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A SURVEY OF ENERGY HARVESTING CIRCUITS: RESEARCH ISSUES AND CHALLENGES

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ABSTRACT

Energy Harvesting is referred to the capability of collecting ambient energy. Circuits has been designed for recovering energy from several sources: radio frequency (RF) signals, thermal energy, kinetic motion and mechanical vibration for naming a few. This solution applies to self-powered devices just like power charging, remote environment monitoring, mobile devices, health and structural monitoring. This paper addresses the circuits implemented for RF energy harvesting. This circuits harvest energy from Digital Television towers, Mobile Networks (GSM) and Wireless LAN. In this paper, the general block scheme is presented and the circuit elements are discussed in detail. Besides some figures of merits like efficiency conversion and output power are illustrated. The practical applications for powering some electronics devices is also analyzed. Finally, some research issues and challenges are also described.

KEYWORDS: RF Energy Harvesting, Energy Efficiency, Green Communications.

RESUMEN

El término Energy Harvesting describe los sistemas recolectores de energía ambiental. Los circuitos que se han diseñado recolectan energía por medio de diversas fuentes: Señales de Radio Frecuencia (RF), energía térmica, movimiento cinético y vibraciones mecánicas por mencionar solo algunas fuentes. Estas soluciones son aplicadas donde se hacen necesarios los dispositivos auto energizados como cargadores, monitorización remota del ambiente, dispositivos móviles y monitorización de parámetros de salud y estructuras arquitectónicas. El presente artículo aborda los circuitos empleados para la recolección de energía RF. Los sistemas implementados recuperan energía a partir de torres de televisión digital, Redes Móviles como GSM y Wireless LAN. Este artículo describe el diagrama en bloques general del sistema y los elementos circuitales son presentados en detalle. Además, algunas cifras de interés como la eficiencia de conversión de energía y la potencia de salida son ilustradas. Adicionalmente, se presentan algunas aplicaciones prácticas para la recarga energética de dispositivos electrónicos. Finalmente se resumen los diversos campos de investigación y retos de estudio.

PALABRAS CLAVES: Sistemas Recolectores de Energía RF, Eficiencia Energética, Comunicaciones Sostenibles Energéticamente.

INTRODUCTION

In regard to the Green Communication issue three different approaches are analyzed: Low Power Design, Power Aware Design, and Battery Aware Design [1]. RF Energy Harvesting circuits are designed for collecting ambient energy in order to provide power to electronic systems in a microwatt scale. This is a design from a battery aware point of view. The original idea of wireless power transmission was developed by Nikola Tesla. He conducted some experiments for testing the capabilities of self-powered devices. In 1899 he transmitted 10^8 V in a high-frequency range at a distance of 40 km to power 200 bulbs and an electric motor. Additionally, he designed the Wardenclyffe tower to demonstrate the transmission of wireless energy globally through Ionosphere. The idea was not further developed due to technology limitations because of low system efficiency. Later, in the period 1920-1930, the invention of the magnetron led to the conversion of electricity into microwaves, which in turn enabled the possibility of transmitting wireless energy over long distances. Finally, in 1964, W. C. Brown invented the rectenna for retrieving energy from microwaves. In this vein, Brown demonstrated the practicality of this solution powering a model helicopter [2].

In cases where electronic systems have not access to a power net the use of batteries represents the standard solution. However, the manual replacement in large scale systems causes increasing costs of maintenance [3] and is far from the concept of perpetually communicating devices. On the other hand, customers are getting aware in regard to the ambient concern. The market for energy harvesting applications was valued for 79.5 million USD in 2009, and this value has grown to 45 million USD by 2009 [3]. By way of example, wireless charging systems will have a market of 4.5 billion by 2016 and this value was estimated to be tripled to 15 billion in 2020 [2]. Other reports exhibit a market of 1894.87 million USD by2017 and growing at a rate of approximately 24% [4]. The power consumption of electronic devises at home such as televisions, laptops and mobile phones represent the 15% of the total power and it is rapidly increasing [5]. Besides, considering the hardware elements from mobile computing the evolution of battery energy capacities represents the slowest growing curve [6].The development of self-powered devices constitutes an emerging trend in current technology.

Leading manufactures for smartphone devises like Samsung, Apple, Huawei [6], Texas Instrument [8], Atmel [9] and Intel Research [5] are introducing their products with built-in wireless charging capability. Additionally, there are different consortiums to develop international standards for wireless charging such as: Wireless Power Consortium, Power Matters Alliance and Alliance for Wireless Power [2, 10]. Besides, European Projects are guiding research and future progress in this regard; an example is given by E-CROPS [11] and WARP [12].

The rest of the paper is organized as follows: Section 2 summarizes the different sources and metrics for describing the energy harvesting circuits. Section 3 presents the reported schemes, and the circuits elements are described in detail. Finally, some challengers and conclusions are presented in Sections 4 and 5.

Sources of energy harvesting and metrics.

The sources of RF energy harvesting are comprised by the electromagnetic emission of current technology such as DTV, GSM900, GSM1800, 3G and Wi-Fi; in which the Wi-Fi source is the lest contributor [13]. The power transmitted by some of these sources are summarized in table 1.

Table 1: Power transmitted by each different source

Sources	Band	Transmitted Power
TV broadcast	80-220 MHz	few tens of kW [14,15], 70 dBm [16]
FM broadcast	88-108 MHz	few tens of kW [14,15]
AM broadcast	540-1600 kHz	few hundred of kW [12]
ISM band	902-928 MHz	4 W (36 dBm) [17,18]
Mobile GSM	800 MHz	1 W to 2 W [14], 4 W of maximum power, -43 dBm (18 dB antenna gain)
Wireless LAN	2.45-5.8 GHz	10-20 W per carrier, 100 mW [21]

The power received at the output of the antenna is computed taking into account the Friis's transmission formula on a logarithmic scale as [22]:

$$P_R = P_T - L_P + G_T + G_R \tag{2.1}$$

Where P_R and P_T are the received and transmitted power, G_T and G_R are the transmitter and receiver gain antenna and L_P represents the free space past lost given by:

$$L_P = 32{,}4 + 20\log_{10} f + 20\log_{10} R \tag{2.2}$$

f is the operating frequency in MHz,R represents the distance in km, G_T and G_R are the transmitter and receiver gain antenna, respectively. Additionally, the sum $P_T + G_T$ is called the Effective Isotropic Radiated Power (EIRP). This expression assumes no additional lost as multipath effect for example. In a real environment the received power is attenuated in power of R^{-2} to R^{-4}. The reported received power from campaign measurements are summarized in table 2.

Table 2: Reported received power

Sources	Received Power	Distance
TV Broadcast [16]	-40 dBm -17 dBm	In natural environment 6,6 km
ISM band	-16 dBm [17] -20 dBm [18]	> 10 m 20 m
GSM1800 [19]	-20 dBm to -35 dBm [23,29] [19] -110 to -53 dBm [20]	20 m
Wireless LAN	-38 dBm	5 m

The circuits for energy harvesting recover the receiver power for powering some electronic systems. In order to bring a measure of quality in regard to the total amount of power recovered two metrics are defined [24]:

1. Efficiency: Usually denoted by η and is given by the output to input power ratio as $\eta = \frac{P_{out}}{P_{in}}$.
2. Sensitivity: Given by the minimum power necessary to power an IC.

This two metrics define the quality of the proposed design. Lowest values of sensitivity allows to recover energy from week signals. Highest values of efficiency determine the maximum amount of energy to be retrieved from the ambient.

Havana city RF survey.

In case of Havana city, some measurement campaign has been made for analyzing the RF environment [25]. The cases analyzed are the transmitters located at Televilla and Habana Libre for Radio and DTV signals. The power transmitted and received for each different source is summarized in table 3. The received power is estimated tuning the receiver filter to 1MHz bandwidth.

Table 3: Transmitted and Received Power for each different source, Havana city [25].

Sources	Frequency [MHz]	Transmitted Power [kW]	Received Power [dBm]	Distance [m]
Radio Reloj (Televilla)	101.5	5	no specified	no specified
Radio Mayabeque (Televilla)	104.7	10	-16	1000
Radio Cadena Havana (Televilla)	99.9	2	no specified	no specified
DTV Channel 38 (Televilla)	617	5	-52	4210
DTV Channel 38 (Habana Libre)	617	no specified	-63	3300

The report in [25] specifies that an antenna of 1.42 m^2 of effective area is required for collecting 1mW. Which is no affordable for practical cases. However, better figures can be obtained in case of highest values of bandwidth for reception.

CIRCUITS

The circuits implemented for RF energy harvesting systems shown in figure 1, are mainly comprised by 5 different elements: antenna, impedance matching network, rectifier, booster circuit an load.

All these elements together transform the receiving RF waveform into dc at the output of the system. The harvested energy can be applied to power or charge a given electronic system for designing self-powered solutions.

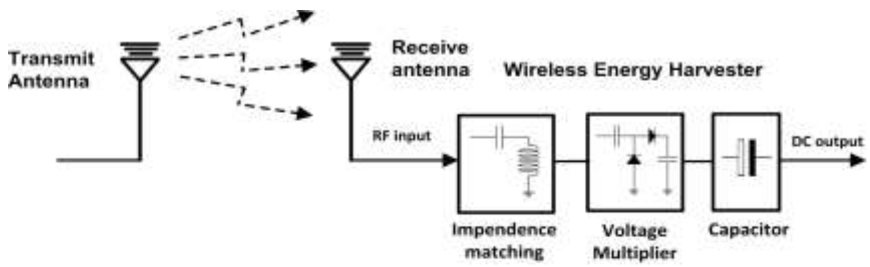


Figure1: General scheme of wireless power transmission [2].

Besides, in the market there are some commercial solutions from RF energy harvesting systems as summarized in table 4 [26, 27].

Table 4: Commercial products for energy harvesting applications.

Products	Applications
Powercast [28]	Transmitter, Receiver, Development Kit and Custom Engineering.
WiTricity [29]	Wireless charging for medical devices. Designs for Original Equipment Manufacturers (OEM's)
PowerMat [30]	Power charger for iPhone, iPod, Blackberry, mobile phone
Fulton Innovation -eCoupled- [31]	OEM's
Qualcomm WiPower [32]	Power charger for devices like wireless keyboards, mice, lamps and digital photo frames.
Mojo Mobility [33]	Power charger for mobile, industrial devices and electric vehicles. OEM's
Atmel [9]	Temperature sensor
Texas Instrument [8]	Wireless Batteryless Sensor Interface using Energy Harvesting

Antenna design.

Antenna is one of the most crucial components in energy harvesting systems to extract maximum power from the environment. Given the wide distribution of different RF sources the ideal design could be a high gain wideband antenna. Many designs have been proposed in this direction, however this is not an easy task.

Usually, printed antennas [34-36] are used in energy harvesting systems since this kind of antennas allow to integrate different components of the system. Particularly, printed dipole [37-39] and microstrip patch [40] are implemented. A basic block diagram of the rectenna's structure is shown in figure 1. The first block is a bandpassfilter centered tothe frequency of operation**.** Generally, this filter is neglected through the use of antennas with higher levels of harmonic rejection parameter[35,41]**.**

The signals generated by the higher contributor wireless services is distributed spectrally in the uhf band. This from 470 mhz (DTV lower bound) to 2.45 ghz (ISM upper bound). The most common bands for harvesting energy are 614 mhz (dtv), 900 mhz (gsm900), 1.8 ghz (gsm1800) and 2.4 ghz (ism band). The harvesting systems should be designed to gather energy in each band of interest.In this manner, multiband antennas have been designed for energy harvesting systems [34, 39, 42, 43]. Table 5 summarizes a study and a comparison of different antenna designs for TV broadcast, GSM and Wi-Fi bands.

Table 5: antennas used for energy harvesting applications.

Type	Source	Frequency Range	Gain	Radiation Pattern
Linear Dipole	DTV	550 MHz	3dBi	Omni-directional
Linear Polarized Folded Dipole	DTV	15 MHz - 800 MHz	2.5dBi	Omni-directional
Broadband Log Periodic	UHF, TV	915 MHz	5dBi	Directional
Yagi-Uda	DTV	545 MHz	6.28dBi	Directional
Rectangular Microstrip Patch	GSM 900/1800	900 MHz-1800 MHz	7dBi	Sectorial
Square Microstrip	GSM 900	900 MHz	9dBi	Sectorial
Planar Microstrip	Multiband	1GHz-6.4GHz	6dBi	Sectorial

MIMO and MISO systems could improve energy harvesting systems performance for two reasons. The Direction of Arrival (DOA) can be estimated and the radiation pattern can be adaptively conformed (DBF) in order to recover maximum energy from the environment. This is known as Adaptive Smart Antennas Systems, a general block diagram of these systems is shown in figure 2.

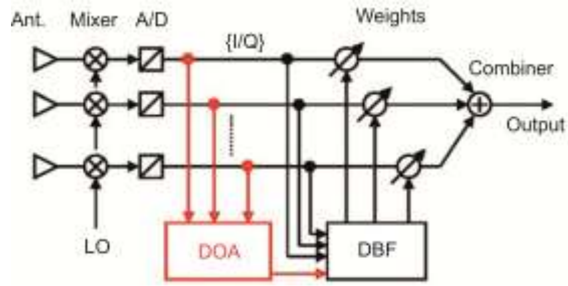


Figure 2: General Scheme of Smart Antenna Systems

The most commonly methods used to conform the radiation pattern are LMS and RLS. The former exhibits less complexity than the others, which in turn leads to a low computational cost. However, this method shows to have higher convergence's time. RLS algorithm solves this problem but complexity is increased.

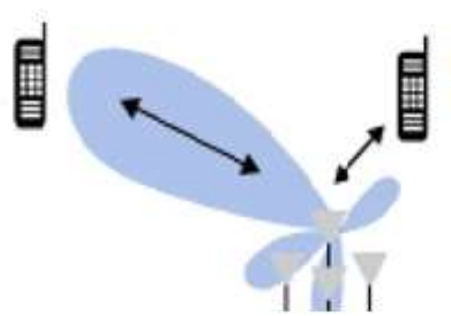


Figure 3: Radiation Pattern of Smart Antenna

Once the above methods are implemented, by means of FPGA technology for example, then the radiation pattern is adjustable adaptively, even in real time. By means of this procedure, the system matches to the environment taking into account the main energy sources. This is shown in figure 3, the main lobe focus on one of the two energy sources depicted as a mobile phone in this figure. In this regard the power received is maximized.

Rectifiers

The rectifiers are employed for transforming the RF signal into DC current with a specific voltage level. A diode rectifies the input voltage taking into account the breakdown voltage V_{br}.As long as the negative peak of the input signal is less than V_{br} then the maximum direct voltage collected at the output will be given by$V_{\max DC} = \frac{V_{br}}{2}$. When the peak to peak value of the input signal is larger than V_{br} then the direct voltage level will no longer increase. In this regard, the maximum output power, given a load resistanceR_L, is given by $P_{\max out} = \frac{V_{br}^2}{4\,R_L}$. In order to guaranty maximum efficiency the value of R_L is typically 1.3 to 1.4 times the intrinsic/video resistance [24].

The antennas can provide RF energy, however the voltage produced are not sufficient to drive current electronic, typically in the range 1-3 V. There exists a variety of topologies using a cascade of diode-capacitor stages; each of these stages uses the previous stage for biasing reference [24]. These topologies are implemented by charge and pump elements in order to obtain a voltage multiplier circuit.

The concept of voltage multiplier circuit was first invented by Heinrich Greinacher in 1919, later Cockcroft and Watson used this concept for accelerating particles in 1951. Nowadays, these circuits are mainly classified in two topologies Villard/Cockcroft-Watson and Dickson multiplier. These two topologies have not significant difference in performance [19]. Usually the charges and pump circuits employs the Dickson topology. Common topologies for recovering the output power were described in [24].

Mainly two different applications use the energy harvesting techniques, Solar Satellite Applications SPS (for great distances and high powers, greater than 1 W) and RF Identification RFID (for ultra-low power harvesting less than 1W). The SPS community implements the solutions based on rectennas for a better efficiency, while the RFID community employs charge and pump configurations for increasing the output voltage.

Technical description

The performance of the diode is described taking into account the efficiency$\eta = \frac{P_{out}}{P_{in}}$. The efficiency of the diode is mainly limited by five aspects [24]:

1. The turn-on voltage V_T: This effect limits the efficiency of the diode at low powers. In case that no sufficient power arrives to the diode then no sufficient energy is available to overcome this barrier. This is typically the most important parameter.
2. The diode reverse breakdown voltage V_{br}: This effects affect the efficiency at high power levels.
3. Impedance matching: In case that the energy harvesting circuit is not matched to the output impedance of the antenna, then part of the incident power will be reflected back. The impedance matching depends on the incident power and the operating frequency.
4. Device parasitic: The efficiency is also reduced by the energy dissipated in diode's equivalent resistance. Besides, the value of diode's capacity (C_j) imposes a cutoff frequency which in turn limits the maximum operating frequency.
5. Harmonic generation: Due to the nonlinearity of the diode this device produce frequency harmonics form the incident power. This in turn reduces the available power at the output.

These five elements reduce the value of efficiency of the diode. An optimal value of efficiency is a tradeoff between this issues. In order to increase the value of efficiency it is desirable to have: lower values of V_T, higher values of V_{br} and lower values of the series resistance (R_s).

The reported solution employs the diodes described in table 6. This diode circuits belongs to the series HSMS-282x, HSMS-285x, HSMS-286x, SMS7630 and HSB276AS. The HSMS-285x is not recommended for higher power level applications (> -20 dBm).

Table 6: Rectifier circuits.

Circuit	Input Power	Input Frequency	V_{br}	Applications
HSMS-282x [69]	> -20 dBm	< 4 GHz	15 V	–DC biased small signal detectors to 1.5 GHz –Biased or unbiased large signal detectors (AGC or power monitors) to 4 GHz –Mixers and frequency multipliers to 6 GHz
HSMS-285x [70]	< -20 dBm	< 1.5 GHz	2 V	–RFID 915 MHz for small signal (HSM-285c)
HSMS-286x [71]	> -20 dBm	915 MHz- 5.8 GHz	4 V	–RF/ID and RF Tag applications –Large signal detection, modulation – RF to DC conversion –voltage doubling.
SMS-7630 [72]	> -20 dBm			– Sensitive RF and microwave detector circuits – Sampling and mixer circuits – High-volume wireless – Wi-Fi and mobile – Low-noise receivers in high-sensitivity ID tags – Radio designs

Booster circuits.

The booster circuits are used for transforming and managing the output voltage from the rectifier step. Usually this is employed for raising the output voltage and powering the electronic devices supervising the charge of the output capacitor. These devices are also named as Power Management Module (PMM). This is used for converting the DC voltage at the output of the rectifier into a DC voltage through a maximum power tracking procedure for optimal energy extraction. Devices commonly employed are the BQ25504, LTC3108, Seiko S-882Z andAS-1310 [21], and most commonly the BQ25504 [45]. The main characteristics are described in table 7.

Table 7: PMM devices.

Device	Input Voltage [mV]	Output Voltage [V]	Efficiency [%]
LTC3108 [46]	20	2,35-5	25-50
Seiko-S882Z [47]	300-350	1.8-2.4	no specified
BQ25504 [45]	330	1.8	70-90

The device BQ25504 implements a sampling network to optimize the transfer of power into the output load. The optimum procedure is obtained by modulating the input impedance of the internal boost charger trough the regulation of the charger’s input voltage. The input voltage is sampled and that value is held with an external capacitor typically in 1.8 V. The device acquires and manage efficiently the power from a variety of DC sources in the range µW to mW. The minimum input voltage is 330mV and the sensitivity is-20 dBm. The applications of this device are summarized by [45].

The Seiko S-882Z is charge and pump circuit with a voltage sensitivity of 300 mV. This device has internally a voltage supervisor which disables the output during the charge period. The circuit is con figured as depicted in figure 4.

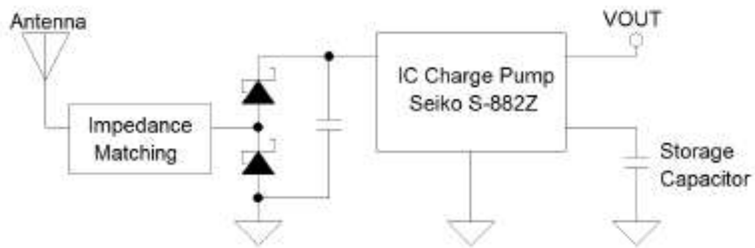


Figure 4: RF harvester using S-882Z.

The LTC is commonly used with photovoltaic cells or thermopile generators. However, in [44] a RF source is integrated into the solution. This device is used for powering microprocessors, sensors and RF links.

Load.

A variety of designs are employed for powering some low power electronics. This is used for sensing and transmitting data. Some of this devices are listed below:

- MSP430F2247-CC2500 [7]: The MSP430F2274 is a low-power 16-bit microcontroller, and the CC2500 is a low-power 2.4GHz transceiver. On average, the radio transmission task consumes 13.14 mA for 3.4 ms, the power needed for this device is in the order of 20mW (13 dBm).
- WISP (Wireless Identification and Sensing Platform) [48]: This are small sensor devices with a power consumption in the range 2µW to 2mW (-26 dBm to 3 dBm). The WISP is used for interfacing sensors such as light, acelerometers, temperature and for RFID and wireless security research.
- MICA2 sensor mote [19]: This sensor has integrated an Atmel ATmega128L microcontroller. The circuit is powered with 1.8V and 30 µA for 54µW (-12 dBm).
- Temperature and humidity meter (Radio Shack) [48]: This device is integrated with and LCD display and usually consumes 25-50µA at 1.5V, which in turn gives a maximum consumption power of 75µW (-11 dBm).

Practical circuit designs.

The practical RF energy harvester circuits retrieve energy from four different sources: DTV, GSM, Wi-Fi, ISM (Industrial, Scientific and Medical). In case of DTV band, the frequency employed depends on the country, but usually these emissions are centered in the range 400-800 MHz. The GSM signals are transmitted in the frequencies 900 and 1800 MHz. The Wi-Fi employs the frequencies 2.4 and 2.48 GHz. Finally, the ISM band is comprised by reserved portions of the spectrum for some additional applications other than telecommunications. The current section describes the reported circuits with the best efficiency and summarizes a variety of designs.

DTV Source

This solution employs the eZ430-RF2480 Demo Kit powered by rectenna [7]. The kit is comprised by a low power 16-bit microcontroller (CC2500) and a 2.4 GHz transceiver (MSP430F2274). The antenna is designed by an All Integrated Antenna (AIA) comprised by linear polarized strip antennas. This solution is implemented through the use of proprietary SimplicitTI protocol. This allows to develop a small-scale network of 256 nodes. A capacitor of 100 µF is employed to store the harvested energy to power the kit. The maximum reported efficiency is 50%. The minimum value of the capacitor is estimated through the expression:

$$C \geq \frac{I_a \cdot T}{V_a - V_{min}} \qquad (3.6.1)$$

Where:

I_a : average input current (13.14 mA)

T : transmission time

V_a : rectenna output voltage

V_{min} : Microcontroller minimum input voltage

GSM900 and GSM1800 Sources.

In this design the reported efficiency is 40% for the GSM900 and GSM1800 bands and input power of -1dBm [43]. The antenna is designed through the design of a multi-resonant annular-ring patch antennas in a circular polarization for guarantying the maximum energy transfer from unknown direction of arrival and polarization. The rectifying circuit is implemented with SMS7630 diode. The circuit is shown in figure 5.

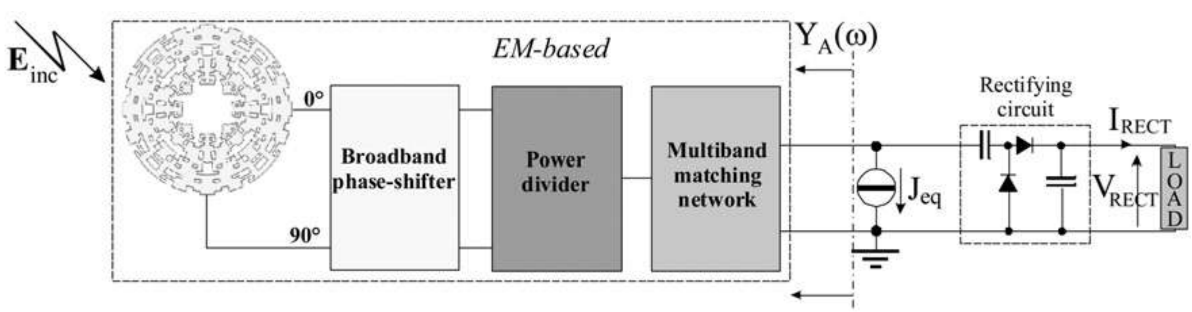
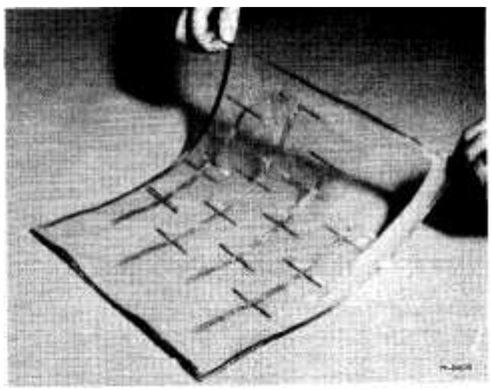
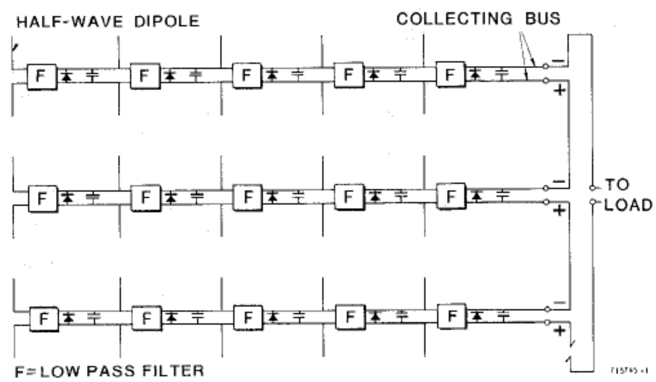


Figure 5: Design for GSM band [43].

WI-FI Source 2.45 GHz.

This design is implemented through the use of a thin-film etched-circuit as depicted in figure 6 a) with a reported efficiency of 85% [49]. In this design the antenna is implemented in a repetitive circuit comprised by dipoles, lowpass filters and rectifiers circuits as depicted in figure 6 b). The rectifier circuits are implemented by a single diode, a microwave transmission line and a capacitor. The design has been tested for an input power of 15 dBm.





a) b)

Figure 6: Rectenna designed for the band 2.45GHz. a) Thin-film antenna design. b) Circuit scheme [49].

Challenges.

The challenges in regard to energy harvesting techniques focus on the description of the channel as well as the transmission of information:

1. Channel State Information (CSI) [2]: The design of channel estimation results of paramount importance since the charging performance is severely deteriorated with the inaccuracy of channel estimation. Additionally, the hardware is limited by the impedance matching. The performance of the matching network is optimal in a limited range.
2. Data Communication [2]:
    a. Duplex communication and multiple access: Currently, the communication protocols only support simplex communication (from charging device to charger). However, a duplex communication becomes useful when the charger need to request for battery status, for example. Besides, the current protocols only support one-to-one communication. Nevertheless, in case that multiple device charging are implemented, then a medium access control (MAC) for multiple access need to be developed.
    b. Secure communications: Similar to other communication standard, in this case this application is vulnerable to the steal of charging and charger device identity, as well as

malicious users may falsify the charging status. In this case secure protocols must be studied.

3. Learning theoretic algorithms for EH systems [4]: In order to optimize the recovered energy some solutions model the arriving energy as deterministic and highly predictable. However, this is a very optimistic description in practice. An interest research direction is given by the study of learning algorithms with reduced suboptimal techniques.
4. Network of EHDs (Energy Harvesting Devices) and energy cooperation [4]: The characterization of network behavior increase in complexity with the number of nodes. Additionally, when these nodes are battery limited and performs EH techniques, then the EH profile must be included in this characterization. Optimal policies depend on the available knowledge of EH profiles for each different node, which in practice is hard to obtain. In this regard, some solutions are reported based on the local information only. On the other hand, when the receiver is provided with EH techniques, then it is possible to wirelessly transmit data and energy simultaneously. This case leads to open research problems related with resource allocation and interference management.
5. Accurate modeling of EH processes and storage elements (SE) imperfections [4]: The reported mathematical model describes a tractable EHDs analysis. However, this models are not always accurate in practice. A realistic description should include a model for storage and power consumption based on actual EH modules, SEs and microprocessor circuits.

CONCLUSIONS

This paper summarizes the most common circuits for harvesting RF energy from ambient sources. Typically, this designs use dipole or patch antennas together with HSMS-282X and HMS-285X rectifiers. Considering all the reported solutions, the average harvested power is around -15 dBm. On the other hand, low power circuits are typically powered with higher power values. For this reason, practical solutions operate on a cycle of two stage, one for collecting energy, and a second one for performing sensing and transmission operations. In regard to the available sources, even when the spectral power density of TV towers is superior to GSM, in suburban areas it is preferable to recover power from GSM towers since they are located in several places to cover the service area. On the contrary, TV towers are stronger within a few kilometers but they are placed in a limited area.

The real advantage of energy harvesting is going to be present when it will be integrated with next generation technologies like a system. The integration of 5G mobile generation, cooperate sensing techniques and smart antenna Systems demand high energy consumption due to digital signal processing inside them. These will be implemented in millimetric wave where will be possible to design large arrays with great gain which will result in upgrading energy harvesting utility.

Power wireless transmission (PWT) will supply a high percentage of the energy of the electrical systems in the future as smart grid of sensors, RFID tags and mobile phones. In general, energy harvesting systems will be one of the most important part of the future telecommunication standards in order to build green communication systems.

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