Radio Frequency Energy Harvesting System and Technologies

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Radio frequency energy harvesting (RF-EH) is a potential technology via the generation of electromagnetic waves. This advanced technology offers the supply of wireless power that is applicable for battery-free devices, which makes it a prospective alternative energy source for future applications.

radio frequency energy harvesting antenna rectenna rectifier

impedance matching network

1. Introduction

To date, radio frequency (RF) harvesters offer exceptional advantages over other sources of ambient solar energy, such as solar, acoustic, and mechanical vibration harvesters. The various notable characteristics of RF energy harvesting technology, including reliability, predictability, controllability, and the ability to simultaneously supply energy to different nodes, have made it the preferable option for certain areas or applications [1][2]. Interestingly, the marginal total energy harvested allows it to be applied in many applications that expect lower power consumption and contain many nodes [3]. The RF energy can be divided into ambient and intended RF [3]. The intended RF emits an RF signal from an RF transmitter directly to a specific area [4]. The advanced development of semiconductor technology and the fabrication process allow for the RF-EH concept realization. The conversion of energy in electromagnetic waves (EM) into valuable electrical energy in RF-EH facilitates the real application of continuous operating sensors [5]. On the other hand, however, the ambient radiofrequency energy is accessible over a broad range of frequency bands, such as LTE (750–800 MHz), DTV (550–600 MHz), UMTS (2150–2200 MHz), GSM-900 (850–910 MHz), GSM-1800 (1850–1900 MHz), Wi-Fi (2.4–2.45 GHz), band for television (TV) and radio applications (900 MHz–2 GHz), ISM (2.1–2.6 GHz), UWB (3.1–10.6 GHz), WLAN (3.1–4.4 GHz), HIPERLAN (5.1–5.3 GHz), and C-BAND (4.4–5 GHz) [6].

Increasing attention is being paid to energy-harvesting technologies that use ambient power sources, including heat, vibration, and electromagnetic waves. The self-sustaining “Zero-Power” standalone electronics have been developed in various energy harvesting systems, such as circuitries, topologies, and energy harvesting devices [7]. Currently, Wi-Fi, Wi-MAX, and GSM applications are more favored because of the services provided, including voice and video calls, short message service (SMS), high-speed data transfer, and broadly accessible internet access. These functional applications are utilized in mobile phones, laptops, and other portable devices that radiate plentiful amounts of RF energy, which can be harvested [8]. Harvesting RF energy is all about protecting RF energy from the radio environment and putting it to use in low-voltage electronic devices. Antennas-like patches with ultra-wideband properties or narrow-band antennas are required to detect radio frequency energy emitted by the radio environment. However, the utilization of the latter depends on the frequency bands that are going to be detected. For instance, an antenna with narrowband properties is required to detect GSM-900 frequencies. In addition, multiple-input-multiple-output systems are employed to improve the functional properties of wireless communication systems [9].

Meanwhile, the disposal of battery waste has become a significant issue in the last few years. Battery waste is mainly disposed of in landfills, which would lead to land pollution and the contamination of underground water due to the dissipation of harmful chemicals from the battery. Besides applying wireless power harvesting (WPH) technology to minimize the reliance on batteries, avoiding the use of batteries is the most effective solution to reduce the issue of battery waste, although it is not ideal [6]. In view of this, wireless RF power harvesting is considered a promising approach to replace or increase the lifespan of batteries. In fact, the ability of RF-EH via ambient RF energy provides an alternative method to reduce the cost of regular maintenance in terms of device improvement [10]. It has been explored [11][12][13][14][15] if radiofrequency energy can be used to replace batteries in low-power embedded systems, given the various energy sources available in the environment. Although the main perspective is to improve the lifespan of multipurpose electronic components, the RF-EH technology is feasible and distinguished through the required applications and its ability in philosophical design. The feasibility of the overall system dramatically relies on the incorporation of modules comprising microwave antennas, direct current (DC) booster, impedance matching network, power management techniques, and rectifying circuits. Therefore, the development of the RF-EH system is defined through critical trade-offs that researchers employ to achieve an optimal system in specific applications [16][17].

2. Radio Frequency Energy Harvesting (RF-EH) System

The RF-EH system has received much popularity over recent years, as the method offers an alternative yet the sustainable approach to supply power to low-powered electronic systems [18][19]. Among the common low-powered electronic systems include the internet of things (IoT)-powered devices, wireless sensor networks (WSN), and smart metering systems. Moreover, RF-EH is a suitable alternative and promising approach to deliver energy to next-generation wireless networks [20]. The energy generated by powerful RF signals can be used to charge an RF-EH circuit’s energy storage unit. For instance, supercapacitors or rechargeable batteries are time-efficient compared to weak signals [21]. The use of energy harvesters to provide power for WSNs is a promising solution. Sensor devices operate on the energy that already exists in the environment, rather than relying on centralized power sources to charge their batteries. To power integrated circuits, a holding capacitor or supercapacitor is used to keep the direct current voltage (DC voltage) that is used to power them [22]. The different output of the RF power presents a considerable setback in the configuration of RF-EHs since the harvester performance, including the efficiency, is proportional to the power input and the RF frequency source as a result of the impedance matching and the turn-on voltage of the RF-EH, respectively [22].

While the design methodology to achieve optimal RF-EH performance has been developed [23], the harvester must be capable of monitoring the frequency and the power level of the operating RF energy to consistently achieve optimum efficiency. In comparison to wireless power transmission (WPT), the nonreliance of power from the operator of the harvester is the key advantage of RF-EH, which constitutes a “free” energy source. Nevertheless, RF-EH is regarded as the most complex energy source due to the varying frequency over the available harvestable power, location, time, energy source distance, and environmental factors. Furthermore, RF-EH has a low power density, particularly in comparison to other renewable energy sources [24]. Despite these limitations, RF-EH faces only minor density problems, particularly the sub-microwatt state (for example, a cellular GSM base station that generated 0.1 μW/cm^2 [25]), significantly different from other ambient energy sources from the sun, through motion, or electrochemical reaction. The small RF density can only be used in ultrapowered devices under constant operation (non-duty-cycled) or low-powered applications, such as duty-cycled operation and low-powered wireless sensors in delay-limited devices, given that an adequate amount of RF energy must be harvested prior to the operation of the system [25].

A typical RF-EH circuit comprises a rectifier, a voltage multiplier, an antenna, and a device for energy storage. The most vital part of the RF-EH circuit is the rectifier, which significantly influences the system’s efficiency. The antenna serves as a transducer to convert the strength of an electric field into a voltage difference, or vice versa. The rectifier, on the other hand, converts RF power to DC power. The voltage multiplier produces a higher output DC voltage level when the sensor or energy storage device is activated. Once the energy has been harvested, batteries or supercapacitors are used to store it. It is critical to measure and investigate the power density of EM fields in the ambient environment before designing an RF-EH circuit. The electromagnetic spectrum has been measured in many countries [26][27] since the preferred frequency band, or bands for radiofrequency energy-harvesting circuits, are the most powerful. The structure of the RF-EH system is illustrated in **Figure 1** [28].

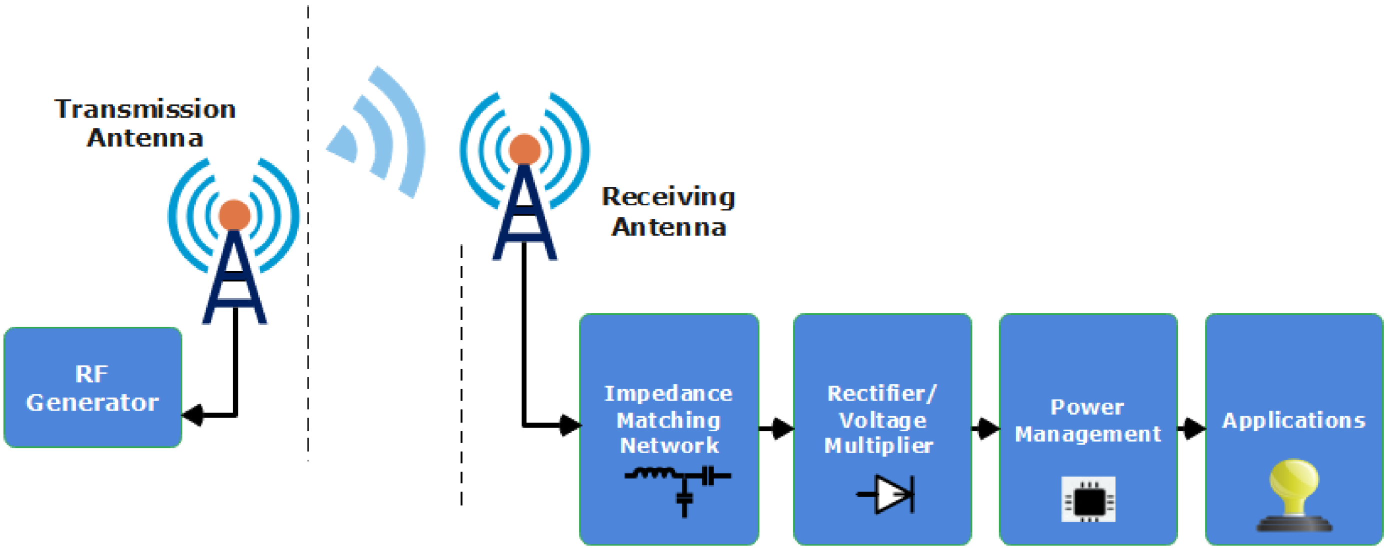

Figure 1. An RF energy harvesting systems conceptual block diagram.

Wireless communication systems’ RF signals would be the best suitable renewable energy source. Energy sources are based on vibration, light, and heat, and are not continuously present everywhere. In contrast, electromagnetic energy occurs in varying magnetic fields surrounding the alternating current power lines or the emission of radio waves from nearby transmitters. The EH application devices are categorized as near-field and far-field [29][30].

3. RF-EH Techniques

Contrary to other energy-harvesting sources, such as wind, solar, and vibrations, the RF-EH is characterized as follows:

(a) Ability to regulate and provide constant energy transfer over a long distance.

(b) The harvested energy is relatively stable and predictable for long-term performance to the fixed distance in an RF-EHN setup.

(c) The different locations of network nodes exhibit a substantial difference in the RF-RH since the total RF-EH relies on how far the dedicated RF source is from the ambient RF source.

3.1. RF-EH from Dedicated RF Sources

The two options are dedicated transfer, which necessitates high power values, and ambient energy harvesting, which necessitates low power values. A circuit that harvests RF energy from a dedicated source over a short distance is expected to generate power levels in the range of 50 nW/cm^2. One example is an RFID chip that is powered by an RFID reader. Because of the dedicated power supply, embedded devices can recharge their batteries [31]. Path loss, energy dissipation, shadowing, and fading are some of the drawbacks of RFH, whereas RFET has a number of promising directions and an advantage over nonradiative wireless energy transfer in terms of relaxed coupling/alignment specifications. Reception sensitivity and maximum radiation limits are all factors in the problem, as is a dramatic reduction in RF conversion efficiency at low receive powers. Additionally, the information reception sensitivity in RFH (typically −60 dBm in data reception vs. −10 dBm in RFH) is several orders of magnitude higher than in wireless data transfer. Due to the current state of the device and RF circuit technology, some applications may not be feasible. This two-hop decode-and-forward relay mode may not be able to work with conventional internode distances (a few tens of meters) because the current achievable energy transfer range is only a few millimeters [32].

3.2. RF-EH from Ambient RF Sources

This source type is further subdivided into two categories:

- Static sources, even though they are stable-power transmitters, are not simplified; the sensor device’s power is supplied by modulating the signal (for instance, by modulating the frequency and transmitted power). Ambient sources, including broadcast radio, mobile base stations, and television, are examples of what is expected [33].

- Dynamic sources. Although these are transmitters that regularly broadcast in a manner that is not monitored by the internet of things' system for such sources to yield energy, an intelligent WEH is required to continuously monitor the channel for potential harvesting opportunities. Unknown ambient sources include Wi-Fi access points, microwave radio links, and police radios, to name a few examples [33].

3.3. RF Energy Transfer between Mobile Devices

Wireless communication devices are able to serve as RF sources to transfer power among nearby devices stably. Previously, certain RF energy transmitters/receivers were designed to simultaneously transmit/receive power and information. The power splitting or time switching setting provides a cheap approach for sustainable wireless system operations in the absence of any transmitter modification. It allows a similar antenna or antenna array to be used for both the RF-EH and the information receiver. In short, mobile devices can be used to transfer information-based RF energy for the relay nodes to prevent the unbalanced consumption of energy [34].

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