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TULTECH

Powering Autonomous Sensors Using Radio Frequency Harvesting for IoT Applications

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Abstract

The abundance of connected devices in modern cities and metropolises has contributed to the development of intelligent infrastructure and networks. More specifically, the integration of devices within the Internet of Things (IoT) has become integral to smart cities, enhancing various aspects such as safety, congestion management, and providing real-time information to users. However, the deployment of IoT networks relies on autonomous sensors capable of collecting and transmitting data in real-time to either other devices or centralized units. Having a reliable and non-stop power source to maintain the sensor operational 24/7 poses a challenge, that is why this paper will focus on analysing radio frequency harvesting, to create a continuous power output for the sensors. Mobile networks spectrums are preferred in our case due to the high-power density they offer, compared to other radio technologies. The RF (Radio Frequency) harvester circuit is built from several components, the Long-Term Evolution (LTE) band antenna, the coupler circuit, the rectifier circuit and the load, which in our case will be the sensor. Various circuit elements are evaluated and compared, addressing the requirements of output voltage and power. The findings from this research provide insights into the practicality of RF harvesting as a sustainable energy solution for autonomous sensors within IoT networks, paving the way in the evolving landscape of connected devices.

Keywords: *Autonomous sensors, IoT networks, RF harvesting, LTE spectrum.*

INTRODUCTION

Sensors are a critical component of IoT networks and applications. An autonomous sensor differs from conventional ones, as it does not only collect raw data to transmit towards an external processor, but is capable of processing the data locally, making decisions and potentially taking actions. The building blocks of an autonomous sensor are the sensing component, the processing unit and the transmitter, all being connected to the power source, where our work is focused.

The radio frequency spectrum covers a broad range of popular services such as commercial radio, broadcast television, mobile and Wi-Fi networks. Studies and measurements performed in several cities determine that the spectrums with the highest RF power density are cellular technologies, which would provide better input and output power for our objectives. The research will depend on power-density measurements, performed by Albanian mobile operators on LTE spectrum. This approach can be adapted on other case-studies, on cities where ICNIRP/WHO radiation guidelines are followed.

To achieve radio frequency harvesting, an electronic circuit is required to utilize the RF power and convert it in DC output for the sensor. This work is built around an asymmetric folded dipole antenna, designed to operate at LTE 2600 MHz band, with a directional radiation pattern. Compared to related studies [1, 2] which focus on an omni-directional design, a directional design can provide higher input powers, but will limit the installation location on real-world scenarios. Following the antenna, the coupler's role is to maximize power transfer towards the load by eliminating reactive impedance. The rectifier, as the last part of the circuit before the load, will convert the AC signal to DC using a Schottky diode. Lastly, work concludes by highlighting scenarios depended on design and implementation.

The integration of Radio Frequency (RF) harvesting in Smart Cities and IoT network introduces a model for powering autonomous sensors, to enhance their energy autonomy using reliable and sustainable power sources.

RADIO FREQUENCY SYSTEMS

The Radio Frequency spectrum may have different designations, according to the organization defining the standards. Widely accepted is the ITU definition of the radio spectrum, split into 12 sub-bands ranging from 3 kHz to 3 THz, used for wireless communications and radar technologies.

Radio systems and radio waves are "chaotically scattered" in our cities, serving everyday needs of the citizens. The most wide-spread systems are the commercial ones: Broadcast DTV, FM Radio, Cellular technologies, Wi-Fi, Navigation systems, etc. To highlight the system with the highest power density, it's required to calculate the Poynting vector using the expression provided in equation 1.

$$S = E \times H \left[\frac{W}{m^2}\right] \quad (1)$$

$$P_{av} = S \cdot A_E = EIRP \cdot G_R \left(\frac{\lambda}{4\pi d}\right)^2 \cdot \cos^2\alpha \quad (2)$$

Studies on RF power density, on urban and semi-urban areas, determine that the bands with the highest power density were mobile technologies GSM, 3G and LTE, respectively on the downlink frequencies. Utilizing the downlink spectrum for our antenna would increase the power input of the harvester circuit.

The power density for electromagnetic radiation in Albania is regulated by the Ministry of Heath, and the guidelines are adopted from ICNIRP/WHO recommendations: "Guidelines for limiting exposure to time – varying electric, magnetic and electromagnetic fields (up to 300GHz)" [3], and EU directives: "Council Recommendation of 12 July 1999 on the limitation of exposure to electromagnetic fields (0 Hz to 300 GHz).

Specifically for the mobile technologies, these limitations and measurements methods were declared by the Ministry of Health's Radiation Protection Commission, on Nr. Prot. 822/2; Date 13.02.2013 [4], as provided on Table 1.

Table 1. Mobile Technologies Radiation Limitations [4]

Band	Frequency (MHz)	E maximal (V/m²)	S maximal (W/m²)
GSM900	880-915	41.5	4.5
	925-960		
LTE1800	1710-1785	58	9
	1805-1880		
UMTS2100	1920-1980	61.4	10
	2110-2170		
LTE2600	2500-2570	61.4	10
	2620-2690		

According to measurements performed from mobile providers in Albania, which are required for site certification, the distance from site where the radiation limitations are reached varies from 15m to 25m, depending on topology and placement. By knowing that power density matches the maximal values of Table 1 on a specific distance from site, it can be used to calculate the power density while moving further away from site location.

CIRCUIT BUILDING BLOCKS AND THEIR ROLE

Components of the circuit

The main goal of our RF harvesting circuit is the production of a continuous DC output, by converting the input electromagnetic waves. The main blocks of the circuit, as described in Figure 1, would be the antenna, the coupler circuit, the rectifier and the load. More blocks can be added in order to offer a reliable and stable output. For instance, a voltage multiplier circuit, to increase the output voltage; a voltage regulator, to maintain low fluctuations of the output voltage; an energy storage unit, to maintain sensor high availability.

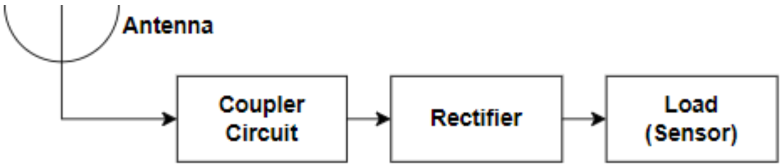

Figure 1. RF harvester circuit building blocks

Antenna equivalent model

As the first and most important element of the circuit, the antenna will enable RF harvesting. Firstly, the operation band of the antenna should be selected, in our case our antenna will operate on LTE2600 downlink band. A good antenna design would increase its ability to extract more power from the radio waves, where in an urban or semi-urban area, a directional antenna could help by increasing input power if aligned with radio stations. Multiband antennas can also be selected for higher input power, operating in the bands (DTV, GSM, 3G, WiFi).

Antenna equivalent model, displayed in Figure 2, is composed from an AC voltage generator operating in the selected band (Vs), in series with an impedance (Zs) including both resistive component (Rs: radiation resistance and Rloss: resistance of circuit elements and connectors) and reactive component (jXs: reactance depended on antenna design, which can be inductive or capacitive. Rloss will be neglected due to its insignificant value.

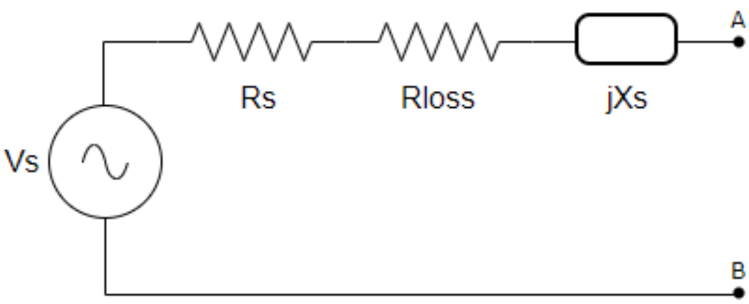

Figure 2. Antenna equivalent model

$$V_S = \sqrt{2R_S P_{av}} \quad (3)$$

$$Z_S = R_S + jX_S \quad (4)$$

$$Z_L = Z_S^* = R_L - jX_L \quad (5)$$

Coupler Circuit Function

Power transfer theorem implies that in the presence of AC current, to maximize the electrical power on the load impedance, the load impedance should equal the conjugated value of source impedance, in the resonating frequency of GSM band. By eliminating the reactive components from the circuit, power will be shared between the resistive components as displayed in Figure 3.

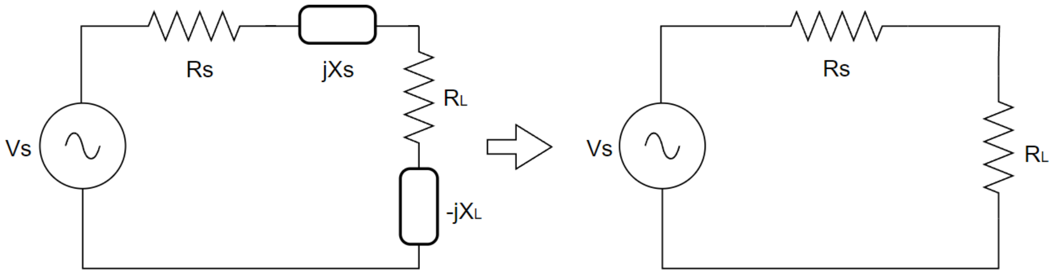

Figure 3. Impedance matching circuit

Rectifier Circuit

The duty of the rectifier circuit is to convert an input AC signal, in our circuit the AC voltage extracted by the antenna, into DC signal in the output. The most common practice for the rectifier circuit is using a diode for a half-wave rectifier, or a diode bridge for a full-wave rectifier. However, a rectifier and multiplier circuit can be mandatory when facing low output voltage, in order to increase voltage output.

A capacitor filter following the rectified signal, will charge and discharge by the input AC voltage, creating in the output a rippled DC voltage, shown in Figure 4. Capacitance value should be selected carefully, in order to maintain the charge between the rectified waves.

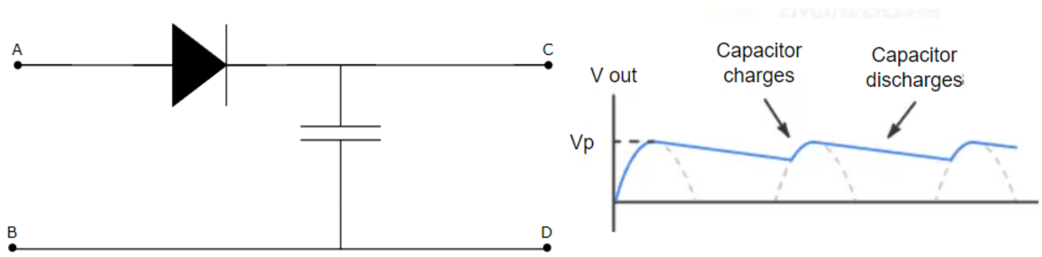

Figure 4. Output of the rectifier circuit

Optional circuit components

Following the rectifier, some complementary but not mandatory blocks can be added. The first block to follow can be a voltage regulator, usually built by using a Zener diode. The regulator will decrease the rippling of the signal output by the capacitor of the rectifier circuit, creating a more stable and smoother DC signal for the components to come.

Energy storage block or power management block can be one of the components prior to the sensor. The excess harvested energy may be collected on an energy storage unit, such as batteries, supercapacitors or ultra-batteries, and reused at a later time, when the circuit output voltage may suffer degradation from external or internal causes.

The last element of the circuit is the load, in this study it will be an autonomous sensor for vehicular networks. The sensors that can be used are limited by the circuit design, as a simple circuit can power and maintain low consumption sensors without disruptions, however, high consumption sensors would require a more complex circuit design and specific components. The best approach would be to design the RF harvester according to the sensor's needs and datasheet.

CIRCUIT DESIGN, SIMULATIONS AND ANALYSIS

Antenna Design

The antenna is designed to operate on both LTE1800 and LTE2600 spectrums, but the simulations and tests are performed only on LTE2600 downlink, due to the high-power density and signal availability in urban and rural areas. An asymmetric folded dipole antenna, is built in HFSS simulator [5], figures 5 and 6 display respectively the design and return loss of the antenna, where the minimal S11 values are on LTE bands.

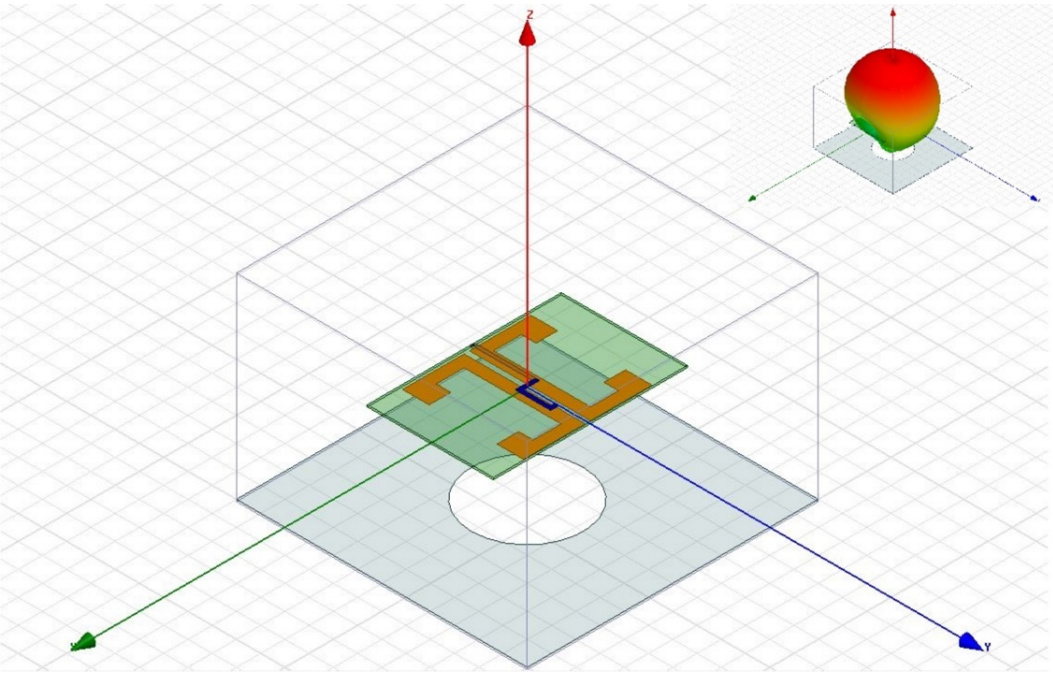

Figure 5. Antenna Design from HFSS

In order to convert our antenna into the equivalent circuit model, equation 2 is used to calculate the average input power on the LTE2600 spectrum, where the RF power density reaches the safety recommended values of 10 W/m² (polarization loss factor cos2α, will be negated in the calculations). Meanwhile the gain and impedance of the antenna required for the equivalent model are shown from the HFSS simulations in Figure 7 and 8.

$$A_E = G_R \cdot \frac{\lambda^2}{4\pi} = 6.3 \cdot \frac{11.3^2}{4\pi}\ cm^2 = 64\ cm^2$$

$$P_{av} = S \cdot A_E = 1000\ \frac{\mu W}{cm^2} \cdot 64\ cm^2 = 64\ mW$$

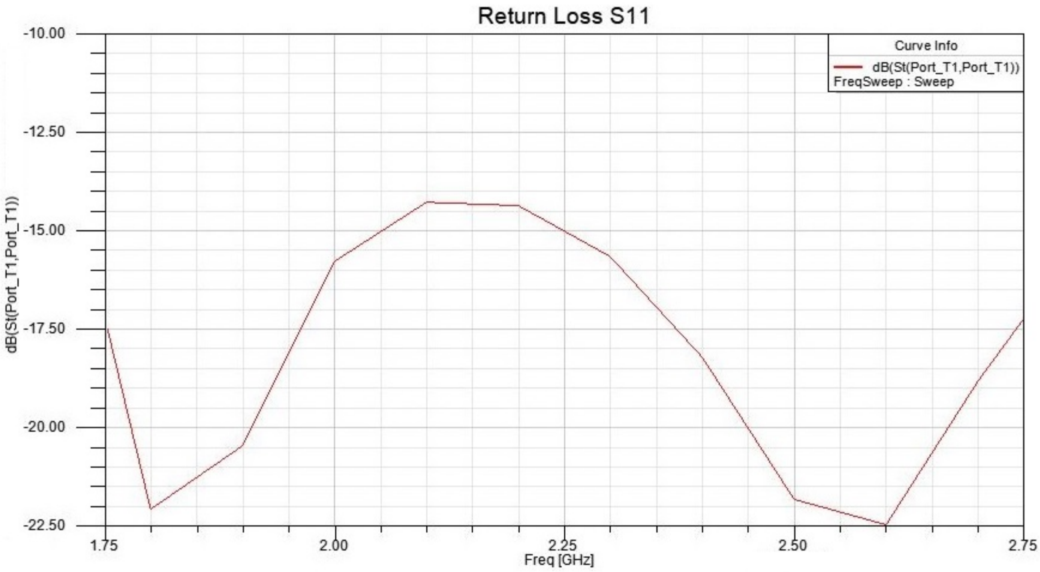

Figure 6. Antenna Return Loss

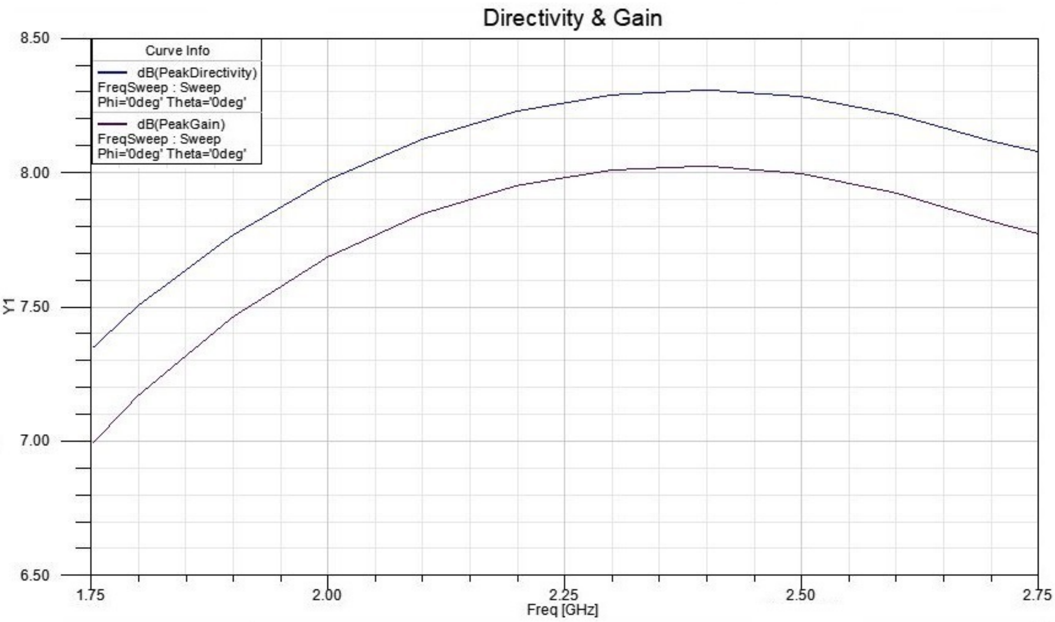

Figure 7. Antenna Directivity and Gain

Making use of both average power and antenna impedance, to calculate the remaining elements of the equivalent circuit model, equations 3 and 4 are applied. Positive value of the reactance indicates the presence of an inductive element in series with the voltage source and antenna resistance.

$$Z_S = R_S + jX_S = 53 + j8\,\Omega$$

$$V_S = \sqrt{2R_S P_{av}} = \sqrt{2 \cdot 53 \cdot 0.064}\,\mathrm{V} = 2.6\,\mathrm{V}$$

$$X_S = 2\pi fL = 8\,\Omega => L_S = 0.49\,\mathrm{nH}$$

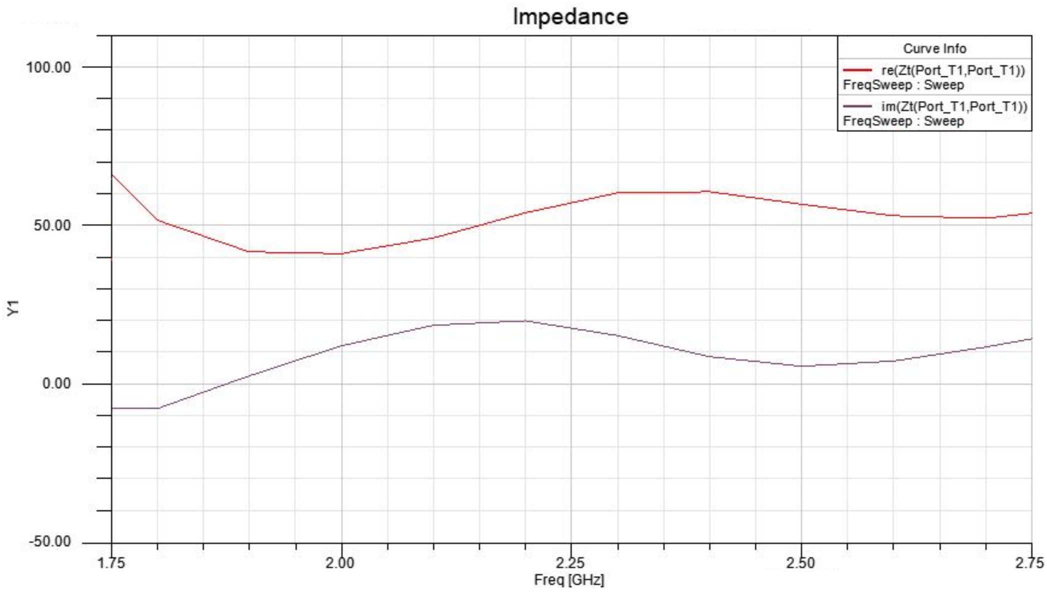

Figure 8. Antenna Impedance

Rectifier Design and Load

The two components of the AC/DC converter are the rectifier circuit and the capacitive filter [6-9]. Due to the voltage values extracted by the antenna, a requirement for the rectifier circuit will be a low forward voltage threshold. A Schottky diode is characterized by both low forward voltage threshold and fast switching speed. The diode model that is considered for the simulation will be HSMS-2850, will SPICE parameter shown on Table 2.

Table 2. Spice parameters for Schottky diode HSMS-2850

SPICE Parameter	Unit	Value
BV	V	3.8
CJ	pF	0.18
EG	eV	0.68
IBV	A	3 10-4
IS	A	3 10-6
N		1.06
RS	Ω	25
PB (VJ)	V	0.35
PT (XTI)		2
M		0.5

The Schottky diode equivalent model is composed of two resistances and one capacitor, as displayed on Figure 9. The variable resistance RJ can be calculated using equation 6, while RS and CJ values can be extracted from Table 2 SPICE parameters. For the capacitive filter, a 1 nF capacitor will be selected for the tests, and for the load, representing the sensor simulations will test 1 kΩ resistance.

$$R_j = \frac{8.33 \cdot 10^{-5}\ nT}{I_F + I_s} \tag{6}$$

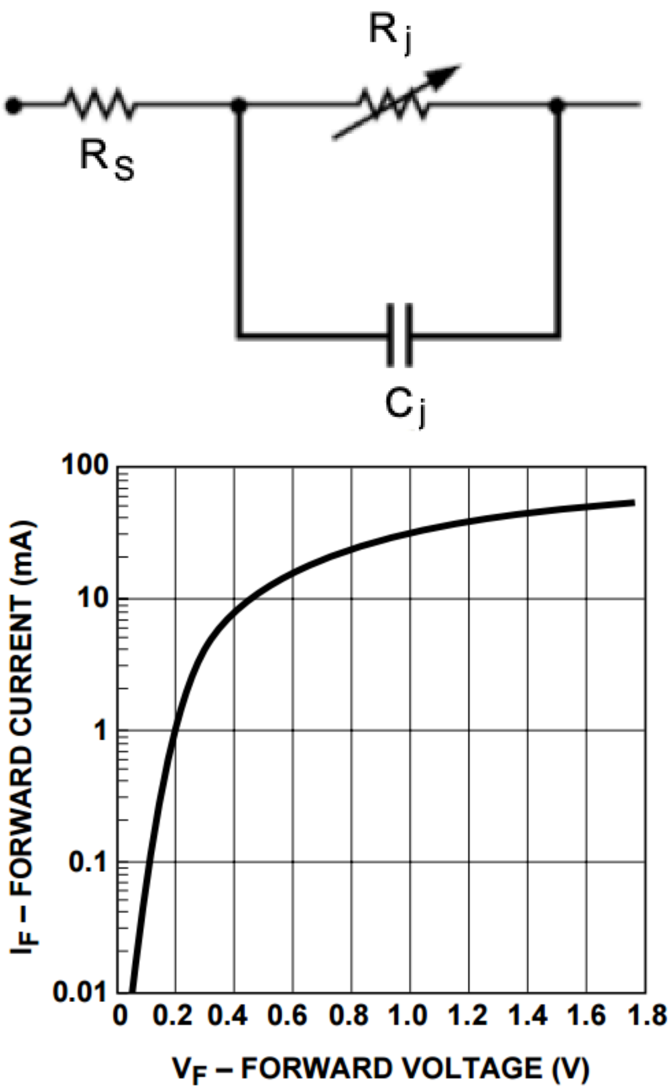

Figure 9. Schottky diode equivalent model and I-V relationship

Coupler Design and Simulations

The last element required to join the antenna equivalent model with the rectifier circuit, is the coupler, or impedance matching circuit. The impedance matching will increase the efficiency of voltage transmitted towards the load. The most common models for the coupler circuit are the L, T and π typologies. Selected for the simulations will be a modified L-model, containing only the inductor to negate the capacitive reactance of the other components. The full RF harvester circuit, with the calculated or selected values is displayed in Figure 10. Inductor's value will be determined by the following simulations.

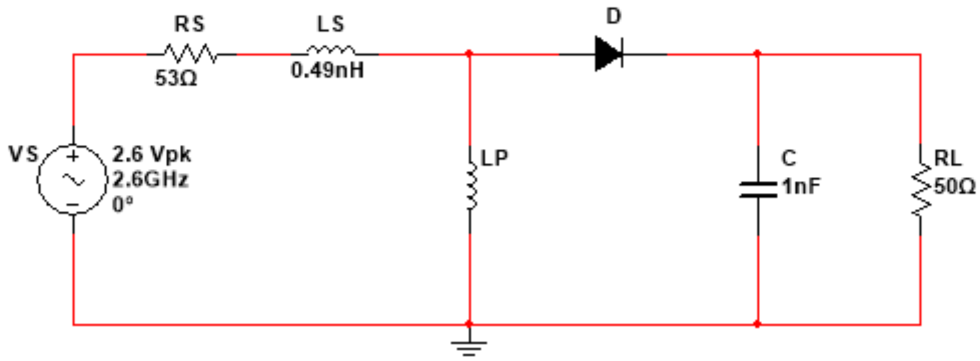

Figure 10. Complete design of the RF harvester circuit

Running a "Parameter Sweep" analysis on the circuit using the simulator Multisim, it can be observed that the changes on the output voltage and current for inductor values ranging between 10 and 100 nH, in hops of 10 nH. From the graph on Figure 11 and Table 3, it is easily distinguishable that approaching 100 nH the output is saturated, reaching a volage of 460 mV and a current of 9.2 mA.

Table 3. Output values for variable inductor value

LP	V_L	I_L	P_L	Efficiency
10 nH	447.0 mV	8.940 mA	3.968 mW	6.20 %
20 nH	458.7 mV	9.175 mA	4.171 mW	6.52 %
30 nH	460.3 mV	9.210 mA	4.216 mW	6.59 %
40 nH	462.6 mV	9.251 mA	4.239 mW	6.62 %
50 nH	463.3 mV	9.267 mA	4.243 mW	6.63 %
60 nH	463.1 mV	9.262 mA	4.260 mW	6.66 %
70 nH	463.8 mV	9.275 mA	4.270 mW	6.67 %
80 nH	463.5 mV	9.270 mA	4.267 mW	6.67 %
90 nH	464.2 mV	9.285 mA	4.272 mW	6.68 %
100 nH	463.9 mV	9.280 mA	4.271 mW	6.67 %

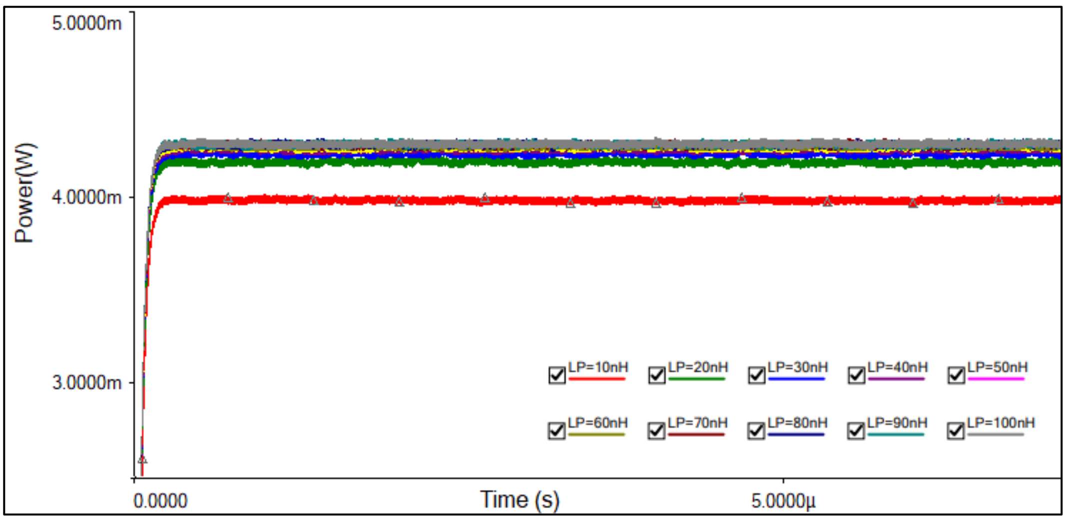

Figure 11. Load power for variable inductor values

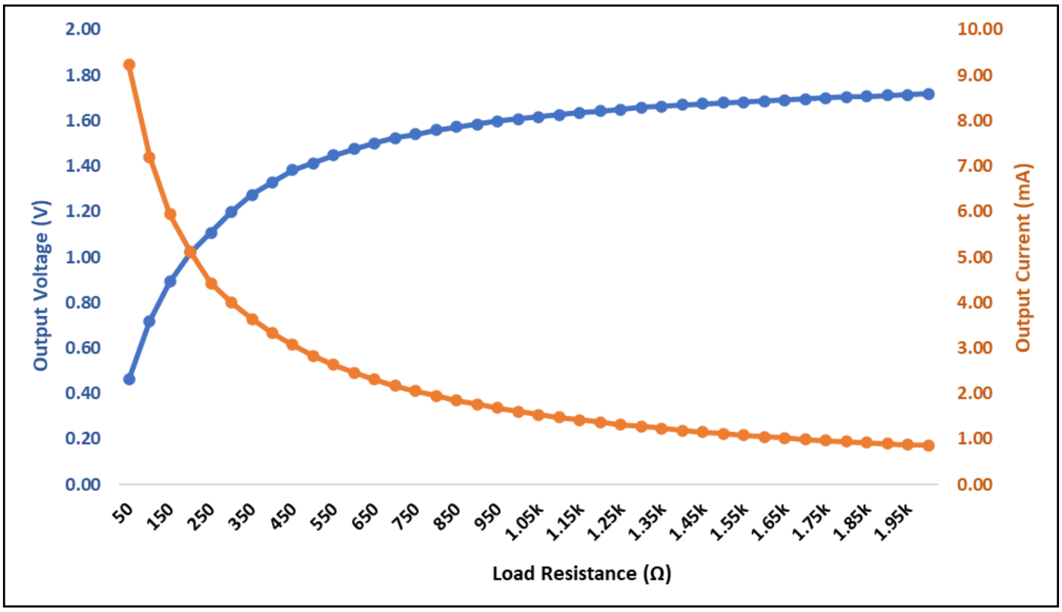

Figure 12. Output voltage with a variable load resistance

After selecting a value for the matching circuit inductor within the range 40 – 100 nH, we can test the output behaviour with a variable load resistance. By increasing the load, the maximum output voltage approaches 1.7V, but it sacrifices the output current as displayed in the Figure 12 graph. Maximal efficiency of 8.3% is reached at 150 Ω, where the output power is 5.3 mW, while voltage and current equal 0.9 V and 5.94 mA respectively.

Considering the LTE2600 power density has a value of 10 W/m2 at a distance of 20m from site, it's possible to deduct the distance related dependence of circuit input parameters, derived from equations 1, 2 and 3, where distance "d" is expressed in meters.

$$S = \frac{EIRP}{4\pi d^2} = \frac{4000}{d^2} \quad => \quad P_{av} = S \cdot A_E = \frac{25.6}{d^2} \quad => \quad V_S = \sqrt{2R_S P_{av}} = \frac{52.1}{d^2}$$

Utilizing the calculated circuit input and the optimal elements' values derived from testing for both coupler circuit and load resistance, when moving away from the site the output is decreased with the respective values shown on Table 4 and Figure 13.

Table 4. Input and output parameters dependence on site distance

d (m)	S (W/m²)	P_{in} (mW)	V_{in} (mV)	V_{out} (mV)	I_{out} (mA)
20	10.00	64.00	2605.00	890	5.94
30	4.44	28.44	1736.67	562	3.75
40	2.50	16.00	1302.50	396	2.64
50	1.60	10.24	1042.00	300	2.00
60	1.11	7.11	868.33	239	1.59
70	0.82	5.22	744.29	191	1.28
80	0.63	4.00	651.25	159	1.06
90	0.49	3.16	578.89	135	0.90
100	0.40	2.56	521.00	114	0.76

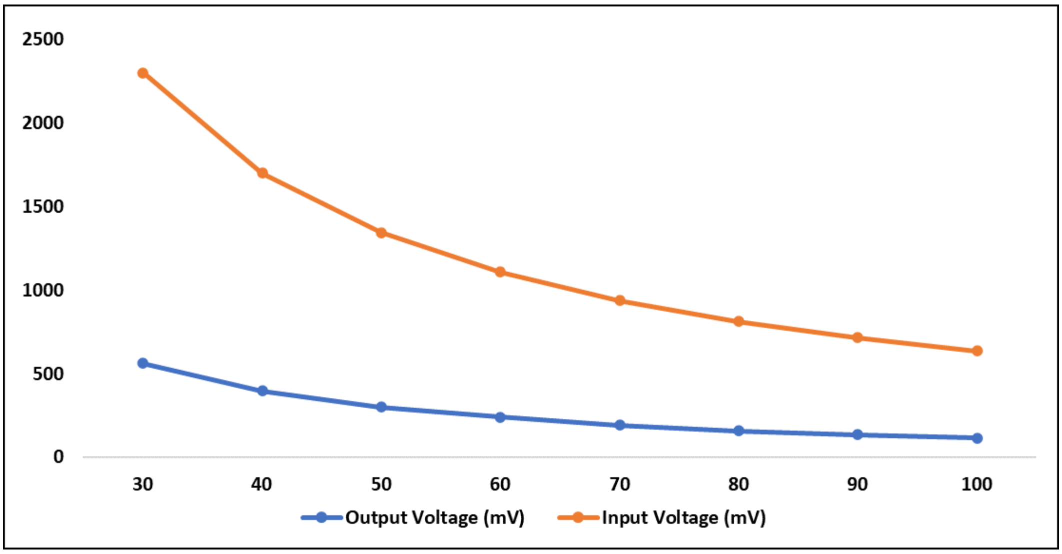

Figure 13. Input and output voltage dependence to site distance (m)

CONCLUSIONS

The proposed and analyzed circuit could successfully operate on the LTE2600 downlink spectrum, but can also be adapted to operate on other high power density RF bands. Implementation of the RF harvester to power autonomous sensors for IoT applications would reduce on-site maintenance visits, financial costs and long-term lower the environmental impact of batteries. A qualitative design and integration of the circuit elements would increase the power output towards the sensor, allowing for a broader range of applications. Optimization of the antenna, rectifier and impedance matching circuit should complement the sensor's input requirements, creating a high efficiency circuit. For the design considered, the output reaches a maximal load volage of 900 mV and a maximal load current of 5.94 mA, with an input-output efficiency of 8.3%.

FURTHER STUDIES

Three main interventions can be considered in the future for the improvement of the circuit design and efficiency:

- Designing multi-band antennas, capable of operating in several RF bands (DTV, GSM, 3G, LTE, WiFi), increasing output reliability, if there are failures in a specific band.
- Including other transducer technologies to complement the RF Harvester (Photovoltaic, Thermoelectric, Piezoelectric), increasing circuit input power.
- Implementing more complex designs for the impedance matching and rectifier circuits, in order to increase power transfer and efficiency.

CONFLICT OF INTERESTS

The authors would like to confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

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