

RF Energy Harvesting Using Mobile Phone Base Station Signals

L. Scucchia, E. Limiti

Abstract – The fundamental goal of energy harvesting systems is to reduce the need for a wired power supply or battery replacements. Until a few years ago, in integrated electronic systems, detection and communication functions were remarkable challenges with regard to their power supply. There have been advances in the reduction of energy consumption and in battery technology; however, there was always the problem of a wired connection or some battery to replace. This work is aimed to acquire knowledge of RF-DC conversion systems working with mobile phone base station signals; in particular, frequency bands around 806 MHz are considered. The study is carried out, firstly designing and realizing an RF-DC conversion circuit and then measuring the voltage levels obtained from the implemented circuit, at the selected frequency. Ambient radio frequency sources are considered thus, for the circuit design, low power levels around -20 dBm are assumed.

Keywords – Base Station, LTE Signal, Matching Network, Mobile Phone, RF-DC Converter, RF Energy Harvesting, Voltage Multiplier.

I. INTRODUCTION

Energy harvesting methods allow gathering energy from the most different sources, such as sun, wind, geothermal energy, electromagnetic waves, etc. Among these scavenging techniques, recently, RF energy harvesting technology has grown enormously due to the huge increase of radio, cellular and Wi-Fi signal sources [1-13]. The electrical power levels, which can be generated using this technique, are very low, some milliwatts, but still enough to drive low power devices.

For the RF energy harvesting, known and unknown ambient sources can be employed, and this work examines the energy harvesting process considering known ambient RF sources, antennas which radiate mobile phone signals.

Specifically, Long Term Evolution (LTE) signals are considered; LTE is a wireless communication standard used for mobile phones and data terminals. This standard is based on the GSM (Global System for Mobile Communication) and UMTS (Universal Mobile Telecommunications System) network technologies. The LTE standard supports all frequency bands currently used by IMT (International Mobile Communications) system; however, in this context, only the LTE 800 MHz band has been considered. This band encompasses the frequencies from 791 MHz to 862 MHz, and Fig. 1 shows the related frequency plan.

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The components of a typical energy harvesting system are presented in Fig. 2; they are a matching network, a multiplier and an energy storage capacitor [1], [3] and [5].

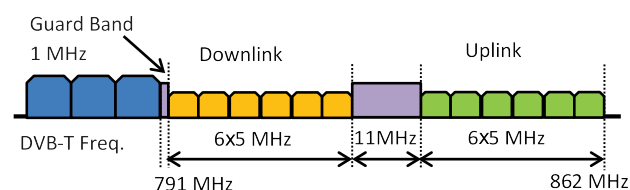


Fig. 1. LTE 800 MHz frequency plan

The matching network, formed by reactive elements, ensures the maximum power transfer from the antenna to the voltage multiplier, and the voltage multiplier performs the actual conversion from RF to DC [1], [3] and [5]. The energy storage capacitor guarantees power delivery to the load when external energy is not available.

An RF energy harvesting process, based on LTE signals, was briefly introduced in [14], where the investigation was accomplished designing and producing a test circuit. In particular, this circuit was fulfilled by means of hybrid technology and the voltage multiplier was implemented exploiting capacitors and Schottky diodes. The test circuit was designed through the following steps; firstly, a reference load and the energy storage capacitor were chosen.

Secondly, a particular Schottky diode was chosen and its model was implemented on the CAD software Advanced Design System (ADS), that is produced by Keysight Technologies. Successively, by ADS software, the voltage multiplier was designed; then, taking into account the multiplier input impedance, assessed by the CAD software, the matching network was designed. Finally, the obtained RF-DC conversion circuit was realized and measured by applying different loads and signal conditions.

In this paper, some fundamental points neglected in previous work are examined; in particular, considering the charge and discharge phases of a typical energy harvesting system, the selection of the storage capacitor and the reference load is discussed in detail.

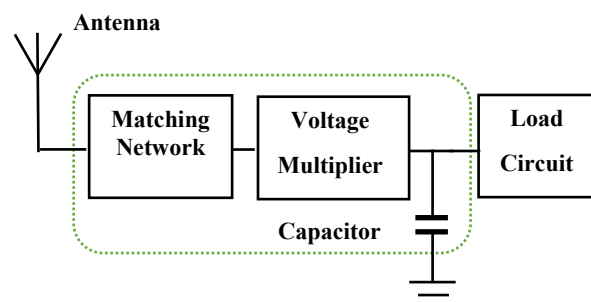


Fig. 2. Block diagram of an energy harvesting system

In addition, measurements of power transfer have been carried out and reported in section IV. This section also includes an estimation of the DC voltage levels versus distance; the values are obtained taking into account typical values for both the base station power levels and the antenna gains.

II. RF-DC CONVERTER DESIGN

In order to fix the required voltage and current levels at the output of the RF-DC converter, as load circuit was selected the microcontroller MSP430L092. This microcontroller works correctly with voltages from 0.9 V to 1.5 V at 1 MHz and can operate in one active mode and five different low-power modes. In the present context two working conditions were assumed, the active mode with supply current equal to 45 $\mu\text{A}/\text{MHz}$ at 1.3 V, and the standby mode with current equal to 6 μA at 1.3 V [15].

Generally, in energy harvesting systems, two phases of charging and discharging can be observed (Fig. 3). During the first phase, the load circuits are in standby or power saving mode, so that, low power is absorbed from the load circuits and energy is stored in the capacitor. In the discharging phase, the capacitor supplies electric energy to the load circuits. In order to represent the behavior of the MSP430L092 in standby mode, a resistor with a value of 100 K Ω was considered, obtaining so a supply current equal to 13 μA greater than the supply current value (6 μA) reported in the MSP430L092 datasheet.

The value of the energy storage capacitor fundamentally affects the velocity of the transient responses. The greater the capacitor value, the greater the voltage rise time, so the capacitor voltage could be not able to reach the available maximum voltage values. Consequently, the capacitor value was selected assuming a discharging time equal to 500 μs .

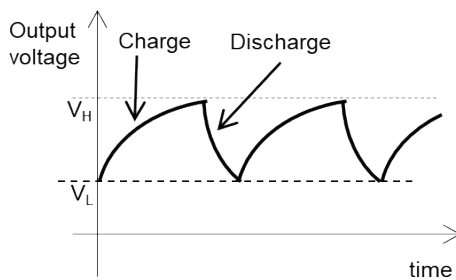


Fig. 3. Charge and discharge phases in energy harvesting systems

At clock frequency equal to 1 MHz, the time interval allows the microcontroller to perform a hundred machine instructions, with an average of five clock cycles per instruction. Consequently, the capacitor has to ensure a voltage that varies from 1.5 V to 0.9 V in an interval time equal to 500 μs .

Assuming, for simplicity, a discharging current constant and equal to 101 μA , the maximum supply current value reported in MSP430L092 datasheet, the charging capacitor value is about equal to 84 nF. Accordingly, a value of 100 nF was selected for the charging capacitor.

Various types of diodes are produced and commercialized; each one has fixed characteristics and is optimized for specific electronic applications. In particular, p-Si Schottky diodes, characterized by low barrier and high series resistance, are specific for applications where the DC bias is not applied.

As a result, considering the Agilent application notes [16] and [17], the Schottky diode HSMS-285C was selected.

The HSMS 285C component is characterized by a SPICE model, and its parameters are reported in datasheets [18]. Additionally, to accomplish a thorough analysis also the package equivalent circuit was utilized [19].

Voltage multipliers are composed by diodes and capacitors, thus, once the diode is selected; a specific capacitor value has to be chosen. For the capacitor, necessary condition is that their impedance has to be low compared to the diode impedance [20]. Therefore, capacitors with a value equal to 100 pF were used; this capacitance, at 800 MHz, produces a reactance about equal to 2 Ω , much less than the impedance of a diode operating at -20 dBm.

To maximize the power conversion efficiency of the RF-DC converter, different topologies were examined: the Greinacher (or Cockcroft-Walton) voltage multiplier, the modified Dickson voltage multiplier and the voltage doubler stack [1] and [21].

All schemes are based on the same base stage, described in Fig. 4a, and the different topologies are realized connecting the same stage in a different way.

Ideally, the output DC voltage (V_{out}) could be incremented increasing the number of stages, with:

$$V_{out} = n \cdot (V_m - V_T) \quad (1)$$

where: V_m is the amplitude of the input ac voltage, V_T represents the diode forward voltage and n is the number of diodes. In practice, however, the voltage regulation property and the conversion RF-DC efficiency decrease as the number of stages increases. Therefore, also, the optimum number of diodes was investigated; and the comparative study between configuration and diode number led to the choice of a Greinacher configuration with six diodes, Fig. 4b.

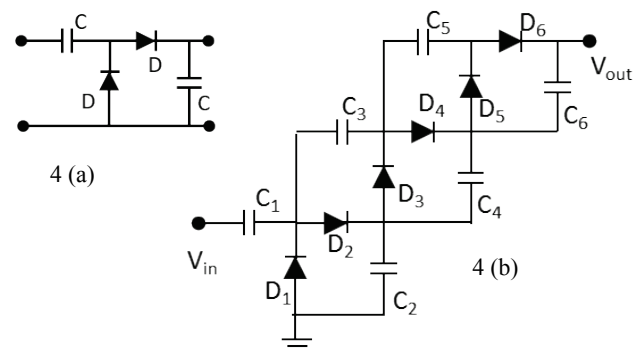


Fig. 4. (a) Base stage, (b) structure of the Greinacher voltage multiplier

The input impedance of voltage multipliers depends on the input power; thus, to synthesize the matching network a reference power level must be selected. Taking into account the real operative condition of the voltage multiplier, a low power level equal to -20 dBm was assumed and the matching network was designed for such level. Moreover, the circuit was implemented on the DiClad 527 laminate, with thickness = 0.76 mm, $\epsilon_r = 2.4 - 2.6$ and dissipation factor = 0.001 - 0.002.

Starting from the above-mentioned points, the matching network was designed and the result is a circuit formed by a short-circuited stub and a transmission line; the achieved RF-DC voltage converter is specified in Fig. 5.

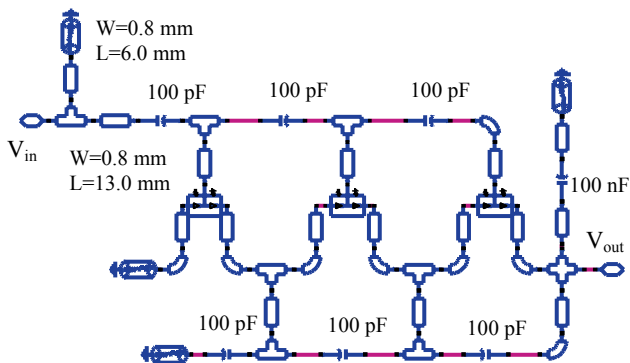


Fig. 5. Scheme of the designed RF-DC converter

III. ACCOMPLISHMENT AND TEST OF THE RF-DC CONVERTER

In the following, the designed matching network was combined with the voltage multiplier and the achieved RF-DC converter was fabricated (Fig. 6).

Successively, the real input matching of RF-DC converter was tested by using the Anritsu 37397D VNA, and Fig. 7 shows simulations and measurements obtained with three different input power levels.

Tested the matching properties of the implemented RF-DC converter, several measurements were accomplished using different loads and RF power levels; in this phase of measurements, the RF source was realized by means of the E4438C Vector Signal Generator.

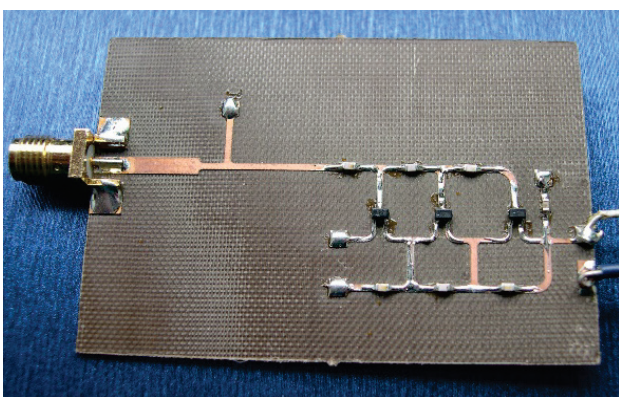


Fig. 6. RF-DC converter photo

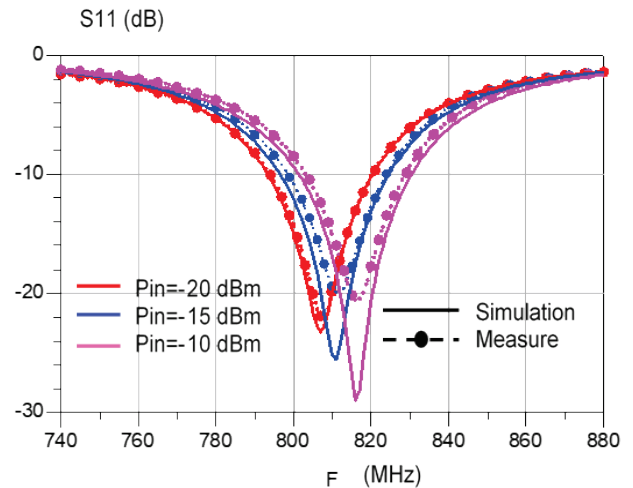


Fig. 7. S11 measurements for input power level equal to -20, -15 and -10 dBm

In Fig. 8, DC voltage values obtained by simulation and measurements are plotted; the graph shows that with a power level equal to -15 dBm and a load of 100 K Ω a DC voltage of 1.0 V can be achieved.

IV. POWER TRANSFER MEASUREMENTS

To investigate the real possibility of receiving energy from base stations, which work on 800 LTE system frequencies, power transmission measurements were carried out at 806 MHz.

The measurement setup is shown in Fig. 9; it consists of a transmission (TX) antenna, which is fed by an RF source (E4438C) and an RF power amplifier (RA25S1G4A); the RA25S1G4A permits to reach the required power levels. The receiving (RX) antenna is connected directly to the RF-DC converter, and for each measure, the output of the circuit is connected to the load selected for the test.

The measurements were performed in an indoor environment but such as to guarantee a distance of at least 1.5 m from floor and ceiling, and at least 2 m from the walls.

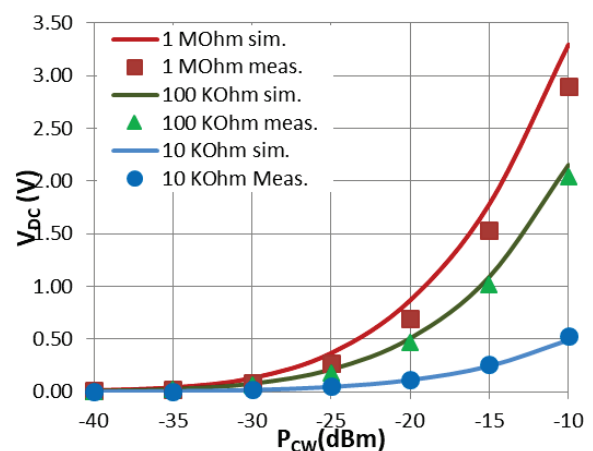


Fig. 8. DC voltage values as a function of loads and power levels

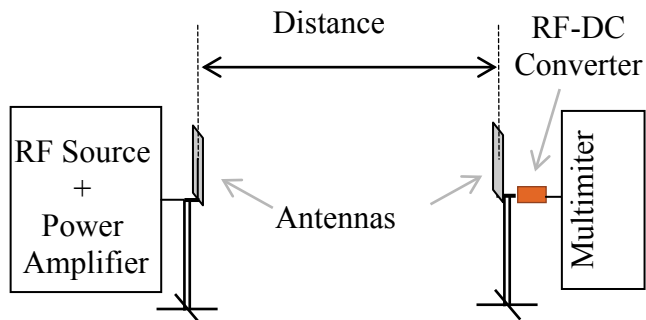


Fig. 9. Measurement setup

The employed antennas are dipoles, produced by Taoglas (TG.30), designed for use with 4G LTE modules (Fig. 10). They are ground plane independent; moreover, across the LTE 800 MHz bandwidth, in the ZX plane and free space, these antennas exhibit omnidirectional radiation pattern with a peak gain about equal to 2.5 dBi [22].

Fig. 11 displays the measured DC voltage values versus the antenna distance, for 100 KΩ. The results were obtained by 30, 33 and 36 dBm of power at the antenna connector, with a frequency equal to 806 MHz. In the graph, the measured DC voltage values are compared with the voltage level obtained by using simulation. In particular, measurements were carried out for distance values from one to ten meters.

Estimated results were achieved by using the Friis transmission formula and the ADS simulations of the designed RF-DC converter, Friis transmission formula can be used for a distance greater than 10 wavelengths, consequently, simulations were carried out and plotted for distance values more than four meters. To note that measurements were performed in an indoor environment so results are slightly better than expected.

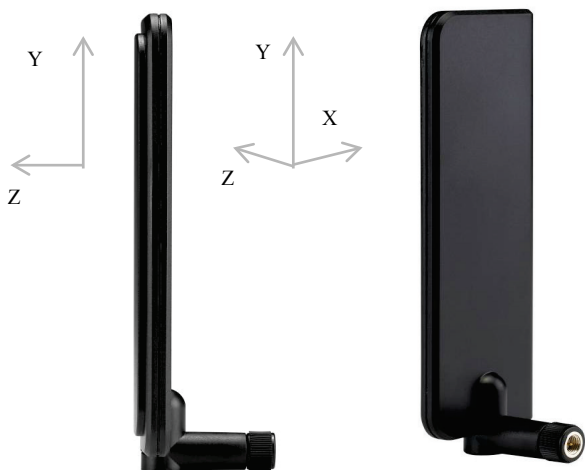


Fig. 10. Antenna TG.30 (by Taoglas)

The indoor power transfer measurements prove that at distances below 10 meters, the achieved voltage levels are greater than 1 V. These voltage levels are sufficient to feed low power MCUs as the MSP430L092, which works with 1.3 V in low power consumption mode [15]. On the other

hand, the purpose of such systems must be to exploit the power that is received from antennas of outdoor base stations. For macrocell base station, typical transmitted power values are 43-48 dBm at the TX antenna connector [23]. Moreover, in the experiment, dipole antennas, with a gain equal to around 2.5 dBi, were used, whereas, for base station TX antennas, typical main-beam gain values are around 17 dBi [23].

By using the Friis transmission formula, under idealized conditions and simulation of RF-DC voltage converter the DC voltage can be estimated as a function of the antenna distance.

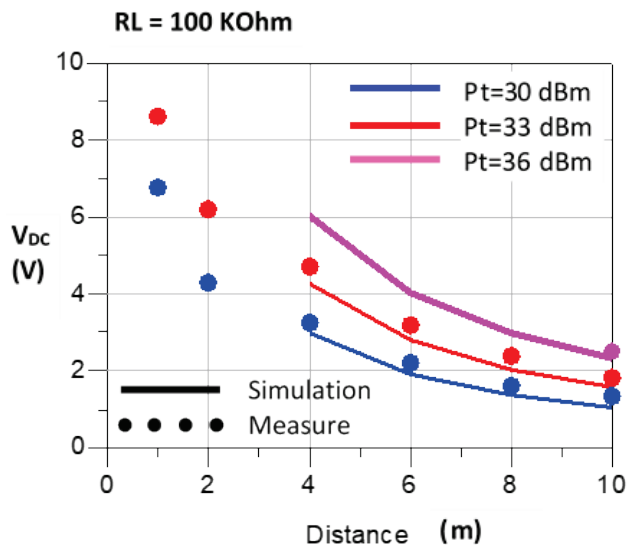


Fig. 11. DC voltage values vs antenna distance for a load equal to 100 KΩ at 806 MHz

Fig. 12 plots V_{DC} levels versus distance values from twenty to a hundred meters, assuming the transmitted RF power equal to 39 dBm and 42 dBm. TX and RX antenna gains are equal to 17 and 2.5 dBi, respectively. The plots show, for instance, that if the antennas are distant each other 100 meters and P_t is equal to 39 dBm; at the output of the RX antenna, a DC voltage greater than 1.6 V is present across a load of 100 KΩ.

V. CONCLUSION

This work points to gain an understanding of RF Energy Harvesting systems, tuned on the Long Term Evolution bands. To get this goal, an RF-DC conversion circuit was designed, realized, and measured. Measurements were carried out at different frequencies, loads, input power levels and compared to the corresponding simulations.

In the last section, indoor power transfer measurements are reported; these were carried out with 30, 33 and 36 dBm of RF power at the TX antenna connector, and they show that a DC voltage, greater than 1 V, can be obtained for distances up to 10 meters across a load equal to 100 KΩ.

These measurements were compared with simulation results, and verified the correspondence between measurements and simulations, the simulation setup was used to estimate DC voltage levels, which can be achieved by using antennas of outdoor base stations. The simulations show that

from an antenna distant 100 m and with a P_t equal to 39 dBm; at the RX antenna output is present across a 100 K Ω load a V_{DC} greater than 1.6 V.

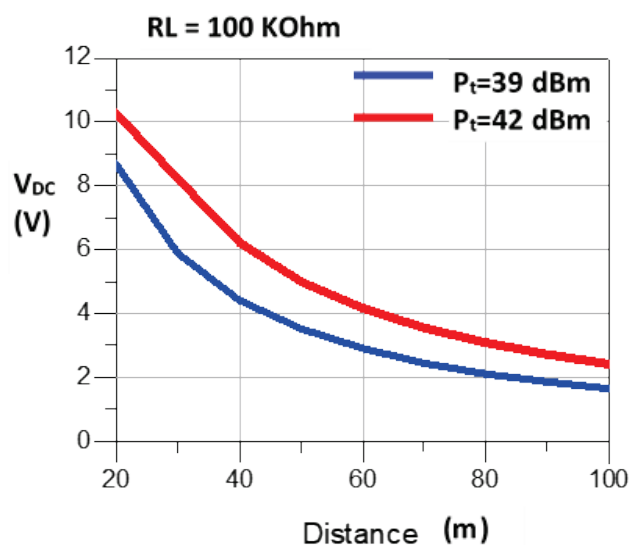


Fig. 12. Estimated DC voltage values vs antenna distance for a load equal to 100 K Ω at 806 MHz

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