European Wireless 2012, April 18-20, 2012, Poznan, Poland ISBN 978-3-8008-3426-9 © VDE VERLAG GMBH

Coexistence Issues for Wireless Body Area Networks at 2.45 GHz

Flavia Martelli, Roberto Verdone
DEIS, University of Bologna, Italy
Email: {flavia.martelli, roberto.verdone}@unibo.it

***Abstract*—This paper deals with coexistence issues that may arise for Wireless Body Area Networks (WBANs) operating at the 2.45 GHz ISM band. Two different sources of interference are considered: IEEE 802.11 (Wi-Fi) and IEEE 802.15.4 (Zigbee). Firstly, these interfering networks are characterized both in the frequency and in the time domains. Then, the coexistence of a WBAN with these interfering systems is assessed. We consider a WBAN as composed of wearable nodes that communicate with an on-body coordinator and we evaluate the achievable performance for three different physical layers and two different Carrier Sense Multiple Access with Collision Avoidance algorithms.**

I. INTRODUCTION

In the recent years the attention of researchers toward Wireless Body Area Networks (WBANs) has greatly increased. The advent of miniaturized sensors and actuators for monitoring, diagnostic, and therapeutic functions, together with advances in wireless systems, can enhance and support new medical and healthcare services. Wearable or implanted sensors can sample, process, and transmit vital signs without constraining the activities of the wearer. The gathered data can be forwarded in real time to a hospital or clinic giving remote access to physicians and nurses, or can be processed locally to trigger a treatment procedure when needed [1]. Existing air interface standards are not suitable to fully satisfy WBANs specific requirements and unique technical challenges, due to the diversity of envisioned applications. Therefore, the IEEE 802.15 Task Group 6 (TG6) was established in November 2007 in order to develop an international communication standard optimized for ultra low power devices and operation on, in, or around the human body to serve a variety of applications, either medical or non-medical. At the time of writing, the standard is in a draft form [2]. Different WBAN protocol proposals can be found in the literature, as well as studies of applicability of existing Wireless Sensor Network (WSN) protocols in WBAN scenarios, see for example [3]–[5].

An envisaged frequency band to be used for WBAN operation is the 2.4 GHz Industrial, Scientific, and Medical (ISM) band. Several existing wireless devices already use the same band, such as IEEE 802.11 (Wi-Fi), IEEE 802.15.4, and Bluetooth. Since WBANs should be used in the daily life in every kind of environment, their coexistence with these interfering systems is of uppermost importance. Studies on coexistence of IEEE 802.15.4 with the other mentioned standards can be found in the literature, see for example [6], [7]. For WBAN, this is still an uninvestigated topic.

The aim of this paper is to characterize WBAN performance achievable when interfering sources are present. Specifically, we account for interference due to IEEE 802.11 and IEEE 802.15.4 networks, suitably characterised both in the frequency and in the time domain. The reported studies have been carried out in the framework of the European project WiserBAN [8]. Therefore, we refer to the WBAN protocol stack defined in the project [9], evaluating network performance achievable with three different modulation schemes at the physical (PHY) layer and two Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithms at the Medium Access Control (MAC) layer.

A proper complete system characterisation is taken into account, starting from a realistic channel model for on-body propagation [10], which, together with the frequency domain interference description, allows to accurately model interference impact at PHY layer, through the evaluation of Signal to Interference plus Noise Ratio (SINR) for each packet. Besides, the time domain interference characterisation leads to an appropriate simulation of MAC dynamics.

The rest of the paper is organized as follows. Section II describes the reference scenario, while Section III is devoted to WBAN protocol architecture. Interference characterization is illustrated in Section IV. Section V shows numerical results from simulations and Section VI concludes the paper.

II. THE REFERENCE SCENARIO

We refer to a WBAN composed of four nodes and a remote control (RC), as illustrated in Figure 1. Nodes positions have been defined according to WiserBAN use-cases [8].

We account for a star topology and a query-based traffic: the RC, acting as network coordinator, periodically sends a query to all nodes asking for data and, upon reception of this query, the WBAN nodes transmit their packets to the RC through direct links. One packet per query is generated by nodes and we assume that nodes have to transmit data having the same size. If a node is not able to transmit its packet before the next query, it has to discard it and the packet is considered as lost.

The scenario defined for coexistence evaluation is shown in Figure 2: in a room of 3m x 3.5m, a person wearing a WBAN is walking according to the trajectory represented by the arrow. In order to evaluate the coexistence with IEEE 802.11, a Wi-Fi access point (AP) and a notebook are located in the room (Figure 2 left), while a Zigbee coordinator (ZC) and 4 Zigbee end devices (ZEDs) are present (Figure 2 right) to assess the

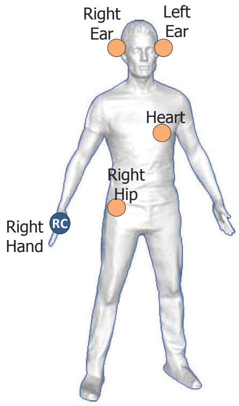

Fig. 1. WBAN reference scenario.

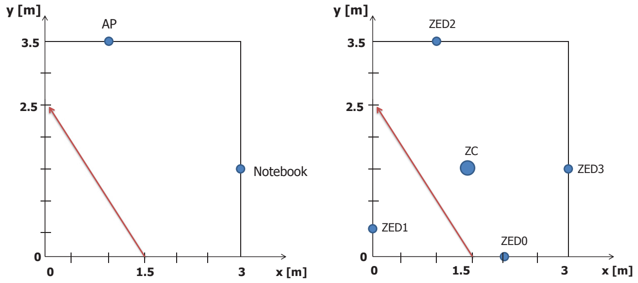

Fig. 2. Reference scenario for coexistence evaluation with IEEE 802.11 (left) and with IEEE 802.15.4 (right).

performance achievable with IEEE 802.15.4 interference. The AP and the ZC are positioned at a height of 3 m, whereas the notebook and the ZEDs are a t an average height of 0.8 m.

We consider a joint mobility-channel model for the human body, as described in [10]: a semi-deterministic on-body channel model is combined with a biomechanical representation of the body, in order to preserve spatial and temporal dependency based on geometrical analysis.

As for the channel model from the interfering devices to the WBAN nodes, the path loss, L, at a distance d, is evaluated in dB as $L_{\text{dB}}(d) = k_0 + k_1 ln(d)$, where $k_0 = 40$ dB and $k_1 = 13.03$ (values obtained for the frequency of 2.4 GHz and a propagation exponent equal to 3).

III. WBAN PROTOCOL ARCHITECTURE

We refer to the WBAN protocol architecture defined in the WiserBAN project [9].

At the PHY, three different options have been specified:

- PHY 1: IEEE 802.15.4-compliant PHY, that is Minimum Shift Keying (MSK) modulation with spreading, with a bit-rate of 250 kbit/s; the actual packet transmission takes place 1 symbol at a time, being a symbol formed by 4 bits. Each symbol is translated to one of 16 nearly orthogonal 32-chip long sequences (Direct Sequence Spread Spectrum technique). The chip sequences for successive symbols are concatenated and the resulting chip stream is modulated onto the carrier through MSK. More details can be found in [11].
- PHY 2: in this case MSK modulation is used, derived starting from PHY 1 and removing the spreading, with a bit-rate of 2 Mbit/s; since no spreading is used, packets are directly formed by bits.
- PHY 3: Bluetooth Low Energy-compliant PHY, i.e. Gaussian Minimum Shift Keying (GMSK) modulation, with a bit-rate of 1 Mbit/s; in this case, as in the previous PHY, being GMSK a binary modulation, packets are directly composed by bits.

The access to the channel is managed by a coordinator node, that is the RC, through the establishment of a superframe (SF). The coordinator periodically broadcasts beacon packets: the period between two consecutive beacons defines the SF. In the following, we consider only the Contention Access Period (CAP) of the SF, where the access to the channel is contention based. Specifically, we evaluate the performance for two different CSMA/CA algorithms, the one defined in IEEE 802.15.4 [11] and the one specified in IEEE 802.15.6 [2].

According to IEEE 802.15.6 algorithm, time is divided into slots, whose duration is equal to 125 μs. When a node has data to be sent, it randomly chooses a backoff counter (BC) in the interval $[1 \div \text{CW}]$, where $\text{CW} \in [\text{CW}_{\text{min}}, \text{CW}_{\text{max}}]$. The values of CW_{min} and CW_{max} depend on the user priority. If the channel has been sensed as idle for a Short Inter Frame Spacing ($pSIFS = 50\mu s$), the node decrements its BC by one for each idle slot that follows. Once the BC has reached zero, the node can transmit its frame. The CW is doubled every two failures, ensuring that it does not become larger than CW_{max}. If the channel is found busy, the BC is locked until the channel becomes idle again for *pSIFS*.

The IEEE 802.15.4 CSMA/CA algorithm, instead, is implemented using units of time called backoff periods, with a duration of 320 μs. Each node maintains two variables for each transmission: NB and BE. NB is the number of times the CSMA/CA algorithm was required to backoff while attempting the current transmission; its initial value is 0 and its maximum value is NB_{max}. BE is the backoff exponent related to the maximum number of backoff periods a node will wait before assessing the channel; its initial value is BE_{min}, and its maximum value is BE_{max}. In CSMA/CA, first, NB and BE are set to the initial values. Then, the node enters in backoff for a random number of backoff periods in the range (0, $2^{\text{BE}} - 1$) [step (1)]. After this delay, the node performs sensing for two subsequent backoff periods. If the channel is found idle in both the backoff periods, the transmission starts. Otherwise, NB and BE are increased by 1, ensuring that BE is not larger than BE_{max}. If the value of NB is lower or equal to NB_{max}, the algorithm returns to step (1); otherwise the algorithm will unsuccessfully terminate, meaning that the node does not succeed in accessing the channel.

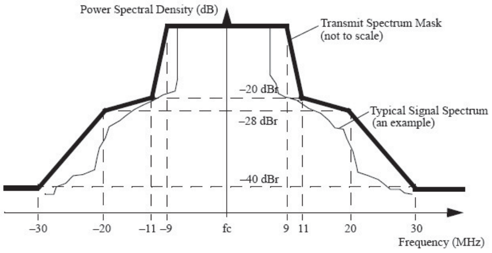

Fig. 3. IEEE 802.11 transmit power spectrum mask [12].

IV. INTERFERENCE CHARACTERIZATION

The sources of interference considered are IEEE 802.11 (Wi-Fi) and IEEE 802.15.4 (Zigbee). The interference has been characterized both in the frequency and in the time domain. The frequency characterization, for the above mentioned interference sources, can be derived from the standards, while time characterization has been performed through specific measurements. For the following studies we specify that the WBAN network can operate in 16 different frequency channels in the 2.4 GHz ISM band, which are characterized by:

- center frequencies: $f_c = 2405 + i \cdot 5$ [MHz], $i = \{0, \dots, 15\}$;
- bandwidth: $B = 5$ [MHz], when MSK modulation is used (PHY 1 and 2); $B = 2$ [MHz], when GMSK modulation is used (PHY 3).

A. Frequency characterization

In order to have a frequency characterization of the considered interference sources to be used as input for the simulator, we have computed the percentage of interfering power falling into WBAN receiver band, denoted as $p_{int}^{(i,j)}$. Indexes (i) and (j) refer to the channel used by the WBAN and by the interfering network, respectively. Indicating with $W(f)$ the power spectral density of the interfering signal and with $F_r(f)$ the receiver filter transfer function, we have:

$$p_{int}^{(i,j)} = \frac{1}{\int_{-\infty}^{+\infty} W^{(j)}(f)df} \cdot \int_{B^{(i)}} W^{(j)}(f)|F_r(f)|^2 df. \quad (1)$$

In the following, we assume an ideal receiver filter:

$$|F_r(f)| = \begin{cases} 1 & \text{if } f \in B^{(i)} \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

As for IEEE 802.11, we consider a power spectral density complying with the mask reported in Figure 3 and we refer to the 13 frequency channels defined for operation in Europe at 2.4 GHz [12]. The values of p_{int} obtained for WBAN channels $i = \{8, 9\}$ are shown in Table I.

As for IEEE 802.15.4, the center frequencies defined in the standard for operation at 2.4 GHz are the same used for the WBAN network in our studies, therefore all the power transmitted by 802.15.4 devices falls into the WBAN receiver band when PHY 1 or 2 are considered, whereas only the $2/5$ of the power will be source of interference when PHY 3 is used ($B = 2$ [MHz]), assuming that 802.15.4 signal is characterized by a 5 MHz bandwidth.

TABLE I
PERCENTAGE OF INTERFERENCE FROM IEEE 802.11 CHANNELS ON WBAN CHANNELS

		PHY 1, 2		**PHY 3**	
		WBAN channel		**WBAN channel**	
		8	**9**	**8**	**9**
IEEE 802.11 channel	**1**	0.010	0.002	0.004	0.001
	2	0.028	0.010	0.011	0.004
	3	0.086	0.028	0.034	0.011
	4	0.508	0.086	0.081	0.034
	5	22.06	0.508	9.93	0.081
	6	24.82	22.06	9.93	9.93
	7	24.82	24.82	9.93	9.93
	8	24.52	24.82	9.93	9.93
	9	2.98	24.52	0.090	9.93
	10	0.109	2.98	0.044	0.090
	11	0.032	0.109	0.013	0.044
	12	0.014	0.032	0.005	0.013
	13	0.003	0.014	0.001	0.005

B. Time characterization

In order to characterize the traffic generated by an IEEE 802.11 network in the time domain, some experiments have been carried out. The traffic between an Access Point (AP) and a notebook, positioned at a distance of 2 m and in Line-of-Sight condition, has been measured using the network protocol analyzer Wireshark Version 1.6.2. Three different traffic flows have been evaluated:

- *No traffic*, in this modality only synchronization packets are supposed to be exchanged;
- *Web browsing*, that refers to simple navigation operations: alternating the opening of web pages with their reading;
- *Heavy traffic*, meaning a more intense web navigation and the download of files with dimensions up to 20 Mbytes.

All the above mentioned traffic modalities have been measured for a time interval of 5 minutes.

Similarly, an IEEE 802.15.4 (Zigbee) networks of Freescale MC1322x devices has been set up. The devices implement the BeeStack protocol stack (Zigbee compliant, as it is defined by Freescale [13]). In order to measure the traffic exchanged between the devices, Daintree SNA software has been used. Experiments were carried out for a different number of ZEDs in the network, respectively 1, 2, and 4. Traffic exchanged could be described as follows:

- the ZC broadcasts a Time Synchronization and Route Request (RREQ) packet every 60 s;
- each ZED replies to every received RREQ with a Route Response packet, broadcasts a Link Status frame every 15 s, and sends to the ZC a Report frame every 30 s.

C. Packet capture model

When two or more packets are simultaneously received by a node, a collision occurs. One of the packets can be successfully decoded by the receiver even in case of a collision: this is

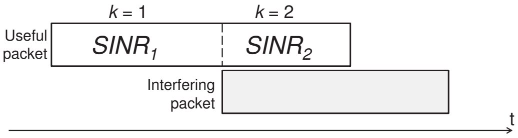

Fig. 4. Example of packets partial overlap.

known as capture effect. We take into account the fact that packets can overlap totally or partially. An example of a partial overlap between two packets is shown in Figure 4. The packet capture effect is modeled as follows.

- For a given packet of interest, sent by a WBAN node on the channel (i), several SINR values can be computed depending on current variations of interference level. Therefore, for every packet portion k (see Figure 4 for an example), we have:

$$\text{SINR}_k = \frac{P_R}{P_n + P_{I_{\text{on}}} + P_{I_{\text{off}}}}, \tag{3}$$

  where P_R is the useful received power, P_n is the noise power, $P_{I_{\text{on}}}$ is the power coming from other nodes of the WBAN, and $P_{I_{\text{off}}}$ is the interfering power from external devices (Wi-Fi or Zigbee).

  P_R can be expressed as:

$$P_R = P_T^{(i)} G_{\text{on}_u}^{(i)}, \tag{4}$$

  considering $P_T^{(i)}$ as the power transmitted by WBAN nodes on channel (i) and G_{on_u} as the on-body channel gain (as modeled in [10], see Section II) for the useful link.

  $P_{I_{\text{on}}}$ and $P_{I_{\text{off}}}$ are respectively evaluated through:

$$P_{I_{\text{on}}} = \sum_m P_T^{(i)} G_{\text{on}_m}^{(i)} b_{k_m}, \tag{5}$$

$$P_{I_{\text{off}}} = \sum_l P_l^{(j)} G_{\text{off}}^{(j)} p_{int}^{(i,j)} b_{k_l}, \tag{6}$$

  where $P_l^{(j)}$ is the power transmitted by the l-th external interferer on channel (j); b_{k_l} (b_{k_m}) is a boolean variable indicating if the l-th (m-th) interferer is present during the packet portion k (in the example of Figure 4, $b_{1_1} = 0$ and $b_{2_1} = 1$). G_{off} is the off-body channel gain, given by $G_{\text{off}} = 1/L$, with L modeled as described in Section II.
- For each computed SINR value, we calculate the Bit Error Rate (BER) or the Symbol Error Rate (SER) for each portion k in a different way for every PHY, in order to derive the Packet Error Rate (PER) according to the following:

$$\text{PER} = \begin{cases} 1 - \prod_{k=1}^{N} (1 - \text{SER}_k)^{N_{\text{s}_k}} & \text{for PHY 1} \\ \\ 1 - \prod_{k=1}^{N} (1 - \text{BER}_k)^{N_{\text{b}_k}} & \text{for PHY 2,3} \end{cases}$$

  where N is the number of packet portions ($N = 2$ in the example of Figure 4) and N_{b_k} (N_{s_k}) is the number of bits (symbols) in the portion k.

PHY 1

In this case the SER has to be computed:

$$\text{SER}_k = \sum_{n=1}^{32} \binom{32}{n} \text{CER}_k^n (1 - \text{CER}_k)^{32-n} \cdot P_s(n), \tag{7}$$

where $P_s(n)$ is the symbol error probability when n chips are not correctly received (values can be found in [14]) and CER is the Chip Error Rate. The expression of the CER as a function of the SINR is evaluated here through the formula $\text{CER}_k = \frac{1}{2} e^{-(\text{SINR}_k)^{0.66}}$. The latter has been obtained through the comparison between experimental derivations of [15] and the PER expression found in [14], and minimum least square fitting.

PHY 2

Without spreading, the expression given above (PHY 1) for the CER applies in this case to the BER, owing to the absence of any sort of bit aggregation to form multi-level symbols:

$$\text{BER}_k = \frac{1}{2} e^{-(\text{SINR}_k)^{0.66}} \tag{8}$$

PHY 3

We consider the following expression, empirically derived for Bluetooth Low Energy PHY [10]:

$$\text{BER}_k = \frac{1}{2} e^{-(\text{SINR}_k)^{0.7}} \tag{9}$$

V. NUMERICAL RESULTS

In order to evaluate the performance of the WBAN when interference is present, simulations (achieved through a C written simulator) have been performed. We have simulated 100 000 SFs, meaning 100 000 packets to be transmitted by each node to the RC.

The packet reception decision is based on the PER value calculated as explained in Section IV-C: considering x as a uniformly distributed random variable in $[0 \div 1]$, drawn for each packet, if $x \geq$ PER the packet is correctly received, otherwise the packet is lost.

For 802.15.6 CSMA/CA, we set $\text{CW}_{\text{min}} = 8$ and $\text{CW}_{\text{max}} = 16$; for 802.15.4 CSMA/CA $\text{BE}_{\text{min}} = 3$, $\text{BE}_{\text{max}} = 5$, and $\text{NB}_{\text{max}} = 4$. The other PHY and MAC simulation parameters are shown in Table II. For the results obtained in presence of IEEE 802.11 interference, we use the *Heavy traffic* flow (see Section IV-B); *Case 1* and *Case 2* in the following figures refer to two different values of p_{int}, that are 0.028% and 24.82%, corresponding to an interfering power fraction equal to -15 dBm and +14 dBm, respectively, considering a total transmit power for 802.11 devices set to +20 dBm. As for performance achieved with IEEE 802.15.4 interference, instead, the interference transmit power is equal to 0 dBm and *Case 1* refers to an 802.15.4 network composed of only 2 nodes (ZC and Dev3), while *Case 2* indicates a networks with all the nodes shown in Figure 2 (right).

TABLE II
PHY AND MAC SIMULATION PARAMETERS

Parameter		**Value**
Transmit power, P_T		0 dBm
Receiver sensitivity	PHY 1	-96 dBm
	PHY 2	-87 dBm
	PHY 3	-90 dBm
Noise power, P_n		-101 dBm
Current consumption, transceiver on		10 mA
Current consumption, stand-by (CPU on)		1.6 mA
Supply voltage		1.2 V
CAP duration		37 ms
PHY header		121 bits
MAC header		9 bytes
Maximum number of retransmissions		3

Performance is evaluated in terms of average packet loss rate (PLR), average delay, and average throughput.

The PLR represents the probability that a packet generated by a node is not received by the coordinator. This can happen due to different possible causes: connectivity problems (the node cannot receive the beacon, meaning that it is not connected to the network), collisions, with packets coming from other WBAN nodes or from an interfering node (a maximum number of retransmissions is allowed), or because the end of the SF is reached. For IEEE 802.15.4 CSMA/CA, there is another cause of loss: the channel is found busy for more than $\mathrm{NB}_{\max} + 1$ subsequent times while trying to transmit the same packet [11].

Figures 5 and 6 show the PLR obtained when PHY 1 is used, as a function of MAC payload, for 802.15.4 CSMA/CA and 802.15.6 CSMA/CA, respectively. We can notice that, as expected, the PLR is higher when an interference source is present, and this is more evident for IEEE 802.11 interference, since the traffic generated is heavier than the one produced by an 802.15.4 network. Besides, even when the channels used by the WBAN and the 802.11 devices are only partially overlapping (*Case 1*), the degradation in the performance is significant, and this is also due to the heavy 802.11 traffic: the channel is very often found busy by WBAN devices, which are therefore not able to correctly transmit their data (main cause of losses for 802.15.4 CSMA/CA is the maximum number of backoff reached, while for 802.15.6 is the end of the SF).

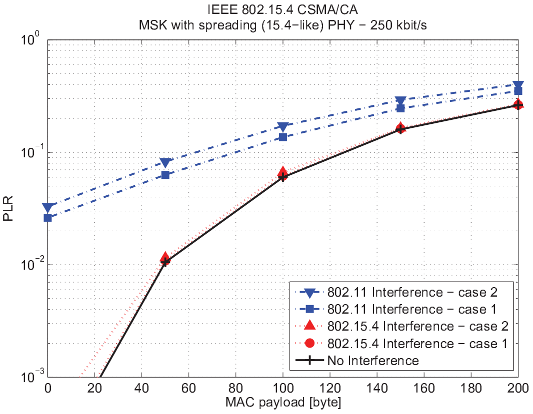

Fig. 5. PLR for IEEE 802.15.4 CSMA/CA, PHY 1.

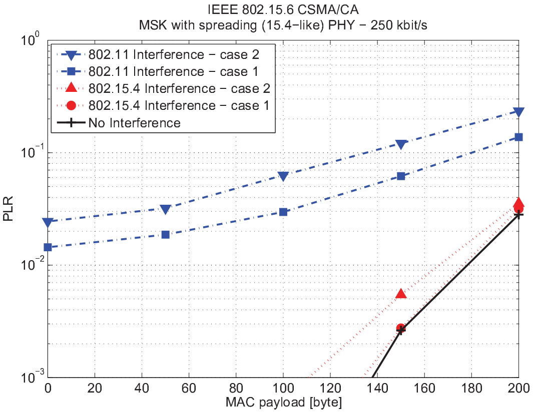

Fig. 6. PLR for IEEE 802.15.6 CSMA/CA, PHY 1.

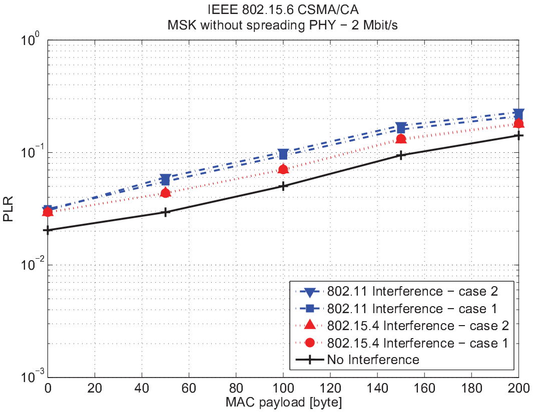

Fig. 7. PLR for IEEE 802.15.6 CSMA/CA, PHY 2.

IEEE 802.15.6 CSMA/CA performs better than the 802.15.4 one, because nodes sense the channel for a longer period. Therefore, we show the PLR obtained with the other PHYs only for 802.15.6, in Figures 7 and 8. For both PHY 2 and 3, the degradation of PLR performance in presence of interference is less evident, because many packets are lost due to connectivity problems (higher receiver sensitivity values).

The delay is evaluated as the time elapsed between the reception of the beacon by the node and the correct reception of the node frame by the coordinator. We also estimate the average energy consumption, that is the average energy consumed by a node to send its packet in the SF. Figure 9 and 10 show the average delay and energy as a function of MAC payload obtained with PHY 1, for both CSMA/CA algorithms. Curves attained with 802.15.4 interference are not reported, because they overlap with the one obtained without interference. When IEEE 802.11 is present, both delay and energy consumption increase, but the degradation is not as significant as for the PLR. IEEE 802.15.6 performs better in terms of average delay, but its energy consumption is higher, due to the longer time spent in the sensing state.

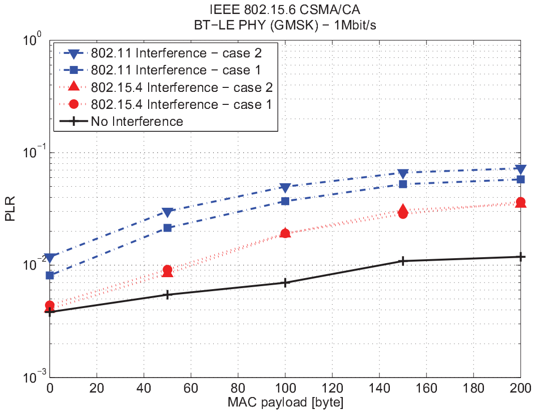

Fig. 8. PLR for IEEE 802.15.6 CSMA/CA, PHY 3.

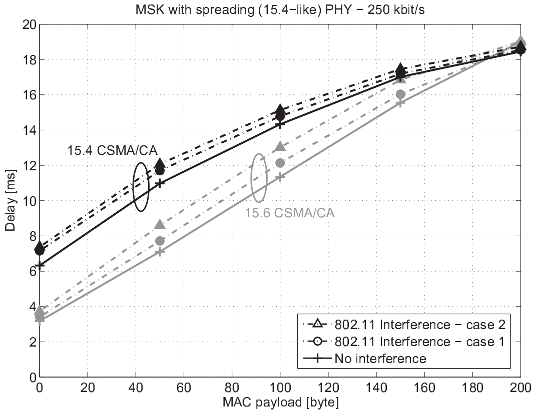

Fig. 9. Average delay for IEEE 802.15.6 CSMA/CA, PHY 3.

VI. CONCLUSIONS

This paper reported coexistence studies carried out in order to evaluate the performance of a WBAN network operating at 2.45 GHz when other wireless networks working at the same frequency are present in the environment, corresponding to source of interference for the WBAN. In particular, two representative interfering systems were considered: IEEE 802.11 and IEEE 802.15.4. They were characterized both in the frequency and in the time domain, and simulations were performed to assess the degradation of WBAN performance with respect to the case without interference.

Results showed that the performance metric that is mainly affected by the interference is the PLR, particularly when IEEE 802.11 interference is present. Therefore, in order to guarantee acceptable performance, an appropriate WBAN channel selection is of great importance, and, given the variability of the environment in which WBANs are supposed to operate, the selection procedure should also be periodically repeated.

ACKNOWLEDGMENT

This work is supported by the European Commission in the framework of FP7 IP Project WiserBAN, contract n. 257454.

The authors would like to thank A. Mancini for his work on the measurements and simulations.

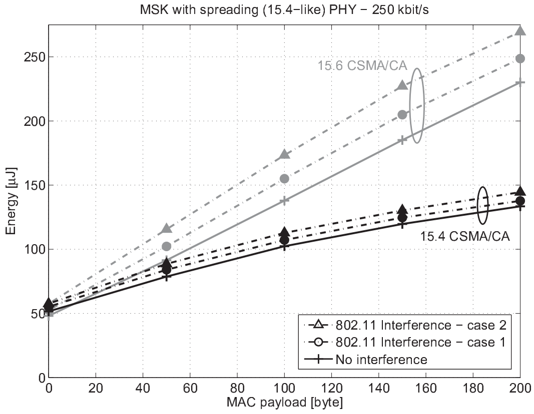

Fig. 10. Average energy consumption per packet for IEEE 802.15.6 CSMA/CA, PHY 3.

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