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Wireless Instrumentation

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85.1 Introduction

Almost anyone knows that a measurement is the process of comparing a quantity with another one of the same type (e.g., length, volume, area) whose result is a number. Such a measurement can be done without ambiguities in a straightforward manner with the help of a measurement system, which requires specific instrumentation for achieving such task [1]. This instrumentation can be a simple instrument for directly measuring a physical quantity (e.g., a voltmeter for measuring an electrical potential difference between two points of a circuit, an ampere meter for measuring a current flowing in a branch of a circuit, a thermometer for measuring temperatures) and can take one of these following forms regarding their internal working and signal processing: analog or digital [2]. The ability to connect and communicate with external devices [3] (using dedicated cables and/or communication networks) as well as the inherent flexibility [4] (their easiness for adding new functions and/or reconfiguration of the existing ones) makes digital instruments have major potential for use in several fields of human activity (heavy industry, medicine, transportation systems, domestic, agriculture, and food industry are some application examples). The next evolutionary step of measurement instruments is integrating functions to provide wireless transfer of data. In this sequence of ideas, the developments of microelectronics and microsystems allowed engineers to successfully develop this new measuring method [5]. This resulted in new possibilities for measuring, acquiring, transferring, storing, and analyzing the physical world: embedded systems [6] and wireless sensors networks [7] are two new possibilities for achieving such a goal, with wireless being the *major attractive technology*. This leads to the wireless instrument concept, which by its nature requires multidisciplinary concepts such as measurement science, electronic circuits design, microelectronics and microsystems fabrication, wireless communication systems, and networking [8]. Figure 85.1 reinforces this idea by showing the different disciplines that must be employed for designing a wireless instrument. The primary focus of this chapter is the presentation and integration of these concepts. This chapter also presents biomedical applications based on wireless instruments and new application concepts.

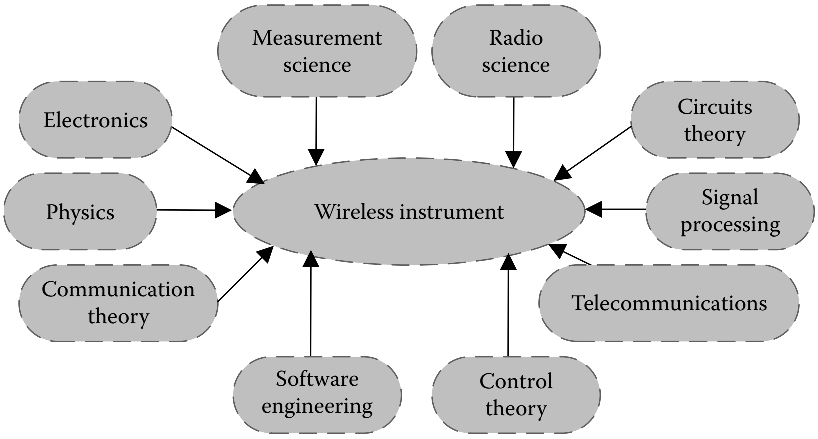


FIGURE 85.1 The multidisciplinary areas to take in account when designing a wireless instrument.

85.2 Instruments and Instrumentation

85.2.1 Measurement Systems

Figure 85.2 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 doesn't require any external sensor because this one is already embedded inside the measuring instrument, thus the sensing tips can directly touch the electrical potentials. In this context, it must be clarified that a sensor cannot be confused with a transducer, because the transducer can perform the same function as the sensor, but if the sensor is passive (e.g., a physical quantity-dependent resistor mounted in a Wheatstone bridge), then additional circuits must be provided for obtaining the signal from the sensor. This means that the set composed of the sensor and powering system makes a transducer, confirming that certain sensors are simultaneously transducers.

The core blocks can include electronics of control for acquisition from the transducer. 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 be done using wired buses (e.g., I²E bus [9], GPIB [10], RS232 [11,12], parallel ports [13], or even USB [14]) or wirelessly (e.g., IEEE 802.11 [15], ZigBee [16], Bluetooth [17], or using a customized solution [18]).

The core blocks of the measurement instruments can be analog or digital. Analog is the less versatile core because it requires the presence of a person to read the measurements. This type of instrument is very limited

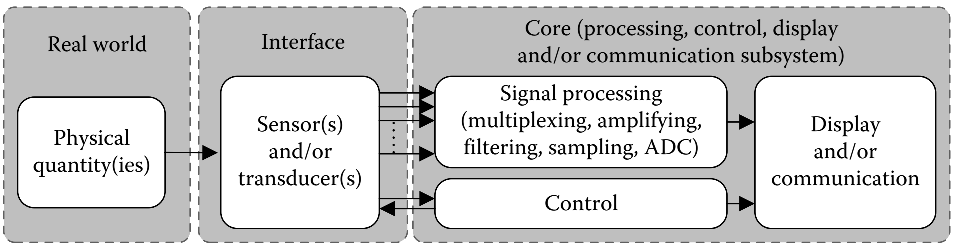


FIGURE 85.2 Block diagram of a generic measurement instrument.

and very difficult to adapt to a wide range of signals to measure. Furthermore, it is not possible to wirelessly send 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 in the conversion component used in the final processing stage, e.g., the sampler and the analog-to-digital converter (ADC) block. The inclusion of multiplexers enables the acquisition of multiple channels with a single measurement instrument. This topic will be the focus of discussion in the next section. 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 display system (e.g., a flat screen) or for remote transmission through a communication interface. This core also allows for changing and/or for programming the amplifier's gain, thus allowing adaptation to wide variations of physical quantities. The latest developments of microelectronics make available transducers with digital outputs (e.g., integrated monolithic temperature transducers [19], Hall effect magnetometers [20], and accelerometers [21], 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 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 [22] (for signal processing).

85.2.2 Multiplexing Structures

A multiplexing operation is required in measurement instruments for simultaneously acquiring more than one signal at once. The signal multiplexing is not a simple matter to treat. The first issue concerns the availability of a variety of multiplexing structures and the decision to select the most suitable. This poses tradeoff problems related to implementation costs (e.g., a more complex multiplexing system costs more) and specifications (e.g., a more general purpose instrument will be more complex and cost more). In the second place, it is mandatory to have a clear knowledge of the input characteristics. The most important issues are the input impedance, the dynamic range, the bandwidth, the balancing type of signals (e.g., single-ended or differential), power-supply interference rejection (e.g., 50 Hz in the Europe and 60 Hz in the United States), interference between input channels due to the multiplexer, and noise.

The multiplexing configuration can assume one of the following classifications: either low level or high level for analog or digital multiplexers, respectively.

The structure illustrated in the Figure 85.3 is the most simple. The signals at the outputs of transducers connect to an analog multiplexer (with single-ended or differential inputs). It is important to have a variable gain amplifier when transducers with different signals are used, in order to provide signals within the full dynamic range of inputs of the ADC. This structure poses significant restrictions for solving speed bottlenecks: First, the multiplexer must be fast enough for switching the different analog channels; in the second place, the bandwidth of the ADC and sample-and-hold (S/H) (which is actually a part of the ADC) circuits must be high enough to avoid distortion of the analog signals for conversion.

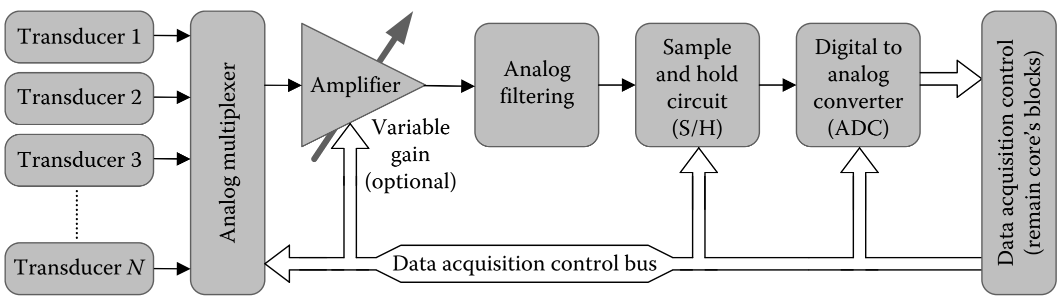


FIGURE 85.3 Low-level multiplexing configurations with shared amplifier.

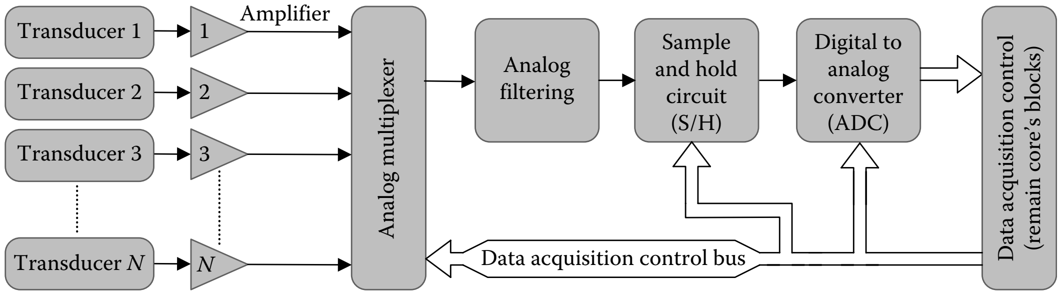


FIGURE 85.4 Low-level multiplexing configurations with dedicated amplifiers.

The low-level shared-amplifier configuration is less flexible in terms of plurality of physical quantities to measure; the ADC must be compatible with the transducer with the highest bandwidth; the direct acquisition of multiple signals can pose shielding problems because the transducers can be located very far away from each other. However, the low-level shared-amplifier configuration is the configuration with the highest potential for fabricating low-size electronic modules with high degree of integration (e.g., one multiplexer, one amplifier, one analog filter, one S/H plus ADC and control electronics).

The structure illustrated in the Figure 85.4 is very similar to that illustrated in Figure 85.3. The only exception is the use of transducers with associated amplifiers. These dedicated amplifiers guarantee signals with equal excursions to use the full dynamic range of the ADC. The bandwidth considerations are the same as those made in the previous multiplexing configuration. A high degree of integration is still possible to achieve with this configuration, but it sacrifices the compactness and low size due to the use of multiple amplifiers. Despite the acquisition of signals with equal amplitudes, the shielding problems remain in applications requiring transducers placed away from each other.

Low-level multiplexing configurations have a high integration potential, allowing the fabrication of wireless instruments with small sizes and low power consumption. However, the shared nature of the analog multiplexer makes them less than ideal. Nonidealities include the finite impedance of unselected analog channels, cross talk between channels, nonzero switching times between channels, and handling of different bandwidths between channels.

Figure 85.5 illustrates a high-level multiplexing configuration, providing a dedicated set of amplifiers, analog filters, S/H circuits, and ADCs for each transducer. After conversion to the digital domain,

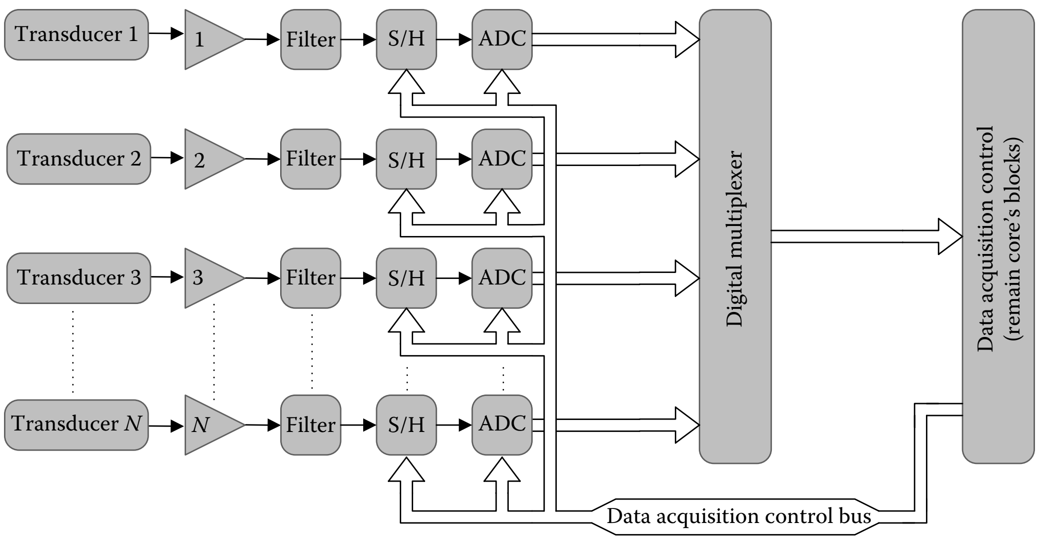


FIGURE 85.5 High-level multiplexing configuration.

the acquired physical measures are digitally multiplexed, avoiding the nonidealities of analog multiplexers. This configuration can pose integration restrictions by requiring circuits with increased sizes because each analog channel requires a dedicated signal-processing chain. However and despite these drawbacks, a high-level configuration is the most flexible of those analyzed because different amplifiers and filters can be provided for an extensive set of transducers. Moreover, this configuration offers the possibility to select the most suitable ADC for the respective analog chain. More important is the ability to accommodate channels with different sampling frequencies, since the switching speed of the analog multiplexer is not exceeded. This configuration also allows a variety of channel-selecting policies for desired channels with desired sampling frequencies.

85.2.3 Wireless Instruments and Communication Protocols

The design of a wireless instrument (as well as a generic measurement instrument) can't be done without taking in account the communication protocol. Table 85.1 shows the layer structure proposed by the OSI (Open Systems Interconnection) model [23].

Layer 1 specifies the modulation in conjunction with the line coding m (*codulation* [24]), the DC balancing, single-ended/differential-ended balancing.

Normally, layer 2 is divided in two sublayers, e.g., the medium access control (MAC) and the logic link control (LLC). The MAC sublayer is on bottom and defines mechanisms (or rules), in which a given transmitter is allowed (or not!) to access the physical medium for signal injection (corresponding to the data intended for the target receiver/s). The top LLC sublayer specifies the types of frames: data or control frames. This sublayer also provides a clear definition of frame formats in terms of their contents (their fields). Basically, the data frames are used to transport useful information in a field known as payload, while the other frames (e.g., the control frames) are used to make the transmitter know if the previous transmissions were received and processed by the receiver with or without errors. The control frames can also be used for performing flow control, in order to avoid data congestion in the receiver or across the network (with possible loss of data).

The network layer specifies a set of procedures for guaranteeing a reliable transmission between consecutive nodes along the network. Examples of procedures include the detection/correction of transmission errors and flow control. This layer also establishes the routing paths for the messages.

The transport layer ensures a reliable communication between terminals, e.g., between end-to-end users. This layer also provides error control procedures to verify the correct reception of all packets that form the messages (e.g., error-free packets). Another important procedure provided by the transport layer is grouping the packets in the correct sequence order to obtain a correct reassembled segment.

The session layer provides mechanisms for allowing the hosts to establish a communication. This layer also provides recovery mechanisms when an interruption occurs during the communication.

TABLE 85.1 Layers in the OSI Model

	Data Unity	Layer	Function
Host layers	Data	Application	Final communicating application
		Presentation	Data formatting and cryptography
		Session	Communication between hosts
	Segments	Transport	End-to-end communication reliability
Medium layers	Packets	Network	Node-to-node routing and communication reliability
	Frames	Data link	Physical identification (MAC and LLC sublayers)
	Bits	Physical	Signal transmission through the communication channel (*codulation*, other physical aspects of signals)

Source: Stallings, W., *Data and Computer Communications*, Prentice Hall, Englewood Cliffs, NJ, 2003.

The definition and conversion between data formats is done in the presentation layer. Normally, it is in this layer that the data are ciphered and/or converted to (and obviously converted from) the format used by the application.

The last layer (e.g., the application layer) provides interfaces between the application itself and between the protocol stack on the bottom.

Figure 85.6 provides a better understanding as how these concepts can be applied when designing a wireless instrument. This example helps to identify the blocks inside the wireless instrument that implement functions defined by the OSI model. This figure shows only the measurement part of the wireless instrument (e.g., the measurement instrument). The system is composed of the core measurement subset including the signal acquisition block, the signal-processing block, the control block, the memory block—a part of the control block—and the display control, which is actually optional in wireless instruments. Additionally and as previously stated, the interface block can be a part of the

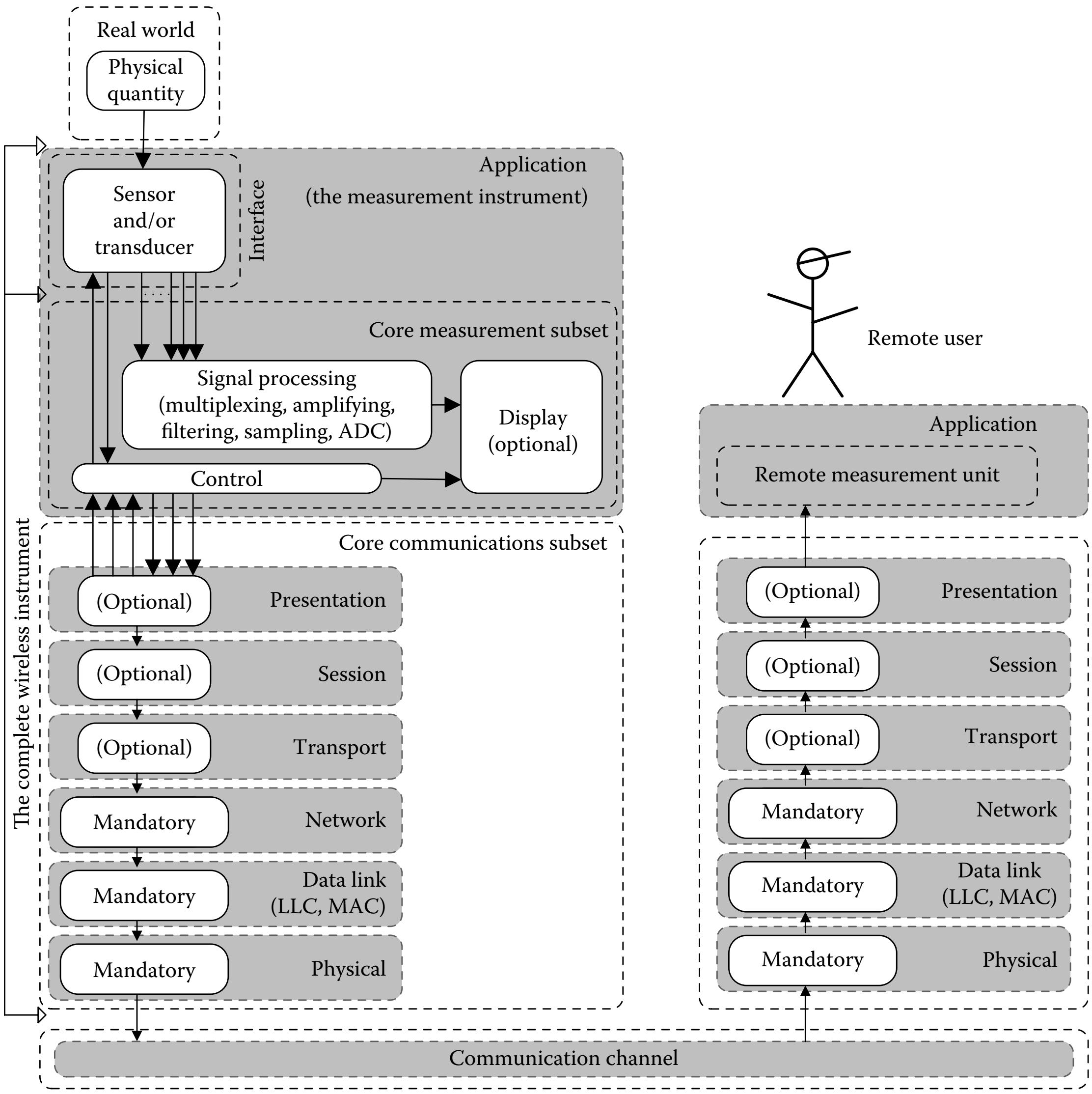


FIGURE 85.6 Relation between wireless instruments with the stacks of the OSI model.

measurement instrument. The remaining part of the wireless instrument is implemented by the core communication subset. This subset is responsible for communicating with external devices (other wireless instruments or with a central processing unit or even a remote measurement unit controlled by a remote user).

Normally and as shown in Figure 85.6, there are three optional functions inside a wireless instrument. This results from the need to simplify the transmission procedures in order to minimize the latencies (this is the case of the IEEE 802.15.4 that supports the low-level layers of the ZigBee protocol stack) and to maximize the data throughput.

The most common function of the network layer is the cyclic redundancy check (CRC) generation (by the wireless instrument on the transmitter side) and decoding (in the receiver side) for detecting transmission errors. It is possible to use forward error correction (FEC) schemes for error correcting but with the cost to send redundant bits for each bit of information (e.g., each bit of acquired data) and larger bit rates. In the case of auto-repeat request (ARQ) schemes, the CRC generation and decoding can be used by the receiver to do a request to the transmitter for retransmission of the erroneous packet.

The LLC sublayer functions can't be bypassed (or at least, a simple implementation must be provided) because at least a frame alignment word (or synchronization character) must be provided in the transmitter in order to allow the receiver to start the bits reception. The LLC implemented by Carmo et al. [18] uses a header composed of an alternate sequence (with a length equal to an integer multiple of eight) 1's and eight 0's for DC balance, while the remaining header contains a synchronization character with 8 bits (this complete header is used by both control and data frames).

The simpler way for implementing MAC sublayer functions is on point-to-point communications with only one transmitter and receiver. In this situation, the transmitter can send data without restrictions because the communication channel is always available and ready for use. Sophisticated MAC protocols are required for managing the medium access when the general scenario (with a multiplicity of transmitters and a multiplicity of receivers) is present. Silva et al. [25] proposes a MAC protocol for transmitting signals from transmitters placed on a multiplicity of paraplegic patients (doing hydrotherapy inside a swimming pool) into a base station, which stores the data for further analysis by a health professional. Note that the most common applications are based on simple point-to-point configurations as it is the case of the work done by Dias et al. [26], where a wireless instrument acquires EEG signals and transmits them to a base station connected to a personal computer for data logging. This solution uses wireless modules based on IEEE 802.15.4, but a solution based on a microcontroller with a simple radio frequency (RF) module could be used for reducing the latencies.

Taking into account the wired case (which can be directly transposed to the wireless case), the physical layer can be implemented by doing a direct connection between the transmitter and the receiver (e.g., connecting the transmitter's output to the receiver's input). A wireless instrument must provide at least one modulation scheme in order to reduce the errors introduced during the communication. A huge set of flexible wireless modules from third-party manufacturers ready for connection into the wireless instrument are available at low cost [27–30]. The modulation is an important issue in wireless instruments, but a coding scheme is recommended either for DC balancing or even for error control and for synchronization. In this context, the RF CMOS receiver at 433 MHz for integration in implantable devices found in [31] was designed taking in account the following *codulation* scheme: simultaneous on/off keying (OOK) modulation and biphase code [31]. Another example of physical layer definition is the RF transmitter proposed by Morais et al. [32] for operation at 433 MHz but with a different codulation scheme: OOK modulation and pulse-width modulation (PWM) code. This RF transmitter is compatible with the commercial receiver unit model LM RXAM2433 (from the manufacturer LPRS Inc.) and was tested with success for soil moisture measurements [33].

85.3 Technology for Wireless Systems

85.3.1 Operational Issues

The selection of the operation frequency is not an easy issue because different factors distinguish between them. In the first place, the dimensions of the antennas are imposed by the frequency. For an acceptable efficiency, the antenna size must be on the order of one-fourth of the wavelength, λ (m), which is given by $\lambda = c/f$ with $c = 3 \times 10^8$ m·s^{-1} being the speed of light in vacuum and f (Hz) the frequency of operation. Decreasing the dimension of an antenna implies the use of high frequencies. This issue can be solved by modulation. The most used modulations in wireless instruments (especially in laboratory environments, e.g., closed and relatively free of common band interference) are *amplitude-shift keying* (ASK), *phase-shift keying* (PSK), and *frequency-shift keying* (FSK). Both ASK and PSK need the same bandwidth given by BW = $2R_b$ (Hz), where R_b (bps) is the bit rate per second. The bandwidth required by FSK modulation is slightly higher and is BW = $2R_b + |f_1 - f_2|$, where $|f_1 - f_2|$ is the frequency shift between the two carriers, f_1 (Hz) and f_2 (Hz). The bit error probability (BEP) of each modulation can be found in Table 85.2, and the plots of their respective values as a function of the ratio E_b/N_0 are shown in Figure 85.7. The ratio E_b/N_0

TABLE 85.2 BEP for the Modulations ASK, PSK, and FSK

Modulation	BEP	
ASK with coherent detection	$Q\left(\sqrt{\frac{E_b}{N_0}}\right)$	$Q\left(\sqrt{\frac{S}{N}}\right)$
ASK with noncoherent detection	$\frac{1}{2}e^{-(1/2)\times(E_b/N_0)}, \left(\frac{E_b}{N_0}\right) > \frac{1}{4}$	$\frac{1}{2}e^{-(S/N)}, \left(\frac{S}{N}\right) > \frac{1}{8}$
PSK	$Q\left(\sqrt{2 \times \frac{E_b}{N_0}}\right)$	$Q\left(\sqrt{2} \times \sqrt{\frac{S}{N}}\right)$
FSK	$Q\left(\sqrt{\frac{E_b}{N_0}}\right)$	$Q\left(\sqrt{1 + \frac{\lvert f_1 - f_2 \rvert}{4r_b}} \times \sqrt{\frac{S}{N}}\right)$

Source: Couch II, L.W., *Digital and Analog Communication Systems*, 5th edn., Prentice Hall, Englewood Cliffs, NJ, 1996.

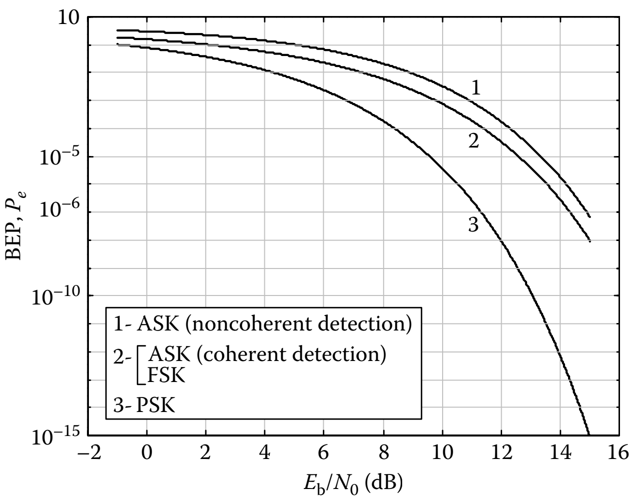


FIGURE 85.7 BEP versus the E_b/N_0 (dB) ratio for the modulations ASK, PSK, and FSK.

is the energy per bit, E_b (J), divided by the spectral density of the noise (additive white Gaussian noise), N_0 (W), which is given by [34]:

$$\frac{E_b}{N_0} = \frac{S/r_b}{N/\mathrm{BW}} = \left(\frac{S}{N}\right) \times \frac{\mathrm{BW}}{r_b} \tag{85.1}$$

where $N = N_0\mathrm{BW}$ (W) is the filtered noise at the output of a band-pass filter BW (Hz).

The selection of the frequency taking only in account the bit rate and antenna size isn't enough because as it is general knowledge, the antenna is perhaps the most critical subsystem in wireless communications. This imposes an antenna small enough for integration with the transmitter but not so small as to compromise this same miniaturization. The size reduction can be a problem because the antenna must be designed for transferring the highest possible power to the receiver. In this context, the size shortening of antennas can introduce additional problems of impedance matching [35] that must be solved. Wafer-level packaging (WLP) techniques can be used for overcoming these problems [36].

The communication range is another issue to take in account when selecting the frequency. This is related to the attenuation of RF signals, whose free-space value increases with transmitter/receiver distance, d (m), and frequency, f (Hz) [37]:

$$L_f(d,f) = -20\log_{10}(d) - 20\log_{10}(f) + K_f(\mathrm{dB}) \tag{85.2}$$

with $K_f = -20\log_{10}[c/(4\pi)]$ (dB). This means that for a simultaneously given transmitted power, P_t (dB), and receiver sensitivity, S_r (dB), the frequency is limited by the range, d_{max} (m):

$$f \le 10^{\frac{(P_t - S_r) - 20\log_{10}(4\pi d_{max})}{20}} \ (\mathrm{Hz}) \tag{85.3}$$

The free-space model is the most optimistic approach for calculating the link budget because the additional losses due to the surrounding environment (lossy propagation mediums, buildings, terrain conditions, vehicles, persons, shadowing, systemic implementations, among other factors) is not taken in account. Therefore, a general loss model must be used [37]:

$$l(d) = \alpha.c^{-n} + \chi, \quad n \ge 2 \text{ and } \alpha < 1 \tag{85.4}$$

Alternatively, $L(d) = -10n\ \log_{10}(d) + 10\log_{10}(\alpha) + \chi_{dB} = A\ \log_{10}(d) + B + \chi_{dB}$ (dB). The factor $A = -10n$ is very important to analyze because it justifies why the distance dependence loss is higher than that observed in free space. The signal fluctuations (also known as fading) don't contribute statically to the loss but dynamically. This dynamic behavior can impose severe restrictions when designing a wireless link because a super dimensioned RF receiver must be provided to overcome the temporary losses of signal power. The distance-dependent loss model is normally enough to predict the link budget especially for short distances (typically under 20 m) and closed spaces (laboratories, hospitals, residences, trains, among others). Very good references can be found in [38–40] to deal with the fading.

Figure 85.8 shows the available frequency bands for the different technologies used in wireless communications. Suitable frequencies for possible use in wireless instruments are those belonging to the so-called ISM band (industrial, scientific, and medical), due to its unregulated usage. These frequencies can be freely used without being subject to standardization but keeping the emission power below the maximum levels imposed by regulations. This usage flexibility leads to widespread new applications as will be discussed further.

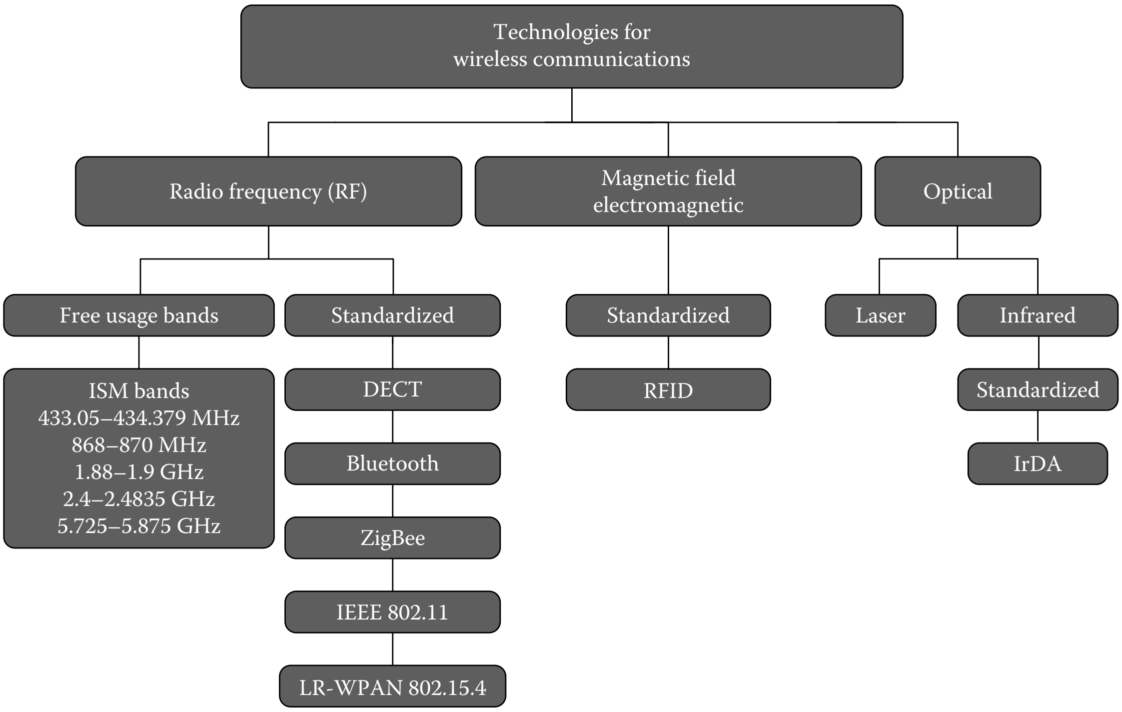


FIGURE 85.8 Currently available frequencies for wireless applications.

85.3.2 RF Interfaces and Examples

A wireless instrument communicates with the external world by RF. Thus, a wireless interface must be provided for allowing RF communications. Figure 85.9 shows a generic schematic block of a wireless microsystem performing functions of a stand-alone wireless instrument. These microsystems are composed of transducers and other electronic components for control and signal processing, by memory and by an RF interface (the RF transceiver) for connecting to an associated antenna. The dimensions of the RF transceiver must be comparable with other elements integrated in the microsystem (e.g., the transducers and remaining 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 remaining electronics allow engineers to design a wide number of devices for a 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

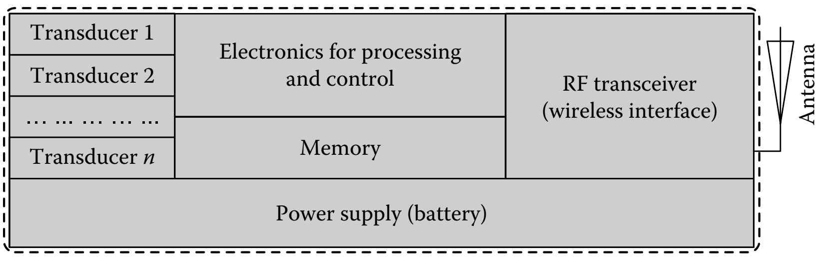


FIGURE 85.9 Generic microsystem architecture connected to an associated antenna.

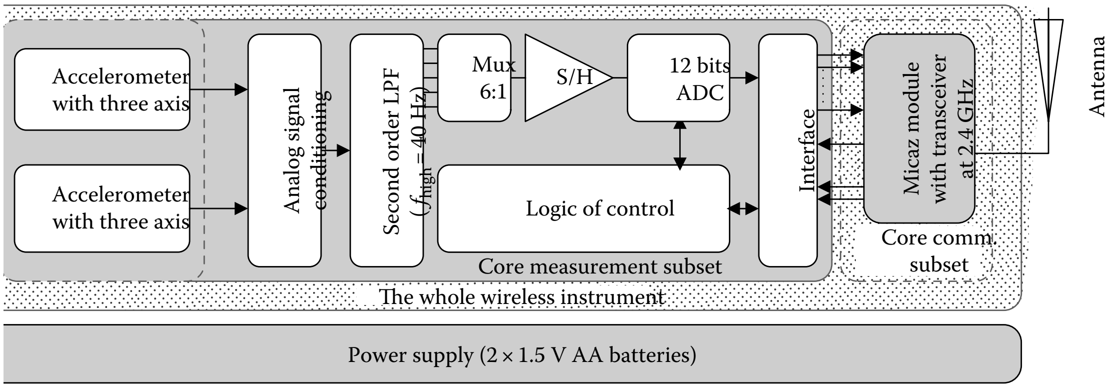


FIGURE 85.10 Block diagram of a wireless instrument at 2.4 GHz ISM band for monitoring the body movements of individuals.

wireless microsystems for use in wireless instruments. In this section, a few examples for each of the ISM bands in Figure 85.8 are presented for a better view of wireless instrument's potential.

85.3.2.1 Monitoring Body Movement

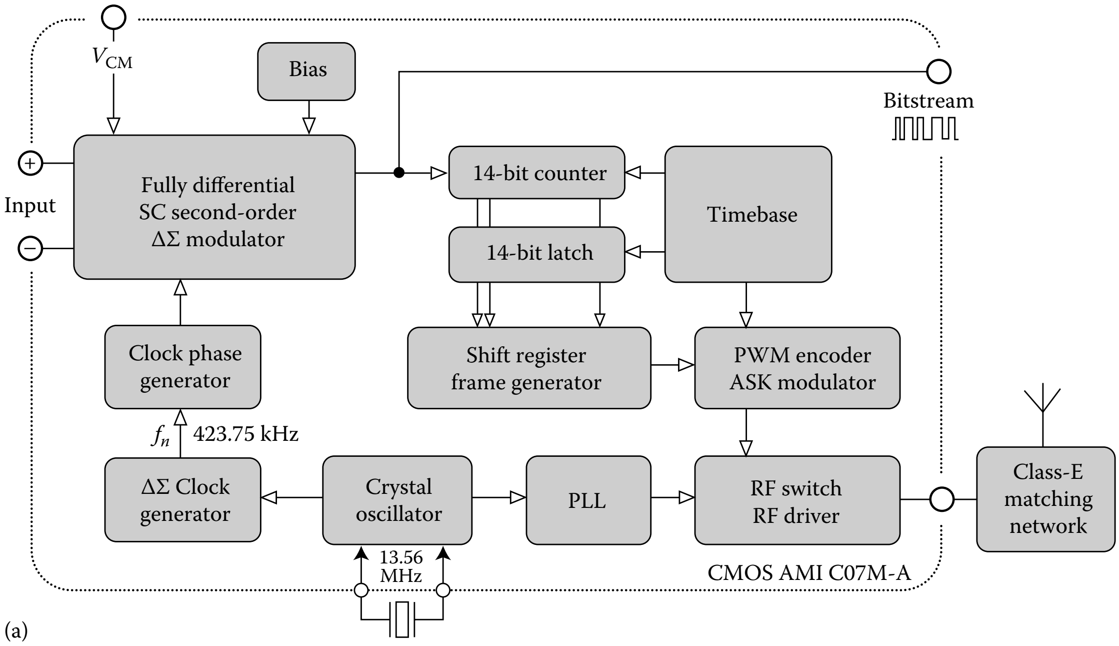
Figure 85.10 shows the block diagram of a wireless instrument for monitoring the body movements of individuals during hydrotherapy [41]. This wireless instrument is modular and is composed of a module with two MEMS accelerometers with three degrees of freedom (with three axes), a module with low-level multiplexing for signal processing and analog-to-digital conversion, and a third-party RF module (with a RF transceiver at 2.4 GHz and control electronics). The analog electronics in the core measurement subset is controlled by the core communications subset. The core communications subset is a Micaz RF module at 2.4 GHz (fabricated by the Crossbow company) for communicating with external devices and for controlling and managing the data acquisition process [42]. The accelerometers module was designed for measuring the movements of the individuals by obtaining information about the instantaneous roll, yaw, and pitch. This wireless instrument was designed for low-power and high-throughput communications using a specific MAC protocol for achieving such goals [43].

85.3.2.2 Connecting to Transducers

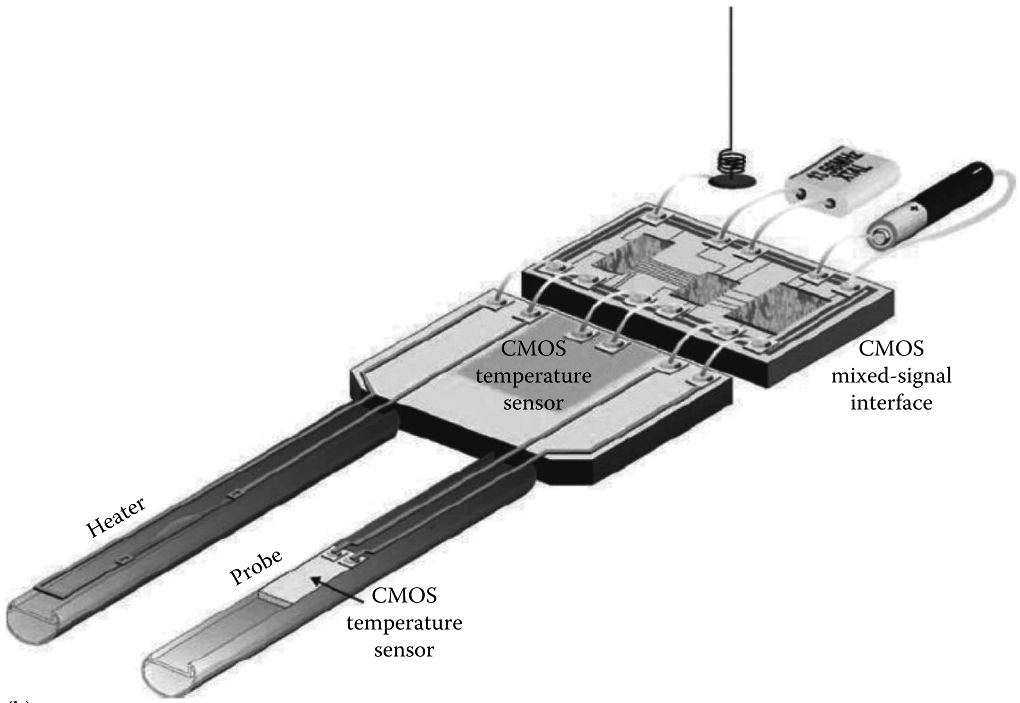
Figure 85.11 illustrates the block diagram of a sensor RF interface for operation at 433 MHz [32]. This RF interface has a differential (instrumentation) analog input for interference reduction purposes and allows the connection of other types of transducers. The analog-to-digital conversion is done by ΣΔ modulator for coding the input analog signals, whose result is a bitstream for encapsulation in a frame for RF transmission. As stated by Morais et al. [32], this interface was especially designed for connecting into the soil moisture transducer developed by Valente et al. [33]. The wireless instrument illustrated in Figure 85.11b was developed for measuring the soil moisture of greenhouses and uses the latter RF interface to send the acquired data to an external storing and/or analyzing unit.

85.3.2.3 Implantable Systems

Figure 85.12a shows the block diagram of a receiver for operation in the 433 MHz ISM band that was developed for use in implantable microsystems [31]. The selected architecture explores the superregeneration 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 modulation combined with a variation of the Manchester code (e.g., a biphase code). The AMIS 0.7 μm CMOS process was selected for targeting the requirement to fabricate a low-cost receiver. Figure 85.12b shows a photograph of the first prototype (shaded area), which was integrated in a die with an area of 5 × 5 mm^2. An advantage of this receiver is being fully compatible with commercial



(a)



(b)

FIGURE 85.11 (a) The block diagram of a sensor interface for operation in the 433 MHz ISM band. (Reproduced from *J. Sens. Actuat. A*, 115, R. Morais, A. Valente, C. Couto, and J. H. Correia, A wireless RF CMOS mixed-signal interface for soil moisture measurements, 376–384, Copyright (2004), with permission from Elsevier.) and (b) a wireless instrument composed by the latter RF interface mounted in a soil moisture transducer for utilization in greenhouse environments. (Reproduced from *J. Sens. Actuat. A*, 115, A. Valente, R. Morais, C. Couto, and J. H. Correia, Modeling, simulation and testing of a silicon soil moisture sensor based on the dual-probe heat-pulse method, 434–439, Copyright (2004), with permission from Elsevier.)

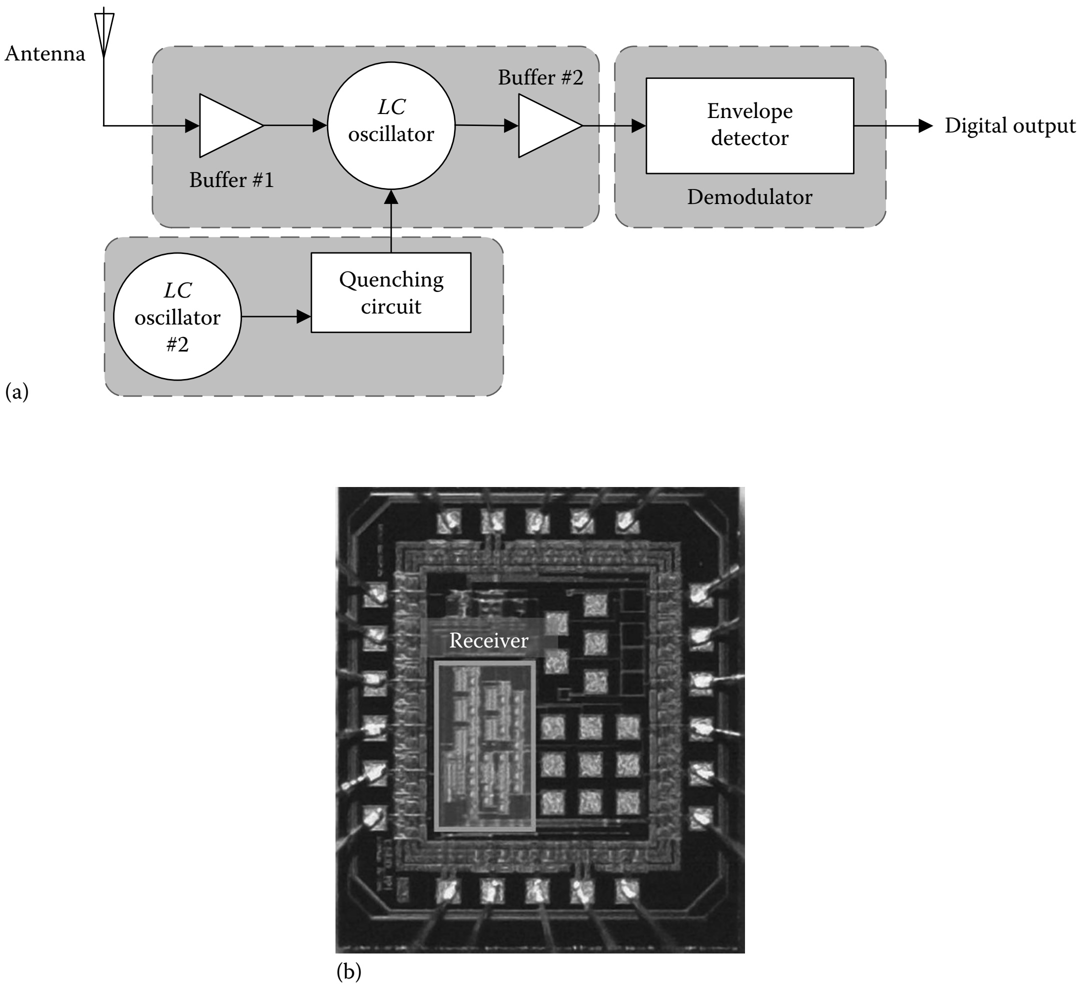


FIGURE 85.12 (a) The block diagram of the superregenerative receiver at 433 MHz and (b) a die photograph containing the first prototype of the superregenerative receiver (the rectangular area under the word Receiver). (Reproduced from *Microelectron. J.*, 42, J. P. Carmo, J. C. Ribeiro, P. M. Mendes, and J. H. Correia, Super regenerative receiver at 433 MHz, 681–687, Copyright (2011), with permission from Elsevier.)

transmitters and the transmitter fabricated by Morais et al. [32], for the same coding scheme (the variation of the Manchester code) in the transmitter.

85.3.3 Power Consumption

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 for the total power consumption, when compared with the whole electronics in the instrument [44]. Furthermore and despite the spreading of microelectronics fabrication processes with the potential to achieve smaller power consumption, the RF transceiver is irremediably the subsystem of higher power consumption [45,46]. This demands the integrated definition of architectures and methods of control, as well as provides means to predict the power consumption of the RF system. Figure 85.13a shows an RF CMOS transceiver at 2.4 GHz that allows the implementation of control actions for optimizing the power consumption [23,47]. This RF CMOS transceiver was fabricated in a standard 0.18 μm CMOS process for achieving low power consumption with

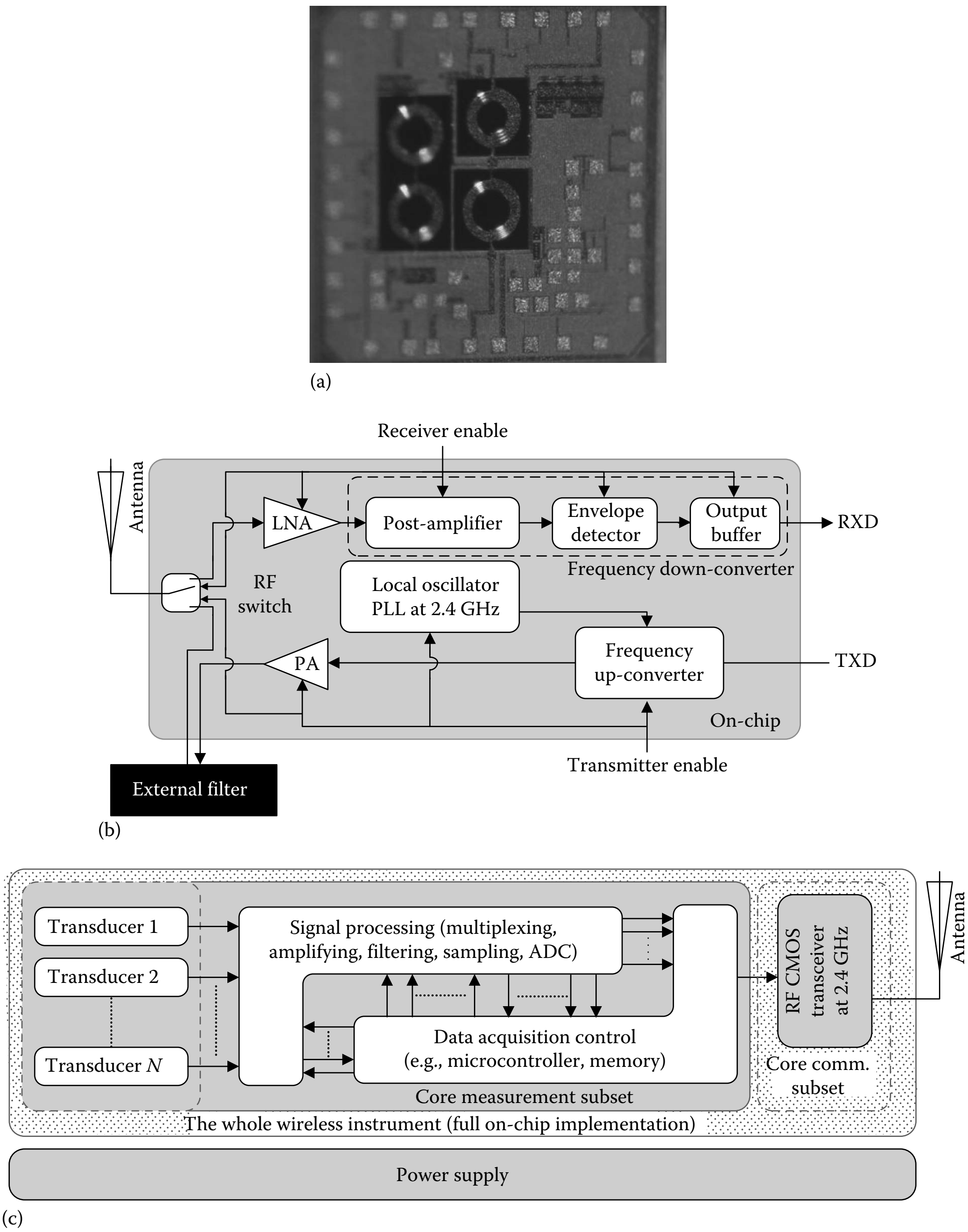


FIGURE 85.13 (a) Photograph and (b) block schematic of a RF CMOS transceiver at 2.4 GHz especially designed for stand-alone wireless instruments in biomedical applications. (c) A schematic illustrating the integration concept of the RF CMOS transceiver, transducers, and electronics in the same microsystem.

a low-voltage supply. As illustrated in Figure 85.13b, the design of this RF CMOS transceiver predicted the use of a control signal to either select the transmitter or the receiver in order to allow its integration with electronics to perform custom control, Figure 85.13c.

It is possible to explore the band located between the 5.7 and 5.89 GHz for implementing wireless instruments [48]. This band permits the fabrication of antennas, whose small dimensions allows their integration with the electronics using WLP techniques [36]. 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 unit. The work presented in [49] takes all of this into account to provide a low-power/low-voltage wireless interface at 5.7 GHz with dry electrodes for implementing wireless instruments as parts of cognitive networks. Figure 85.14a shows a photograph of the wireless interface measuring of 1.5 × 1.5 mm. The schematic illustrated in the Figure 85.14b 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 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 low power consumption using a 0.18 μm CMOS process is in [50]. This microdevice is composed of an RF transceiver, a reduced instruction set computer (RISC) microcontroller, a random access memory (RAM),

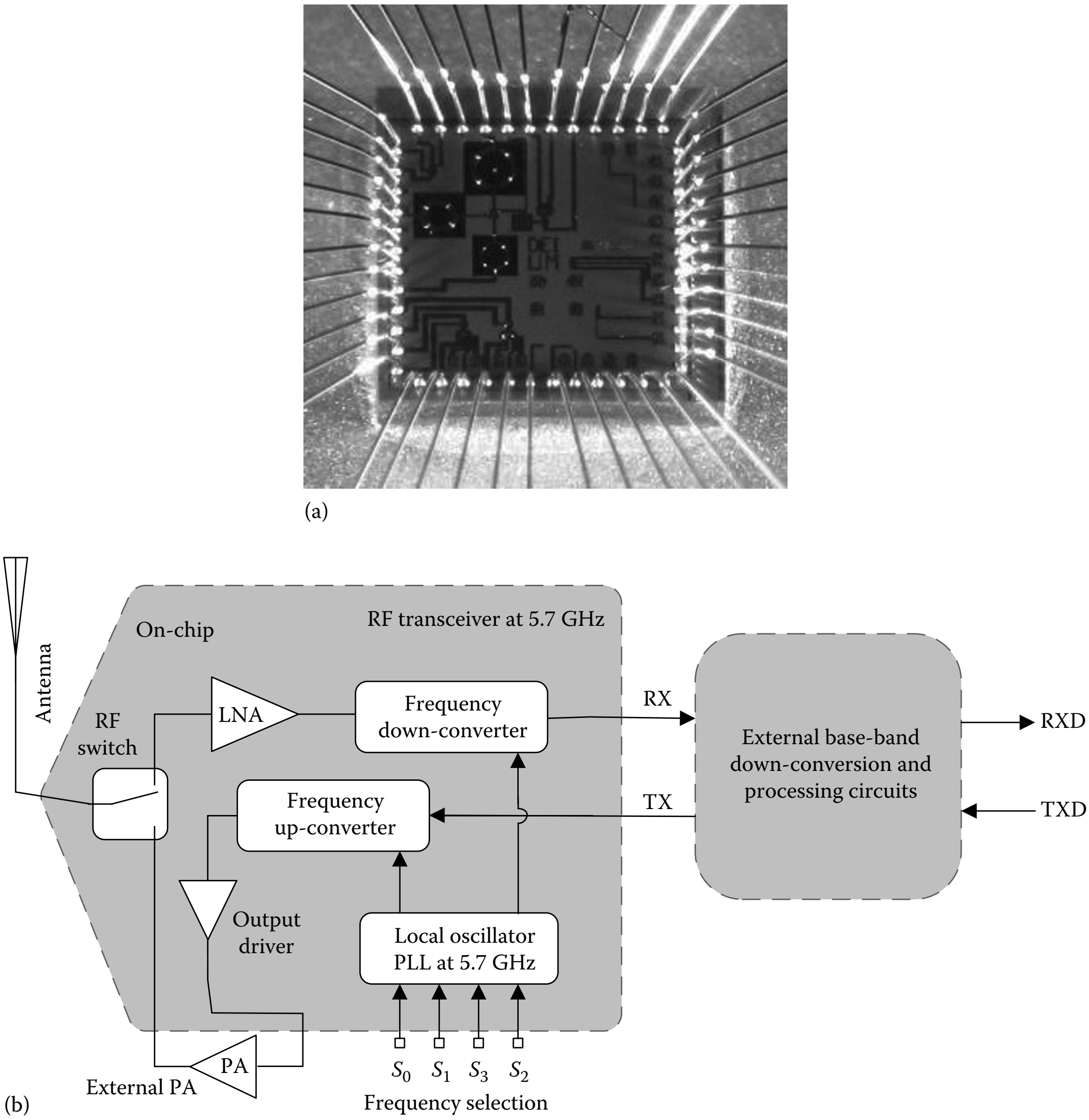


FIGURE 85.14 For the frequency of 5.7 GHz: (a) photograph and (b) schematic block of the RF part of a wireless interface at 5.7 GHz.

a power-supply management circuit, analog electronics of signal conditioning and analog-to-digital conversion (ADC), and 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 to the authors, this protocol working together with their RF transceiver achieves power consumptions thirty times smaller than those obtained with the IEEE 802.15.4 (which defines OSI layers 1 and 2 functions). Furthermore, the operation frequency can be selected from 433 to 868 MHz, as well as either with the OOK modulation or the FSK modulation. According to [50], their RF transceiver has a receiver power of 2.5 mW and a transmit power of 39 mW.

85.3.4 Networks of Wireless Instruments

A wireless sensors network can be considered a network of wireless instruments whose sensor nodes are the wireless instruments itself. The stand-alone operation without the need of a human operator for doing maintenance and/or for replacing the batteries (that provide the supply of power) are the main differences of these kind of wireless network compared to conventional networks. In this sequence and as illustrated in Figure 85.15, a wireless sensors network can be considered a distributed sensor network constituted by a high density of nodes. It is expected for each node to run simple protocols and provide low data rates in order to keep power consumption below reasonable levels. These issues are of major interest especially for nodes powered by batteries and without energy-harvesting capabilities because their useful life will be limited by the remaining charge.

In a wireless sensors network, each node acquires the physical data from the sensors and transmits by RF these same data toward a base station for storing and further analysis. The adjacent sensorial nodes can be used for storing the information and relaying into the base station, when the establishment of an RF link between a given sensor node and the base station is not possible. The information of a hidden node (with relation to the base station) is not lost because it can be relayed across the distributed infrastructure that forms the network of wireless sensors. However, their distributed nature and the nonexistence of a central controller imply the development of complex algorithms to deal with the multiplicity of nodes. This is especially true, when the topology of the network changes due to the malfunction of a node and/or when a new node is placed in the network or even when the existent nodes occupy new physical positions [51]. Moreover and contrary to what happens on wired networks, this type of network brings new problems: propagation aspects of RF signals and power-supply issues. The shared nature of the propagation medium is another problem because this makes the signals vulnerable to interference and multiple paths (fading), especially for mobile nodes and when a wide number of surrounding obstacles are present [52]. The shared medium also introduces problems related to the security and confidentiality of the data.

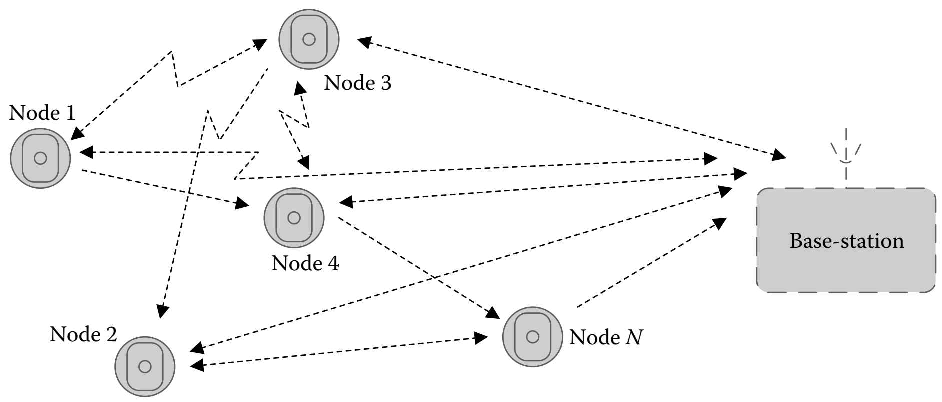


FIGURE 85.15 A schematic illustrating the wireless sensors network concept.

The increased application potential of wireless sensors networks in several fields of the human society (such as industrial, biomedical, transportation, domestic, and energy fields, among others) resulted in the need of their standardization as well as in their wide acceptance. Historically, the first wireless networks were mere technologic extensions of IEEE 802 local networks. Basically, the target of the local wireless networks was the interconnection of computers (as it was a common wired network). With time, other wireless networks appeared such as Bluetooth for connecting computers to their peripherals and IEEE 802.15.4 for wireless sensors networks. The IEEE 802.11 and the Bluetooth protocols are very difficult, complex, and, thus, with the potential to require devices with high power consumption. These are the reasons that made these protocols not suitable for wireless sensors networks but only for point-to-point connections. In this context, the need of protocols with low power consumption and simple procedures resulted in the establishment of the IEEE 802.15 workgroup. The joint actions developed by this workgroup resulted in the proposal of three different classes of wireless operation. The focus of the first class of operation targeted bit rates, whereas the second targeted power consumption, while the third class was more concerned with the quality of service (QoS). The need of protocols for low-power devices resulted in the proposition of the IEEE 802.15.4, as a basic set of rules for application in wireless sensors networks. The IEEE 802.15.4 protocol was developed for low-complexity applications and distances up to 10 m, allowing bit rates up to 250 kbps. Furthermore, the IEEE 802.15.4 protocol was proposed for a wide range of uses, ranging from consumer electronics, industrial and domestic automation, personal healthcare, and interconnection of computer peripherals. The IEEE 802.15.4 protocol defines two lower OSI layer functions. Figure 85.16 shows two versions of the physical layer of the IEEE 802.15.4 protocol [53].

The first version of the physical layer uses 868 MHz in Europe or 915 MHz in the United States. The European version permits only one RF channel for transmitting the maximum bit rate of 20 kbps, whereas the U.S. version allows the use of 10 simultaneous channels spaced by 2 MHz and a maximum bit rate of 40 kbps per channel. The second version of physical layers uses the 2.4 GHz band and supports the use of 16 simultaneous channels spaced by 5 MHz and a maximum bit rate of 250 kbps per channel. Table 85.3 shows that the IEEE 802.15.4 protocol uses spread spectrum techniques for increasing the resilience against a variety of factors that include interference from other radio stations and fading resulting from a multiplicity of radiowave paths. The spread spectrum techniques also ease the clock synchronization task in the receiver. These modulations belong to the constant amplitude modulations group and are very complex to implement because analog products in four quadrants are required. Fortunately, the RF *transceiver* CC2420 from the Chipcon company [54] is commercially available.

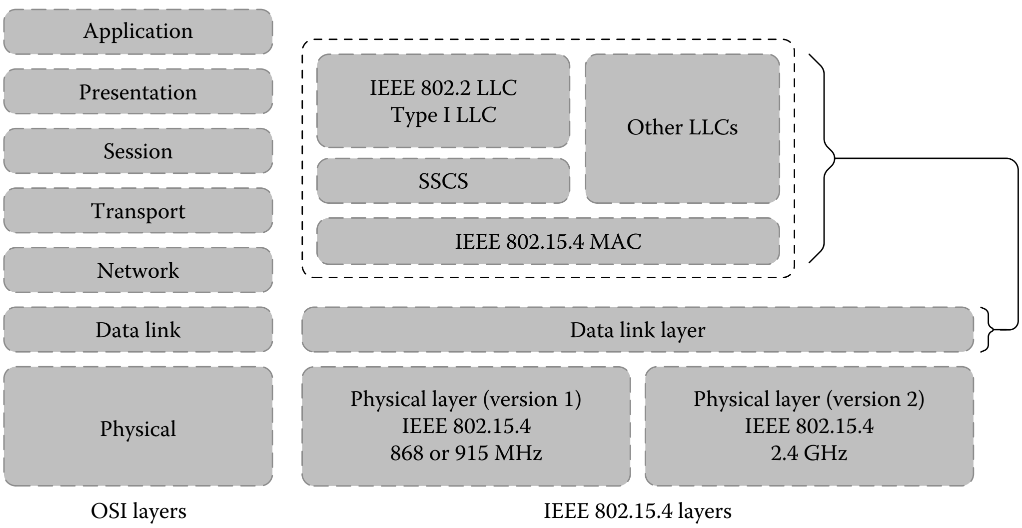


FIGURE 85.16 The OSI layer functions can be found in the IEEE 802.15.4 protocol.

TABLE 85.3 The Main Characteristics of the Physical Layer of the IEEE 802.15.4 Protocol

Band	Frequencies	Bit Rate (kbps)	Symbol Rate (ksymbols/s)	Spreading Parameters	
				Modulation	Chip Rate
868 MHz	868–868.6 MHz	20	20	BPSK	300 kchips/s
915 MHz	902–928 MHz	40	40	BPSK	600 kchips/s
2.4 GHz	2.4–2.4835 GHz	250	62.5	O-QPSK	2 Mchips/s

This RF transceiver contains a core ready for implementing all the IEEE 802.15.4 functions (naturally, the second version of the physical layer) and consumes only 19.7 mW when operating in the receiving mode as well as 17.4 mW when operating in the transmitting mode.

The IEEE 802.15.4 also defines data link layer standardized protocols (e.g., MAC and LLC). In this context, the LLC sublayer of the IEEE 802.15.4 uses the same type I LLC frame formats and procedures specified by the standard IEEE 802.2. The main difference between those used by local area networks and those used by wireless sensors networks is the adopted MAC sublayer. The MAC sublayer adopted by the IEEE 802.15.4 (e.g., the IEEE 802.15.4 MAC) is closer in hardware than the ordinary MACs adopted for local area networks. The service-specific convergence sublayer (SSCS) allows the adoption of other proprietary LLCs as an alternative to this one defined by the IEEE 802.2 (e.g., the type I LLC). The purpose of this model is to allow the IEEE 802.15.4 MAC to implement medium access mechanisms not defined in the IEEE 802.2 [53]. The structure of the MAC sublayer frames is flexible enough to allow the deployment of networks with a wide range of topologies and applications. Typically, an IEEE 802.15.4 MAC frame contains the following fields: a control field to indicate its type, a sequence field to indicate the number of frames for transmission, two fields with receiver and sender addresses information, a field with the information itself (designated as payload), and a field for data integrity check (e.g., the CRC for transmission errors verification).

Figure 85.17 shows that the ZigBee protocol is an extension of the IEEE 802.15.4 protocol. ZigBee uses the IEEE 802.15.4 protocol to implement the physical and data link layer functions. Furthermore, ZigBee supports a wider range of high-level functionalities (not present in the IEEE 802.15.4, which is closer to the hardware) as used in cryptography, management policies in environments with multiple users, as well as error control [53]. CC2430 is another integrated circuit fabricated by the Chipcon company [55] that eases the task of implementing ZigBee networks. CC2430 contains internally an RF transceiver and an additional core for implementing the ZigBee high-level functions. The RF part of CC2430 consumes 21 mW in the receiving mode and 30 mW in the transmitting mode. The CC2430 is at this date the first

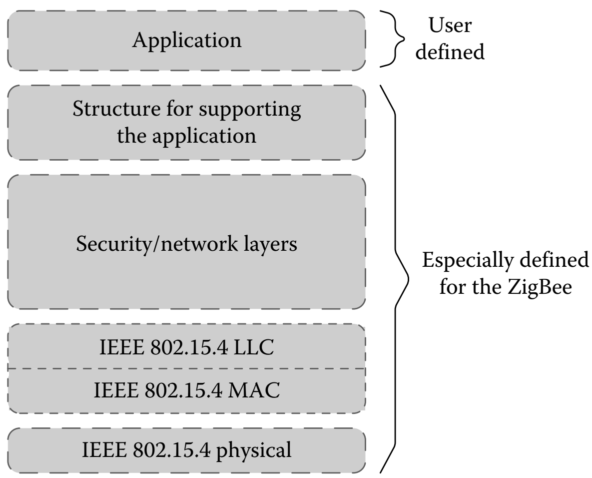


FIGURE 85.17 Adopted layers from the OSI model for use by ZigBee.

integrated circuit to offer a full ZigBee solution for the market. This integrated circuit has flash memory up to 128, 8 kbytes of RAM, an SPI interface, and a few pins for connecting analog and digital signals.

The ZigBee protocol was defined in response to the increased demand for wireless sensors by industry and the need for new personal applications. Thus, ZigBee allows fast prototyping of wireless sensors networks. A wide number of solutions are possible for wireless sensors networks. A few companies (that include Crossbow [42], Dust Networks [56], and Sensicast Systems [57]) offer products such as radios (motes) and sensor interfaces. The motes are battery-powered devices that run specific software. In addition to running the software networking stack, each mote is easily customized and programmed, since it runs open-source operating systems that provide low-level event and task management. Mote processor/radio module families working at 2.4 GHz ISM band that support IEEE 802.15.4 and ZigBee are available from the Crossbow company.

However, despite the inherent ease of the solutions based on motes, they can be very expensive when full custom network prototypes are required. The wireless sensors network solution found in [18] uses microcontrollers PIC from the Microchip company to meet a wide range of small volume applications with a low cost and in a ready to use fashion. Their solution uses a PIC microcontroller to provide the basic services of communication and control. Thanks to the serial connection of ADC chains, this solution is scalable in the sense that is possible to expand the number of attached transducers. The main drawback is that the maximum sampling frequency is limited by the number of transducers: the maximum sampling frequency per transducer is limited to f_S/N (Hz), where f_S (Hz) is the maximum sampling frequency when only one transducer is present and N is the number of transducers. To finish, the reprogramming of the microcontroller increases the functionalities to yield new services of nodes.

85.4 Biomedical Applications

85.4.1 COTS and Customized Applications

Biomedical applications have a high potential for using wireless instruments. An example that confirms this statement is the wireless monitoring systems of human body information as a growing field. A body area network comprises smart sensors able to communicate wirelessly to a base station.

An example of these applications is the wireless electroencephalogram (EEG), which is expected to provide a breakthrough in monitoring, diagnostics, and treatment of patients with neural diseases. Wireless EEG modules composed of the neural electrodes, processing electronics, and a RF transceiver with an associated antenna will be an important breakthrough in EEG diagnostics. Two approaches can be used for implementing wireless EEG systems: commercial off-the-shelf (COTS) and customized solutions. A COTS solution uses discrete integrated circuits and passive components for making wireless instruments, whereas a customized solution is designed from the scratch and further integrated on a single microdevice in order to optimize the size and power consumption and allow a power supply with small batteries (e.g., class AA, coin-sized batteries). The system proposed by Dias et al. [58] is an example of a COTS system for acquiring EEG signals and transmission by RF. This wireless EEG system uses a Micaz module [42] at 2.4 GHz for RF transmission and for controlling and converting the physical data. This system uses two 1.5 V class AA batteries for power supply and achieves maximum bit rates of 120 kbps. Other features of this system include 4 μV resolution, 15 mW power consumption, five single-ended channels, and size of 5.7 × 4.8 × 2.0 cm. Figure 85.18 shows the acquisition part of this wireless EEG system. A reference voltage must be added to the acquired signals before the analog-to-digital conversion because negative potentials are not provided by the power supply (the batteries can provide the following electrical potentials: ground, V_{dd}, and $V_{dd}/2$). Further explanations of this analog circuit (especially for the necessity of neutral and signal ground, SGND, electrodes) can be obtained in [59].

Customized solutions require the development of dedicated microelectronic systems or at least dedicated application-specific integrated circuits (ASICs). The wireless EEG system proposed by Yazicioglu

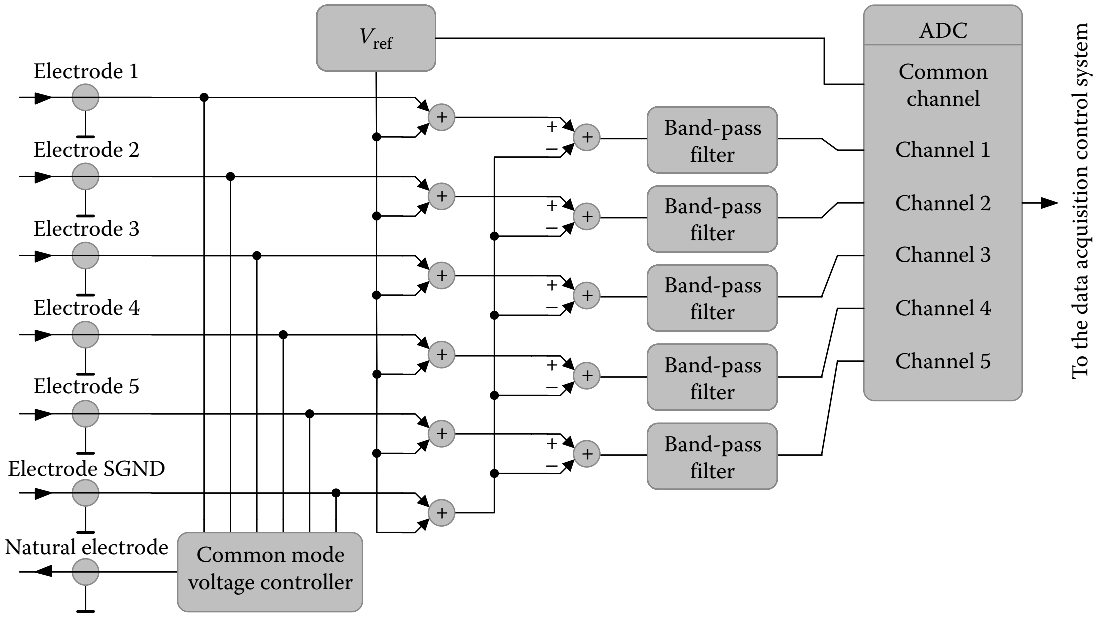


FIGURE 85.18 The analog signal-processing part found in. (From Dias, N.S. et al., A wireless system for bio-potential acquisition: An approach for non-invasive brain-computer interface, *Proceedings of IEEE International Symposium on Industrial Electronics—ISIE 2007*, Vigo, Spain, pp. 2709–2712, June 4–7, 2007.)

et al. [60] pushes further the concept of wireless EEG, by using the heat of human body for powering the whole wireless instrument itself. Their wireless EEG system uses a thermoelectric generator to convert the temperature differences between the environment (the coldest side, at temperature T_c [K]) and the forehead of the subject (the hottest side, at temperature T_h [K]) [60]. The output voltage depends on the Seebeck effect [61] temperature difference $\Delta T = T_h - T_c$ (K). This wireless EEG system can acquire signals from eight EEG channels, whose inputs are differential (instrumentation) for noise and interference reduction. Each channel uses a new concept developed by them and known as AC-coupled chopper-stabilized instrumentation amplification (ACCIA) for achieving high common-mode rejection ratio (CMRR) and at the same time eliminating the flicker noise of the transistors as well as for filtering the differential DC voltage generated between two EEG electrodes [60]. A dedicated ASIC was developed for achieving a complete readout front end for the eight EEG channels, and thanks to it, the complete wireless EEG module mounted with the RF front end and with a backup lithium battery occupies a volume of 1 cm^3.

Another example of customized solution is the Sensium TZ1030 sensor interface illustrated in Figure 85.19a [62]. The Sensium TZ1030 sensor interface was developed by Toumaz Technology Limited Company for operation in the following bands: 863–870 MHz in Europe and 902–928 MHz in the United States. Internally, the TZ1030 is composed of analog and digital electronics for interfacing and calibrating the sensors. The sensors are external to the TZ1030 and can attach directly to it. An RF transceiver, an 8051 compatible microcontroller, RAM, and flash memories are also provided and make the TZ1030 a compact solution for an easy placement on the subject's body. The control software contains procedures for local processing of the information, in order to reduce the amount of information and the total transmission times. These features make the TZ1030 a low power consumption solution. Together with an appropriate external sensor, the TZ1030 is ready for acquiring electrocardiograms (ECGs), temperature, glucose levels, and oxygen levels in the blood. Figure 85.19b illustrates a possible architecture for rapid development of wireless body area networks (BANs), offering the possibility.

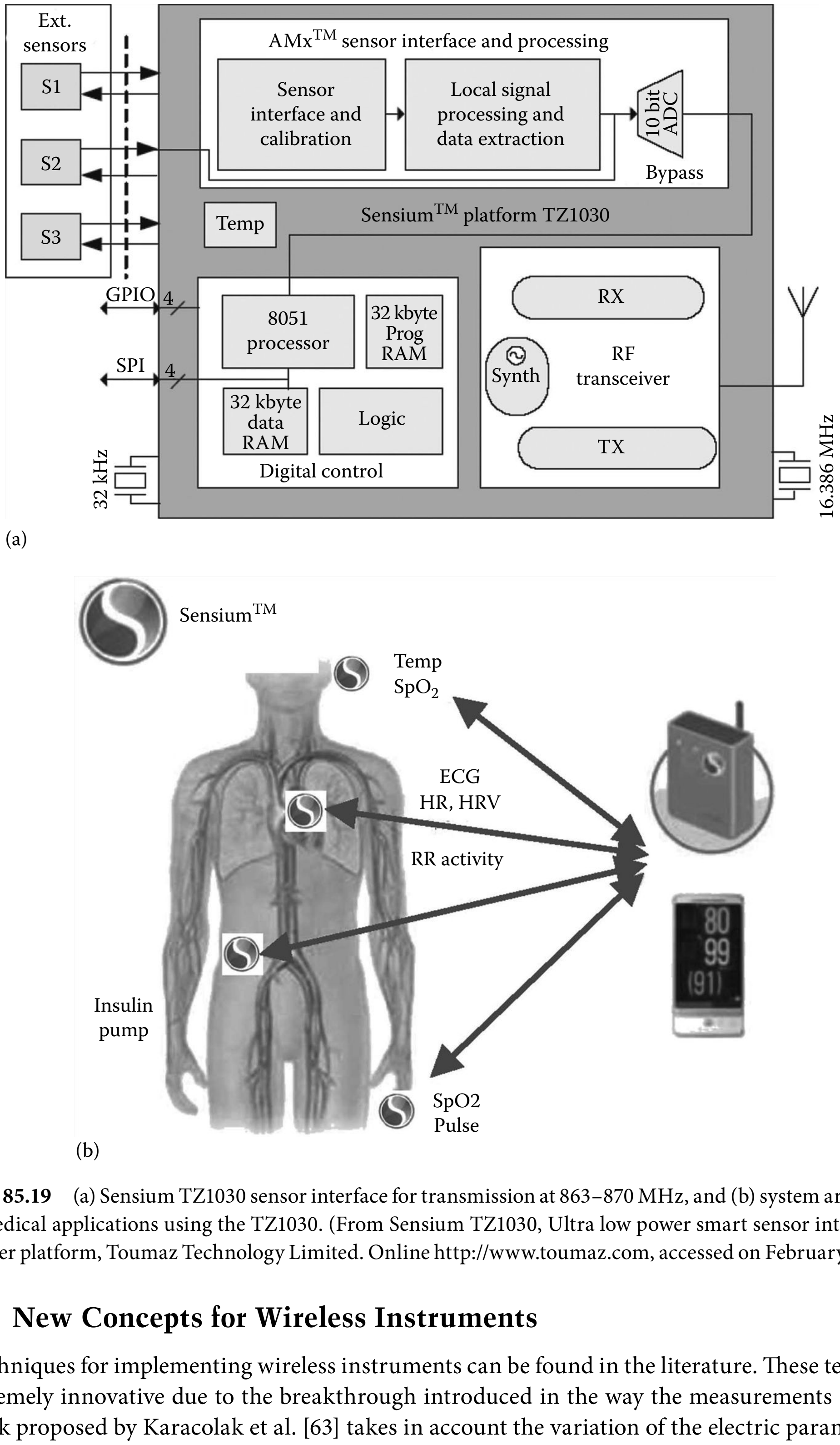


FIGURE 85.19 (a) Sensium TZ1030 sensor interface for transmission at 863–870 MHz, and (b) system architecture for biomedical applications using the TZ1030. (From Sensium TZ1030, Ultra low power smart sensor interface and transceiver platform, Toumaz Technology Limited. Online http://www.toumaz.com, accessed on February 27, 2012.)

85.4.2 New Concepts for Wireless Instruments

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. [63] takes in account the variation of the electric parameters for continuously measuring glucose (the electric parameters vary with the sugar concentration).

Alternatively, the research group of Chow et al. [64] explores an uncommon (but still very innovative) methodology that makes use 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 through the tissues of the human body.

Finally, the work proposed by Rodrigues et al. [65] uses a MEMS antenna with a U-shaped cantilever structure. 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 acquired by the reading circuit. The major innovation of this technique allows the integration of antennas with implantable devices by way of WLP techniques for achieving the fabrication of small-sized devices. Their antenna occupies an area of only 1.5×1.5 mm [65].

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