-body medical applications (example of ECG monitoring with 6-electrode).

Thus, we show in Figures 11, 12, and 13 the distribution of received packets at different time intervals for the three cases respectively, when the transmission power varies from -10 to 3dBm.

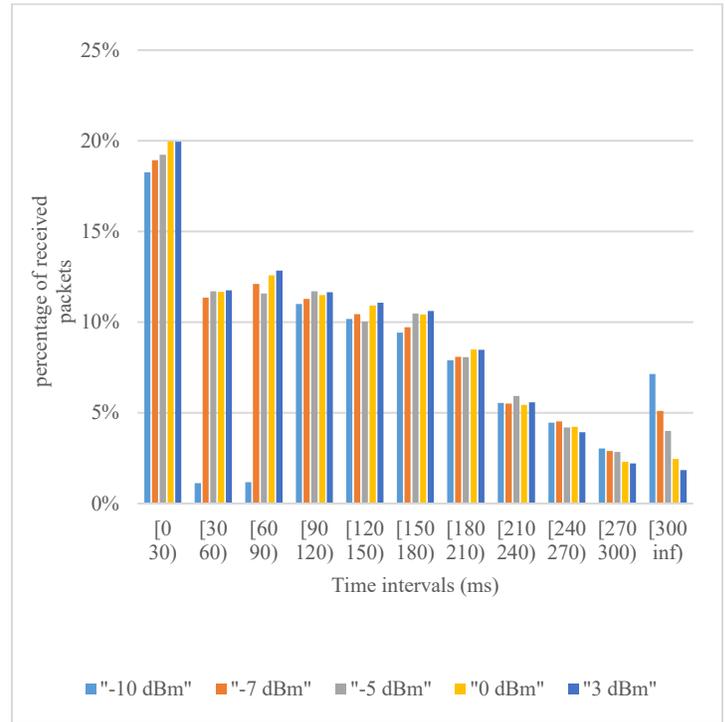


Figure 11: latency for low data rate medical applications (DBPSK)

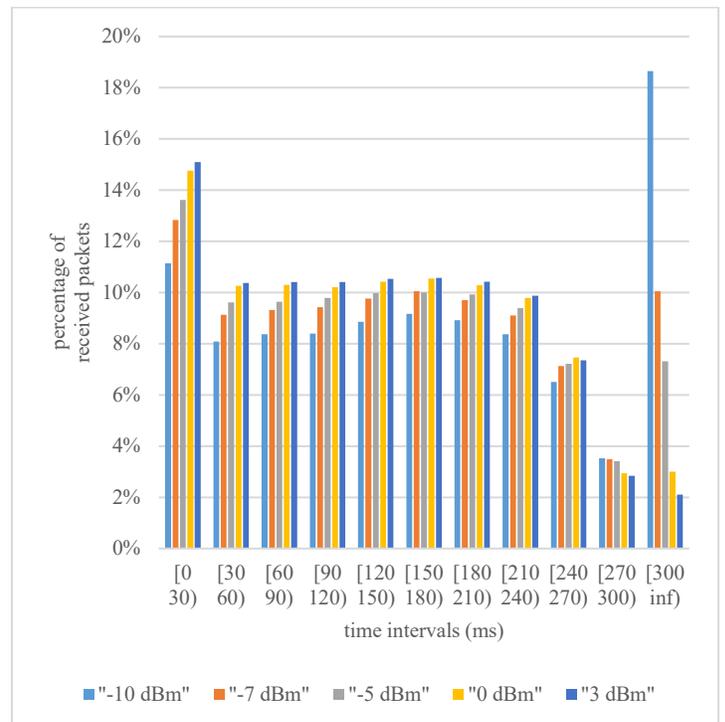


Figure 12: latency for medium data rate applications (between 32 and 43 kbps)

Table 7. Optimal modulation scheme and transmit power values for medical on-body applications

| Medical applications   | Optimal values of transmit power  | Optimal modulation scheme |
|--|---|---------------------------|
| <b>Medium data rate medical applications: EEG monitoring (12 leads) and SpO2</b> | -10 dBm<br>PLR <10 %<br>Throughput: 2270 p/s<br>Latency: 52 % of packets received before 240 ms     | DBPSK                     |
|  | -5 dBm<br>PLR <10 %<br>Throughput: 2418 p/s<br>Latency: 69 % of packets received before 240 ms      |                           |
|  | 0 dBm<br>PLR <10 %<br>Throughput: 2555 p/s<br>Latency: 81 % of packets received before 240 ms       |                           |
|  | 3 dBm<br>PLR <1 %<br>Throughput: 2559 p/s<br>Latency: 84 % of packets received before 240 ms        |                           |
|  | -10 dBm<br>PLR <10 %<br>Throughput: up to 456p/s<br>Latency: 86 % of packets received before 240 ms |                           |
| <b>Low data rate medical applications: (&lt;10 kbps)</b>                         | -5 dBm<br>PLR <3 %<br>Throughput: up to 585 p/s<br>Latency: 90 % of packets received before 240 ms  | DBPSK                     |
|  | 0 dBm<br>PLR <2 %<br>Throughput: up to 593p/s<br>Latency: 92 % of packets received before 240 ms    |                           |
|  | 3 dBm<br>PLR <1 %<br>Throughput: up to 594 p/s<br>Latency: 93 % of packets received before 240 ms   |                           |
|  | -10 dBm<br>PLR =19 %<br>Throughput: 2850 p/s<br>Latency: 60 % of packets received before 240 ms     |                           |
|  | -5 dBm<br>PLR = 8 %<br>Throughput: 3208 p/s<br>Latency: 70 % of packets received before 240 ms      |                           |
| <b>ECG (6 leads)</b>   | 0 dBm<br>PLR <10 %<br>Throughput: 3377 p/s<br>Latency: 79 % of packets received before 240 ms       | DQPSK                     |
|  | 3 dBm<br>PLR <10 %<br>Throughput: 2380 p/s<br>Latency: 84 % of packets received before 240 ms       |                           |

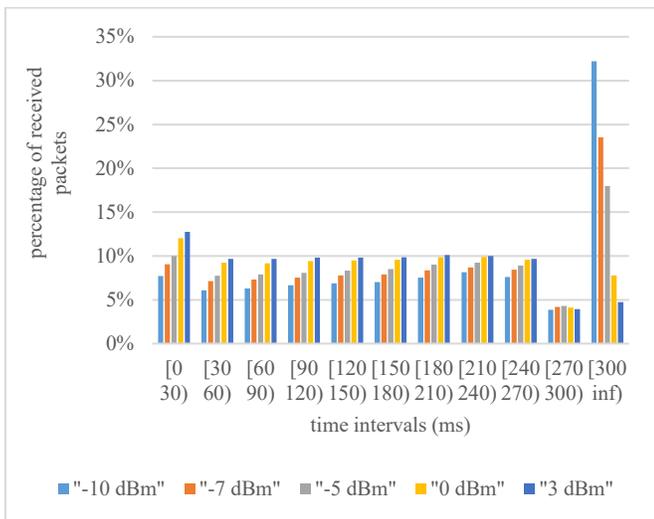


Figure 13: Latency for high data rate applications (72 kbps)

#### 4.2. Discussion and synthesis

E-health applications can be classified into real-time and near real-time applications [37–38]. Nevertheless, the QoS requirements of each of these applications may differ depending on the context in which the service is invoked. This means that in emergency cases, for example, remote medical monitoring will require real-time data transmission, with no tolerance for data loss. Whereas in non-emergency situations, vital signs transmission does not require the same level of QoS (can tolerate delay). In addition, depending on the application demands, three basic data delivery models can be distinguished [39–40] : continuous model, query model and event model. The continuous model is the most basic data delivery model, which aims to periodically transmit the data collected by sensor nodes, which can either be real-time data such as voice or image that does not tolerate delay (but packet loss can be tolerated within threshold limits), or non-real-time continuous data where latency and packet loss can be permissible. However, In the query data delivery model, the coordinator requests the transmission of packets to sensors, this model requires

reliable and timely data transmission. As for event-delivery model, data transmission only takes place when an event of interest occurs. In this case, reliable and real-time data transmission is required. Moreover, the QOS requirements also depend on the needs of the patients, for some patients it may be enough to send their signals every few minutes, while others may need to transmit the collected data every few seconds [41].

The simulation results of our WBAN model have shown that in the case of low data rate medical applications (about 10 kbps), including blood pressure, glucose and body temperature measurement, we can note that DBPSK modulation can guarantee a PLR < 10% even when nodes transmit in the lowest power range. At -10 dBm for example, a PLR of about 8% is achieved with 86% of packets received under 250 ms, and a throughput of 456 packets/s. So if the target of these applications is non-emergency continuous real-time monitoring, the choice of DBPSK modulation with the lowest power level (-10 dBm) can guarantee the intended results.

## 5. Conclusion

In this paper we have studied a realistic WBAN model based on the 2.4 GHz narrowband of the IEEE 802.15.6 standard and dedicated to on-body medical applications. With this model, we have investigated the adequacy of the modulation schemes proposed by the standard in this frequency band as well as transmission power, while considering the requirements of these applications in terms of PLR, throughput and latency. Simulation results have shown that DBPSK modulation can be a good choice for low and medium data rate applications. However, DQPSK modulation would be more suitable for high data rate medical applications. Regarding the transmission power, low data rate medical applications can accept minimum transmission powers (-10 dBm for example). However, when the required application data rate increases, higher transmission powers, e.g. 0 dBm, must necessarily be used to ensure a reduced packet loss rate, acceptable latency, and higher throughput.

The 2.4 GHz frequency band is through a band adopted by several other technologies such as Wifi, Bluetooth etc. This is likely to influence the operation of the proposed WBAN model if it is located in an environment that includes these technologies or other WBANs. This is known as mutual interference, which must be taken into account in the physical layer configuration.

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