RF HARVESTING USING ANTENNA STRUCTURES ON FOIL

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Abstract: In this paper we present a device for RF harvesting, i.e. harvesting the energy contained in electromagnetic waves. We have designed, modeled and fabricated an RF harvester using optimized antenna structures. Energy densities in e.g. GSM or WiFi frequency bands are very low (< 1 μW/cm^2), so the harvesting antennas need to have a considerable area. An alternative to ambient RF energy harvesting is to use a dedicated RF source, which enables smaller antenna surfaces.

Key words: RF harvesting, Rectennas, wireless, autonomous.

1. INTRODUCTION

The low power consumption of silicon-based electronics combined with the significant power densities of modern primary or rechargeable batteries has enabled a broad variety of battery-powered handheld, wearable and even implantable devices. All these devices need a compact, low-cost and lightweight energy source, which enables the desired portability and achieves a certain level of energy autonomy. In the 100μW range power consumption, wearable wireless sensor nodes are situated.

Emerging wireless sensors are finding growing application in body area networks and health monitoring of machine, industrial and civil structures. This paper focuses on emerging methods for power generation and power management of these wireless autonomous transducer systems that can enable energy autonomy over the entire lifetime of the device. Particularly for wireless applications, this is essential as battery replacement is unpractical or simply not feasible. Simply increasing the size of the battery to ensure energy autonomy during the lifetime of the system would increase system size and cost beyond what is tolerable. As a consequence, there is a clear need for alternative methods for powering or charging these sensor nodes, as a major increase in the energy density of batteries is not expected

2. AMBIENT RF POWER DENSITIES

With the ability to analyze and design rectennas (rectifying antennas), the question arises if it is possible to employ *ambient RF energy* for powering miniature, wireless applications. With *ambient* RF energy we mean RF energy not specifically introduced for wirelessly powering an application [1], [2], but RF energy available through pubic telecommunication services. Our main interest is in telecommunication services operating in the microwave region of the frequency spectrum, especially Global System for Mobile Communications (GSM) and Wireless Local Area Network (WLAN). For these services, printed antennas can be made with dimensions in the order of a few cm^2, satisfying our constraint for miniature sensors.

To assess the feasibility of employing the ambient RF energy supplied by the mentioned systems, we need to assess power density levels in different surroundings (e.g. inner city, outer city, industrial area, in house, outside, etc. for GSM) and settings (e.g. traffic: peak hours and off-peak hours for GSM and WLAN).

When harvesting energy in the GSM or WLAN band, one has to deal with very low power density levels. For distances ranging from 25m to 100m from a GSM base station, power density levels ranging from 0.1mW/m^2 to 1.0mW/m^2 may be expected for single frequencies [3] (see Figure 1a). For the total GSM downlink frequency bands these levels may be elevated by a factor between one and three, depending on the traffic density. First measurements in a WLAN environment indicate power density levels that are at least one order of magnitude lower (
Figure 1b, [4]). Therefore, GSM nor WLAN is likely to produce enough ambient RF energy for wirelessly powering miniature sensors, unless a large area is used for harvesting.
Alternatively, the total antenna surface can be minimized if one uses a dedicated RF source, which can be positioned close (a few meters) to the sensor node, thereby limiting the transmission power to levels accepted by international regulations.
In the following sections we discuss the design of the rectenna and charging circuit and show some experimental results.

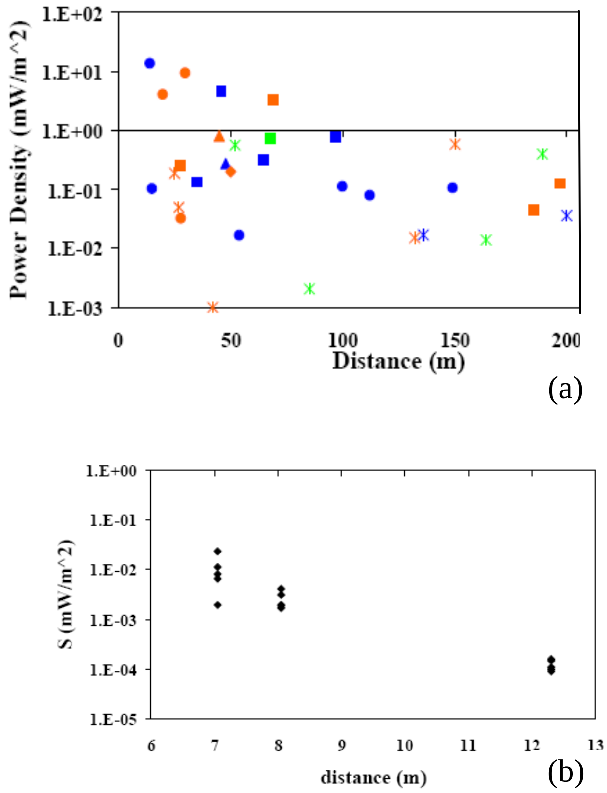

Figure 1: Measured GSM-900 peak power density levels as a function of distance to the nearest base station (derived from [3]) (a). For comparison, WLAN peak power density levels as a function of distance to the nearest WLAN router ([4]) (b).

3. RECTENNA DESIGN

For covering large areas with rectennas, we have chosen for manufacturing antennas on foil (see figure 2). Closed form equations have been derived for the analysis of the rectifying circuit and for the analysis of the antenna element to be used. The antenna element is a series array of re-entrant folded dipoles. Such an antenna may be tuned to create a complex input impedance that is the complex conjugate of the rectifying circuit's input impedance. Thus, antenna and rectifier may be connected directly, resulting in a compact, efficient RF-to-DC power converter. The closed form equations for rectifying circuit and antenna result in fast calculation times when implemented in software. The analysis may be employed in an optimization scheme for an automated rectenna design within one hour, employing standard office computing equipment.

In order to make a foil harvesting device, an array of re-entrant folded dipole array antenna elements and rectifiers (rectennas) are needed. Every element will provide around 0.6V.
For the final harvesting device we foresee a realization based on using optically transparent, electrical conducting material, like e.g., Indium Tin Oxide (ITO). Thus, large areas occupied by windows may be used to accomadate the harvesting device. Figure 3 shows an example of an optically transparent antenna.

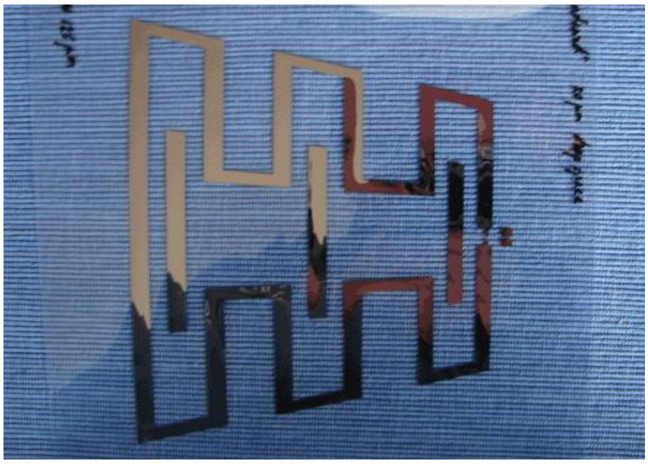

Figure 2: Three elements series array of re-entrant folded dipole antennas fabricated on PET foil.

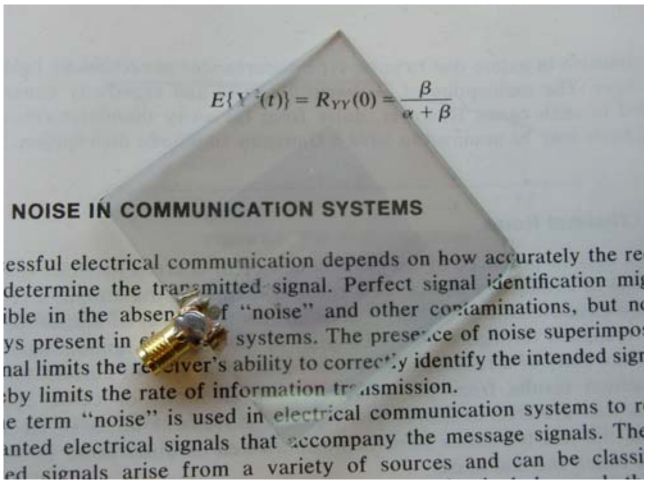

Figure 3: Example of an optically transparent (microstrip patch) antenna, realized by ITO on glass.

4. CHARGER CIRCUIT DESIGN

The AC equivalent electric scheme of the rectenna-charger is sketched in Figure 4.

Since a Li-ion battery has to be charged, a 3-4.2 V voltage range is needed [5]. This can be accomplished by connecting several rectenna-elements in series. The size of each element depends on the targeted frequency. At 2.45GHz, each element is expected to be

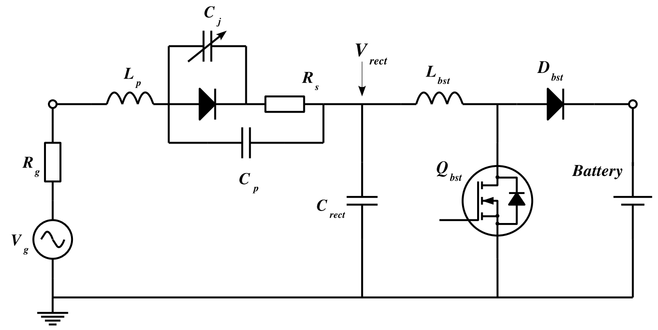

Figure 4: Equivalent-circuit diagram of an RF harvester with rectenna followed by a boost converter. The antenna is represented by voltage source V_g and impedance R_g. L_p and C_p are parasitic inductance and capacitance, respectively, due to the packaging of the diode. C_j is the diode's junction capacitance which depends on the voltage over the diode and R_s is the bulk resistance. The DC voltage V_{rect} across the smoothing capacitor C_{rect} is boosted up to the battery voltage by inductor L_{bst}, switching MOSFET Q_{bst} and diode D_{bst}.

around 6cm x 10cm, leading to approximately a size of $1m^2$ for the harvesting device. The circuit is dimensioned such that the Li-ion battery can be charged directly by the rectenna. However, in case of lower input power, the available voltage will drop and as a consequence the battery can not be charged anymore. Therefore, a boost converter between the smoothing capacitor C_{rect} and battery will take care for the voltage matching at lower input power. In order to obtain a matched load, the load should be linearly resistive and constant. Therefore the boost converter will operate in the critical conduction mode (CCM) with a fixed on-time t_{on} of the switching MOSFET Q_{bst}. The input resistance will be equal to $2L_{bst}/ t_{on}$.

5. EXPERIMENTS

A fresh Li-ion battery from a battery manufacturer has been used during the experiments. Since the employed commercial battery has a specified State-of-Charge [5] upon delivery, the battery has firstly been activated by using an automated battery-tester from Biologic [6]. The activation procedure performed at 25 C started with Constant-Current (CC) discharging at a 0.5C-rate followed by a two hours resting period.

Furthermore, three standard Constant-Current-Constant-Voltage (CCCV) and subsequent 0.5C-rate discharge cycles, after which constant (dis)charge behaviour was attained, have been applied. Standard charging was carried out with a constant maximum current at a 0.5 C-rate in the CC-mode until the maximum charge voltage of 4.2 V was attained in the subsequent CV-mode. Evidently, the charging currents dropped in the CV-mode and charging was terminated at a predefined minimum current of a 0.05 C-rate, after which the battery has been considered fully charged. Discharging was terminated in this case when the cut-off cell voltage of 3.0 V was reached.

A single activation cycle was always completed by a four hours resting period. The long rest step has been chosen in order to start a new cycle always from the equilibrium state [6]. The Li-ion battery voltage in Volts during the first activation cycle is illustrated in Figure 5 as a function of the experiment time in hours.

After the activation procedure has been completed the Li-ion battery has been connected to the RF harvesting circuit. In a first case, 8 PCB microstrip rectenna elements, see figure 6, have been connected in series. As a result, a voltage corresponding with the Li-ion battery voltage range, *i.e.* 3 - 4.2 V, has always been obtained at the output when a distance of maximum 20cm between the transmitter and the rectennas has been considered. So, in this case, a power management circuit is not needed for charging the battery from the rectenna. It should be noted that when the distance between the transmitter and rectenna increases the voltage at the output may be lower than the battery voltage range. In this case a boost DC-DC converter needs to be designed for converting the low RF harvester voltage to the battery voltage (see section 4).

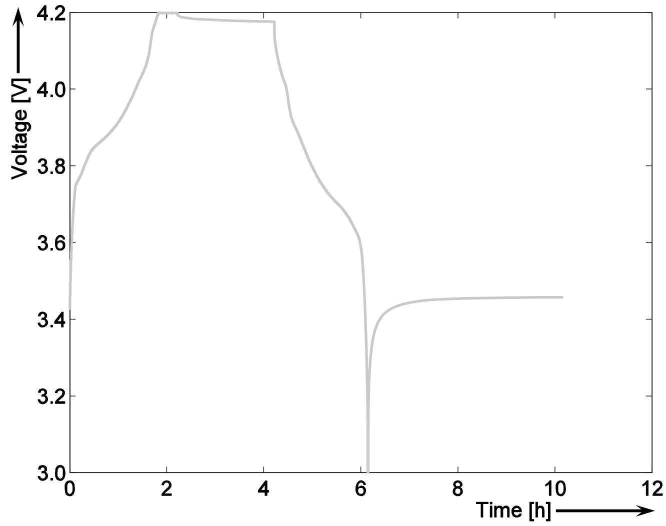

Figure 5: The voltage from the first activation cycle for the Li-ion battery as function of the experiment time in hours. The battery has been charged by means of the CCCV charging mode by limiting the (dis)charging voltage and current. In this case, voltage levels of 3.00 - 4.2 V, respectively, have been considered.

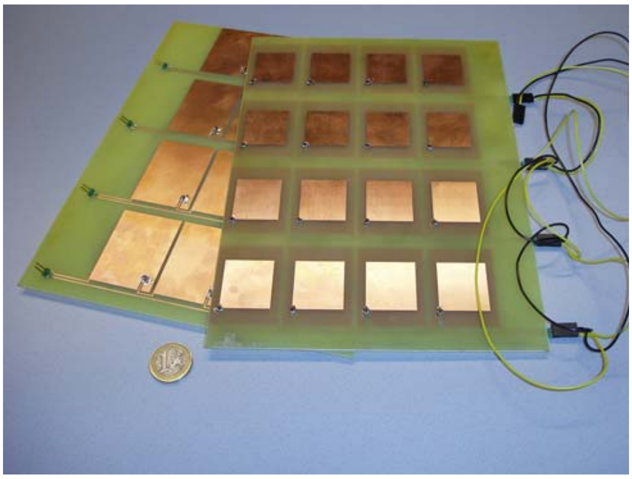

Figure 6: 2.45GHz microstrip rectenna boards, back and front views. Every row of four elements are connected in series. These four rows may be combined in parallel or series connection. For the experiment, we have used two rows only, connected in series

6. CONCLUSIONS

A device for RF energy harvesting is proposed. The device consists of an array of so-called rectennas, i.e., rectifying antennas, that is connected to a rectifying circuit for charging a battery. The RF-harvesting battery charger is foreseen to include an array of optically transparent folded-dipole array antenna elements realized on foil. This will enable to stick the large area RF collector to a window without compromising the window function. In this paper we have shown the feasibility of the components of the RF charger realized with an array of microstrip rectenna elements on 1.6mm thick FR4, operating at 2.45GHz.
energy harvesting device and we have shown first experimental results with an RF-harvesting battery

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