6

Wireless Instrumentation and Biomedical Applications

João Paulo Carmo and José Higino Correia

CONTENTS

6.1 Introduction

Modern telemedicine, telehealth, and mobile health systems are almost all dependent on the appropriately designed and implemented sensors, wireless instruments and instrumentation systems, and networks for gathering the relevant information and transmitting it to target databases for further processing. Therefore, it is important to have an appreciation of the basic technology and operational principles of wireless instruments and instrumentation systems. This chapter describes such technologies and gives examples as they are applied in biomedicine. Many other examples can be found throughout the book.

Almost anyone knows that a measurement is the process of comparing a quantity with another one of the same species (e.g., length, volume, and 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 a specific instrument for achieving such a task [1]. This instrument can be a simple instrument for directly measuring a physical quantity (e.g., a voltmeter for measuring an electric potential difference between two points of a circuit, an ammeter for measuring a current flowing in a branch of a circuit, and 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] (the ease of adding new functions and/or reconfiguration of the existing ones) makes digital instruments undoubtedly

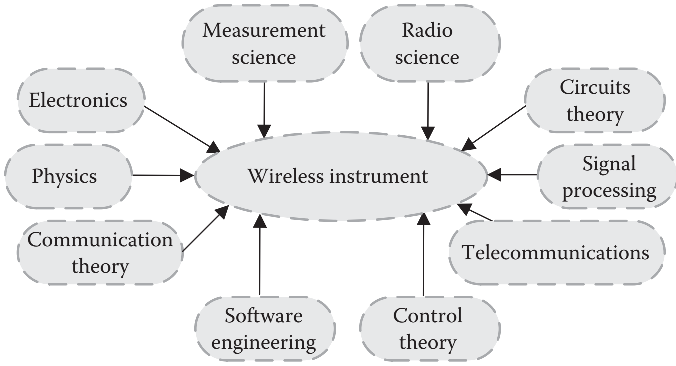


FIGURE 6.1
The multidisciplinary areas to take into account when designing a wireless instrument.

those with major potential for use in several fields of human activity (heavy industry, medicine, and transportation systems are some application examples). The current evolutionary step of measurement instruments is integrating functions to provide wireless transfer of data. In this sequence of ideas, the developments of the microelectronics and microsystems industry allowed the engineers to successfully develop this new measuring paradigm [5]. This resulted in new possibilities for measuring, acquiring, transferring, and storing and for analyzing the physical world: the embedded systems [6] and wireless sensors networks [7] are two new ways for achieving such goals, with wireless being the leader. This lead 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 6.1 reinforces this idea by illustrating how many disciplines 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 the new application concepts.

6.2 Measurement Systems

Figure 6.2 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

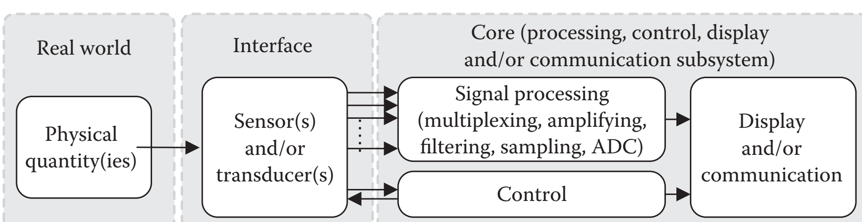


FIGURE 6.2
Block diagram of a generic measurement instrument.

the physical quantity to be acquired), the interface block (with the sensor), and the core (e.g., the instrument itself).

There are situations where the interface block can be part of the core; e.g., a voltmeter does not require any external sensor because this 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 should not be confused with an instrument, because the latter can perform the same function of the former; but if the former is passive (for example, a physical quantity–dependent 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 an instrument.

The core blocks can include electronics of control for acquisition from the sensor. The core also provides signal-processing functions for signal-conditioning purposes. These latter functions include amplification (with the possibility of adjusting the gain), filtering (either low-pass or band-pass or even high-pass filtering), and analog-to-digital conversion (ADC). 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., I^2E bus [9], general-purpose interface bus [GPIB] [10], RS-232 [11–12], parallel ports, [13] or even universal serial bus [USB] [14]) or wirelessly (e.g., IEEE 802.11 [15], ZigBee [16], or Bluetooth [17] or using a customized solution [18]).

The core blocks of measurement instruments can be analog or digital. Analog is the less versatile core because it requires the presence of a person to record 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 sensors (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 block. The inclusion of multiplexers enables the acquisition of multiple channels with a single measurement instrument. This topic is the focus of discussion in the following subsection. Then and after the analog-to-digital 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 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 for adapting to wide variations in physical quantities. Finally and thanks to the latest developments in microelectronics, by making available sensors with digital outputs (for example, integrated monolithic temperature sensors [19], Hall-effect magnetometers [20], and accelerometers [21], among others), it is possible to have full digital and reusable cores.

The judicious selection of sensors and cores can be decisive points for fabricating wireless instruments with low power, reduced sizes, and low prices. This statement is especially evident for measurement instruments composed of reusable cores (for controlling and displaying/communicating), monolithic sensors (for signal acquisition), and on-chip signal-conditioning circuits [22] (for signal processing).

6.2.1 Multiplexing Structures

The multiplexing operation is required in measurement instruments for simultaneously acquiring more than one signal at once. Signal multiplexing is not as simple a matter to treat at first sight as it seems to be. The first issue is concerned with the availability of a variety of multiplexing structures and the decision to select the most suitable. This poses trade-off problems related to implementation costs (e.g., the more complex the multiplexing system, the higher will be the cost) and specifications (e.g., the more general purpose the device, the higher will be the complexity and the cost). Secondly, 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, and 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.

Figure 6.3 shows the simplest structure. The signals at the outputs of sensors connect to an analog multiplexer (with single-ended or differential inputs). It is important to have a variable-gain amplifier when sensors 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; second, 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.

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 sensor with the highest bandwidth; the direct acquisition of multiple signals can pose shielding problems because the sensors 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 small electronic modules with a high degree of integration (e.g., one multiplexer, one amplifier, one analog filter, one S/H plus ADC, and control electronics).

Figure 6.4 structure is very similar to that illustrated in Figure 6.3. The only exception is the use of sensors with associated amplifiers. These dedicated amplifiers guarantee signals with equal excursions for use in 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 by sacrificing the compactness and small size due to the use of multiple amplifiers.

The 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 can cause problems, such as finite

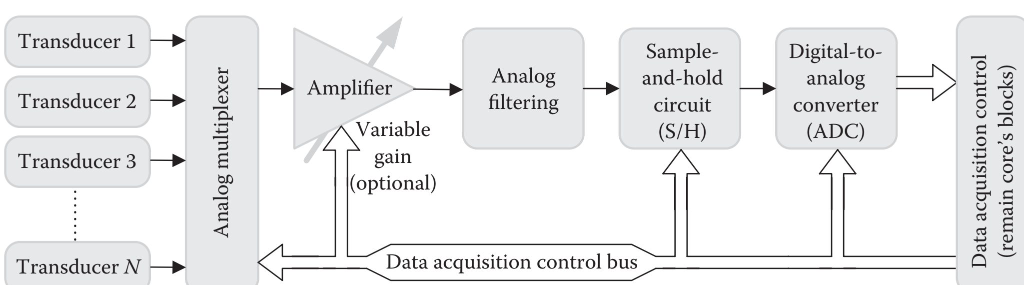


FIGURE 6.3
Low-level multiplexing configurations with shared amplifier.

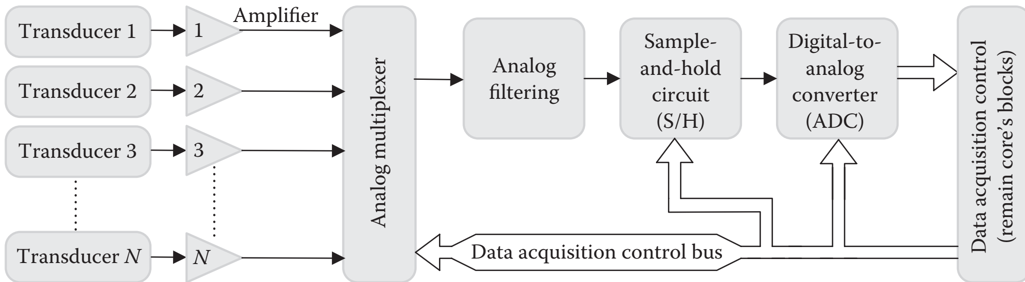


FIGURE 6.4
Low-level multiplexing configurations with dedicated amplifiers.

impedance of nonselected analog channels, cross talk between channels, nonzero switching times between channels, and handling of different bandwidths between channels.

Figure 6.5 shows a high-level multiplexing configuration, providing a dedicated set of amplifiers, analog filters, S/H circuits, and ADCs for each sensor. After conversion to the digital domain, the acquired physical measures are digitally multiplexed, avoiding the problems of the 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 sensors. Moreover, this configuration offers the possibility to select the most suitable ADC for the respective analog chain. More important is that it can 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.

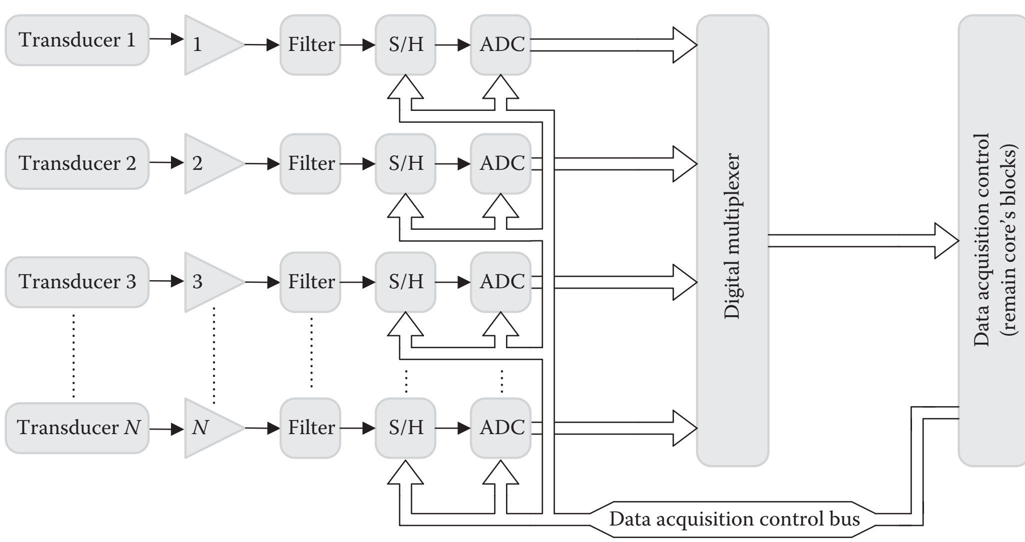


FIGURE 6.5
High-level multiplexing configuration.

6.2.2 Wireless Instruments Seen from the Communication Protocol Point of View

The design of a wireless instrument (as well as a generic measurement instrument) cannot be done without taking into account the communication protocol. Table 6.1 shows the layer structure proposed by the Open Systems Interconnection (OSI) model [23].

Basically, layer 1 specifies the modulation in conjunction with the line coding m (coding and modulation = codulation [24]), the direct-current (DC) balancing, and single-ended/differential-ended balancing.

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

The *network layer* specifies a set of procedures for guaranteeing a reliable transmission between consecutive nodes along the network. Examples of procedures include, for example, the detection/correction of transmission errors and flow controlling. 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 for obtaining 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.

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

TABLE 6.1

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 (medium access control [MAC] and logical link control [LLC] sublayers)
	Bits	Physical	Signal transmission through the communication channel (codulation; other physical aspects of signals)

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

Figure 6.6 provides a better understanding of 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.

The application is simply the measurement part of the wireless instrument (e.g., the measurement instrument), which is composed of the core measurement subset (this subset includes the signal-acquisition block, the signal-processing block, the control block, the memory block—a part of the control block—and the display control—actually, this block is optional in wireless instruments). Additionally and as previously stated in Subsection 6.2.1, the interface block can be a part of the 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).

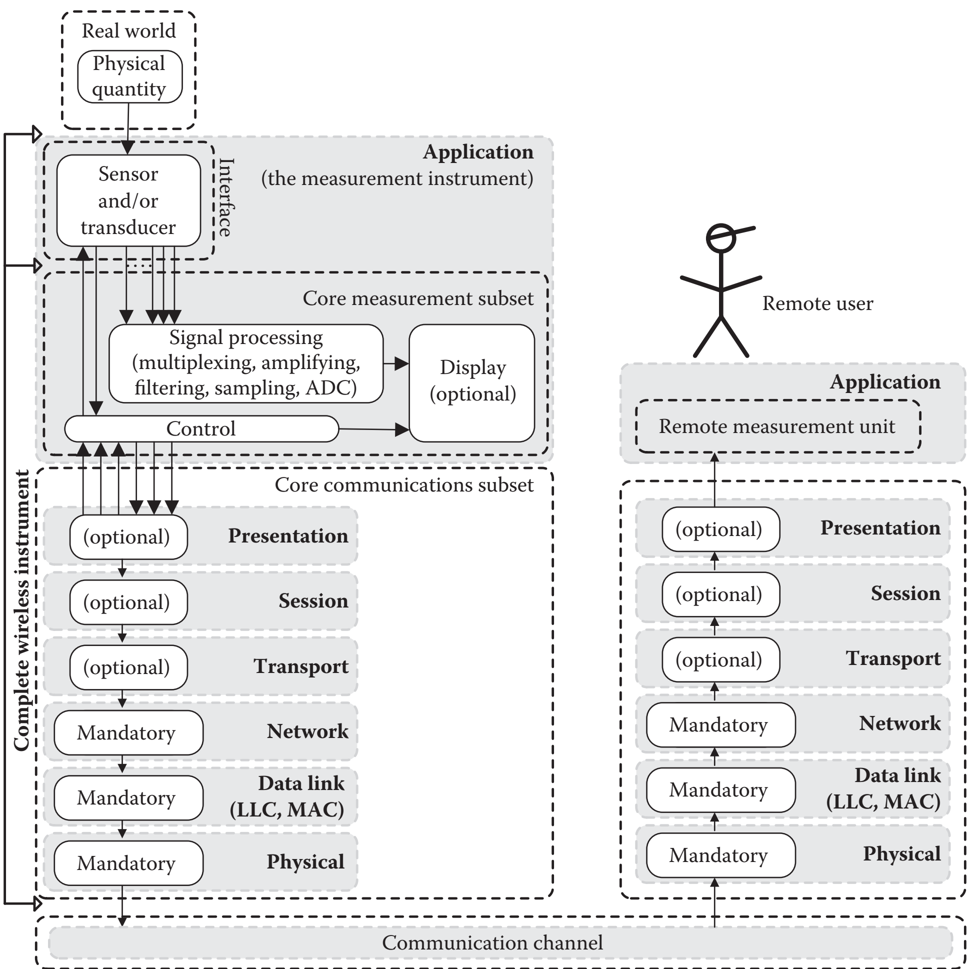


FIGURE 6.6
Relation between wireless instruments with the stacks of the OSI model.

Normally and as shown in Figure 6.6, 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 maximize the data throughput.

The most common function of the network layer is the cyclic-redundancy check (CRC) generation (by the wireless instrument in the transmitter's side) and decoding (in the receiver's side) for detecting transmission errors. It is possible to use forward error correction (FEC) schemes for error correcting but with the cost of sending 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 an erroneous packet.

The LLC sublayer functions cannot 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 8) 1s and eight 0s 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 in 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 into 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.

Finally and 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 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]. 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 complementary metal–oxide–semiconductor (CMOS) receiver at 433 MHz for integration on implantable devices by Carmo et al. [31] was designed taking into 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 Low Power Radio Solutions [LPRS] Inc.) and was tested with success for soil moisture measurements [33].

6.3 Technology for Wireless Systems

6.3.1 Operational Issues

The selection of the operation frequency is important. In the first place, the dimensions of the antennas are imposed by the frequency. For an acceptable efficiency, the antenna size must be the same order as one-quarter 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 a vacuum and f [Hz] the frequency of operation. Decreasing the dimension of an antenna implies the use of high frequencies for achieving such size. This issue can be solved by modulation. The most used modulations in wireless instruments (especially in laboratory environments, e.g., closed and relatively absent of common band interferences) 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 is in Table 6.2 [34], as well as the plots of their respective values as function of the ratio E_b/N_0 shown in Figure 6.7. The ratio E_b/N_0 is the energy per bit, E_b [J] divided by the spectral density of the noise (additive white Gaussian noise) N_0 [W] given by Couch [34]:

$$\frac{E_b}{N_0} = \frac{S/r_b}{N/\mathrm{BW}} = \left(\frac{S}{N}\right) \times \frac{\mathrm{BW}}{r_b}, \tag{6.1}$$

where $N = N_0$BW [W] is the filtered noise at the output of a band-pass filter BW [Hz].

The selection of the frequency considering only the bit rate and antenna size is not enough because as is general knowledge, the antenna is perhaps the most critical subsystem in wireless communications. This requires 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 small size of antennas can

TABLE 6.2

BEPs 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	$\frac{1}{2}e^{-\left(\frac{1}{2}\right)\times\left(\frac{E_b}{N_0}\right)}, \left(\frac{E_b}{N_0}\right) > \frac{1}{4}$	$\frac{1}{2}e^{-\left(\frac{S}{N}\right)}, \left(\frac{S}{N}\right) > \frac{1}{8}$
PSK	$Q\left(\sqrt{\frac{2\times E_b}{N_0}}\right)$	$Q\left(\sqrt{2}\times\sqrt{\frac{S}{N}}\right)$
FSK	$Q\left(\sqrt{\frac{E_b}{N_0}}\right)$	$Q\left[\sqrt{1+\left(\frac{\lvert f_1-f_2\rvert}{4r_b}\right)}\times\sqrt{\frac{S}{N}}\right]$

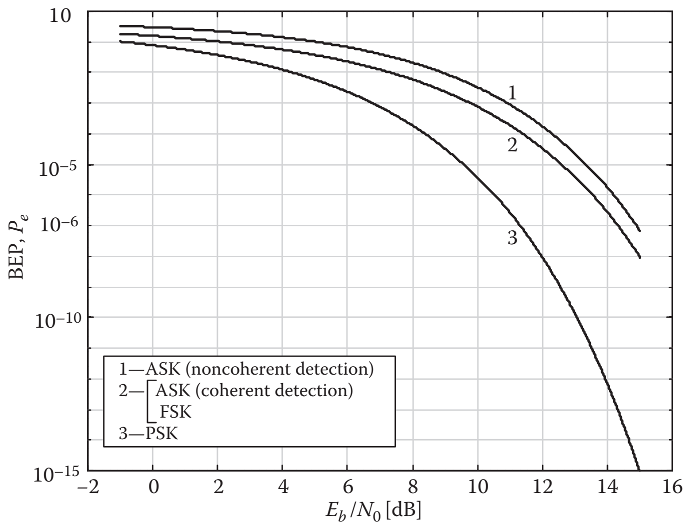


FIGURE 6.7
BEP versus the E_b/N_0 [dB] ratio for the modulations ASK, PSK, and FSK.

introduce additional problems of impedance matching [35] which must be solved. As seen later, wafer-level-packaging (WLP) techniques can be used for overcoming these problems [36].

The communication range is another issue to take into 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]:

$$L_f(d, f) = -20\log_{10}(d) - 20\log_{10}(f) + K_f \text{ [dB]}, \qquad (6.2)$$

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

$$f \le 10^{\left[(P_t - S_r) - 20\log_{10}(4\pi d_{max})\right]/20} \text{ [Hz]}. \qquad (6.3)$$

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, and systemic implementations, among other factors) is not taken into account. Therefore, a general loss model must be used [37]:

$$L(d) = \alpha c^{-n} + \chi,\ n \ge 2, \text{ and } \alpha < 1. \qquad (6.4)$$

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) do not contribute statically to the loss, but dynamically. This dynamic behavior can impose severe restrictions when designing a wireless link because a superdimensioned 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, and trains, among others). Very good references can be found in Pätzold [38], Blaunstein and Andersen [39], and Bertoni [40] to deal with the fading.

Figure 6.8 shows the available frequency bands for the different technologies used in wireless communications. Suitable frequencies for possible use in wireless instruments are those that belong to the so-called industrial, scientific, and medical (ISM) band, due to its unregulated usage. These frequencies can be freely used without being subject to standardization but keeping the emission powers below the maximum levels imposed by regulations. This usage flexibility leads to the widespread use of new applications as will be discussed further.

6.3.2 RF Interfaces

A wireless instrument communicates with the external world by RF. Thus, a wireless interface must be provided for allowing RF communications. Figure 6.9 shows a generic schematic block of a wireless microsystem performing functions of a stand-alone wireless instrument. These microsystems are composed of sensors and electronics 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 sensors and remaining electronics). The miniaturization of electronics and the spreading of fabrication processes for integrating heterogeneous technologies (e.g., CMOS, SiGe, III/V technologies, microelectromechanical

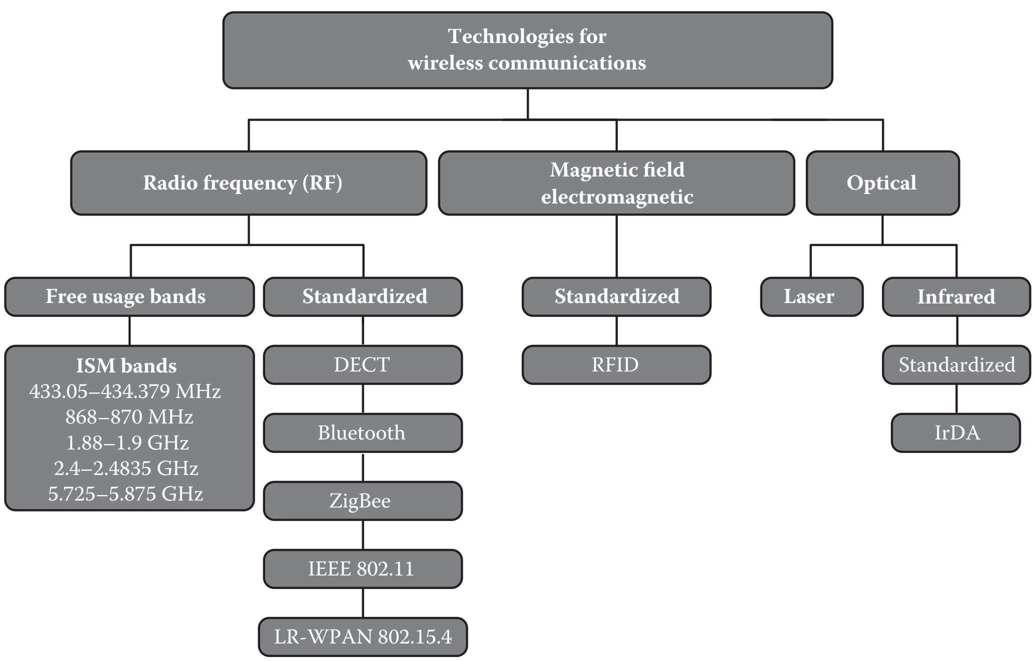


FIGURE 6.8
Currently available frequencies for wireless applications.

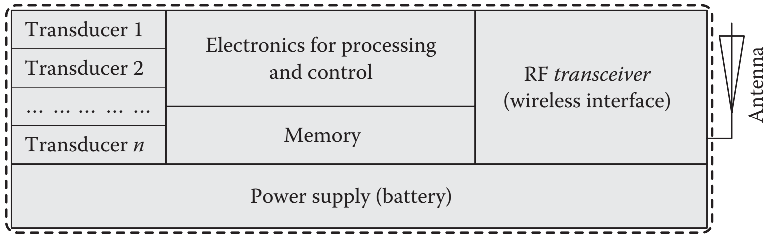


FIGURE 6.9
Generic microsystem architecture that connects to an associated antenna.

systems [MEMSs], among others) results in the mass production of wireless microsystems at low prices. All these issues combined with the flexibility to select which and the number of sensors 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 multichip-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 of allowing the fabrication of wireless microsystems for use in wireless instruments. In this section, a few examples for each of the ISM bands in Figure 6.8 are presented for a better view of wireless instruments potential.

Figure 6.10 shows the block diagram of a wireless instrument for monitoring the body movements of individuals doing hydrotherapy [41]. This wireless instrument is modular and is composed as follows: 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 an 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].

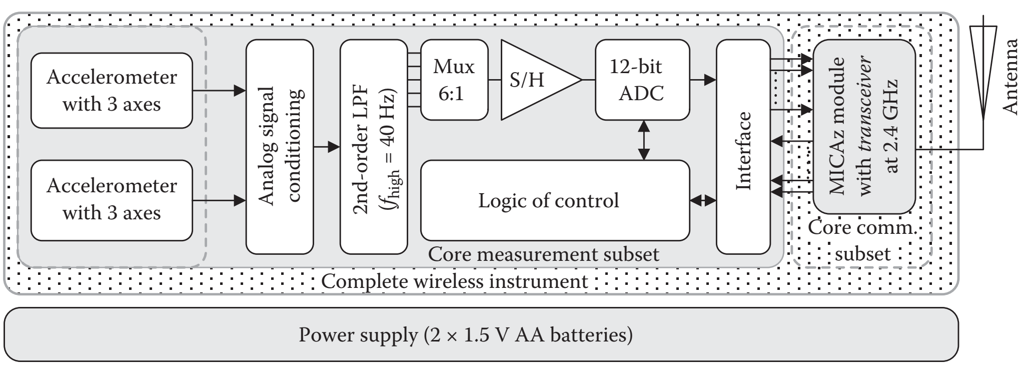


FIGURE 6.10
Block diagram of a wireless instrument at 2.4 GHz ISM band for monitoring the body movements of individuals.

Figure 6.11 shows the block diagram of a sensorial 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 sensors. The analog-to-digital conversion is done by a ΣΔ modulator for coding the input analog signals, whose result is a bit stream 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 sensor developed by Valente et al. [33]. The wireless instrument illustrated in Figure 6.11b was developed for measuring the soil moisture of greenhouses and uses the latter RF interface to send the acquired data into an external storing and/or analyzing unit.

Figure 6.12a 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 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 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 6.12b 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 transmitters and the transmitter fabricated by Morais et al. [32], for the same coding scheme (the variation of the Manchester code) in the transmitter.

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 cannot neglect this issue because this is the block with major impact in the total power consumption, when compared with the entire electronics in the instrument [44]. 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 [45–46]. Hence, it demands the integrated definition of architectures and methods of control, as well as providing the means to predict the power consumption of the RF system. Figure 6.13a shows a photograph of 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 a low-voltage supply. As shown in Figure 6.13b, the design of this RF CMOS transceiver predicted the use of the control signal to either select the transmitter or the receiver in order to allow its integration with electronics to perform custom control (Figure 6.13c).

It is possible to explore the band located between 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 by using WLP techniques [36]. The integration of antennas and electronics in the same microsystem results in fewer impedance mismatching problems. Moreover, the antenna and electronics cointegration systematizes the fabrication process and, at the same time, results in microsystems with a small cost per unit. The work by Dias et al. [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 6.14a shows a photograph of the wireless interface measuring 1.5 × 1.5 mm^2. The schematic in Figure 6.14b 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.

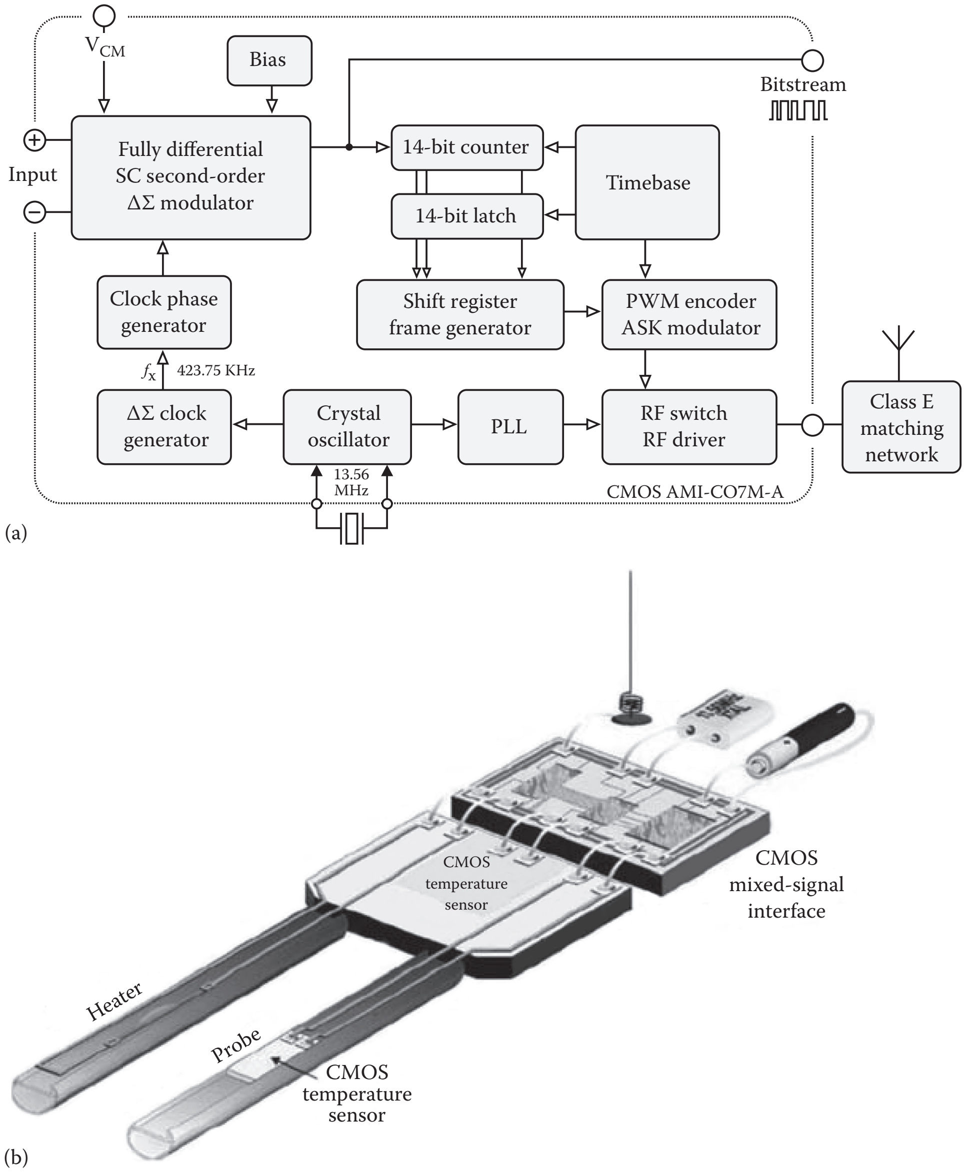
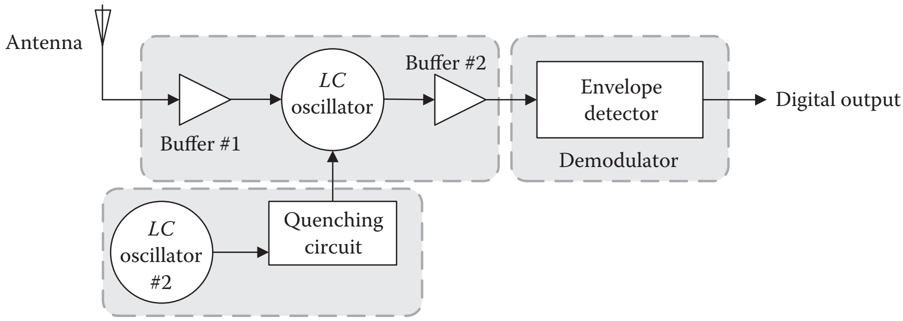
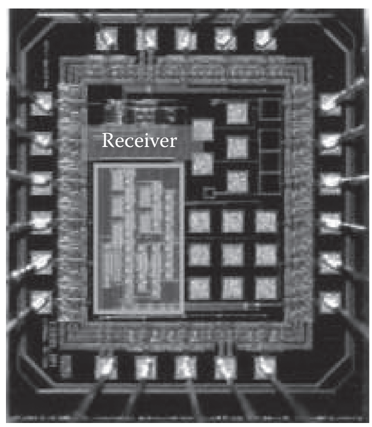


FIGURE 6.11
(a) The block diagram of a sensorial RF interface for operation in the 433 MHz ISM band. (Reprinted from *Journal Sensors and Actuators A: Elsevier Science Direct*, 115, Morais, R., Valente, A., Couto, C., and Correia, J. H., A wireless RF CMOS mixed-signal interface for soil moisture measurements, 376–384, Copyright (2004), with permission from Elsevier.) (b) A wireless instrument composed of the RF interface mounted in a soil moisture sensor for utilization on greenhouse environments. (Reprinted from *Journal Sensors and Actuators A: Elsevier Science Direct*, 115, Valente, A., Morais, R., Couto, C., and Correia, J. H., 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.)



(a)



(b)

FIGURE 6.12
(a) The block diagram of the super-regenerative receiver at 433 MHz and (b) a die photograph containing the first prototype of the super-regenerative receiver. (Reprinted from *Microelectronics Journal: Elsevier Science Direct*, 42, Carmo, J. P., Ribeiro, J. C., Mendes, P. M., and Correia, J. H., Super regenerative receiver at 433 MHz, 681–687, Copyright (2011), with permission from Elsevier.)

An integrated low-cost solution for wireless instruments based on a microdevice fabricated with low-power consumption 0.18 μm CMOS process is presented by El-Hoiydi et al. [50]. This microdevice is naturally composed of an RF transceiver, a reduced instruction set computer (RISC) microcontroller, random-access memory (RAM), a power-supply management circuit, analog electronics of signal conditioning and analog-to-digital conversion, and circuits for providing communication based on serial peripheral interface (SPI) and inter-integrated circuit (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 30 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 and 868 MHz, as well as with either OOK modulation or FSK modulation. According to El-Hoiydi et al. [50], their RF transceiver presents a power consumption of either 2.5 or 39 mW, when either the receiver or the transmit operation mode is selected.

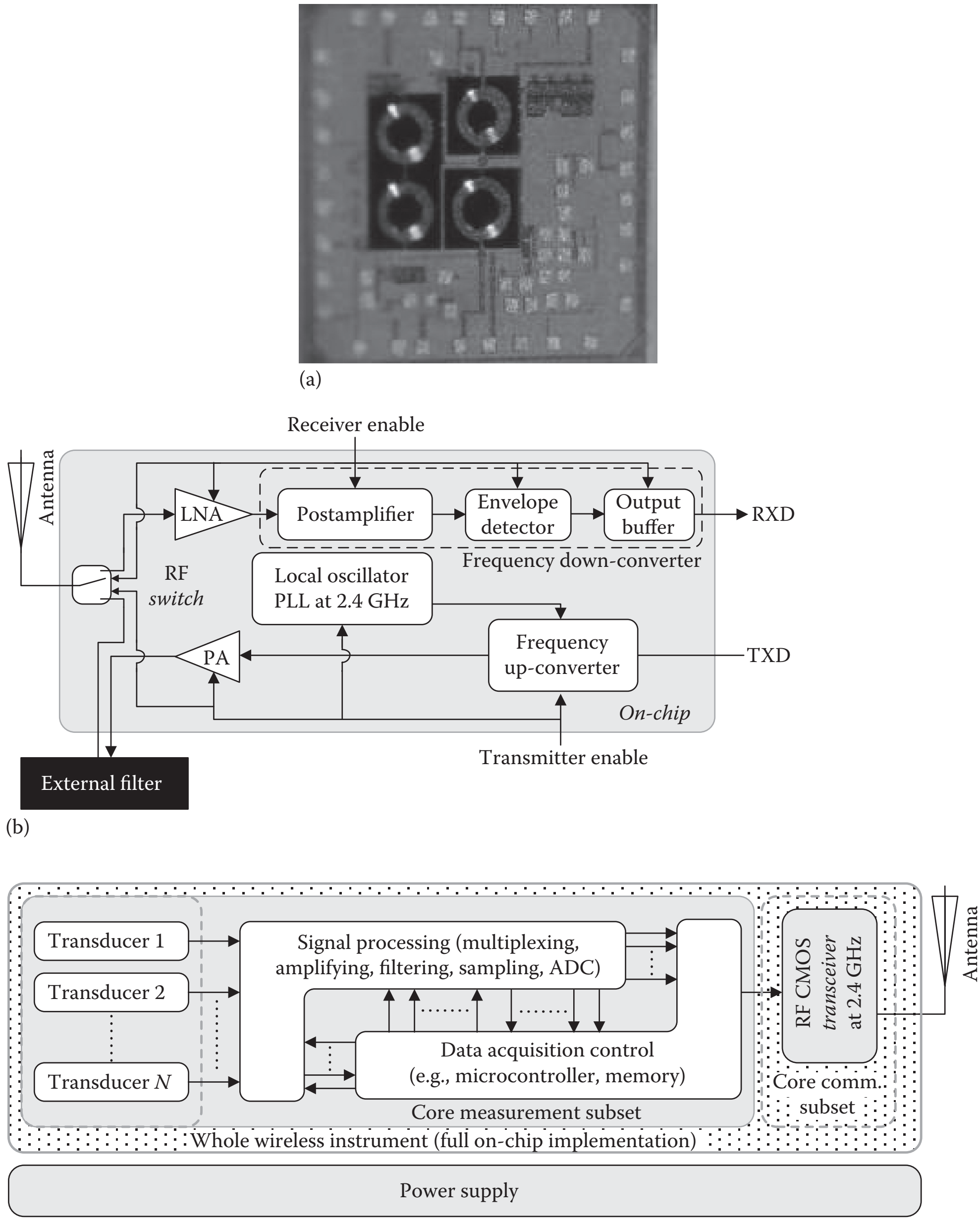


FIGURE 6.13
(a) Photograph and (b) block schematic of an RF CMOS transceiver at 2.4 GHz specially designed for stand-alone wireless instruments in biomedical applications; (c) a schematic showing the integration concept of the RF CMOS transceiver, sensors, and electronics in the same microsystem.

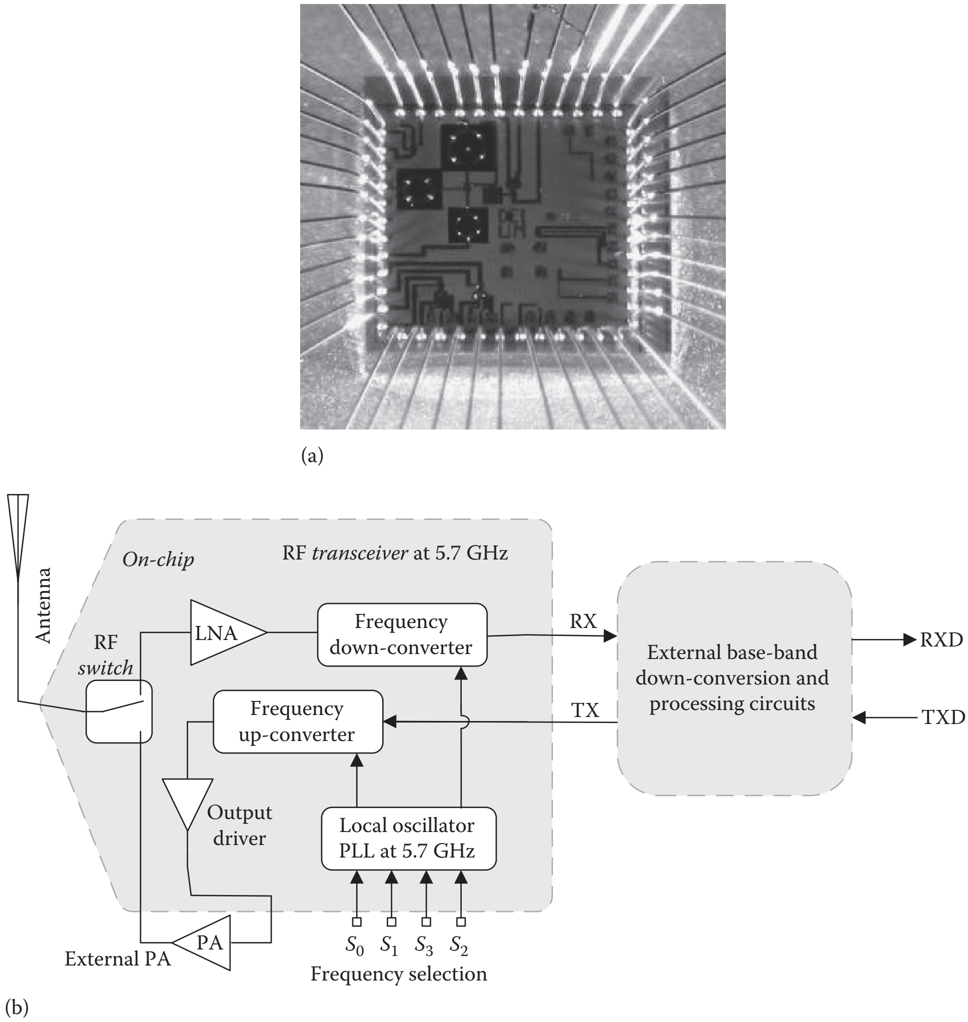


FIGURE 6.14
For the frequency of 5.7 GHz: (a) a photograph and (b) the schematic block of the RF part of a wireless interface at 5.7 GHz.

6.4 Networks of Wireless Instruments

A wireless sensor network can be considered (in a *latum sense*) a network of wireless instruments whose sensorial nodes are the wireless instruments themselves. 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 this kind of wireless instrument from the most conventional available. In this sequence and as shown in Figure 6.15, 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 consumptions below

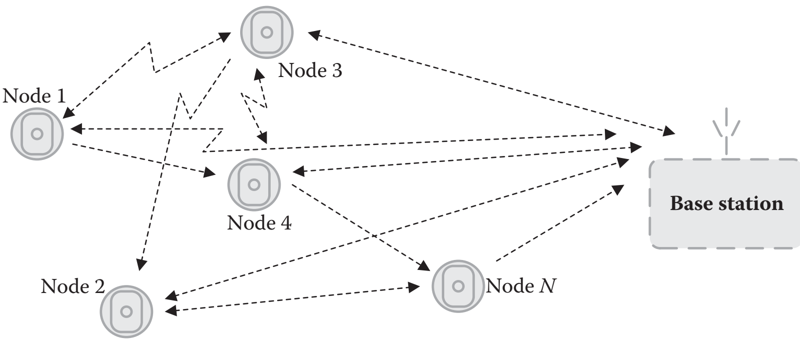


FIGURE 6.15
A schematic illustrating the wireless sensors network concept.

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 sensor 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 it into the base station when the establishment of an RF link between a given sensorial node and the base station is not possible. Upon resuming, the information in a hidden node (in 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 for dealing 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 in 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 mediums also introduce problems related to the security and confidentiality of the data.

The increased application potential of wireless sensors networks in several fields of human society (such as the industrial, biomedical, transportation, domestic, and energy fields, among others) resulted in the need for their standardization as well as for 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. IEEE 802.11 and Bluetooth protocols are very heavy and complex and, thus, have 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 for protocols with low power consumption and simple procedures resulted in the establishment of the IEEE 802.15 work group. The joint actions developed by this work group resulted in the proposal for three different classes of wireless operation. The focus of the first class of operation prioritized the bit rates, whereas the second was targeted at power consumption, while the third class was more concerned with the quality of service (QoS). The need for protocols for low-power devices resulted in the proposal of IEEE 802.15.4 as a basic set of rules for application in wireless sensor networks. The IEEE 802.15.4 protocol was developed for low-complexity applications and distances of up to 10 m, allowing bit rates of 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. To resume, the IEEE 802.15.4 protocol defines the two lower OSI layer functions. Note in that Figure 6.16, two versions of the physical layer of the IEEE 802.15.4 protocol can be provided [53].

The first version of the physical layer uses either 868 or 915 MHz in Europe or in the United States, respectively. The European version uses only one RF channel for transmitting the maximum bit rates of 20 kbps, whereas the US version allows the use of 10 simultaneous channels spaced 2 MHz apart and maximum bit rates 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 5 MHz apart and maximum bit rates of 250 kbps per channel. Table 6.3 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 the fading resulting from a multiplicity of radio-wave paths. The spread-spectrum techniques also make easy 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. This RF transceiver contains internally 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

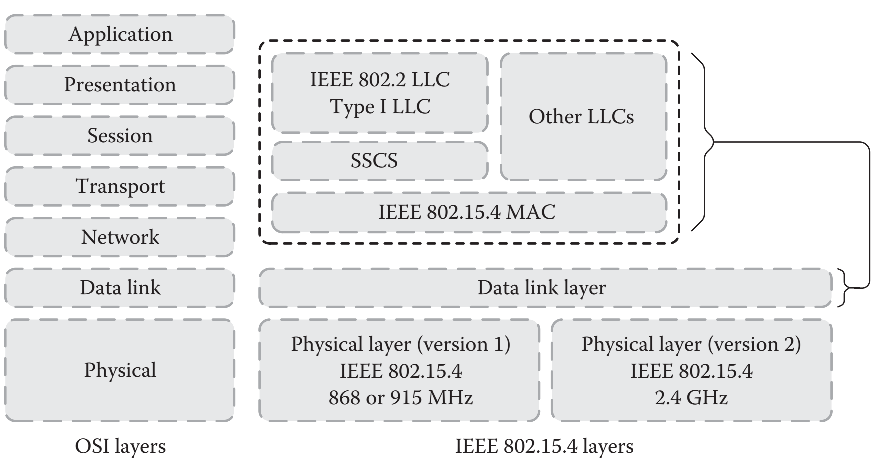


FIGURE 6.16
The OSI layer functions in the IEEE 802.15.4 protocol.

TABLE 6.3
The Main Characteristics of the Physical Layer of the IEEE 802.15.4 Protocol

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

frame formats and procedures specified by the standard IEEE 802.2. The main difference between those used by the local area networks and those used by the wireless sensor 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 to the 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., CRC for transmission errors verification).

Figure 6.17 shows that the ZigBee protocol is an extension of the IEEE 802.15.4 protocol. The ZigBee uses the IEEE 802.15.4 protocol to implement the physical and data-link layer functions. Furthermore, the ZigBee supports a wider range of high-level functionalities (not present in the IEEE 802.15.4, which is closer to the hardware) as in the case of the cryptography and management policies in environments with multiple users, as well as error

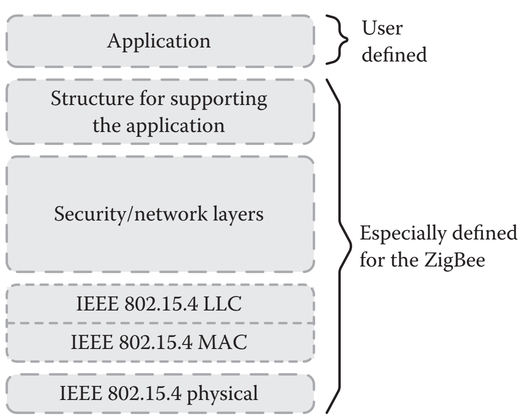


FIGURE 6.17
Adopted layers from the OSI model for use by ZigBee.

control [53]. The CC2430 is another integrated circuit fabricated by the Chipcon Company [55] that simplifies the task of implementing ZigBee networks. The CC2430 contains internally an RF transceiver and an additional core for implementing the ZigBee high-level functions. The RF part of the CC2430 consumes 21 mW in the receiving mode and 30 mW in the transmitting mode. The CC2430 is at this date the first integrated circuit to offer a full ZigBee solution for the market. This integrated circuit is also composed of flash memory up to 128 kB, 8 kB 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 the industry and the need for new personal applications. Thus, ZigBee was developed to allow the fast prototyping of wireless sensor networks. In this context, it is possible to find a wide number of solutions to implement wireless sensor 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 can be easily customized and programmed, since it runs open-source operating systems which provide low-level event and task management. Mote processor/radio module families working in the 2.4 GHz ISM band that support IEEE 802.15.4 and ZigBee are available from the Crossbow Company.

However and despite the ease inherent in the solutions based on motes, they can be very expensive when full custom network prototypes are required. The wireless sensors network solution by Carmo et al. [18] uses peripheral interface controller (PIC) microcontrollers 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 it is possible to expand the number of sensors to be attached. The main drawback is that the maximum sampling frequency is limited by the number of sensors: the maximum sampling frequency per sensor is limited to f_S/N [Hz], where f_S [Hz] is the maximum sampling frequency when only one sensor is present and N is the number of sensors. To finish, the reprogramming of the microcontroller increases the functionalities with new services of nodes.

6.5 Examples of Wireless Instruments in Biomedical Applications

6.5.1 Commercial Off-the-Shelf (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. Body area networks comprise smart sensors able to communicate wirelessly to a base station.

Examples of applications are a wireless EEG, which is expected to provide a breakthrough in the monitoring, diagnostics, and treatment of patients with neural diseases. Wireless EEG modules composed of the neural electrodes, processing electronics, and an RF transceiver with an associated antenna will be an important breakthrough in EEG diagnostics. Two approaches can be used for implementing wireless EEG systems:

the COTS and the customized solutions. A commercial off-the-shelf solution uses discrete integrated circuits and passive components for making the wireless instrument, whereas a customized solution is designed from 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 (for example, 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. Basically, 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 a power supply and achieves maximum bit rates of 120 kbps. Other features of this system include resolution of about 4 μV and power consumption of 15 mW and acquiring of signals with five single-ended channels. This wireless acquisition system fits approximately in 5.7 × 4.8 × 2.0 cm^3. Figure 6.18 shows the block diagram of the acquisition part of this wireless EEG system, and note that a reference voltage must be added to the acquired signals before the analog-to-digital conversion can be done because negative potentials are not provided by the power-supply system (the batteries can provide the following electrical potentials: ground V_{dd} and $V_{dd}/2$). Further explanations of this analog circuit (especially for the requirement of neutral and signal ground [SGND] electrodes) are provided by van Rijn et al. [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 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 is fully autonomous in terms of power supply and uses a

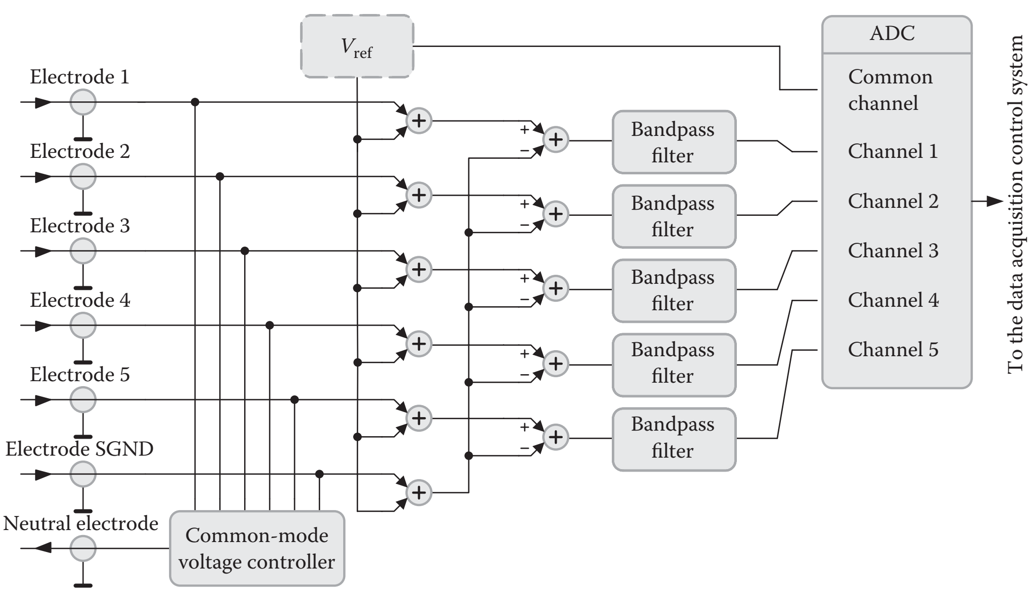


FIGURE 6.18
Block diagram of the EEG analog signal-processing part found by Dias et al. [58].

thermoelectric generator to convert the temperatures differences between the environment (the coldest side, at the temperature T_c [K]) and the forehead of the subject (the hottest side, at the temperature T_h [K]) that uses the wireless EEG system [60]. The output voltage depends on the temperature difference $\Delta T = T_h - T_c$ [K], explained by the Seebeck effect [61]. 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 Yazicioglu et al. [60] that is known as alternating current–coupled chopper-stabilized instrumentation amplification (ACCIA) for achieving a 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 a customized solution is the Sensium TZ1030 sensor interface shown in Figure 6.19a [62]. The Sensium TZ1030 sensor interface was developed by Toumaz Technology Limited for operation in the following bands: 863–870 and 902–928 MHz in Europe and the United States, respectively. 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 ECGs, temperature, glucose levels, and oxygen levels in the blood. Figure 6.19b shows a possible architecture for rapid development of wireless BANs.

6.5.2 Active Concepts for Biomedical 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 into account the variation in the electric parameters for continuously measuring the concentration of glucose (the electric parameters vary with the sugar concentrations).

Alternatively, the research group of Chow et al. [64] explores an uncommon (but still very innovative) methodology that uses 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. [65] uses a MEMS antenna with a U-shaped cantilever 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 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^2 [65].

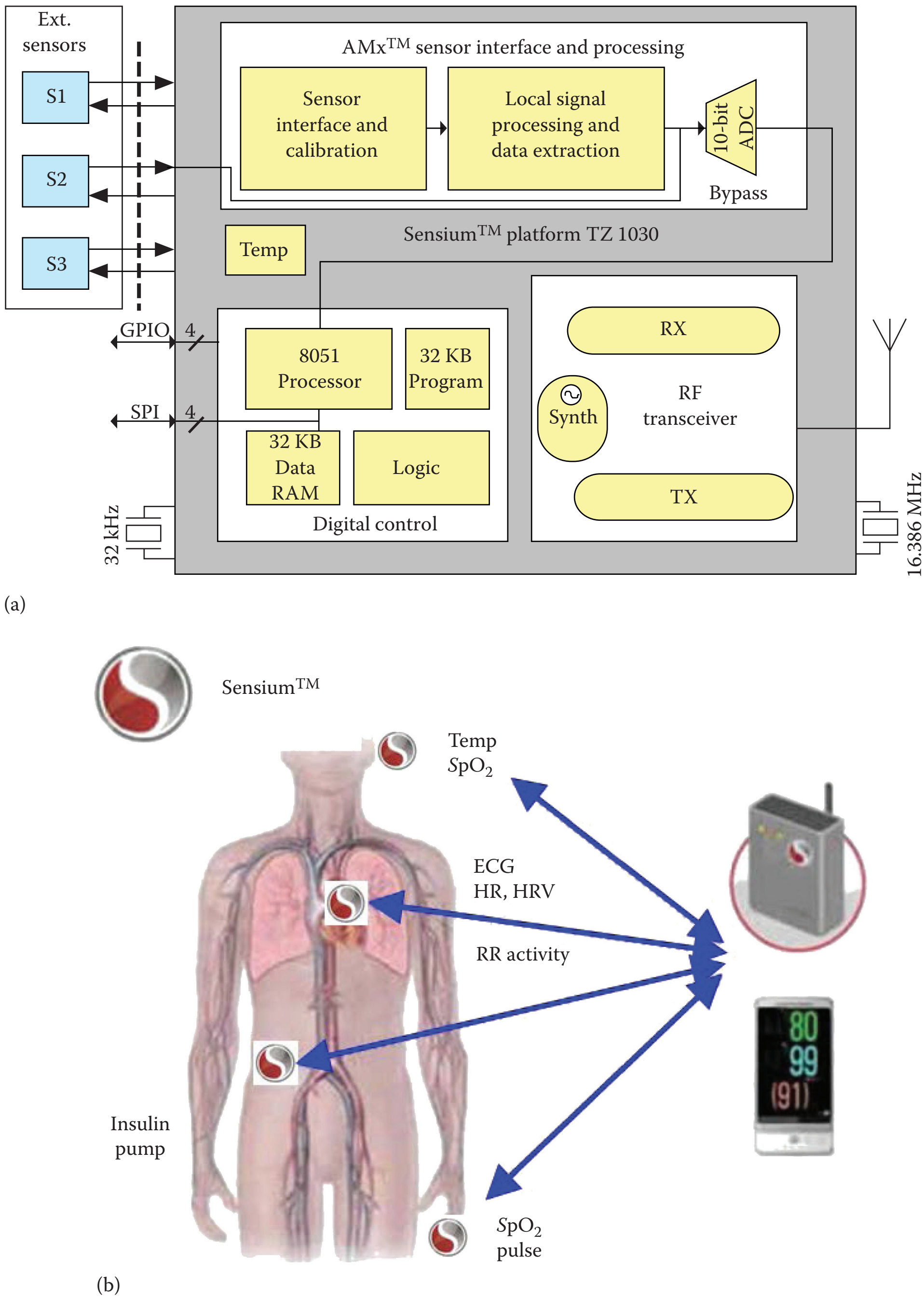


FIGURE 6.19
(a) Sensium TZ1030 sensor interface for transmission at 863–870 MHz and (b) system architecture for biomedical applications using the TZ1030. (Reproduced from Sensium TZ1030, Ultra low power smart sensor interface and transceiver platform, Toumaz Technology Limited, online [August 27, 2014]: http://www.toumaz.com. With permission.)

References

1. D. Buchla and W. McLachlan, *Applied Electronic Instrumentation and Measurement*, First edition, Prentice Hall, 1991.
2. W. D. Cooper and A. D. Helfrick, *Electronic Instrumentation and Measurement Techniques*, Third edition, Prentice Hall, 1985.
3. J. H. Correia, G. de Graaf, M. Bartek, and R. F. Wolffenbuttel, "A single-chip CMOS optical microspectrometer with light-to-frequency converter and bus interface," *IEEE Journal Solid-State Circuits*, Vol. 37, No. 10, pp. 1344–1347, October 2002.
4. G. R. Tsai and M. C. Lin, "FPGA-based reconfigurable measurement instruments with functionality defined by user," *EURASIP Journal on Applied Signal Processing*, pp. 1–14, January 2006.
5. I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Computer Networks*, Vol. 38, No. 4, pp. 393–422, March 2002.
6. V. Raghunathan, C. L. Pereira, M. B. Srivastava, and R. K. Gupta, "Energy-aware wireless systems with adaptive power-fidelity tradeoffs," *IEEE Transactions on Very Large Scale Integrated (VLSI) Systems*, Vol. 13, No. 2, pp. 211–225, February 2005.
7. W. Wu, M. A. T. Sanduleanu, X. Li, and J. R. Long, "17 GHz RF front-ends for low-power wireless sensor networks," *IEEE Journal of Solid State Circuits*, Vol. 43, No. 9, pp. 1909–1919, September 2008.
8. H. Eren, *Wireless Sensors and Instruments: Networks, Design and Applications*, CRC Press, 2006.
9. J. H. Correia, G. de Graaf, M. Bartek, and R. F. Wolffenbuttel, "A CMOS optical microspectrometer with light-to-frequency converter, bus interface and stray-light compensation," *IEEE Transactions on Instrumentation & Measurement*, Vol. 50, No. 6, pp. 1530–1537, December 2001.
10. F. J. Naivar, "CAMAC to GPIB interface," *IEEE Transactions on Nuclear Science*, Vol. 25, No. 1, pp. 515–519, February 1978.
11. L. Korba, S. Elgazzar, and T. Welch, "Active infrared sensors for mobile robots," *IEEE Transactions on Instrumentation & Measurement*, Vol. 43, No. 2, pp. 283–287, April 1994.
12. R. Mukaro and X. F. Carelse, "A microcontroller-based data acquisition system for solar radiation and environmental monitoring," *IEEE Transactions on Instrumentation & Measurement*, Vol. 48, No. 6, pp. 1232–1238, December 1998.
13. D. R. Muñoz, D. M. Pérez, J. S. Moreno, S. C. Berga, and E. C. Montero, "Design and experimental verification of a smart sensor to measure the energy and power consumption in a one-phase AC line," *Measurement: Elsevier Science Direct*, Vol. 42, No. 3, pp. 412–419, April 2009.
14. A. Depari, A. Flammini, D. Marioli, and A. Taroni, "USB sensor network for industrial applications," *IEEE Transactions on Instrumentation & Measurement*, Vol. 57, No. 7, pp. 1344–1349, July 2008.
15. G. Bucci, E. Fiorucci, C. Landi, and G. Ocera, "Architecture of a digital wireless data communication network for distributed sensor applications," *Measurement: Elsevier Science Direct*, Vol. 35, No. 1, pp. 33–45, January 2004.
16. A. Wheeler, "Commercial applications of wireless sensor networks using ZigBee," *IEEE Communications Magazine*, Vol. 45, No. 4, pp. 70–77, April 2007.
17. L. Ferrigno, V. Paciello, and A. Pietrosanto, "Performance characterization of a wireless instrumentation bus," *IEEE Transactions on Instrumentation and Measurement*, Vol. 59, No. 12, pp. 3253–3261, December 2010.
18. J. P. Carmo, P. M. Mendes, C. Couto, and J. H. Correia, "*A low-cost wireless sensor network for industrial applications*," Proceedings of Wireless Telecommunications Symposium 2009, Praha, Czech Republic, Session D-2, pp. 1–4, April 22–24, 2009.
19. A. Bakker and J. H. Huijsing, "Micropower CMOS temperature sensor with digital output," *IEEE Journal of Solid-State Circuits*, Vol. 31, No. 7, pp. 933–937, July 1996.

20. M. Motz, D. Draxelmayr, T. Werth, and B. Forster, "A chopped hall sensor with small jitter and programmable 'true power-on' function," *IEEE Journal of Solid-State Circuits*, Vol. 40, No. 7, pp. 1533–1540, July 2005.
21. J. Chae, H. Kulah, and K. Najafi, "A monolithic three-axis micro-g micromachined silicon capacitive accelerometer," *IEEE Journal of Microelectromechanical Systems*, Vol. 14, No. 2, pp. 235–244, April 2005.
22. A. Arnaud and C. Galup-Montoro, "Fully integrated signal conditioning of an accelerometer for implantable pacemakers," *Analog Integrated Circuits and Signal Processing*, Vol. 49, No. 3, pp. 313–321, 2006.
23. W. Stallings, *Data and Computer Communications*, Prentice Hall, 2003.
24. B. Pattan, *Robust Modulation Methods and Smart Antennas in Wireless Communications*, Prentice Hall, 1999.
25. H. R. Silva, L. A. Rocha, J. A. Afonso, P. C. Morim, P. M. Oliveira, and J. H. Correia, "*Wireless hydrotherapy smart-suit network for posture monitoring*," Proceedings of IEEE International Symposium on Industrial Electronics—ISIE 2007, Vigo, Spain, pp. 2713–2717, June 2007.
26. N. S. Dias, J. P. Carmo, P. M. Mendes, and J. H. Correia, "Wireless instrumentation system based on dry electrodes for acquiring EEG signals," *Medical Engineering & Physics: Elsevier Science Direct*, Vol. 34, No. 7, pp. 972–981, 2012.
27. Taiyo Yuden Functional Modules, Taiyo Yuden Co. Online (August 27, 2014): http://www.yuden.co.jp/ut/product/category/module/.
28. Linx RF modules, Linx Technologies Inc. Online (August 27, 2014): http://www.linxtechnologies.com/.
29. Radiometrix Wireless Data Transmission, Radiometrix Ltd. Online (August 27, 2014): http://www.radiometrix.com/.
30. Wireless Solutions for a Connected World, Low Power Radio Solutions (LPRS Ltd.). Online (August 27, 2014): http://www.lprs.co.uk/.
31. J. P. Carmo, J. C. Ribeiro, P. M. Mendes, and J. H. Correia, "Super regenerative receiver at 433 MHz," *Microelectronics Journal: Elsevier Science Direct*, Vol. 42, pp. 681–687, 2011.
32. R. Morais, A. Valente, C. Couto, and J. H. Correia, "A wireless RF CMOS mixed-signal interface for soil moisture measurements," *Journal Sensors and Actuators A: Elsevier Science Direct*, Vol. 115, pp. 376–384, September 2004.
33. 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," *Journal Sensors and Actuators A: Elsevier Science Direct*, Vol. 115, pp. 434–439, September 2004.
34. L. W. Couch II, *Digital and Analog Communication Systems*, Fifth edition, Prentice Hall, 1996.
35. M. D. Weiss, J. L. Smith, and J. Bach, "RF coupling in a 433-MHz biotelemetry system for an artificial hip," *IEEE Antennas and Wireless Propagation Letters*, Vol. 8, pp. 916–919, 2009.
36. P. M. Mendes, J. H. Correia, M. Bartek, and J. Burghartz, "*Analysis of chip—Size antennas on lossy substrates for short-range wireless microsystems,*" Proceedings SAFE 2002, Veldhoven, The Netherlands, pp. 51–54, November 27–28, 2002.
37. J. D. Parsons, *The Mobile Radio Propagation Channel*, Pentech Press, 1992.
38. M. Pätzold, *Mobile Fading Channels*, Wiley-Blackwell, 2002.
39. M. Blaunstein and J. B. Andersen, *Multipath Phenomena in Cellular Networks*, Artech House Publishers, 2002.
40. H. L. Bertoni, *Radio Propagation for Modern Wireless Systems*, Prentice Hall, 2000.
41. L. A. Rocha, J. A. Afonso, P. M. Mendes, and J. H. Correia, "*A body sensor network for e-textiles integration,*" Proceedings of Eurosensors XX, Gothenburg, Sweden, September 2006.
42. Crossbow (2009). Wireless measurement systems, Crossbow Inc. Online (August 27, 2014): http://www.xbow.com.
43. J. A. Afonso, L. A. Rocha, H. R. Silva, and J. H. Correia, "*MAC protocol for low-power real-time wireless sensing and actuation,*" Proceedings of IEEE International Conference on Electronics, Circuits and Systems—ICECS 2006, Nice, France, December 2006.

44. J. A. Gutierrez, M. Naeve, E. Callaway, M. Bourgeois, V. Mitter, and B. Heile, “IEEE 802.15.4: Developing standards for low-power low-cost wireless personal area networks,” *IEEE Network*, Vol. 5, No. 15, pp. 12–19, September/October 2001.
45. C. Enz, N. Scolari, and U. Yodprasit, “*Ultra low-power radio design for wireless sensor networks,*” Invited Paper, Proceedings of the IEEE International Workshop on Radio Frequency Integration Technology: Integrated Circuits for Wideband Communication and Wireless Sensor Networks, Singapore, December 2005.
46. C. C. Enz, A. El-Hoiydi, J. D. Decotignie, and V. Peiris, “WiseNET: An ultralow—Power wireless sensor network solution,” *IEEE Computer*, Vol. 37, No. 8, pp. 62–70, August 2004.
47. J. P. Carmo and J. H. Correia, “Low-power/low-voltage RF microsystems for wireless sensors networks,” *Microelectronics Journal: Elsevier Science Direct*, Vol. 40, No. 12, pp. 1746–1754, December 2009.
48. Callaway, Jr., E. H., Chapter 3: The physical layer, *Wireless Sensor Networks, Architectures and Protocols*, CRC Press, 2004.
49. N. S. Dias, J. P. Carmo, P. M. Mendes, and J. H. Correia, “A low-power/low-voltage CMOS wireless interface at 5.7 GHz with dry electrodes for cognitive networks,” *IEEE Sensors Journal*, Vol. 11, No. 3, pp. 755–762, March 2011.
50. A. El-Hoiydi, C. Arm, R. Caseiro, S. Cserveny, J. D. Decotignie, C. Enz, F. Giroud, S. Gyger, E. Leroux, T. Melly, V. Peiris, F. Pengg, P. D. Pfister, N. Raemy, A. Ribordy, D. Ruffieux, and P. Volet, “*The ultra low-power WiseNET system,*” Proceedings Design, Automation and Test in Europe, DATE ‘06, Munich, Germany, pp. 1–5, March 6–10, 2006.
51. J. A. Afonso, H. D. Silva, P. Macedo, and L. A. Rocha, “An enhanced reservation-based MAC protocol for IEEE 802.15.4 networks,” *Sensors*, Vol. 11, No. 4, April 2011.
52. W. Y. Lee, *Wireless and Cellular Communications*, Second edition, McGraw-Hill, 1998.
53. E. Callaway, P. Gorday, L. Hester, J. A. Gutierrez, M. Naeve, B. Heile, and V. Bahl, “Home networking with IEEE 802.15.4: A developing standard for low-rate wireless personal area networks,” *IEEE Communications Magazine*, Vol. 40, No. 8, pp. 2–9, August 2002.
54. Smart RF CC2420, 2.4 GHz IEEE 802.15.4/ZigBee-ready RF transceiver, Texas Instruments Incorporated. Online (August 27, 2014): http://www.ti.com/.
55. Smart RF CC2430, A true system-on-chip solution for 2.4 GHz IEEE 802.15.4/ZigBee, Texas Instruments Incorporated. Online (August 27, 2014): http://www.ti.com/.
56. Dust, Dust Networks Inc. Online (February 27, 2012): http://www.dust-inc.com/.
57. Sensicast, Sensicast Systems. Online (August 27, 2014): http://www.sensicast.com/.
58. N. S. Dias, J. F. Ferreira, C. P. Figueiredo, and J. H. Correia, “*A wireless system for biopotential 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.
59. A. C. M. van Rijn, A. Peper, and C. A. Grimbergen, “High-quality recording of bioelectric events, Part 1: Interference reduction, theory and practice,” *Medical & Biological Engineering & Computing*, Vol. 28, No. 5, pp. 389–397, September 1990.
60. R. F. Yazicioglu, T. Torfs, P. Merken, J. Penders, V. Leonov, R. Puers, B. Gyselinckx, and C. V. Hoof, “Ultra low-power biopotential interfaces and their applications in wearable and implantable systems,” *Microelectronics Journal: Elsevier Science Direct*, Vol. 40, No. 9, pp. 1313–1321, September 2009.
61. J. P. Carmo, L. M. Goncalves, and J. H. Correia, “Thermoelectric microconverter for energy harvesting systems,” *IEEE Transactions on Industrial Electronics*, Vol. 57, No. 3, pp. 861–867, March 2010.
62. Sensium TZ1030, Ultra low power smart sensor interface and transceiver platform, Toumaz Technology Limited. Online (August 27, 2014): http://www.toumaz.com.
63. T. Karacolak, A. Z. Hood, and E. Topsakal, “Design of a dual band implantable antenna and development of skin mimicking gels for continuous glucose monitoring,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 54, No. 4, pp. 1001–1008, April 2008.

64. E. Y. Chow, Y. Ouyang, B. Beier, W. J. Chappell, and P. P. Irazoqui, "Evaluation of cardiovascular stents as antennas for implantable wireless applications," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 57, No. 10, pp. 2523–2532, October 2009.
65. F. J. O. Rodrigues, J. H. Correia, and P. M. Mendes, "*Modeling of a neural electrode with MEMS magnetic sensor for telemetry at low frequencies*," Proceedings MicroMechanics Europe, MME 2009, Toulouse, France, pp. D19/1–D19/4, September 20–22, 2009.