9 A System Perspective

9.1 Introduction

In recent years, significant scientific and industrial efforts have been directed toward ubiquitous sensing electronics. The concepts of "smart" devices, buildings, and cities providing us with useful information about our surrounding environment in order to improve our living conditions implicitly require the installation of a very large number of sensor and actuator devices communicating wirelessly with each other and with other networking devices. The notion of such an "Internet of Things" of devices connected to the Internet has been visualized since the early 1990s [1, 2]. Energy harvesting technologies are particularly suitable for such devices, which require very low power consumption and large energy autonomy, permitting them to operate for long periods of time without (secondary) battery recharging or the need for (primary) battery substitution.

In addition to exploring harvesting the available ambient energy in its various forms, ultralow power communication, control, and sensing electronics are necessary. Integrated electronics technologies such as CMOS have already enabled the implementation of commercially available electronic circuits dissipating power in the order of a few μW and down to tens or a few hundred nanowatts. There exists, for example, a plurality nanowatt commercial comparator circuits, such as [244]. Furthermore, complete systems such as passive UHF radio frequency identification (RFID) tag integrated circuits (ICs) require as low as 6.2 μW to be read wirelessly from a reader device [245].

Having presented various energy harvesting solutions as well as power conversion circuits in the previous chapters, in this chapter we discuss the challenges for wireless sensing platforms exploring energy harvesting.

9.2 Wireless Sensing Platforms

The architecture of a wireless sensing platform with energy harvesting capability is shown in Figure 9.1 [246]. It comprises a number of transducer devices harvesting power from different energy sources such as solar, thermal, vibration, or RF and converting it to dc electrical power. A suitable dc–dc converter circuit converts the dc output voltage of the transducers to a suitable dc voltage value

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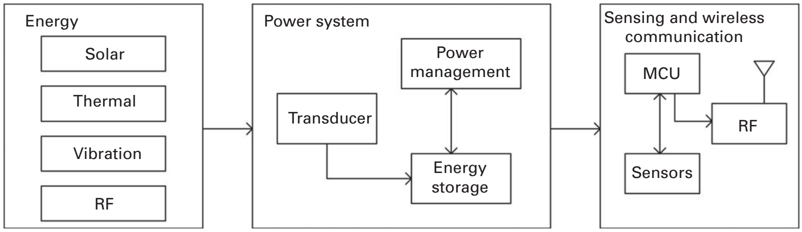

Figure 9.1 Block diagram of wireless sensing platform with energy harvesting capability.

and supplies a storage device. A power management unit (PMU) optimizes the conversion efficiency of the dc electrical power and controls the operating duty cycle of the platform. The collected power is used to power a microcontroller device that reads various sensors, computes the required information, stores to or retrieves information from memory, and finally communicates information wirelessly using a suitable transceiver device.

The combination of multiple energy harvesting transducers is preferred due to the strongly time-varying and unpredictable nature of the available ambient energy. A summary of typical values of available power density is presented in Table 9.1 [246]. Although RF ambient energy availability appears to be very low compared to other forms of energy, the easy integration of RF energy harvesters with wireless transceivers and other transducers (we have seen in previous chapters that rectennas can be easily integrated with solar cells and even thermoelectric generators) as well as the capability of integration with intentional wireless power transmission devices makes it a convenient source of energy for such platforms.

Efficient combination of dc sources that are variable and may have very different relative values is not a trivial task due to the fact that the efficiency and impedance of each source depend on the input ambient energy and also the fact that each source presents a load to the others, which can affect the combined efficiency of the system. Efficient combination of different RF energy harvesters has been addressed, for example, in [145, 223, 247]. In [247], it was demonstrated that the loading effect of the different source inputs can be mitigated by the use of additional circuit paths that include "shortcut" diode elements in order to minimize the loading effect of underperforming rectifier circuits. Efficient combination of solar cell outputs into solar modules is also discussed broadly in the literature, such as in [248, 249]. In the case of solar modules, one simple method to isolate the various cells and eliminate undesired loading is through the use of blocking diodes. In the case of low available power scenarios, one needs to carefully consider the efficiency loss associated with the power dissipated within the dc blocking or shortcut diodes. An efficient power combining circuit from a light and RF harvester was demonstrated in [250] where two different rectifier paths are included and are optimized under different light intensity and

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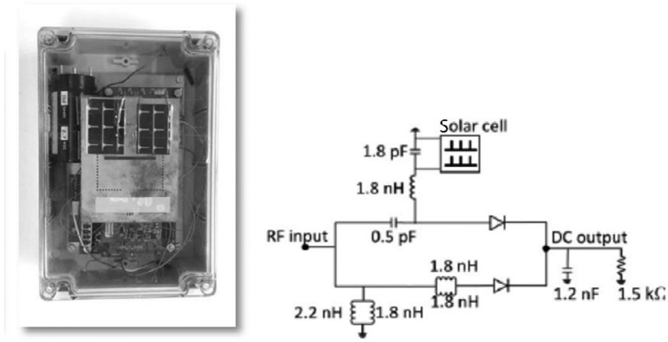

Figure 9.2 Solar and RF power combining prototype sensor [250].

RF power conditions (Figure 9.2). In general, added circuit complexity results in a potentially lower maximum achievable efficiency due to the use of more (nonideal) circuit elements, but it achieves a better average efficiency for different input energy scenarios. One further possibility when one of the two power sources is much lower than the other is the use of the low-power source as an efficiency-boosting circuit for the higher-power source, as was done by the authors in [251] by using the output of a thermoelectric energy harvester to prebias an RF energy harvesting circuit.

Table 9.1 Selected ambient energy sources and available transducers [246].

Parameter/ energy	Solar	Thermal	Vibration	RF
Power density	100 mW/cm^2	60 μW/cm^2	200 μW/cm^3	0.00002–1 μW/cm^2
Output voltage	0.9 V (a-Si cell)	20–500 mV ($\Delta T < 10$ deg)	10 V	10–100 mV
Power	60 mW	0.52 mW	8.4 mW	1.5 μW
Condition	6.3 × 3.8 cm Flex. cell AM1.5 illum.	TEG $\Delta T = 5.6°$	Piezoel. Shoe mounted	Power dens. 0.15 μW

9.3 Voltage Conversion Circuits for Energy Harvesting Transducers

The output voltage of the various energy harvesting transducer circuits varies significantly during the operating time of the transducer as well as between different transducer types as shown in Table 9.1. Therefore, dc–dc voltage conversion circuits are necessary in order to bring the output voltage to a value that is

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suitable for the microcontroller, sensing and wireless communication circuits of the wireless sensing platform (Table 9.1).

Table 9.2 shows some low-power voltage conversion circuits that are typically used in existing sensing platforms. The input voltage sensitivity of such circuits is typically in the order of a few hundred mV. Furthermore, typically dc–dc converter circuits present hysterisis in their behavior, which results in a higher voltage required for them to begin operation from zero input conditions, known as cold start. Once operating, the input voltage may be reduced below the cold start value maintaining operation. The LTC3107 device uses a self-oscillating converter with a transformer-based oscillator, which allows it to have a very low sensitivity and begin operation for input voltages as low as 20 mV, when a transformer with a 1:100 ratio is used [106]. Despite the very low startup voltage, the input impedance of the self-oscillating dc–dc converter is also low in the order of a few Ω [106], which makes it unsuitable for RF energy harvester comprising rectifier circuits where the optimum load impedance at low input powers is in the order of a few KΩ (see Section 7.3). In addition, it is not possible to control the input impedance, which makes it unsuitable to implement some type of maximum power point tracking (MPPT) system [252]. The output voltage is determined by the electronics of the sensing platform, and sometimes it can be changed or the converter circuit may provide a plurality of different output voltage values. The quiescent current represents the dissipated power that the converter itself requires to operate when no output load is connected to it, i.e., the microcontroller, sensor, and RF transceiver circuitry is not active.

Table 9.2 Selected low-power voltage conversion circuits for energy harvesting transducers [246].

Name	Manuf.	Quiesc. I_q	Sensitivity	V_o	EH source
LTC3107, LT3108	Analog Dev.	80 nA 200 nA	20–500 mV	2.35 V, 3.3 V 4.1 V, 5V	Thermal
BQ25505	TI	325 nA	100 mV 330 mV (cold)	5.0 V	Solar, thermal
SPV1050	STMicro		180 mV	3.6 V	Solar, thermal
MAX17710	MAXIM	625 nA	750 mV	6.0 V	RF, solar, thermal
PCC110	Powercast		−17 dBm	-	RF

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9.4 Low-Power Microcontroller Units (MCU)

The TI MSP430 microcontroller family has traditionally been used for low-power applications, especially related to RFID systems [253, 254]. Other low-power microcontrollers such as the SiM3C1XX family from Silicon Laboratories or the PIC24F16KA102 from Microchip Technologies present suitable alternatives. Table 9.3 summarizes some of the available MCUs.

Table 9.3 Low-power microcontroller (MCU) circuits for wireless sensing platforms [15].

Name	Clock speed	Operating voltage	Current
TI MSP430	16 MHz 4 KHz	1.8–3.6 V	7 mA 5–6 μA
Microchip PIC24F	32 MHz 32 KHz	1.8–3.6 V	11 mA 8–15 μA
Silicon Labs SiM3C1XX	80 MHz 16.4 KHz	1.8–3.6 V	33 mA 175–250 μA

A higher clock speed results in faster computation but also in a higher dissipation. In fact, the energy E_{MCU} dissipated in an MCU that is operated for a time interval T is given by [252]

$$E_{MCU} = V_{CC} I_o T + V_{CC} m(V_{CC}) T F_{CLK}, \tag{9.1}$$

where $m(V_{CC})$ is the slope of the linear curve of the current versus clock frequency F_{CLK}, which depends on the supply voltage V_{CC}. I_o is the current that is dissipated by the MCU in active mode when the clock frequency is $F_{CLK} = 0$ Hz. A typical current versus clock frequency curve is shown in Figure 9.3. The energy dissipation can be reduced by reducing the supply voltage V_{CC}, the clock frequency f_{CLK}, and the total operating time T. The computational requirements for such low-power sensing platforms are typically not heavy and therefore one can strive to use the minimum possible clock frequency. Nonetheless, there is some minimum fixed energy dissipation overhead associated with the current I_o that can be minimized by reducing as much as possible the operating interval T. This can be done by maximizing the efficiency of the implemented code programming the MCU because the number of executed instructions is proportional to $T f_{CLK}$ [252]. The minimum supply voltage of the MCU is limited by the voltage required for its memory, which for example is limited to 1.8 V for FRAM memory technologies.

Finally, all MCUs have active modes where they perform computation, read or write to the memory, or communicate with the peripheral devices such as sensors and wireless communication circuits and additionally power saving modes in order to be able to reduce their overall power consumption [252]. One type of

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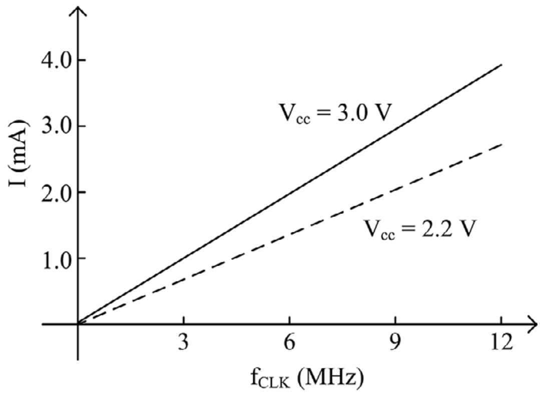

Figure 9.3 Representation of MCU current consumption versus clock frequency f_{CLK} for different supply voltage values V_{CC}, based on [252].

power saving mode is "hibernate" modes, where all clocks are stopped. A second type of power saving mode is one where only a real-time clock (RTC) oscillator with frequency in the order of 5–60 kHz operates. Hibernate modes are the least power consuming, but the MCU requires an external stimulus to wake up from this dormant state, and the energy required to operate such a sensor should be considered in the overall system energy budget. It is possible to use an external timer circuit that has a very low current consumption (e.g., 30 nA) to bring the MCU out of the hibernate mode [252]. The RTC mode is less energy efficient; however, the active oscillator requires a current in the order of 0.5 μA.

9.5 Sensor Circuits

Texas Instruments and many other companies offer a series of low-power sensors that can be used together with the various microcontroller and radio transceiver circuits for the wireless sensor platforms. One example is the digital (11 bit) low-power humidity and integrated temperature sensor HDC1000. Its average current for a humidity and temperature measurement is 1.2 μA from a 3 V supply. A variety of low-power digital or analog sensors can be considered. Nonetheless, sensor circuits may significantly increase the dissipation power requirements of the platform, and they need to be carefully selected.

Alternatively, antenna-based sensing techniques [255, 256] can be used that minimize the power dissipation. According to antenna-based sensing, an antenna can be designed such that a change in a desired sensing parameter – temperature, material permittivity, a level of some liquid, or the presence of cracks in a material, just to name a few examples – can result in a modification of an antenna parameter such as its input impedance matching or gain. The antenna is part of an RFID tag, and modification of the antenna parameter results in a reduction in the backscattered power toward the reader when the tag is interrogated, which,

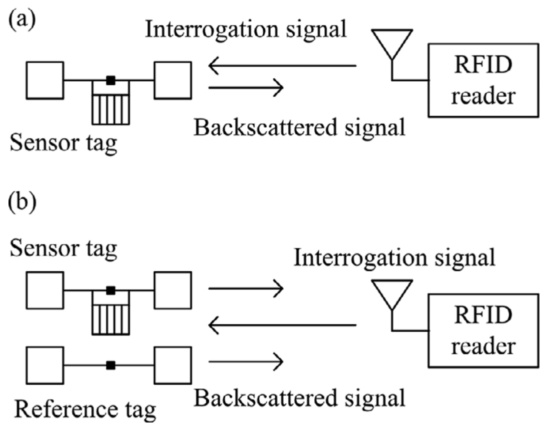

Figure 9.4 RFID tags with antenna-based proximity sensing: (a) single tag, (b) dual tag, based on [257].

in turn, can be translated by the reader in a sensing parameter. There are several challenges in an antenna-based sensing scheme regarding measurement accuracy and repeatability; however, the fact that the sensing capability is superimposed in the communication scheme without essentially requiring additional power makes it an attractive sensing option. One way to improve or facilitate the sensing measurement is to implement a differential measurement by employing two tags in proximity to each other where one tag is a reference tag and the second tag is the sensing tag. The reader interrogates both tags and determines the sensing parameter by comparing the backscattered power from the two tags. One such system implementing a proximity sensor, as shown in Figure 9.4, was demonstrated in [257].

9.6 Wireless Transceivers and Backscatter Communication

Finally, there exist also several low-power wireless communication transceiver modules that can be used in such platforms and a selected subset of them is presented in Table 9.4. Commonly used license-free frequency bands are used that range from sub-GHz range including 315 MHz, 433 MHz, and UHF RFID frequency bands of 868 MHz and 915 MHz to the 2.45 GHz industrial, scientific, and medical (ISM) band [252]. Many of the devices support the IEEE 802.15.4 standard at 868 MHz, 915 MHz, and 2.45 GHz bands, although some of the devices are designed for proprietary modulation, such as the TI CC2500 device. The transmit power is limited by the operating band regulations and typically ranges from 5 to 15 dBm, although the trade-off between power dissipation minimization and operating range maximization may further limit the transmitted power.

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Table 9.4 Selected low-power transceiver circuits for wireless sensing platforms [252].

Manufacturer	Device	Frequency
Analog Devices	ADF7241	2.45 GHz
	ADF7020	433, 868, 915 MHz
Atmel	AT84RF23X	2.45 GHz
	ATA5428	433, 868 MHz
Microchip	MRF24J40	2.45 GHz
	MRF89XA	868, 915 MHz
TI	CC25XX	2.45 GHz
	CC11XX	315, 433, 868, 915 MHz
Silicon Labs	Si4420	315, 433, 868, 915 MHz

Low-power wireless communication transceivers require an amount of power that is in the order of mW when transmitting or receiving. Backscatter communication presents a very low-power alternative that does not use an active transmitter or receiver circuit, thereby minimizing the dissipated power for communication to the μW range. In backscatter radios, information is transmitted by modulating the load connected to an antenna [6]. A receiving antenna typically scatters partially an impinging wave [258]. When a load connected to the antenna is changed according to a pattern that corresponds to an information signal that we want to transmit, the signal scattered by the antenna is modulated according to the load and therefore it contains the desired information. In a passive RFID system, the signal that impinges on the antenna is an interrogating carrier signal from a reader device. The reader then receives the scattered signal from the antenna and demodulates the information that has been added to it by the tag. The tag uses the carrier signal from the reader to power itself before it can modulate the backscattered signal to the reader. A conceptual block diagram of the system is shown in Figure 9.5. Current tags require a minimum power in the order of 6.2 μW to power themselves [201]. Commercial reader devices transmit power in the order of 30 dBm depending on regulations and use antennas with approximately 7 dB of gain.

The operating range of the backscatter communication system is limited by the minimum power required to power the tag. The tag range can be estimated by applying the Friis transmission formula twice, once for the carrier signal propagating from the reader to the tag and a second time for the backscattered signal from the tag to the reader, resulting in

$$R = \frac{\lambda_o}{4\pi}\sqrt{\frac{P_t G_t G_r \tau}{P_{th}}}, \tag{9.2}$$

where λ_o is the wavelength, P_t is the transmitted power by the reader, G_t is the gain of the reader antenna, G_r is the gain of the tag antenna, P_{th} is the sensitivity of the RFID chip, and τ is the transmission coefficient [259],

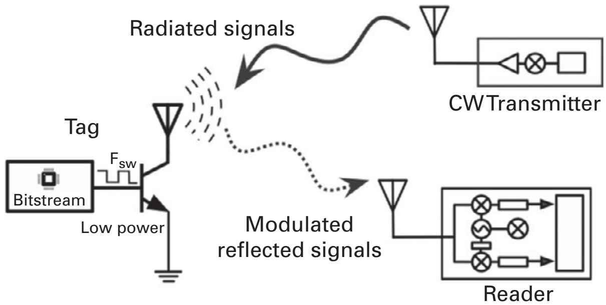

Figure 9.5 Backscatter communication.

$$\tau = \frac{4R_a R_c}{|Z_c + Z_a|^2}. \tag{9.3}$$

$Z_c = R_c + jX_c$ and $Z_A = R_A + jX_A$ are the complex impedances of the RFID chip and the tag antenna respectively. The power transmission coefficient τ reflects how good is the impedance match between the RFID tag antenna and chip and becomes equal to 1 when $Z_c = Z_A^*$, where $()^*$ denotes the complex conjugate. The range equation (9.2) can be normalized to a reference range factor R_o

$$R_o = \frac{\lambda_o}{4\pi}\sqrt{\frac{P_t G_t}{P_{th}}} \tag{9.4}$$

as

$$\frac{R}{R_o} = \sqrt{G_r \tau}. \tag{9.5}$$

Using $P_t = 30$ dBm, $P_{th} = 6\ \mu$W, $\lambda_o = 0.33$ m corresponding to an operating frequency of 915 MHz and $G_t = 7$ dB, one can compute that the reference range factor of an RFID system is $R_o = 23.8$ m. This is an optimistic estimate of the actual achievable range as typically a tag antenna may have less gain than 0 dB and also the τ parameter can be less than 1 due to an impedance mismatch. Furthermore, one should keep in mind that the propagation environment may result in additional losses that correspond to a worse performance than the one predicted by applying the Friis transmission formula.

It is possible to increase the operating range by implementing a bistatic configuration where the reader is separated in a power supply circuit that can be placed closer to the tsg and a receiver circuit that can be placed much further from the tag. This way it was possible to demonstrate experimentally an operating range between the tag and the receiver of more than 100 m [260].

Perhaps the most widely known wireless sensing platform based on backscatter communication is the wireless Internet service provider (WISP) platform. It implements a backscatter communication tag using an MSP430F1232 microcontroller, it is modular, and it can integrate a number of sensors. A block diagram of the WISP circuit is shown in Figure 9.6.

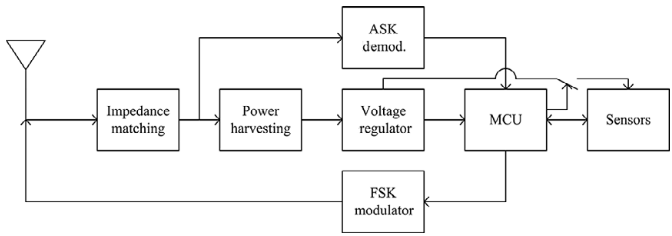

Figure 9.6 Representation of WISP circuit block diagram, based on [253].

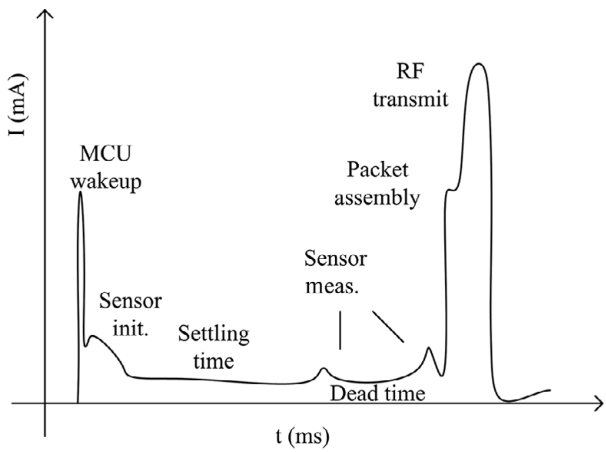

Figure 9.7 Representation of current drawn during a packet transmission, based on [252].

9.7 Energy Consumption

An example of the current drawn from a storage element during a transmission cycle of a wireless sensing platform is shown in Figure 9.7 [252]. In Figure 9.7, we can identify the different stages of the packet transmission from the wakeup of the MCU to the sensor measurements and transmission of a packet. How can we minimize the energy consumption of the system? The RF transmission power can be greatly reduced by employing a backscatter communication system if the operating range of the system permits it. A significant amount of power is dissipated in the sensor through long settling times and time intervals between measurements corresponding to a dead time. It is therefore imperative to properly select low-power sensors or if possible employ techniques such as antenna-based sensing if possible.

Assuming that the energy storage element is a capacitor with capacitance C that the duration of the interval where the system is active is T, an approximate expression of the required energy is given by [253]

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$$V_{cc}(I_s + I_m)T \leq \frac{1}{2}C\left(V_{req}^2 - V_{cc}^2\right), \tag{9.6}$$

where I_s is the average current dissipated by the sensor, I_m is the average current dissipated by the MCU and the communication unit, and V_{cc} is the supply voltage. V_{req} is the required voltage that the capacitor must be charged in order to have sufficient energy to power the wireless sensor platform.

9.8 Ambient Backscattering

Backscatter communication permits us to reduce the power consumption of the wireless sensing platform by not requiring an active transceiver due to the fact that an external reader device provides the energy for the transmission and reception of information. Actually, the reader provides a carrier signal, which is used both to power the tag and to convey the information. The concept of ambient backscattering, proposed by a team of the University of Washington [261], further eliminates the need for the reader transmitting a carrier to power the tag and transfer the information back to the reader. In ambient backscattering, a tag modulates the scattered ambient signals from its antenna by changing its load. Furthermore, the tag may be powered by ambient RF signals such as FM, TV, or cellular phone signals. This is a circuit that relies on ambient RF signals to both power itself and to communicate. In [261], information bit rates of 100 bps, 1 bps, and 10 bps were used to demonstrate communication between the tag and the receiver reader for distances of a few feet in indoor and outdoor scenarios while the ambient signal was provided by a TV station.

We also implemented at Heriot-Watt University an ambient backscatter system and demonstrated communication using ambient FM signals (see Figure 9.8) [262]. The tag modulated scattered signals from an FM station in the Edinburgh area located 34.6 km away from the laboratory. The power of the FM station carrier signal was measured to be approximately −51 dBm in the vicinity of the tag antenna in the laboratory. Indoor experiments in the lab were performed, shown in Figure 9.9, where an operating distance between the tag and the receiver of a few meters was demonstrated.

9.9 Problems and Questions

1. How does the MCU current consumption depend on the supply voltage and on the clock frequency?
2. What is antenna-based sensing?
3. What are the fundamental circuit blocks of a wireless sensing platform?
4. Describe the operating principle of backscatter communication. What is the difference between a monostatic and a bistatic configuration?

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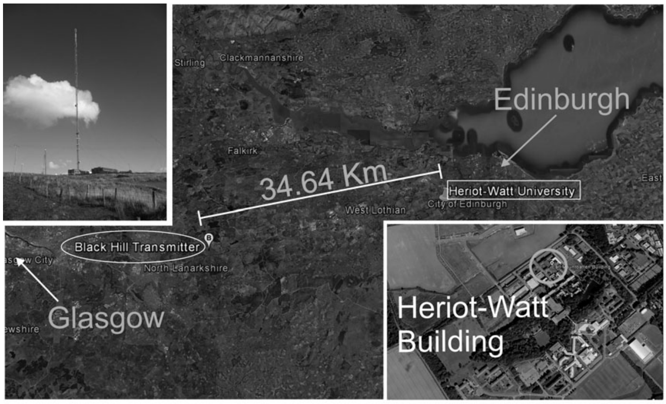

Figure 9.8 Ambient backscattering experiment using an FM radio station near Glasgow located 34.6 km from Edinburgh and Heriot-Watt University. ©2017 IEEE. Reprinted with permission from [262]

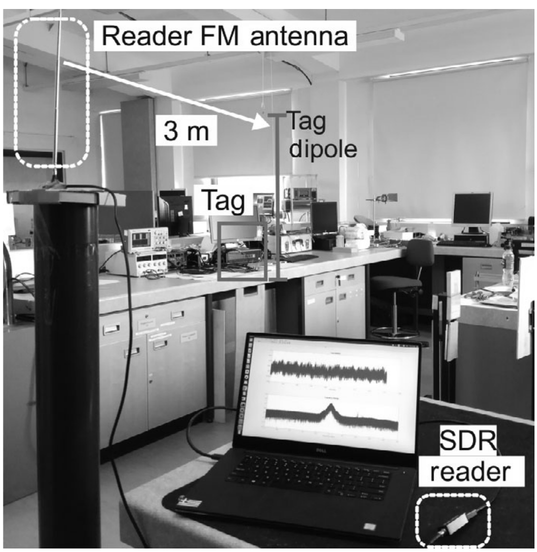

Figure 9.9 Ambient backscattering experiment lab setup at Heriot-Watt University. ©2017 IEEE. Reprinted with permission from [262]

5. What is the theoretical operating range of an 868 MHz perfectly matched RFID tag with sensitivity −20 dBm and gain −5 dB, when it is used with a reader that transmits 30 dBm of power with a 7 dB antenna (assume no polarization mismatch between the two antennas)?
6. What is ambient backscattering?
7. Given a backscatter system with an energy storage capacitor $C = 1\ \mu$F and a supply voltage of 1.8 V, what is the required minimum voltage that the capacitor must be charged to in order for it to be able to actively operate for 1 μs?

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