Coexistence of Wireless Technologies in Medical Scenarios

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***Abstract*—The goal of this paper is to provide a comprehensive overview of the coexistence nature of wireless technologies most likely to be found in medical scenarios' environment. The diversity and number of these technologies is increasing constantly leading to potential interference problems and performance degradation of wireless medical applications which are expected to become popular in 5G systems. The industrial, scientific and medical (ISM) bands in the 2.4 GHz are already very crowded to the point that the location and use of medical devices have to take into account the pervasive presence of other wireless devices operating in that region of the spectrum. A temporary solution is to use more the 5 GHz bands currently not so heavily utilized. This scenario will change in the near future as unlicensed long-term evolution (LTE) solutions such as MulteFire start operating in those bands. This paper provides a summary of the wireless technologies and devices present in hospitals and other medical care scenarios. It also provides recommendations for the rational share of the spectrum in those scenarios.**

Keywords—spectrum management; unlicensed band; licensed band; wireless body area network; healthcare applications; 5G system;

I. INTRODUCTION

The use of wireless communications systems has increased considerably in hospitals and health care scenarios. A recent report [1] estimates that the market for wireless medical devices is expected to show about 25.1% market growth over the next five years. The worldwide market has the potential to expand from $3.6 billion in 2015 to about $11.0 billion by 2020. These days it is common to find in hospitals a variety of wireless devices that monitor patients' vital signs, that help locate doctors, nurses, and equipment, and that are used to communicate among care givers. Patients, their visitors, and the hospital personnel continuously use cellular communications and wireless local area networks (WLAN). The presence of microwaves and wireless devices that monitor the building environment, e.g. thermostats, lighting, also adds to the electromagnetic radiation present in medical scenarios.

Electromagnetic compatibility or more specific coexistence of wireless devices and other sources of electromagnetic radiation must be carefully monitored and controlled in hospitals and other health care environments to ensure the safety of the patients and their care givers. The scope of this paper is to survey relevant features of the wireless technologies present in this type of scenarios, in particular their spectrum occupancy, power levels and data rates.

Section II provides a summary of wireless technologies that have been specifically designed for medical applications or that are most likely to be used by medical devices. Section III summarizes other wireless technologies that are present in medical scenarios that in some cases complement those described in Section II but in other cases compete with them for spectrum occupancy. Section IV discusses relevant technical specifications of medical devices currently in the market. Coexistence among wireless technologies most likely to be found in medical scenarios and recommendations are discussed in Section V.

II. ON- AND IN-BODY DEVICES/SYSTEMS

The large majority of wireless devices used in medical applications operate in the unlicensed bands of the spectrum, in particular those bands that have been designated for industrial, scientific, and medical (ISM) communication purposes. They are unlicensed but they are still regulated, e.g. in Europe by CEPT (European Conference of Postal and Telecommunications Administrations) [2]. Several well established technologies, such as Bluetooth [3], ZigBee [4], radio-frequency identification (RFID) [5] and IEEE Std. 802.11 [6] operate in the ISM bands. Some of these bands are globally designated as being unlicensed, e.g. 2.400 GHz to 2.483 GHz with some variations from region to region. But all bands are not common, for example in Europe the ISM 863-870 MHz band is designated for SRD but it is not in the US (the closest is the 902-928 MHz band).

In the next paragraphs a brief summary of wireless technologies that are commonly found in medical scenarios is presented. Most of them are on-body devices but recently there has been an increase of in-body devices, as well as devices used by medical device providers. The main characteristics of the technologies described in this section is shown in Table 1.

Bluetooth is a wireless technology that has been around for over twenty years and has gone through several iterations, each improving or expanding the features of the previous one.

Table 1. Characteristics of wireless body area network (WBAN) technologies.

	Frequency Band	Channel bandwidth	Modulation	Bit Rate	Transmit Power
BLE [3]	2401 – 2481 MHz	2 MHz	GFSK	1 Mbps	-20 to 10 dBm
Classic Bluetooth [3]	2401.5 – 2480.5 MHz	1 MHz	GFSK / π/4-DQPSK / 8DPSK	721 kbps 3 / 24 Mbps	0 / 4 / 20 dBm
IEEE Std. 802.15.6 [8]	NB: 402 – 2483.5 MHz UWB: 3 – 10 GHz HBC: 18 – 26 MHz	NB: 300 – 1000 kHz UWB: 499.2 MHz HBC: 5.25 MHz	NB: DBPSK/GMSK UWB: OOK, DBPSK/DQPSK, BFSK	NB: 75.9 – 971.4 kbps UWB: 0.487 – 15.6 Mbps	-16 dBm / -40 dBm at 403.65 MHz -10 dBm at other frequencies
ETSI SmartBAN [9]	2401 – 2481 MHz	2 MHz	GFSK	0.2-1 Mbps	max. 10 dBm EIRP
ANT / ANT+ [10]	2400 – 2524 MHz ANT+: 2547 MHz	1 MHz	GFSK	1 Mbps	Up to 4 dBm
Sensium [11]	868 / 915 MHz	200 kHz	BPSK	50 kbps	- 7 / -10 dBm
Zarlink [12]	402 MHz – 405 MHz 433 MHz – 434 MHz 2.45 GHz for wake-up	100 – 200 kHz	2FSK 4FSK	18.18 / 40 / 200 / 400 / 800 kbps	-3 to -30 dBm
BodyLAN [13]	2.4 GHz	–	GFSK	250 kbps 1 Mbps	0 dbm

A low-power version (Bluetooth 4.0), called Bluetooth Low Energy (BLE) or Bluetooth Smart was introduced in 2010. It consumes little power and can be operated with small power sources or by harvesting energy. It is becoming widely used on a large variety of medical devices, e.g. heart rate and blood pressure monitors. It operates in the 2.4 GHz ISM band. Its medium access control (MAC) protocol uses 3 advertising channels strategically positioned to minimize interference and channel occupancy. Recent update, Bluetooth 5.0 improves further this technology's suitability for the Internet of Things (IoT) applications by increasing range, speed and broadcasting capacity.

IEEE 802.15.6 [8] and ETSI SmartBAN [9] standards are the first ones tailored specifically for body area networks that can be used in health, medical, and sport applications. The IEEE Std. 802.15.6 is intended for low-power devices to be used in wireless body area networks. This standard offers three physical (PHY) layer options: narrowband (NB), ultra-wideband (UWB) and human body communications (HBC). The MAC layer for this standard has three different modes and thus it offers flexibility for operation in different scenarios. The ETSI SmartBAN standard is more recent than IEEE Std. 802.15.6. The frequency of operation of this standard is between 2.401 GHz and 2.481 GHz with 2 MHz spacing, i.e. similar to the classic Bluetooth. This protocol uses separate channels for data and control messages and like the IEEE Std. 802.15.6 it has different channel access modes [9].

ANT/ANT+ [10] is low-power proprietary protocol designed for low data rate sensor and body area networks that can be configured in different topologies, e.g. peer-to-peer, star, and mesh. It operates in the 2.400 – 2.524 GHz band, the ANT+ devices operates in the 2.457 GHz frequency. The ANT channels are 1 MHz wide. The protocol is time division multiple access (TDMA) based with channel hopping capabilities. The flexibility features of this protocol allow ANT devices to adapt to hostile conditions by changing the amount of control overhead depending on the amount of experienced interference.

Sensium [11] is a proprietary protocol that operates in the 868 MHz and 915 MHz frequency regions. The SensiumVitals system is designed for the monitoring of patient's vital signs relying on a radio chip in compliance with the IEEE Std. 802.15.6 narrowband PHY layer.

Zarlink [12] is a low-power proprietary transceiver designed for medical implantable applications. It operates in 402 – 405 MHz and 433 – 434 MHz bands. It can operate in both implants and in an on-body hub devices. When operating in an implant device, the radio is in a sleep mode most of the time and it makes use of a wake-up radio that operates in the 2.4 GHz band or it wakes up directly using a clock mechanism within the implantable device.

BodyLAN [13] is a proprietary technology that operates in the 2.4 GHz band. It is focused on fitness equipment and devices but is also deployed in medical devices and consumer electronics. It relies on transmissions of short burst durations, very low duty-cycle, and Gaussian frequency-shift keying (GFSK) modulation. These features minimize the interference from IEEE Std. 802.11g orthogonal frequency-division multiplexing (OFDM) / direct sequence spread spectrum (DSSS) packets.

III. COMPLEMENTARY/COMPETING WIRELESS TECHNOLOGIES

This section has a description of wireless technologies that are likely to be found in medical scenarios. These technologies can be complementing or enhancing the functions of the technologies described in Section II, but in other cases they are performing non-medical related functions, e.g. building environmental control, occupying the same spectrum bands used by medical devices and potentially interfering with their performance. A brief description of several of these technologies is given next.

The IEEE 802.11 [6] is an ever evolving set of PHY and MAC layer standards specifications for the implementation of WLAN communications. The original version of this standard was released in 1997. Ever since then it has been revised increasing the range of its features, in particular the bit rates. When operating in the 2.4 GHz frequency bands (802.11b/g) it runs into a lot of completion with other wireless devices and even electric/electronic appliances, e.g. microwave ovens.

Table 2. Characteristics of technologies in hospital environment.

	Frequency Band	Channel BW	Modulation	Bit Rate	Tx Power
IEEE Std. 802.15.4	868 / 915 MHz 2.4 GHz UWB: 249.6 to 749 MHz 3.1 to 4.8 GHz 5.8 to 10.6 GHz	1 (868 MHz) 10 (915 MHz) 16 (2.4 GHz) UWB: 500 to 1354 MHz	BPSK O-QPSK UWB: BPM-BPSK	20 kbps 40 kbps 250 kbps UWB: 0.11 - 27 Mbps	-32 to 0 dBm
IEEE Std. 802.11a	5 GHz	20 MHz	OFDM	6 – 54 Mbps	14-20 dBm
IEEE Std. 802.11b/g	2.4 GHz	22 MHz	DSSS/OFDM	1 – 54 Mbps	20 dBm
IEEE Std. 802.11n	2.4 GHz 5 GHz	20 MHz 40 MHz	MIMO-OFDM	7 – 288 Mbps 15 – 600 Mbps	16-20 dBm 14-20 dBm
IEEE Std. 802.11ac	5 GHz	40 MHz 80 MHz 160 MHz	OFDM M-QAM	500 Mbps – 1 Gbps max 6.93 Gbps	20 dBm
RFID	135 / 13.56 kHz 2.45 / 5.8 GHz	0.5 MHz when in 2.45 GHz	ASK - OOK when in 2.45 GHz	30 to 40 kbps when in 2.45 GHz	~0 dBm for active RFIDs at 2.45 GHz
LoRa	150 MHz - 1 GHz	125, 250 and 500 kHz,	Chirp spread spectrum	0.3 - 50 kbps	max. 14 dBm
MulteFire	5 GHz ISM band 3.5 GHz (US)	20 MHz	OFDM, M-QAM	Up to 400 Mbps	20 dBm
LTE-U	LTE and unlicensed bands	20 MHz	OFDM, M-QAM	300 Mbps	20 dBm
NB-IoT (LTE)	LTE bands	180 kHz	OFDM/SC-FDMA	20 – 250 kbps	23 dBm
LTE-M	LTE bands	1.08 MHz	OFDM/SC-FDMA	Up to 1 Mbps	23 dBm

The 802.11a version of the standard operates in the 5 GHz region avoiding the congested 2.4 GHz region. It uses 52-subcarriers (OFDM) with a maximum of 54 Mbps. 802.11g operates in the 2.4 GHz region but it uses the same type of OFDM scheme as 802.11a and is able to provide a maximum rate of 54 Mbps. Substantial increase in bit rates, reliability, and throughput, are achieved with the 802.11n version. The use of multiple antennas, an efficient MAC layer, and a wider channel (40 MHz) allows for a theoretical maximum of 600 Mbps. 802.11n can operate in the 2.4 GHz and 5 (5.725-5.850) GHz frequency ranges. A recent (2013) version, 802.11ac, can provide a maximum data rate of 6.75 Gbps. It has the option to operate on 40 MHz, 80 MHz, and 160 MHz bandwidths in the 5 GHz ISM band.

For building automation and environment conditions monitoring, the ZigBee [4] and LoRa [14] solutions might become common in future deployments. ZigBee is based on IEEE Std. 802.15.4 and most of the solutions are operating at congested 2.4 GHz band. LoRa technology is operating at sub-GHz bands. 3GPP group is also actively developing IoT solutions, such as NB-IoT and LTE-M which will operate in licensed cellular bands [15].

RFID devices are being used widely in all type of environments, including hospitals and medical care facilities. They use several regions of the spectrum, e.g. 135 kHz, 13.56 MHz, 2.45 GHz and 5.8 GHz. Of particular interest are the tags that work in the 2.45 GHz and 5.8 GHz where many of the devices used in medical scenarios are also used. Interference of RFIDs with medical equipment has been found to be a direct function of the distance between the tag and the medical devices.

There are several competing proposals to bring LTE performance to the unlicensed 5 GHz region of the spectrum in order to increase the capacity of cellular networks. These proposals have originated, to this date, contradictory reports about the coexistence of LTE-U (unlicensed) and Wi-Fi networks [16], [17]. An approach to improve the capacity is to combine the use of unlicensed spectrum with licensed bands (LTE License Assisted Access (LAA) and LTE - Wi-Fi link aggregation (LWA)). There has been a flurry of proposals in the literature aiming to improve the coexistence of LTE and Wi-Fi networks. MulteFire is a new technology which enables to use LTE technology solely in unlicensed band, particularly at 5 GHz [18]. A summary of the main features of the technologies described in this section are shown in Table 2.

IV. COMMERCIALLY APPROVED MEDICAL DEVICES

It is useful to have an inventory of what is the current state of the art regarding commercial devices currently in use at medical care locations. The majority of these devices are on-body type, i.e. they are deployed on the body or within very close proximity of the human body. In-body devices are becoming more common but communication environment is more challenging and it takes a longer time to have them tested and approved, thus they are not numerous in the market. Finally, there are on-body medical wireless devices that are used by medical providers to assist them when carrying out their work, e.g., drawing blood. Table 3 shows a representative sample of commercially available wireless medical devices. From Table 3 it is apparent that, other than implant medical devices, the majority of the current commercially available wireless medical devices use Bluetooth Low Energy technology. BLE operates in the crowded 2.4 GHz frequency bands. It is expected than many future medical devices will operate in 5 GHz frequency bands to improve their wireless connectivity. It should be noted that because of health considerations not all medical devices can operate at those frequencies not even at the 2.4 GHz, e.g., pacemakers.

Table 3. Examples of commercial medical devices.

Type	Vendor/Device	Measures	Wireless technology
On-Body	iHealth/BP7 [1]	Blood Pressure	Bluetooth V3.0+EDR Class 2 SPP
	Trisa/Cardio Pro 4.0 [2]	Blood Pressure	Bluetooth
	Withings [3]	Blood Pressure	Bluetooth, BLE
	Nonin/3230 [4]	Pulse Oximeter	BLE
	iHealth/PO3 [5]	Pulse Oximeter	BLE
	Visiomed/BW-OX1 [6]	Pulse Oximeter	BLE
	LIFESYNC [7]	Electrocardiogram	Bluetooth
	QardioCore [8]	Electrocardiogram	BLE
	Emotiv/EPOC+ [9]	Electroencephalogram	BLE, proprietary in the 2.4 GHz
	Medtronics/MiniMed 640G [10]	Blood sugar level/Insulin pump	802.15.4 (proprietary data format)
	Quell [11]	Pain management	BLE
	Eko Core [12]	Heart, lung sounds (stethoscope)	BLE
	VitalConnect [13]	ECG, heart & respiratory rate, temperature, fall detection	BLE
	Moticon/OpenGo [14]	Food dynamics (pressure distribution, weight, balance, and motion	BLE
	BioRadio [15]	ECG, EEG, EMG, respiration, SpO2, Temperature, Spirometry, & Galvanic Skin Response (GSR)	BLE
Near-Body	Dräger Infinity (M300) [16]	ECG, heart rate, pulse oximetry	Wi-Fi
In-Body	Senseonics/Eversense [17]	Continuous glucose monitoring	13.56 MHz inductive link, on-body BLE
	Boston Scientific/Vitalio [18]	Pacemaker	916.5 MHz
On-body medical provider	Evena/Eye-On Glassess 3.0 [19]	Vascular multispectral imaging	Bluetooth, Wi-Fi, 3G Wireless

V. Coexistence and Recommendations

Fig. 1 summarizes the locations, in the frequency spectrum, of the common wireless technologies. It is apparent that a large variety of technologies are using unlicensed ISM bands, the 2.4 GHz band being the most crowded.

The majority of the commercially available state-of-the-art on-body devices use BLE. This technology operates in the 2.4 GHz and has features that make it, to a certain degree, resilient to interference. There are a few medical and wellness care devices using the IEEE Std. 804.15.4 [7]. This standard has been shown consistently, via experiments and analytical studies, to be vulnerable to Wi-Fi in the 2.4 GHz region. Special attention must be given to the physical location of the sensor nodes, the frequency channels they are using, and the location of the Wi-Fi routers.

In scenarios where devices using Bluetooth and 802.15.4 are operating in the same physical space experimental studies have shown that Bluetooth is more vulnerable to 802.15.4 than vice versa [19]. The most likely explanation is the higher channel occupancy of 802.15.4. Properly control of duty cycles and power levels of 802.15.4 devices, and Bluetooth / BLE frequency hopping, can minimize this interference.

Recent experimental measurements at hospitals [20] show that for the time being there is still sufficient available spectrum in the 2.4 GHz region for the various medical wireless devices and other wireless systems to work at their normal levels without any intervention or control, even at peak hours. However, the fact that the unlicensed bands in the 2.4 GHz are becoming more and more congested has led to efforts to share those bands in a more rational way instead of reactive ad-hoc solutions. For medical scenarios, proposals such as the one described in [21] are worth to consider. They propose a generic protocol stack that allows for different wireless technologies with different higher level stacks. In simple terms, it recognizes the presence of heterogeneous networks. It attempts to use common features and then implements a cognitive procedure for the layers to share information available to each particular protocol stack. In addition, it must be noted that recently defined spectrum slots, around the 2.4 GHz ISM band, have been designated for medical communication in Europe (2.4835-2.5 GHz) and in the US (2.36-2.4 GHz). These spectrum slots may play an important role in wireless medical applications in the 2.4 GHz region.

The ISM band at 5 GHz is currently much less crowded than the 2.4 GHz band. However, state-of-the-art Wi-Fi base stations are now able to operate both in 2.4 GHz and 5 GHz ISM bands and therefore more traffic is expected to appear in the 5 GHz bands. In addition, new wireless communications technologies such as MulteFire have been recently launched to operate in the 5 GHz band. The use of the 5 GHz frequency bands to extend LTE services has created new coverage opportunities but also concerns about the coexistence of LTE with Wi-Fi services [17]. There are reports highlighting the negative impact of LTE on Wi-Fi, but there are also reports concluding that such impact is very small. A more realistic solution moving forward is that both sides of this issue, the Wi-Fi industry and the telco operators, will have to adapt their standards to share the spectrum in a constructive way. The use of LTE in the 5 GHz will be go a long way in solving the problem of continuously monitoring patients as they move from one place to another since devices will be able to

[1] http://bit.ly/2j4utuZ
[2] http://bit.ly/2lKH37s
[3] http://bit.ly/2ln4gvu
[4] http://bit.ly/2ml1SCY
[5] http://bit.ly/2lu7OKD
[6] http://bit.ly/2m6Qa2L
[7] http://bit.ly/2l7598Y
[8] http://bit.ly/1VpTe5k
[9] http://bit.ly/2ln8rYg
[10] http://bit.ly/1StHlcr
[11] http://bit.ly/2luk1iq
[12] http://bit.ly/22mp2rY
[13] http://bit.ly/2lnaaN4
[14] http://bit.ly/2mbpjzt
[15] http://bit.ly/2kYnu7g
[16] http://bit.ly/2kL9ank
[17] http://bit.ly/2kL01va
[18] http://bit.ly/2luf6hG
[19] http://bit.ly/2lFbxqT

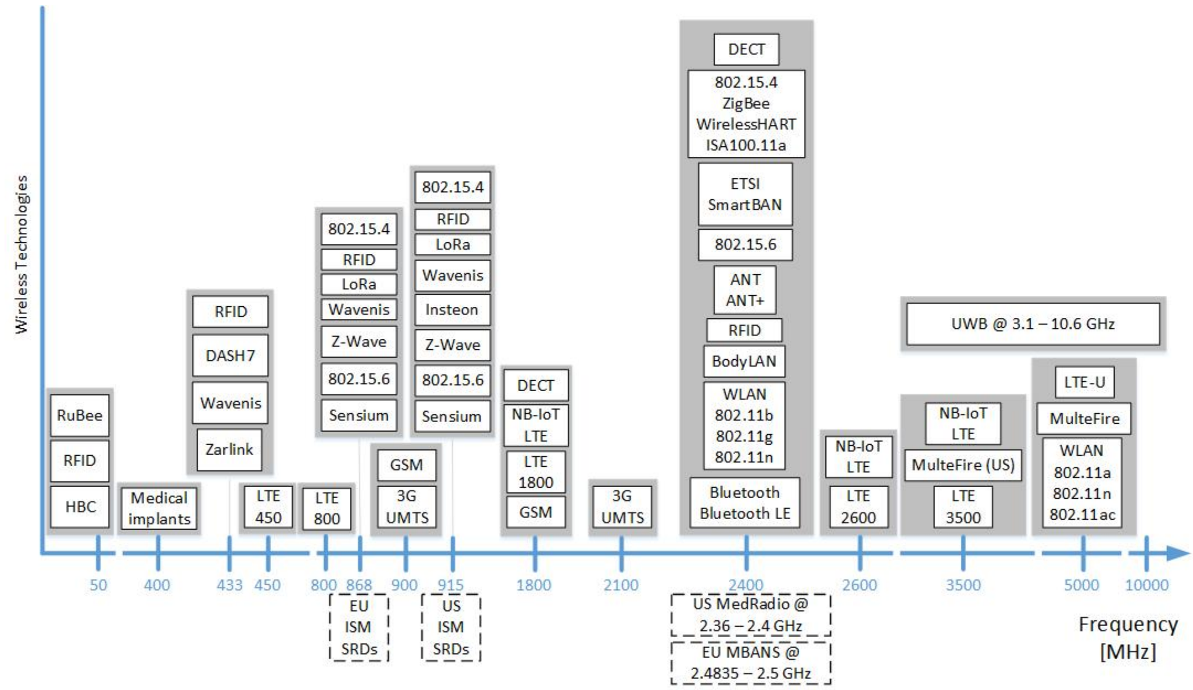

Fig. 1. Common wireless techniques at different frequencies.

leverage well tested LTE mobility features.

Spectrum sensing techniques developed for cognitive radio could be used to dynamically sense the spectrum in a medical scenario and a selection of free channel could be made. However, this solution is not comprehensive and suitable for time critical applications since the channel access cannot be guaranteed. Here it is recommended that for a privately owned environment, like hospital area, the frequency spectrum should be managed in a centralized manner. Not only information from dynamic spectrum sensing devices, but also from geolocation databases should be used to aid in the proper sharing of the spectrum. The information collected can be processed to optimize a priority-based spectrum sharing process in order to guarantee minimum communication requirements of critical applications in a medical care facility. The spectrum coordinator could for example, restrict the bandwidth available to visitors in certain areas in order to guarantee that the medical devices can get enough bandwidth to meet their functions.

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