Chapter 7
RF Energy Harvesting Networks: Existing Techniques and Hardware Technology

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7.1 Introduction

Radio frequency (RF) is any of the electromagnetic wave frequencies that lie in the range extending from below 3 kHz to about 300 GHz, and that include the frequencies used for communications or radar signals [115]. The radio spectrum is bounded on the lower limit by low frequency signals like sound and on the higher limit by signals such as visible light, as shown in Fig. 7.1.

RF signals can be primarily generated from two sources: dedicated and ambient. The former can be deployed to provide energy when predictable supply is expected, usually from license-free frequency bands of radio spectrum. The latter refer to RF transmitters originally not intended for energy transfer, such as TV towers, radio towers, and Wi-Fi routers. The continuous miniaturization of electronics has led to an increasing interest in ever more tiny wireless autonomous sensor systems. This, in turn, has led to the need for low-power electronics and alternatives to battery power. Of the different methods that exist for scavenging energy (e.g., solar, wind, vibration, and thermal), RF energy is seen as an attractive possibility.

This introductory chapter provides a basic understanding of RF energy harvesting (RFEH) techniques. Starting with a brief explanation of existing wireless power transfer techniques in Sect. 7.2, we explain the advantages of RFEH over other techniques, then describe the underlying electronics hardware design of an RFEH system from the power source (e.g., dedicated and ambient) to the energy scavenger components. Sections 7.3 and 7.4 present the design considerations, current

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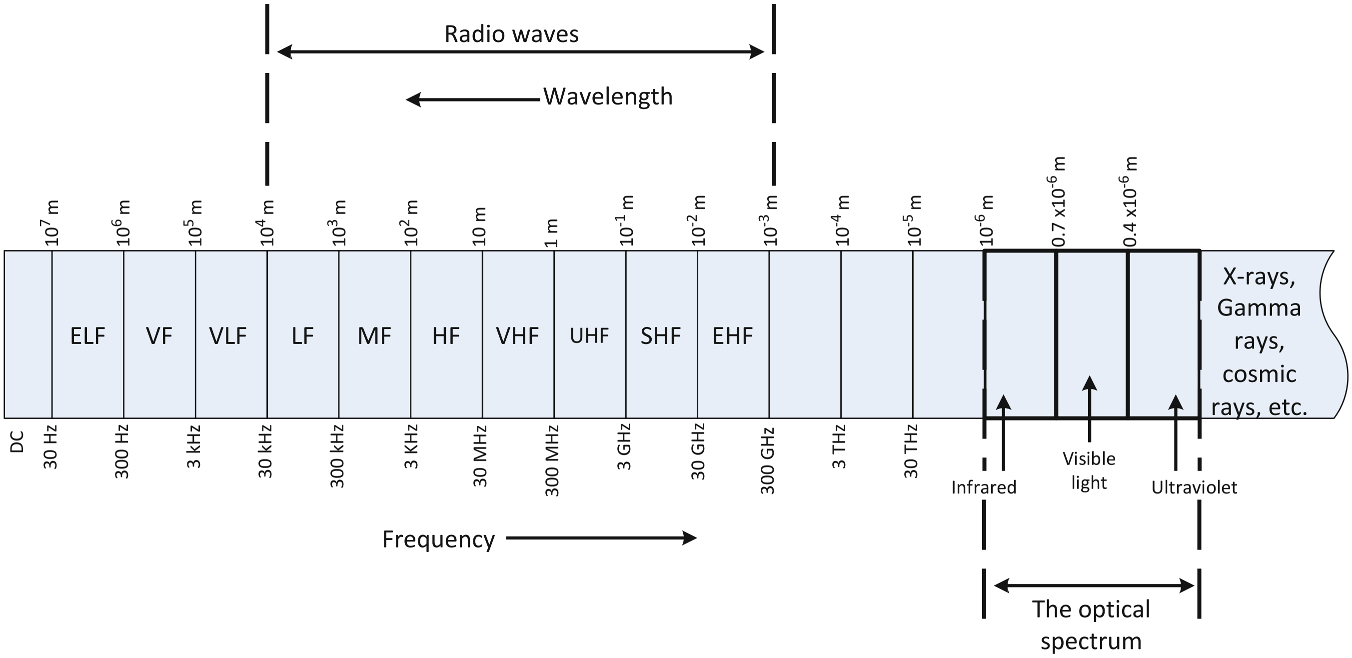


Fig. 7.1 Electromagnetic spectrum

state-of-the-art applications and commercially available products for dedicated and ambient sources, respectively, and finally expand to future applications and challenges ahead. We finally provide a brief summary in Sect. 7.5.

7.2 RF Energy Harvesting Techniques

RFEH, also referred to as RF energy scavenging, is one of the main wireless energy transfer (WET) techniques. The other methods are inductive coupling, magnetic resonance coupling, and capacitive coupling. In the following originally subsections, we survey and compare these three transfer methods, then focus on RFEH systems.

7.2.1 Overview of RF Energy Harvesting

7.2.1.1 Wireless Power Transfer Techniques

The development of wireless charging technologies is advancing toward two major directions: radiative wireless charging (or RF-based) and non-radiative wireless charging (or coupling-based) such as inductive, magnetic resonance, and capacitive. Inductive coupling [60] is based on magnetic coupling that delivers electrical energy between two coils tuned to resonate at the same frequency. The electric power is carried through the magnetic field between the coils. Magnetic resonance coupling [92] utilizes evanescent-wave coupling to generate and transfer electrical energy between two resonators. The resonator is formed by adding a capacitance on an induction coil. Both these techniques are near-field wireless transmissions featured with high power density and conversion efficiency. The power transmission efficiency depends on the coupling coefficient, which further relies on the distance between two coils/resonators. The power strength is attenuated according to the cube of the reciprocal of the distance (60 dB per decade of the distance) [122, 197], which results in limited transfer. Besides, both inductive and resonance couplings require calibration and alignment of coils/resonators at transmitters and receivers sides. Therefore, they are not suitable for mobile and remote replenishment or charging.

On the other hand, in capacitive power transfer (CPT), the electric field is confined between conductive plates, alleviating the need for magnetic flux guiding and shielding components that add bulk and cost to inductive solutions [85]. Although CPT is developing quickly, it is perceived as only suitable for low-power levels over short transfer distances, and it is limited in range to short gap distances (i.e., <1 mm) [25]. Furthermore, the realizable amount of coupling capacitance is restrained by the available area of the device, imposing a challenging design constraint.

In contrast, RF energy transfer has no such limitation. As the radiative electromagnetic wave cannot retroact upon the antenna that generated it at a distance of above $\lambda/2\pi$ [71], RF energy transfer can be regarded as a far-field energy transfer technique. The idea to use electromagnetic radiation for power transfer was pioneered by Nicolas Tesla in the end of the nineteenth century by conducting experiments on microwave technology. In 1931, he demonstrated the principle by wirelessly powering a light bulb located 5 m away from a power source of 15 kW in New York. It was until 1964, when W.C. Brown, who is regarded as the principal engineer of practical wireless charging, realized the conversion of microwaves to electricity through a rectenna [15]. In powering a model helicopter, Brown demonstrated the practicality of microwave power transfer. During the past decade, with the advancement in complementary metal-oxide-semiconductor (CMOS) circuit design, higher circuit density, and efficient energy storage, low-power transfer for powering wireless sensors began to attract increasing attention. Table 7.1 shows a comparison of the four main WET techniques.

Table 7.1 Contents of the wireless energy transfer (WET) techniques

WET technique	Field region	Propagation	Effective distance	Efficiency	Applications
RF energy transfer	Far field	Radiative	Typically from several meters to several kilometers (depends on distance, frequency, and sensitivity of the harvester)	0.4% at −40 dBm, >18.2% at −20 dBm, and >50% at −5 dBm input power, respectively [116]	Wireless sensor networks [132], wireless body networks [226]
Resonant inductive coupling	Near field	Non-radiative	From a few millimeters to a few centimeters	From 5.81 to 57.2% when frequency varies from 16.2 to 508 kHz	RFID tags, smart cards, electric vehicle [64, 129], cell phone charging [153], and inductive toothbrush [181]
Magnetic resonance coupling	Near field	Non-radiative	From a few centimeters to a few meters	From >90 to >30% with distance from 0.75 to 2.25 m [209].	PHEV charging [82], cellular phone [211]
Capacitive coupling	Near field	Non-radiative	Less than a millimeter	From 90 to 40% for air gaps varying from 0.1 to 1 mm [25].	Electric vehicle [26], contactless USB [205], rotating machinery [109]

7.2.1.2 Radiative RF Power Transfer

Radiative far-field wireless power transfer utilizes diffused RF/microwave as a medium to carry energy. Under idealized conditions, the received energy is governed by the *Friis' free space equation*:

$$p_r = G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 p_t, \tag{7.1}$$

where p_r is the received RF power, d the distance between the receiver and the source power p_t, G_t the source antenna gain, G_r the receiver antenna gain, and λ the wavelength of the carrier frequency.

Friis' equation is accurate for long-distance transmission such as satellite communications when there is negligible atmospheric absorption. However, these ideal conditions are almost never achieved in ordinary terrestrial communications due to obstructions, absorption, reflection, and more particularly in the case of wireless rechargeable sensor networks, to polarization loss and effects of power rectification and conversion. Therefore, empirical adjustments are sometimes necessary [159]. A more general form of average received power can be estimated as follows:

$$p_r \propto G_t G_r \left(\frac{\lambda}{d} \right)^n p_t. \tag{7.2}$$

However, to get useful results, further adjustments are usually necessary resulting in much more complex relations, such the Hata Model for Urban Areas [52].

Radiative RF power transfer can be further sorted into directive RF power beamforming (radiated toward a direction) and nondirective RF power transfer (radiated isotropically) [147]. For point-to-point transmission, beamforming transmits electromagnetic waves [225] and can improve the power transmission efficiency. However, the limitation of beamforming lies in the fact that the charger needs to know the exact location of the energy receiver. Due to the obvious limitation of this technique, RF wireless charging is usually realized through nondirective radiation.

7.2.1.3 RF Energy Harvesting System

An RFEH system consists of the following three elements:

- An RF energy source,
- An RF energy harvester, and
- A load used for the application.

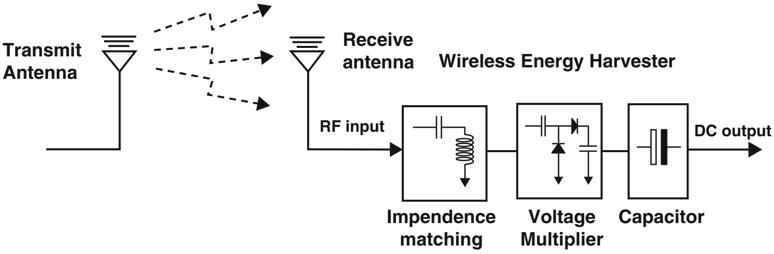


Fig. 7.2 RF energy harvesting (RFEH) system [108]

Figure 7.2 illustrates the block diagram of a typical RF energy harvester made of an antenna, an impedance matching circuit, a rectifier/filtering circuit, a voltage multiplier or boost converter, and a power management module that may include an energy storage unit. Each element of the system is described in the next sections.

7.2.2 RF Energy Sources: Dedicated Vs. Ambient

Unlike energy scavenging from environmental sources such as solar, wind, thermal, or kinetic energy, radiative radio-frequency must provide controllable, steady, and stable power over distance for the energy harvesters. For example, in a fixed RFEH Network, the harvested energy is predictable and relatively stable over time due to fixed distance [208].

RF energy can be generated and captured from two origins: intentional or dedicated RF sources, and unintentional or ambient RF sources. The former can be deployed to provide energy when predictable supply is expected, usually from license-free frequency bands of the radio spectrum. The latter refer to RF transmitters originally not intended for energy transfer, such as TV or radio towers, and Wi-Fi routers.

7.2.2.1 Dedicated RF Sources

Dedicated RF sources can be deployed to transmit in the license-free ISM frequency bands. However, these sources may incur high costs. Moreover, ISM-bands output power is limited by regulations, such as the FCC and the general ISM regulations, out of safety and health concerns related to radiations [66]. For example, in the 915 MHz ISM band, the maximum allowed power is 4 W [46]. Even at this highest setting, the received power at a moderate distance of 20 m is attenuated down to only 10 μW. Due to these restrictions, several dedicated RF sources may need to be set up in order to meet user's demand. Power beacons (PB) [63], which are stations deployed in an existing cellular network for recharging sensors and mobile devices, illustrate such scenario by creating direct line-of-sight (LOS) links to mobiles. Sharp energy beams formed at PBs aim to counteract propagation loss and reduce power consumption of mobile devices, enabling close-to-free-space power transfer [56].

As the RFEH process with dedicated origin is fully controllable, it is suitable to support applications with QoS constraints. These sources can also be mobile, to travel and transfer power to rechargeable wireless network nodes. In [40–42, 103], different transmission schemes for mobile RF power transmitters are investigated for replenishing wireless sensor networks (WSNs).

7.2.2.2 Ambient RF Sources

Ambient RF sources refer to transmitters not intended for energy transfer. This energy is essentially free. Their transmission powers vary significantly, from around 10^6 W for TV tower, 10 W for cellular systems, to about 0.1 W for mobile devices and Wi-Fi systems. These sources can further be split into static and dynamic sources.

- Static ambient RF sources: provide relatively stable and foreseeable power over time, such as TV and radio towers. However, there could be long-term and short-term fluctuations due to service schedule (e.g., TV and radio) and fading, respectively. Their power density is usually very small. As a result, a high-gain antenna for many frequency bands and a rectifier designed for wideband spectrum should be considered. In [48], the performance analysis of a sensor powered by static ambient RF sources is performed using a stochastic geometry approach. An interesting finding is that when the distribution of RF sources exhibits stronger repulsion, larger RFEH rate can be achieved at the sensor.
- Dynamic ambient RF sources: work periodically or use time-varying transmit power (e.g., a Wi-Fi access point and licensed users in a cognitive radio network (CRN)). The energy collected from these sources has to be adaptive and possibly intelligent to search for harvesting opportunities in a certain frequency range. The study in [97] is an example of energy harvesting from dynamic ambient RF sources in a CRN. A secondary user can harvest RF energy from nearby transmitting primary users and transmit data when it is sufficiently far from primary users, or when the nearby primary users are idle.

7.2.3 General Architecture of an RF Energy Harvester

Most of the RF energy harvester circuit implementations use semiconductor-based rectifying elements to convert RF to DC power thanks to their low cost and small form factor. The semiconductors are either bridges of discrete components such as Schottky diodes or integrated circuits (ICs) based on CMOS technology with diode-connected transistors. Schottky diodes are regularly chosen when large amounts of power are required, such as in space Solar Power Station (SPS) systems. Examples of Schottky diodes implementation of RF rectifiers are shown in Table 7.2, which include Avago Technologies' HSMS [10] and Skyworks' SMS [176] families of surface mount microwave detector diodes. On the other hand, CMOS technology is employed at low power because of lower parasitic values and customizable rectifiers that significantly increase the harvester efficiency. Furthermore, digital logic can be incorporated onto the same die [198]. Table 7.2 shows the circuit performance of some up-to-date designs.

Literature characterizes energy harvesting circuits from two different metrics: efficiency and sensitivity. Efficiency can be expressed as a total energy harvesting circuit efficiency or a power-conversion efficiency, while sensitivity is defined as the minimum power necessary to power an IC [198]. The efficiency of the energy scavenger depends on the performance and type of antenna, the accuracy of the impedance matching between antenna and load, and the power efficiency of the rectifier and voltage multiplier. On the other hand, sensitivity depends on the semiconductor technology used and the application, as different sensors and protocols may cause an increase in sensitivity value.

Table 7.2 RFEH circuits performance comparison [208]

Literature	Minimum RF input power	Peak conversion efficiency	Frequency	Rectifier element
Kocer and Flynn [86]	−19.58 dBm @ 1 V	10.90% @ −12 dBm	450 MHz	0.25 µm CMOS
Yi et al. [215]	N/A	26.50% @ −11 dBm	900 MHz	0.18 µm CMOS
Mandal and Sarpeshkar [110]	−17.70 dBm @ 0.8 V	37% @ −18.7 dBm	970 MHz	0.18 µm CMOS
Shameli et al. [166]	−14.10 dBm @ 1 V	N/A	920 MHz	0.18 µm CMOS
Le et al. [94]	−22.60 dBm @ 1 V	30% @ −8 dBm	906 MHz	0.25 µm CMOS
Yao et al. [213]	−14.70 dBm @ 1.5 V	15.76% @ −12.7 dBm	900 MHz	0.35 µm CMOS
Salter et al. [156]	−25.50 dBm @ 1 V	N/A	2.2 GHz	130 nm CMOS
Vera et al. [199]	N/A	42.1% @ −10 dBm	2.45 GHz	SMS 7630
Papotto et al. [138]	−24 dBm (4 µW) @ 1 V	11% @ −15 dBm	915 MHz	90 nm CMOS
Seunghyun and Wentzloff [160]	−32 dBm @ 1 V	N/A	915 MHz	130 nm CMOS

(continued)

Table 7.2 RFEH circuits performance comparison [208]

Literature	Minimum RF input power	Peak conversion efficiency	Frequency	Rectifier element
Masuch et al. [112]	N/A	22.70% @ −3 dBm	2.4 GHz	130 nm CMOS
Scorcioni et al. [161]	−17 dBm @ 2 V	60% @ −3 dBm	868 MHz	0.13 µm CMOS
Taris et al. [188]	−22.50 dBm @ 0.2 V −11 dBm @ 1.08 V	N/A	900 MHz	HSMS-2852
Sun et al. [184]	−3.20 dBm @ 1 V	83% @ −1 dBm	2.45 GHz	HSMS-2852
Karolak et al. [75]	−21 dBm @ 1.45 V −21 dBm @ 1.43 V	65.20% @ −21 dBm 64% @ −21 dBm	900 MHz 2.4 GHz	13 nm CMOS
Roberg et al. [155]	40 dBm @ 30 V	85% @ 40 dBm	2.45 GHz	SMS-7630
Nintanavongsa et al. [130]	−10 dBm @ 1 V	10% @ −10 dBm	915 MHz	HSMS-2852
Franciscatto et al. [49]	0 dBm @ 1.2 V	10.9% 70.40% @ 0 dBm	2.45 GHz	HSMS-2852
Scorcioni et al. [163]	−16 dBm @ 2 V	58% @ −3 dBm	868 MHz	130 nm CMOS
Stoopman et al. [178]	−26.30 dBm @ 1 V	31.50% @ −15 dBm	868 MHz	90 nm CMOS
Wang and Mortazawi [204]	−39 dBm @ 2.5 V	N/A	AM freq	N/A
Thierry et al. [194]	−10 dBm @ 2.2 V −20 dBm @ 0.4 V	N/A	900 MHz 2.4 GHz	HSHS-2852
Nimo et al. [128]	−30 dBm @ 1.9 V	55% @ −30 dBm	13.56 MHz	HSMS-286B
Alam et al. [3]	−15 dBm @ 0.55 V	N/A	2.45 GHz	HSMS-2850
S. Agrawal et al. (2014)	−10 dBm @ 1.3 V	75% @ −10 dBm	900 MHz	HSMS-2852
Stoopman et al. [179]	−27 dBm @ 1 V	40% @ −17 dBm	868 MHz	90 nm CMOS

7.2.3.1 Antenna Module

The antenna is the first stage of an RFEH and is responsible for capturing sufficient signals that would further be converted into voltage. The main parameters to consider in designing such an antenna are the size, gain, and the frequency it is tuned to. The average received input RF power P_{RF} depends on the input power density S and the antenna's aperture A_{real} (equivalent area which intercepted the incident power density), expressed as follows:

$$P_{\mathrm{RF}} = S \times A_{\mathrm{real}}. \tag{7.3}$$

When a receiving antenna intercepts incident electromagnetic waves, a voltage V_{oc} is induced across its terminals. To a generator feeding a transmitting antenna, the

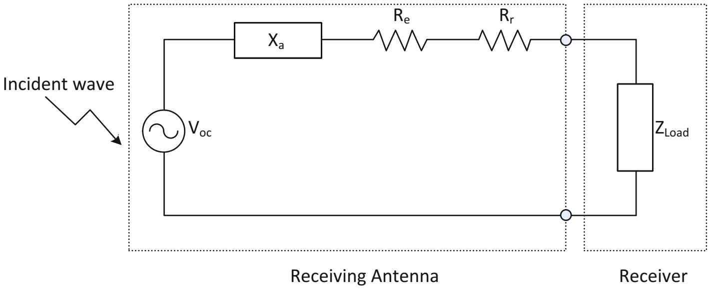


Fig. 7.3 Antenna equivalent circuit

antenna appears as a load. In the same manner, the receiver circuitry connected to a receiving antenna's output terminal will appear as a load impedance. The electrical model of an antenna can be represented by an equivalent circuit as in Fig. 7.3, where X_a is the antenna reactance, R_l the loss resistance (related to the material used), R_r the wave radiation resistance, and Z_{load} the input impedance of the receiver.

The antenna impedance Z_a is given by:

$$Z_a = (R_l + R_r) + jX_a = R_a + jX_a. \tag{7.4}$$

Common values of Z_a are 300 Ω (closed dipole antenna), 75 Ω (open dipole antenna), and 50 Ω (wireless systems). The antenna reactance X_a depends on the antenna structure; it is usually inductive for a loop antenna and capacitive for a patch antenna [140]. Various antenna types for electromagnetic energy harvesting have recently been proposed: dipole [2], Yagi-Uda [78, 185], microstrip [7, 172], monopole [51, 221], loop [95, 133], patch (coplanar, L-shape, U-shape, E-shape, start shape, circular, or square) [154], bow tie [23, 121], and spiral antenna [28]. For a detailed comparison of existing antenna structures, readers can refer to [222].

A trade-off exists between antenna size and performance, hence the main design challenge is to obtain high conversion efficiency. For example, in order to increase the conversion efficiency, several broadband antennas, large antenna arrays, and circularly polarized antennas are encountered in the existing literature:

1. Broadband antennas receive relatively high power of high frequency (on order of 1 GHz) from various sources [126, 200, 214, 216, 220].
2. Antenna arrays increase incident power delivered to the diode for rectification. It is an effective mean of increasing the receiving power but a trade-off arises between the antenna size and the radiation gain [11].
3. Circularly polarized antennas offer power reception with less polarization mismatch.

The antenna module can be designed to work on either single frequency or multiple frequency bands, in which the application can harvest from a single or multiple sources simultaneously. Research efforts have been made for narrow-band

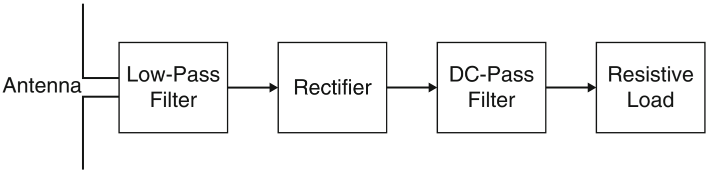


Fig. 7.4 Block diagram of a rectenna

antenna (typically from several to tens of MHz) designs in a single band [3, 8, 9], in dual bands [6, 99, 223] as well as in triple bands [30, 79, 111]. The antenna module can also include a rectifying circuit, as detailed in the next subsection (Fig. 7.4).

Rectenna

A rectenna is a particular type of antenna that rectifies incoming electromagnetic waves into DC current [170]. Over the last century, the development of rectennas for wireless power transmission and SPS transmission [169] has achieved great success in implementing specific functions and applications as diverse as Radio Identification (RFID) tagging systems, WLANs, WiMax, cognitive radio systems, and wireless body area networks (WBAN).

There are two approaches to achieve high conversion efficiency with rectennas. The first option is to collect the maximum power and deliver it to the rectifying diode, and the second one is to suppress the harmonics generated by the diode that reradiate from the antenna as the power lost. Among various types of antenna used in rectennas, microstrip antennas, and especially patch, are gaining popularity in wireless applications owing to their low profile, light weight, simple, and inexpensive to manufacture using modern printed-circuit technology. The other reason for the wide use of patch antenna is their versatility in terms of resonant frequency, polarization, pattern, and impedance when particular patch shape and mode are chosen [170].

7.2.3.2 Impedance Matching

Following the antenna in an RF energy harvester, the impedance matching network performs impedance transformation to assure maximum power delivery by reducing the transmission loss from antenna to rectifier, and increasing the voltage gain at the rectifier input [1].

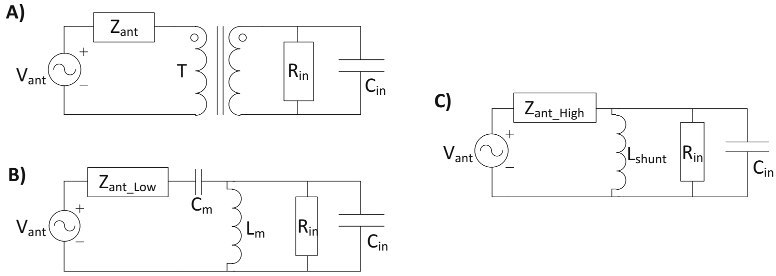


Fig. 7.5 Matching circuits: (**a**) transformer, (**b**) shunt inductor, and (**c**) LC network [143]

A matching network is a resonator circuit operating at the designed frequency and is usually made with reactive components such as coils and capacitors that are not dissipative. Several topologies of matching circuits exist; three main ones widely used are shown in Fig. 7.5.

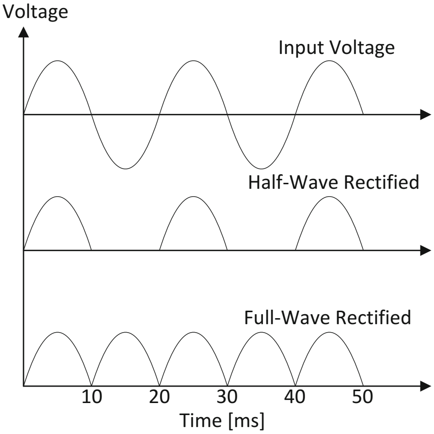
Maximum power transfer can also be realized when the impedance at the antenna output and the impedance of the load are conjugates of each other, thus eliminating the need of an impedance matching network. However, many energy harvesting circuits are made up with nonlinear devices such as diodes, thus exhibiting a nonlinearity. This implies that the impedance of the energy harvesting circuit varies with the amount of power received by the antenna [130]. For example in [47], a method to dynamically maximize the delivered power from an RF source to a receiving antenna is proposed using a finite number of discrete capacitors. The control of the dynamic impedance matching is assigned to a Control Unit that runs an algorithm to estimate the input power of the circuit and then set the capacitance with the best value in the impedance matching network.

7.2.3.3 Rectification and Filtering

The function of a rectifier is to convert the AC current induced in the antenna by received RF signals into a DC voltage. Two topologies for signal rectification exist:

1. Half-wave rectification: either the positive or negative half of the AC wave is passed, while the other half is blocked. Rectifiers yield a unidirectional but pulsating direct current; and
2. Full-wave rectification: converts the whole of the input waveform to one of constant polarity (positive or negative) at its output. Full-wave rectification converts both polarities of the input waveform to pulsating DC (direct current) and yields a higher average output voltage.

Fig. 7.6 Half-wave and full-wave rectification



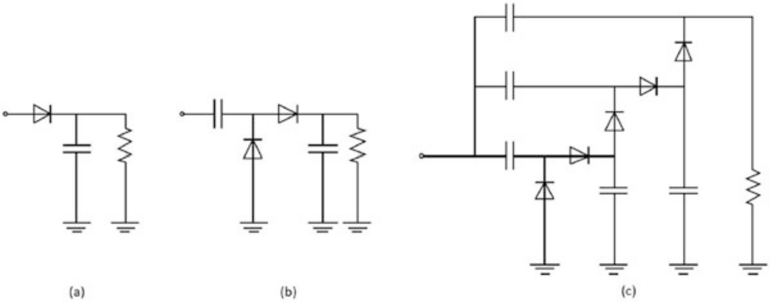


Fig. 7.7 Types of rectifiers circuits: (**a**) Basic rectifier, (**b**) voltage double, and (**c**) voltage multiplier

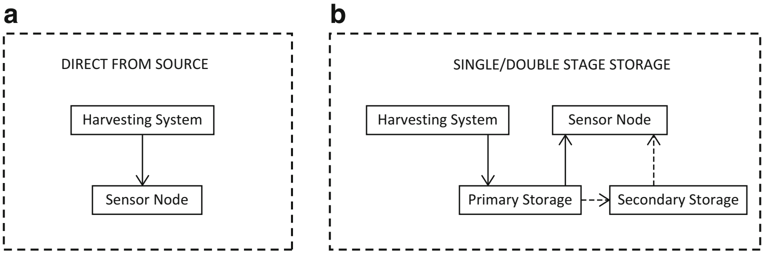


Fig. 7.8 Energy harvesting architectures with and without storage capability [183]. (**a**) Harvest–use, (**b**) Harvest–store–use

Half-wave rectifiers produce far more ripple than full-wave rectifiers, and much more filtering is needed to eliminate harmonics of the AC frequency from the output (Figs. 7.6, 7.7, and 7.8).

As mentioned in Sect. 7.2.3.1, a single diode in a serial configuration that also acts as a half-wave rectifier is the most common rectifying circuit. Generally, higher

Table 7.3 Comparison of rectifier circuits

Rectifier type	Structure	Topology
Basic (single-stage) rectifier	Single diode connected in series with a load. A capacitor may be added as a filter to smoothen the ripple in the output	Half-wave or full-wave
Voltage doubler	Rectifies the full-wave peak-to-peak voltage of the incoming AC signal using two stages to approximately double up the DC voltage	Full-wave. Villard circuit (single shunt), Greinacher circuit (dual diode), bridge (Delon) circuit [29, 88], and Dickson charge pump
Voltage multiplier	Multistage rectifier to further increase the voltage using a network of capacitors and diodes	Full-wave. Cockcorft–Walton circuit [83, 86], multiplier resonant [68, 145], Villance multiplier [127], and boost converter [87]

conversion efficiency can be achieved by diodes with lower built-in voltage such as Schottky diodes. CMOS technology can be deployed as an alternative to diodes. In [93, 175, 217], floating-gate devices were designed to passively reduce the threshold voltage of the rectifier circuit. Furthermore, the floating-gate rectifier technique allows the threshold of the rectifier circuits to be programmed and optimized to operate over a wide range of output current.

When the received power is not high enough, the rectifier input needs to be amplified in order to power the circuit. In these cases, a rectifier circuit that includes a multiplier may be used. There exist three main options of rectifier circuit designs: basic rectifier using a single diode and capacitor, voltage doubler with two diodes and capacitors, and voltage multiplier. Table 7.3 shows a comparison of the rectifiers.

The RF signal source and received power dictate the type of rectification circuit to implement. Different values of DC voltage could be obtained with the same circuit but different RF sources. The multiplier is usually formed by different stages, each with diodes and capacitors. The higher the number of stages, the higher the voltage output. However, because diode loss increases with the stage number, the system efficiency is affected [140]. The measure to quantify the effect of the multiplier is its efficiency η_{rect}, which depends on input power P_{inrect} and output power P_{outrect}.

$$\eta_{\text{rect}} = \frac{P_{\text{outrect}}}{P_{\text{inrect}}}. \tag{7.5}$$

7.2.3.4 Power Management Module

The power management module decides whether to store the electricity obtained from the scavenger or to use it for the application immediately. It can adopt two methods to control the incoming energy flow: harvest–store–use and harvest–use.

The harvest–store–use method is the conventional architecture in most energy harvesting systems. Here, the network node is equipped with an energy storage device (battery or supercapacitor) that stores the converted electricity. Whenever the collected energy is greater than the node's consumption, it is stored for future use [219]. The storage component itself may be single-stage (primary) or double-stage (primary and secondary). Secondary storage is a backup storage for situations when the primary storage is exhausted [69]. However, harvest–store–use method suffers from several issues that will be described in Sect. 7.2.3.5.

In the harvest–use method, the harvested energy is directly used to power the application or network node with no need of storage and voltage converter [96]. Therefore, for a network node to operate normally, the converted electricity has to constantly exceed its minimum energy demand. Otherwise, the node will be disabled. Some energy management techniques for harvest–use such as *energy neutral operation* that adjusts the duty cycle of operation to the predicted rate of harvest, *time-switching approach* where a sensor node harvests energy for a percentage of time frame and transmits data for the rest of the time, and *converter-less operation* to provide almost constant voltage directly to the target device without using a voltage converter were proposed in [74, 171], and in [96], respectively.

In both schemes, the aim is to create a balanced energy management between the RF source and the load in order to avoid energy deficiency in a network. Most of the power management efforts in the literature mainly focus toward efficient node's energy consumption. The aim is to use algorithms, which take into account the limited RF energy supply constraints as well as to develop applications with minimum energy consumption. Some strategies include duty cycling [168], energy driven [22], adaptive sensing rate [120], event driven [158], data compression [119], data prediction [12], mobility based [210], and fuzzy control [5].

7.2.3.5 Energy Storage

Energy storage is of paramount importance in energy harvesting. Depending on the level and duration of storage, proper technique has to be selected. There are several technologies that vary in properties such as capacity, energy density, power density, number of charge cycles, leakage, equivalent series resistance (ESR), lifetime, temperature effects, etc. Because of these wide variations, it is important to understand the differences between technologies and choose a storage device that is well-suited for a given application [150].

For example, in traditional RFEH networks, it is common practice to use rechargeable batteries for repositing energy owing to their high-energy density, which is the energy extracted per unit volume (volumetric: Wh/l) or mass (gravimetric: Wh/kg). In contrast, power density is extracted from a battery per unit volume (W/l) or mass (W/kg) and mainly depends on the internal impedance of the battery. Some batteries are specially designed to promote power density through reduced internal impedance. Batteries designed to improve power density have less energy

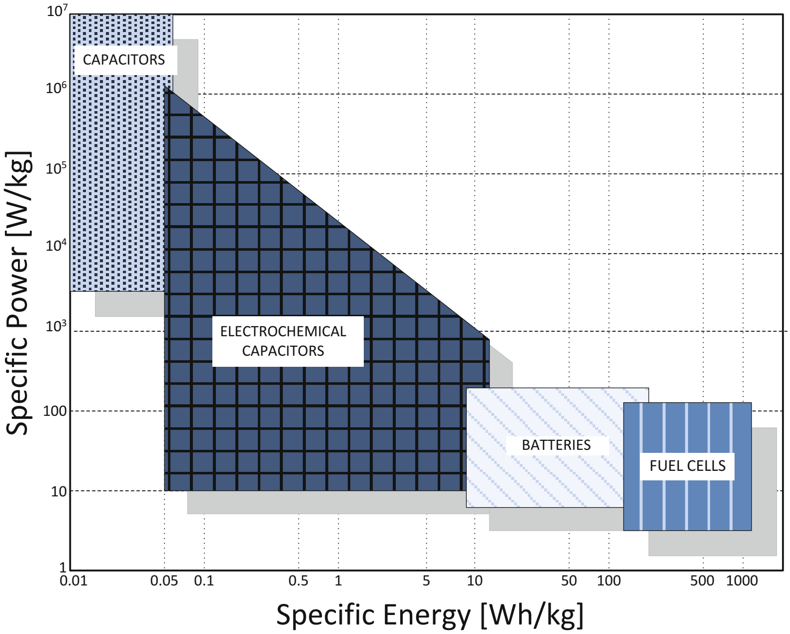


Fig. 7.9 Power density vs energy density (Ragone plot) of energy storage units [39]

density for the same battery size (and vice versa). Figure 7.9 shows a generic graph of the power density versus the energy density of storage units. As noticed in the figure, power density decreases with increasing energy density.

There are essentially two devices known for storing harvested RF energy: supercapacitors and batteries. In this section, we discuss their general properties (Fig. 7.10).

Batteries

Batteries extract electrical power from a chemical reaction. They comprise of one or more basic electrochemical units known as cells, which are connected in series or in parallel to obtain the desired voltage and capacity. Each cell contains a negative electrode (anode), a positive electrode (cathode), and an ionic conductor (electrolyte). The anode and cathode are physically isolated by the electrolyte which provides the medium for charge transfer (via ions) inside the cell.

The most common rechargeable batteries for autonomous low-cost, low-power wireless sensors are Nickel Cadmium (NiCd), Nickel metal hydride (NiMH), and Lithium based (Li-ion or Li polymer). The performance of these batteries systems is compared in Fig. 7.11.

Fig. 7.10 Electrochemical cell at discharge [101]

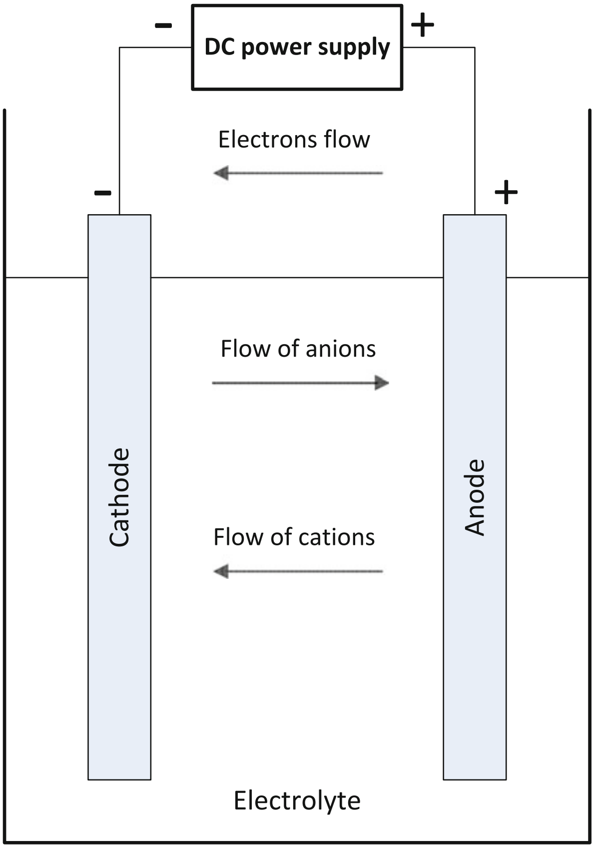
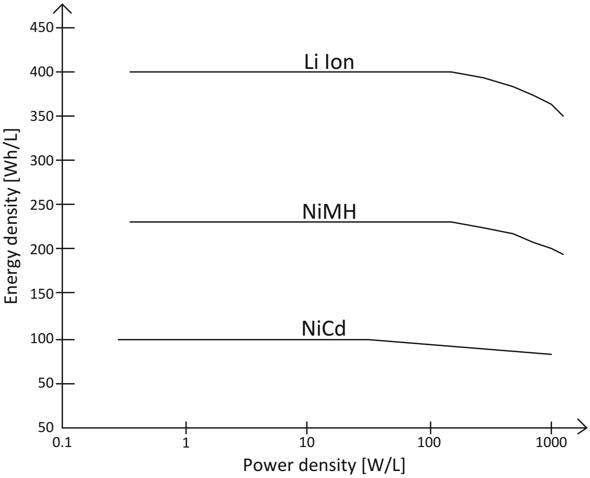


Fig. 7.11 Comparison of rechargeable 14500 Li-ion, AA-size NiMH, and NiCd batteries at 20 °C [101]



1. NiCd batteries use nickel hydroxide $Ni(OH)_2$ for the cathode, Cd as the anode, and an alkaline Potassium hydroxide (KOH) electrolyte. Their small size and high discharge capacity made them suitable for portable tools and other consumer applications. In addition, their cells, with nominal potential of 1.2 V, are sealed and utilize a recombinant system [37] to prevent electrolyte loss and extend the useful life. Once the battery of choice for low-power products, they have lost market share to NiMH and Li-ion batteries which have superior energy density and performance characteristics.
2. The components of NiMH batteries include a cathode of nickel hydroxide, an anode of Hydrogen absorbing alloys, and a KOH electrolyte, which are collectively more benign than the active chemicals used in rival Lithium batteries. Their cell voltage is 1.2 V. The cells operating temperature range has been extended to over 100 °C, far exceeding the range currently achievable by Lithium cells. However, they suffer from high discharge rate and much lower energy density.
3. Typical Lithium-ion cells use Carbon for their anode and Lithium Cobalt dioxide or a Lithium Manganese compound as the cathode. The electrolyte is usually based on a Lithium salt in an organic solvent. Cell voltage is typically 4.2 V. They have many attractive performance advantages which make them ideal for low-power applications such as mobile phones, laptops, cameras, sensors, and other consumer electronic products; and as well as higher power applications such as automotive and standby power.

Internal impedance in batteries depends on factors such as cell size and construction, number of connected cells, chemistry, wiring, and contact type [17]. Manufacturers datasheet often provide discharge profile graphs as well as AC impedance plots at a specific frequency. However, the data found in these plots are not sufficient to predict a battery's voltage behavior under pulsed loads, such as that of WSNs. Thus, the prediction of the transient response of the supply voltage of low-power sensors requires a suitable electrical model like the Min and Rincon-Mora model [20]. Such representation can be useful for predicting the runtime of autonomous sensors and estimating the useful lifetime of the battery.

Many of today's WSNs rely on batteries as the primary power source. Batteries are frequently cited as the primary limiting factor in the lifetime of WSNs. Due to the limited number of recharge cycles and their inability to hold full charge for long duration, batteries often require replacement after 1–2 years. Such recurring maintenance cost is very expensive or prohibitive for thousands of deeply embedded nodes, which may also be spread out in remote locations. In both cases, the battery is the primary limiting factor to operating maintenance-free for several years at nontrivial data rates [173]. In addition to their low-power density and tendency to leak, explode, or fail abruptly, batteries are losing favor among researchers [150]. Removing the battery altogether and storing energy solely in a supercapacitor is now an alternative option for achieving longer life operation.

Supercapacitors

Supercapacitors are not only an excellent compromise between "electronic" or "dielectric" capacitors (such as ceramic and tantalum) and rechargeable batteries but are also a valuable technology for providing a unique combination of characteristics, particularly very high-energy, power, and capacitance densities. They have been found to be a good choice of energy storage for several reasons. As shown in the Ragone plot of Fig. 7.9, supercapacitors are placed between capacitors and batteries, indicating that they have the advantage of power density higher than batteries as well as energy density higher than ordinary capacitors [89]. They do not undergo irreversible chemical reactions, thus tolerate many more charge and discharge cycles [123]. They exhibit much longer lifetime than batteries with minimal environmental impact, accept and deliver charge much faster, with less complex charging circuitry [206].

Supercapacitors are governed by the same basic principles as conventional capacitors. However, they incorporate electrodes with larger surface areas and much thinner dielectrics between the electrodes [57], which lead to increase in both capacitance C and energy E as seen in the following equations:

$$C = \frac{Q}{V}, \tag{7.6}$$

where Q is the stored positive charge and V the applied voltage;

$$E = \epsilon_0 \times \epsilon_r \times A \times D, \tag{7.7}$$

where ϵ_0 is the dielectric constant (or permittivity) of free space, ϵ_r the dielectric constant of the insulating material between the electrodes, A the surface area of each electrode, and D the distance between the electrodes.

A block diagram of supercapacitors is given in Fig. 7.12. Various schematics of supercapacitors have been proposed through equivalent circuit models such as the RC model, the parallel-branch model, the transmission-line model, the multibranch model, and the multistage ladder model [118, 167].

Based upon current R&D trends, supercapacitors can be divided into three general classes: electrochemical double-layer capacitors, pseudocapacitors, and hybrid capacitors. A graphical taxonomy of the different classes and subclasses of supercapacitors is presented in Fig. 7.13.

The main criteria for selecting a supercapacitor are the values of capacitance, leakage current, and ESR. Since the amount of energy to be accumulated depends on the capacitance value, the larger it is, the higher the amount of energy to be gained. However, it has been found that supercapacitors with larger capacitance undergo larger losses in stored energy due to leakage [212], which is the current required to keep a capacitor charged at the rated voltage [124] for 72 h. Thus a supercapacitor with large capacitance will not only take longer to charge but also discharge faster. This implies that the number of operations that could be performed at a particular

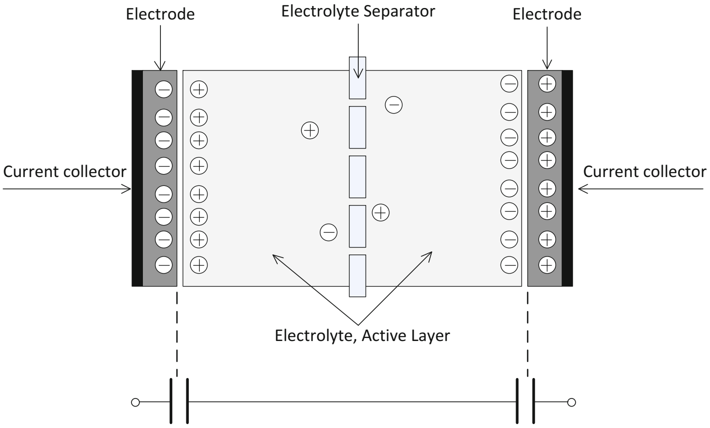


Fig. 7.12 Schematic of an electrochemical double-layer capacitor

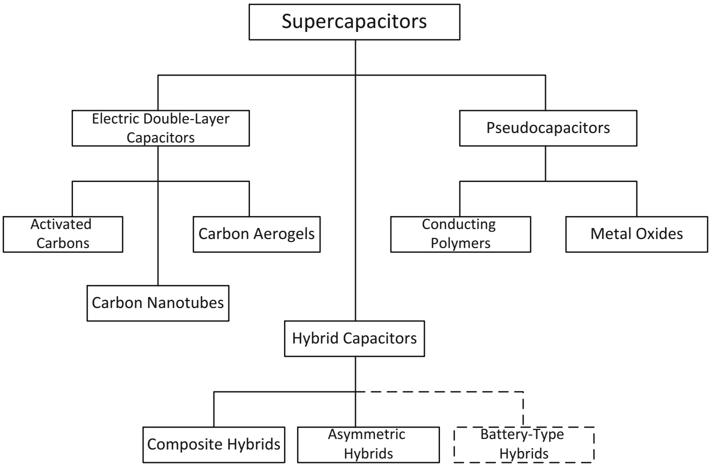


Fig. 7.13 Taxonomy of supercapacitors [57]

rate would be less than the number of operations that could be performed by a lower capacitance value, at the same rate. This could lead to scenarios where the rate at which a node performs operations has to be increased in order to be comparable to a low capacitance storage device. On the other hand, a small capacitance would not be adequate to store enough energy. Hence, it is wise to choose an appropriate value based on the application's requirements or on the rate of collected energy [18].

The major drawback of supercapacitors is their reported high leakage (also referred to as self-discharge), which has been shown to increase exponentially with terminal voltage (energy stored) [114], or to internal charge redistribution [113]. Some researchers suggest that loss of charging efficiency due to internal charge distribution can be partially offset if the supercapacitor undergoes more than three cycles of a fixed pattern of charging [16]. However, others suggest that leakage is higher in supercapacitors that go through frequent charge cycles [113]. Another disadvantage is their ESR that prevents from achieving power densities closer to theoretical limits. Thus, determining how to lower the ESR of supercapacitors is becoming an important area of research. Several methods for reducing the ESR have already been developed, including polishing the surface of the current collector, chemically bonding the electrode to the current collector, and using colloidal thin-film suspensions [57]. Finally, elevated temperatures have a direct effect on supercapacitors ESR and consequently on their lifetime. While measurements indicate that supercapacitor lifetime degrades by a factor of 2 with a 10 °C rise in temperature [90], it has also been shown that the temperature of supercapacitor banks increases exponentially after being charged for a given duration of time at constant current [24].

Hybrid Storage

In certain scenarios, it is not advisable to use batteries in energy harvesting applications because of their internal impedance. Similarly, drawbacks in supercapacitors such as high leakage are not found in batteries. Thus, when an application requires high power density as well as high-energy density, it is possible to employ a mixture of both devices. Storage units comprising of a battery and a supercapacitor operating in tandem are known as *hybrid systems*.

There are extensive works done with hybrid-storage units to prolong the runtime and life extension of storage units under pulsed load [34, 61, 69, 177]. However, their advantages have not been thoroughly assessed and tested in low-power WSNs which operate with pulsed load currents in the order of tens of milliamperes. In [142], a comprehensive theoretical analysis provides design guidelines for choosing a supercapacitor in parallel with a battery. The analysis was supported by experiments comparing the performance between two low-capacity batteries and their hybrid-storage unit counterparts when using an electronic load as a pulsed current sink. It was proven that the hybrid-storage units always achieved a higher runtime and the sensor node runtime was extended by 16%.

Likewise, in [187], a hybrid system was further optimized by adding a DC–DC converter coupled with a supercapacitor to extend the battery autonomy of ultralow power WSNs with minimal operating voltage of 2.1 V or less. The basic idea was to supply power to the sensor node from the supercapacitor with the DC–DC converter disabled, and enabling it on demand for efficiently recharging the supercapacitor. Several tests were conducted with two low ESR supercapacitors, yielding a battery autonomy extension of at least 19%.

7.3 Dedicated RF Energy Harvesting Applications and Products

Dedicated RFEH systems, also referred to as “RF power-on-demand” or “anticipated” power sources, consist of a power source or charger that intentionally utilizes license-free ISM bands to transmit power, and a receiver that captures the transmitted signals to convert to a DC voltage in order to operate. This can be achieved either via directive RF power beamforming or via nondirective RF power transmission. Therefore, the transmitter can consist of either a fixed device or a mobile device that periodically moves and transfers RF energy to network nodes [210]. The transmitter also may or may not be oriented toward a receiver, i.e., with LOS or not. Similarly, the receiving device may or may not be mobile. Applications of RF power-on-demand systems include WSNs, WBANs in the healthcare industry, and RFID tags. Additionally, RFEH can be used to provide charging capability for a wide variety of low-power mobile devices such as electronic watches, MP3 players, wireless keyboard, and mouse, as most of them consume only microwatts to milliwatts range of power.

WSNs are by far the most widely used applications of RF-powered energy scavenging. A variety of wirelessly powered sensors have been reported or proposed in the past decade for monitoring data such as temperature, conductivity, vibration, humidity, luminosity, etc. Sensing in adverse conditions, such as in toxic manufacturing, would benefit from maintenance-free wireless sensors that gather typically low-duty cycle data. Furthermore, there are a lot of practical opportunities for low-cost residential and commercial building sensors with no need of battery replacements for knowing environmental parameters such as occupancy, humidity, temperature, light level, water level, air flow in pipes, air quality, appliance activity, etc. Examples of WSNs powered with anticipated RF sources can be found in [4, 33, 44, 139, 141]. In [77, 134, 164], multi-hop RF-powered WSNs are demonstrated through experiments.

In the healthcare industry, many existing implanted devices are powered inductively, which requires proximity of the powering device to the patient and is often uncomfortable. Recently, it has been shown that loosely coupled coils at farther range can be effective for powering cardiac implants [152]. Some implanted devices could benefit from far-field powering, e.g., during the night when the person is confined to the bedroom, which can increase the battery life and time between surgical battery replacements. Thus, low-power medical devices can achieve real-time work-on-demand power from anticipated RF sources, which further enables a battery-free circuit with reduced size. Examples of body device implementations can be found in [148, 174, 207].

Finally, another application that has caught intensive research investigation is RFID, widely used for identification, tracking, and inventory management [230]. As depicted in Fig. 7.14, these devices can be classified based upon the presence or absence of radio transmitter or battery [32]:

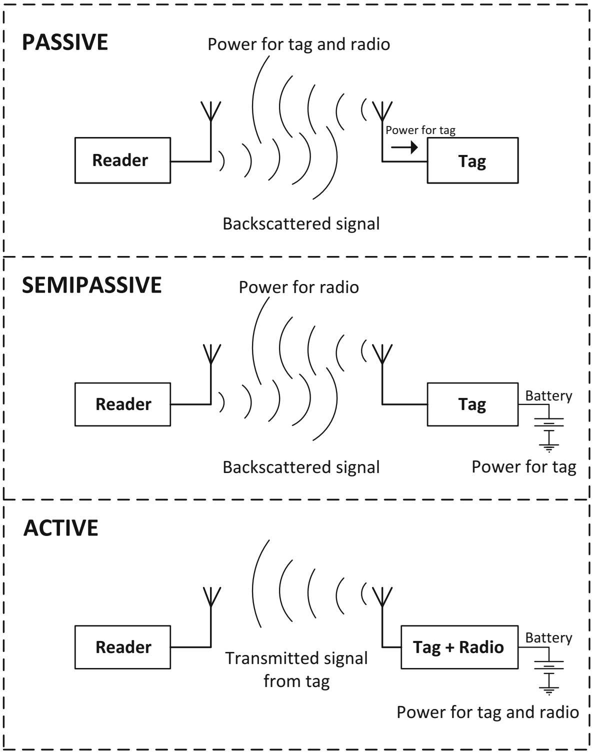


Fig. 7.14 Classification of Radio Identification (RFID) systems [32]

1. Passive tags: with no independent source of electrical power to drive the circuitry, they have no radio transmitter of their own and rely instead on the received power from a reader to be turned on as well as sending information through amplitude modulation (AM). In exchange to their simplicity, small size, and low cost, their read range is very short and limited, and their computational power is minimal.
2. Semi-passive tags: also known as battery-assisted passive tags, they incorporate a battery to power their circuitry but still use backscattered communications [58] for uplink communications, also via AM modulation. They are typically used in automobile tolling applications. The trade-off is their increase in size, cost, and maintenance requirements.
3. Active tags: configured as conventional bidirectional communication devices, they include both an internal power source and a conventional transmitter tuned to specific frequency channels via frequency-division multiplexing (FDM) in the presence of other tags. They naturally suffer from the same trade-offs as their semi-passive counterparts.

Recent developments in low-power circuit and energy harvesting technology can extend the lifetime and operation range of conventional RFID tags. Instead of relying on the readers to activate their circuits passively, RFID tags can harvest RF energy and perform communication actively [104]. Consequently, RFID technology is evolving from simple passive tags to smart tags with newly introduced features such as sensing, on-tag data processing, and intelligent power management [135]. Research progress has covered the designs of RFID tags with energy harvesting in rectenna [62], rectifier [73], RF-to-DC converter [161], charge pump [27], and power harvester [19]. Despite the stellar advancement made in the RFID technology, several issues such as reliability, security, speed of communications, and evolution to a global standard still need to be addressed appropriately.

In the rest of the section, we present the major considerations to take when designing a dedicated RFEH system, describe some prototype implementations as well as commercial products, and finally expand with potential future applications.

7.3.1 Design Considerations

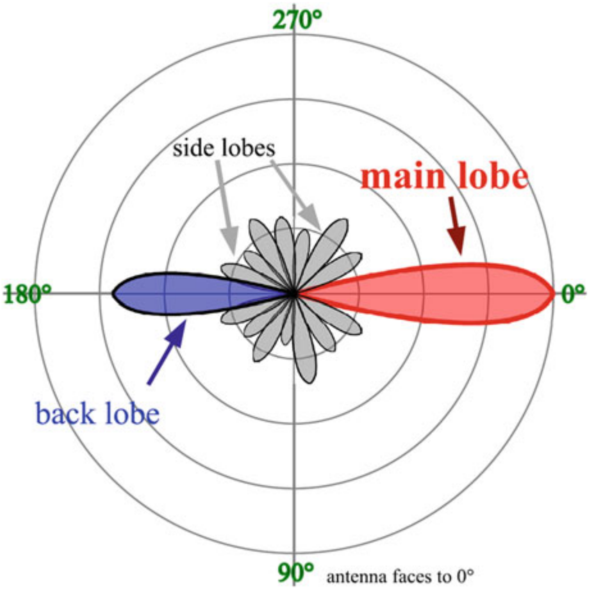
Depending on the electromagnetic transmission model, the energy source and receivers must be designed and possibly adapted for maximum efficiency. This includes selecting and assessing the frequency range to transmit, the adequate antenna type, the power limitations and management, and the storage technologies.

7.3.1.1 RF Energy Source Design Constraints

Most anticipated RF power sources transmit in one of the common ISM bands (center frequencies of 433 MHz, 915 MHz, 2.4 GHz, or 5.8 GHz). These bands however do not allow for high power transmissions as they are limited by government regulatory bodies such as the FCC [46] in the USA due to concerns over interference, safety, and health. For example, in the 915 MHz band, the maximum threshold is 4 W. Even at the highest setting, the received power at a moderate distance of 20 m is attenuated down to only 10 μW [208]. Due to this limitation, several dedicated RF sources may need to be deployed to meet the user demand.

Proper selection of the antenna is crucial. Several parameters must be taken into account such as radiation pattern, gain, power rating, size, distance between transmitting antenna and receiving antenna, etc. Radiation pattern depends on the type of antenna selected. Most antennas show a pattern of "lobes" or maxima of radiation. In a directive antenna, shown in Fig. 7.15, the largest lobe in the desired direction of propagation is called *main lobe*. The other lobes are called *side lobes* and usually represent radiation in unwanted directions. On the other hand, in the radiation pattern of a simple omnidirectional antenna, the antenna is at the center of the "donut" or *torus*. Radial distance from the center represents the power radiated in that direction. Common types of low-gain omnidirectional antennas are the whip antenna, vertically oriented dipole antenna, horizontal loop antenna, and the halo antenna.

Fig. 7.15 Antenna radiation patterns [196]



The antenna gain is not a mere amplification of the RF signal, but rather a measure of the focus of the signal (degree of directivity of the antenna's radiation pattern). Hence, a high-gain antenna will radiate most of its power in a particular direction, while a low-gain antenna will radiate over a wider angle.

7.3.1.2 RF Energy Harvester Design

The antenna selection of the energy harvester should be identical to the one used by the RF source. Because antenna efficiency is related to the frequency, dedicated RF energy harvester usually has an antenna with small bandwidth, in contrast with ambient RFEH where a wideband receiver antenna can be used to capture signals from multiple sources or multiple frequency bands.

Good matching circuits are essential to achieve maximum power and improve efficiency. For financial reasons, RFID tags and WSNs use shunt inductors and LC networks as matching networks instead of transformers [140]. Moreover, it is recommended for high impedance antennas like dipole antennas to use parallel coils [143], whereas small impedance antennas may employ LC networks for ambient RFEH (e.g., Wi-Fi antenna), or when the available power is low [93].

Choice of rectification circuits depends on the strength of the RF signal and power received, since different values of DC voltage could be obtained with the same circuit and different RF sources. When the distance from the RF source is far and the received power is not high enough, the rectifier input needs to be amplified in order to power the circuit (most WSNs and RFID tags require at least 3.3 V).

The power management design is rendered easier to accomplish for a dedicated energy transmitter, thanks to a predictable and stable power transmission. Similarly, more energy is expected to be stored within a shorter period of time than in ambient RFEH, thus requiring sufficient storage capability.

7.3.2 Commercial Products

Besides the well-known RFID systems, there exist few commercial products for RF wireless power transfer aimed for WSNs and WBANs. In this subsection, we introduce some manufacturers and their products.

7.3.2.1 Powercast Corp.

Built in 2003, Powercast Corp. [149] brings remote, wireless power capability to micro-power devices such as wireless sensors, data loggers, and active RFID tags. The company's energy scavenging technology provides wireless power by converting electromagnetic signals into a DC power, thus reducing or eliminating battery replacement by trickle charging rechargeable batteries, or using supercapacitors and thin-film energy cells. Their products address existing and future markets by providing a full suite of FCC approved products:

- Powerharvesters receivers: chips that harvest directive or ambient RF energy and convert to DC power. These chips include the P1110 Powerharvester Receiver (short-range, higher power), the P2110B Powerharvester Receiver (long range), and the PCC110 or PCC210 chipsets (for OEM volume applications).
- Powercaster transmitter TX91501: provides a reliable source of 915 MHz wireless energy to power, over a distance, devices equipped with Powerharvester receivers. It comes in two versions that output either 1 or 3 W equivalent isotropically radiated power (EIRP) with a transmitter ID broadcast.

In addition, the company supplies development kits and evaluation boards to enable simple and fast testing and prototyping with RF-based wireless power technology. Figure 7.16 shows the *P2110-EVAL-01 lifetime power energy harvesting development kit for wireless sensors*.

7.3.2.2 Texas Instruments

A more renowned company, Texas Instruments [189], introduced in December 2014 its new family of sensor transducers designated *RF430FRL15XH*. The devices are the first sensor transducers designed to operate over the traditional 13.56 MHz radio spectrum and powered by scavenging energy from a nearby NFC-enabled reader or smartphone. It is advertised to be implemented in applications ranging from

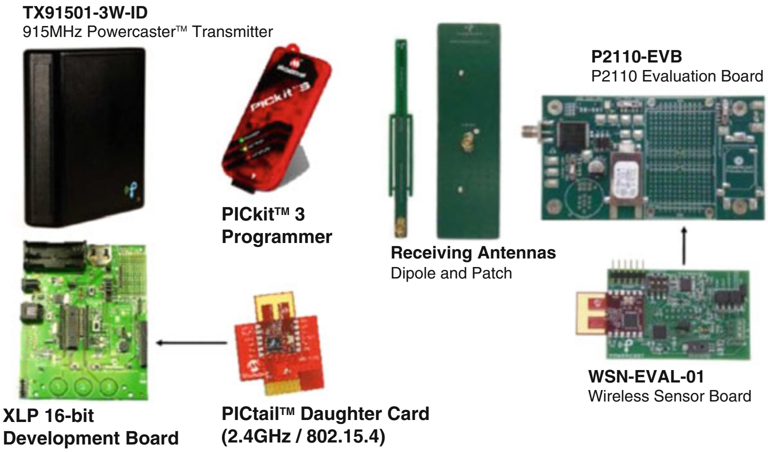
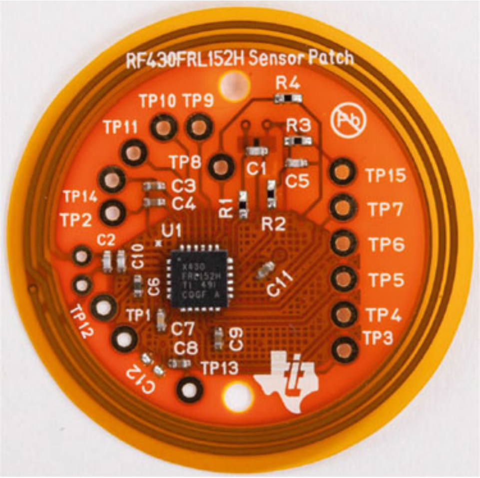


Fig. 7.16 Lifetime power energy harvesting development kit for wireless sensors [149]

Fig. 7.17 Battery-less NFC/RFID temperature sensing patch



medical, health and fitness, and industrial where instantaneous measurements are required and a battery is not feasible or desired. Connections to power via other options such as battery or USB are also offered as an alternative. An evaluation board, *RF430FRL152HEVM*, is available for purchase to evaluate the key features of the device and some sensor measurements. Application report *SLOA212A* demonstrates the implementation of a single chip NFC/RFID field powered temperature sensor system with the *RF430FRL152H*, illustrated in Fig. 7.17.

7.3.2.3 Energous Corp.

Silicon Valley startup Energous Corp. [38] is developing a new technology called *WattUp*. Its transmitters deliver energy to devices via microwave beams: small antennas embedded in speakers, televisions, and dedicated router-size boxes that can direct wireless power to toys, lights, and mobile phones over several meters distance. WattUp's sophisticated localization and beamforming technology allows multiple RF antennas to emit low-power, 5.8 GHz beams along different paths that converge in a "pocket" around the targeted device to reach the receiving antenna, even not in direct LOS. Energous claims that a *WattUp* transmitter is capable of delivering microwaves up to four devices simultaneously. The amount of power the beams deliver is dependent on distance: 4 W within 1.5 m, 2 W within 3 m, and 1 W within 4.6 m. The company says that its eventual goal is 25% end-to-end efficiency of the system for integration into near-market consumer devices.

7.3.2.4 Ossia Inc.

Energous has a competitor in Ossia Inc., based in Washington, which is also developing an RF power delivery system named *Cota*. The *Cota* system uses a Wi-Fi-like signal designed to charge many devices simultaneously, stationary or moving, using their patented smart antenna technique. The company asserts that at an effective radius of 10 m, a single Cota charging station can feed rechargeable battery-operated devices in every room of an average home or office suite. Under license from Ossia, consumer electronics manufacturers will be able to include Cota receivers in new products and have the opportunity to build their own branded transmitters.

7.3.2.5 Farsens S.L.

Farsens S.L. [45] is a Spanish company based in San Sebastian that has developed a wide range of wireless and battery-free RFID sensor tags. Its UHF RFID ICs harvest energy from the RF field created by commercial RFID readers and use that power to drive sensors, actuators, or other electronics effectively creating battery-free devices from a distance as far as 1.5 m. It also offers development platforms to create one's own wireless and battery-free sensors.

7.3.2.6 Texzon Technologies, LLC.

On a much larger scale, Texzon Technologies LLC. [191] in Texas introduced a novel wireless power transmission system concept at the 2016 IEEE symposium for Wireless and Microwave circuits, which is capable of transferring megawatts of power. They intend to revolutionize the current electrical power distribution systems by switching to a global wireless scheme utilizing a Zenneck surface wave [144] between optimally sited power generation facilities and local distribution grids and microgrids. This wireless power system will employ a “transmitter probe” located near a power generation plant, to launch a Zenneck carrier wave. Receiver antennas will be positioned appropriately around the world to receive the signal and download the power into a local microgrid or conventional grid architecture. The company claims that the consequential RF exposure levels are more than ten times lower than the FCC, OSHA [193] and ANSI [192] recommended limits.

7.3.3 Future Directions

7.3.3.1 RF Energy Harvesting and Aerial Vehicles

Since the demonstration by W.C. Brown and Raytheon company of a model helicopter powered via microwaves in the early 1960s [15], various similar research in microwave-powered airplanes took off. Strassner and Chang summarize in [180] the historical milestones achieved in the USA as well as internationally. The present day desire to remotely power unmanned aerial vehicles (UAVs) or drones [36] continues to serve as the main driving force behind current advancements being made in RFEH, particularly in rectenna array components [43]. The use of UAVs for communication and surveillance is seen as a huge potential, especially in the military. Future uses for RFEH include powering probes from space stations into deep space, and robots to enter perilous environments like nuclear contaminated areas.

7.3.3.2 Simultaneous Wireless Information and Power Transfer

This book chapter focuses on energy transmission via electromagnetic waves. Even so, the prime application of RF signals is for wireless communications. Hence, since RF signals carry energy as well as information, theoretically energy harvesting and information transfer can also be performed from the same signal input. This is referred to as the simultaneous wireless information and power transfer (SWIPT) [228] concept. It allows the information receiver and energy harvester to share the same antenna or antenna array. Figure 7.18 displays the corresponding receiver architecture for SWIPT. Wireless information is modulated on the amplitude and phase of RF waves, while WET is carried out through far-field radiation.

The traditional information receiver architecture designed for information reception may not be optimal for SWIPT because information reception and RFEH work on very different power sensitivities (e.g., -10 dBm for energy harvesters versus -50 dBm for information receivers) [224]. This inspired the research efforts in devising receivers for RF power/information receivers. Currently, there are four typical types of receiver architectures [208]:

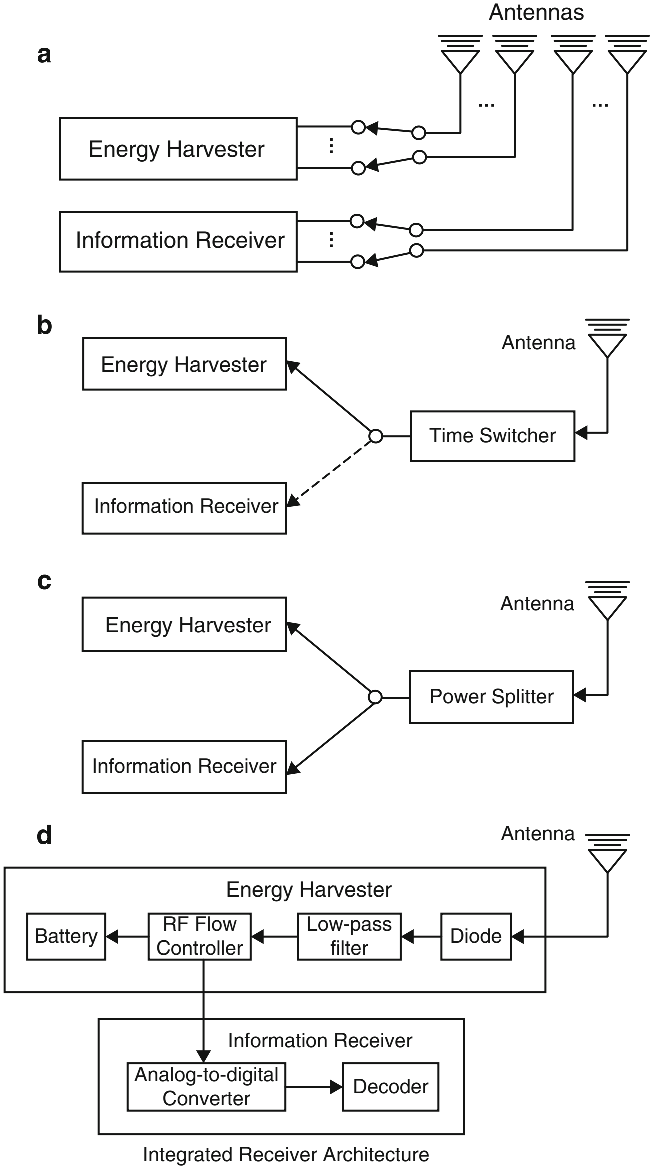


Fig. 7.18 Receiver architecture designs for RF-powered information receiver [208]: (**a**) Separated receiver architecture; (**b**) time-switching architecture; (**c**) power-splitting architecture; and (**d**) integrated receiver architecture

- Separated receiver architecture, also known as antenna-switching: equips an energy harvester and information receiver with independent antenna(s) so that they observe different channels.

- co-located receiver architecture: categorized into time-switching and power-splitting models, it allows a power harvester and an information receiver to share the same antenna(s) so that they observe the same channel(s).
- Integrated receiver architecture: implementation of RF-to-baseband conversion for information decoding is integrated with the RFEH via the rectifier circuit.
- Ideal receiver architecture: assumes that the receiver is able to extract the RF energy from the same signals used for information decoding.

The studies in [228] show that when the circuit power consumption is relatively small compared to the received signal power, the integrated receiver architecture outperforms the co-located receiver architecture at high harvested energy region, whereas the co-located receiver architecture is superior at low harvested energy region. However, when the circuit power consumption is high, the integrated receiver architecture performs better. They also mentioned that for a system without minimum harvested energy requirement, the integrated receiver achieves higher information rate than that of the separated receiver at short transmission distances.

The above study and other related publications [21, 125] assume a linear energy harvesting model where the RF to DC conversion efficiency does not depend on the input power level. In practice however, there is a nonlinear relationship between input and output as described in [54, 94, 198]. In [14], a practical nonlinear model and corresponding resource allocation algorithm was proposed for SWIPT networks, unveiling a greater performance gain over traditional linear models.

A key concern for both wireless information and energy transfer is the decay in efficiency with the increase of transmission distance due to propagation path loss. Such problem is especially severe in a single-antenna transmitter that generates omnidirectional radiations. This low energy transfer efficiency calls for advanced multi-antenna and signal processing techniques such as beamforming [31, 91, 107].

7.3.3.3 Beamforming

Point-to-point transmission of RF waves is referred to as power beamforming [224]; its sharpness improves with the number of transmit antennas. In RFEH networks, beamforming designs have been explored to steer the RF signals toward the target receivers with different information and/or energy harvesting requirements. Figure 7.19 shows the SWIPT beamforming general model.

The knowledge of channel state information (CSI) plays an important role in beamforming performance optimization. To accurately estimate a channel state, a significant overhead (e.g., time) can be incurred at a receiver. Normally, the longer the time for channel state estimation, the more accurate CSI becomes. However, it may result in reduced time for transmission, and also less amount of collected energy. As a result, an optimization of RF energy transfer or SWIPT entails a trade-off between data transmission and channel state estimation duration [208].

Distributed Energy Beamforming enables a cluster of distributed energy sources to cooperatively emulate an antenna array by transmitting RF energy simultaneously in the same direction to an intended harvester for better diversity gains. The potential

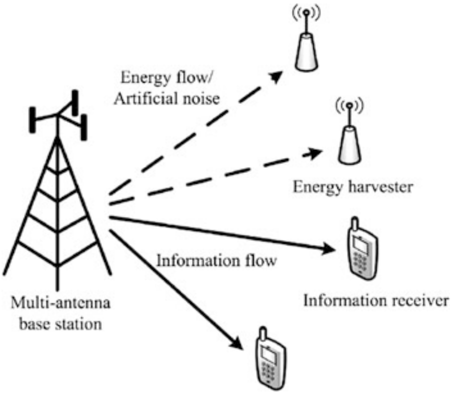


Fig. 7.19 A general model for simultaneous wireless information and power transfer (SWIPT) beamforming system [208]

energy gains are expected to be the same as from information beamforming. However, challenges arise in the implementation, e.g., time synchronization among energy sources and coordination of distributed carriers in phase and frequency so that signals can be combined constructively at the receiver side [208].

7.4 Ambient RF Energy Harvesting Applications and Products

The obvious appeal of harvesting ambient RF energy over dedicated power transmission is the utilization of "free" energy generated by radio transmitters such as radio (AM and FM) towers, TV towers, cellular phone towers, and Wi-Fi routers. Similar to dedicated RFEH applications, in ambient RFEH, the most popular research attention is found on WSNs [100, 147] and WBAN [13, 70]. Other than the above popular applications, devices powered by ambient RF energy is also attracting increasing research attention. For example, in [68], the authors present a design of an RF circuit that enables continuous charging of mobile devices especially in urban areas where the density of ambient RF sources is high. Liu et al. [102] demonstrate that an information rate of 1 kbps can be achieved between two prototype devices powered by ambient RF signals, at the distance of up to 75 and 45 cm for outdoors and indoors, respectively.

Additionally, RFEH can be used to provide charging capability for a wide variety of low-power mobile electronic devices as most of them consume only microwatts to milliwatts range of power. Existing literature has also presented many implementations of battery-free devices powered by ambient energy such as mobile electronic devices, electronic watches, MP3 players, wireless keyboard, and mouse from Wi-Fi [136, 186], GSM [53, 146] and Digital Television (DTV) bands [79, 81]. Furthermore, in [105], a novel approach to embed systems in clothes is presented.

In the following subsections, we explore the constraints and requirements for the development of an ambient RFEH system, the current research orientations and finally conclude with some novel applications.

7.4.1 Design Considerations

As ambient RF levels are lower than those provided by an anticipated source, the availability of the RF power, the efficiency of the harvesting system, and its minimum startup power are of critical importance. In order to assess the feasibility of deploying ambient harvesters, the available RF power needs to be evaluated in different locations. Such measurements, in conjunction with knowledge on harvester performance, can then be used to determine the locations at which RF harvester powered devices can be successfully deployed.

7.4.1.1 Power Density Measurements

The surface power density (or specific power) is the amount of power per unit area, usually expressed in W/m^2. The input RF power density measured by a spectrum analyzer is calculated summing all the spectral peaks across the band. These levels provide a snapshot of source availability at the time and location of the measurement [146]. Several RF spectral surveys, which measure ambient RF power levels from sources such as television and mobile phone base stations, were undertaken with spectrum analyzers in unknown measurement locations and with no regard of the conditions that might affect the evaluation (e.g., outdoor, indoor, street, bus, etc.) [59, 201]. In order to demonstrate the feasibility for implementing ambient RFEH, a rigorous spectral survey must be taken first, indicating the exact time/location, and the associated RF bands with sufficient input power density levels for harvesting. Also, appropriate equipment to measure the electric field strength should be selected, such as an RF analyzer and a calibrated antenna.

The Effective Radiated Power (ERP) is the transmitter power delivered to the antenna multiplied by the directivity or gain of the antenna [46]. Since high-gain antennas direct most of the energy toward the horizon and not toward the ground, high ERP transmission systems such as used for UHF-TV broadcast tend to have less ground level field intensity near the station than FM radio broadcast systems with lower ERP and gain values. In urban areas, available RF energy in areas close to transmission towers provides an opportunity to harvest that energy. Some of the most prominent sources are AM radio transmission (540–1700 kHz, maximum ERP of 50 KW), FM radio transmission (88–108 MHz, maximum ERP of 100 KW), TV transmission (180–220 MHz, ERP from 3 KW for low-power VHF to 1000 KW for full-power UHF), cellular and Personal Communications Services (PCS) transmission (824–896 and 1850–1990 MHz, up to 500 W per channel), Wi-Fi (2.45 or 5.8 GHz, transmit power around 100 mW), and mobile phones (transmit

Table 7.4 RF power density

Band name	Frequency	Distance to base station	Power density	Applications
AM station	540 MHz	from 5 to 10 km	from 0.159 to 0.04 $\mathrm{mW/m^2}$	Radio [229]
GSM-900	950 MHz	from 25 to 100 m	from 1.0 to 0.1 $\mathrm{mW/m^2}$	Phone [201]
GSM-1800	1747.5 MHz	from 25 to 100 m	from 1.0 to 0.1 $\mathrm{mW/m^2}$	Phone [201]
UMTS-2100	2110 MHz	from 11.8 to 150 m	from 2 to 0.2 $\mathrm{mW/m^2}$	Phone (3G) [185]
WLAN	2.4 GHz	7 and 12 m	1 and 0.1 $\mu\mathrm{W/m^2}$, respectively	WLAN [201]

power of 1–2 W). Cellular towers can be used as a continuous source of renewable energy as they transmit 24 h. Table 7.4 summarizes some examples of power density measurements in an urban environment.

7.4.1.2 Antenna and Circuit Design

Once the RF power density levels for harvesting are known, antennas can now be fabricated. As discussed in Sect. 7.2.3, rectennas are the most common designs mentioned in the existing literature. A well-designed rectenna should ideally be capable of harvesting energy across an entire band, and thus it is important to calculate the total band power. Furthermore, the antenna needs to match the impedance of the rectifying device over a range of input power levels to optimize efficiency. Other requirements for the antenna include the fact that they must be omnidirectional and dual-linear polarized since the exact location of the transmitter is assumed to be unknown and the propagation environment includes scattering.

In addition, proper power management technique must be selected (e.g., harvest–store–use or harvest–use). In the case of harvest–store–use, the DC output of the converted signals should not be directly connected to the storage device to avoid discharging under some conditions [147]. Monitoring of the available stored energy, the received DC power, the power management circuit control, the sensor data collection, and duty cycle, etc., are necessary functions that need to be accomplished at the lowest possible potency. There are a number of very low-power microcontrollers on the market, and some of their parameters like clock speeds can be adjusted to reduce the power in different modes of operation.

Finally, energy storage could use supercapacitors or various types of rechargeable batteries. If there is not enough energy captured, sensor data cannot be transmitted and there is a danger of damaging the storage device. Therefore, the available rectified RF power and the available energy stored should be monitored in a closed-loop system allowing for adaptive adjustment of the data transmission duty cycle.

7.4.1.3 Multiband RF Energy Harvesting and Hybrid Systems

Most early research on RF energy scavenger designs focus on a single frequency band [8, 50]. Lately, there have been design implementations of dual-band [131], triple-band [72], and multiband antenna designs [146]. Due to relatively low-power density and availability of ambient RF sources, it is highly advisable for a harvester to capture signals over a large number of frequency bands to ensure continuous and steady voltage for sensors operation.

A multiband harvester may have one antenna and circuit to harvest each frequency band separately, then store the overall DC power in a single device. However, this configuration needs many antennas, thus increasing the overall costs, weight, and size of the harvesting system. To overcome this problem, a possible solution is to use only one ultrawide band or multiband antenna. In this case, adequate matching networks must be constructed to overcome the nonlinearity of the diodes with respect to both frequency and RF power input. An alternative was presented in [141], where rectifying circuits tuned at different frequencies were connected in series, allowing better rectification and DC-combining efficiency. Unfortunately, this architecture would not identify the optimum load in terms of harvested DC power since the input of each rectifier circuit changed with the frequency of the signal.

One of the first commercial applications of multiband ambient RFEH was pioneered with Freevolt, a trademark of Drayson Technologies Ltd [35]. It is branded as a new innovative technology that provides power for low energy Internet of Things (IoT) devices by scavenging power from wireless and broadcast networks such as 2G, 3G, 4G, Wi-Fi, and DTV. The approach was implemented in the CleanSpace Tag, a personal air quality pollution sensor. It claims no interference with the data connectivity and does not require any increase in transmission power.

The use of ambient RFEH for WSNs depends on the application, the distance to the base station, the frequency, the distance between nodes, etc. Table 7.5 depicts the commercial requirements of existing sensor network nodes. The results deduced from Tables 7.2 and 7.5 indicate that energy solely harvested from the ambiance is typically insufficient as a primary power source of WSNs. Hence, it may be combined with other energy harvesting sources. As an example, for outdoor applications, when the base station is far from the nodes, RFEH can be combined with photovoltaic [98], or even piezoelectric [76] sources. In a similar way, for human body sensors, it can be associated with other sources such as thermal or vibration [140]. These types of dual harvesting systems are called “hybrid energy harvesting systems.”

7.4.2 Hardware Implementation and Future Directions

Harvesting energy from the ambient environment is a promising field that opens the door to many different applications, the bulk of which relates to sensing nodes.

Table 7.5 Comparison of power consumption of some selected sensor network nodes [229]

Operating conditions	Crossbow MICAz	Waspmote	Intel IMote2	Jennic JN5139
Radio standard	IEEE 802.15.4 ZigBee	IEEE 802.15.4/ZigBee	IEEE 802.15.4	IEEE 802.15.4/ZigBee
Typical range	100 m outdoor, 30 m indoor	500 m	30 m	1000 m
Data rate	250 kbps	250 kpps	250 kbps	250 kbps
Sleep mode	15 μA	62 μA	390 μA	2.8 μA
Processor consumption	8 mA active mode	9 mA	31–53 mA	2.7 + 0.325 mA/MHz
Transmission	17.4 mA (+0 dBm)	50.26 mA	44 mA	34 mA (+3 dBm)
Reception	19.7 mA	49.56 mA	44 mA	34 mA
Supply voltage (min)	2.7 V	3.3 V	3.2 V	2.7 V
Average power	2.8 mW	1 mW	12 mW	3 mW

While several concepts of energy harvesting through RF signals have been proposed mainly in the academia, a commercial product that works solely on energy harvested from thin air has yet to be offered. In the following paragraphs, we survey the latest achievements in ambient RFEH and future directions.

7.4.2.1 Harvesting from Cell Towers

There are 4 GSM frequency bands operating in the world, with 850 and 1900 MHz in America, and 900 and 1800 MHz in the rest of the world [65]. The aggregated power density over some GSM frequency bands is shown in Table 7.4. Most publications focus on the proof of concept rather than on a viable option for energy replenishment. Some examples of DC power scavenged from cellular towers radiations are in [8, 53, 76]. However, it remains that energy scavenging from cellular towers still suffers from very low efficiency and long duty cycle.

7.4.2.2 Digital Television Band Energy Harvesting

Cellular base transceiver stations and TV broadcast represent the most promising ambient RF sources due to their high transmit power (e.g., TV) and ubiquity in urban environments. Collecting energy from DTV signals was first investigated by Intel [157] in 2009, where 60 μW of power was harvested at a distance of 4 km from a broadcasting TV station. Other practical examples of DTV band energy harvesting can be found in [78, 84, 132, 168, 202].

7.4.2.3 Wi-Fi Energy Harvesting

With the ubiquity of Wi-Fi signals in urban environments and the fact that it operates mainly in the crowded 2.45 GHz band (same with RFID, cordless phones, Bluetooth, ZigBee, etc.), harvesting energy from Wi-Fi has become a hot topic. Wi-Fi transmission operates in "bursts," i.e., a router emits power only when it is sending data packets to a host, with a typical power of 100 mW at short range. Thus, while a harvester can capture power during transmission, the power leaks during silent periods, limiting the minimum voltage requirement needed to turn on a sensor. Many prototype implementation of devices operating on Wi-Fi energy were demonstrated in the academia [72, 136, 186] but are yet to match the efficiency and effectiveness of a dedicated source. Nevertheless, the research and development divisions of companies like Samsung, Intel, Qualcomm, and Texas Instruments are currently hard at work trying to make harvesting from ambient Wi-Fi signals a reality.

7.4.2.4 Cognitive Radio

A CRN powered with RF energy can provide a spectrum and energy-efficient solution for wireless networking [106]. The idea of utilizing electromagnetic signals from primary transmitters to power secondary devices was initially proposed in [97]. In an RF-powered CRN, the scavenging capability allows secondary users to gain and store energy from nearby transmissions (of primary users). Then, the secondary users can transmit data when far away from primary users or when nearby primary users are idle. Thus, they must not only identify spectrum availabilities for opportunistic data transmission but also explore for occupied spectrum channels to harvest energy [208].

Figure 7.20 shows a general network architecture for RF-powered CRNs. There are three zones associated with the primary user: energy harvesting, transmission, and inference zones. In the harvesting zone, a secondary user can receive RF energy from a primary user on transmission. The transmission zone refers to the communication coverage of the primary user; if the secondary user is still in the harvesting zone, he can scavenge power from the primary user. If the latter occupies the channels, then the secondary user cannot transmit data if he is in the interference zone.

Cognitive radio consists of four main functions to support intelligent and efficient dynamic spectrum access:

1. Spectrum sensing: to detect the activities of primary users accurately
2. Spectrum access: to access spectrum while protecting primary users from collision and to provide fair and efficient sharing of available spectrum
3. Spectrum management: to achieve high spectrum utilization for both communication and RFEH by performing channel selection
4. Spectrum handoff: to switch a secondary user from one channel to another

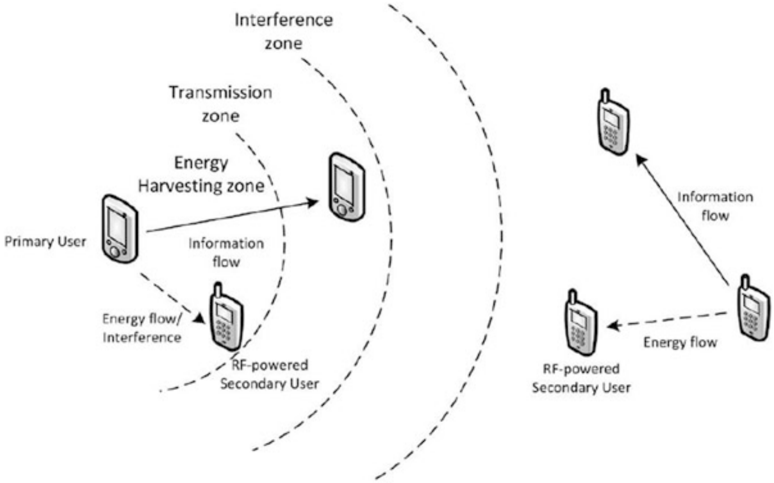


Fig. 7.20 A general network architecture of RF-powered cognitive radio networks (CRNs)[208]

Detailed research issues in the RF-powered CRN related to these four functions can be found in survey paper [208].

7.5 Summary

Energy harvesting from radiative wireless charging is a promising field that opens the door to many different applications, the bulk of which relates to sensing nodes. It enables wire-free operation, simple scalability, low-cost setup and maintenance, reliable, controllable, and environmentally friendly solution for networks placement. The energy can be scavenged either from dedicated or from ambient transmitters. Dedicated sources can be deployed where a stable and predictable amount of power to meet user's demand is expected, while ambient sources are transmitters not primarily intended for this purpose, thus granting freely available signals in the environment. Harvesting energy from the latter is very challenging, given the amount of energy density available (0.04–$2\,\mathrm{mW/m^2}$), whatever the transmitter type may be.

This chapter surveyed the general architecture of a harvester from both anticipated and ambient RF origins, in order to meet the future demand for self-powered devices. All the subsystems of the harvester were discussed: antenna design, matching circuit, rectifier, power management, and energy storage. In addition, potential RF signals scavenging applications and techniques beyond wireless sensor nodes power were explored, such as long-distance electrical power distribution, SWIPT, beamforming, and cognitive radio. While several concepts of energy harvesting through RF signals have been proposed mainly in the academia, it remains that very few products are commercially available in the market. With the ubiquitousness of the IoT, Wi-Fi signals, which work in the 2.4 GHz/5 GHz band, are gaining lots of research interests. Currently, the research and development divisions of companies like Samsung, Intel, Qualcomm, and Texas Instruments are hard at work trying to make harvesting from Wi-Fi signal and other ambient sources a reality. The first to market with a viable solution will create huge amounts of goodwill.

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