RF Energy Harvesting for Low-Powered IoT Devices

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Abstract

This paper presents the practical challenges linked to the design & development of rectenna system to power up Internet of Things (IoT) devices. An ambient RF energy survey is presented which highlights the amount of energy available in various ambient RF frequency bands. The design practices related to various components of rectenna i.e., antenna, matching network, rectifier and power management unit are discussed. The recommendations to design an efficient rectenna systems has also been presented and discussed.

1 Introduction

In the last decade, the field of Internet of Things (IoT) has made a significant advancement. The IoT devices are now deployed in various sectors, for control & monitoring, including offices, homes, transportation, healthcare, automobiles, agriculture and environment. With an estimate of 42 billion devices in 2019, it is expected that the number of connected IoT devices will exceed 50 billion by 2050 [1]. The efficient powering of these devices is one of the key research challenges. Batteries may be used for this purpose; however, they require constant maintenance and difficult to replace especially if the IoT devices are deployed in inaccessible areas. Therefore, charging batteries wirelessly or designing battery free systems are being considered [2].

Several energy harvesting sources available that can be used to power up IoT devices. The solar energy is available only during the daytime; however, it requires large area and has orientation issues. The piezoelectric energy is activity dependent and has a variable output. Similarly, the thermoelectric energy is continuously available but has low output power. On the other hand, the RF power is widely available, and its harvesting system requires less space. However, RF power decreases with an increase in distance. Both ambient and dedicated RF power harvesting sources can be used to power up IoT devices. However, the focus of this paper is on ambient RF energy for harvesting purposes i.e., to capture green invisible RF energy and convert to usable DC voltage [2]. The history of RF energy harvesting dates back to 1963, when first RF energy harvesting system was developed by R. George using an array of 28 $\lambda/2$ dipole antennas and a bridge rectifier. Afterwards, there was a significant development in this research area [3]. Several ambient RF energy sources are available in an urban environment i.e., FM/AM/DTV broadcast, mobile communication and Wi-Fi. The energy from these sources can be harvested to power up IoT devices. It is pertinent to mention that with an integration of RF energy harvesting and IoT system, one can achieve several advantages including increased portability, compact products, increased efficiency and simultaneous energy/data transfer.

In this paper, the practical challenges related to the design & development of rectenna system are discussed. The ambient RF energy survey is presented which is essential to initiate the design of rectenna. The tradeoffs between design parameters of various rectenna components are also highlighted. The organization of this paper is as follows: Section 2 presents the ambient RF energy survey. The components of rectenna system are discussed in Section 3 followed by conclusion in Section 4. The acknowledgement and references are followed afterwards.

2 Ambient RF Energy

The first step in rectenna design is to analyze the available ambient RF energy levels and identify the usable frequency bands. It can be done with the help of antenna connected to a spectrum analyzer as shown in Fig. 1.

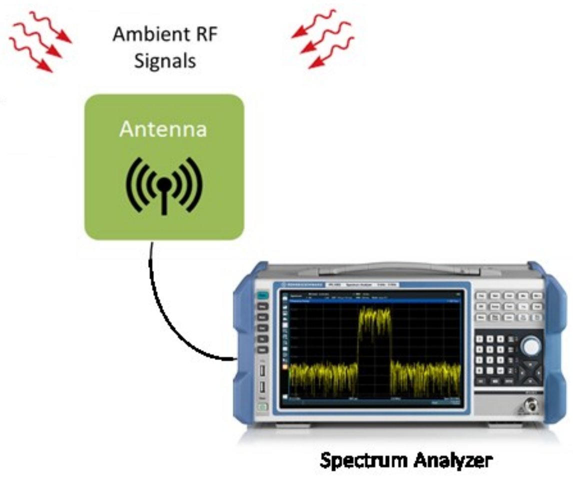

Fig. 1. Measurement setup illustration for ambient RF energy survey

In above context, an ambient RF energy survey was carried out in a semi-urban environment i.e., RIMMS-NUST [4]. The wideband omni-directional whip antennas (operating from 66 MHz to 2.7 GHz) along with a portable spectrum analyzer were used. The measurements were carried out at different times of the day and an average was computed.

The average peak available power is shown in Table I. It was observed that the GSM-900 band has the highest available power i.e., ≤ -10 dBm, which means it has maximum potential for harvesting, however, it was time-varying. The FM band has stable signal strength and low attenuation indoors, while the Wi-Fi was dependent on number of nearby available Wi-Fi sources and has good indoor consistency which makes them suitable to power up devices inside homes and buildings. The UMTS and GSM-1800 also have a potential for energy harvesting.

Table I. Available Peak Ambient Power

Frequency Band	Peak Ambient Power (dBm)
FM (88 – 108 MHz)	≤ -30
GSM 900 (800 - 960 MHz)	≤ -10
GSM 1800 (1710 - 1880 MHz)	≤ -30
UMTS (1920 - 2140 MHz)	≤ -35
Wi-Fi (2300 – 2490 MHz)	≤ -45

3 Components of Rectenna

Once the ambient RF energy survey is done, then an appropriate rectenna can be designed to harvest energy to power up IoT devices. The word 'rectenna' is composed of two terms i.e., antenna and rectifier as shown in Fig. 2(a). However, the necessary components of a rectenna are shown in Fig. 2(b). The main purpose of rectenna is to convert the received RF energy to a useful DC power to power up the load i.e., an IoT device. Several rectenna topologies are reported in literature [2] such as, (i). using multiple antennas with RF power combination and a single rectifier, (ii). using multiple antennas with separate rectifiers for each branch and a single DC combination at the end, (iii). hybrid of (i) and (ii). For the first topology, larger breakdown diodes are required to handle the higher power levels. On the other hand, in second topology, the rectenna efficiency will be lower than the first one as multiple diodes are used. Depending on the application, the available ambient RF power levels & frequency bands and output DC power, the desired topology may be selected.

The research challenges related to various components of the rectenna are discussed as follows:

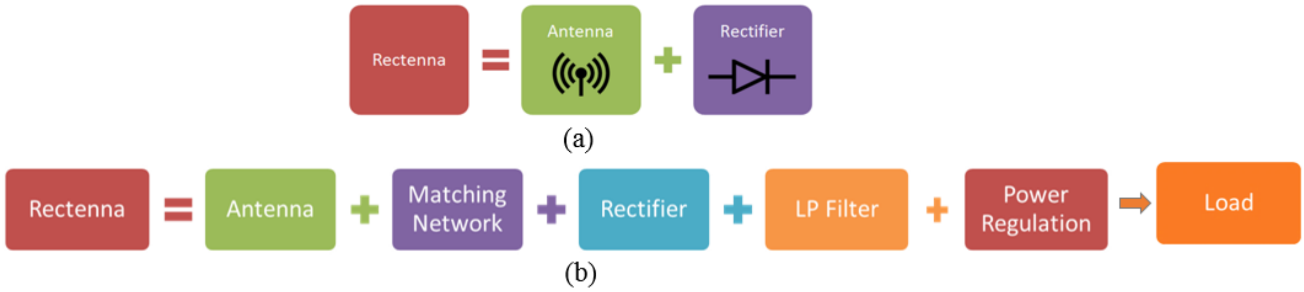

Fig. 2. (a) Rectenna, (b) Components of Rectenna

3A. Antenna:

The antenna is an integral part of rectenna. The antenna receives the ambient power signals to harvest energy. The preferred characteristics of harvesting antenna include high gain, compact size, circular polarization, broadband/ wideband and omnidirectional/ directional. However, there always exists a tradeoff between these antenna characteristics while designing it. For example, for high gain antenna, an antenna array can be designed, however, it will increase in antenna size making it unsuitable for portable devices. If an omni-directional antenna is used, then it will have lower gain as compared to a directional antenna which may have large size. Similarly, a broadband or multiband antenna shall be used so that it may be able to harvest energy available in different frequency bands mentioned in Table I. In addition, integration of low frequency antenna (i.e., operating at FM band) and higher frequency antenna (i.e., operating at GSM-900/1800, UMTS and WiFi) shall be carried out in order to harvest as much energy as possible. The low frequency antennas typically have large size. For FM frequency band, the loaded monopole antenna may be used [4, 5]. For higher frequency, the microstrip patch antennas are commonly used due to their useful features including compact size, low profile, light weight, low cost, ease of fabrication and conformity to planar & non-planar surfaces. The output power from different antennas can be combined using broadband cascaded Wilkinson power combiner and fed to the impedance matching network.

3B. Matching Network:

The impedance matching network is required to ensure minimum losses due to reflection between antenna and rectifier. The matching network is employed between antenna and rectifier such that, at certain input power level, the antenna input impedance is complex conjugate of rectifier input impedance. The matching network can be made using lumped components (operating lower than 1 GHz) or distributed elements (operating higher than 1 GHz). The design of multiband matching network is a challenging task since the input impedance of the rectifier is complex, frequency & input power dependent as well as load dependent. This makes the impedance matching network a multi-dimensional task [2, 6-7].

3C. Rectifier:
The rectifier is an important component of rectenna that converts the harvested RF signal to DC voltage. The rectifier is based on single or multiple diodes. The RF-DC conversion efficiency (η) is key parameter of rectenna performance which is also dependent on this rectifier. It is defined as:

$$\eta = \frac{P_{DC}}{P_{in}} \quad (1)$$

where, P_{in} is the RF power input to the rectifier while the P_{DC} is the output DC power. Several rectennas are presented in literature with efficiency as higher as above 70 % [4].

Several rectifier topologies are commonly used including series diode, voltage doubler and the Greinacher rectifiers. The series diode is used when the input RF power levels are very low whereas, Greinacher rectifiers are used in case of high RF power. On the other hand, the voltage doubler rectifiers are commonly used for ambient RF energy harvesting as ambient RF energy levels vary between low and medium intensity range [2, 8-10].

The input impedance of the rectifier is complex, frequency & input power dependent as well as load dependent, which in case of single diode can be represented as:

$$Z_{diode} = \frac{V_{ac}\sin(\omega t) - 0.5V_{dc}}{I_S\left[B_O\left(\frac{V_{ac}}{mV_T}\right)\exp\left(\frac{-0.5V_{dc}}{mV_T}\right) - 1\right]} \quad (2)$$

where, V_{ac} is the input AC voltage, ω represents frequency and V_{dc} is output DC voltage. For RF energy harvesting, the diode shall have the following characteristics:

- Low threshold (turn on) voltage
- Low series resistance
- High break down voltage
- High switching speed
- Low junction capacitance

In above context, the commercially available diodes i.e., Agilent Schottky HSMS series and Skyworks diodes SMS series are commonly preferred for rectenna design for harvesting RF energy [2, 4]. A comparison of few commercially available diodes is shown in Table II. For low power handling applications, the diode with minimum threshold voltage is preferred, while for high power applications, the diode with high breakdown voltage is preferred.

Table II. Parametric Comparison of Commercially available Didoes

Diode Model	Power-Handling Capability	Threshold Voltage (mV) @ 1 mA	Break-down Voltage (V)	Junction Capacitance (pF)	Series resistance (Ω)
HSMS 8202	low	250-350	4	0.26	14
HSMS 2860	high	250-350	7	0.18	6
SMS 7630	low	135-240	2	0.14	20
SMS 7621	low	260-320	3	0.10	12

3D. LP Filter:

A standard low pass (LP) filter comprising a resistor and a capacitor can be connected between rectifier and load/power regulation unit. It suppresses the higher order harmonics from the rectifier DC output.

3E. Power Regulation:

The power regulation or management unit is essential in rectenna design to provide a stable DC output since the ambient RF energy varies with time. In addition, some applications also use ultra-low power DC-DC boost converters with battery management unit to charge a storage element i.e., a capacitor [2]. This is to ensure that the IoT device get a stable DC power, when required. However, the DC-DC boost converters may decrease the rectenna efficiency due to their inherent losses.

4 Conclusion

This paper has presented an overview of rectenna system followed by ambient RF energy survey. It is observed that GSM-900 has the highest available RF power among various other ambient frequency bands. The receiving antenna shall be a circularly polarized broadband antenna with high gain and compact size. The impedance matching network shall be broadband or multi-band composed of lumped (< 1 GHz) or distributed elements (> 1 GHz). The voltage doubler rectifier topology is typically used to convert RF to DC. The rectenna system also requires a power management and power storage circuitry to efficiently power up the IoT devices. It is also observed that some rectenna system also employed the DC-DC boost converters to boost the DC output power level.

It is pertinent to mention that, even though RF energy harvesting is a great solution for frequent battery replacement and elimination of wires, however, achieving reasonable DC voltage & current using ambient RF energy to power up practical IoT sensors is still a major challenge due to low and time-varying ambient RF power levels. It is expected that the observations and recommendation made during this study will be useful to design & develop efficient future rectenna systems to power up IoT devices.

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