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Energy Harvesting and Optimisation from Ambient RF Sources: A Review

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Abstract
Energy harvesting from ambient sources has attracted a lot of research recently due to the high demand for cheaper and greener energy. Energy harvesting from RF sources involves three major stages, the first stage is the reception of the RF signal using an antenna, secondly the signal is conditioned using the appropriate circuits. Finally the signal is either used directly by a load or is stored in a battery or a capacitor. Several researchers have investigated the possibility of harvesting energy from ambient RF energy sources such as Wi-Fi, GSM, microwaves, CDMA, UHF and even AM signals. But in most of these researches, the harvested energy is too low, especially when the energy harvester is far from the transmitting station.This paper reviews the techniques used in RF energy harvesting and optimization of the harvested energy. The aim is to review past and present developments and approaches employed in harvesting energy from RF sources. The areas that require attention will also be presented. This paper will contribute positively towards research and development in the field of energy harvesting from ambient RF sources such as cell phone radiations, FM and AM radio signals, Wi-Fi signals and cellular networks signals.
Keywords: Energy harvesting, Optimisation, RF signals

INTRODUCTION

Energy harvesting refers to the process by which energy is derived, captured and stored from external sources. Energy has been harvested from several external sources such as thermal, mechanical, optical, RF signals and salinity gradient [1]. Some of the energy harvesting techniques include RF energy, piezoelectric, pyroelctric, electrostatic, photovoltaic, Biomechanical, magnetostatic and thermoelectric.

The basic structure of an energy harvester includes a harvesting element, a conditioning circuit and a means of storing or using the harvested energy. Figure 1 shows the basic structure of an energy harvester.

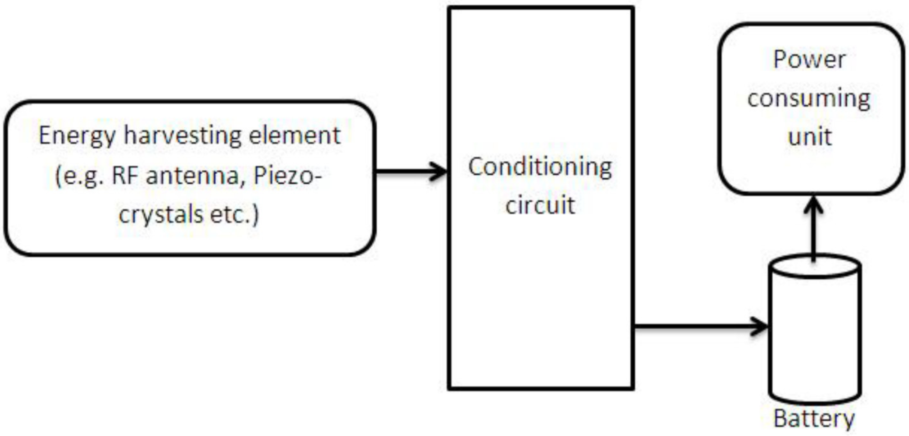

Fig.1 Basic structure of an energy harvester

The amount of energy harvested is greatly affected by the method of energy harvesting employed, the power densities for the different energy harvesting techniques are summarized in table 1[11].

TABLE 1
POWER DENSITIES FOR DIFFERENT ENERGY HARVESTING TECHNIQUES

ENERGY HARVESTING TECHNIQUE	CLASSIFICATION	POWER DENSITY
Piezoelectric	Mechanical Energy	200 $\mu W/cm^3$
Air flow	Mechanical Energy	177$\mu W/cm^3$
Blood Flow	Mechanical Energy	0.93W/100mmHg
Body Motion	Mechanical Energy	800$\mu W/cm^3$
External Heat	Thermal Energy	153$\mu W/cm^3$
RF Energy	Radiant Energy	0.02$\mu W/cm^3$
Solar Energy	Radiant Energy	100mW/cm^3

Radio waves are electromagnetic waves in the frequency range of 3 kHz to 300 GHz. Radio frequency signals are being used in wireless communications such as FM, AM, Wi-Fi, microwaves, GSM, and UHF. Harvesting energy from RF signals involves capturing the signal with an antenna and then conditioning the signal to produce a D.C signal that can be used to power devices. Figure 2 shows a block diagram of a typical RF harvester.

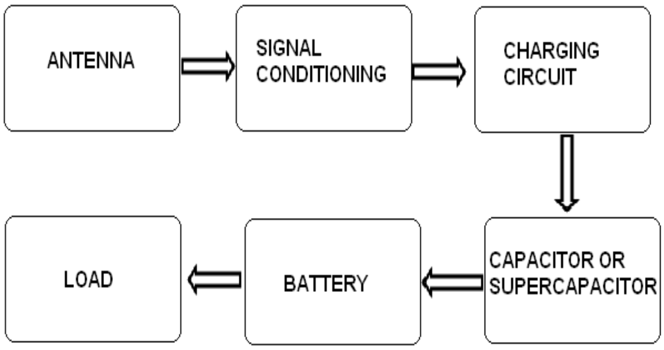

Fig.2 block diagram of a typical RF harvester.

ENERGY HARVESTING FROM RF SOURCES

Overview

Harvesting energy from RF signals has attracted a lot of attention because of the simplicity of the harvester. The structure is shown in figure 3[6].

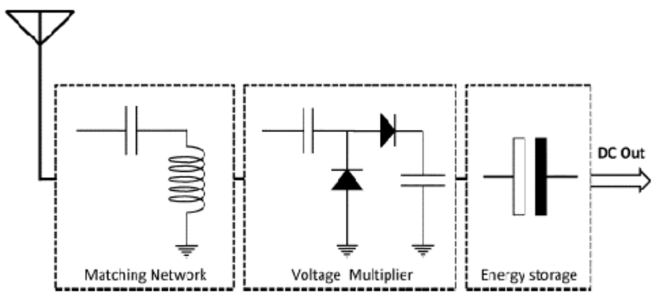

Fig.3 Structure of an RF energy harvester

However, RF energy harvesters suffer from low power outputs and this is attributed to the unpredictable nature of the input power, the received signal is also prone to distortion by obstacles and bad weather and has very low power density as compared to other sources. Nevertheless, a lot of researchers have investigated the possibility of harvesting power from RF sources that will be enough to drive commercial components such as wireless chargers, WSN and wireless earphones. The power densities of some of the RF signals are shown in table 2[12]

TABLE 2
POWER DENSITIES FOR DIFFERENT RF SOURCES

SOURCE	V/m	dBm
FM Radio	0.15 to 3	
Analogue TV	0.3 to 2	
Digital TV	0.2 to 2.4	-40 to 0.0
Cellular		-65 to 0.0
Wi-Fi		-30

The power density of any RF signal at a distance R from the transmitter is given by

$$P_D = \frac{P_T}{4\pi R^2} \quad (1)$$

Where P_T is the transmitted power

It can be seen from equation 1 that the power density of RF signals decrease rapidly as the distance increases. The power density is inversely proportional the square of the distance between the transmitter and the receiver.

Another equation that is useful when analyzing the power harvested from RF signals is the Friis Equation. The equation is given as follows

$$P_r = P_t G_t G_r \left[\frac{c}{4\pi R f}\right]^2 \quad (2)$$

Where:

c is the speed of light
f is the frequency of the wave
Pr is the received power
Pt is the transmitted power
Gt is the gain of the transmitter antenna
Gr is the gain of the receiver antenna
R is the distance between the transmitter and the receiver

Prior Research

There has been extensive research on RF energy harvesting. Most of these researches focus on optimizing the harvested energy because currently it is very low to power commercial loads.

A research by Sim et al [10] investigated the possibility of enhancing the power harvested by an RF harvester by optimising the antenna design, they used two antenna designs and evaluated the power output from each design in a soil wireless sensor network, The first design is a low-profile folded shorted patch antenna (FSPA) and the second design is a modified FSPA structure. They used a dedicated transmitter to supply microwave energy at frequencies of 867MHz and 2.45 GHz to the sensor nodes, their harvester was able to produce power levels of 1.5-2.2mW, this value is considerable high from an RF harvester, but since they used a dedicated transmitter, the harvested power is much less than the power transmitted, this caused the efficiency to be very low.

Bouchouicha et al [2] investigated the power densities from broadband and narrowband systems. their research also investigated the effect of the antenna and load on the harvested energy, their research concluded that the energy harvested from both the broad and narrow band systems was too low to directly power a low power device but could be stored in a capacitor or a micro battery, their research also concluded that the choice of load and antenna had an effect on the harvested energy due to impedance matching

Harrist [5] carried out a research on an RF energy harvester used to charge a phone. The research used a charge pump with peak detector circuit to charge a capacitor. The study used a commercially available quarter-wave whip antenna with a seven stage voltage doubler with an output capacitor to harvest RF energy from a 915MHz signal transmitted from a dedicated transmitter. SPICE was used to carry out optimization of the circuit parameters. The software allows the user to input a range of values for a given parameter and then specifies the value of increment for each of the parameters, this way the user is be able to detect the range of values that will yield maximum output power. The study showed that as number of stages increase, the output voltage also increases, but the voltage stabilized when the number of stages reached 6, any additional stage resulted in a decrease in the output voltage and this could be explained by the fact that the voltage gain becomes negligible as the number of stages reach six. Any additional stage will consume power without having any effect on the output voltage. The harvester was tested on two phones, the first was a Nokia 3570 which required a power of 1.26 Watts to charge the battery, and the second phone was a Motorola V60i which required a power of 2.36 Watts to charge the battery. The harvester was able to only power the phones for a short while and then failed to sustain the power levels required due to low energy output levels, but the harvester was able to recharge the batteries when the phones are off, the study was able to show that the harvester reduced the charging time of the mobile phone batteries by half.

Arrawatia et al [1] studied the feasibility of harvesting energy from cell tower in the frequency band of 900MHz, the cell towers investigated were broadcasting a CDMA signal. The research used a broadband electromagnetically coupled Square microstrip antenna (SMSA). The research yielded promising results, the harvester was able to produce voltages of 0.87V when a single stage voltage doubler was used and 2.78V when six stage voltage doublers were used. The effect of using schottky diodes on the circuit was also analysed, the research also concluded that the voltage levels increased considerably when schottky diodes were used, this can be attributed to their low threshold voltage of 230 mV.

Circuit optimization

Optimization of the harvester circuit systems result into considerable improvements in the harvested energy. This is evident from Friss Equation, if the value of the receiver gain is high, the power received will be high and this will consequently improve the output power from the harvester. Several approaches have been considered by researchers to optimize the energy harvested from RF sources.

Mikeka and Arai [7] considered optimising the RF energy harvester circuit by optimising the conversion efficiency of the RF energy harvesting circuit under stringent conditions such as arbitrary polarisation, low power incidences and varying incident power densities. The research optimised the harvester's power output by selecting the optimum operating conditions for the harvester. A modified Digital Television (DTV) antenna printed on FR4 substrate was designed for the study, the antenna feed the signal to an RF-DC converter that is made from Schottky diodes, the Schottky diodes were selected to produce very efficient conversion rates between the input and the output. The research also investigated the effect of Schottky diode's junction capacitance and resistance. The harvester was used to carry out experiments on low power DTV rectenna and medium power rectenna placed at a distance of less than 100m from the transmitter, the harvester was able to power a wide range of low power sensors and produced voltage levels of up to 3.7V when there is no load on the Harvester (Mikeka & Arai, 2011).

Molnar et al [8] investigated the possibility of designing an ultra-low power transceiver for WSNs. The research optimized the circuit by minimising the power consumption of the circuit from the battery, The effect of reusing the bias current of the circuit to run other low power components in the circuit was also investigated, a single high-Q off-chip inductor was included to drive all other RF circuits. The research showed that the circuit consumed 1.3mW while radiating 250µW of power and consumed 1.2mW when receiving the signal, the sensitivity of the transceiver was maintained at 94dBm and was able to send and receive data at a distance of 16m when operated indoors.

Hagerty et al [4] carried out a research on efficient broadband RF energy harvesting for wireless sensors. A theoretical and experimental analysis on broadband signals was carried out. The study used a dual circularly polarized wideband rectenna "wallpaper" array and an efficient power processing circuitry. Each spiral antenna element receives one of the two circular polarizations and couples the incident power to a Schottky diode, without any additional matching or harmonic tuning circuitry. The primary challenge for the power processor was to continuously extract energy from the rectenna source at the peak power point despite variations in the incident power and rectenna efficiency, while efficiently integrating the energy to a storage element and delivering regulated power to a sensor load. The study was able to achieve and maintain an efficiency of 70% over a wide range of output voltages at a constant input power of 10µW.

ENERGY STORAGE AND USAGE

Storing and using the harvested energy is one of the most important aspects of an energy harvester. Once the energy has been conditioned using the appropriate circuitry, it can either be used by the load directly or it can be stored. Using the harvested directly is usually very challenging due to the fact that the power output from the harvester is not constant and varies proportionally as the input power, secondly, the harvested power is usually less than the required power and thus the harvester may fail to power the load directly [9].

Storing the harvested energy is the most practical and most commonly used approach used to power loads, the harvested energy can be directly stored in a battery which will then supply the power to the load or it can be stored in a capacitor which then discharges through the battery. The value of the capacitance has an effect on the life of the battery, smaller values will results in quicker but shorter charging pulses while a larger value will result in slower but longer charging pulses

Battery recharging

The energy harvested from RF signals can be used to recharge a battery. The battery will accumulate this energy over some time and then it can be used to run low power loads. A charging circuit will have to be used in this approach.

Supercapacitors

Supercapacitors also known as ultracapacitors differ from a regular capacitor in that it has very high capacitance. Traditional capacitors store energy by means of static charge while a supercapacitor stores energy by means of static charge and chemical reactions. Capacitors can be either electrostatic, electrolytic or supercapacitor, supercapacitors have high frequent charge and discharge cycles at high current and short duration, they operate at voltage range of 2.5-2.7V. Despite having high capacitance, these capacitors cannot be used to power devices directly due to the non-linear nature of its output, they are therefore commonly used to recharge batteries or supply power to the load during short power blackouts or interruptions. Figure 4 shows basic construction of a supercapacitor [12].

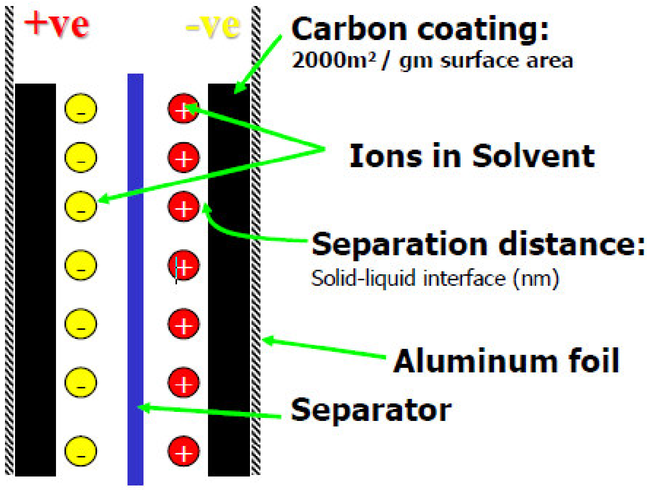

Fig. 4 Construction of a supercapacitor

The time required to charge a typical supercapacitor is about 10 seconds, the charging characteristics is similar to that of a normal battery and is primarily affected by the charging circuit, the supercapacitor has little tendency to go into overcharge and therefore does not require full-charge detection. Unlike the electrochemical battery, the supercapacitor can be charged and discharged an unlimited number of times. Table 3 compares some of the operating parameter of a typical Li-Ion battery with a supercapacitor [12].

TABLE 3
COMPARISON BETWEEN A Li-Ion BATTERY AND A SUPERCAITOR

PARAMETER	SUPERCAPACITOR	LITHIUM-ION BATTERY
Charge time	1-10 seconds	10-60 minutes
Cycle life	1 million or 30,000h	500 and higher
Cell voltage	2.3 – 2.75V	3.6-3.7V
Specific energy (Wh/Kg)	5	100-200
Specific power (W/Kg)	Upto 10,000	1,000-3,000
Cost per Wh	$ 20.00	$0.5-$1.00
Service life	10-15 years	5-10 years
Charge temperature	-40-65oC	0-45oC
Discharge temperature	-40-65oC	-20-60oC

CONCLUSION

A review of the approaches and developments in RF energy harvesting and optimization has been presented. Through this review, it was shown that there is a lot of ongoing research in the field of RF energy harvesting. However, the studies that have been carried out so far have only managed to produce very low energy outputs from the harvester.

Further research is needed to investigate new and more efficient ways of harvesting energy from RF sources. In addition, some RF sources such as FM have not been studied, yet they could produce favorable results.

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