

# Spectrum Opportunities for Electromagnetic Energy Harvesting from 350 MHz to 3 GHz

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**Abstract**—This paper presents spectrum opportunities for radio frequency (RF) energy harvesting identified through power density measurements from 350 MHz to 3 GHz. The field trials have been performed in two different cities (Covilhã and Lisbon), by using the NARDA-SMR and the Signal Hound spectrum analysers and the PROLINK 4-4C signal meter, respectively. The scope of our research considers RF energy harvesting devices, enabling to convert RF energy to direct current (DC), providing an alternative source to power supply wireless sensor network (WSN) devices. Printed antennas, able to operate at GSM (900/1800) bands, are proposed with gains of the order 1.8-2.06 dBi and efficiency 77.6-84%. Guidelines for the choice of textile materials for a wearable antenna are also provided.

**Keywords**—Energy harvesting, Printed antennas, Power transmission, Spectrum opportunities.

## I. INTRODUCTION

Energy harvesting will allow for recharging batteries or supercapacitors, and will have a great impact on the lifetime of wireless sensor networks (WSNs). This has particular importance as the network size increases, since, for the typical situation, the replacement of the batteries is not practical. The common sources of energy harvesting include the following ones [1]: mechanical, thermal, electromagnetic, natural (wind, solar and other) and human body energy. Nowadays, energy harvesting devices efficiently and effectively capture, accumulate and store energy, to power up the sensor nodes for short periods of time, in order to perform helpful tasks. However, in a not too distant future, they will enable to supply all the nodes of WSN without the need of replacement of batteries. This energy can be used overnight to increase the battery charge or prevent power leakage. In a hazardous situation, if a battery or a solar-collector/battery package completely fails, harvested energy from the radio frequency (RF) energy enables the system to transmit a wireless distress signal, whilst potentially maintaining critical functionalities. In [2], the authors present the state-of-the-art of energy harvesting techniques for low power systems such as power conversion, power management, and battery charging, as well as the advances in energy harvesting from vibration, thermal, and RF

sources. Prototypes for the energy harvesting from the ambient RF have been proposed in [3], [4], [5] and [6], enabling to power supply low-power systems. The authors from [7] present an electromagnetic based generator which is suitable for generating power from human body motion. This prototype was built and placed inside a rucksack to be tested during walking and slow running conditions. The power output was measured. A power output between 0.3 mW and 2.46 mW has been achieved. The authors from [4] proposed a scheme for energy harvesting from environment electromagnetic sources between 800 MHz and 6 GHz, namely from GSM, UMTS, Wi-Fi, Bluetooth, DECT, GPS, DVB-T and Radar. This scheme is based on rectennas [4], which considers an ultra-wide band (UWB) spiral antenna with high RF to direct current (DC) conversion efficiency. The authors from [5] consider a MICA2 node charged just with RF harvesting. In the context of wireless body area networks (WBAN) electromagnetic energy harvesting is accomplished by using wearable antennas allowing for power supply the sensor nodes [8]. Ubiquitously available RF sources, operating at different bands, are exploited for RF electromagnetic energy harvesting purposes.

The remaining of this paper is organized as follows. Section II presents the motivation of our work as well as the power density for different energy sources. Section III addresses the spectrum measurement devices that enable to identify the spectrum opportunities. Section IV presents the measured spectrum opportunities in both indoor and outdoor scenarios. Section V describes energy efficient single- and dual-band antennas for collecting RF energy, and gives guidelines for the choice of textile materials to use in future developments of wearable antennas. Finally, Section VI draws the conclusions.

## II. RF ENERGY SCAVENGING

Finite battery lifetime has become a major concern over the past years. Hence, there is a need to seek for innovative solutions enabling to power supply the nodes. Energy harvesting holds a promising future in the next generation of WSNs. Since there are a variety of energy sources available for energy harvesting in the environment, the opportunities are

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vast. Table I presents the power density measurements for different energy harvesting sources [1].

Our vision is that energy harvesting from RF electromagnetic holds a promising future for power supply wirelessly electronics devices. Nowadays, RF energy is currently broadcasted from billions of radio transmitters (e.g., mobile communications base stations and television/radio stations) that can be collected from the ambient or from dedicated sources, enabling wireless charging to power supply the low-power devices. Additionally, RF transmitters and receivers can be used when other potential intermittent energy scavenging sources (e.g., solar, vibration and heat) are not available. Hence, by adding new energy harvesting capabilities to the sensor nodes, we provide a predictable and reliable power system that uses controlled broadcasted RF energy for wirelessly charge the battery systems. Powercast offers several Powerharvester receivers [9] modules that have been designed for charging batteries, energy storage devices and for direct power applications. The P2110 Powerharvester long range receiver module has the following characteristics:

- Low RF input for longer range operation;
- RF scavenging range down to -11 dBm input power;
- Frequency range from 850-950 MHz;
- Configurable regulated output voltage up to 5 V;
- Received signal strength indicator (RSSI) and data output.

According to the experiments conducted in [10], Table II shows the time to charge a battery with a capacity of 1150 mAh using the P2110 module at a given distance. One advantage of collecting RF energy is that it is essentially “for free”. Besides, RF energy is universally present over an increasing range of frequencies and power levels, especially in highly populated urban areas. These radio waves represent a unique and widely available source of energy if it can be effectively and efficiently harvested. Moreover, the growing number of wireless transmitters is naturally increasing RF power density and availability. Dedicated power transmitters will enable engineered and predictable wireless power solutions.

TABLE I. POWER DENSITY AND PERFORMANCE FOR DIFFERENT HARVESTING METHODS (EXTRACTED FROM [1])

Energy Source	Power Density & Performance
Acoustic Noise	0.003 $\mu\text{W}/\text{cm}^3$ @ 75dB 0.96 $\mu\text{W}/\text{cm}^3$ @ 100dB
Temperature Variation	10 $\mu\text{W}/\text{cm}^3$
Ambient RF	1 $\mu\text{W}/\text{cm}^2$
Ambient Light	100 $\text{mW}/\text{cm}^2$ (direct sun) 100 $\mu\text{W}/\text{cm}^2$ (illuminated office)
Thermoelectric	60 $\mu\text{W}/\text{cm}^2$
Vibration (micro generator)	4 $\mu\text{W}/\text{cm}^3$ (human motion - Hz) 800 $\mu\text{W}/\text{cm}^3$ (machines - kHz)
Vibration (piezoelectric)	200 $\mu\text{W}/\text{cm}^3$
Airflow	1 $\mu\text{W}/\text{cm}^2$
Push buttons	50 $\mu\text{J}/\text{N}$
Shoe Inserts	330 $\mu\text{W}/\text{cm}^2$
Hand generators	30 $\text{W}/\text{kg}$
Heel strike	7 $\text{W}/\text{cm}^2$

TABLE II. AMOUNT OF POWER HARVESTED BY P2110 HARVESTER USING A PATCH ANTENNA (EXTRACTED FROM [10])

Distance (m)	P ( $\mu\text{W}$ )	I ( $\mu\text{A}$ )	Recharge Time (h)
1.52	1925	1604	42.24
3.05	386	322	210.50
4.57	189	158	429.40
5.49	131	109	618.50
6.10	102	85	797.50
7.62	50	41	1639.00
9.14	19	16	4353.00
10.67	5	4	15517.00
10.97	1	1	70019.00

Since the power consumption of wireless devices is decreasing and the sensitivity of passive RF harvesting receivers is increasing, the applications for wireless charging by means of RF-based wireless power and energy harvesting will continue to grow.

### III. SPECTRUM MEASURING DEVICES AND RECEIVED POWER

One of the main contributions from this work is the identification of spectrum opportunities through power density measurements from 350 MHz-3 GHz. The field trials were performed by using the NARDA-SMR [11], the Signal Hound spectrum analysers and PROLINK 4-4C signal meter [12], as shown in [13]. By analysing the power density measurements in 36 different indoor/outdoor locations in Covilhã, we have been able to decide which are the best opportunities that may be taken in order to conceive wideband or multiband antennas for electromagnetic energy harvesting.

To convert the electric field measured by the spectrum analyser to the received power, we consider the power density,  $P_d$ , in  $\text{W}/\text{m}^2$ . To compute the received power,  $P_r$ , as a function of  $P_d$  we consider the effective area of the receiver antenna and gain  $G = 1$  (0 dBi) as follows:

$$P_d = \frac{|E|^2}{120\pi} \quad (1)$$

$$P_{r[\text{dBm}]} = 10 \cdot \log\left(P_d \frac{\lambda^2 G}{4\pi}\right) + 30 \quad (2)$$

where  $E$  is the electric field and  $\lambda$  is the wavelength.

To decide which are the best frequency bands for electromagnetic energy harvesting, we have calculated the average of each of the  $n$  values of the received power,  $P_{r_i[W]}$ , in linear terms, in five different scenarios, where  $n$  is the number of taken measurements, for each frequency. The average received power, in  $\text{dBm}$ , is given as follows:

$$\overline{P_{r[\text{dBm}]}} = 10 \cdot \log\left(\frac{\sum_{i=1}^n P_{r_i[W]}}{n}\right) + 30 \quad (3)$$

## IV. IDENTIFICATION OF SPECTRUM OPPORTUNITIES

### A. Covilhã

#### 1) Higher education institution - indoor

Figure 1 shows that, the set of frequencies with high energy available for harvesting comprises the range from 934 to 960 MHz (GSM900), 1 854 to 1 892 MHz (GSM1800), 2 116 to 2 160 MHz (UMTS), 2 359 MHz (amateur, SAP/SAB applications, video), and 2 404 to 2 468 MHz (Wi-Fi).

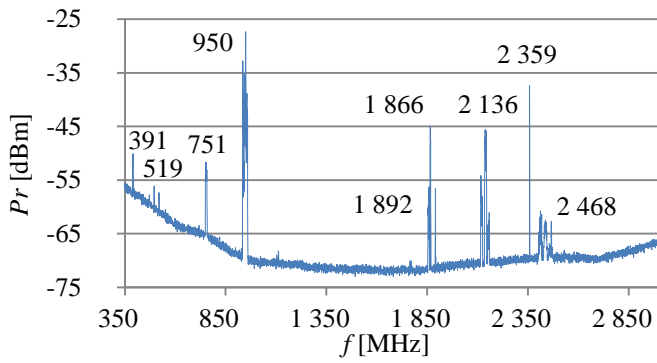


Figure 1. Average received power as a function of the frequency for all measurements in the University scenario (indoor).

## 2) Public places - outdoor

In this scenario, the set of available systems uses the frequency bands from 390 to 399.9 MHz (emergency broadcast stations), 470 to 600 MHz (television broadcast stations, SAP/SAB Applications), 751 to 759 MHz (television broadcast stations), 890 to 960 MHz (GSM900), 1710 to 1930 MHz (GSM1800), 2110 to 2170 MHz (UMTS). Figure 2 shows that the range of frequencies with more energy available for harvesting is in the set from 391 MHz (emergency broadcast stations), 750 to 759 MHz (television broadcast stations), 935 to 960 MHz (GSM900), 1854 to 1870 MHz (GSM1800) and 2115 to 2160 MHz (UMTS).

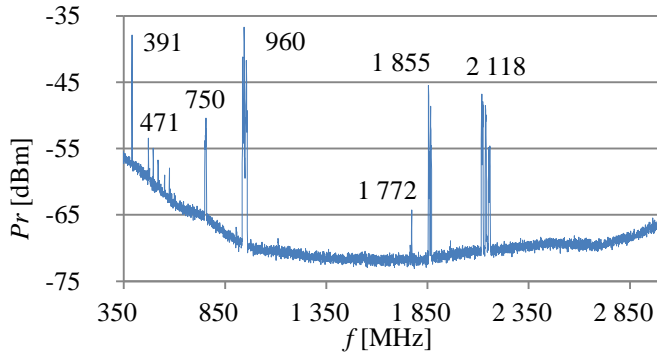


Figure 2. Average received power as a function of the frequency for all measurements in scenario "Public Places (outdoor)".

## 3) Away from the city - outdoor

In this suburban scenario, the range of frequencies with more available energy for harvesting is 391 MHz, from 750 to 758 MHz (television broadcast stations), 935 to 960 MHz (GSM900), 1855 to 1869 MHz (GSM1800) and 2115 to 2160 MHz (UMTS). The corresponding values for the average received power are shown in Figure 3.

### B. Lisbon: Higher education institution - outdoor

The range of frequencies with more energy available for harvesting is near 936.5, 937.1, 946.5, 957.2 and 958.5 MHz (GSM900), 1860 to 1865.4 MHz (GSM1800) and from 2116 to 2120 MHz, from 2121 to 2125 MHz, from 2137 to 2138 MHz, from 2151 to 2154 MHz, from 2155 to 2159 MHz (UMTS). The corresponding measured values of the power for GSM900 are shown in Figure 4.

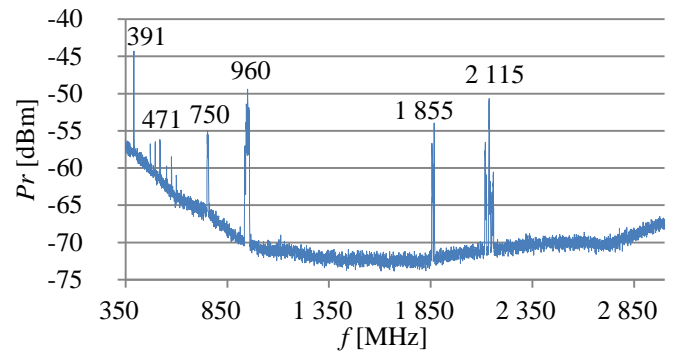


Figure 3. Average received power for all measurements in scenario "Away from the city (outdoor)".

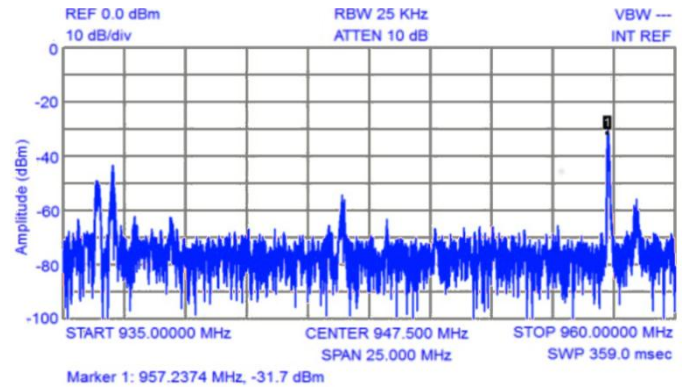


Figure 4. Display of Signal Hound. Measurements for GSM900 in the scenario "Students Pavilion (outdoor)".

## C. Global analysis on the average received power

The set of frequency bands that are identified more frequently are the following ones:

- 471 to 600 MHz (television broadcast stations, SAP/SAB Applications);
- 895 to 958 MHz (GSM900);
- 2117 to 2159 MHz (UMTS).

By observing Figure 5, we conclude what is the set of frequency bands with more available energy for harvesting.

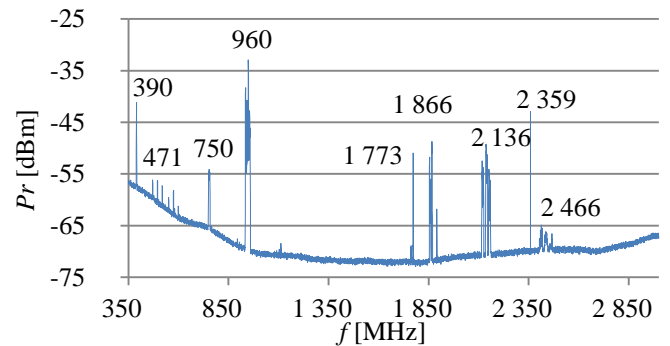


Figure 5. Average received power for all measurements.

The sets of frequency bands with more available energy are:

- 390 to 392 MHz (emergency broadcast stations);
- 750 to 759 MHz (television broadcast stations);

- 934 to 960 MHz (GSM900);
- 1 763 to 1 773 MHz (GSM1800);
- 1 854 to 1 892 MHz (GSM1800);
- 2 115 to 2 160 MHz (UMTS);
- 2 359 MHz (Amateur, SAP/SAB Applications);
- 2 404 to 2 468 MHz (Wi-Fi).

The main applications for this set of frequency bands are presented in [14].

## V. ANTENNAS FOR RF ENERGY HARVESTING

### A. Single-band antenna

From the performed measurements and the analysis presented in the previous sections, it is clear that the best frequency band for energy harvesting purposes is the GSM900.

In this section, we propose a possible implementation of a textile antenna suitable to be introduced within clothes for body-worn applications, and has the ability to harvest energy in the GSM900 band that, in Europe, covers frequencies from 880 to 960 MHz. The proposed single-band antenna design is shown in Figure 6(a). Table III presents the corresponding dimensions.

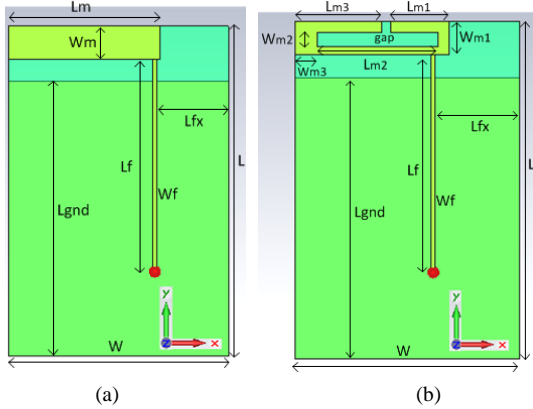


Figure 6. Proposed (a) single-band and (b) dual-band antenna geometry.

A *Cordura*<sup>®</sup> cloth type was considered it presents a permittivity,  $\epsilon_r$ , of 1.9 and a loss tangent,  $\tan \delta$ , of 0.0098, having a relative height of 0.5 mm. For the conductive sections of the antenna an electrotextile (*Zelt*), with an electric conductivity  $1.75 \times 10^5$  S/m was considered. The return loss obtained from numerical simulations of the proposed single-band antenna is presented in Figure 7. Considering a return loss  $S_{11} < -10$  dB (shaded area in Figure 7), this antenna presents an operating frequency range from 850 to 1 150 MHz, covering completely the E-GSM band.

Since the privileged direction of signal reception is not known, the best possible radiation pattern for the antenna is an omnidirectional radiation one. The obtained radiation pattern in the YZ and XZ planes (see Figure 6) for the proposed antenna, based on numerical simulation is depicted in Figure 8.

Although a slight bend in the radiation pattern is noticeable, which is due to the geometry of the antenna, the obtained radiation pattern is clearly omnidirectional.

TABLE III. PROPOSED SINGLE-BAND ANTENNA DIMENSIONS

Parameter	Dimension [mm]
$L, L_{gnd}, L_f$	120, 100, 78
$L_m, L_{fx}$	55, 26
$W, W_f, W_m$	80, 1.5, 12

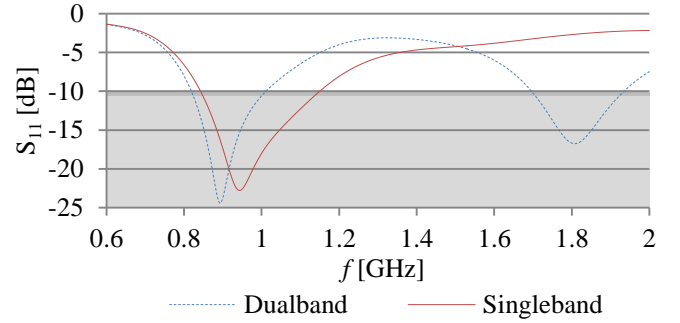


Figure 7. Simulated return loss of the single- and dual-band antennas.

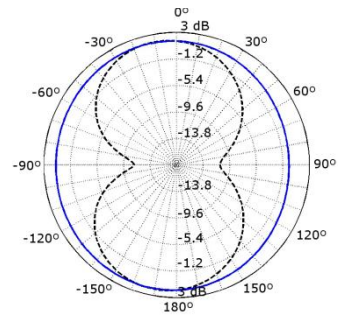


Figure 8. Simulated radiation pattern for the single-band antenna in the YZ plane (dashed) and XZ plane (blue solid).

In energy harvesting applications, to achieve the best performance possible, the antenna should present the highest gain and the highest efficiency possible. The gain obtained from numerical simulation to the proposed antenna is about 2.05 dBi, allied with 84% radiation efficiency, which are adequate results for this type of antenna.

### B. Dual-band antenna

Given the fact that the power level from radio waves in the DCS1800 band is also quite considerable, some changes in the previous model have been performed, in order to allow the operation at both GSM900 and DCS1800 bands (dual-band). As so, a second monopole antenna, based on the same materials as for the single-band one, is considered, according to the geometry presented in Figure 6(b), and the dimensions from Table IV.

The return loss obtained from numerical simulation for the dual-band proposed antenna is shown in Figure 7, from which both the antenna's operating frequency bands are clear. The lowest band is from 820 MHz to 1 000 MHz, covering the entire E-GSM band, while the highest band is from 1 690 MHz to 1 930 MHz, covering the entire DCS1800 band (1 710 to 1 880 MHz). In the lowest operating frequency (900 MHz), the radiation patterns from the dual- and single-band antennas shown in Figure 9 are similar. However, the radiation pattern for the dual-band antenna suffers a deformation at 1800 MHz.

TABLE IV. PROPOSED DUAL-BAND ANTENNA DIMENSIONS

Parameter	Dimension [mm]
$L, L_{gnd}, L_f, L_{fx}$	120, 100, 78, 30
$Lm1, Lm2, Lm3, gap$	21, 43, 31, 3
$W, W_f, Wm1, Wm2, Wm3$	80, 1.5, 12, 5, 8

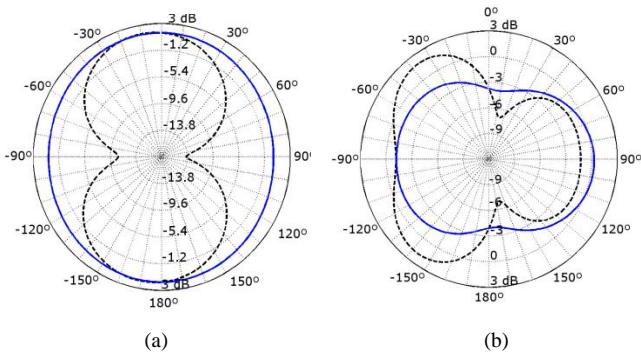


Figure 9. Simulated radiation pattern for the dual-band antenna in the YZ plane (dashed) and XZ plane (blue solid), at (a) 900 MHz and (b) 1800 MHz.

The gains for the dual-band antenna are about 1.8 dBi and 2.06 dBi, for the lowest and highest operating frequency bands, respectively. As in the previous case, these are fairly good for the antenna type proposed. The radiation efficiency determined by numerical simulation is also high, with 82% and 77.6% radiation efficiency for the lowest and highest operating frequency bands, respectively.

#### C. Guidelines for the development of wearable flexible antennas

Specific requirements for wearable antennas are the planar structure and flexible materials. Textiles, being universally used and easily available, are good materials to design wearable antennas. However, some characteristics of the materials highly influence the performance of the antenna. For instance, the selection of fabrics for dielectrics must consider the dielectric constant and the loss tangent, for a specific frequency, the thickness, the moisture content in a specific environment (Regain), as well as the geometrical and mechanical stability of the fabric. In general, ordinary textiles present a very low dielectric constant, in the range between 1 and 2 (as they are very porous). However, textile materials are constantly exchanging water molecules with the environment which might increase their dielectric constant. Therefore, fabrics for dielectrics should present a low Regain. For the conductive components of planar antennas, specific electrical conductive textiles and have been successfully used, are available on the market [15], [16], [17].

## VI. CONCLUSION

Energy harvesting can increase significantly the lifetime of WSN and eliminate or reduce the need for battery replacement, reducing costs and failures of sensors. In this paper we have analysed the development of a wearable antenna that will enable to charge low-power devices, as well as extending the lifetime of tiny devices by using electromagnetic energy harvesting. Moreover, since radio frequencies are present in almost everywhere, some devices have the possibility to be

continuous charged, avoiding power fail situations. The frequency bands, from 934 to 960 MHz (GSM900), are the ones most frequently present, in terms of power and bandwidth. Some other frequency bands, with more available energy to be harvested in many different scenarios, are from 2115 to 2160 MHz (UMTS). For the GSM (900/1800) frequency bands, printed antennas are proposed, with gains of the order of 1.8-2.06 dBi and 77.6-84% efficiency. As future work we intended to create a flexible and wearable antenna, with the described characterization.

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