RF microsystems for wireless sensors networks

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Abstract - **This paper presents RF microsystems constituted by low-power devices for use in wireless sensors networks. As it is expected, the major emphasis is given to the fabrication of RF transceivers for integration in these microsystems. Features like low-power and low-voltage operations are discussed, at the same time are presented RF transceivers for the frequencies of 433 MHz, 2.4 GHz and 5.7 GHz, in order to comply with mandatory issues of WSN, e.g., working independently from a human operation, management and maintenance. Another reason for this, is the suitableness of these wireless microsystems to use thermoelectric energy scavenging systems.**

Keywords - **RF microsystems, wireless sensors networks.**

I. Introduction

Wireless communication microsystems with high density of nodes and simple protocol are emerging for low-data-rate distributed sensor network applications such as those in home automation and industrial control. This type of wireless microsystem with sensors and electronics are becoming of interest for biomedical applications. Moreover, in order to implement an efficient power-consumption wireless sensor it is necessary to develop low-power/low-voltage radio-frequency (RF) transceivers. As is of common knowledge, the CMOS technology has reached its maturity. Therefore, design engineers used it for developing RF circuits. The advantages of CMOS technology are the higher integration, low-power consumption, low-voltage supply and low-cost compared with Bipolar technology. The use of CMOS process with low length for the channels of the MOSFETs is very important for high-frequency devices. This paper presents several wireless microsystems for use in wireless sensors networks and for a wide variety of frequencies. In this sequence, and as will be seen further, this was one of the main reasons that were behind the chose of a 0.18 μm CMOS process to design, optimize and fabricate, radio-frequency (RF) transceivers for the operation in frequencies such as the 2.4 GHz and 5.7 GHz.

II. System requirements

In wireless sensors networks, the communication is made by way of a RF link. Thus, in order to such a communication be possible, a wireless interface must be designed. This wireless interface is a RF transceiver, which after be connected to an associated antenna, makes possible to wirelessly communicate with the exterior. The RF transceiver must present dimensions comparable with the other elements of the microsystem, in which it will be integrated, such as the sensors and the electronics of processing and control. Miniaturized microsystems makes possible to have mass productions with low prices, favoring the spread of applications relying on these same microsystems. Moreover, solutions relying in wireless microsystems, offer a flexibility such as it is possible to chose how many and which are the sensors to be integrated together with the RF transceiver and the remain electronics. Using multi-chip-module (MCM) techniques and a limited number of components in different technologies, it is possible to fabricate devices for a huge range of applications.

In wireless communications, the antenna is one of the most critical subsystem, thus, in order to not compromise the desired miniaturization, the antenna must be small enough to comply with size constraints of the microsystems. The investigation of new frequency bands [1] and new geometries [2] will make possible to have smaller antennas to integrate in wireless microsystems [3,4]. This makes the chose of the most suitable frequency, one of the more decisive aspects in the design of RF transceivers. Normally, the desired range, baud-rate and power consumptions are key-aspects in the design to take in account, when the frequency of operation is to be selected. At a start-up point, the range limits the maximum usable frequency, because the loss suffered by the radiowaves in the free-space increases with the distance. However, to keep or even increase the useful life of the batteries, such a variation in the transmitted power is not possible to do. Moreover, in the case of applications requiring higher baud-rates, the transmitted bandwidth must also be higher, in order to support these applications. However, the frequency can't be arbitrarily increased, because this have implications in the power consumptions, e.g., at high frequencies, the transistors must switch faster, thus the energy dissipation will be bigger.

Figure 1 shows the available frequency bands for the different technologies used in wireless communications. The most suitable frequencies are those belonged to the so called ISM band (Industrial, Scientific and Medical), due to its unregulated usage, e.g., these frequencies are not subjected to standardization and can be freely used, since the emitted power are maintained below the maximum levels imposed by the legislation. Such a flexibility leaded to the rising and spreading of interesting applications.

III. Microsystems for wireless sensors networks

The need of a powerful tool, to help health professionals with rapid, accurate and sophisticated diagnostic concerning cardiopulmonary disease in order to evaluate the presence of breathing disorders in free-living patients, leaded to develop a solution for transmitting biometric data through a wireless link. Figure 2 shows a photograph of a microdevice, containing a low-power, low-voltage, RF CMOS transceiver with the size dimensions of 1.6 mm×1.5 mm, for operating at 433 MHz with ASK modulation. A commercial antenna for this frequency must be used at the same time, two 1.5 V class AA batteries must be provided, in order to supply the RF transceiver with 3 V. This RF transceiver was fabricated in the 0.7 μm AMIS CMOS process, which provides two layers of metals, one layer of polysilicon, high-resistor values with low-tolerances as well as high-capacitors. The biomedical applications that use wireless links with this RF transceiver are powerful tools, helping health professionals with rapid, accurate and sophisticated diagnostic in order to evaluate the presence of health disorders in free-living patients [5].

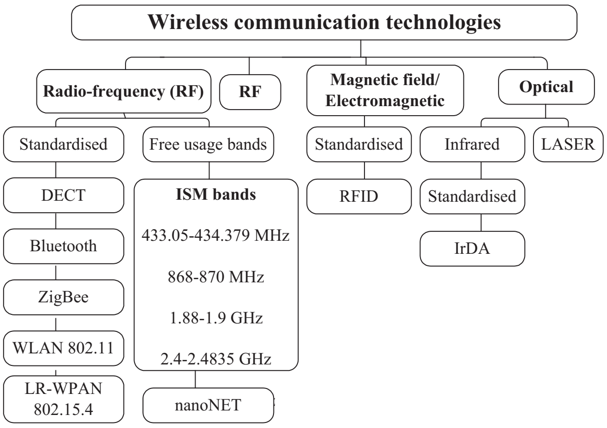


Figure 1: Available frequency bands and respective applications.

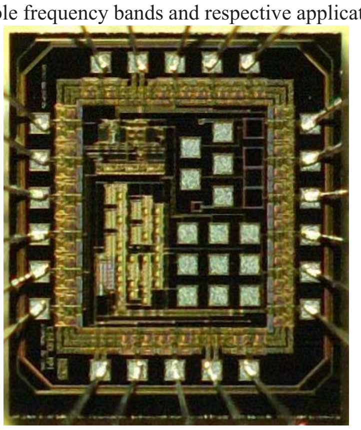


Figure 2: RF transceiver at 433 MHz (11.6 mm × 1.5 mm size dimensions).

Figure 3 shows the block diagram and the respective interface for monitoring the body movements of individuals. This interface connects to a set of accelerometers with three axis, which are used to measure the relative position of members to the thorax. This was the first attempt to have a real wireless interface for data acquisition and transmission using the wireless sensors network paradigm. This interface uses an analog multiplexer followed by an analog-to-digital converter (ADC) to acquire and process the signals. All of the analog electronics of control and processing is managed using the control logic of the interface. A third party RF module the uses a 2.4 GHz wireless link to exchange data.

Higher frequencies such as those in the range 5.7-5.89 GHz makes possible to have antennas sufficiently small, in order to fabricate microsystems, containing the wireless interface and antenna. Moreover, these kind of solutions helps to reduce the problems related to impedance mismatches, while at the same time, it increases the systematization of the manufacturing processes and delivers microsystems with an even reduced price [6]. Figure 4(a) shows a microsystem, where it can be seen the RF transceiver mounted together with a chip-size antenna of planar type, which were optimized and fabricated for the operation in the 5.7 GHz ISM band and measures 7.6×7.7mm [4].

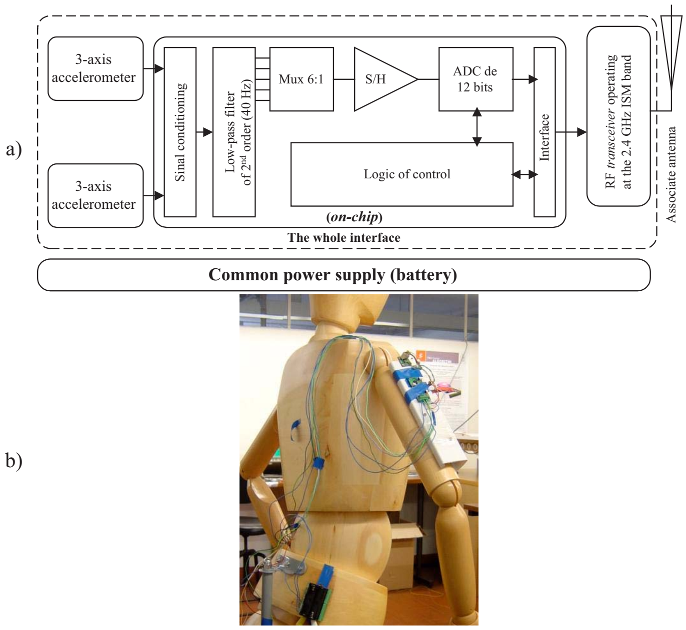
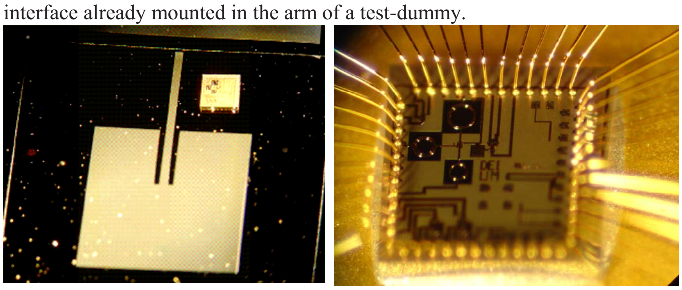


Figure 3: a) The block diagram of a wireless interface for operation at the 2.4 GHz ISM band and ready to be used in biomedical applications; and an interface already mounted in the arm of a test-dummy.



a) b)

Figure 4: a) Chip-size antenna for operation at 5.7 GHz assembled with a RF transceiver and b) a magnified photograph of the same RF transceiver [4].

The microdevice shown in Figure 4(b), is the RF transceiver used for the transmission at 5.7 GHz. This RF transceiver uses the ASK modulation to transmit the data. As stated before, the chose of the best suitable technology, felt in a 0.18 μm CMOS process, because it allows to trade the high-frequency capability of minimum-length transistors with lower current consumption by biasing the devices at lower current densities, even for devices working at RF. This process provides a polysilicon and six metal layers, the use of integrated spiral inductors (with a quality factor of ten), high-resistor values (a special layer is available) and with a low power-supply. The transceiver has a Low-Noise Amplifier (LNA) that provides a 50 Ω input impedance, the amplified RF signal is directly converted to the baseband with a single balanced active MOS mixer. The internal oscillator is a Phase-Locked Loop (PLL) working at 5.7 GHz. The transceiver is able to operate at the [5.4200–5.8265 GHz] frequency range. This is done by changing the frequency division ratio in the feedback path of the PLL. The PLL has four digital inputs for the division ratio programming. The output frequency is $f_{out}=f_{ref}\times 2\times(200+D)$, and D is the decimal representation of the division ratio. The used reference frequency was f_{ref}=13.56 MHz. In high frequency PLLs, the high power consumption is mainly due to the first stages of the frequency divider that often dissipates half of the total power. At frequencies in the range [5.4200-5.8265 GHz], the measurements show for the LNA a gain in the range [9.597-9.807 dB], a NF in the range [0.775-0.841 dB] and a stabilization factor K of 1.209, making the LNA unconditionally stable (K>1). Measurements show for the LNA, a power consumption of 9.65 mW. The power consumptions are about of 9.51 mW for the mixers, and 4.14 mW for the PLL.

In wireless sensors networks, the continuous working time of sensorial nodes are limited by its average power consumption [7]. Excluding the RF transceiver, the sensors and the remain electronics has no great impact in the power consumption of wireless nodes [8]. In fact, it's well demonstrated that the RF transceiver is the subsystem with the biggest power consumption, in spite to be available a lot of technologies with increased power-consumption efficiencies [9]. The co-definition of new architectures and algorithms is a topic of even more concern, in order to quantify in advance the exact implication of the RF system in the total power consumption [10]. To conclude, without proper design, communication will increase network power consumption significantly because listening and emitting are power-intensive activities [11]. Thus, in order to optimize the power consumption, it was designed a RF transceiver for the operation in the 2.4 GHz ISM band (known as RF CMOS transceiver) [12]. It was used the same 0.18 μm CMOS process used in the fabrication of the 5.7 GHz RF transceiver, which were presented previously. Moreover, in order to optimize power management, the RF transceiver design predicts the use of control signals. With these control signals it is possible to enable and disable all the subsystems of the transceiver. These signals allows, e.g., to switch off the receiver when a RF signal is being transmitted, to switch off the transmitter when a RF signal is being received, and allows the transceiver to enter to sleep when RF signals are neither being transmitted, nor being received. An important feature that this RF CMOS transceiver must allow, is the possibility to be integrated together in the same microsystem with sensors and the remain electronics of processing and control, in order to reduce the number of supply-points. This makes more practical and easy to supply all the subsystems, since it needs to attach a single battery. The RF CMOS transceiver, which consists of a receiver, a transmitter, an antenna-switch and a Phase-locked Loop (PLL) as a frequency synthesizer. The receiver adopts a direct demodulation, by means of envelope detection.

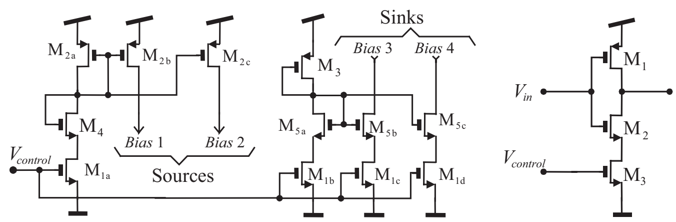
The power budget of the RF link must be made, in order to have in any noise condition and with the maximum baud-rate of 250 kbps, a bit error probability (BEP) less that 10^{-6}. This target quality of service (QoS) is for a maximum transmitted power of P_T=0 dBm (p_t=1 mW) with Amplitude Shift Keying (ASK) modulation. Using an antenna with an output impedance of 50 Ω (at the frequency of 2.4 GHz) and a Spectrum Analyzer, model *Agilent E4404-B*, several noise measurements were made. It was observed that the noise power never crossed above $N=10\log_{10}(n)$=-104 dB, where n [W] is the noise power expressed in Watt. The previous known of noise levels and the QoS of the system are mandatory, in order to know the minimum sensitivity of the receiver. Starting with the equation that gives the BEP for ASK with envelope detection [13]: BEP=$\frac{1}{2}e^{-\frac{1}{2}\gamma}$ (γ»1), where γ is the signal-to-noise ratio (snr) at the receiver (calculated as $\gamma=p_r/n$, where p_r [W] and n [W] are the signal and noise powers in the receiver site), and in order to have BEP≤10^{-6}, it is necessary a minimum snr in the receiver site of $\gamma\geq 26$ (γ_{dB}=SNR=$10\log_{10}(\gamma)=10\log_{10}(p_r/n)=P_R-N$=14 dB). This imposes a minimum signal power, S_{min} [dBm], in the receiver such that $\gamma_{dB}=P_R-N\geq S_{min}-N\geq$14 dB. Then, the sensitivity of the receiver must be at least $S_{min}=14+N$=-90 dB$\underline{\Delta}$-60 dBm. From the transmitted power, P_T=0 dBm$\underline{\Delta}$-30 dB and applying the free-space loss equation [14]: $L_F(d_m)=20\log_{10}[75/(\pi d_m f_{MHz})]$, where d_m is the distance (in meters) and f_{MHz} is the frequency (in MHz), the signal-to-noise ratio SNR=$10\log_{10}(snr)$ [dB] for a ten (#10) meters range is such that $\gamma_{dB}=P_T-L_F(d$=10m$)-N\cong$+13.96 dB. This SNR is very close the required +14 dB with a relative error less than 0.29%, thus it is not necessary to modify the specifications of the transceiver. However, a further theoretical validation must be made, in order to confirm that the noise measurements really met the specifications of the RF transceiver. Let's consider the use of unipolar NRZ (non-return to zero) pulse shaping for ASK transmission and the typical noise level of +22 dBμV/MHz for a large city and/or for ignition noise [14]. This means that the bandwidth of the link can be approximately by the twice of the maximum band-rate (e.g. 2×250 kHz), thus the noise signal will have in this case, a amplitude equal to +11 dBμV, which corresponds a noise voltage of $n=10^{+11/20}\approx$3.55 μV. Finally, assuming a perfect matching between the antenna and the receiver, the noise power will be $N=10\log_{10}(\frac{1}{2}.n^2/50)\approx$-129 dB, which is less of the supra-cited maximum measured value (N=-104 dB). This proves clearly that the noise measurements didn't imply an optimistic sensitivity of the receiver, e.g., there is no risk to break with the specifications. The receiver's front-end is a chain composed of a Low-Noise Amplifier (LNA), a post-amplifier, an envelope detector and by an output buffer. The post-amplifier provides additional gain to the RF signal coming from the LNA and the envelope detector senses the presence of the 2.4 GHz carrier. Then, after the envelope detection, the resulted signal is injected in the output buffer, in order to transform it in a perfect NRZ rail-to-rail signal.

For analog blocks, the Figure 5(a) shows the principle used to switch on and off. The transistors M_{1x} are normally in the cut-off state due to theirs gate-source voltages be zero.

However, when a voltage, $V_{control}$ of 1.8 V is applied, they start to conduct; then the current sources constituted by the transistors M_{2a} e M_4 are activated. M_4 behaves like a resistor, thus making the transistors M_{2b}, M_{2c} and further (if more were available) behaving like current sources, e.g., they start to inject current in the branches *Bias* 1 and *Bias* 2. In a same way, the current sources constituted by the transistors M_{5a} e M_3, are also activated, which makes the transistors M_{5b}, M_{5c} and further, behaving like sinks. These sinks absorbs the currents which travels from the branches *Bias* 3 and *Bias* 4. Figure 5(b) shows the principle to control digital blocks, and it can be seen the addition of the transistor M_3 to the inverter constituted by M_1 and M_2. Normally, the M_3 is also in the cut-off state, because as in the previous case, its gate-source voltage is also zero, thus the power consumption of the inverter will be zero. Digital drivers with high-impedance outputs applied in digital buses use this same principle, when outputs with a high impedance are desired.

The transmitter is constituted by a chain of subsystems, which the first of all is a modulator circuit, where a preliminary version of a digital ASK signal is generated to be combined with the bitstream to be transmitted at the frequency of 2.4 GHz. Then, this signal enters in an external filter, followed by a switched Power Amplifier (PA), whose output is the modulated ASK signal at the input of the antenna. The 2.4 GHz carrier is locally generated by the PLL. The PA allows to select the transmitted power. Table I lists the several possibilities of transmitted power for all the combination of digital signals to select the transmitted power.

An internal antenna-switch makes this transceiver a true complete system-on-a-chip (SOC). The antenna-switch connects the antenna to one of the receiver or transmitter path, that are connected to the receiving and transmitting ports, respectively. The isolation between non-connected ports must be high. In order to have a power efficient transceiver without degrading its sensitivity, the losses in the switch must be low.



a) b)

Figure 5: a) Principle used to enable and disable analog blocks; and b) principle used to enable and disable digital blocks.

TABLE I: POSSIBILITIES IN THE TRANSMISSION POWERS AND THE RECEIVER POWER CONSUMPTIONS.

Control bits	Power consumption of the transmitter [mW]	Power consumption of Power Amplifier [mW]	Transmitted power [mW]
0 0			
0 1	10.67	4.97	0.28
1 0	12.62	6.91	1.01
1 1	13.61	8.02	1.21

The experimental tests made to the RF CMOS transceiver, shown a total power consumption of 6.3 mW for the receiver (4 mW for the LNA, and 2.3 mW for the envelope detector and for the post-amplifier), and 11.2 mW for the transmitter. The transmitter delivers a maximum output power of 1.28 mW (very close to the specified 0 dBm) with a power consumption of 11.2 mW. When enabled, the power at the output of the PA, can be selected from the following values: 0.22 mW, 1.01 mW and 1.21 mW. It was observed for the LNA, a S_{21} of 19.2 dB, a noise figure (NF) of 3 dB, a 1 dB compression point (IP1) of -9 dBm, and a third order intercept point (IP3) of -5.4 dBm. The LNA has also a stabilization factor of K=1.8 (grater than the unity), that makes this amplifier unconditionally stable.

Figure 6 shows a photograph of the first prototype of a low-power/low-voltage RF CMOS transceiver, which occupies an area of 1.5×1.5 mm^2.

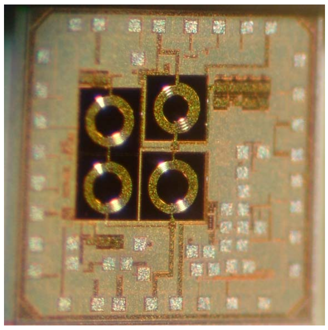


Figure 6: A die photograph of the fabricated RF transceiver at 2.4 GHz.

The interest in the development of low-power/low-voltage wireless microsystems is justified by the fact that energy scavengers are currently emerging for a number of applications from automotive to medicine. Micro energy scavengers are small electromechanical devices which harvest ambient energy and convert it into electricity. Energy scavengers could harvest different types of energies. Solar energy can be harvested with photovoltaic solar cells, thermal energy can be harvested with thermoelectric generators, mechanical energy can be harvested with piezoelectric, electromagnetic or electrostatic converters, and finally electromagnetic energy can be harvested through RF resonators. It exists two types of energy scavenging systems: macro energy scavengers, typically in the cm^3 range, and micro energy scavengers, typically in the mm^3 range and manufactured using micromachining techniques. Micro energy scavengers are still in the R&D phase. Direct thermal-to-electric energy conversion without moving mechanical parts is attractive for a wide range of applications because it provides compact and distributed power, quiet operation, and is usually environmentally friendly. Thus, worldwide efforts are undertaken to expand the technology of thermoelectric devices into the field of micro-systems technologies (MEMS). Previsions made by the specialists of the microsystems area, shows that the most expected growth of these devices, will be with medical applications. An emerging technology for ultra-low power communication platforms triggered renewed interest in power sources for wireless-sensor, in special wireless-wearable-sensors, with power consumption nodes of few mW. Today, almost all of these platforms are designed to run on batteries which not only have a very limited lifetime, but are also in many areas a cost-prohibitive solution. An attractive alternative is powering the sensors with energy harvested from the environment. Thus, it is growing, the interest of solutions for energy microgeneration through energy harvesting by taking advantage of temperature differences. A viable energy source for low-powered devices such as micro sensor systems, ZigBee chipsets, wearable electronics, implantable medical devices, active RFID tags and many other applications is proposed, provided a temperature difference exists, between the two surfaces of a thermoelectric microgenerator (in a wearable device, the difference between the body and environment can be tens of degree, depending on the environment temperature). This temperature difference can be converted into electrical energy using the Seebeck principle. Since many of wireless sensors are powered in a peak basis (e.g., the transmission of data needs much more current than standby or receiving mode) and the temperature gradient could not always be present, the energy is stored in a rechargeable thin-film battery of the Li-ion type (integrated in the system). Ultra-low power electronics performs DC-DC rectification with a variable conversion factor and recharge the battery on optimal conditions. Since a small volume is required, integration into an IC is desirable. A single-chip regulated thermoelectric power source is the final goal to be achieved [15]. Future investigations, must prove if the operation from low temperature gradients and the power of 2 mW/cm^2 are possible to be obtained. The fabrication of macro-scale thermoelectric devices is based on standard technologies for decades. Bismuth and antimony tellurides was be used as thermoelectric materials since these materials have the highest performance figure-of-merit (*ZT*) at room temperature [16]. The co-deposition method was used to fabricate these thermoelectric thin films. A very stable evaporation rate of each element (Bi/Te and Sb/Te for the bismuth telluride and antimony telluride, respectively) allows the deposition of polycrystalline n-type and p-type materials, when the substrate is heated in the range 200-300 ºC. The design of a thermoelectric microdevice, with vertical microcolumns, connected in series by metal contact areas, requires the application of microsystem technologies [17]. Reactive ion etching, lift-of and wet-etching (hydrochloridric acid / nitric acid solution) techniques were tested to create the vertical columns. A thin (50 nm) layer of nickel (deposited by e-beam) interfaces between the thermoelectric material and the metal contact areas (1 μm of aluminum), preventing the diffusion of the metal from the contacts into the thermoelectric film. The contact resistance plays a major role in the performance of the device, and a value smaller then 1×10^{-6} Ω.cm^2 was achieved. A silicon substrate was used for integration with microelectronics, while at same time providing good thermal contact with heat source and sink. The fabricated battery, as well as, all the electronic circuitry to receive the energy and to recharge the thin-film integrated Li-ion battery (open circuit voltages between 1.5 V and 4.2 V, maximum current of few mA/cm^2 with a charge-storage capacity around 100 μAh/cm^2), was placed on the bottom side of the generator. Thin-film solid-state batteries show a very high life cycle and are intrinsically safe [18]. Figure 7 shows an artist impression of a thermoelectric microdevice, with vertical microcolumns, connected in series by metal contact areas [15]. On this thermoelectric generator will be placed the thin-film integrated battery and all the electronic circuitry to receive the energy and to recharge the battery.

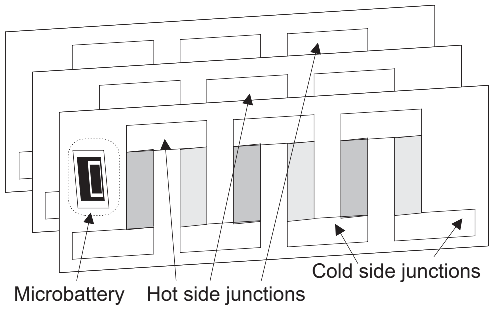


Figure 7: Artwork of a thermoelectric device.

As the final goal of thermoelectric scavenging energy systems are to supply the wireless acquisition modules in wireless sensors networks, these must present low-power consumptions in order to match with the power sources, as a way to put these same modules to works without human intervention, e.g., either to switch the battery or to recharge it.

Another growing demand of applications requiring RF microsystems includes implantable devices. Figure 8 shows an artist impression of a possible implantable device for induce mitrition in spine injury patients, which must be small enough to fit inside the spinal cord, will allows to deliver the required stimulus and it must be possible to communicate with the device using a RF signal. The parts of such a microsystem includes the electrostimulation and the RF subsystems. The electrostimulation part is a box made in a glass wafer, whose groves were etched to pass the nerves to be stimulated. Above the stimulation box is putted a cover containing electrodes that make electrical contacts with the nerves. Using wafer-level packaging (WLP) techniques the RF and the electrostimulation parts are joined together. This implantable microsystem allows the reception at the frequency of 433 MHz of user commands to activate the micturition function and the erection (on males) patients. The microsystem has an area of 5×5mm^2. As shown in Figure 9, the cover must fit well in the box, and the contacts used to touch the nerves, can't make friction with the side walls of the grooves. Moreover, their thickness must be smaller than 1 μm in order to not scratch the nerves and thus, to not make damages on it. As shown on Table II, the 433 MHz is the one with the less but still acceptable loss, e.g. an equivalent free-space-loss for a distance of 14 meters. Thus, a RF transceiver designed for short-range communications at this frequency [5] can be used as a RF part in the implantable microsystem.

IV. FUTURE TRENDS

It is expected that MEMS (Micro Electro Mechanical Systems) components will make a breakthrough in the design of RF microsystems [19]. An application for such a technology is in the replacement of crystal-based oscillators. These type of components are hugely employed as reference frequency-generators in PLLs. However, and contrary to MEMS-type devices, crystal oscillators need huge areas, e.g., much bigger when compared with those used by the associated electronics (when it exist - inductances and capacitors are not included in this set). Thus, an additional and significant space must be provided in the surface of the PCB (Printed Circuit Board) with the consequence of an increase in the total production cost. Moreover, the accuracy and the stability of the output frequency of these oscillators are temperature dependant, thus, the error is multiplied by the PLL. If the reference frequency is $f_{ref2}=f_{ref}\times(1\pm\Delta f)$, the carrier frequency will be $f_{out2} = N.f_{ref2} = N.f_{ref} \pm N.f_{ref}.\Delta f = f_{out} \pm \Delta f_{out}$, where N is the division ratio of a PLL, f_{ref} [Hz] is the error-free reference frequency of a PLL, $\pm\Delta f$ [Hz] is the drift (above or below) in the reference frequency, f_{out} [Hz] is the error-free carrier frequency. A special concern must be taken in account, specially for high division ratios, N, and high reference frequencies, f_{ref} [Hz], in the PLL, because the overall drift (or propagated error) in the frequency at the output of the PLL, $\Delta f_{out} = N.f_{ref}.\Delta f$ [Hz], can be critical. Beyond the advantage to have a small area occupancy, MEMS resonators allows to make an accurate trimming in the frequency of oscillation. Moreover, the simple matter of fact this adjustment could be made in an electrically form constitutes an inexorable advantage over the Crystal oscillators [20]. Also, it is possible to compensate any drift in the oscillation frequency due to any variation in the temperature.

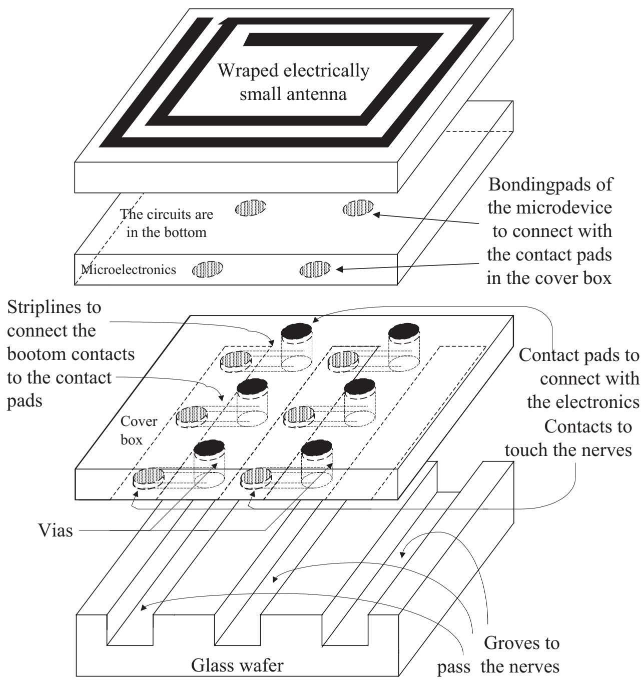


Figure 8: An artist impression of the complete wireless microsystem.

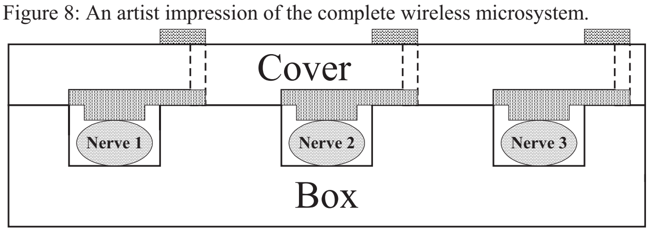


Figure 9: A side view of the complete electrostimulation part.

TABLE II: SKIN-DEPTH, δ[mm] AND LOSSES [dB] FOR δ AND FOR 20 cm.

Frequency	Skin-depth δ [mm]	Loss $L_1(\delta)$ [dB]	L_2(20 cm) [dB]
433 MHz [5]	18.0759 mm	4.3429	48.1
2.4 GHz [12]	5.0383 mm	4.3429	172.4
5.7 GHz [4]	2.2287 mm	4.3429	389.7

ACKNOWLEDGEMENTS

This work was sponsored by FCT/REEQ/379/EEI/2005.

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