A Survey on Wireless Body Area Networks: Technologies and Design Challenges

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***Abstract*—Interest in Wireless Body Area Networks (WBANs) has increased significantly in recent years thanks to the advances in microelectronics and wireless communications. Owing to the very stringent application requirements in terms of reliability, energy efficiency, and low device complexity, the design of these networks requires the definition of new protocols with respect to those used in general purpose wireless sensor networks. This motivates the effort in research activities and in standardisation process of the last years. This survey paper aims at reporting an overview of WBAN main applications, technologies and standards, issues in WBANs design, and evolutions. Some case studies are reported, based on both real implementation and experimentation on the field, and on simulations. These results have the aim of providing useful insights for WBAN designers and of highlighting the main issues affecting the performance of these kind of networks.**

***Index Terms*—Wireless Body Area Network, Channel Modelling, Energy Efficiency, Coexistance, MAC protocols, IEEE 802.15.4, IEEE 802.15.6, Bluetooth LE.**

I. Introduction

A WIRELESS Body Area Network (WBAN) typically consists of a collection of low-power, miniaturised, invasive or non-invasive, lightweight devices with wireless communication capabilities that operate in the proximity of a human body. These devices can be placed in, on, or around the body, and are often wireless sensor nodes that can monitor the human body functions and characteristics from the surrounding environment.

On one hand, WBANs enable new applications and thus new possible markets with respect to Wireless Sensor Networks (WSNs), on the other hand, their design is affected by several issues that call for new paradigms and protocols.

The diversity of envisioned applications, which span from the medical field (e.g., vital signs monitoring, automatic drug delivery, etc.) to the entertainment, gaming, and ambient intelligence areas, creates a set of technical requirements with a wide variation in terms of expected performance metrics, as throughput or delay, therefore flexible architectures and protocols are needed. The main communication standard solutions considered as reference are: IEEE 802.15.4 [1], IEEE 802.15.6 [2], and Bluetooth Low Energy [3]. IEEE 802.15.4 (published in 2006), specifies the physical (PHY) and medium access control (MAC) layers for short-range wireless communications, devised to support low power, low cost, and low bit rate networks. The IEEE 802.15.6 (published in 2012), was specifically designed for wireless communications in the vicinity of, or inside, a human body. Finally, Bluetooth Low Energy (BT LE) (published in 2010) is the ultra-low power consumption configuration of Bluetooth technology, targeting several applications for small and cheap devices powered by button-cell batteries, such as wireless sensors. Due to the quite large number of available standards, it is necessary to identify the best solution, depending on the application requirements.

For what concerns the main issues to be accounted for in the design of a WBAN, the impact of wireless medium, the battery lifetime and the coexistence with other wireless networks are of fundamental importance. The presence of the human body affects the radio wave propagation, leading to a specific and peculiar radio channel, which has to be properly accounted for in the design of the protocols. The need for long battery lifetime shall be addressed through energy efficient solutions since frequent battery replacements must be avoided, being a very hard task in some application (e.g., medical applications where nodes are implanted). The third main issue to be taken into account is the outage occurrence due to coexistence with other wireless networks operating in the same frequency band. As it will be remarked later in the paper, many standard solutions for WBAN operate in the licence-free Industrial Scientific and Medical (ISM) band centered at 2.45 GHz and this leads to coexistence issues with other networks operating in the same band (e.g., Wi-Fi IEEE 802.11).

This paper provides a survey on WBANs over the period 2005-2013, including their applications and standard technologies, the main features and challenges in their design and the possible future research directions. After the definition of the main applications and requirements, the standard solutions identified above are described and compared through the introduction of some case studies. Particular attention is paid to the IEEE 802.15.6 standard, being optimised for low power devices and operation on, in or around the human body. Moreover, the paper presents some insights with reference to the main issues identified above, by introducing other case studies, with the aim of showing the impact on the WBAN performance of some key factors to be addressed in the design, as the impact of the radio channel, the energy consumption, and the coexistence with external interfering networks.

The main new contribution of this paper, beside presenting an updated survey of the WBAN technologies, is to provide to the scientific community a broad overview of the most

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TABLE I
SURVEYS ON WBAN

Subject	Ref.s
Requirements	[4-7]
Security	[8-9]
General applications	[4],[6-7]
Medical applications	[10-18]
Channel modelling	[19]
MAC protocols	[20-24]
Energy efficiency	[10-11], [24-26], [144]
Routing	[21-22],[27]

challenging aspects in the design of a WBAN, and to give useful hints about the way to tackle these challenges. The latter is achieved also by introducing some novel numerical results, with particular reference to the IEEE 802.15.6 and coexistence studies, mainly derived through experimentation on the field performed at the University of Bologna.

The remainder of this paper is organised as follows. The next section reports a set of already published surveys on WBAN; a taxonomy of WBANs is presented in Sec. III. In Sec. IV some of the most common applications for WBANs are described along with the broad range of system requirements needed by these applications. Sec. V gives an overview of the standards mainly adopted to realise a WBAN. Sec. VI follows where a comparison of the standards is presented through simulations and experimental results. The main challenges related to the design of a WBAN are then treated in Sec. VII, where some case studies are reported as examples to show the impact of the different key factors affecting the WBAN performance, with the aim of providing a good insight to the designer. Sec. VIII reports on the possible future research directions and Sec. IX provides a interesting use case, showing the utility of the topics addressed in the paper. Lastly, Sec. X concludes this paper.

II. RELATED WORKS

This section provides an overview of general surveys on WBANs and surveys on more specific aspects of the WBANs, as applications or protocols as summarised in Table I. The reader can also find related works dealing with more specific topics, as channel modelling, energy-efficiency and coexistence in Sec. VII.

Several surveys on WBANs can be found in the literature of recent years, among them [4]–[7] present general overviews on WBAN technical requirements, the application scenarios in which they could be involved and the candidate wireless technologies to be considered as possible *de facto* standards. The key research aspects that should be addressed in the near future are specifically considered in [4], with a detailed analysis that spans from the most suitable frequency band selection up to security and privacy aspects, covering the entire system architecture. An interesting overview of the most important characteristics and limitations of the types of sensors commonly used in WBANs devices is provided in [7], highlighting how important a proper choice of the hardware is, in order to realise systems fulfilling application-dependent requirements. Surveys on solutions to increase WBAN reliability, security and availability is given in [8] and [9].

In contrast with the above mentioned works, this paper aims to introduce the reader to the main issues in WBAN design, namely the radio channel modelling, the minimisation of the energy consumption and the coexistence with other WBANs. Simulation and experimental numerical results are provided to show their real impact on the performance of a WBAN, therefore the reader is guided to the best approach to challenge these issues according to the system requirements.

As for the surveys on applications, a special emphasis on medical ones and healthcare is given in [10]–[13], with [14] specifically focusing on cardiac patients monitoring. In particular, a detailed list of existing healthcare monitoring applications is provided both in [12] and [13], the latter giving also an insight into the peculiar research challenges faced by healthcare systems like the ones presented. The authors of [15] and [16] consider the issue of mobility of patients in an hospital wearing a WBAN. In their works they surveyed the handover mechanisms for intra-mobility, that is the mobility of sensor nodes between different access points, but always within the same network domain. Surveys on mobile phone sensing and human activity recognition using wearable sensors are given in [17] and [18] respectively.

In [19] is described the activity carried out by the COST Action 2100 on WBAN, focused on channel modelling and antenna design. Different in-body, on-body and on-body to off-body channel models are presented along with related antenna designs. The quality of links between on-body devices is explored in term of cumulative distribution function of packet loss rate by means of measurements.

Protocol solutions specifically designed for WBANs and for body centric communications are also reviewed in [20]–[23]. While [20] presents a comparison of different MAC protocols, the other three referenced works propose an overview also on physical layer solutions. As one of the most critical aspects to be considered when dealing with WBANs for medical applications, authors in [10], [11] and [24] stress the importance of designing energy-efficient MAC protocols to enhance devices battery-life keeping their size as smaller as possible. A survey on duty cycle mechanisms to keep the energy consumption low in wireless sensor network is given in [25], while [26] is a survey on energy harvesting techniques that can be also applied in WBAN using the human body as source of energy. Routing protocols for WBAN are reviewed in [27], the authors classify routing protocols into six categories: thermal aware, cluster based, cross layers based, quality of service aware, and delay tolerant aware routing protocols and they discuss the advantages and the performance for each category. Finally, particular emphasis is given in [21], [22] to routing protocols and cross-layer approach to improve the performance.

In contrast with the above mentioned works, this paper is much more general and deals with different aspects, as applications, requirements, MAC protocols, energy efficiency, radio channel and coexistence.

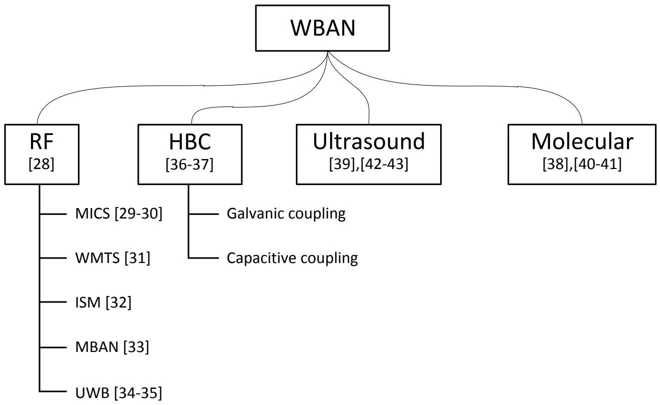


Fig. 1. Taxonomy of WBAN.

III. A TAXONOMY OF WBANS

WBANs can be categorised according to the wireless communication technology employed. In this section we present on overview of these technologies, considering not only Radio Frequency (RF) solutions, but also other technologies, as Human Body communication (HBC), molecular communications and ultrasonic waves. This classification of WBAN is summarised in Fig. 1. The rest of the paper is on RF WBANs, being the main focus of this survey.

The majority of the works that can be found in the literature are about WBANs based on RF techniques, which can be classified according to the frequency band they operate in. Worldwide communication authorities regulate the use of the frequency spectrum, however, it is not straightforward for the WBAN designer to choose the most appropriate band for the target application. To this end the IEEE 802.15 Task Group 6 delivered a report that provides an overview of frequency regulations for medical applications in different countries and regions [28]. The different bands are illustrated in Fig. 2 and a description of them follows.

Wireless Medical Telemetry System (WMTS) and Medical Implant Communications Service (MICS) bands were allocated exclusively for body-worn and implanted medical applications [29], which require simple point-to-point communication. They were introduced to overcome the range, bit rate and reliability limitations imposed by the magnetic coupling communication technology used in the early wireless medical devices. Within the MICS band is possible to achieve a bit rate up to 400 kbps and a communication range around 2 meters [30] to satisfy the requirements of application such as cardiac pacemakers, implanted defibrillator and neurostimulator. Application like the swallable camera pill may require bit rate in the order of 1 Mbps, which are achievable in the WMTS band. An example of WBAN using a combination of devices operating in the MICS band for short range intra-BAN communication, and in the WMTS band for medium range communication with a central data collector, can be found in [31].

The unlicensed ISM bands are defined by the International Telecommunication Union (ITU) and are designated for purposes different from telecommunications and, some of them are subject to specific country's radio regulations [32]. Being unlicensed, the ISM bands are prone to coexistence issues that must be taken seriously into account by the WBAN designer, as discussed in Sec. VII-C. The band between 2.4 and 2.5 GHz is often preferred among the others because of its worldwide availability. An interesting action was taken by the Federal Communications Commission (FCC) on May 2012 to allocate 40 MHz of spectrum between 2.36-2.40 GHz on a secondary basis for a new Medical Body Area Network (MBAN) licensed service [33]. This will be an effective way to mitigate the interference experienced by devices working in the adjacent ISM unlicensed band.

Another option is Ultra-wide Band (UWB). An UWB signal is formally defined by ITU as any signal that occupies more than 500 MHz of spectrum. The regulatory authority specifies, however, that the power spectral density shall not exceed -41.25 dBm/MHz, which is around 30 dB below the maximum allowed for a signal in the 2.4-2.5 GHz ISM band [28]. Some positive features that make UWB a good candidate technology for WBANs are the low susceptibility to multipath fading that improves the performance of indoor systems, the immunity to interference, the very high bit rate (up to 500 Mbps). Moreover, intrinsically secure communication is possible thanks to the low energy and spectral density, which is below the noise floor of conventional receivers, and the simplicity of the transceiver architecture. The interested reader can find a primer on UWB in [34], while an example of a WBAN with cognitive radio features based on UWB is presented in [35].

The focus of this survey is primarily on RF WBANs, however recent works have shown that other wireless communication paradigms can be applied in this framework.

One of this technique is neither wireless nor wired, in fact, it uses the human body as communication medium. It is called *Human Body Communication* (referred to also as Intra Body Communication and Body Channel Communication). The propagation signal through the human body is possible by capacitive coupling of the human body to its surrounding environment, and galvanic coupling achieved by coupling alternate current into the human body. The benefits HBC can bring to a WBAN are: intrinsic security since signals are confined to the persons proximity and receiving data requires body contact, the energy consumption can be kept as low as one order of magnitude compared to UWB at around 10 Mbps, coexistence with other HBC WBAN is possible because the communication is confined in or in the immediate proximity of the human body. An extensive survey of HBC can be found in [36], while a general model for HBC is derived from Maxwell's equations in [37].

Considering in particular in-body WBANs, molecular and ultrasonic communications can represent good alternatives to RF solutions. The former refers to the use of molecules as messages transferred between a transmitter and a receiver using nanotechnology [38], while the latter is based on the use of ultrasound, i.e. acoustic waves at non-audible frequencies [39].

Due to their intrinsic biocompatibility, diffusion-based *molecular communications* are promising for nanomedicine applications, such as restoration of the glucose feedback loop in diabetic patients, recognising and destroying tumours

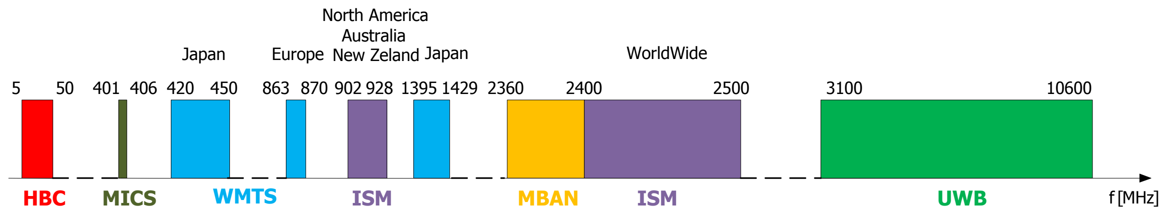


Fig. 2. Some of the available bands for WBAN based on RF technology.

with engineered bacteria, or even intracellular surgery with nanorobots [40]. On the other hand, their use brings crucial challenges that have to be addressed to allow the realisation of reliable networks. Channel characteristics differ significantly from those of classic RF medium in terms of propagation delays, noise, applicable modulations, and achievable capacity. The nature of molecular movement (based on Brownian motion) has to be taken into account when designing MAC and routing solutions, which have to be as simple as possible, given the very low memory and processing capabilities of nanomachines [40]. In [41] Yen et al. described how Brownian motion makes the physical channel very different from the one experienced in conventional wireless communications. They show how a new paradigm of channel coding can enhance the overall system reliability and how conventional Multi-Input-Multi-Output techniques can be applied to molecular communications.

Ultrasonic waves can overcome some of the limits of RF propagation inside the human body, as the high attenuation values. They have been used for decades as the preferred technology solution for underwater communications and they are thus considered a suitable option for enabling communications inside the human body, which is mostly made up of water [39], [42]. Proper design choices have to be done at the PHY, MAC, and network layers to exploit the possible high capacity and to realise WBANs based on ultrasonic communications. In [43] the authors derived a model for ultrasonic communications inside the human body and proposed a multiple access MAC protocol; simulation results show high performance of their proposal in terms of throughput, packet loss rate and energy consumption of their proposal.

IV. WBAN Applications and Requirements

The ability to deploy a finite number of wireless sensor nodes on the human body leads to the opportunity of developing a large number of applications in several fields. In this section we first present a set of possible applications for WBANs, then the requirements imposed by these applications will be listed and discussed.

A. Applications

1) Healthcare: At a first glance this is the most promising field of application for a WBAN. Several non-intrusive sensors deployed inside or on the human body allow the patients and the doctors to sample continuous waveform of biomedical signals in a remote and continued fashion [23]. Events that require prompt assistance like heart attack and epileptic seizure, can be detected and even foreseen thanks to the continuous monitoring of the heart and brain activity, respectively. WBANs cannot only detect fatal events and anomalies, they can also improve the life style of hearing and visually impaired people by means of earing aid, cochlear implant and artificial retina, respectively [44]–[46]. The following is a non-exhaustive list of applications that can benefit from WBAN usage: electrocardiogram (ECG), electroencephalogram (EEG), electromyogram (EMG), pulse oximetry, drugs delivery, post operative and temperature monitoring, glucose level, toxins, blood pressure, etc..

2) Sport and Entertainment: A real-time log of vital parameters like blood pressure, heart beat, blood oximetry and posture can improve fitness and sport experiences. In this way users can gather information concerning their sport activity and use them to prevent injuries and to plan future training to improve their performance.

WBANs bring more realism in the user experience in the field of entertainment. Motion capturing techniques make possible to track the position of different parts of the body by means of a network of gyroscopes and accelerometers wirelessly connected to a central node and worn by the user. The real-time information about the motion allows the user to use his body as a controller in videogames. Moreover, film industry takes advantage of motion capture along with post production techniques to realise highly realistic digital movies where actors play the role of non-human subjects [47].

3) Military and Defence: Network-Enabled Capability (NEC) is the name of the long term program aimed to achieve enhanced military effect through the use of information systems [48]. New capabilities added by a WBAN will enhance the performance, at both individual and squad level, of soldiers engaged in military operations. At individual level, a set of sensors can monitor vital parameters and provide information about the surrounding environment in order to avoid threats, while information taken at squad level will make the commander able to better coordinate the squad actions and tasks. Spatial localisation techniques and communication between different WBANs (inter-WBAN communications) play an important role in this field, as well as security in order to prevent sensitive information from being caught by the enemies [49].

B. Requirements

To develop a WBAN is a challenging task because of the broad range of requirements imposed by the applications described in Sec. IV-A. The most important requirements, as recommended by the IEEE TG6 [50], are detailed in this section. Some of them are better analysed and discussed in the following sections. In particular, some details about

TABLE II
BIT RATE AND QOS REQUIREMENTS FOR SOME WBAN APPLICATIONS [51].

Application	Bit rate	Delay	BER
Deep brain stimulation	< 320 kbps	< 250 ms	$< 10^{-10}$
Drug delivery	< 16 kbps	< 250 ms	$< 10^{-10}$
Capsule endoscope	1 Mbps	< 250 ms	$< 10^{-10}$
ECG	192 kbps	< 250 ms	$< 10^{-10}$
EEG	86.4 kbps	< 250 ms	$< 10^{-10}$
EMG	1.536 Mbps	< 250 ms	$< 10^{-10}$
Glucose level monitor	< 1 kbps	< 250 ms	$< 10^{-10}$
Audio streaming	1 Mbps	< 20 ms	$< 10^{-5}$
Video streaming	< 10 Mbps	< 100 ms	$< 10^{-3}$
Voice	50 - 100 kbps	< 100 ms	$< 10^{-3}$

transmission range, topology, bit rate and security are provided in Sec. V, with reference to the different considered standard solutions, while some indications about the quality of service achievable with such standards are provided in Sec. VI. Finally, Sec. VII deals with details about the radio channel, power consumption and coexistence issues.

1) Bit rate and Quality of Service: The bit rate requirement varies on a very broad range depending on the application and on the type of data to be transmitted. It goes from less than 1 kbps (e.g., temperature monitoring) to 10 Mbps (e.g., video streaming). The bit rate can refer to a single link or to multiple links, when several devices transmit/receive information to/from one coordinator at the same time (e.g., multiple leads ECG). A list of possible applications with their target bit rates is proposed in [4]. High level of QoS should be guaranteed in medical and military applications. Appropriate error correction and interference-avoidance methods should be implemented at MAC and PHY layers to reduce the bit error rate (BER). Other important parameters are: the end-to-end delay, the delay variation and the capability to provide fast and reliable reaction to emergency situations. Furthermore, for this kind of WBAN the capability to handle traffic with different priority levels is important [50]. In Table II is reported a list of requirements for different WBAN applications.

2) Range and Topology: The communication range should not be larger than few meters ($3 \div 6$ m) for most of the applications, as presented in [4]. Thus, a simple star topology is usually enough, however, the human body can represent an obstacle itself for the radio propagation, especially for the implanted nodes. In this case, a multi-hop communication must be established and a relaying technique should be accounted for in order to exploit node spatial diversity, as proposed for example in [52], [53]. The number of nodes forming the WBAN ranges from two (e.g., glucose meter) to ten and can vary at run time. Therefore, the network should implement reliable association and disassociation procedures to allow nodes to join and leave the network as needed by the application. In Sec. V transmission range and possible topologies for the different standards are provided.

3) Security: Security is of primary importance, especially for what concerns medical and military applications, and it should be addressed in terms of privacy, confidentiality, authorisation, and integrity [4]. As it will be briefly described in Sec. V, each of the standard intended to be used in the WBAN context provide some techniques to deal with security issues. Anyway, conventional data encryption mechanisms or authentication process result to be not perfectly suitable for these kind of networks due to limited processing power, memory, and energy constraints of WBAN nodes. Hence, novel lightweight and resource-efficient methods are being developed [54], [55]. A promising solution in this context is the use of biometric identification based mechanisms [56], [57]. In Sec. V some details about the security provided by the different standards are given.

4) Antenna and radio channel: As already stated, antenna design can be a very critical issue and researches on miniaturisation should lead to quite efficient solutions [58], always considering the proper trade-off between antennas sizes and their efficiency. Moreover, the presence of the human body could not be neglected since it affects antenna's radiation and polarisation characteristics, according to the specific device on-body position [59], [60]. A good radio channel characterisation is then mandatory in order to design an antenna able to provide the proper radiation properties. The impact of radio channel on network performance is accounted for in Sec. VII-A.

5) Power Consumption: The power consumption requirement is very dependent on the nature of the application. However, WBAN devices are generally battery-powered and the battery lifetime is required to be up to several years for implanted devices (e.g., pacemakers require at least five years) [61]. Ultra-low power design for radio transceivers is essential, as well as power-wise MAC protocol design. A common technique for the latter at the expense of end-to-end delay is lowering the duty cycle, which allows devices to be in sleep mode (transceiver and CPU shut down) for most of the time. This solution is effective for applications that require infrequent transmissions, however, a proper trade-off between delay and power consumption should be found. Energy scavenging could also be an option to lessen the need for a battery [62], [63], in particular from body heat [64] or from human movements [65]. Power consumption issues are addressed in Sec. VII-B.

6) Coexistence: Most of the WBANs are designed to operate in the license-free ISM band centered at 2.45 GHz. This is an overcrowded radio band, indeed, Wi-Fi (IEEE 802.11), Bluetooth (IEEE 802.15.1), IEEE 802.15.4/ZigBee and other standards operate in this band. Many WBAN applications (e.g., medical applications) require very high reliability, especially when an emergency or alarm traffic has to be established, therefore techniques to avoid or reduce interference should be studied and implemented. A proper evaluation of the real impact on WBAN performance in terms of packet loss rate or transmission delay due to the presence of interfering systems is then of outmost importance. Some works that address this topic are reported in [66]–[68], which study coexistence aspects between several sources of interference (i.e., systems working according to Wi-Fi standard or IEEE 802.15.4a) and different PHY Layer solutions for the WBAN (i.e. narrowband PHY at 2.45 GHz, IEEE 802.15.6 UWB). Moreover, as specified in [50], in order to reduce or eventually eliminate possible damaging effect of simultaneous activity, proper techniques of interference rejection should be considered as proposed in [69]–[72], just to give some examples. Anyway, the presence of other nearby networks should not be seen just as a potential source of interference, but also as possible useful relay networks to forward the information in a non fully connected scenario for delay-tolerant applications [73], [74]. Coexistence issues are addressed in Sec. VII-C.

7) Form Factor: Size constraints can be stringent; the most critical aspect of this is to fit the antenna and the battery into a very tight case while providing good radiation property and lifetime. This is true mainly for implantable devices, anyway, when a WBAN node is designed to be worn, flexibility and stretchability may be more relevant in order to be comfortable for the user, especially in sport, fitness and military applications. For recent advances in stretchable electronics the interest reader should refer to [75], while [76]–[78] focus on stretchable antennas and RF circuits. Recent advances in integrated circuit design and miniaturisation of both radio components and antennas strive to realise devices with adequate form factor to be implanted or comfortably worn.

8) Signal processing: WBAN applications are power consumption limited and the radio circuits are often the power-greedy part of the system [79]. However, power efficient signal processing techniques can help the designer to keep under control the power consumption related to the acquisition and analysis of the biological signals. To this extent compressed sensing (CS) is a technique that allow to sample a sparse analogue signal at a sub-Nyquist rate, and saving energy without loosing the information contained in it [80], [81]. CS has been applied to many WBAN scenarios such as EEG [82], ECG and EMG [83], where the authors show that power consumption can be lowered by reducing the amount of data to be transmitted using CS to compress data up to a factor of 16. In [84] the authors show how to use block sparse Bayesian learning to reconstruct a sub-Nyquist sampled signal (fetal ECG) exploiting its correlation, and they proved the effectiveness of their approach with experimental results. [85] presents a wavelet transform based algorithm used to detect the QRS complex of a down-sampled ECG signal. An overview of CS applied to WBAN design can be found in [86].

9) Safety for the human body: At the frequencies of interest for WBANs, the known health-related effects centered around human tissues include only heating. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) specifies general restrictions and limits that have to be met to guarantee health safety when the body is exposed to time-varying electromagnetic fields [87]. For the frequency range from 100 kHz to 10 GHz such restrictions are established in terms of Specific Absorption Rate (SAR). SAR represents the mass normalized rate at which RF power is coupled to biological tissues and it is typically expressed in units of watts per kilogram [W/Kg]. Low power devices, such as WBAN ones, do not radiate enough power for the whole-body SAR to be a concern, while attention has to be paid to the localised SAR, which is the SAR measured in specific parts of the body most exposed to RF fields. Therefore, WBANs should minimise the localised SAR and comply with international [87] or regional SAR regulations (such as those defined by the European Union for Europe [88] and by the FCC for USA [89]).

V. Standard Solutions

The benefits brought by standardisation are manifold: manufacturers can rely on solid bases and specifications in developing their products, costs for both the vendors and consumers are lower and the latter are no longer dependent on a specific vendors; moreover, the enhanced interoperability enables a seamless use and spread of the technology. In this section we describe the main solutions considered as reference: IEEE 802.15.4 [1], IEEE 802.15.6 [2], and Bluetooth Low Energy [3].

The former was published in 2006, specifying the PHY and the MAC layers for short-range wireless communications, devised to support low power, low cost, and low bit rate networks. Nowadays, it can be regarded to as a *de-facto* standard for WSNs. The second standard solution, instead, was specifically designed for wireless communications in the vicinity of, or inside, a human body. IEEE 802.15 Task Group 6 initiated WBAN standardisation activities in November 2007, recognising that existing standards did not fully meet the medical (proximity to human tissues) and relevant communication regulations for some application environments and they were not suitable to support the combination of reliability, low power, bit rate, and non-interference required to broadly address the breadth of WBAN applications. A first draft was released in May 2010, the final version was published in February 2012. Finally, Bluetooth Low Energy (BT LE) is the ultra-low power consumption configuration of Bluetooth technology, as defined in the latest Bluetooth core configuration (June 2010) [3]. BT LE targets several applications for small and cheap devices powered by button-cell batteries, such as wireless sensors.

A. The IEEE 802.15.4 Standard

IEEE 802.15.4 wireless technology is a short-range (up to 100 m) communication system intended to enable applications with relaxed throughput and latency requirements in Wireless Personal Area Networks (WPANs). The key features of IEEE 802.15.4 wireless technology are low complexity, low cost, low power consumption, low bit rate transmissions, to be supported by cheap either fixed or moving devices. The main field of application of this technology is the implementation of WSNs. The network topologies supported are the star, tree and mesh [90]. The IEEE 802.15.4 standardises the two bottom layers of ISO/OSI protocol stack, namely PHY and MAC layers. There are two options for the upper layers definition: ZigBee protocols, specified by the industrial consortia ZigBee Alliance, and 6LowPAN [91].

IEEE 802.15.4 specifies a total of 27 half-duplex channels across three frequency bands, organised as follows: i) The 868 MHz band with just a single channel with bit rate of 20 kbps; ii) The 915 MHz band, where ten channels with a bit rate of 40 kbps are available; iii) The 2.45 GHz ISM band with sixteen channels with bit rate equal to 250 kbps.

At the MAC layer the IEEE 802.15.4 defines two different operational modes, namely the beacon-enabled and the non beacon-enabled, which correspond to two different channel access mechanisms. In the beacon-enabled mode the access to the channel is managed through a superframe (SF), starting with a packet called beacon, transmitted by the WPAN coordinator. The superframe may contain an inactive part, allowing nodes to go in sleeping mode, whereas the active part is divided into two parts: the Contention Access Period (CAP), where a slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol is used, and the Contention Free Period (CFP), where guaranteed time slots may be allocated to specific nodes in the network by the coordinator.

The CSMA/CA algorithm is implemented using units of time called backoff periods. Each node maintains three variables for each transmission attempt: NB, CW and BE. NB is the number of times the CSMA/CA algorithm was required to backoff while attempting the current transmission. CW is the number of backoff periods that need to be clear of channel activity before the transmission can start. BE is the backoff exponent related to the maximum number of backoff periods a node will wait before attempting to assess the channel. The algorithm follows the following steps. First, NB, CW, and BE are initialized to 0, 2, and BE_{min}, respectively. Upon reception of the beacon, any activity is delayed (backoff state) for a random number of backoff periods in the range (0, $2^{BE}-1$) [step (1)]. After this delay, channel sensing is performed for one backoff period [step (2)]. If the channel is assessed to be busy, CW is set to 2 and NB and BE are increased by 1, ensuring that BE is not larger than BE_{max}. If the value of NB is lower than 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. If the channel is assessed to be idle, instead, CW is decremented by 1 and compared with 0. If $CW > 0$, the algorithm returns to step (2); otherwise a transmission may start.

In the non beacon-enabled mode nodes only use an unslotted CSMA/CA protocol [1].

IEEE 802.15.4 standard defines a encryption algorithm to be used when cyphering the data to transmit, however, the standard does not specify how the keys have to be managed or what kind of authentication policies have to be applied. These issues are treated in the upper layers which are managed by ZigBee, as an example. The encryption algorithm used is AES (Advanced Encryption Standard) with a 128-bit key length. The AES algorithm is not only used to encrypt the information but also to validate the data which is sent. This concept is called data integrity and it is achieved using a Message Integrity Code (MIC) which is appended to the message. This code ensures integrity of the MAC header and payload data attached. ZigBee implements two extra security layers on top of the IEEE 802.15.4: the Network and Application security layers. All the security policies rely on the AES 128-bit encryption algorithm.

B. The IEEE 802.15.6 Standard

IEEE Task Group TG6 was established in November 2007 to realise a standard specifically designed for WBANs, namely IEEE 802.15.6, whose final version was released in February 2012 [2]. Due to the broad range of possible applications, three different PHYs have been defined:

I) *Narrowband (NB) PHY:* A compliant device shall be able to support transmission and reception in at least one of the following optional frequency bands: *402-405 MHz*, *420-450 MHz*, *863-870 MHz*, *902-928 MHz*, *950-958 MHz*, *2360-2400 MHz* and *2400-2483.5 MHz*. In particular, the latter is in the ISM band and it is extremely interesting because of its worldwide availability, but there may be coexistence issues with other standards working in the same band (e.g., IEEE 802.15.4).

II) *UWB PHY:* UWB is divided into a low (3.25-4.75 GHz) and a high (6.6-10.25 GHz) band, both sub-divided into operating channels of 500 MHz bandwidth each. UWB PHY is specifically designed to offer robust performance for high quality, low complexity and ultra low power operations. Two types of UWB technologies are considered: *impulse radio UWB (IR-UWB)* and *wideband frequency modulation (FM-UWB)*. Two operational mode are also defined: *default* for medical and non-medical applications, and *high quality of service* for high-priority medical applications. Both modes shall support IR-UWB as mandatory PHY, but the *default* one also supports FM-UWB as optional.

III) *HBC PHY:* This PHY solution uses the human body as a communication medium. The band of operation is centred at 21 MHz with a bandwidth of 5.25 MHz.

A wide range of bit rates is supported by the standards. They can be found in Table III.
The transmission range is limited to 3 m for in-body applications and has to be at least 3 m for body-to-body applications. The network topology is allowed to be a star or at most a 2-hops tree. Even if different PHY solutions are proposed in the standard, just a single MAC protocol is presented. In order to support different applications and data flows types (i.e., continuous, periodic, non-periodic and burst), each one characterised by specific performance requirements, the MAC protocol should be the most flexible as possible, combining both contention-based and contention-free access techniques [92]. A BAN coordinator could decide whether to operate in one of the following three access modes:

a) *Beacon mode with beacon periods (superframes)*: The coordinator establishes a common time base by sending beacon packets that define the beginning of an active beacon period. It shall also divide each active superframe (SF) into applicable access phases ordering them as shown in Fig. 3, and defining their specific duration. In the Exclusive Access Phase (EAP), used only for the transmission of emergency data, Random Access Phase (RAP) and Contention Access Period (CAP), nodes use CSMA/CA or Slotted ALOHA methods. In the managed access period (MAP), the coordinator may schedule intervals, or poll nodes [2].
In CSMA/CA the node shall obtain a contended allocation selecting a backoff counter (BC) among the equiprobable values in the interval [0-CW(UP)]. CW is the Contention Window value, it could vary between a maximum and

TABLE III
IEEE 802.15.6 SUPPORTED BIT RATES

PHY	Frequency band (MHz), center frequency (MHz), or moulation	Bit rate 0 (kbps)	Bit rate 1 (kbps)	Bit rate 2 (kbps)	Bit rate 3 (kbps)	Bit rate 4 (kbps)	Bit rate 5 (kbps)	Bit rate 6 (kbps)	Bit rate 7 (kbps)
NB	**402 - 405**	75.9	151.8	303.6	455.4	-	-	-	-
	420 - 450	75.9	151.8	187.5	-	-	-	-	-
	863 - 870	101.2	202.4	404.8	607.2	-	-	-	-
	902 - 928	101.2	202.4	404.8	607.1	-	-	-	-
	950 - 958	101.2	202.4	404.8	607.1	-	-	-	-
	2360 - 2400	121.4	242.9	485.7	971.4	-	-	-	-
	2400 - 2483.5	121.4	242.9	485.7	971.4	-	-	-	-
UWB	**Non-coherent**	394.8	789.7	1579	3159	6318	12636	-	-
	Differentially-coherent	487	975	1950	3900	7800	15600	557	1114
	FM	202.2	-	-	-	-	-	-	-
HBC	**21**	164	328	656	1312.5	-	-	-	-

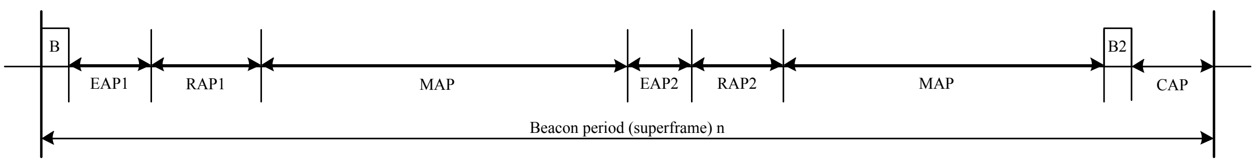


Fig. 3. IEEE 802.15.6 SF structure for beacon mode with beacon periods access technique, including EAP, RAP, MAP and CAP periods.

minimum that are dependent on the data type and its User Priority (UP); larger CW values are set for data with less stringent requirements. If the channel is sensed as idle for a minimum interval of time the node shall decrement its BC by one for each idle CSMA slot that follows, and once BC reaches the value 0, the node obtains a contended allocation during which the frame transmission could take place. The BC is locked to a specific value when the channel is sensed as busy, and the count down is resumed as soon as the channel returns in idle conditions. CW value is set according to the result of the last contention attempt, following specific assignment rules.

As for the slotted ALOHA technique, a node transmits the packet in a given slot if $z \leq CP[UP]$, where z is a value the node draws at random from the interval [0-1], and CP is the Contention Probability value, which is set according to the result of the last contended allocation, and whose value depends on the data UP (smaller for lower priority data).

b) *Non-beacon mode with superframes*: In this mode a coordinator may have only a MAP in any SF, and it may organise the access to the medium as explained above for the MAP phase in the beacon enabled access mode.

c) *Non-beacon mode without superframes*: A coordinator may provide unscheduled allocation interval. After determining that the next frame exchange will take place in non-beacon mode without SF, a node shall treat any time interval as a portion of EAP1 or RAP1 and employ CSMA/CA based random access to obtain a contended allocation [2].

As it could be seen from this brief description, the huge variety of channel access techniques proposed in the standard gives a great flexibility to the protocol, but at the same time it is not so immediate for the designer to choose the best options and to find the optimal solution to be implemented.

Security aspects are also accounted for in the standard and they are addressed with nodes choosing among three different security levels: *level 0:* unsecured communications, it provides no measures for message authenticity and integrity validation, confidentiality and privacy protection; *level 1:* authentication but not encryption, messages are transmitted in secured authenticated but not encrypted frames, providing measures for authentication and integrity validation but not confidentiality and privacy protection; *level 2:* authentication and encryption are considered, resulting in the most secure transmission condition provided by the standard. The security selection in turn sets off a security association between communication ends for activating a pre-shared or generating a new shared master key. As part of message security, replay protection is also provided [2].

C. Bluetooth Low Energy

Bluetooth wireless technology is a short-range communication system intended to replace the cable(s) connecting portable and/or fixed electronic devices. The key features of Bluetooth wireless technology are robustness, low power consumption, and low cost [3]. There are two main core configurations of Bluetooth technology systems: Basic Rate

(BR), with optional Enhanced Data Rate (EDR), and Low Energy (LE). BR is the "classic" Bluetooth, which allows a bit rate up to 3 Mbps with EDR. The LE system includes features designed to realise products characterised by lower current consumption, transmission range up to 30 m, lower complexity, and lower cost than BR/EDR. The LE system is also designed for use cases and applications with lower bit rates and duty cycles. LE aims at small and cheap devices, powered by button-cell batteries, such as wireless sensor devices, for several applications: sports and fitness (sport equipment and monitoring devices, speedometer, heart rate meter, pedometer), healthcare and illness treatment (weight scale, blood pressure monitor, glucose meter, pulse oximeter), home automation and entertainment (remote controls, home sensors and switches), automotive (tyre pressure monitoring, parking assistant, keyless entry), watch/wrist wearable devices (music players and mobile phones remote controls, proximity detection).

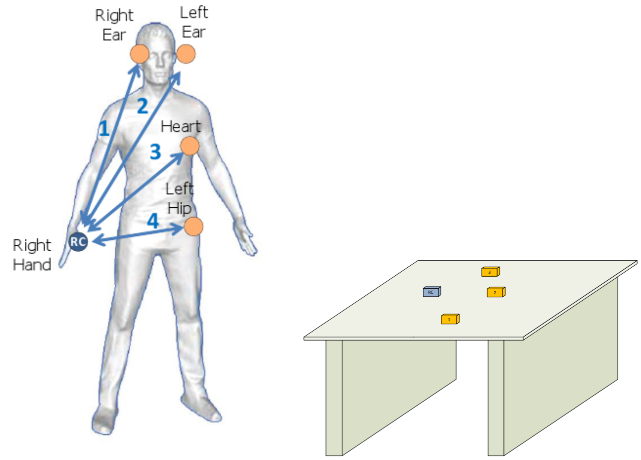
Bluetooth LE specifications regard the whole protocol stack. Only star topologies are possible. Two implementation options are defined for LE: a single-mode (stand-alone) implementation, targeted at applications requiring low power consumption and small size (typically button cell battery powered devices), and a dual-mode implementation, an extension to the classic Bluetooth radio, targeted at mobile phones and PCs.

Bluetooth LE operates in the 2.45 GHz ISM band, where 40 channels, each one is 2 MHz wide, are defined. The modulation is Gaussian Frequency Shift Keying (GFSK) and the supported bit rate is equal to 1 Mbps.

At the Link Layer (LL), the radio channels are allocated into two different types: advertising physical channels and data physical channels. The three advertising channels are used for discovering devices, initiating a connection, and broadcasting data. The remaining data physical channels are used for communication between connected devices during normal operations. In both cases, channels are sub-divided into time units known as events: advertising events and connection events, respectively. On data channels, the communication is managed by a master node, which defines the timings of transmissions and channel hopping procedures.

Since Bluetooth is a well-known and widespread technology, it could be a good option for WBANs. The most recent mobile phones and tablets come with dual-mode Bluetooth radio, and some monitoring devices equipped with LE can already be found on the market (e.g., heart rate belts) [93]. The main drawbacks of Bluetooth LE are the lack of multihop communication and the limited scalability, in fact only star topologies are possible.

Bluetooth LE offers various security services for protecting the information exchange between two connected devices. Most of the supported security services can be expressed in terms of two mutually-exclusive security modes called *LE security mode 1* and *LE security mode 2*. In the first mode paying (through authentication or not), encryption and data integrity are provided, while in the second mode encryption is not foreseen. Encryption and authentication techniques are implemented using Counter with Cipher Block Chaining-Message Authentication Code (CCM) Mode and a 128-bit Advanced Encryption Standard (AES) block cipher. The LL connection may be either encrypted and authenticated or unencrypted and unauthenticated. In the first case, messages shall be encrypted and authenticated, and authentication is performed by appending a specific field to the packet payload. Each security mode accounts with different levels, which express requirements as to the type of pairing that has to be used. Pairing is a procedure by which the devices generate and distribute key material. Standard also implements some privacy features, indeed devices hide they real address using instead randomly generated addresses that change during time. Privacy is then guaranteed since these random addresses could be resolved only knowing the proper key.



(a) On body (b) On table

Fig. 4. The WBAN scenarios considered. (a) Nodes are placed on body, Ptx = 0 dBm. (b) Nodes are placed on a table, Ptx = 10 dBm.

VI. Standards Comparison: Case Study

This section presents examples of numerical results of the performance achievable with the standard solutions described in Sec. V, in terms of packet loss rate (PLR), average delay and network throughput. The reader can refer to [94] for a comparison of the standards in terms of bit error probability (i.e., performance related to the PHY layer). Our aim is to give useful insights to the reader by providing a fair comparison of the network performance of the most suitable standards for WBAN, and to provide indications about the best solution to be chosen, depending on the application requirements.

Results shown in this section have been obtained through: i) simulations, using a discrete-event simulator written in C++, implementing the different standards; ii) experiments made using the IcyCom SoC [95], implementing at the MAC layer the IEEE 802.15.4 and the IEEE 802.15.6 protocols.

A typical WBAN scenario is studied: some sensor nodes are assumed to be distributed on a body and they have to transmit data to a given receiver, called remote controller (RC), which is the coordinator of the network (see, for example, Fig. 4a). We consider a small number of devices, as in most of the actual WBAN applications. However, we expect to obtain the same comparison among the standards also for larger networks, with the only difference that the quality of service will decreases, due to the larger number of nodes competing for the channel.

TABLE IV
PHY AND MAC SIMULATION PARAMETERS

Parameter	Value
Transmit power	0 dBm
Frequency band	ISM 2400-2500 MHz
Receiver sensitivity (IEEE 802.15.4)	-96 dBm
Receiver sensitivity (BT LE)	-90 dBm
Noise level	-102 dBm
RC antenna gain	3 dB
Nodes antenna gain	-15 dB
PHY+MAC header size	23 Bytes
Number of retransmissions	3
CAP duration	37 ms
$\{BE_{min}, BE_{max}, NB_{max}\}$	{3, 5, 4}

A query-based traffic is also considered, being used in almost all the WBAN applications: the coordinator (i.e., the RC) periodically sends a query packet to nodes and it waits for replies from them. One packet per query is generated by nodes, and this packet should be correctly received by the RC before the transmission of the subsequent query, otherwise the packet is discarded and considered as lost.

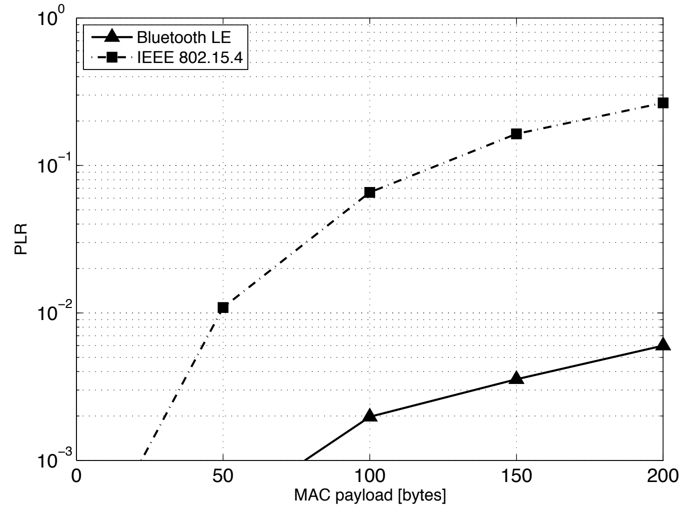
In both cases, simulations and experiments, acknowledgement (ACK) packets are used and nodes may retransmit packets up to three times. Moreover, results have been achieved by averaging over 10.000 packets transmitted by each node toward the RC.

Performance is evaluated in terms of: i) PLR: the ratio between the number of packets lost and the number of generated packets; ii) Average delay: the time interval between the beginning of query from the RC and the correct reception of the node packet at the RC, averaged over the total number of correctly received packets; iii) Network throughput: average number of information bits per seconds received by the RC. Note that packets can be lost due to connectivity, collisions, or because a packet is not correctly received before the transmission of the subsequent query.

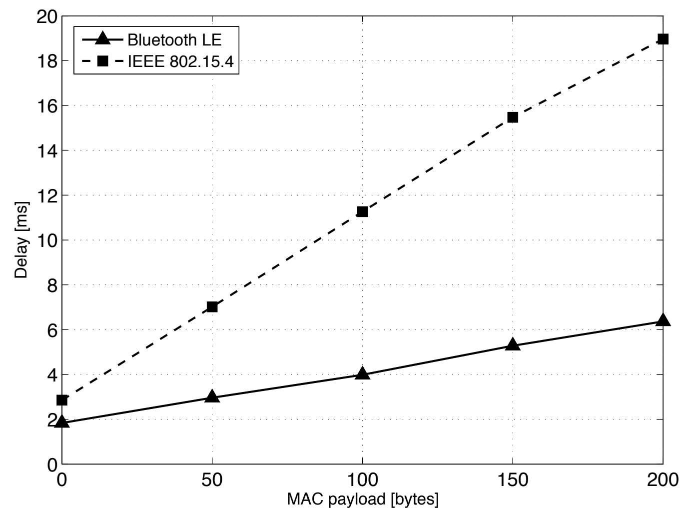
We first study the impact of having different PHY layers, comparing the IEEE 802.15.4 and BT LE, while for a performance comparison of the different modulation and coding schemes for the narrow-band PHYs defined by the IEEE 802.15.6, the reader could refer to [96].

In particular, we compare the GMSK modulation with a bit rate of 1 Mbps (BT LE PHY layer) with the MSK modulation with spreading with a bit rate of 250 kbps (IEEE 802.15.4 PHY layer). On top of these two PHY layers the IEEE 802.15.4 CSMA/CA protocol in beacon-enabled mode is considered. The query interval coincides with the superframe (SF) duration and only the CAP is implemented.

Results have been achieved through simulations, considering four nodes on a body transmitting to the RC, which is held in the right hand as depicted in Fig. 4a. In the simulations the channel between the RC and the other four nodes was accounted for considering real-time channel data acquired through an extensive indoor measurement champaign, for the characterisation of the space-time variations of the channel. A detailed description of the channel characterisation can be found in [59]. The capture effect implemented, that is the correct reception of one of the two or more simultaneously transmitted packets, is described in [66]. Other PHY and MAC parameters used in the simulation are reported in Table IV.



(a) PLR



(b) Average delay

Fig. 5. Performance of two different PHY layers using the CSMA/CA MAC protocol (simulation results).

Fig. 5 shows the results of the simulations for the PLR averaged over the four links and for the average delay. From Fig. 5(a) it can be observed that for BT LE the PLR is almost two order of magnitude smaller that the PLR of 802.15.4, this is because the BT LE is characterised by an higher bit rate as compared to the IEEE 802.15.4. A larger bit rate leads to a lower number of packets lost due to end of SF or collisions, since the channel stays busy for a shorter amount of time. For what concerns the average delay (Fig. 5(b)) BT LE outperforms 802.15.4 thanks to the higher bit rate.

With reference to the application requirements of Table II, the audio streaming application requirements on BER equal to 10^{-5}, which is equivalent to a PLR of 8×10^{-3} for a 100 byte packet,[1] can be satisfied by Bluetooth LE but not by

[1] $PLR = 1 - (1 - BER)^z$ where z is the packet size in bits, assuming that a packet reception fails if at least one bit is erroneously received.

TABLE V
PHY AND MAC EXPERIMENT PARAMETERS

Parameter	Value
Transmit power	10 dBm
Frequency band	ISM 863-928 MHz
Modulation	MSK
Bit rate	200 kbps
PHY header size	11 Bytes
MAC header size	12 Bytes
Number of retransmissions	3
CAP duration	60 ms
$\{BE_{min}, BE_{max}, NB_{max}\}$	{3, 5, 4}
$\{CW_{min}, CW_{max}\}$	{4, 8}
$\{CP_{min}, CP_{max}\}$	{1/4, 1/8}

IEEE 802.15.4 PHY (see Fig. 5(a)) in the considered scenario (query-based traffic with four transmitting devices).

With the aim of comparing only the MAC protocols defined by the standards using the same PHY layer, we present results achieved through experiments performed by implementing the IEEE 802.15.4 and the IEEE 802.15.6 on the IcyCom SoC [95]. In the case of the IEEE 802.15.6 standard the beacon mode with beacon periods is implemented, including only one CAP phase in each SF, where the CSMA/CA protocol or the Slotted ALOHA could be used. For the IEEE 802.15.4 the beacon-enabled mode is still considered. The traffic is generated as described above, while in this experiments we deploy a network composed of one RC and three nodes placed on a table (Fig. 4b) and we transmit with a higher power with respect to the previous scenario, to neglect connectivity issues and to consider only the MAC performance. We refer to Sec. VII-A to show the impact of connectivity. The set of parameters used in the experiments is detailed in Table V.

Performance is evaluated in terms of PLR, average delay and network throughput defined by Eq. 1, where z is the payload size in bit, $N = 3$ is the number of nodes generating data in the network, and $T_{query} = 75ms$ is the query interval, that is the data generation period, equal to the SF duration.

$$T = \frac{(1 - PLR) \cdot z \cdot N}{T_{query}} \left[\frac{bit}{s}\right] \tag{1}$$

The PLR is reported in Fig. 6(a), as expected Slotted ALOHA performs worse than CSMA/CA because of the absence of the sensing phase, so collisions cannot be avoided. From the comparison between the two CSMA/CA algorithms, it can be noticed that the one implemented according IEEE 802.15.6 has better performance, this is because there is no limitation on the maximum number of attempts to sense the channel after finding it busy, differently from IEEE 802.15.4 where the parameter NB_{max} limits the amount of retries. This limitation makes the algorithm discarding those packets for which the channel has been sensed busy more than NB_{max} times. Moreover, the amount of packets discarded grows with the size of the packet itself, since larger packets keep the channel busy for longer, and this explains the increasing of the PLR with the rising of the payload size. Anyway, the IEEE 802.15.6 exhibits a flat PLR since the CAP is long enough to fit all the possible retransmissions and there is no limitation on the the amount of times the channel has been sensed busy.

The delay results are shown in Fig. 6(b). Again, Slotted ALOHA performs worse than CSMA/CA because collisions are not avoided, so a larger number of packets are retransmitted as compared to CSMA/CA. The two curves related to CSMA/CA show that the two algorithms have more or less the same performance, however, since there is no limitation on the number of times the channel can be sensed as busy, the IEEE 802.15.6 algorithm waits more, on average, before transmitting the packet than the IEEE 802.15.4 one.

Fig. 6(c) show the network throughput computed according to Eq. 1, it can be seen that up to 50 bytes of payload size all the three protocols have the same behaviour, while for bigger payload sizes the Slotted ALOHA tends to have worse performance because of the increasing of collisions.

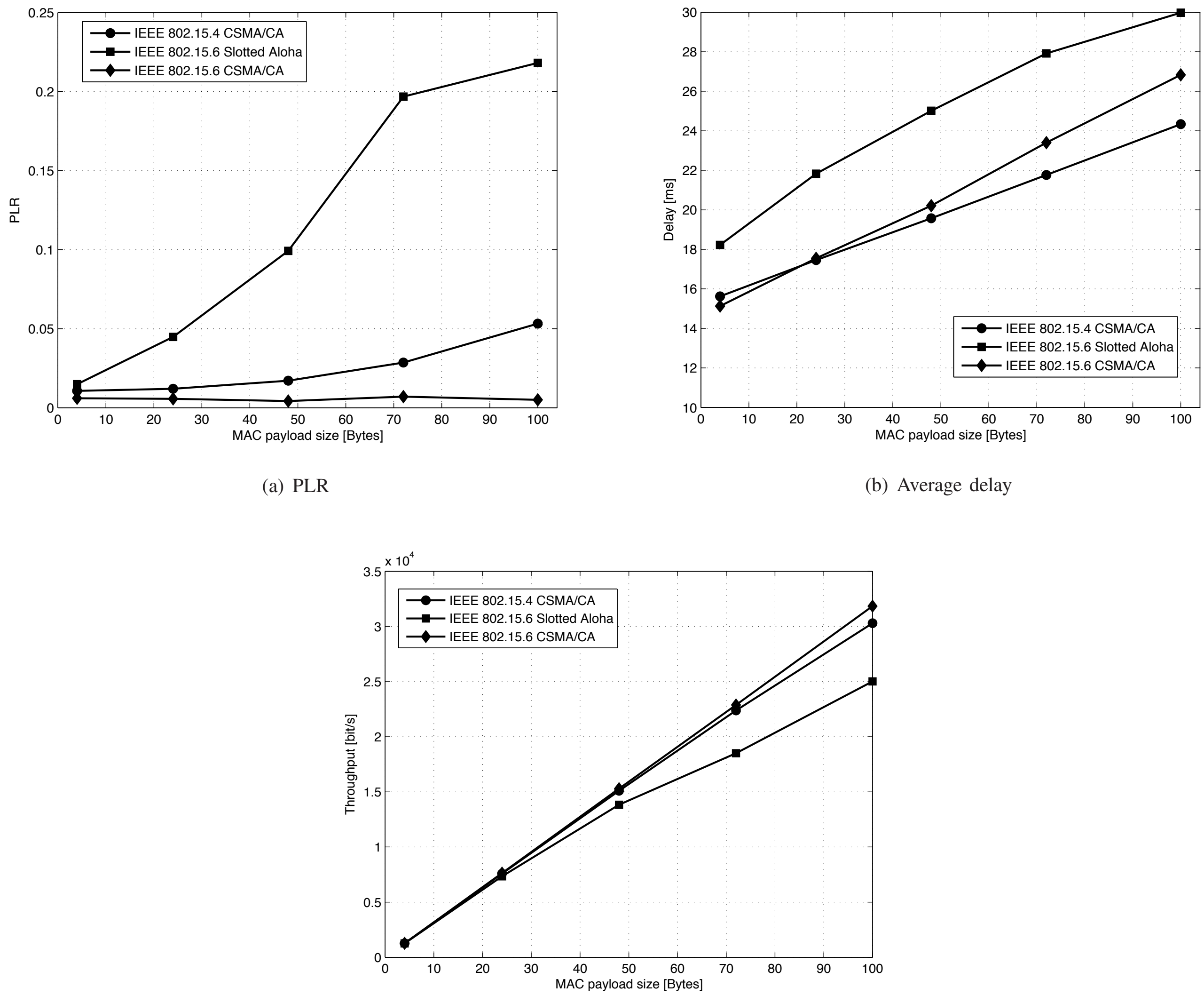
The results presented in this section should give to the reader an insight on the approach to be taken when designing a WBAN for a specific application. In particular, the PHY layer of BT LE, working at larger bit rate, provides the best performance, while from the MAC layer viewpoint the IEEE 802.15.6 seems to be the best solution. As stated above, the results shown in this section could be useful for the design of many WBANs, being the reference scenario and the application considered very typical.

VII. MAIN ISSUES IN WIRELESS BODY AREA NETWORKS DESIGN

This section explores the main issues of WBANs, that is those aspects that make the design more challenging. Along with a description of the issues, we provide to the reader possible ways to mitigate the problem. First we address the impact of the human body on the radio propagation, then the problem of minimising the energy consumption by adopting efficient MAC protocol solutions, and finally coexistence with other radio networks will be discussed. The simulation and experimental results presented are mainly to demonstrate the impact of the different issues raised in this section on the performance of a WBAN, and to show to the reader how the standards described in Sec. V cope with these issues.

A. Impact of the Radio Channel

Devices forming a WBAN are placed on the human body or even implanted in it. In order to realize systems optimised for body centric communications, a deep knowledge of the radio channel is of outmost importance. Even if this section focuses on the characterisation of links between *on-body* devices and how it affect network performance, several works were performed on different communication scenarios, defined by the relative position of devices, as presented in [97]. Channel characterisation for transmissions between implanted devices is reported in [98]–[101] for the MICS band, whereas in-body propagation at 2.45 GHz is investigated in [102]–[104] for different human tissues. As a promising frequency band for in-body communications, UWB channel is described in [105], [106]. Path loss models for channels between implants and on-body devices are provided again in [98]–[100]. Links between an implanted device and one placed outside the human body



(a) PLR

(b) Average delay

(c) Network throughput

Fig. 6. Performance of three MAC protocols (experimental results).

(e.g., an access point, a laptop, etc.) are characterized in [107]–[110] for the MICS band, accounting for human movements and environment effect.

A limited contribution is available on the characterisation of the channel between an on-body device and an external one (*off-body* case) or between on-body nodes located on different human subjects (*body-to-body* case). In [111]–[113] the *off-body* channel was characterised in dynamic conditions at 2.45 GHz, both in indoor and/or anechoic chamber. First and second order statistics were provided in [114] to describe channel features at 868 MHz in different environments. Cross-correlation coefficients between the signal fading measured by the different bodyworn devices were also given. Indoor UWB measurements were realised in [115]–[117], where authors investigate radio channel under different propagation conditions (i.e., static/dynamic, Line of Sight/Non Line of Sight).

As for Body-to-body (B2B) communications, the radio channel between two WBANs was investigated by authors in [118]–[120], where they present a characterisation at 2.45 GHz in indoor environment, accounting for different human movements and devices on-body positions. A similar study is reported in [121], where indoor wideband measurements were performed at 5.5 GHz to extract a model that is given in terms of path loss, large and small-scale fading. Outdoor environment was also investigated and results are presented in [122], [123]. Finally, authors in [124] propose an UWB channel model extracted from acquisitions performed in anechoic, accounting for different orientations of the human subjects.

Focusing now on the reference case of on-body transmissions, one way to characterise the on-body propagation is through the theoretical description of electromagnetic propagation phenomena using anatomically accurate models of the human body. Accounting for the different surrounding environments is practically intractable due to the large computational volume, in this case a ray-tracing model can be adopted for indoor propagation channel modelling [125]. The theoretical channel model is intended for detailed description of specific aspects of the propagation, for example, the influence of the body structure on the antenna patterns.

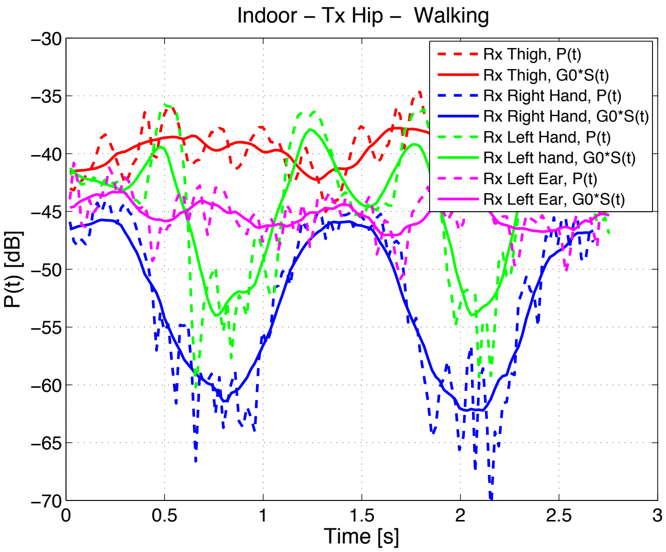


Fig. 7. Channel power transfer function evolving in time as the user walks.

Another approach consists in the adoption of an empirical model to characterise the channel. Several examples of this type could be found in literature, but they normally lack in accounting for different source of channel variability (such as different body shapes or environments) and they do not consider human movement [126]–[132]. Moreover, these kind of models are often given as a function of the distance between nodes, whereas it has been demonstrated that the specific on-body node position and the movement reproduced by the user have a strong impact on the definition of channel characteristics [133]. In particular, an extensive measurement campaign has been performed at CEA-Leti (Grenoble) to characterise the time-variant on-body transmission channel [59]. An example of result is reported in Fig. 7, where it is shown how the channel power transfer function for different links in a WBAN evolves in time. The reference scenario is similar to that of Fig. 4a. The specific time-domain measurement test-bed was composed of a digital oscilloscope at the transmitting side, and four low noise amplifiers at the receiving side, in a SIMO (Single Input Multiple Output) configuration. The test-bed can collect simultaneously up to four channel impulse responses, each one corresponding to a different receiver location on the body. Four human subjects were involved in the measurements campaign, each one reproducing several movements (standing still, walking, sitting down/standing up). All acquisitions were repeated both in anechoic chamber and in indoor. Fig. 7 shows an example of the analysis performed, presenting the evolution over time of the dynamic channel power transfer function (dashed curves), $P(t)$, each color referring to a specific investigated on-body link. It could be noticed how the node position and the movement performed by the user affect the temporal evolution of $P(t)$. In particular, it is possible to point out a slow-varying component (continuous curves) strictly related to the body presence that dynamically shadows the communication while the subject moves. For example, following the trend of the continuous curve which refers to the link between the right hand and the hip, it is possible to reconstruct the swinging movement of the arms while performing a walk. The dips of the curve refer to the time instants for which the arm is behind the subject's torso, when the body completely shadows the communication, resulting then in a strong channel attenuation.

Moreover, an additional fast-fading contribution could be extracted, which is the remaining part of $P(t)$ once subtracting the slow-varying component. It accounts mainly for the fading effect due to the multipath contributions, originating from diffractions or reflections from the body or the environment. More details on the time-variant channel model extracted through these measurements campaign could be found in [133] and [59].

As expected, the behaviour of the channel shown in Fig. 7 strongly affects the network performance. Experimental results, described in [134], validate this assumption by evaluating the performance of an IEEE 802.15.4 network. The experimental setup was composed of four IEEE 802.15.4 compliant devices deployed on the human body and one coordinator held in the right hand (see Fig. 4a). A beacon-enabled MAC was implemented with a query based traffic model. The devices attempt to transmit a packet of fixed size to the coordinator at the beginning of each superframe. The packet is considered as lost if it is not correctly received by the end of the current superframe. Fig. 8 shows the PLR as a function of the packet payload size for each link. As expected, the best link is the one connecting the coordinator and the right ear, while the worst link is the one between the coordinator and the left ear. This is because of the shadowing effect introduced by the subject's head. Links 3 and 4 have intermediate performance because the propagation is shadowed by the human body roughly for half of the duration of the experiment, due to the typical swinging movement of the arm while walking. These results are in accordance with those obtained through a numerical PHY-MAC simulation campaign, as described in [135], [136].

The aim of this section was to introduce the reader to the importance of a proper characterisation of the radio channel for the design of WBANs. As shown in Fig.s 7 and 8 the channel power transfer function has different trends depending on the nodes' position, moreover abrupt variations up to 20 dB takes place if the person is moving and the performance of the WBAN may be seriously affected. Thus, the characterisation of the links between nodes should be properly taken into account when developing and simulating MAC and routing protocols, in order to get ore realistic performance.

B. Energy Consumption Issues

The most promising applications for a WBAN are in the field of healthcare, as pointed out in Sec. IV-A. When one or more devices have to be implanted or worn be a person, it is of outmost importance to reduce the stress caused by the battery replacement/recharge, which in some cases may require surgery. The problem of reducing energy consumption can be tackled by the designer by realising energy efficient PHY and MAC layers. [137], for instance, describes a Time Division Multiple Access (TDMA) based strategy, focusing on a non dynamic network for vital signs monitoring. In [138] nodes can decide whether or not to transmit their data in the assigned slot, depending on their battery status and buffer

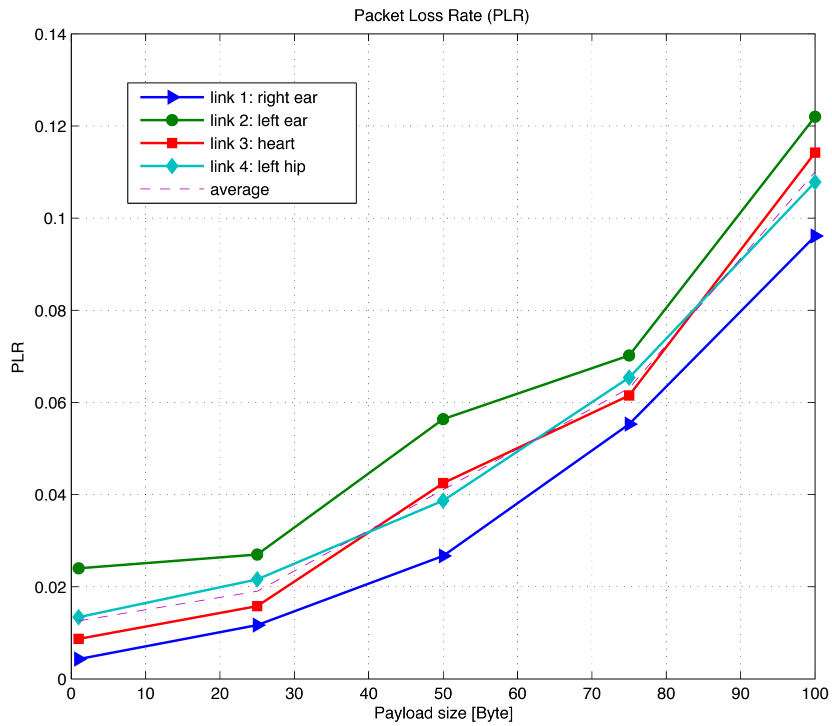


Fig. 8. PLR for different links.

occupancy, aiming at maximising device lifetime. A wake-up strategy is introduced in [139] to deal with failed transmissions and alarms management. [140] focuses on reducing devices duty-cycle, using an out of band centralised and coordinated external wake-up mechanism. [141] and [142] present dynamic features to adapt to time changing characteristics of WBANs: in particular, the former is traffic aware and varies accordingly the wake-up interval, while the latter proposes an adaptive scheme to allocate channel and time for coexisting WBANs.

As widely addressed in the literature, several sources contribute to the energy inefficiency, including collisions, overhearing, and idle listening [143], [144]. Apart from collisions, already discussed in the previous sections, idle listening incurs when a node listens to an idle channel to receive possible traffic, while overhearing occurs when one node receives a packet that is intended to other nodes. If the traffic load is centrally managed, overhearing and idle listening can be ignored, but in the case of contention-based MAC protocol, these issues should be accounted for.

Among the standard solutions described in Sec. V, there is a trade-off between reliability and power consumption for the different channel access algorithms. As an example, we compare the energy consumed by the different standards considering the scenario shown in Fig. 4a and the parameters set described in the previous section. As it can be seen from Fig. 9, the IEEE 802.15.6 CSMA/CA implementation drains more energy than the IEEE 802.15.4. This is due to the fact that in the former case sensing is always performed before decrementing the back-off counter, while in the latter the sensing phase takes only two back-off periods when the back-off counter reaches zero. On the other hand, the probability of successfully transmitting a packet is higher in the first case because devices adopting IEEE 802.15.6 CSMA/CA have a deeper knowledge of the channel status. If the power consumption is a primary issue, as for implanted devices, the IEEE 802.15.6 Slotted-ALOHA may be the best choice, since the sensing phase is missing, at the expenses of a higher probability of packet collisions.

With the aforementioned mechanisms the problems of overhearing and idle listening are still not fully addressed, a possible solution to this problem may be the implementation of a duty-cycled MAC. Preamble sampling, also referred to as LPL (Low Power Listening), is a key technique used by a large number of MAC protocols in order to save energy. In LPL nodes save energy by keeping their radios off most of the time to reduce idle listening. An extensive survey of MAC protocols, with a section dedicated to preamble sampling protocols can be found in [144].

Two solutions have been mainly considered in the literature [145], [146]: transmission of a single long preamble and transmission of a burst of short preambles. The second solution is more energy efficient since it prevents the overhearing problem by dividing the single long preamble into a series of short preamble packets, each one containing the address of the target node.

Fig. 10 depicts how the LPL works. Devices save energy by alternating sleeping and active phases, whose durations are denoted as T_s and T_{on}, respectively. Each node wishing to send a data to a given receiver, or to a set of receivers, will

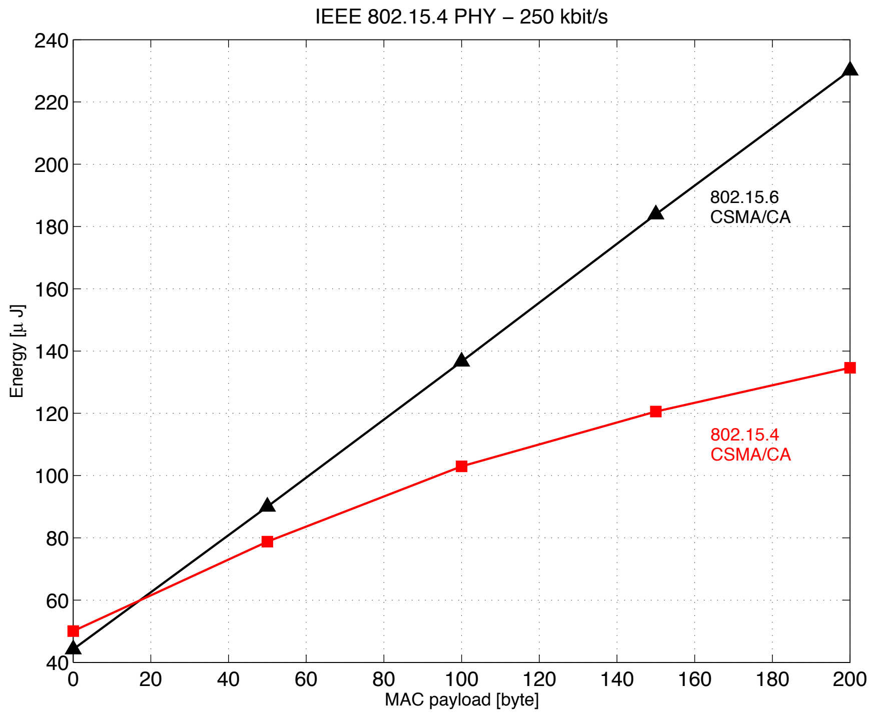


Fig. 9. Simulation of the energy drained for different CSMA/CA algorithms.

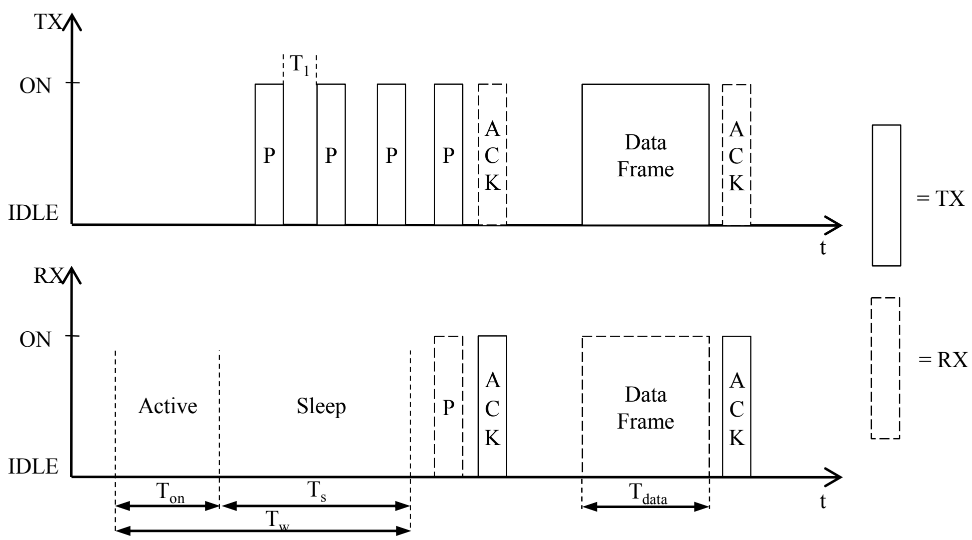


Fig. 10. The LPL mechanism.

transmit a burst of short preambles, separated by an interval of time T_1, for the reception of the ACK. Once the preambles are sent, which contain the addresses of all the intended receivers, the transmitter will wait for the ACK from all these devices. To check the status of the channel the node will listen the channel for T_{on} before the transmission of the first preamble, in order to check that no other devices are transmitting preambles. To be sure that the intended destination node receives at least one preamble, the transmitter has to send preambles for at least the duration of the sleep period of the destination node. When a node wakes up and receives a short preamble packet, it looks at the target node address that is included in the packet: if the node is not the intended recipient, it returns to sleep immediately and continues its duty cycling as if the medium had been idle; if the node is the intended recipient, it replies with an acknowledgement and remains awake for the subsequent data packet.

An example of numerical results related to LPL is shown in Fig. 11. Results have been achieved through experiments on the field when considering a transmitter generating data at random instants to be sent to a receiver. Experiments were performed using the IcyCom SoC [95] and locating devices next to other and transmitting at 10 dBm, such that no connectivity issues may occur. Fig. 11 shows the behaviour of the average energy spent by the transmitter and by the receiver for the transmission/reception of one packet. We set

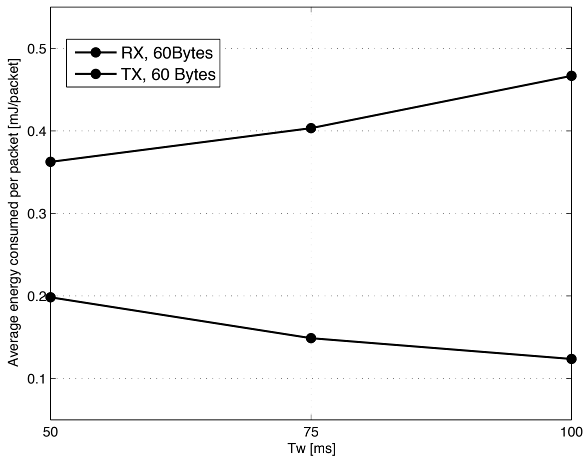


Fig. 11. Average energy consumption per packet transmitted/received when LPL is used for different values of T_w.

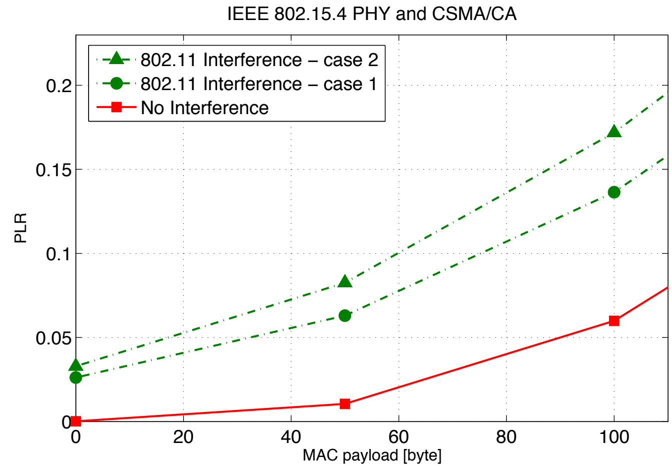


Fig. 12. Simulated PLR as a function of the MAC payload with IEEE 802.11 interference.

$T_{on} = 5$ ms, $T_1 = 3.3$ ms, the packet size was equal to 79 bytes, the preamble size was 19 bytes, the ACK was 15 bytes and the bit rate was 200 kbps. The current consumption values are: 3 mA for transmission, 2.5 mA for reception, 50 μA for data acquisition at 10 kHz sampling rate, while the processor absorbs 500 μA in normal mode and 2 μA in hibernation mode. Thus, the power consumption not related to the transceiver activity can be neglected. As can be noted, the energy consumed at the transmitter increases by increasing T_w, since more preambles have to be transmitted to wake-up the receiver, meanwhile at the receiver the average energy consumed decreases, since the receiver may stay more time off. Therefore, a proper trade-off must be founded.

To conclude this section, the LPL is an effective approach to reduce the energy consumption of a WBAN up to 98% [147] when the target application is characterised by a loose traffic, for example, emergency alarm, and a larger delay compared to the TDMA and contention based approaches can be tolerated. When the network traffic increases (e.g., audio streaming), the energy efficiency of LPL decreases significantly, due to the need of transmitting preambles before data packets.

C. Coexistence Issues

The ISM unlicensed band at 2.45 GHz is very crowded nowadays because of its worldwide availability. Coexistence of WBAN with other systems operating in this band (e.g., IEEE 802.11 (Wi-Fi), Bluetooth, IEEE 802.15.4) is of primary importance to guarantee reliability during daily life. However, this topic has been only little investigated yet.

Some works about coexistence issues with other technologies working at 2.45 GHz can be found in the literature. Focusing on IEEE 802.15.4, for example, [148]–[150] show that the interference caused by an IEEE 802.11 network leads to a significant PLR degradation (the first two works report results of experimental tests in a hospital room and in an apartment, respectively, while the third work presents a model based on timing and power aspects). Tests of coexistence with a microwave oven have also been performed [151], leading to the conclusion that its impact is negligible for distances longer than 2 meters. A coexistence framework focusing specifically on WBANs can be found in [66], where a complete system characterisation is taken into account (realistic channel model for on-body propagation, detailed frequency and time domain interference description for IEEE 802.11 and IEEE 802.15.4 interfering sources). Coexistence studies between UWB-based WBANs has been performed in [152], [153]. The latter takes into account coexistence between IEEE 802.15.6-based and IEEE 802.15.4a UWB WBANs showing that the bit error rate of the IEEE 802.15.6 UWB receiver is not affected by the interfering power coming from another IEEE 802.15.6 network or an IEEE 802.15.4a network as long as the desired signal power is larger than -30 dBm, beyond this threshold, severe degradation occurs. The problem of increasing the robustness to interference of a WBAN is also addressed in [154], where the authors propose a beacon corruption recovery scheme as an extension of the IEEE 802.15.4 beacon-enabled mode, and a centralised access scheme that employs cognitive spectrum sensing capabilities to access the channel. Results shows that the centralised access scheme achieves four times better performance, in term of throughput, respect to the IEEE 802.15.4 standard in presence of Wi-Fi traffic. Among the standards described in Sec. V Bluetooth LE is the best one in coping with other networks operating in the ISM 2.45 GHz band thank to the frequency hopping scheme. However the new release of IEEE 802.15.4, IEEE 802.15.4e [155], adopts channel hopping as well to improve the robustness of the network in presence of interference.

In order to evaluate how much WBAN performance can degrade when interfering devices are present, a complete characterisation of the interference is needed, both in the frequency and in the time domain. In [66] such a coexistence study is carried out considering Wi-Fi and IEEE 802.15.4 networks as possible interfering sources, and their impact on WBAN performance is reported.

Fig. 12 shows an example of WBAN PLR degradation due to an IEEE 802.11 interfering network, obtained through simulations. The reference scenario is an hospital room of 3m x 3.5m, where a person wearing a WBAN (as the one

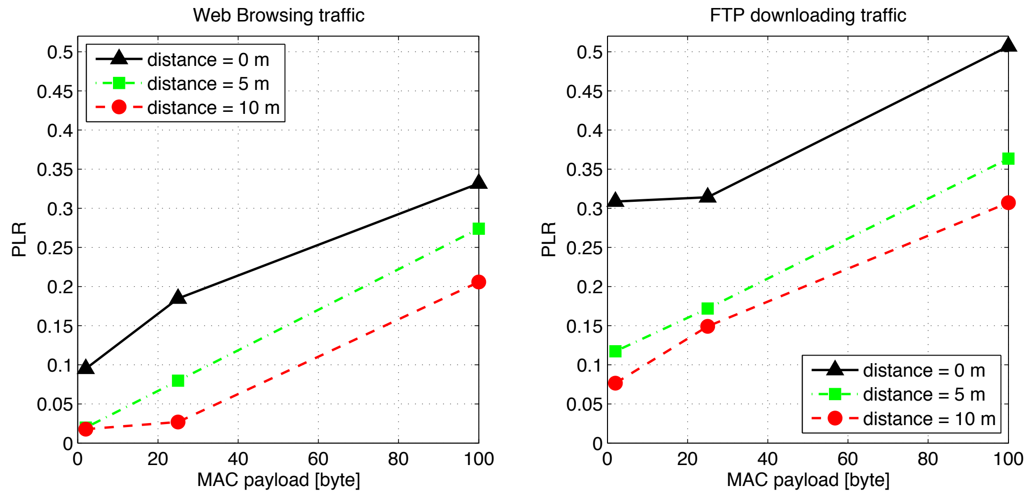


Fig. 13. Experimental PLR as a function of the MAC payload with IEEE 802.11 interference (completely overlapping channel) for two different interference traffics: web browsing (left) and FTP downloading (right).

of Fig. 4b) is walking. An IEEE 802.11 access point (AP) and a laptop are located in the room, and they exchange a traffic corresponding to a web browsing session (i.e., simple navigation operations, such as the opening of web pages with their reading), using a transmit power of 20 dBm. IEEE 802.15.4 PHY and MAC are considered for the WBAN, with the transmit power set to 0 dBm, the device and coordinator antennas efficiency equal to -15 dB and -3 dB, respectively. Two different operating channels are considered for the WBAN: the first one overlaps in frequency with the channel used by IEEE 802.11 interfering only partially with it (case 1 in the Fig. 12), while the second one is characterised by a complete overlap (case 2). As expected, the PLR is higher when interfering sources are present, with a significant degradation also for the case of partial channel overlapping. This is due to the fact that the IEEE 802.11 traffic is heavy as compared to the WBAN one, and WBAN devices often find the channel busy, being therefore not able to correctly transmit their data to the coordinator. Experimental results are illustrated in Fig.s 13 and 14. The experiments have been performed with IEEE 802.15.4-compliant Texas Instrument devices in an indoor office environment. A Wi-Fi AP and a laptop have been located 30 cm apart, and they operate with IEEE 802.11 in channel 5 (center frequency of 2432 MHz). The two IEEE 802.15.4 devices (one receiver and one transmitter) have been placed at different distances from the interfering IEEE 802.11 sources. Fig. 13 shows the PLR as a function of the payload obtained when IEEE 802.15.4 devices work on a channel completely overlapped with the IEEE 802.11 one. Two different traffics are shown: web browsing (figure on the left), and FTP downloading (figure on the right), where files with dimensions up to 30 Mbytes were downloaded from an FTP site.

A preliminary experiment was carried out to test the PLR without interference, which was negligible. Therefore, from Fig. 13 we can see that the degradation of the performance when IEEE 802.11 interferes are active is significant. To give an example, the PLR shall be lower than 1% when 100 byte packets are transmitted in an hearing aid application for audio streaming, however, the experimental results show that even for small packet sizes the PLR is always above 10%.

In Fig. 14 the PLR obtained for different IEEE 802.15.4 channels is reported. A web browsing traffic is considered, and IEEE 802.15.4 MAC payload is set to 2 bytes. Channel 17 completely overlaps with the one used by IEEE 802.11, channel 14 partially overlaps with it, while channel 26 does not overlap.

Again, the degradation of the PLR can be noticed, especially when the two networks are close to each other, and also for only partially overlapping channels.

This section shows that up to now the coexistence issue between WBAN and other network operating in the same band has not been properly addressed by the current standards. However, we believed that much more effort should be spent to improve coexistence, especially with Wi-Fi that is already widely deployed and uses a transmission power higher than the one adopted by a WBAN.

VIII. Future Research Directions

The aim of this section is to give to the reader an idea of the future research directions in the field of WBANs, we will first discuss the research trends for what concerns the main issues of WBANs that is channel modelling, energy consumption and coexistence, then we will consider future possible applications for WBANs.

As for the future perspectives for the radio channel modelling, some deeper studies should be performed for the *off-body* and *B2B* scenarios, which are currently little investigated and lack in a standardised widely accepted model. Moreover, the research community should move towards an agreement on a common experimental test-bed, which could allow channel data and related models coming from different measurements campaigns to be fairly compared. Another important aspect that should be addressed when considering channel modelling for WBAN, is the antenna impact on channel characteristics. Currently proposed models always include antenna effect,

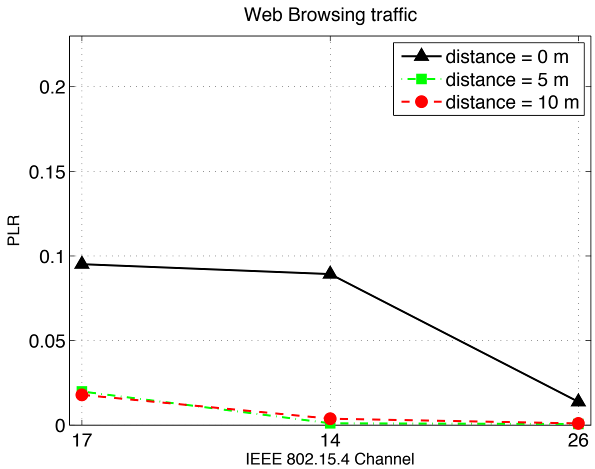


Fig. 14. Experimental PLR obtained on different channels with IEEE 802.11 interference, web browsing traffic.

but future works should aim at de-embedding it, in order to provide a channel characterisation not biased by the specific antenna used in the acquisition process. The research trend in microelectronics is oriented to the realisation of SoC increasingly smaller and with lower consumption. This will make possible to realise WBANs composed of hundreds of nodes for which a simple star topology cannot be used, to this extend, routing protocols based on multi-hopping tailored for WBAN applications need to be explored. The requirements in terms of maximum delay and reliability will become even more stringent due to the larger number of nodes. Moreover, techniques like cooperative Multiple-input and Multiple-output (MIMO) [156], [157] and cooperative beamforming [158] can be employed in a WBAN to improve the reliability and reduce the energy consumption.

A thorough study for what concerns the mitigation of the interference generated by such a high density of nodes is needed. For what concerns the coexistence with other wireless network, cognitive wireless communication paradigms can be considered as a successful approach to improve the reliability of WBANs which is a serious issue due to their low transmission power, as highlighted in Sec. VII-C.

With reference to possible new applications of WBANs made of a large number of nodes are the so called Factories of the Future (FoF). FoF is one of the three Public-Private Partnership included in the European Commission's recovery package and it consists of a research programme of 1.2 billion Euro to support the manufacturing industry in the development of new and sustainable technologies [2]. The research in this field aims at the transformation of present factories, towards re-usable, flexible, modular, intelligent, affordable, easy-to-adapt, easy-to-operate, easy-to-maintain and highly safe and reliable FoF. To this aim a large number of sensors could be distributed on robot, machines and on suites dressed by workers, to prevent accidents.

As mentioned in Sec. III molecular networks are gaining more and more interest. Up to now the research on this field is at its very early stage, but in the long term it is expected to grow thanks to its non-invasiveness making also possible the realisation of hybrid molecular/RF WBANs that use the molecular technology inside the body and the RF technology to communicate with the outside.

IX. Discussion

This work can be considered as a starting point in the WBAN design and can be used to choose the best way to tackle the issues raised by the system requirements. To give an idea, let us consider an example of a WBAN composed of a cardiac implant, a wearable hearing aid and a smartphone used as network coordinator. First of all, the two different channels (in-body and off-body) have to be properly investigated in order to obtain a reliable model for the propagation between the two devices and the smartphone. This model should be employed when the behaviour of the network is explored through simulations. Then, based on the stringent requirements on power consumption for the cardiac implant, an energy efficient design should be oriented to LPL protocols when delays in the order of the adopted duty-cycle can be tolerated. On the other hand, when the PLR and delay requirements are more stringent than the ones on the energy consumption, for example for audio streaming from the wearable hearing aid or ECG data transmission from the cardiac implant, a proper trade-off between reliability and delay should considered and the choice should be oriented to Slotted-Aloha, CSMA/CA or TDMA based MAC protocols. The next step should be to consider how the designed protocols behave in presence of interference coming from other devices operating in the same band, and adopt proper solutions to counteract the degradation of the performance due to the presence of interference.

X. Conclusion

The research effort in WBAN has significantly increased in recent years motivated by the attracting applications that can be enabled by this technology is a multitude of fields. However, the wide applicability of WBANs makes their design challenging. Throughout this paper we presented to the reader the main characteristics of a WBAN and a list of possible applications and requirements they impose. We described the main standards that can be used as a reference in a RF-based WBAN design paying more attention to the IEEE 802.15.6. With the aim of introducing the reader to the main issues in a WBAN design, namely the peculiarities of the radio channel, the power consumption and the coexistence with other RF-based systems, we surveyed a large amount of literature dealing with these problems and we provided simulation and experimental numerical results to show the real impact of them on the performance of a WBAN.

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[2]See the website: http://ec.europa.eu/research/industrial_technologies/factories-of-the-future_en.html.

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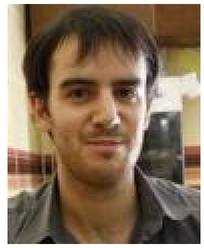

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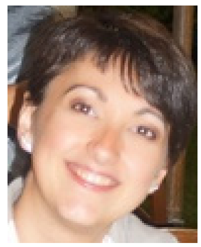

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