

WiserBAN



Project Acronym: WiserBAN

Project Title: Smart miniature low-power wireless microsystem for Body Area Networks

Call: FP7-ICT-2009-5, Collaborative project

Grant Agreement no.: 257454

Project Duration: 36 months

Coordinator: CSEM

Beneficiaries:

CSEM Centre Suisse D'Electronique et de Microtechnique SA – Recherche et Development	CSEM	CH
Commissariat a L'Energie Atomique et aux Energies Alternatives	CEA	FR
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SignalGeneriX Ltd	SG	CY
RTD TALOS Ltd	TALOS	CY

WiserBAN

Smart miniature low-power wireless microsystem for Body Area Networks

Deliverable identifier: D5.2

Deliverable title: Computer Simulation Results and Test of BAN Protocols over Benchmark Platform

Due date of deliverable: M18

Actual submission date: M20 (April 10,2012)

Start day of project: 01/09/2010

Duration: 36 months

WP Number: WP 5 Miniature BAN components

Organization name of lead partner for this deliverable (partner name): TUB

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Document Status: Delivered

Project funded by the European Commission within the Seventh Framework Programme		
Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Revision History

Version	Date	Changed page(s)	Cause of change	Partner
V1	Dec 14 2011	All	Creation	UNIBO
V2	March 9	All	Editing of all the Deliverable	UNIBO
V3	March 23	All	Editing of almost all the Deliverable	UNIBO
V5	March 25	All	Revision of all the document	CEA
V6	March 31	All	Final revision	UNIBO
V7	March 10	minor	Final review	CSEM

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Executive Summary

The WiserBAN project will create an ultra-miniature and ultra low-power RF microsystem for wireless Body Area Networks (BAN) targeting primarily wearable and implanted devices for healthcare, biomedical and lifestyle applications.

This Deliverable is the first issued by Task 5.3, dealing with the BAN multi-node platform, having the aim of developing and validating the BAN concept, combining the elements of Tasks 5.1 and 5.2 with the BAN protocol delivered in WP4.

This document aims at validating the radio communication protocol performance in the context of a simple network topology, that is a star topology, and at validating the simulation results on MAC protocols included in the Deliverables of WP4.

The BAN protocols have been tested over a separate, stable and commercially available platform, developed by Texas Instruments, to create a proper benchmark for performance evaluation purposes to be used in the later stages of the project.

This Deliverable contains the results of the first tests on the BAN MAC protocol achieved through experimentations on the field, using the benchmark platform. Performance was evaluated in terms of Packet Loss Rate and average delay. Coexistence issues are also discussed.

It is shown that, apart from discrepancies related to the HW/SW platform constraints, the qualitative behavior predicted by simulations of the protocols envisaged, is confirmed by the experimentations. This proves that the simulation tool developed within the project is useful to predict the performance variations of the WiserBAN communication protocol stack.

1 Introduction

This Deliverable is the first issued by Task 5.3 and it reports about the benchmark platform which has been developed in the last months at UNIBO. This platform will be considered as a reference and benchmark for the rest of the project, to be used for comparison with the final WiserBAN platform.

The Deliverable aims at:

- Validating the simulation results on Medium Access Control (MAC) protocols included in D4.1 and D4.2, through comparison with results achieved on the field with the benchmark.
- Providing some results on the performance of the WiserBAN MAC protocols, achieved through experimentations on the field.
- Providing some results, through both experimentations and simulations, on the coexistence among the WiserBAN network and external interference, like Wi-Fi networks.

2 The Benchmark Platform

A platform, already available on the market, has been identified to create a proper benchmark for performance evaluation purposes. The BAN protocols, defined in D4.1, have been implemented on the benchmark platform to provide some preliminary results on the performance achievable by the WiserBAN devices and to validate simulation results, included in D4.1 and D4.2.

Due to the lack of commercially available devices implementing the IEEE 802.15.6, an IEEE 802.15.4-compliant platform has been selected to be used as benchmark. As a result the only available Physical (PHY) layer is the one implemented by IEEE 802.15.4, using Minimum Shift Keying (MSK) modulation with spreading. Therefore the results achieved through the tests on the benchmark will be compared with the simulation results achieved when using MSK with spreading.

From the MAC layer viewpoint, instead, both the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) defined by IEEE 802.15.4 and the Slotted ALOHA protocol, as defined in D4.1, have been implemented on the platform.

In the rest of this Section we report some details about the selected platform and the results obtained through a measurements campaign made on the field.

The CC2530 produced by Texas Instrument (TI) has been selected as benchmark platform. It is a second generation IEEE 802.15.4-compliant System-on-Chip with an optimized 8051 microcontroller unit (MCU) core and radio for the 2.4 GHz unlicensed Industrial Scientific

and Medical (ISM) band. It is a good example of existing state-of-the-art 2.4GHz SoC, but yields size and power consumptions that are way above the WiserBAN targets, and is nonetheless very suitable for the required benchmarking process.

The CC2530 ZigBee Development Kit used for the benchmark is shown below.

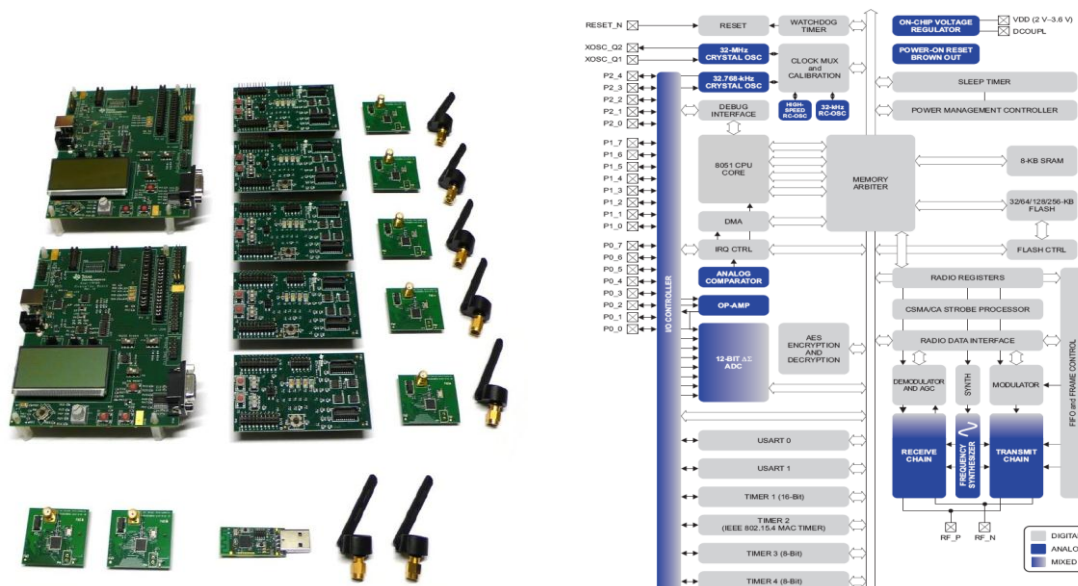


Figure 2-1: Left part: The TI Development Kit. Right part: The Integrated Circuit [1]

The main characteristics are:

- Radio Frequency transceiver compliant with the IEEE 802.15.4 at 2.4 GHz;
- Programmable transmit power up to +4.5 dBm;
- Receiver sensitivity of -97 dBm;
- RAM (random access memory) of 8KB and 256 KB of flash;
- Low power consumptions: i) Transmission at +1 dBm (CPU Idle): 29mA; ii) Reception (CPU Idle): 24mA; iii) Idle: three different modalities up to 0.4 mA.

Other technical characteristics of such devices are reported in the tables below [1].

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
I _{core}	Core current consumption	Digital regulator on. 16-MHz RCOSC running. No radio, crystals, or peripherals active. Medium CPU activity: normal flash access ⁽¹⁾ , no RAM access		3.4		mA
		32-MHz XOSC running. No radio or peripherals active. Medium CPU activity: normal flash access ⁽¹⁾ , no RAM access		6.5	8.9	mA
		32-MHz XOSC running, radio in RX mode, -50-dBm input power, no peripherals active, CPU idle		20.5		mA
		32-MHz XOSC running, radio in RX mode at -100-dBm input power (waiting for signal), no peripherals active, CPU idle		24.3	29.6	mA
		32-MHz XOSC running, radio in TX mode, 1-dBm output power, no peripherals active, CPU idle		28.7		mA
		32-MHz XOSC running, radio in TX mode, 4.5-dBm output power, no peripherals active, CPU idle		33.5	39.6	mA
		Power mode 1. Digital regulator on; 16-MHz RCOSC and 32-MHz crystal oscillator off; 32.768-kHz XOSC, POR, BOD and sleep timer active; RAM and register retention		0.2	0.3	mA
		Power mode 2. Digital regulator off; 16-MHz RCOSC and 32-MHz crystal oscillator off; 32.768-kHz XOSC, POR, and sleep timer active; RAM and register retention		1	2	µA
		Power mode 3. Digital regulator off; no clocks; POR active; RAM and register retention		0.4	1	µA
I _{peri}	Peripheral Current Consumption (Adds to core current I _{core} for each peripheral unit activated)					
	Timer 1	Timer running, 32-MHz XOSC used		90		µA
	Timer 2	Timer running, 32-MHz XOSC used		90		µA
	Timer 3	Timer running, 32-MHz XOSC used		60		µA
	Timer 4	Timer running, 32-MHz XOSC used		70		µA
	Sleep timer	Including 32.753-kHz RCOSC		0.6		µA
	ADC	When converting		1.2		mA
	Flash	Erase		1		mA
		Burst write peak current		6		mA

Table 2-1: CC2530 current consumptions [1]

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
Receiver sensitivity	PER = 1%, as specified by [1] [1] requires -85 dBm		-97	-92 -88	dBm
Saturation (maximum input level)	PER = 1%, as specified by [1] [1] requires -20 dBm		10		dBm
Adjacent-channel rejection, 5-MHz channel spacing	Wanted signal -82 dBm, adjacent modulated channel at 5 MHz, PER = 1 %, as specified by [1]. [1] requires 0 dB		49		dB
Adjacent-channel rejection, -5-MHz channel spacing	Wanted signal -82 dBm, adjacent modulated channel at -5 MHz, PER = 1 %, as specified by [1]. [1] requires 0 dB		49		dB
Alternate-channel rejection, 10-MHz channel spacing	Wanted signal -82 dBm, adjacent modulated channel at 10 MHz, PER = 1 %, as specified by [1] [1] requires 30 dB		57		dB
Alternate-channel rejection, -10-MHz channel spacing	Wanted signal -82 dBm, adjacent modulated channel at -10 MHz, PER = 1 %, as specified by [1] [1] requires 30 dB		57		dB
Channel rejection ≥ 20 MHz ≤ -20 MHz	Wanted signal at -82 dBm. Undesired signal is an IEEE 802.15.4 modulated channel, stepped through all channels from 2405 to 2480 MHz. Signal level for PER = 1%.		57 57		dB
Co-channel rejection	Wanted signal at -82 dBm. Undesired signal is 802.15.4 modulated at the same frequency as the desired signal. Signal level for PER = 1%.		-3		dB
Blocking/desensitization 5 MHz from band edge 10 MHz from band edge 20 MHz from band edge 50 MHz from band edge -5 MHz from band edge -10 MHz from band edge -20 MHz from band edge -50 MHz from band edge	Wanted signal 3 dB above the sensitivity level, CW jammer, PER = 1%. Measured according to EN 300 440 class 2.		-33 -33 -32 -31 -35 -35 -34 -34		dBm
Spurious emission. Only largest spurious emission stated within each band. 30 MHz-1000 MHz 1 GHz-12.75 GHz	Conducted measurement with a 50-Ω single-ended load. Suitable for systems targeting compliance with EN 300 328, EN 300 440, FCC CFR47 Part 15 and ARIB STD-T-66.		< -80 -57		dBm
Frequency error tolerance ⁽¹⁾	[1] requires minimum 80 ppm		±150		ppm
Symbol rate error tolerance ⁽²⁾	[1] requires minimum 80 ppm		±1000		ppm

Table 2-2: CC2530 technical characteristics [1]

3 The MAC Protocol Implementation

To manage the access to the channel, the superframe (SF) reported in the figure below and defined within the WiserBAN project (see D4.1) has been implemented on the benchmark platform.

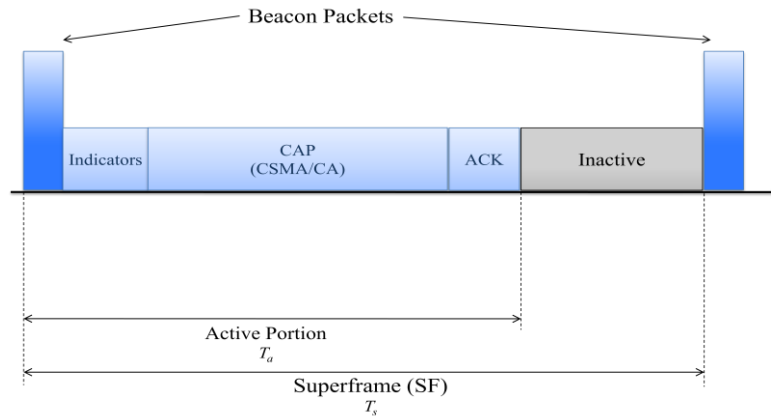


Figure 3-1: The WiserBAN Superframe

In the Contention Access Period (CAP) portion of the superframe the following protocols have been implemented:

- The IEEE 802.15.4 CSMA/CA protocol
- The slotted ALOHA protocol of the IEEE 802.15.6 standard (as defined in D4.1).

We refer to D4.1 for details about the superframe and the MAC protocols.

The reference scenario considered is the integrated scenario shown in Figure 3-2, where four WiserBAN devices are present on the body (see D4.1 for details). In simulations we had considered three different sub-scenarios, with different possible positions of the Remote Control (RC), supposed to be held in the left hand (scenario A), to be held in the right hand (scenario B), or to be carried in a pocket (thigh position, scenario C). In the case of experimental measurements, performed with the benchmark platform, only scenario B has been addressed, therefore all the tests have been performed with the RC on the right hand.

Therefore results refer to a network composed of four nodes transmitting data to the Coordinator (that is the RC), organized in a star topology and using the CAP portion of the SF, as depicted in Figure 3-1.

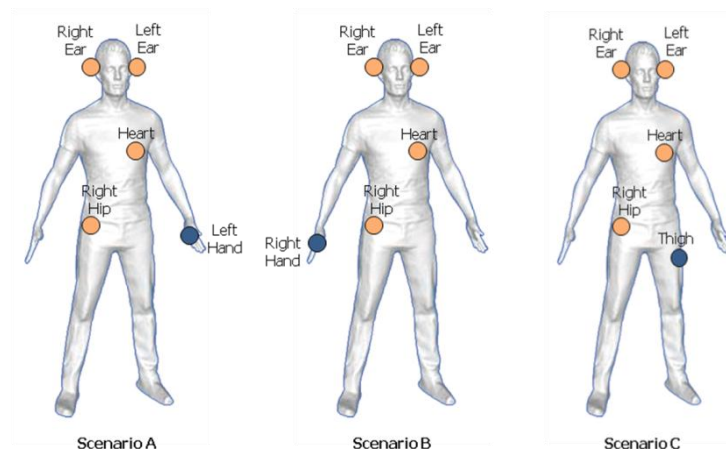


Figure 3-2: Integrated scenarios for the simulator

To implement the above described MAC protocol, the Texas Instruments Medium Access Control Software (TIMAC) has been used. TIMAC implements: the interface toward the physical layer; the MAC layer; and a simple application layer (see Figure 3-3). The interface toward the PHY layer is the HAL (Hardware Abstraction Layer), which allows the management of all the peripherals, the radio and the CPU (Central Processing Unit) of the system of chip (SoC). On top of this level, there is the OSAL (Operative System Abstraction Layer), enabling functionalities, like creation, initialization and synchronization of tasks, and management of the timers, interrupts and memory. The MAC and application layers are implemented above the OSAL layer.

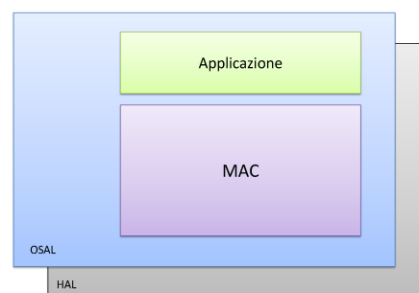


Figure 3-3: TIMAC Architecture

UNIBO has implemented on the TIMAC software the same application considered in the simulations, described in the following. At the beginning of every SF, each node generates one packet to be transmitted toward the Coordinator (that is the RC). Packets generated by nodes have all the same length. If a node does not succeed in sending correctly its packet to the RC by the end of the current SF, the packet is considered lost. A maximum number of 3 retransmissions is allowed in both, simulations and experimentations. 10.000 SFs, meaning 10.000 packets to be transmitted from each node to the RC are sent in the experiments.

The flow-chart of the software developed at the application layer on TIMAC is shown in Figure 3-4).

Performance are evaluated in terms of:

- Packet Loss Rate = (Number of packets lost) / (Number of packets generated). Packets can be lost due to connectivity, collisions, or the end of the superframe. The PLR is averaged among the PLR achieved by the different nodes in the network.
- Delay: time interval between the beginning of the SF and the correct reception of the node packet at the Coordinator. The delay is averaged among the delays achieved by the different nodes in the network.

A Matlab interface has been implemented, in order that it is possible to visualize in real-time the performance of the network, during the experiments. In particular, the interface shows the power received by the RC (connected to a PC via UART, during the experiments), when transmitted by the different nodes in the network, the delay with which packets are received and the number of packets lost. The interfaces are shown in

Figure 3-5.

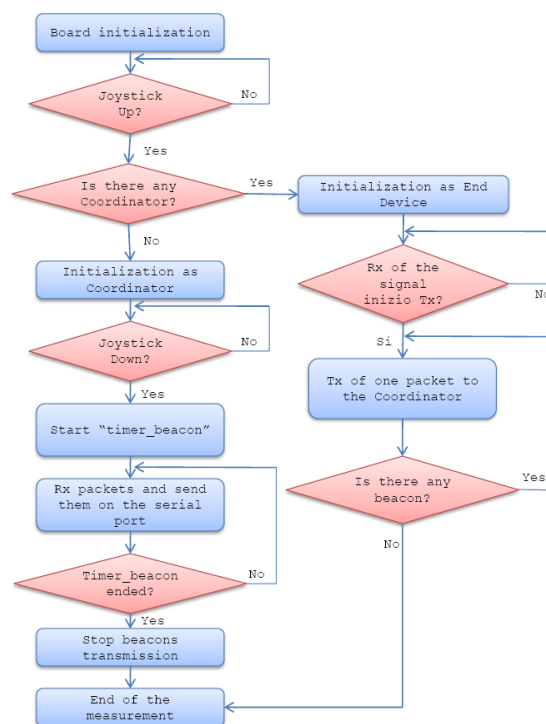


Figure 3-4: The flow-chart of the software implemented on the benchmark devices



Figure 3-5: The software interface

3.1 Computer Simulation Results

In this section we briefly report the results achieved in the framework of WP4 through simulations. We refer to D4.1 and D4.2 for details.

Since the benchmark platform will implement the IEEE 802.15.4-compliant physical layer and there is no way to modify such layer, we will refer only to the MSK with spreading modulation at 250 kbit/s.

In the simulations to account for the real WiserBAN radio channel, measurements made on the field performed within D3.1 (WP3), have been directly included into the simulator. In such a way, simulations account for the real attenuation in the different communication links.

The simulation parameters settings are reported below.

Parameter	Value
SIFS	50 μ s [15.6]
PHY header + preamble	121 bits [15.6]
MAC header + FCS	9 bytes [15.6]
Beacon MPDU length	9 + 14 + payload = 23 bytes + payload [15.6]
Ack MPDU length	9 bytes [15.6]
Maximum number of retransmissions	3
Ack Timeout	2 ms
T_B	1 ms
T_{Ind}	1 ms
T_{Ack}	1 ms
T_a	40 ms
BE_{min}	3
BE_{max}	5
NB_{max}	4
Transmit power	0 dBm
Receiver sensitivity	-96 dBm
Antenna gain, RC	-3 dB
Antenna gain, nodes	-15 dB

Table 3-1: Simulation parameters setting

The following figures show the numerical results achieved in the case of the PHY layer of IEEE 802.15.4 (MSK with spreading) and when top loaded (TL) and planar monopole (PL) antennas are used. Results refer to the case of walking scenario, meaning that the subject was walking during the experiments performed in WP3 and included into the simulator for computing the attenuation in the different links. Such a case, in fact, is the one considered also in the experiments performed with the benchmark platform and reported in the next section.

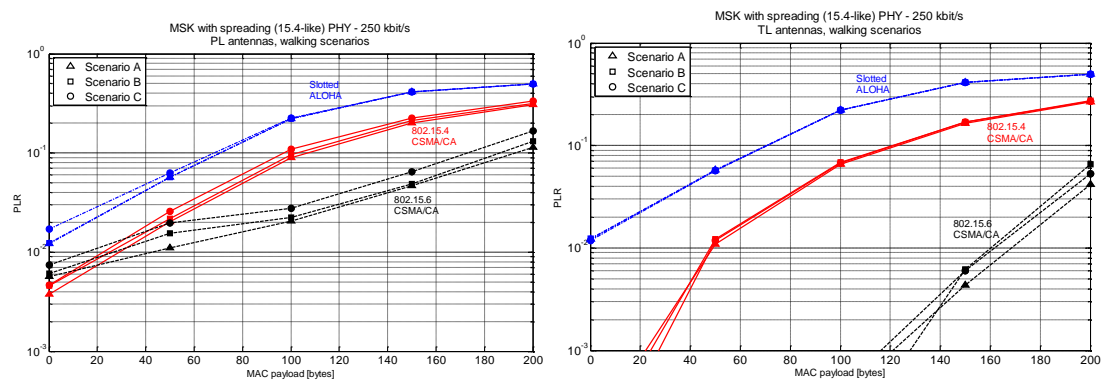


Figure 3-6: PLR obtained for MSK with spreading PHY for PL antenna (left) and TL antenna (right)

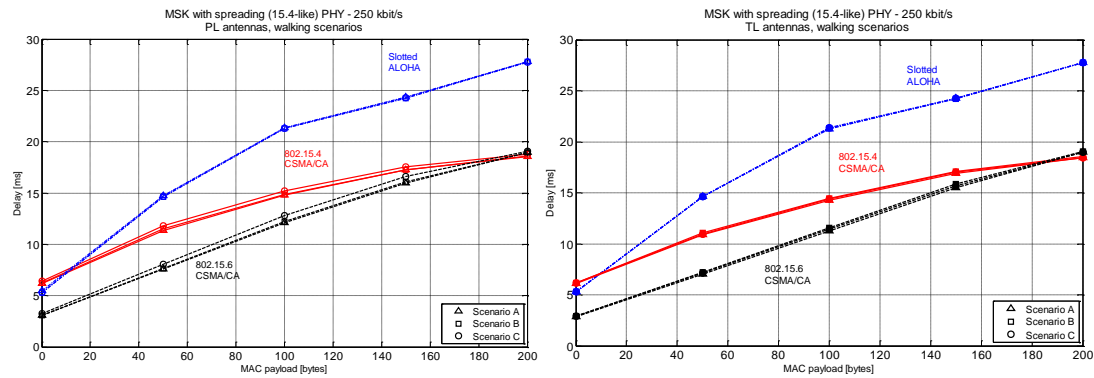


Figure 3-7: Delay obtained for MSK with spreading PHY for PL antenna (left) and TL antenna (right)

3.2 The Benchmark Results: the IEEE 802.15.4 CSMA/CA Protocol

As stated above, the reference scenario considered in the experimentations is scenario B shown in Figure 3-2. The subject performed several walking cycles in an indoor environment, using alternatively monopole antennas with normal (PL) or tangential (TL) polarization with respect to the body surface.

The figures below show the environment where the experiments were performed.



Figure 3-8: The performed experiments

3.2.1 Results on the IEEE 802.15.4 CSMA/CA Protocol

In the benchmark we set the transmit power equal to -22 dBm, instead of 0 dBm, to account for the negative antenna gains reported in Table 3-1 and characterizing the final WiserBAN devices (see D3.1).

Figure 3-9 shows the PLR as a function of the packet payload in the case of PL and TL antennas. Performance in the case of PL are worse with respect to the case of TL antennas (as shown in the simulations); however, in the case of experiments, due to the large mass

plan of the board, the impact of the antennas polarization is lower with respect to the simulation results, accounting for a measurements campaign performed with different boards. The figure demonstrates the good agreement between simulation and experimental results; the slight differences, when comparing the two curves, could be explained considering how differently the connectivity could affect the results. Indeed, the antennas used on the benchmark and those used in the measurements campaign included in the simulators, present different radiation characteristics, even if the polarization is the same. Similar considerations could be drawn for the node emplacement and the environments considered in the two cases.

In Figure 3-10 we show the PLR as a function of the packet payload for the different links. As expected, the best link is the one connecting the RC and the right ear, since the two devices are on the same side of the body, while the worst link is the one connecting the RC with the left ear. The reason of the crossing among some of the curves is that the experiments performed with different payloads have been done at different moments and performing walking that are very similar, but could not be exactly the same (in terms of movements performed by the subject).

In Figure 3-11 the comparison between simulated and measured average delay, as a function of the packet payload, is shown. The measurements achieved in the case of TL and PL antennas are shown. Also in this case the curves follow the same trend, confirming the reliability of the numerical results obtained, presenting a constant difference of approximately 5 ms. This could be explained considering that experiments obviously deal with real hardware devices, whose intrinsic delays are not taken into account in the simulations. This delay is mainly due to processing at the device.

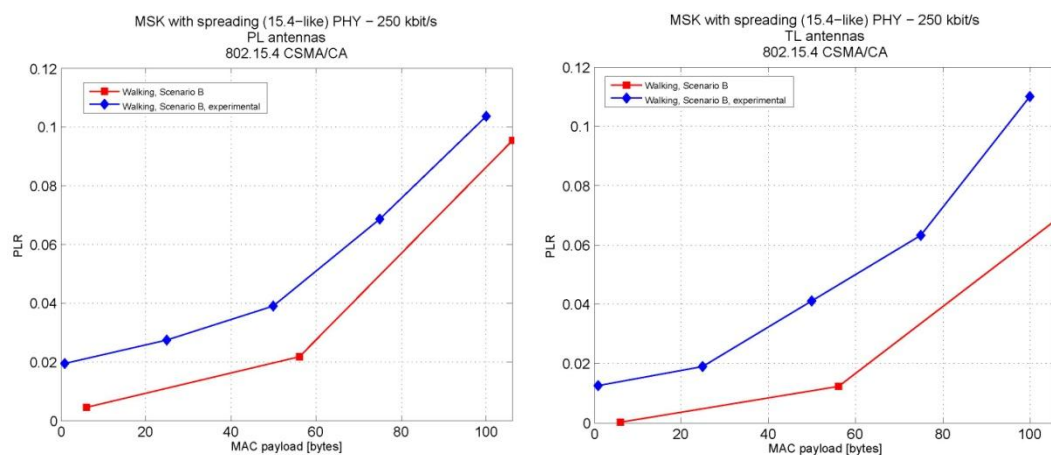


Figure 3-9: PLR: simulations and experiments

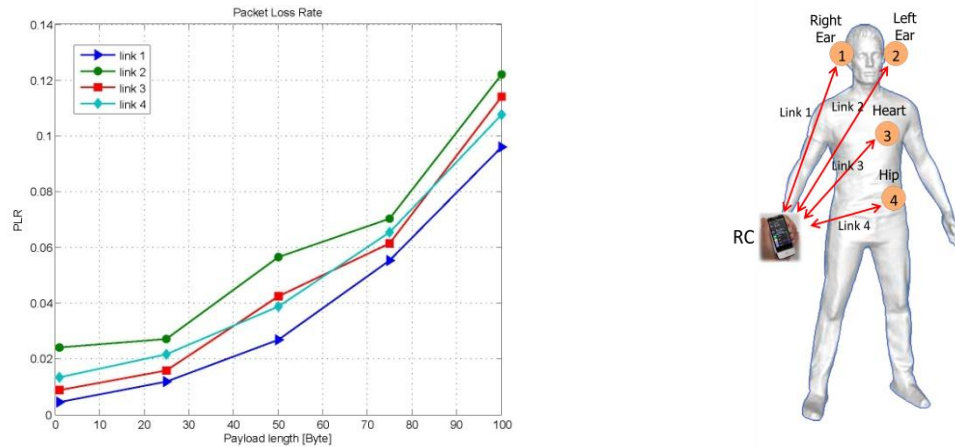


Figure 3-10: PLR achieved in experiments for the different links

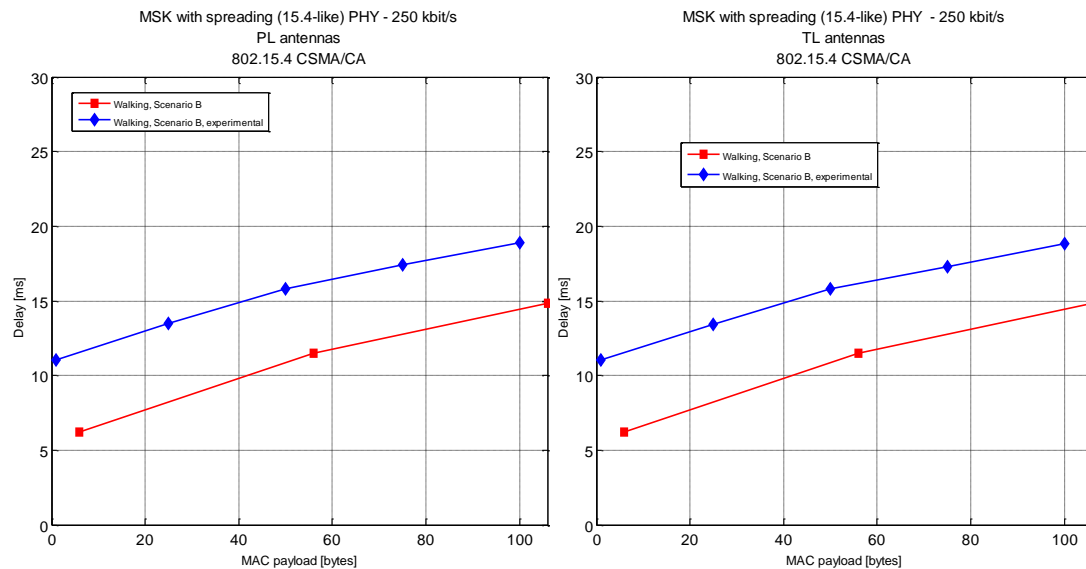


Figure 3-11: Average Delay: simulations and experiments

3.2.2 Results on the Data Aggregation Strategy

To decrease the energy consumption we developed on the benchmark platform a data aggregation strategy. In the experiments shown in the previous section, three retransmissions are allowed for trying to transmit correctly the packets within the same superframe. However, if a packet is lost due to connectivity issues, mainly caused by the shadowing effect of the body, performing retransmissions immediately after transmission is useless, since the channel will most probably be the same. In such a case, all the energy spent by nodes for retransmitting the packet is wasted. During the walking, in fact, the body movement generates the alternation of situations in which nodes are in visibility and in which nodes are shadowed by the body. This is mainly due to the typical arm movement performed during the walking. Therefore, it is possible to take advantage of the movement, avoid to retransmit packets till visibility between nodes is gained.

To improve the performance, mainly in terms of energy consumption, we implemented on the benchmark the following aggregation strategy. When a node does not receive the ACK from the RC, instead of retransmitting the packet in the same SF, it will wait for a given number of SFs, during which it will only store the generated data, without transmitting them. After a given number of SFs, the node will try to transmit a single packet, containing the lost data plus all the data generated and not transmitted, in an aggregated packet. We denoted as *min_Aggr_Pkt* the number of packets aggregated in case of packet loss. Therefore, once a packet is lost, the node will only store data for the following *min_Aggr_Pkt*-2 SFs and at the (*min_Aggr_Pkt*-1)-th SF it will transmit a packet with a payload equal to: *min_Aggr_Pkt**payload. In Figure 3-11 an example of aggregation strategy is shown.

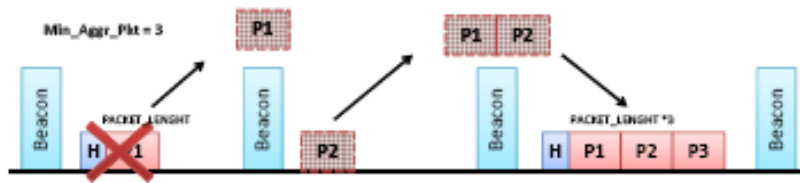


Figure 3-12: The Aggregation strategy implemented: an example

As a first step we evaluate the optimum value of *min_Aggr_Pkt* to be set. We set the superframe duration equal to 30.72 ms, that is we set the superframe order (equal to the beacon order) to 1. The presence of the optimum can be motivated as follows: when *min_Aggr_Pkt* is too small, there is still correlation between the channel experienced by the transmission and the one experienced by the retransmission; when *min_Aggr_Pkt* is too large, the size of the transmitted packet becomes very large, therefore collisions may occur (i.e., the channel is uncorrelated and no connectivity issues could be present, by MAC collisions may occur). The optimum is reached when the trade-off is found. This optimum is shown in Figure 3-13 for the case of payload equal to 1 byte. As can be seen the optimum value is equal to 30, which means approx. 900 ms (accounting for the SF duration), that is approx. the time needed for a subject to perform one cycle of a walk.

In Figure 3-14 we show the PLR when 3 retransmissions are implemented, in the case of no retransmissions and when the aggregated strategy is implemented. The reason why the PLR in the case of aggregation is larger with respect to the case of 3 retransmissions is the fact that we impose no retransmissions also when the aggregated packet is sent. However, having such packet a large size, it could suffer from collisions, therefore it could be useful to implement retransmissions in such a case. In fact, thanks to the optimization performed on the *min_Aggr_Pkt* parameter, when the transmission occur the channel should be “good”.

On the other hand, thanks to aggregation, nodes could save energy, assuming that they will switch off the radio for all the SFs where they just have to store the information data. Obviously this is obtained at expense of an increase of the delays.

In Figure 3-15 we show the number of times the different nodes in the network will use the aggregation protocol (*N_aggr*) in one experiment. This parameter refers to the number of

SFs, over the total number of 10.000 transmissions (i.e., SFs) implemented, a node lost a packet and used aggregation. This metric is useful to compute the percentage of inactive time, that is the percentage of time during which the node could turn off the radio, saving energy, since it has not to transmit data. This percentage is shown in Figure 3-16 for the different nodes. Note that link 2, which is the worst link in terms of connectivity, is the one using more times aggregation, and saving more energy.

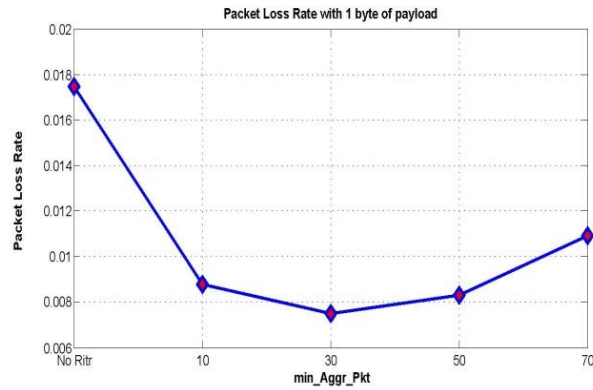


Figure 3-13: The PLR as a function of min_Aggr_Pkt when payload = 1 byte

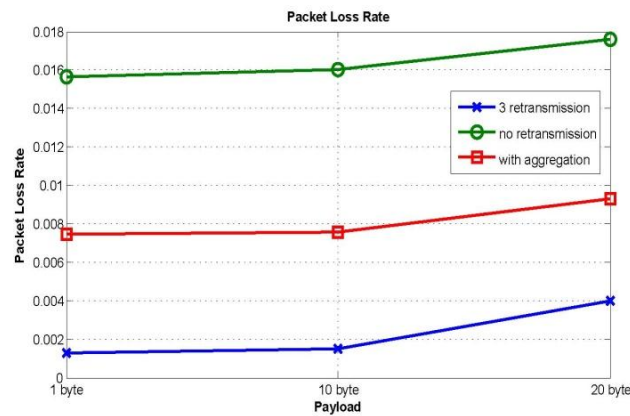


Figure 3-14: The PLR as a function of the packet payload

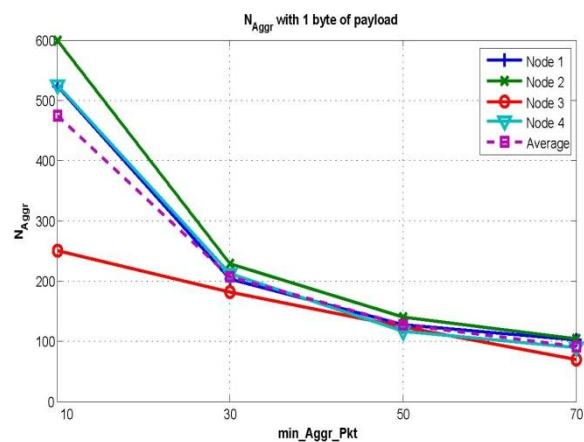


Figure 3-15: N_{Aggr} as a function of min_Aggr_Pkt for the different nodes

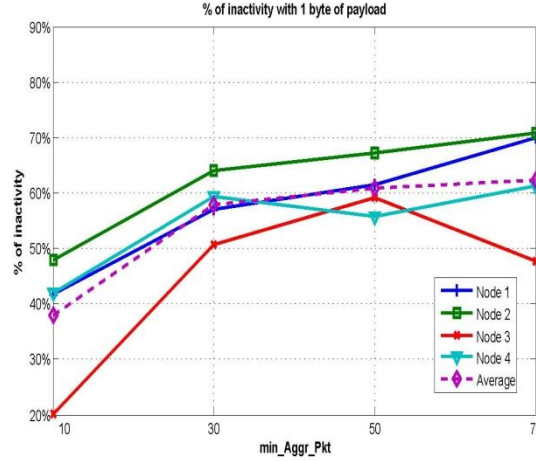


Figure 3-16: The % of time during which nodes could switch off the radio

3.3 The Benchmark Results: the Slotted ALOHA Protocol

To implement the Slotted ALOHA protocol, we have modified the software implementing the MAC layer into the TI platform and the functionalities of the co-processor radio (CSP) of the SoC CC2530.

According to the protocol defined in IEEE 802.15.6, the SF is divided into slots. Once a node has a packet to be transmitted (i.e., after the reception of the beacon), it will transmit in the current slot with a probability CP (contention probability). CP ranges in the interval $[CP_{min}, CP_{max}] = [1/8, 1/4]$. See D4.1 for details.

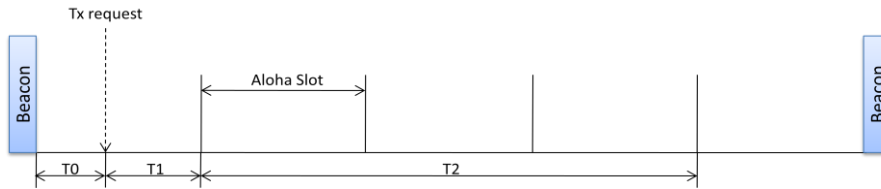


Figure 3-17: The Access to the Channel: Slotted ALOHA

The procedure used to set the slot duration is as follows. Each slot should contain the packet transmission, the acknowledge (ACK) transmission, one TurnAroundTime and a Guard Time. In the Table 3-2 we report the parameters set in the experiments. T_s is the symbol time for IEEE 802.15.4, which is equal to 16 μ s.

In the benchmark, since not all parts of the TIMAC software are accessible, devices need to wait for an interval of time equal to $54 \cdot T_s$ for the ACK, before performing retransmission. To avoid implementation problems, we included this $54 \cdot T_s$ (denoted as ACK time) into the slot, resulting in a larger slot duration in the experiments with respect to simulations and also with respect to the performance we could expect to have on the final platform. Larger slot size, in fact, will bring to a lower number of slots available for transmitting packets into the

CAP, therefore larger PLR. This could be observed in Figure 3-19 (right part) where results achieved in the case of slot duration implemented has shown in Figure 3-19, and in the case of slot without the ACK time. The performance in the latter case is derived through post-processing on the data measured.

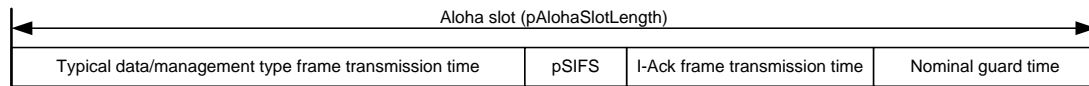


Figure 3-18: The ALOHA Slot: an example

Payload [Byte]	Tx time [T _s]	TurnAroundTime pSIFS [T _s]	ACK time [T _s]	Guard Time [T _s]	Slot duration [T _s]
6	46	12	54	4	120
31	96	12	54	4	180
56	146	12	54	4	220
81	196	12	54	4	280
106	246	12	54	4	320

Table 3-2: The Slot size

The comparison of results achieved in the case of CSMA/CA and Slotted ALOHA are reported below (Figure 3-19). As expected, slotted ALOHA has worse performance in terms of both average delay and PLR. However, as stated in D4.1, it is simpler and it allows to reduce the energy consumption. Note that the duration of a single slot will increase by increasing the payload and the number of available slots in each CAP will decrease by increasing the slot size.

In Figure 3-20 we report the comparison between simulations and experimental results. Once again simulations are validated by the measurements results.

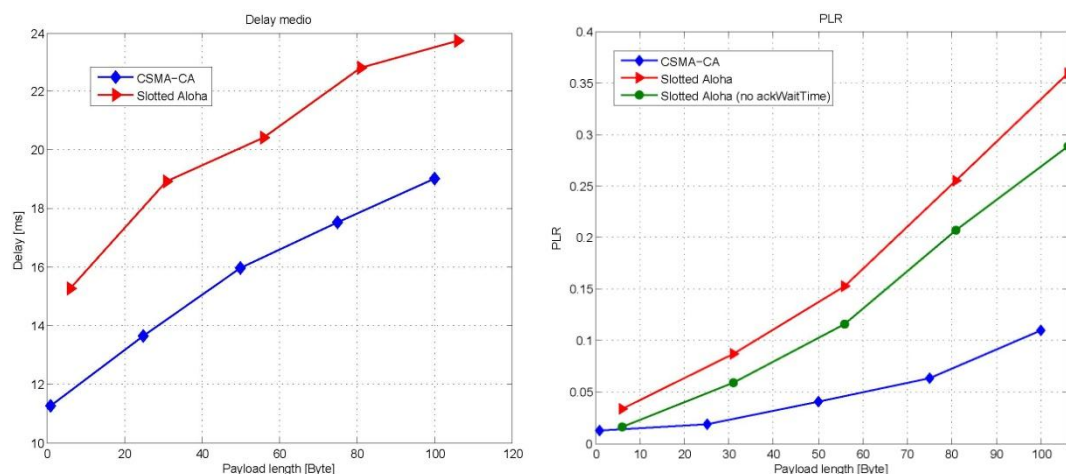


Figure 3-19: Average Delay and PLR in the case of ALOHA and CSMA/CA

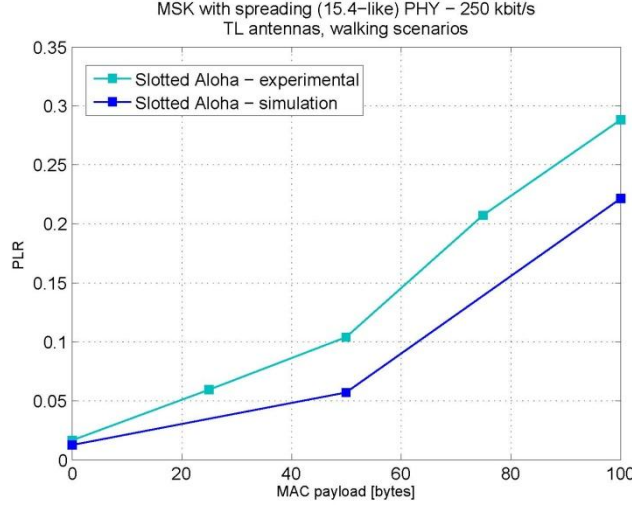


Figure 3-20: PLR in the case of ALOHA: simulations and experimentation

4 Coexistence Issues and Results

In this section we report the results of coexistence studies regarding the performance achievable by the WiserBAN network when an IEEE 802.11 (Wi-Fi) network is present as source of interference. Results have been achieved via both simulations and experimentations.

We refer to IR4.2 for simulation results related to the interference caused by IEEE 802.15.4 (ZigBee) networks on the WiserBAN network.

We report here only results related to the PHY layer of IEEE 802.15.4 (MSK with spreading), being the PHY implemented by the benchmark. We refer to IR4.2 for simulation results related to the other PHYs.

4.1 Simulation Results

4.1.1 Interference Characterization

The interference has been previously characterized in both the frequency domain and in the time domain. In particular, since the above mentioned interference sources are standardized networks, their frequency characterization could be derived from the standards, while time characterization has been performed through specific measurements.

In the following studies we assume that the WiserBAN network works in the following frequency channels characterized by:

- Center frequencies $f_c = 2405 + i \cdot 5$ [MHz], $i = 0, \dots, 15$;
- Bandwidth $B = 5$ [MHz], when MSK modulation is used.

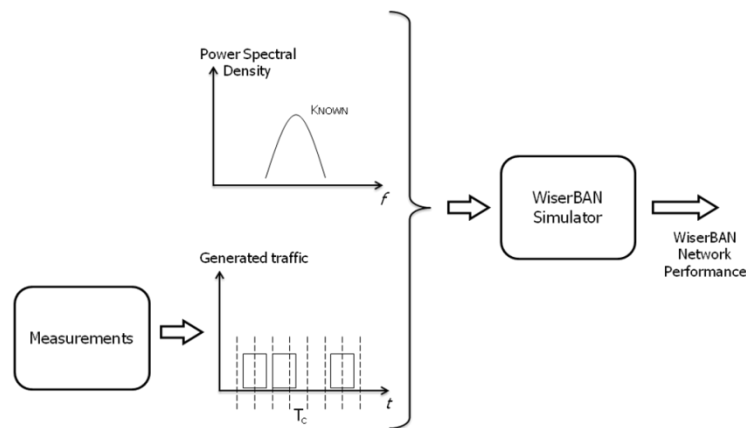


Figure 4-1: The Coexistence studies

4.1.1.1 Frequency Characterization

We refer to the versions of IEEE 802.11 standard operating at 2.45 GHz in the ISM band, namely IEEE 802.11 b/g/n. In these cases, the standard defines 13 channels of 22 MHz each, as illustrated in Figure 4-3. The spectrum mask that an IEEE 802.11 signal must respect is shown in Figure 4-2.

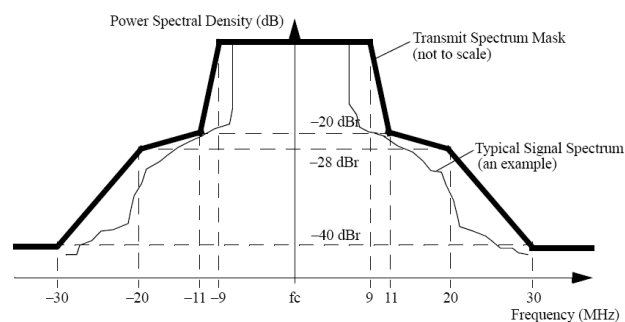


Figure 4-2: IEEE 802.11 transmit power spectrum mask

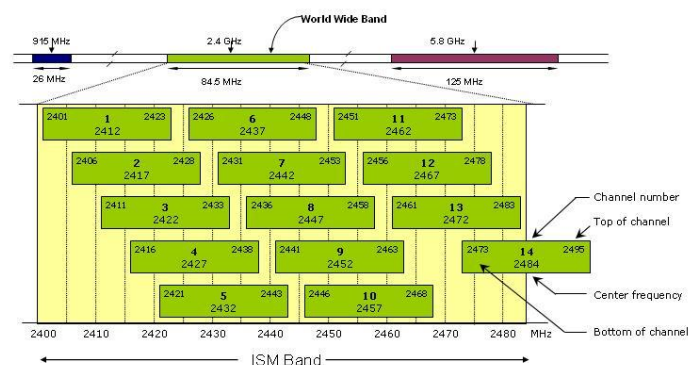


Figure 4-3: IEEE 802.11 channel

Being WiserBAN channels 5 MHz or 2 MHz wide, depending on the considered PHY, only part of the IEEE 802.11 interfering power will fall inside the receiver band. A graphical example of

overlapping between IEEE 802.11 and the considered WiserBAN channels is reported in Figure 4-4.

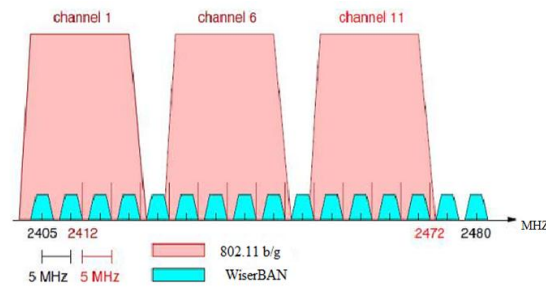


Figure 4-4: Example of overlapping between IEEE 802.11 and WiserBAN channels

In order to have a frequency characterization of IEEE 802.11 interference to be used as input for the simulator, we computed the percentage of interfering power falling into the WiserBAN receiver band. For the sake of simplicity, we assume that: i) the receiver filter is ideal (amplitude equal to 1 in the band of interest and equal to 0 outside); ii) the interference amplitude complies with the spectrum mask shown in Figure 4-2. The values obtained are reported in Table 4-1. As an example, from the table, we can see that when an interfering IEEE 802.11 network operating in IEEE 802.11 channel 1 is present, the 24.52% of the power transmitted by IEEE 802.11 devices is source of interference for a WiserBAN network working in WiserBAN channel 1, while if WiserBAN devices use channels from 5 to 16 less than 1% of IEEE 802.11 transmitted power is received by them and sensed as interfering.

		WiserBAN canne															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
IEEE 802.11 channel	1	24.52	24.82	24.82	22.06	0.508	0.086	0.028	0.010	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
	2	2.98	24.52	24.82	24.82	22.06	0.508	0.086	0.028	0.010	0.002	0.002	0.002	0.002	0.002	0.002	0.002
	3	0.109	2.98	24.52	24.82	24.82	22.06	0.508	0.086	0.028	0.010	0.002	0.002	0.002	0.002	0.002	0.002
	4	0.032	0.109	2.98	24.52	24.82	24.82	22.06	0.508	0.086	0.028	0.010	0.002	0.002	0.002	0.002	0.002
	5	0.014	0.032	0.109	2.98	24.52	24.82	24.82	22.06	0.508	0.086	0.028	0.010	0.002	0.002	0.002	0.002
	6	0.003	0.014	0.032	0.109	2.98	24.52	24.82	24.82	22.06	0.508	0.086	0.028	0.010	0.002	0.002	0.002
	7	0.002	0.003	0.014	0.032	0.109	2.98	24.52	24.82	24.82	22.06	0.508	0.086	0.028	0.010	0.002	0.002
	8	0.002	0.002	0.003	0.014	0.032	0.109	2.98	24.52	24.82	24.82	22.06	0.508	0.086	0.028	0.010	0.002
	9	0.002	0.002	0.002	0.003	0.014	0.032	0.109	2.98	24.52	24.82	24.82	22.06	0.508	0.086	0.028	0.010
	10	0.002	0.002	0.002	0.002	0.003	0.014	0.032	0.109	2.98	24.52	24.82	24.82	22.06	0.508	0.086	0.028
	11	0.002	0.002	0.002	0.002	0.002	0.003	0.014	0.032	0.109	2.98	24.52	24.82	24.82	22.06	0.508	0.086
	12	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.014	0.032	0.109	2.98	24.52	24.82	24.82	22.06	0.508
	13	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.014	0.032	0.109	2.98	24.52	24.82	24.82	22.06

Table 4-1: Percentage of interference from IEEE 802.11 channels on WiserBAN channels

4.1.1.2 Time Characterization

In order to characterize in the time domain the traffic generated by an IEEE 802.11 network, some experiments have been carried out. The measurement set up considered is shown in Figure 4-5. To measure the traffic between the Access Point (AP) and the notebook, the network protocol analyzer Wireshark Version 1.6.2 has been used.



Figure 4-5: Experiment setup for IEEE 802.11 traffic characterization

Three different traffic flows have been measured:

- *No traffic*, meaning that the notebook was left with an open browser application, but with no interaction with the user, in this modality only synchronization packets are supposed to be exchanged;
- *Web browsing*, that refers to simple navigation operations during which the user performs general operations with a web browser, alternating the opening of web pages with their reading;
- *Heavy traffic*, meaning a more intense web navigation, which involves both actions described in the *web browsing* case and the download of files from emails or ftp sites, with dimensions up to 20 Mbytes.

All the above mentioned traffic modalities have been measured for a time interval of 5 minutes, with the AP and the notebook positioned at a distance of 2 m and in Line-of-Sight condition.

From the results captured with Wireshark, some elaborations were performed to produce .txt files that served as simulation inputs for later analysis. These files report the presence/absence of IEEE 802.11 packets, coming from the AP or the notebook, as a function of time and with the resolution needed in the WiserBAN simulator.

4.1.2 Simulated Scenario

The simulated scenario is illustrated in Figure 4-6. It represents a hypothetical room of 3 x 3.5 m. A human subject wearing the WiserBAN nodes walks in the room, following the trajectory represented by the red arrow in the figure. The WiserBAN network is composed of

4 devices and one RC held in the right hand (integrated scenario simulated in D4.1 for CAP performance evaluation, scenario B of Figure 4-18 in D4.1 document).

The AP is located at the coordinates $(x, y, z) = (1, 3.5, 3)$ m. The notebook is positioned at $(x, y, z) = (3, 1.5, 0.8)$ m.

Simulations have been performed with the *Heavy traffic* input file for the traffic characterisation of IEEE 802.11 link (see Section 4.1.1.2).

Both the AP and the notebook are supposed to use a transmit power equal to +20 dBm (100 mW). We have considered two different cases of overlapping between IEEE 802.11 and WiserBAN channels; specifically, for MSK with and without spreading PHYs we have selected:

- *case 1*: situation with 0.028% of interfering power falling into WiserBAN receiver band (for instance, IEEE 802.11 channel 1 with WiserBAN channel 7). This situation corresponds to an interfering power approximately equal to -19 dBm;
- *case 2*: situation with 24.82% of interfering power falling into WiserBAN receiver band (for instance, IEEE 802.11 channel 1 with WiserBAN channel 2 or 3). This situation corresponds to an interfering power approximately equal to +14 dBm.

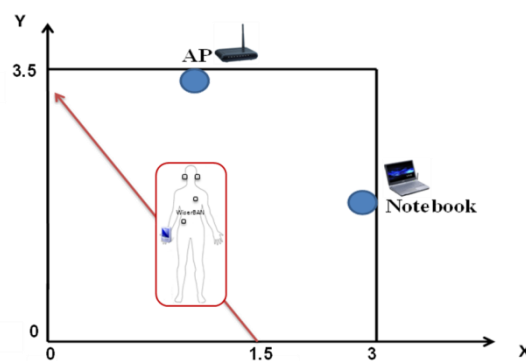


Figure 4-6: Simulation scenario for WiserBAN coexistence evaluation with an IEEE 802.11 network

We refer to D4.1 for details about the channel model considered and the packet capture model.

An average human walking speed of 3 m/s has been considered.

As for the channel model between IEEE 802.11 devices and WiserBAN nodes, a free space propagation is considered:

$$L(d) = k_0 + k_1 \ln(d),$$

where L is the attenuation in dB for devices located at a distance d [m], $k_0 = 40$ dB and $k_1 = 13.03$ (values obtained for the frequency of 2.45 GHz and a propagation constant equal to 3). The free space attenuation has been chosen for the sake of simplicity; in fact, it has to be considered as the worst case scenario, since it does not include the additional attenuation produced by the presence of the human body.

In order to compare the results reported hereafter with the ones obtained without interference, all the simulation parameters (CSMA/CA, MAC, PHY, and energy consumption values) have been set as in Deliverable D4.1.

4.1.3 Numerical Results

The average PLR obtained in presence of IEEE 802.11 interference is shown below.

We can notice that in presence of an IEEE 802.11 interfering network, WiserBAN performance in terms of PLR degrades significantly. The results obtained for simulated *case 1* and *case 2* appear to slightly differ. This means that IEEE 802.11 interference affects WiserBAN PLR performance even when the utilized channels are only partially overlapping. This can be explained remembering that we have simulated a worst case scenario, because of two reasons:

- the traffic exchanged between the AP and the notebook was a *heavy traffic*;
- the attenuation between interfering nodes and WiserBAN devices is modeled as a free space propagation.

Under these circumstances, the channel is very often found busy by WiserBAN devices, which are therefore not able to correctly transmit their data.

The average delay obtained in presence of IEEE 802.11 interference is shown below. From the figures, we can state that the presence of a IEEE 802.11 interfering network does not degrade WiserBAN performance in terms of delay significantly (the degradation with respect to the case without interference is around 1 ms at maximum).

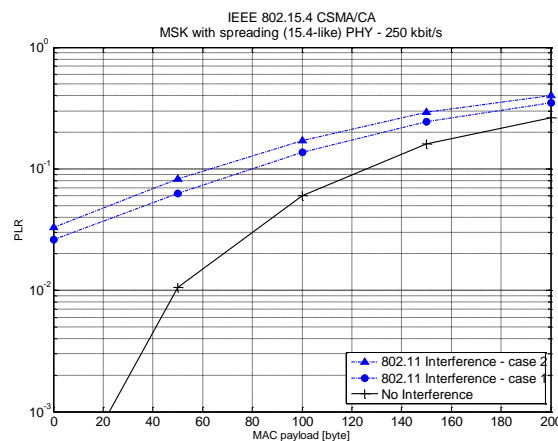


Figure 4-7: PLR with IEEE 802.11 interference

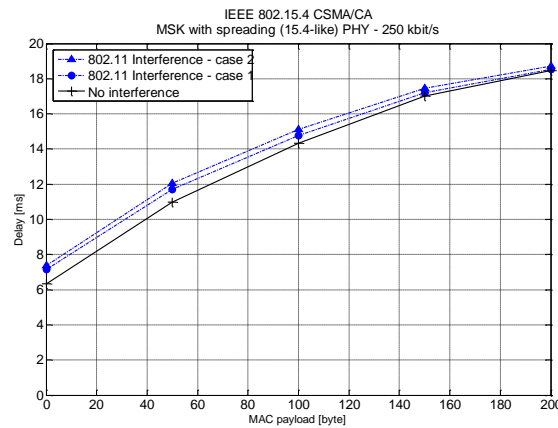


Figure 4-8: Delay with IEEE 802.11 interference

4.2 The Benchmark Results

The coexistence measurements have been performed according to the reference scenario shown in Figure 4-9. The subject was still at a given distance, d , from the Wi-Fi access point (AP).

As shown in Figure 4-9 the set up was the following: The Wi-Fi network was composed of a PC (PC2) downloading, through a wireless link, a file from another PC (PC1) passing through the AP. PC1 was connected through cable to the AP, such that this link (PC1 – AP) was not generating wireless traffic. The transmit power of the AP was set equal to +19 dBm, while the one of the BAN devices was set equal to -22 dBm.

In Figure 4-10 we show the channel used by the AP and by the BAN on the subject. Two channels have been considered for the BAN: a complete overlapped channel and a partially overlapped channel.

In Figure 4-11 we show the PLR on the BAN when the four devices are transmitting packets through the CSMA/CA protocol to the RC, as a function of the distance, d , from the AP, for different values of the packet payload. The file download has been performed during all the duration of the experiment. As can be seen, when the channels are completely overlapped, the PLR is near to 100%. This could be mainly due to the following causes:

- 1) The AP transmits with a power that is approx. +40 dBm larger with respect to the one used by devices;
- 2) The link between the body and the AP is almost free-space, whereas the links of the BAN (among the devices and the RC) are strongly affected by the shadowing caused by the body;
- 3) The PC continuously downloads data from the AP during all the measure, that is BAN devices will never find the channel free.

When, instead, the channels used by the AP and the BAN are only partially overlapped, the performance improves significantly and do not change very much by varying the

distance from the AP. This is also due to the fact that in the environment considered there was a background electromagnetic activity almost constant on all the frequency band, due to the presence of many interferers on the ISM band.



Figure 4-9: The reference scenario for the measurements

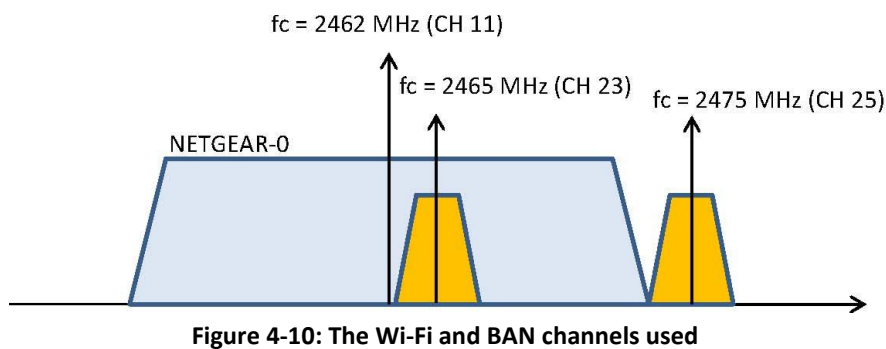


Figure 4-10: The Wi-Fi and BAN channels used

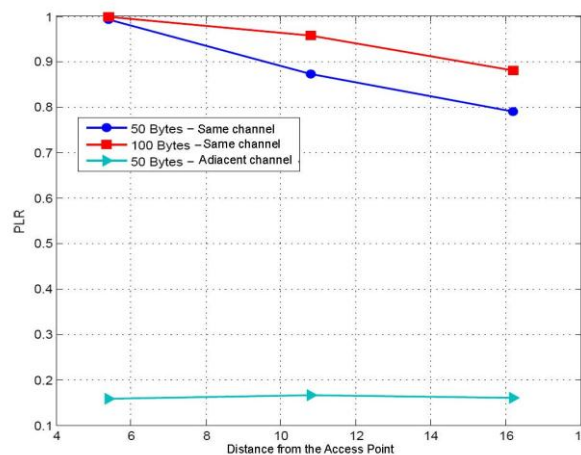


Figure 4-11: The BAN PLR when affected by Wi-Fi interference

5 Concluding remarks

This Deliverable reports about the development of the benchmark platform. The CC2530 SoC, produced by Texas Instrument has been used for the development of the benchmark. The chip implements the IEEE 802.15.4-compliant physical layer. On top of this the WiserBAN MAC protocol has been implemented. In particular we have implemented:

1. The WiserBAN superframe including the IEEE 802.15.4-compliant CSMA/CA protocol in the CAP portion;
2. The slotted ALOHA protocol, as it has been defined in D4.1, to be used as an alternative to CSMA/CA in the CAP portion;
3. A data aggregation strategy to save energy;
4. The WiserBAN application considered in the simulations reported in D4.1 and IR4.2.

We can summarize the outcomes of the Deliverable as follows.

- First results of the performance of the WiserBAN protocols, achieved on the field, have been shown;
- Validation of the simulation results contained in D4.1 and D4.2, thanks to comparison with experimental measurements, has been obtained;
- Results on experiments made on the field, related to coexistence issues, have shown that care must be taken in environments populated by WiFi APs;
- A benchmark platform, implemented over a stable and commercially hardware, to be considered as reference for the rest of the project, has been developed.

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6.3 List of references

[1] Texas Instruments, “A True System-on-Chip Solution for 2.4-GHz IEEE 802.15.4 and ZigBee Applications”.

6.4 Abbreviations

ACK	Acknowledge
CPU	Control Processing Unit
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSP	Co-Processor Radio
HAL	Hardware Abstraction Layer
ISM	Industrial Scientific Medical
MAC	Medium Access Control
MCU	Microcontroller Unit
MSK	Minimum Shift Keying
OSAL	Operative System Abstraction Layer
PHY	Physical
PLR	Packet Loss Rate
RAM	Random Access Memory
SF	Superframe
TI	Texas Instruments