# Wireless microsystems (MSTs) for biomedical applications: a review with the state-of-the-art

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***Abstract*—This paper presents the state-of-the-art related to wireless microsystems for biomedical application. Aspects including the radio-frequency systems, data acquisition, application specificities (especially in the context of implantable devices), power consumption and their integration are presented. A review of new concepts concerning the technologies and implementations are also presented.**

***Keywords: Wireless instrumentation, data acquisition, data transmission, wireless microsystems, biomedical applications.***

## I. INTRODUCTION

INVASIVE and implantable biomedical devices for doing diagnostics and for therapy purposes can be expected in applications ranging from neural [1] to endoscopic capsule systems with video transmission [2]. The potential of these systems to open significant business activities in the near future is high due to the new emerging innovative technologies. The success of such systems can be explained in part with the advent of microtechnologies, which allowed the miniaturization of sensors and actuators followed by their integration with readout and communication electronics. Wireless implantable Microsystems constitute a breakthrough in the way the internal pathologies can be treated. This means that the radio-frequency (RF) chips can play an important role. In this context, this review starts by discussing the issues associated with wireless instrumentation targeted for biomedical applications; this review also presents the technological aspects related to such devices, and finishes by presenting future directions of technology and applications.

## II. TECHNOLOGY FOR WIRELESS SYSTEMS

### *A. Operational issues*

The Figure 1 shows the available frequency bands for the different technologies used in wireless communications. The suitable frequencies for possible use in wireless instruments are those belonged to the so called ISM band (Industrial, Scientific and Medical), due to its unregulated usage. These frequencies can be freely used without being subjected to standardization but keeping the emission powers below the maximum levels imposed by regulations. This usage-flexibility leaded to the widespread of new applications as will be discussed further. The selection of a frequency for an implantable device is easy but not trivial to do. First, the sizes of these devices must be the minimum as possible. In this context and as it is of general knowledge, the antenna is one of the most critical subsystems in wireless communications, which means that the antenna must be small enough to comply with size constraints of the microsystems to not compromise the desired miniaturization. The size reduction can be a problem because the antenna must be designed for transferring the highest power into the receiver.

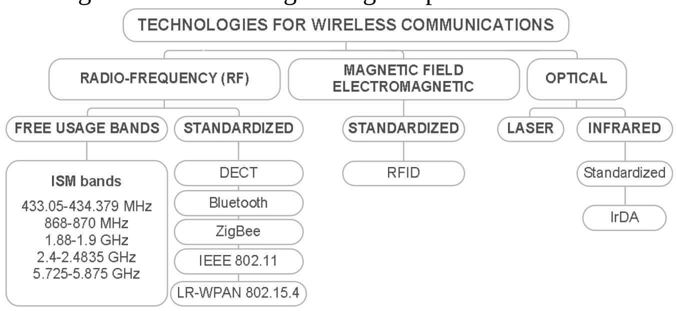



Figure 1. Currently available frequencies for wireless applications [3].

In the context of implantable devices, the size shortening of antennas can introduce additional problems of the impedance matching [4]. Additional issues include the biocompatibility and the bandwidth broadening for avoiding secondary effects related to frequency shifts. However, the environmental issue (and the most forgotten one) that limits the performance of an antenna (either transmitting or receiving antenna) is operating inside a lossy medium. This means that contrary to what happens in the free space, the medium constituted by the human tissue will dominate the radiation performance of the whole RF link [5]. The antennas can be integrated with RF chips using either the on-package, or the on-chip or even the on-wafer technique. In case of on-package integration, the antenna is coupled into the package where the RF chip is supported. This first technique is the most simple of all. The on-chip integration requires more than one integration process for more than one technology, which can lead to a situation where the technology for fabricating the RF chip can be incompatible with the one used for fabricating the antenna. Finally, the technique that seems to be promising is the on-wafer because wafer-level-packaging (WLP) techniques for joining heterogeneous technologies are offered by the industry with a relatively low-price. This last technique is especially suitable for integrating patch-antennas (due to their planar shape) are easy to package with the RF chips [6]. A variety of antennas with a variety of shapes and physical placement are related in the literature, as it is the work done by Soontornpipit *et al* [7] who fabricated implantable patch antennas with spiral and serpentine shapes. The folded shorted-patch antenna in the Figure 2 was fabricated by Mendes [8] and it exploits the third dimension for fabricating small antennas with relatively good radiation characteristics.

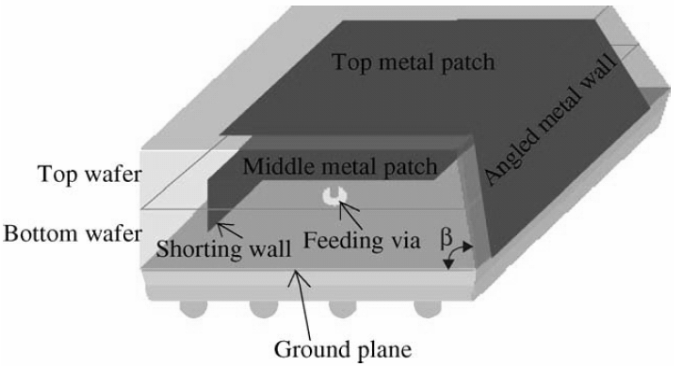



Figure 2. Folded shorted-patch antenna concept. Fabricated by Mendes [8].

Finally, the research group of Chow *et al* [9] explores an outstanding methodology that makes profit of cardiovascular stents to receive RF signals inside the human body. The precise modelling of the propagation chanell inside the human body in conjunction with the equation of skin-depth, $\delta$[m], gives a rough estimative of the radiowaves penetration. The averaged parameters help to obtain the skin-depth and the path-loss characteristics of the propagation medium. However, the simple consideration of path-loss is not simpler because as stated by Scanlon *et al* [10], the electrical parameters of the surrounding tissue around the RF receiver and the body's structure have a strong influence in the radiation pattern of the receiving antenna. The main consequences of this are difficulties due to fading caused by radiation pattern fragmentation especially observed in the azimuthal plane. This happen because the human body is composed by a variety of tissues comprising the skin, fat, muscle, bone, nerve, among others, it is required to do an averaging of the several electric parameters. A common role of thumb consists on applying a factor of 2/3 to the muscle, indicating that this is the dominating type of tissue in an average and healthy human subject [11]. It is a difficult task to obtain both the electric conductivity, $\sigma$ [S.m$^{-1}$], and the dielectric constant, $\varepsilon_r$, as the needed parameters for calculating the actual path-loss. Nevertheless and independently of the electrical parameters that are used, the following skin-depth equation can be used for obtaining an estimative of the expected path-loss [12]:

$$\delta = \left( 2\pi 10^9 f_{GHz} \sqrt{\frac{\mu_0 \varepsilon_0 \varepsilon_r}{2} \left( \sqrt{1 + (\frac{18\sigma}{f_{GHz}\varepsilon_r})^2} - 1 \right)} \right)^{-1} \quad (1)$$

where $\varepsilon_0=10^{-9}/(36\pi)$ F.m$^{-1}$ and $\mu_0=4\pi 10^{-7}$ H.m$^{-1}$, are the electric permittivity and the magnetic permeability for the free-space (note that $(\varepsilon_0\mu_0)^{-1/2}=c$), respectively. The quantity $f_{GHz}$ is the RF frequency expressed in giga-cycles per second. To have an idea of how such difficult is to get the parameters, the cortical bone can present an electrical conductivity, $\sigma$, of 0.1032 S.m$^{-1}$ and a dielectric constant, $\varepsilon_r$, of 13.77 [11]. Additionally, in [13] these values are found to be $\varepsilon_r$=5.2, $\sigma$=0.11 S.m$^{-1}$, muscle $\varepsilon_r$=57, $\sigma$=1.12 S.m$^{-1}$, and fat $\varepsilon_r$=15, $\sigma$=0.26 S.m$^{-1}$ for bone, for muscle and for fat respectivelly. The difficulty is even more evident when looking these parameters varying with the frequency, as described in [11] where a disparity of values are presented: $\varepsilon_r$=53, $\sigma$=1.10 S.m$^{-1}$ and $\varepsilon_r$=51.6, $\sigma$=1.56 S.m$^{-1}$ for 418 MHz and 916.5 MHz, respectively. This difficulty can also be used in a positive way, as it happened with the work done by Karacolak *et al* [14] for continously measuring the itens of glucose (the variations of the electric parameters are used for measuring the sugar concentration). The previous parameters were used for obtaining the skin-depth for 433 MHz, 2.4 GHz and 5.7 GHz, whose values were observed to be much equal between them. This means that for high frequencies, the path-loss can't be the only criterion to follow. In the studies carried out by Siwiak [15], the muscle tissue of the human body was modeled as a lossy wire antenna for simulating its interaction with radiowaves. More precisely, the human body were modeled as a cylinder of saline water with frequency dependeny electrical parameters. These studies resulted in skin-depths of aproximately 60 mm and 26 mm for 433 MHz and 2.4 GHz, respectively [15].

### *B. Measurement and data acquisition systems*

The Figure 3 shows a block diagram of a generic measurement instrument. The blocks of a measurement system can be grouped into three major types: the real world (representing the physical quantity to be acquired), the interface block (with the sensor) and the core (e.g., the instrumentation itself). There are situations where the interface block can be part of the core, e.g., a voltmeter don't requires any external sensor because this one is already embedded inside the measuring instrument, thus the sensing tips can touch directly the electrical potentials. In this context, it must be clarified that a sensor can't be confused with a transducer, because the later can perform the same function of the former but if the former is passive (for example, a physical quantity dependant resistor mounted in a Whitestone bridge) then additional circuits must be provided for obtaining the signal from the sensor. This means that the set composed by sensor and powering system makes a transducer, confirming that certain sensors are simultaneously transducers. The core blocks can include electronics of acquisition.

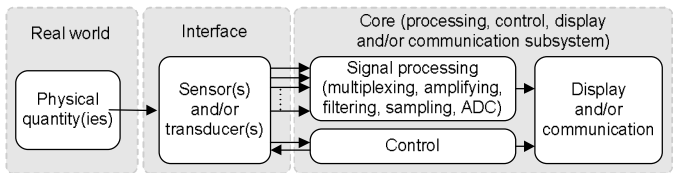



Figure 3. The block diagram of a generic measurement instrument.

The core also provides signal processing functions for signal conditioning purposes. These last functions include amplification (with the possibility to adjust the gain), filtering (either low pass or band pass or even high pass filtering) and analog to digital conversion. Then, the user can read the acquired values in a dedicated display. A more sophisticated core system can interface with the external world either to connect several measurement instruments or to send data to a central unit for further processing. These communications can use wired (I2E [16], GPIB [17], RS232 [18], parallel ports [19] or even USB [20]) or wireless buses (IEEE 802.11 [21], ZigBee [22], Bluetooth [23] or customized solution [24]).

The core blocks of the measurement instruments can be analog or digital. The analog is the less versatile core because requires the presence of a person to annotate the measurements. This type of instrument is very limited and very difficult to be adapted to wide disparities of signals to measure. Furthermore, it is not possible to send wirelessly the physical quantities, unless a specific interface with an analog modulation scheme is provided. A digital core can be used for connecting transducers (whose output can provide signals in the analog or in the digital domain). The difference from their analog counterparts resides on the conversion component used in the final processing stage, e.g., the sampler and the analog-to-digital (AD) converter (ADC) block. The inclusion of multiplexers enables the acquisition of multiple channel with a single measurement instrument. This topic will be focus of discussion in the next section. Then and after the ADC conversion, the acquired measurements can be presented in a numerical display. These cores can also be built with internal memory for storing the ADC converted samples for rendering in a more complete displaying system (e.g., a planar screen) or for remote transmitting through a communication interface. This core also allows for changing and/or for programming the amplifier's gain, thus allowing itself for adapting to wide variations of physical quantities. Finally and thanks to the latest developments of microelectronics, by making available transducers with digital outputs (for example, integrated monolithic temperature transducers [25], Hall's effect magnetometers [26] and accelerometers [27], among others) it is possible to have full-digital and reusable cores. The judicious selection of transducers and cores can be decisive points for fabricating wireless instruments with low-power, reduced sizes and low-prices. This statement is especially evident on measurement instruments composed by reusable cores (for controlling and displaying/communicating), monolithic transducers (for signal acquisition) and on-chip signal conditioning circuits [28] (for signal processing).

### *C. RF interfaces*

A wireless instrument communicates with the external world by radio-frequency (RF). Thus, a wireless interface must be provided for allowing RF communications. The Figure 9 shows a generic schematic block of a wireless microsystem doing functions of a stand-along wireless instrument. These microsystems are composed by transducers, electronics for control and signal processing, by memory and by a RF interface (the RF transceiver) for connecting to an associated antenna. The dimensions of the RF transceiver must be comparable with others elements integrated in the microsystem (e.g., the transducers and remain electronics). The miniaturization of electronics and the spreading of fabrication processes for integrating heterogeneous technologies (e.g., CMOS, SiGe, III/V technologies, MEMS, among others) will result in the mass production of wireless microsystems at low prices. All these issues combined with the flexibility to select which and the number of transducers for integrating together with the RF transceiver and remain electronics allows engineers to design wide number of devices for wide number of applications. This last goal can be easily achieved with multi-chip-module (MCM) techniques applied to a limited number of components (which can be of different technologies). In conclusion, the technology is also a major point to allow the fabrication of wireless microsystems for use in wireless instruments. In this section, few examples for each of the ISM band in the Figure 4 are presented for a better view of wireless instruments potential.

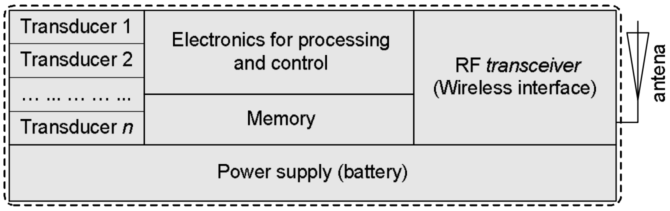



Figure 4. A generic microsystem architecture with an associated antenna.

The Figure 5 shows a photograph of the first prototype (shading area) of a receiver for operation in the 433 MHz ISM band that was developed for use in implantable Microsystems [29] and it was integrated in a die with an area of $5{\times}5\ \mathrm{mm}^2$. The selected architecture explores the super-regeneration phenomena to achieve a high sensitivity. This receiver can be supplied with a voltage of only 3 V for demodulating signals with powers in the range [-100,-40] dB. The combination of modulation and coding scheme is OOK (on/off keying) modulation combined with a variation of the Manchester code (a Biphase code). The AMIS 0.7 μm CMOS process was selected for targeting the requirement to fabricate a low-cost receiver. This receiver is compatible with commercial transmitters and the transmitter fabricated by Morais *et al* [30].

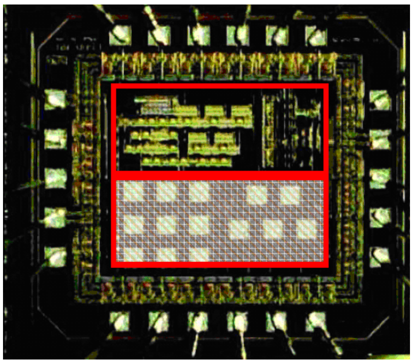
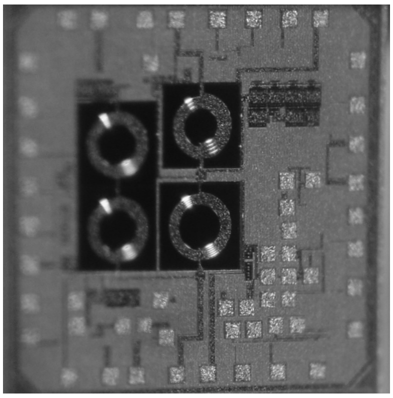
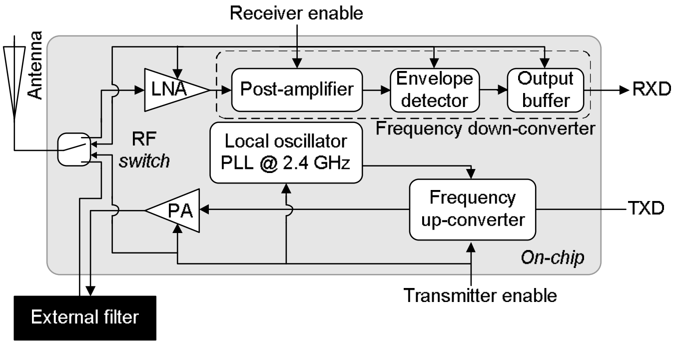


Figure 5. A die photography containing the first prototype of a super-regenerative receiver at 433 MHz (the non-shaded area) [29].

The power consumption of a wireless instrument limits its working time, especially when functioning with batteries. In this context, the selection (or even further, the design) of RF transceivers can't neglect this issue because this is the block with major impact in the total power consumption, when compared with the whole electronics in the instrument [31]. Furthermore and despite the spreading of microelectronics fabrication processes with the potential to achieve smaller power consumptions, the RF transceiver is irremediably the subsystem of higher power consumption [32,33]. This demand for the integrated definition of architectures and methods of control, as well as to provide means to predict the power consumption of the RF system. The Figure 6(a) shows a photograph of a RF CMOS transceiver at 2.4 GHz to allow the implementation of control actions for optimizing the power consumption [34]. This RF CMOS transceiver was fabricated in a standard 0.18 μm CMOS process for achieving low-power consumption with low-voltage supply. As illustrated in the Figure 6(b), the design of this RF CMOS transceiver predicted the use of control signal to either select the transmitter or the receiver in order to allow its integration with electronics to perform custom control.



(a)

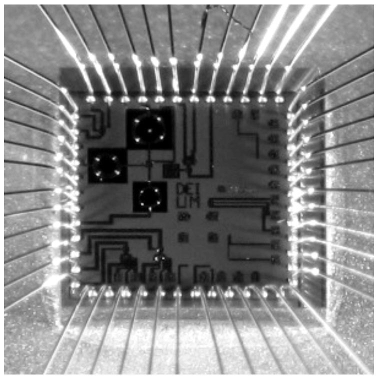



(b)

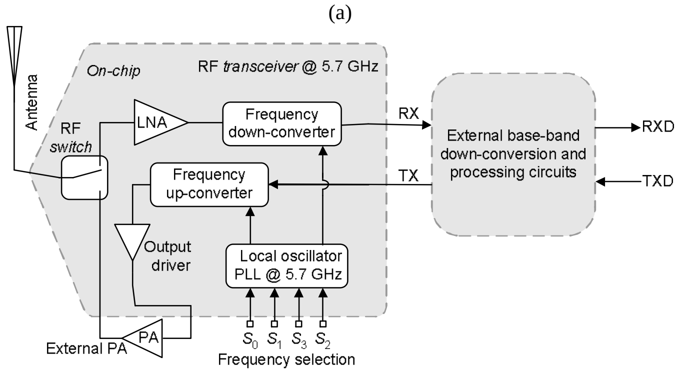
Figure 6. (a) Photography and (b) block schematic of a RF CMOS transceiver at 2.4 GHz [34].

It exists the possibility to explore the band located between the 5.7 GHz and the 5.89 GHz for implementing wireless instruments [35]. This band allows the fabrication of antennas, whose small dimensions allows their integration with the electronics using Wafer-Level-Packaging (WLP) techniques. The integration of antennas and electronics in the same microsystem results in smaller impedance mismatching problems. Moreover, the antenna and electronics co-integration systematizes the fabrication process and at the same time results in microsystems with a small cost per unity. The Figure 7(a) shows a photograph of the wireless interface measuring of $1.5 \times 1.5\ \mathrm{mm}^2$. The schematic illustrated in the Figure 7(b) shows the block diagram of the RF part at 5.7 GHz. The digital signals$\{S_0,S_1,S_2,S_3\}$ select the target frequency in the range $f_{out}=f_{ref}\times(400+2S)=f_{ref}\times[400+2(S_0+2S_1+4S_2+8S_3)]$, whose range is located between 5.42 GHz and 5.83 GHz for a reference frequency $f_{ref}$=13.56 MHz.

An integrated low-cost solution for wireless instruments based on a microdevice fabricated with a low-power consumption 0.18 µm CMOS process can also be found in [36]. This microdevice is naturally composed by a RF transceiver, by a RISC (Reduced Instruction Set Computer) microcontroller, by RAM (Random Access Memory) memory, by a power-supply management circuit, by analog electronics of signal conditioning and analog-to-digital conversion (ADC), and by circuits for providing communication based in SPI and $I^2C$ buses. The control electronics was developed for implementing a specific communication protocol for use with multiple wireless instruments and low-power consumption, e.g., the WiseMAC protocol. According the authors, this protocol working together with their RF transceiver achieves power consumptions thirty times smaller that those obtained with the IEEE 802.15.4. Furthermore, the operation frequency can be selected from 433 MHz and 868 MHz, as well as either with the OOK modulation or the FSK modulation. According which is stated in [37], their RF transceiver presents a power consumption of either 2.5 mW or 39 mW, when either the receiver or the transmit operation mode is respectively selected.



(a)




(b)

Figure 7. (a) A photograph and (b) the respective schematic block of a RF transceiver at 5.7 GHz [36].

Due to its inherent high sensitivity, the new developments around the super-regenerative architecture are very notorious in the later years. This is a contradictory point because the super-regeneration principle was accidentally discovered by Edwin Armstrong in 1922 [38]. The super-regenerative architecture allows the fabrication of receivers with high sensitivity and high simplicity of construction and low power consumption [39]. However and despite these positive points, this architecture was left forgotten during a long period of time due to inherent poor selectivity and frequency instability [38]. The interest in the super-regenerative receivers stated to grow in the recent years with a tentative to make such receivers with commercial off-the-shelf components [41], culminating with a fully on-chip solution fabricated in a 0.8 µm BiCMOS process [42]. This last solution was one of the first successful approaches for obtaining integrated RF chips with receivers based on the super-regenerative architecture. Since these first steps were done, a wide variety of circuits were published in the literature for a wide number of applications fabricated with the available processes. The work done by Chen *et al* [41] resulted in a receiver fabricated in a 0.13 μm CMOS process and able to operate at 2.4 GHz with passband tuning. The super-regenerative receiver fabricated by Moncunill-Geniz *et al* [44] also operates at 2.4 GHz and was conceived for high-speed data transfer purposes (e.g., 11 Mbps). Finally, the work proposed by Moncunill-Geniz *et al* [45] pushes the super-regenerative concept further by presenting two new architectures for achieving non-coherent detection of direct-sequence spread spectrum (DSSS) signals. To finish, it is expected that the potential for use the super-regenerative in modern applications didn't reached the end-of-line and new developments are expected in the newer future.

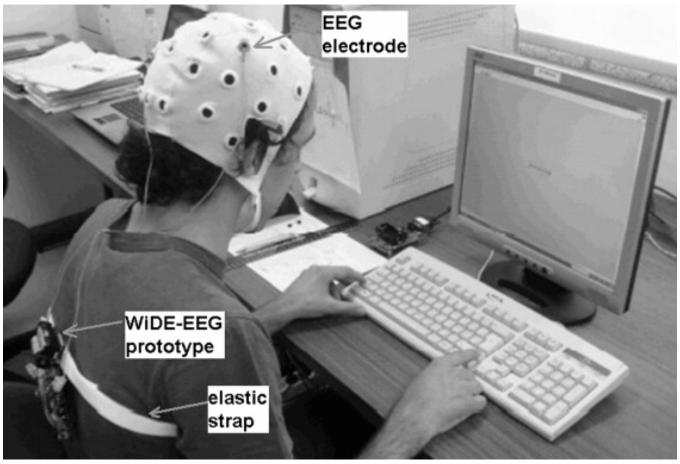



Figure 8. A subject with a wireless data acquisiton, logging and transmission system prototype fixed with the help of an elastic band (the white strap) on the thorax region [46].

## III. COTS SOLUTIONS

It is now clear that the biomedical applications are these with the higher potential for using wireless instruments. An example that confirms this statement is the wireless monitoring systems of human body information as a growing field. Body area network comprises smart sensors able to communicate wirelessly to a base station. Examples of applications are the wireless electroencephalogram (EEG) which is expected that will provide a breakthrough in the monitoring, diagnostics and treatment of patients with neural diseases. Wireless EEG modules composed by the neural electrodes, processing electronics and a RF transceiver with an associated antenna will be an important breakthrough in EEG diagnostic. Two approaches can be used for implementing wireless EEG systems: the Commercial Off-The-Shelf (COTS) and the customized solutions. As said by its name, a Commercial Off The Shelf solution uses discrete integrated circuits and passive components for making the wireless instruments, whereas a customized solution is designed from the scratch and further integrated on a single microdevice in order to optimize the size, power consumption and allow power supply with small batteries (for example, class AA, coin sized batteries). The system proposed by Dias *et al* [46] is an example of a COTS system for acquiring EEG signals and transmission by RF. Basically, this wireless EEG system uses a micaz module [47] at 2.4 GHz for RF transmission and for controlling and converting the physical data. This system uses two class AA batteries of 1.5 V for power-supply, and achieves the maximum bit rate of 120 Kbps. Other features of this system include the resolution of about 4 μV and presents the power consumption is 15 mW and can acquire signals with the help of five single ended channels. This wireless acquisition system fits approximately in $5.7\times4.8\times2.0\ cm^3$. The Figure 8 shows such a wireless system fixed into a human subject with the help of an elastic band (the white strap) on the thorax region.

## IV. NEW CONCEPTS

New techniques for implementing wireless instruments can be found in the literature. These techniques are extremely innovative due to the breakthrough introduced in the way the measurements are done. The work proposed by Karacolak *et al* [48] takes in account the variation of the electric parameters for continuously measuring the items of glucose (the electric parameters varies with the sugar concentrations). Alternatively, the research group of Chow *et al* [49] explores an uncommon (but still very innovative) methodology that makes profit of cardiovascular stents to receive RF signals inside the human body. In this work, the stents are used as radiating structures for transmitting the measurements across the tissues of the human body. Finally, the work proposed by Rodrigues *et al* [50] uses a MEMS antenna with a U-cantilever shaped structure. Basically, this cantilever is sensitive to the magnetic field component of electromagnetic waves and will oscillate. A piezoelectric material layer of polyvinylidene fluoride (PVDF) is used to convert the magnetic field into a voltage useful enough to be understood by the reading circuit. The major innovation of this technique is allow the integration of antennas with implantable devices by way of Wafer-Level-Packaging (WLP) techniques for achieving the fabrication of small sized devices. Their antenna occupies an area of only $1.5\times1.5\ mm^2$ [50]. Finally, a new breakthrough can be obtained by doing the co-integration of the electronics with microbatteries made of thin-film materials to provide energy in a harvested fashion. This microbattery supply the microsystem in an enough time to increase the useful life of the microsystem [51].

## ACKNOWLEDGEMENTS

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