

Experimental study of energy harvesting in UHF band

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Abstract. A huge progress of down-sizing technology together with trend of decreasing power consumption and, on the other hand, increasing efficiency of electronics give the opportunity to design and to implement the energy harvesters as main power sources. This paper refers to the energy that can be harvested from electromagnetic field in the unlicensed frequency bands. The paper contains description of the most popular techniques and transducers that can be applied in energy harvesting domain. The overview of current research and commercial solutions was performed for bands in ultra-high frequency range, which are unlicensed and where transmission is not limited by administrative arrangements. During the experiments with Powercast's receiver, the same bands as sources of electromagnetic field were taken into account. This power source is used for conducting radio-communication process and excess energy could be used for powering the extra electronic circuits. The paper presents elaborated prototype of energy harvesting system and the measurements of power harvested in ultra-high frequency range. The evaluation of RF energy harvesters for powering ultra-low power (ULP) electronic devices was performed based on survey and results of the experiments.

1. Introduction

In recent years, the energy harvesting domain has been generating great interests amongst researchers, scientists and engineers. The energy harvesting is defined as the process of extracting small amounts of energy from various sources and its further conversion into electricity [1]. The energy available for harvesting applications is mainly provided by ambient light [2], ambient radio frequency [3], thermal [4] and mechanical sources [5]. Down-sizing efficiency demands and low power consumption trends opened novel research lines on battery recharge via available power sources. The devices that are able to convert dissipated energy into electricity can be used either as battery rechargers in various environments or as the independent power sources [6]. This is particularly relevant to the installation of wireless sensor networks in areas that are inhospitable or difficult to reach. This includes safety monitoring devices, structure embedded micro sensors and medical implants. There are also environmental benefits associated with limiting the disposal of batteries.

2. Scope of energy harvester source

The scope was prepared in the context of available and usable energy sources for harvesting techniques that are still being developed to improve efficiency of energy conversion process. The most popular of these can be classified according to scheme shown in figure 1.



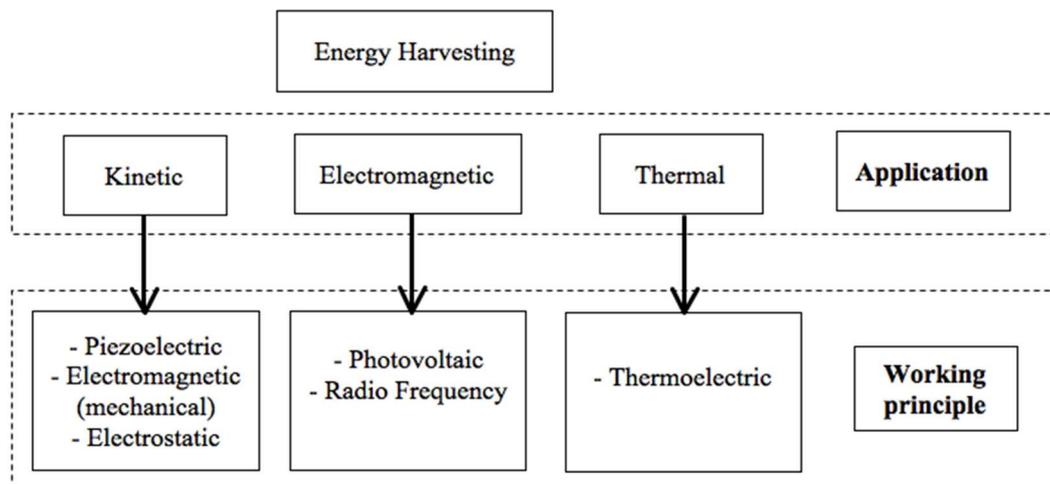


Figure 1. Classification of the main energy harvesting techniques.

For medium and large scale harvesting, the techniques such as solar, wind, hydro and geothermal are well known. Solar energy harvesting is one of the most practical applications due to its higher energy density compared with the other sources. However, it can operate only in the presence of sunlight, which makes the generation of energy during night-time and cloudy day limited. For small scale systems, energy harvesting is used as an alternative energy source to supplement a primary power source [5]. Due to the fact that vibration sources are ubiquitous in the ambient environment, vibration-based energy harvesting is one of the attractive solutions for powering autonomous small-scale microsystems. There is a wide variety of mechanical energy sources including vibrations from industrial machinery and transport, fluid flow, such as air movements, direct human action from walking or in-body motion, such as chest and heart movement, which can be used e.g. for powering pacemakers and orthopedic implants. A great number of these sources is also known and used for large scale power generation (e.g. wind power). However, energy harvesting techniques are mainly focused on a very small scale power generation. Typically, they are used for supplying small electronic devices, where mains or battery power does not provide a viable or convenient solution. Basically, the vibration-to-electricity conversion mechanism can be implemented by piezoelectric, electromagnetic, electrostatic, and magnetostrictive transducers. The piezoelectric transducers are being widely investigated due to their high efficiency and they are commonly used for vibrations. Kinetic energy harvesting is mainly based on the acceleration of a mass. When the base moves, a vibration is set up in the mass-spring system, from which electrical energy can be harvested. On the other hand, the piezoelectric energy harvesters are based on Micro Electro-Mechanical Systems (MEMS) with a few of movable components. Additionally, energy harvester is creating electric power only when the source or base is in motion. Exemplary systems for energy harvesting are listed in table 1.

In context of energy harvesting, the best way, is to use permanently working sources of energy. Each year, more than 120.000 new base stations around the world, only for the cellular network, are deployed [6]. This significant increase of the wireless networks results in a rise of Radio Frequency (RF) power in the form of electromagnetic waves in the environment. Nonetheless, only a small amount of RF power is used for communication and the rest is wasted by dissipation of heat or absorption in other materials. Wasted RF energy can be used as a green source of energy, and RF energy harvesting system powered from ambient can be applied as a power supply of various ultra-low power electronics devices. The electrical power generated by RF energy harvesting system is usually low therefore, depending on technique, it is possible to supply only ULP devices in steady way. For example one can supply wireless sensor network in medical application, battery systems and radio frequency identification (RFID) systems [12].

Table 1. Typical energy harvesting sources.

Energy source	Condition	Performance	Parameters	Elaboration
Solar GaAs	One Sun 1000 W/m ²	33.3 mW	0.9927 cm ²	[Kayes et al. 2011]
Solar InGaAsSb	Infrared	200 mW	-	[Choi et al. 2013]
Electrostatic Al/poliester	4.76 Hz	58 μ W	780 g	[Tashiro et al. 2002]
	6.0 Hz	36 μ W	1200 g	
Thermal	$\Delta T = 5$ °C	60 μ W/cm ²	1.12 mm ²	[Mathna et al. 2009]
Thermal	$\Delta T = 10$ °C	135 μ W/cm ²	-	[Mathna et al. 2009]
Piezoelectric PZT	0.91 Hz	8400 μ W	37161 mm ³	[Shenck 1999] [Shenck et al. 2001]

Table 2. Typical RF energy harvesting sources.

Antenna type	Bandwidth [MHz]	Power [μ W]	Gain [dBi]	Elaboration
Dipole	81.9-84.7	10	1.37-1.83	[Noguchi 2013]
Dipole	DTV-3G	3.1	4.5	[Piñuela et al. 2013]
Dipole	868	1.9	0.659	[Sun 2013]
PCB	955	2.5	-	[Stoopman 2014]
Yagi-Uda	900, 2100	3.1	9.9-13.3	[Din 2012]
Patch	3G	398	-	[Ahn 2014]
Patch fractal x9	2400	3.1	4.5	[Olgun 2012]

RF energy harvesting is receiving increasing interest as evidenced by the growing number of scientific papers. There are not many reports showing accurate measurements and descriptions of the systems, complete data and examples of practical applications. For this reason, the authors have attempted to develop a position and to perform the measurements that show real results.

3. RF energy harvester setup

The application of harvested RF power coming from the ambient environment should cope with two real-life challenges: low RF power density and limited computational capabilities. The problem related to small amount of RF radiated power can be alleviated by storing the harvested energy in battery cell or even in supercapacitor. Obviously, this is a slow and time-sensitive process. The second issue implies that merely simple operations can be reasonably expected from the harvested power, which may perfectly concur with the power consumption profile of wireless sensors. This means that for current applications, only powering low duty cycle devices is meaningful. Moreover, the size of an RF energy harvester is usually designed to be small as compared to other harvestable sources of energy (thermal, mechanical, etc.). It is well known that an antenna or antenna array can be enlarged and designed to coherently capture more wireless energy, which could present an approach to enhancing the received power. However, it is not appropriate when the size of the power harvester is too large to be practical. Elaborated prototype of energy harvesting system consists of transmitter, designed receiving antenna, the rectification unit, step-up converter and the load. The block diagram of the setup is shown in figure 2.

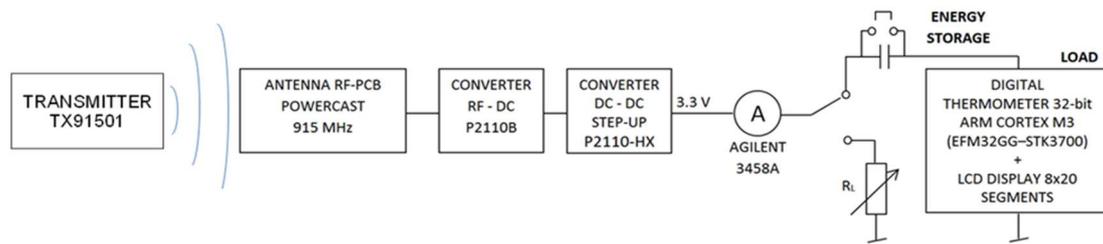


Figure 2. Block diagram of measurement energy harvesting system.

4. Results and discussion

A first step in designing the RF energy harvesting system is to select the frequencies at which power will be harvested.

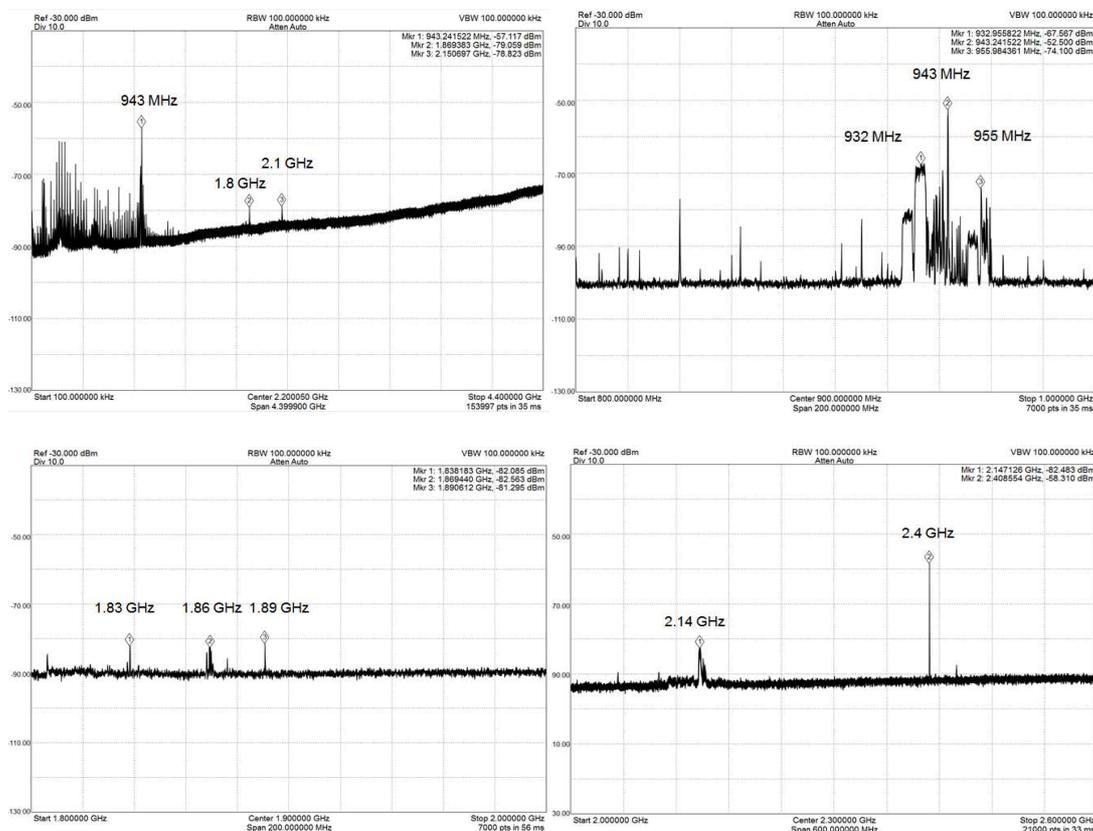


Figure 3. The measured power densities in a typical ambient environment. The measurement method is not accurate enough to provide a quantitative information, but these data are representative of what spectra can be expected in an urban environment.

The wireless spectrum shown in figure 3, is full of signals with different frequencies and power levels, ranging from cellular standards, WLANs and TV signals. The criteria that control the selection of certain frequencies for the purpose of energy harvesting are wide deployment and power level. Obviously, due to multipath electromagnetic wave propagation effects, nonuniform base-station grids and various human-related movements, RF power density is not always constant and uniform over space and time. GSM 900/1800 and DTV signals cover most of the world except for Europe [20] (as shown in figure 2). Thus it is almost guaranteed that GSM signals would be available regardless of where the harvesting

system is placed. Additionally, narrow band signals are appropriate in connection with high quality factor (high-Q) harvester circuits, and they are available all the time, which is highly desirable for most of the applications.

In the next step we designed five simple antennas based on standard types. The antennas were designed with a radiator printed on the bottom of a dual-layer FR4 substrate with thicknesses of 0.5 mm and 1 mm, in which ground plane lies at the bottom of the structure. On top of FR4 dipole (1 dBi, figure 9, 11) and patch (6.1 dBi, figure 10) structure of the antennas were printed. Additionally, microstrip (figure 8) [17, 20, 21], triple bands (0,3 dBi, figure 7) [22] and three dipole windings 1/4/8 turns (figure 4, 5, 6, respectively) antenna with 0.2 mm wire [23] were designed. This structures are very simple but they are used and described in the scientific papers.

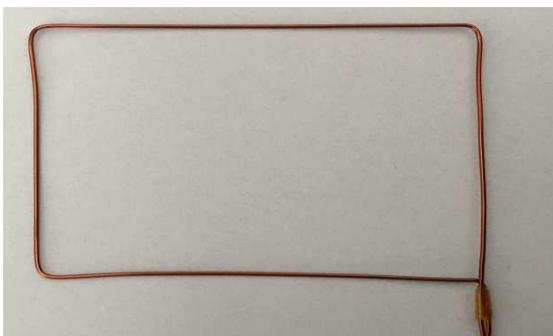


Figure 4. Sample of dipole winding / 1 turn antenna.



Figure 5. Sample of dipole windings / 4 turns antenna.

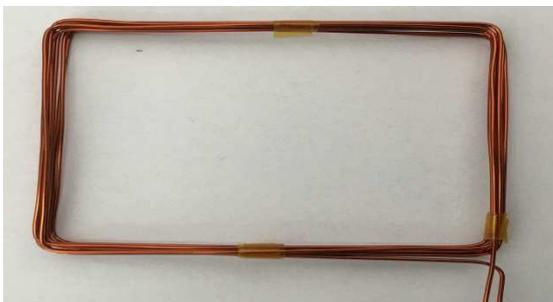


Figure 6. Sample of dipole windings / 8 turns antenna.

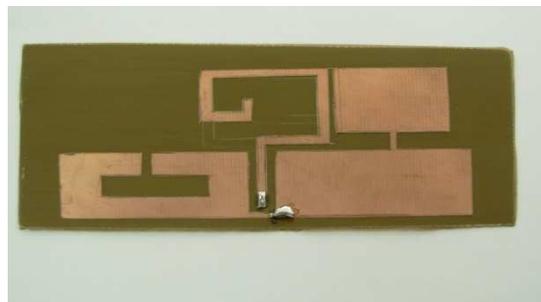


Figure 7. Sample of triple bands antenna.

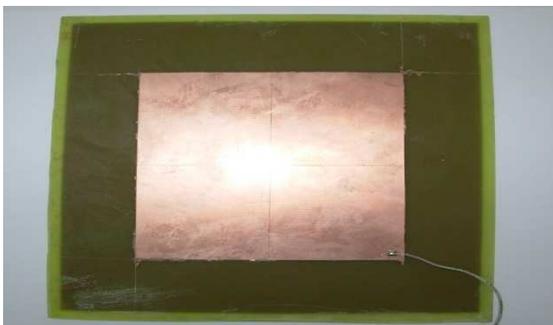


Figure 8. Sample of microstrip antenna.



Figure 9. Sample of dipole antenna.



Figure 10. Sample of patch antenna.



Figure 11. Radio Frequency Energy Harvesting system with dipole antenna.

The impedance matching network is the most critical element in RF energy harvesting system and it has to be designed very carefully for optimal output. The matching circuit, to match the load impedance to impedance of the source (antenna in this case), is designed for 50Ω and is tuned to 915 MHz. Harvested energy can be stored or transmitted to the step-up DC-DC converter P2110-HX with adjusted output voltage at level 3.3 V. Powercast TX91501 transmitter that provides a maximum power of 3 W EIRP (Equivalent or Effective Isotropic Radiated Power) in the UHF band around 915 MHz, was used as temporary and reference power source. This frequency was chosen because it is representing data uplink from mobile phone to GSM station in communication between them and does not violate European restriction (according to the Nordic Mobile Telecommunication System). The measurements were performed with an application of high accuracy multimeter Agilent 3458A. In order to determine the operating conditions, efficiency and tracking of maximum power output of the harvester, the demo board DC2080A with 32bit ARM CORTEX M3 microprocessor was applied as the load. The received power P_R at a given distance d was calculated from Friis equation:

$$P_R = P_0 G_0 G_R \left(\frac{\lambda}{4\pi d} \right)^2 \quad (1)$$

Where G_0 and G_R are the antenna gains (with a respect to an isotropic radiator) of the transmitting and receiving antennas, respectively and λ is the wavelength.

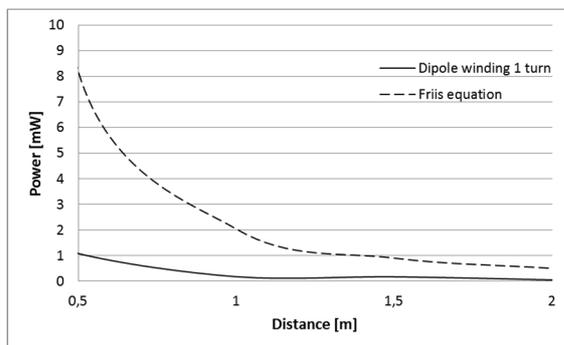


Figure 12. Sample of dipole winding / 1 turn antenna.

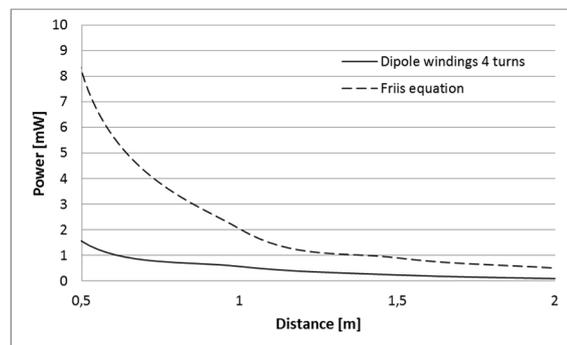


Figure 13. Sample of dipole winding / 4 turn antenna.

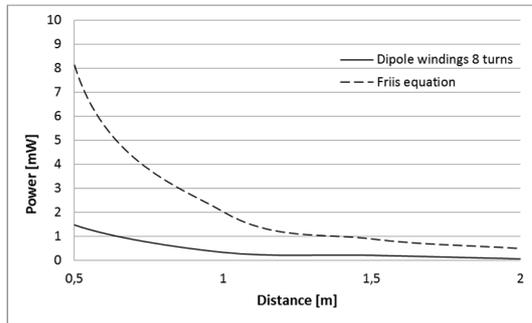


Figure 14. Sample of dipole winding / 8 turn antenna.

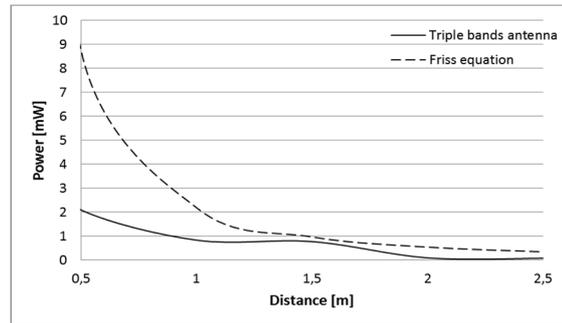


Figure 15. Sample of triple bands antenna.

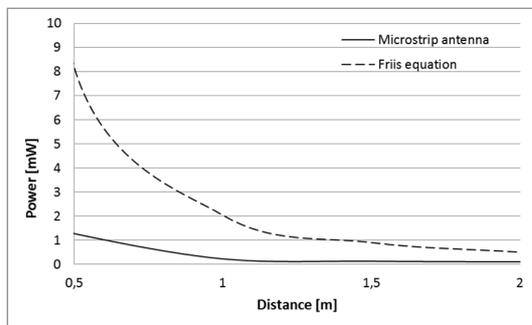


Figure 16. Sample of microstrip antenna.

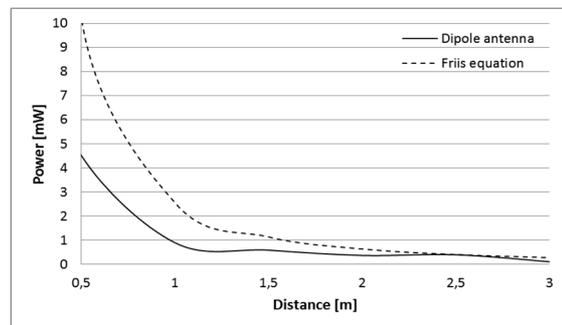


Figure 17. Sample of dipole antenna.

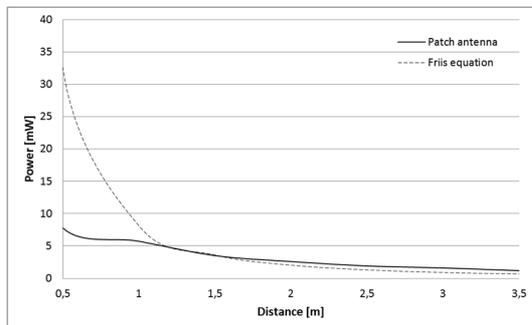


Figure 18. Sample of patch antenna.

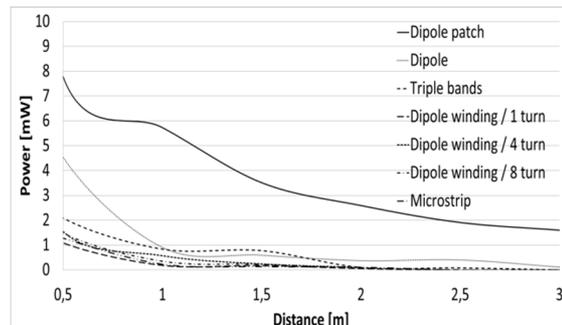


Figure 19. The measured power results obtained for different types of antennas versus distance.

Graph presented in figure 19 shows power gained from the energy harvesting system working in band with 915 MHz center frequency. The highest values of power were obtained at the distance of 0.5 m and they reached 7.77 mW for dipole patch antenna with 6.1 dBi gain and 1400 Ω load resistance R_L . It was enough to wake up the processor from deep sleep mode to active mode in time t_{ON} around 0.8 s. All the tests proved that described energy harvester can work as a power supply and maintain continuously an active state of demo board using the energy harvested from ambient. Table 3 summarizes the performance of the voltage multiplier and RF energy harvesting system.

Table 3. Test results of elaborated antennas at distance 0.5 m in band with 915 MHz center frequency.

Antenna type	R_L [k Ω]	I [mA]	P [mW]	t_{ON} [s]
Dipole patch	1.4	1.74	7.77	0.8
Dipole	2.4	1.38	4.54	1.5
Triple bands	5.2	0.63	2.10	25.5
Dipole winding / 1 turn	10.0	0.33	1.09	3.0
Dipole winding / 4 turn	7.0	0.47	1.55	10.2
Dipole winding / 8 turn	7.3	0.45	1.49	17.1
Microstrip	8.5	0.39	1.28	3.4

Further tests, during which the mobile phone working in EGSM band played the role of a power source, were performed for antenna with the highest value of gained power. Table 4 summarizes the performance of the voltage multiplier and RF energy harvesting system.

Table 4. Test results of elaborated antennas at distance 0,5m in EGSM band.

Antenna type	R_L [k Ω]	I [mA]	P [mW]	t_{ON} [s]
Dipole patch	40	83	0.27	230
Dipole	110	30	0.10	650
Triple bands	250	20	0.04	1600

5. Conclusions

Presented results prove that the electromagnetic energy, which is naturally abundant in many practical applications, can be scavenged and channelled to a rechargeable energy storage device (e.g., a battery). By applying low-power and duty-cycling techniques to the loading system the harvested energy can viably replenish the total energy consumed by the system, potentially extending its operational life indefinitely without manual/external recharge or battery replacement cycles, which may be otherwise prohibitive in applications such as remote wireless microsensors and bio implantable devices.

6. References

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