Wireless Energy Harvesting from Hz to GHz

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(Invited Paper)

***Abstract*-In this paper, wireless energy harvesting from Hz to GHz is discussed. At lower frequencies, the focus is on harvesting energy around 50 Hz power lines while at higher frequencies, the attention is paid to harvesting the energy from radio communication systems such as WiFi and mobile radio in the frequency range from 470 MHz to about 3 GHz. The main technology for both the lower and higher frequencies is the same: to use rectennas to receive the wireless energy and then covert it to DC energy. But the frequency difference has resulted in very different antenna designs and the bandwidth requirements. Some novel ideas have been introduced and discussed. At lower frequencies, a narrow band system is developed while at higher frequencies, a broadband system is produced in order to maximize the harvested energy. The designs are optimized to obtain the maximum energy conversion efficiency and then validated by experiments. The results demonstrate the excellence of these designs which can be applied for a wide range of applications.**

I. INTRODUCTION

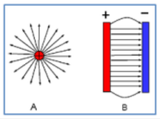
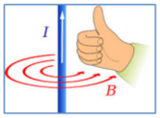
Wireless energy harvesting has become a popular research subject which has been mainly driven by the emerging demand for such as wireless sensor networks and low power IoT (Internet of Things) devices [1, 2]. Devices powered by battery are out of fashion, the main reason (most of the time) is not the cost of the battery but the cost to replace the battery!

What are the alternatives of a "battery"? Solar energy is certainly one since we have already seen that many devices (such as calculators, some toys and garden lights) are powered by solar energy. A distinct advantage of this energy source is that the power density is very high and it has a very broad frequency spectrum, a lot of energy can be harvested. But it is only available in day time. There are some other alternatives such as wind energy, electric field energy, magnetic field energy, thermal energy, mechanical vibration energy and energy from different radio systems. A comparison of some common energy sources is given in Table 1.

In this paper, we are only interested in electromagnetic (EM) energy within the frequency range between Hz and GHz (thus solar energy is not included). The energy is harvested using a *rectenna* (rectifying antenna) which is now a well-known device for such an application. The aim is to harvest enough energy from the intended environment to drive low-power monitoring devices for both indoor and outdoor applications. At lower frequencies, the energy source of interest is from the power line which carries electricity at around 50 Hz and available in places with desired applications. At higher frequencies, the EM energy is mainly from radio systems such as radio and television broadcasting and mobile radio systems. The frequency is typically from 88 MHz to about 3 GHz.

It should be pointed out that wireless energy harvesting (WEH) and wireless power transfer (WPT) are similar in terms of the technology: they both use rectifying antennas (rectennas). But WEH is about "receiving" and the power density level is normally low while WPT is more about "transmitting" and the power level is high. This paper is about WEH.

TABLE 1
COMPARISON OF SOME COMMON ENERGY SOURCES

Energy sources		Advantages	Disadvantages
	**Solar energy**	High energy density in a good weather condition	Power not always available and require energy storage unit
	**Wind energy**	Can work even when the power line is turned off	Power not always available and high maintenance costs
	**Electric field**	Energy available as long as the power line is turned on	Low energy density and suffers from the loading effect
	**Magnetic field**	Energy available as long as a current passes through	Relative low energy density and depends on the current flow.

II. WEH AT LOWER FREQUENCIES

A. *Energy at lower frequencies*

At lower frequencies (below 30 MHz), the wavelength is long. To be an efficient radiator, the dimension of the source or device should be comparable with (or larger than) the wavelength. Thus, we can hardly find such a source to provide decent energy. At lower frequencies, the energy harvesting device is most likely operating in the near field of the source where the ration of the electrical field and magnetic field is not a constant (377 ohms in free space), the energy could be dominated by either electric or magnetic energy. The largest EM power density at lower frequencies is probably from power lines which carry electricity around 50 Hz and the magnetic energy is relatively strong when close to the power line.

B. *Possible applications at lower frequencies*

There are many possible applications by harvesting lower frequency energy. For example, we could harvest the EM energy from overhead power lines to power devices for smart grids or railway condition monitoring and fault detection.

C. *Designs and results*

At the moment, there are some devices which are not convenient (e.g. clamped on the power line) or not efficient or too large [3]. Ideally the energy harvesting device should be away from the power line, **the main challenge is how to harvest enough energy using a given space.** Two alternative designs have been proposed by us [4, 5]. The main difference between these designs is the ferrite core/coil type. In ref [3], the ferrite core/coil is the conventional solenoid while in [4] and [5] it is a bow-tie core and a helical coil, respectively. As shown in Fig. 1, these three designs work differently and a comparison of their performance under the same magnetic field is shown in Table 2. We can see that the bow-tie design has produced a much (15 times) larger power density than the solenoid design by increasing the effective permeability (which is determined by the core material and geometry, in this case the geometry is different). This is achieved by changing ferrite core shape and demagnetization performance [4]. Helical coil design is step change where the design can produce a much larger magnetic flux density (hence more power) in the device compared with previous designs. The power density for the device with 2000 turns under 18.5 μT is around 66.6 μW/cm^3 (note that this is *volume power density* and different from the definition of the far field *surface power density*) which is near the case of a solar panel working in a cloudy day. The value is the largest and hence the most efficient design for the lower frequency WEH up to now. Of course, these designs are actually antennas to convert the EM energy to current and voltage at the signal frequency which have to be converted to DC energy by a rectifier with an impedance matching network [4] to ensure the optimum energy conversion efficiency is obtained. We are now exploring applications for smart grids and railway condition monitoring.

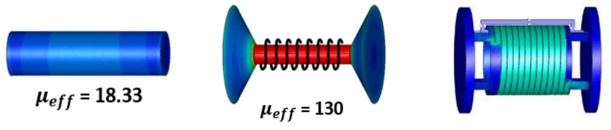


Figure 1. Three different designs (solenoid, bow-tie and helical).

TABLE 2

COMPARISON OF THREE DIFFERENT DESIGNS

The Coil Type	Solenoid [3]	Bow-tie Coil [4]	Helical Coil [5]
Physical Length	50 cm	15 cm	15 cm
Applied Flux Density	18.5 μT$_{rms}$	18.5 μT$_{rms}$	18.5 μT$_{rms}$
The Number of Turns	40,000	40,000	***2000***
Power Density	0.85 mW/cm^3	***13.0 mW/cm^3***	***66.6 mW/cm^3***

→ *15 times* → *5 times*

III. WEH AT HIGHER FREQUENCIES

A. *Energy at higher frequencies*

At higher frequencies (above 30 MHz), the wavelength is shorter. The dimensions of many sources or devices are comparable with (or larger than) the wavelength. Thus, we can find many EM sources to produce decent wireless energy. The most common ones are radio and TV broadcasting transmitters (from 88 to about 860 MHz), mobile base stations (from 700 to about 3800 MHz) and WiFi routers (2.54 and 5 GHz). Measurement results have shown that the typical power density is between 10 to 100 μW/m^2 from most of these sources [2, 5]. At these frequencies, the energy harvesting device is most likely operating in the far field of the source where the ration of the electrical field and magnetic field is a constant (377 ohms in free space). In such a case, the incoming EM wave could be of any polarisation and incident angle at different frequencies. The dominant signal in indoor and outdoor environments is often different. In indoor environments, WiFi signals might be the dominant source while in outdoor environments, TV or mobile signals are normally the dominant ones.

B. *Possible applications at higher frequencies*

Unlike at lower frequencies, the antenna and the whole rectenna could be made small at higher frequencies although the power density is not necessarily higher than that at lower frequencies. Thus, there more possible applications typical examples are low power wireless sensor networks, IoT (Internet of things) devices and many currently battery-powered small devices (e.g. clocks and alarms).

C. *Designs and results*

There have been many rectennas developed for WEH. Again, **the main challenge is still about how to harvest enough energy using a given space.** Most of them are single or dual band and the energy conversion efficiency is relatively high (> 80%). However, the overall power received is normally not enough for most applications. A solution is to employ broadband/multiband rectennas since the overall power received is the integration over the whole band. However, this is challenging since the rectenna is a non-linear device, the energy conversion efficiency from RF to DC is a function of the incoming wave (power, frequency and polarisation), impedance matching and load impedance. Thus, the energy conversion efficiency over a broadband/multi-band is normally small and the system tends to be more complex. Some good designs have been proposed [2, 6, 7, 8]. This is a fast-developing area. We started with a broadband rectenna design which covers 1.8 to 2.5 GHz with the best efficiency around 55% for the input power to rectifier around -10 dBm in 2015 [6] and then developed a novel six-band dual circularly polarized rectenna working from 550 MHz to about 2.5 GHz [7]. Another major attraction of this design is that it is not sensitive to the load impedance and can produce about 26 μW for a typical outdoor environment. The achieved energy conversion efficiency at different input power levels are shown in Fig. 2.

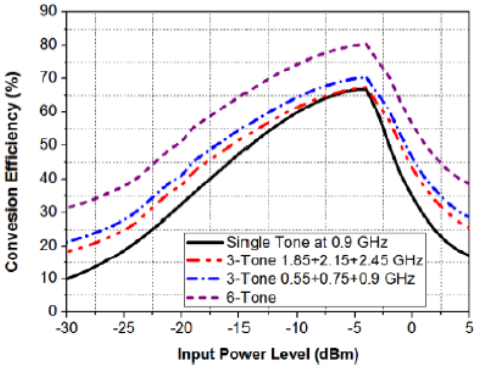


Figure 2. Energy conversion efficiency as a function of the input power

When all six bands are used, the highest conversion efficiency is over 80% around -5 dBm.

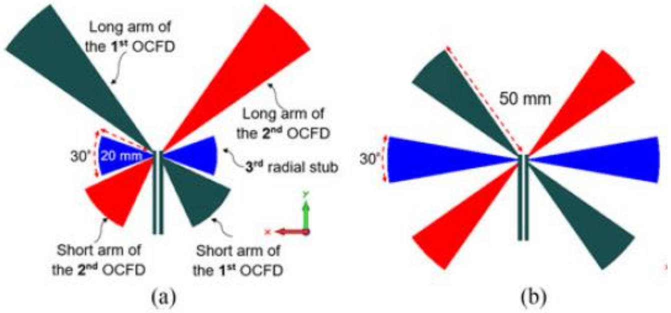


Figure 3. (a) a new design and (b) a conventional antennas design

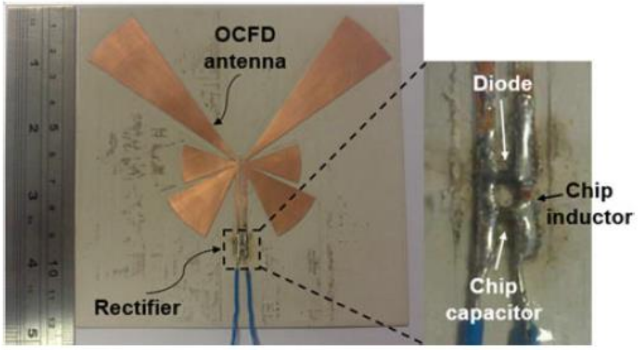


Fig. 4 Fabricated prototype

Further improvements have been made. One radical change is to remove the impedance matching network by changing the antenna design to ensure that its impedance can be tuned to the desired value and directly provides a complex conjugate match to the impedance of a rectifier. An example is given in Fig. 3 where a conventional cross-dipole antenna design and a new off-centre-fed dipole antenna are shown. The new antenna impedance could be changed by tuning the feeding point. A fabricated proto-type is shown in Fig. 4. Its conversion efficiency is also very high, about 75%. The structure is simple and cost effective. It is envisaged that more innovative designs will emerge with the aim to harvest as much energy as possible for a given location and space.

IV. CONCLUSIONS

In this paper, we have investigated different rectennas for wireless energy harvesting at different frequencies. It has shown that at lower frequencies (< MHz), ferrite coils are the best “antennas” which have been specially designed to maximize the harvested energy. At higher frequencies (> MHz), there are many different approaches to maximize the harvested energy. Some innovative examples have been given. It has been demonstrated that broadband/multiband rectennas could provide over 26 μW (depending on many things, including the number of antenna element) for a typical application environment to power low-power devices.

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