RF Energy Harvesting for Low Power Electronic Devices

Student project

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***Abstract*—Different methods for RF energy harvesting from radio transmitters with working frequency of up to 108 MHz are examined. Experiments are conducted especially with the LW transmitter near Vakarel village (261 kHz) (Sofia, Bulgaria) and the transmitter of the National Radio “HristoBotev” at radio-tower “Kopitoto” (92.9 MHz) (Sofia, Bulgaria). Partial success is achieved with electrically small loop antenna resonated at 261 kHz.**

***Index Terms*—wireless power, RF energy harvesting, small loop antenna.**

I. INTRODUCTION

THE progress of the electronics production enables wider application and improved properties like performance and power consumption. Sensors and sensor-networks become wide-spread in different fields of the industry and everyday life. To cut the operating costs, the conventional power supply (battery) can be replaced by some kind of an energy harvester which uses ambient energy. Often these are light sources, wind, vibrations and EM radiation from radio transmitters or other kind of electric devices.

In the paper, different radio transmitters are examined (LW and VHF). Three types of antenna systems are analyzed. An attempt is made to classify the pros and cons of each one of them.

II. ENERGY STORAGE

The energy storage consists of a diode and an electrolytic capacitor. Two types of diodes were used (1N34A and BAT754). The first one is germanium diode, while the second is Schottky. The diode is connected in series with the capacitor. Utilization of a standard or low-ESR capacitor is recommended. High-impedance (super) capacitor like the Panasonic’s GoldCap (double layer) isn’t well suited for the purpose, because the input impedance of the energy storage is additionally increased.

The I-V curve of the 1N34A diode is shown in fig. 1. From the graphic shown in fig. 2 it becomes clear, that the input impedance is very high for small voltages and it drops suddenly when the voltage increases. This variable impedance poses difficult task to solve.

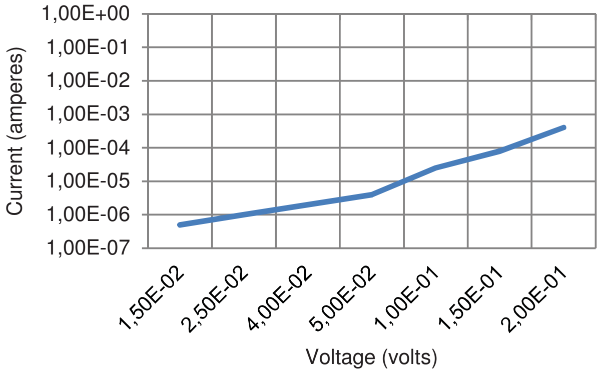

Fig. 1. I-V curve of 1N34A diode.

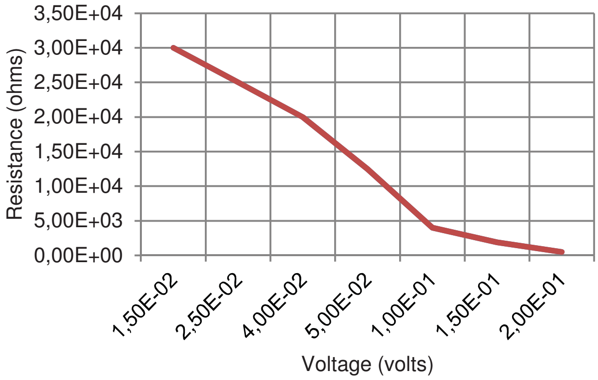

Fig. 2. Resistance of 1N34A up to 200mV.

III. DIPOLE ANTENNA

It is suitable for reception at the VHF band. The transmitter of the National Radio “HristoBotev” (Sofia, Bulgaria) is used, which transmits at frequency of 92.9 MHz. It has power output of 10 kW. There is no detailed information about the transmitter’s antenna, so ordinary dipole is assumed with gain of 2.15 dBi.

The transmitter’s location is (N42.636734 E23.244045), and the receiver’s location is at (N42.655400 E23.354123). The distance between them is about 9.4 km.

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Fig. 3. Elevation profile between the transmitter and the receiver.

In fig. 3 is shown the elevation profile. There are no natural obstacles between the transmitter and the receiver.

The theoretical receive power is calculated according to the Friis equation.

$$P_{rcv} = Tr_P \cdot Tr_G \cdot Rcv_G \cdot \left(\frac{\lambda}{4 \cdot \pi \cdot r}\right)^2 \tag{1}$$

It is estimated to be 20.1 μW. The greatest measured power was 0.94 μW across a 68-ohm resistor. Matching the resistor to the theoretical 73 ohm real impedance of the dipole didn't reveal any better performance.

Connecting the antenna to the energy storage via impedance transformer didn't give any positive results.

The transformer's turn ratio is calculated in accordance with eq. (2).

$$TR = \sqrt{\frac{R_{load}}{R_{source}}} = \sqrt{\frac{20 \cdot 10^3}{73}} = 16.55 \tag{2}$$

Two-hole (binocular) rf ferrite core from an old TV antenna was used to form beverage transformer. Additional examination is required to solve the problems.

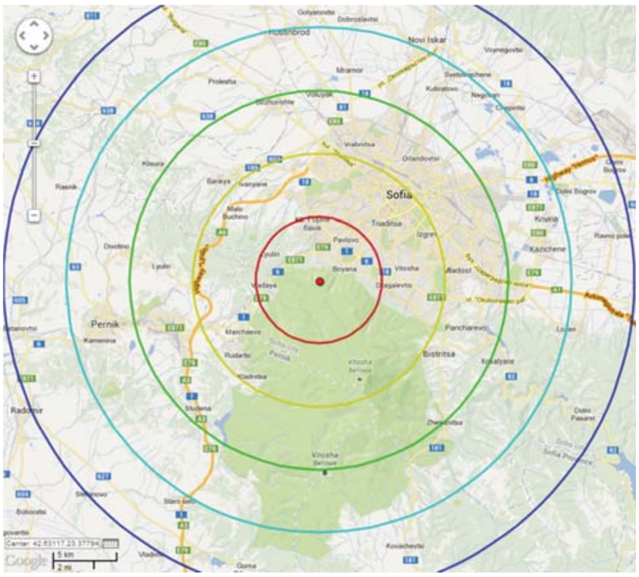


Fig. 4. Location and coverage of the transmitters of the "Kopitoto" tower (Vitosha Mountain, Sofia, Bulgaria).

In fig. 4 is presented the transmitter's location according to the nearby city.

IV. ELECTRICALLY SHORT WHIP ANTENNA

When the diameter of the antenna $d \ll l$, the effective height is $h_{eff} = \frac{1}{2}h$ [1, p. 401; 2, p. 53 (4.3)]. The open-circuit voltage is found by $V_{OC} = Eh_e cos\psi$. [1. p. 426 (4.3.1)]

Five meters tall mast is used to raise 2 mm diameter solid copper wire. The mast is made from a fiber-glass telescopic fishing rod. The antenna load is connected between the raised wire and a 30 cm copper pipe fixed into the ground. The output power of short monopole can be calculated from (3): [1, p. 406, (4.3.5)]

$$P_{out} = \frac{E^2 h_e^2 R_L}{(R_r + R_l + R_L)^2 + (X_a + X_L)^2} \tag{3}$$

where R_r is the radiation resistance; R_l is the resistance of the antenna; R_L is the resistance of the receiver. When $X_L = 0$ the equation becomes [1, p. 407, (4.3.11)]:

$$P_{out} = \frac{E^2 h_e^2 R_L}{R_L^2 + X_a^2} \tag{4}$$

The greatest output power in non-resonant conditions is achieved when $R_L = X_a$:

$$P_{out} = \frac{E^2 h_e^2}{2X_a} \tag{5}$$

When the antenna is resonated ($X_a = -X_L \propto 0$), the power is maximized [1, p. 406, (4.3.6)]:

$$P_{out} = \frac{E^2 h_e^2 R_L}{(R_r + R_l + R_L)^2} \tag{6}$$

The output power is greatest when $R_L = R_r + R_l$ [1, p. 406, (4.3.8)]

$$P_{out} = \frac{E^2 h_e^2}{4R_l} \tag{7}$$

A series of experiments were conducted at a test site with coordinates (N42.655400 E23.354123). First the open-circuit voltage is shown:

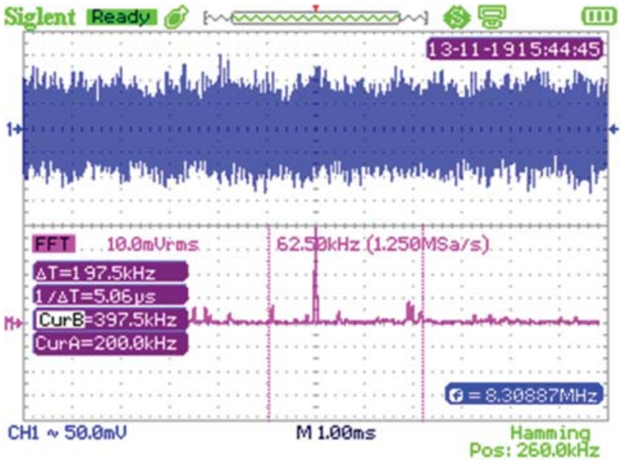


Fig. 5. Amplitude of the received signal (open-circuit). Over 30mV.

In fig. 5 the spectrum of the received signal is shown including adjacent channels.

Next the antenna output is loaded with a 1 kOhm resistor. The greatest power in this case should be achieved by use of a 17 kOhm load, because the capacitance of the antenna at the specified frequency (the antenna's capacitance is 34 pF). Loading of the antenna gives more information for unknown transmitters:

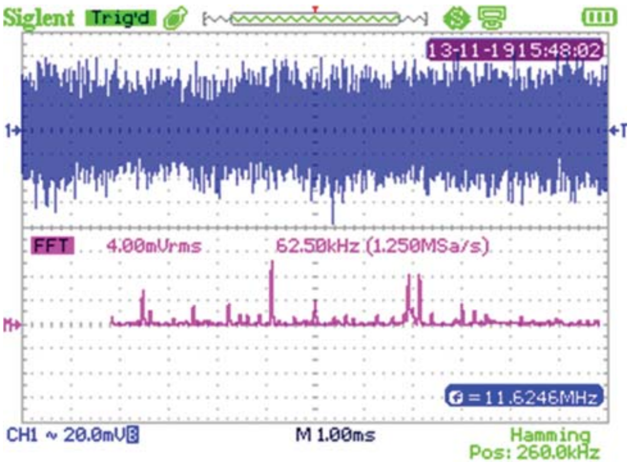


Fig. 6. Spectrum of the signal by 1 kOhm load.

Unknown sources of signal were observed, which power is greater than the target transmitter at 261 kHz. They can improve the total available energy from the antenna, but a wideband matching is required. In fig. 6 one can see different sources of signal with frequency of 60 kHz to 150 kHz away from the central frequency.

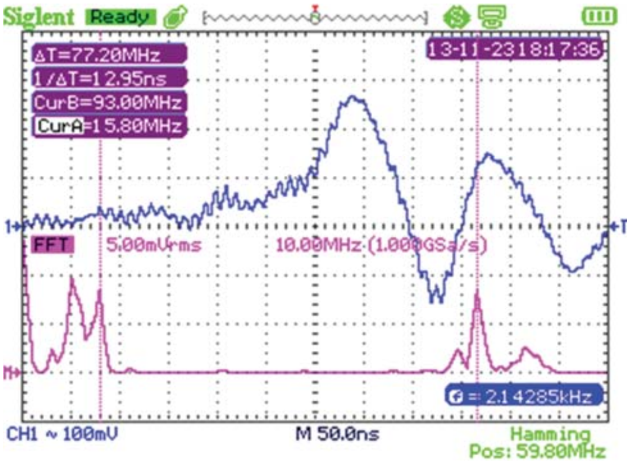


Fig. 7. Signal spectrum up to 120 MHz.

In fig. 7 expanded spectrum of up to 120MHz is represented. The results are obvious – strong signal is received on 10 MHz, 20 MHz, 93 MHz and 103 MHz. While the first two are local sources near the university building, the last two are the 10 kW transmitters of the "Kopitoto" tower.

V. ANALYSIS OF THE AVAILABLE POWER FROM THE LONG-WAVE TRANSMITTER "VAKAREL" WITH USE OF LOOP ANTENNAS

A square loop antenna was built with side length of 140 cm. It uses PVC pipes frame. Enameled copper wire of 0.18 mm diameter is wound to form 20 turns. The gap between the turns is 1 cm. The theoretical calculation of the loop according to the Wheeler's equation is 1415 μH, and the measures inductance is about 1.5 mH. The Thomson's formula $f=\frac{1}{2\pi\sqrt{LC}}$ is used to find the required capacitance for resonance at 261 kHz.

$$C=\left(\frac{1}{2\pi f\sqrt{L}}\right)^2=\left(\frac{1}{2\pi\cdot 261\cdot 10^3\cdot\sqrt{1.5\cdot 10^{-3}}}\right)^2 \\ =3\cdot 10^{-9}F \qquad (8)$$

Transmitter's data:

1. Power $P_T = 75$ kW
2. Frequency $f = 261$ kHz
3. Antenna gain $G_T = 2.15$ dBi ≈ 1.64

Note: the antenna gain is assumed to be 2.15 dBi, because there is no data how much it is in real. Also the antenna was constructed for different frequency, and today it is inductively loaded.

Receiver's data:

1. Distance to the transmitter: $r = 33$ km. The receiver is in the far-field.
2. Number of turns: $N = 20$
3. Area per turn: $A = 1.96$ m^2

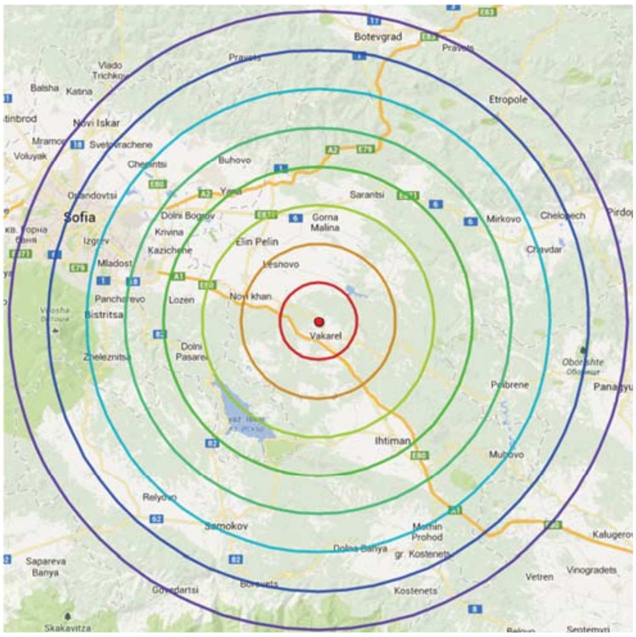


Fig. 8. Position and coverage of the "Vakarel" radio-transmitter (near Sofia, Bulgaria).

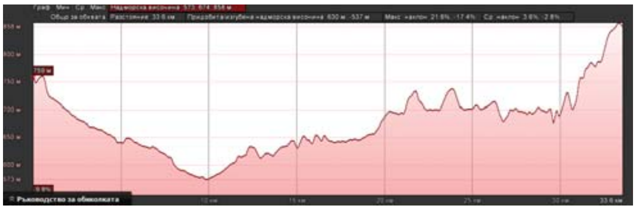


Fig. 9. Elevation profile between the transmitter and the receiver.

In fig. 8 is represented the transmitter's location according to the nearby cities and artificial lake. The harvested energy can be used for water quality measurements.

In fig. 9 the elevation profile is shown. No direct obstacles can be seen.

Calculation of the electric field strength E at the receiver's location:

$$\mathrm{E} = \frac{\sqrt{30\, P_T G_T}}{r} \approx 82.3 \cdot 10^{-3}\ \mathrm{V/m} \tag{9}$$

However, the propagation of the EM waves at these frequencies cannot be properly calculated with the above equation. It is convenient to use a free computer program called "Field Strength Pro" (National Institute of Information and Communications Technology, Japan), which is able to calculate properly the field strength for frequencies from 40 kHz to 500 kHz and distances of up to 4000 km.

The power is:

$$P = \frac{E^2}{377} \approx 18 \cdot 10^{-6}\ \mathrm{W/m^2} \tag{10}$$

The magnetic field strength H and the magnetic flux B are calculated:

$$H = \frac{E}{Z_0} = \frac{82.3 \cdot 10^{-3}}{377} \approx 218.4 \cdot 10^{-6}\ \ \mathrm{A/m} \tag{11}$$

$$\begin{aligned} B = \mu_0 \mu_r H &= 4\,\pi \cdot 10^{-7} \cdot 218.4 \cdot 10^{-6} \\ &= 2.744 \cdot 10^{-10}\ \ \mathrm{T} \end{aligned} \tag{12}$$

With the calculated values, the effective height of the antenna $h_{eff} = \frac{2\pi NA\cos(\theta)}{\lambda}$ [2, p. 54 (4.4)] is computed:

$$h_{eff} \approx 0.214 \tag{13}$$

The expected open-circuit voltage (non-resonant conditions) is found using eq. (14) [1, p. 415, (4.4.3)] or using the antenna's effective height.

$$V_{OC} = 2\pi f NAB\cos(\theta) \tag{14}$$

$$V_{OC} = h_{eff} E \approx 17.6 \cdot 10^{-3}\mathrm{V} \tag{15}$$

The capacitance was adjusted for maximum voltage across the LC tank. Voltage of up to 500 mV peak (pk-pk) was measured. The schematic was extended with additional BAT754 Schottky diode and a 1F supercapacitor:

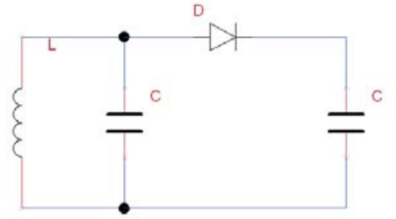


Fig. 10. Schematic of the antenna and the energy storage.

In fig. 10 the schematic of the antenna connected to the energy storage is shown. The left part consisting of an LC tank represents the resonated antenna.

The voltage between the diode and the capacitor was 100 mV peak. For 9 hours (between 00:00 to 09:00 AM) the voltage of the capacitor increased to 36 mV (1 mV initial voltage). The net energy obtained for the period is found by (16):

$$E = \frac{1}{2} C U_{fin}^2 - \frac{1}{2} C U_{init}^2 \tag{16}$$

The total stored energy is 646 µJ, which is about 2 nJ (2 nW) per second.

Loading of the LC tank with 2200 Ohm resistor leads to 17 mV Vrms across it. The current is 7.72 µA and the average power is about 131 nW (131 nJ per second).

Main disadvantage of the schematic is the utilization of the supercapacitor with high impedance.

$$Z = \frac{Z_L Z_C}{Z_L + Z_C} \tag{17}$$

$$Z_L = 2\pi(261 \cdot 10^3) \cdot 1.5 \cdot 10^{-3} \approx 2460 \tag{18}$$

$$Z_C = \frac{1}{2\pi(261 \cdot 10^3) \cdot 3 \cdot 10^{-9}} \approx 203 \tag{19}$$

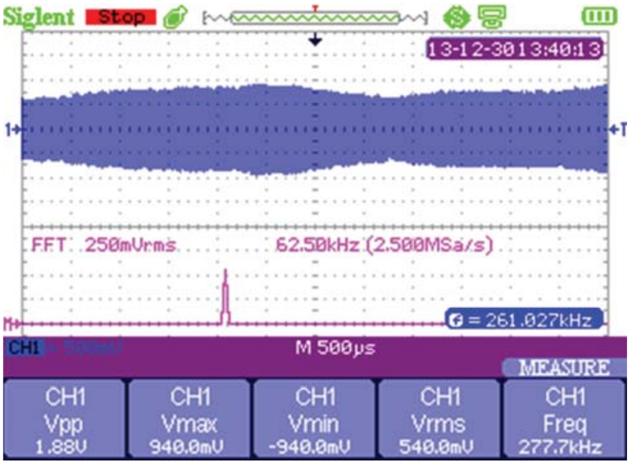
Smaller loop antenna with thicker wire (2 mm diameter) was built. It has 20 turns and 70 cm side length. The measured inductance is 575 µH, and the calculated capacitance for resonance at 261 kHz is 0.6 nF.

It is very important to consider the oscilloscope's probe capacitance. It introduces a great amount of capacitance to the circuit.

The supercapacitor is replaced by ordinary electrolytic capacitor. Power measurements after the diode were performed according to eq. (16). The time zone is GMT+2.

Location (N42.636 E23.297) (29.12.2013) (the same elevation profile as in fig. 9)

- Diode1N34 (outside)– 0.145 µW (22:06PM)
- Diode1N34 (in the house) – 0.102 µW (21:21PM)
- Location (42.636 23.297) (30.12.2013)
- 1N34A(in the house) – 0.050 µW (15:08PM)
- BAT754 (in the house) – 0.089 µW (14:18PM)
- 1N34A (outside) – 0.129 µW (15:35PM)
- BAT754 (outside) – 0.094 µW (15:47PM)



CH1 Vpp 1.88V
CH1 Vmax 940.0mV
CH1 Vmin -940.0mV
CH1 Vrms 540.0mV
CH1 Freq 277.7kHz

Fig. 11. Open-circuit signal spectrum and amplitude of the second loop antenna in resonance.

In fig. 11 is shown the RMS and peak voltage of the resonated antenna. The antenna construction permits better efficiency due to the thicker wire involved.

Location (N42.641589 E23.451201). In fig. 12 is represented the path between the transmitter and the receiver. At a distance of 1.2 km from the transmitter there is a hill 819 m above sea level, whereas the transmitter’s antenna height is 820m above sea level.

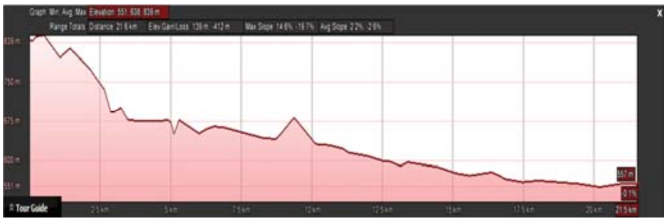


Fig. 12. Elevation profile between the transmitter and the receiver.

Used diode vs. power:

- 1N34A –0.328 μW (16:42PM)
- BAT754 – 0.217 μW (16:36PM)
- both in parallel – 0.163 μW (16:47PM)

VI. CONCLUSIONS

The conducted experiments show that the input impedance of the energy storage used may be too high. Thus it is important to use a capacitor with lower input impedance.

The efficiency is highly dependent on the source’s impedance. As it was shown in the beginning, the impedance of the energy storage is very high with small voltages, and increased voltages lead to its decrease. The parallel LC circuit exhibits maximum impedance at resonance, hence it forms a high-impedance voltage source. Thus the impedances are somewhat matched and the energy transfer from the antenna to the energy storage is improved.

The utilization of series resonance for short whip (reducing the capacitive reactance) and small loop gave no successful results.

Also the resistive properties of the wire are important for better efficiency. Utilization of solid copper wire is recommended, while Litz-wire is not recommended because the extra capacitance which it introduces in the circuit.

The experiments conducted with dipole antenna gave about 50 mV open-circuit voltage at a distance of about 10 km from the transmitter. Matching the antenna to the energy storage using impedance transformer was unsuccessful.

If one wants to power a device by RF energy harvesting, they should first locate the nearby transmitters. LW, MW or SW transmitters are preferred. Increased frequency means shorter wavelength, which is directly proportional to the antenna efficiency. Also the MW or SW transmitters are usually very powerful. Therefore it may be more convenient to use MW or SW transmitter instead of LW. For the VHF band the energy harvesting device should be closer to the transmitter due to the transmitter’s reduced power and higher path loss.

Some of the market trends are focused on the development of low-power devices. For example the MSP430L09 achieves 45 μA current consumption at a voltage of 0.9 V (40.5 μW)in active mode and 5.4 μW in standby mode. Another solution is the Microchip’s XLP series MCUs, which can consume down to 54 μW in active mode and down to 16 nW in sleep mode.

The extracted energy from EM waves may not power a device constantly, but it can be collected and used in periods of time.

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