WIRELESSLY READ-OUT TEMPERATURE SENSOR REMOTELY POWERED BY A GSM PHONE

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Abstract: This paper reports a sensor, sensing temperature every seven seconds and wirelessly transmitting the data to a remote computer in the 2.4GHz license-free frequency band for Industry Science and Medicine (ISM). The temperature sensor and radio are wirelessly powered by a nearby GSM-900 cell phone, transmitting at 900MHz. For the power reception, an array consisting of four strip Yagi-Uda antennas on foil has been realized. Within this array, every element is impedance matched to a schottky diode voltage doubler and by connecting these rectifying antennas (rectennas) in series, the required power and voltage (>4V) are realized for powering the sensor and radio without needing a voltage boost circuit.

Keywords: wireless, low power, antenna, rectenna, battery-less

INTRODUCTION

Harvesting energy from ambient RF signals seems an attractive alternative to employing batteries. However, the low power densities of ambient RF signals would require large area receiving antennas and thus prevent the harvesting for small wireless sensors [1]. RF energy transport, i.e. using a dedicated RF source for powering wireless sensors is feasible, as has been demonstrated in [2].

An easily accessible RF source is a 'common' cell phone. A GSM-900 cell phone is transmitting at roughly 900MHz with a peak power of 2W and - due to a 1:8 duty-cycling [3] - with an average power of 250mW. Once a wireless connection has been established, the transmitting power will be reduced to a minimum required for a reliable communication link. With these power levels it is possible to power a low-power wireless sensor that is not too far removed from our 'RF source'.

To demonstrate the feasibility of this concept we have taken a low-power temperature sensor with a Nordic nRF2401 radio chip set [4]. The device has been set up for transmitting measured temperature data every seven seconds and we have powered this device with a rectenna sensitive for 900MHz RF signals. For this feasibility demonstration we have chosen to power the device directly from incoming RF signals, i.e. without a DC-to-DC boost converter and without a rechargeable battery for energy storage.

TEMPERATURE SENSOR AND RADIO

The sensor is based on the temperature sensing unit integrated in the Texas Instruments MSP430 microcontroller [5]. The choice for this device has been motivated by the low power consumption. As an example, the power consumption equals 3μW at 2V source voltage under the condition that the Digital Crystal Oscillator clock is still in active mode [3].

For the radio, use is made of the Nordic Semiconductor low-power nRF2401 chip-set, operating in the 2.4GHz license-free ISM frequency band. The chip-set may operate in four distinct modes: Reception, transmission, standby and power down. To give an indication, the power consumption in these four modes at a 2V source voltage is [3]

- Reception: 36mW;
- Transmission: 21mW;
- Standby: 24μW;
- Power down: 1.8μW.

The power consumption of the complete wireless temperature sensor has been optimized (minimized) by carefully switching the components on and off. In this switching scheme a trade-off has been made between the power consumption requested during the component wake-up and the mean power consumption of the component in the active state. A further means of optimizing the power consumption has been found by implementing one supply voltage for the complete application. Herein, a trade-off has been made between the quality of the data processing and the transmission range and the power consumption of the complete application [3].

As a final result, a temperature measurement is taken and transmitted every seven seconds, resulting in a mean power consumption of the whole system of 10μW at a source voltage of at minimum 4V. This value makes a harvesting of RF energy feasible.

RECTENNA: RECTIFYING ANTENNA

To collect and use RF energy, transmitted by a remote source, we need an antenna that is connected to a high-frequency rectifier. The way to design such a rectifying antenna or rectenna is to start with the analysis of a chosen rectifier. After determining the RF input impedance of this circuit, an antenna is designed for having an input impedance that is the complex conjugate of that of the rectifier [6]. Thus a direct impedance matching between antenna and rectifier is feasible, surpassing the need for an impedance matching network. Such a network could give rise to RF-to-DC conversion efficiency reduction. The rectenna should deliver sufficient power and a sufficient voltage to power the wireless temperature sensor.

The available power at the rectenna is dictated by the transmit power of the RF source, P_T, the gain of the transmit antenna, G_T, the gain of the antenna in the rectenna G_R, the used frequency, $f=c_0/\lambda$, c_0 being the velocity of light, and the distance, r, between source (GSM-900 cell phone) and receiver (rectenna). All these quantities are related to each other through the Friis transmission equation, a.k.a. the radio equation:

$$P_R = P_T G_T \frac{G_R \lambda^2}{(4\pi)^2 r^2}. \qquad (1)$$

The quantity $P_T G_T$ is known as the Effective Isotropic Radiated Power (EIRP).

The voltage at the output of the rectifier, V_0, is calculated by [2]

$$I_0\left(\frac{q}{nkT}\sqrt{8mR_g P_{inc}}\right) = \left(1+\frac{mV_0}{R_L I_s}\right) e^{\left(1+\frac{m(mR_g+R_s)}{R_L}\right)\frac{q}{nkT}V_0}, \qquad (2)$$

where I_0 is the zero-order modified Bessel function of the first kind, R_g, R_s and R_L are internal resistances of the rectenna, diode and load respectively, q is the electron charge, n is the diode's ideality factor, k is Boltzmann's constant, T is the temperature in Kelvin, I_s is the diode's saturation current and m is the number of diodes in a Cockroft-Walton voltage multiplier circuit, see Figure 1.

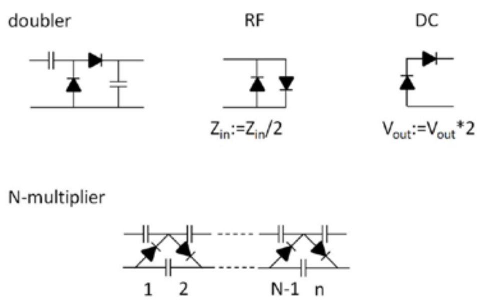

Fig. 1: Rectifier circuits. Top left: Voltage doubler. Top middle: RF equivalent of doubler. Top right: DC equivalent of doubler. Bottom: N-stage Cockroft-Walton voltage multiplier.

A realistic assessment for a mobile phone antenna gain will be G_T=1. For a receive antenna with G_R=10 (a rather large antenna in terms of wavelengths) and a voltage doubler (m=2) based on the AVAGO HSMS2850 Schottky diode, the received power, P_R, as a function of distance, r, has been calculated using equation (1). The results are shown in Figure 2. In the same Figure, the rectifier output voltage, V_0, as a function of incident power, P_{inc}, is shown for a 200Ω load resistance, R_L.

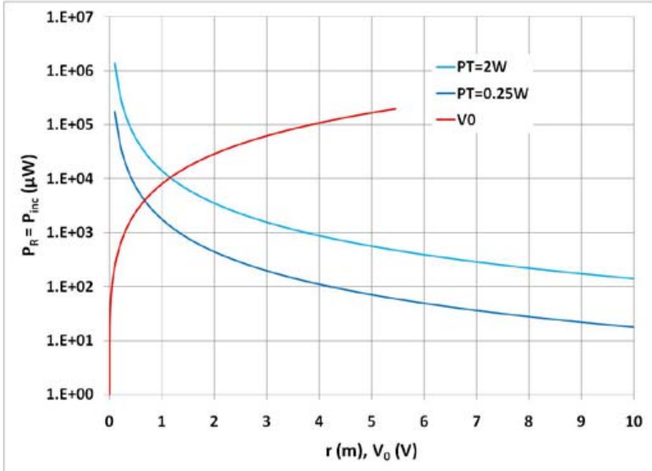

Fig. 2: Received power as a function of distance for two transmit power levels and rectifier output voltage as a function of incident power.

The graph should be read as follows: Suppose that the receive antenna is at a distance of 4m from the transmitter that is transmitting at 2W. Then from the light blue curve we see that we receive a power of approximately 1000µW. Now we move from this point on the blue curve, over the horizontal 1000µW line to the left until we reach the red curve. At the interception point with the red curve, we read from the horizontal axis a voltage of approximately 0.3V.

The Figure clearly shows that the 10µW constraint is not a problem at all; the 4V voltage is however. For realizing a compact system, a DC-to-DC boost converter is necessary. A DC-to-DC boost converter has been demonstrated in [2], where it was used in a RF battery charger. In that circuit the to-be charged battery was used to start up the converter. Eventually, this circuit will also be used in combination with GSM-900 cell phone powered sensors. For demonstrating the GSM-900 RF powering *concept* we have thought it wise to devise a completely battery-less system.

Therefore we will realize the necessary voltage by employing multiple 10dB gain rectennas, connected in series. From Figure 2 we see that with one 10dB gain antenna at a distance of about 0.3m from a 0.25W transmitting antenna, we may generate 1V of output voltage. We will thus connect four of these rectennas in series.

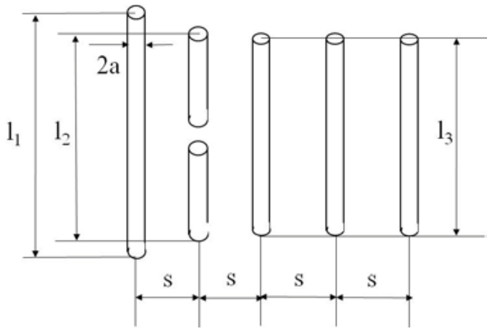

Fig. 3: Five elements, wire Yagi-Uda array antenna.

Table 1: Dimensions five elements, wire Yagi-Uda array antenna.

Dimension	**mm**
a	1.42
s	66.67
l_1	160.67
l_2	166.67
l_3	142.67

10DB GAIN ANTENNA DESIGN

To realize a low-profile antenna with sufficient gain, we will employ a Yagi-Uda linear array antenna with one driven element, one reflector and three directors [7]. The directivity is well over 10dB so that some losses can be allowed in the antenna structure. Starting from the tables of Viezbicke, we find for the antenna shown in Figure 3 the dimensions as stated in Table 1 for an antenna resonant at 900MHz.

Next, we transfer the wire antenna into a strip antenna, taking for the strip width, W, the quasi-static approach [8]

$$W = 4a, \qquad (3)$$

and, finally, we tune the antenna dimensions to obtain an input impedance that is the complex conjugate of the input impedance of a HSMS2850 based voltage doubler circuit at 900MHz. The impedance of a single Schottky diode is calculated with a RK4 time-marching algorithm [6], the results of which are stated in Table 2.

Table 2: HSMS2850 Schottky diode input impedance.

P_{inc} (dBm)	**f=875MHz**	**f=900MHz**	**f=925MHz**
-40	14.7-j322.7	14.1-j313.4	13.4-j304.5
-37.5	14.8-j322.1	14.1-j313.4	13.5-j304.4
-35	14.9-j322.0	14.2-j313.4	13.6-j304.4
-32.5	15.1-j322.0	14.4-j313.3	13.8-j304.4
-30	15.4-j322.0	14.8-j313.3	14.1-j304.4
-27.5	16.1-j322.0	15.4-j313.3	14.7-j304.4
-25	17.4-j321.9	16.6-j313.2	15.9-j304.3
-22.5	19.7-j321.7	18.8-j313.0	17.9-j304.2
-20	24.4-j321.3	23.3-j312.7	22.1-j303.8
-17.5	34.3-j320.0	32.7-j311.5	31.1-j302.8
-15	54.7-j315.8	52.1-j307.6	49.5-j299.3
-12.5	90.8-j301.8	86.6-j294.7	82.4-j287.4
-10	139.1-j264.2	133.5-j259.8	127.7-j255.1
-7.5	174.1-j203.3	168.7-j202.1	163.0-j200.7
-5	182.0-j143.5	178.0-j144.1	173.8-j144.7
-2.5	173.8-j99.6	171.3-j100.8	168.6-j102.1
0	160.4-j69.3	158.9-j70.5	157.3-j71.9

The input impedance of a voltage doubler is half that of a single diode, see also Figure 1.

For a low to medium input power (-25dBm<P_{inc}<-10dBm), a good average input impedance for the antenna will be Z_{ANT}=(35+j150)Ω.

The antenna, made out of 70µm thick copper strips, on a 125µm thick polyethylene foil has been analyzed using CST Microwave Studio®. The driven element has been lengthened with a factor 1.04 with respect to the value given in Table 1. The antenna is shown in Figure 4.

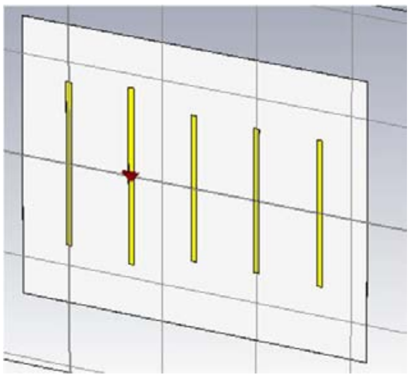

Fig. 4: Copper strip Yagi-Uda array antenna.

The input impedance at 900MHz is found to be Z_{ANT} =(32+j150)Ω, which is nearly identical to the desired value. The radiation pattern is shown in Figure 5.

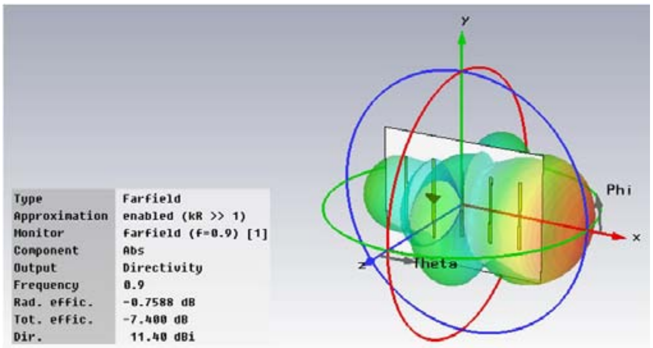

Fig. 5: Radiation pattern of copper strip Yagi-Uda array antenna.

The directivity of the antenna is 11.4dBi, the radiation loss is -0.76dB, meaning that the gain is according to specifications. Note that the direction of maximum sensitivity is in the plane of the Yagi-Uda array antenna. With all the elements of the GSM-900 cell phone powered wireless temperature sensor now being determined, we can test the system.

SYSTEM TEST

An array consisting of four Yagi-Uda array antennas on foil has been created by using adhesive copper tape. Every Yagi-Uda array antenna is directly connected to a voltage doubler rectifying circuits. The outputs of these circuits are connected in series, see Figure 6.

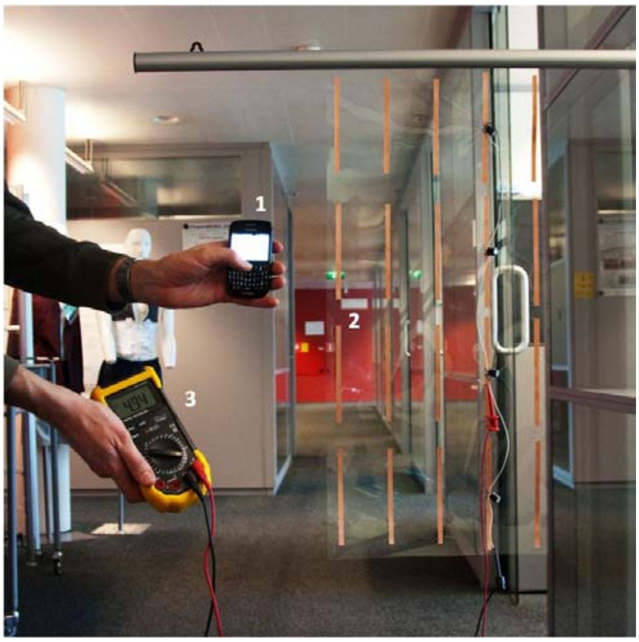

Fig. 6: Array consisting of four Yagi-Uda rectennas, connected in series.

The Figure shows a nearby transmitting GSM-900 cell phone (1), the array of four Yagi-Uda antenna based rectennas (2), and the measured 4.94V open-circuit voltage (3), measured from the four rectennas connected in series. The array is next connected to the wireless temperature sensor, see Figure 7.

Fig. 7: Array consisting of four Yagi-Uda rectennas, connected in series, powering a wireless temperature sensor.

The Figure shows a transmitting GSM-900 cell phone (1). A part of the transmitted power is intercepted by the rectenna array (2) and is powering the wireless temperature sensor (3). The DC voltage delivered to the sensor is displayed on a volt meter (3a). The 2.4GHz radio of the wireless temperature sensor (3) transmits the measured temperature every seven seconds to a remote wireless base station (4). This base station relays the received data to a computer (5) for storage and a convenient display.

Although the wireless temperature sensor and the base station are put close together in Figure 7 for presentation purposes, they may be separated up to a distance of 15m.

CONCLUSION

The feasibility of using a GSM-900 cell phone for RF-powering a low-power wireless sensor has been demonstrated. In a practical application a rechargeable energy storage system will be included, which will also allow the use of a DC-to-DC boost converter. This will lead to a more compact design and will allow a larger distance between cell phone and sensor. This is shown in Figure 8 that shows V_0 as a function of distance, where a minimum value of 0.2V is needed for operating the boost converter.

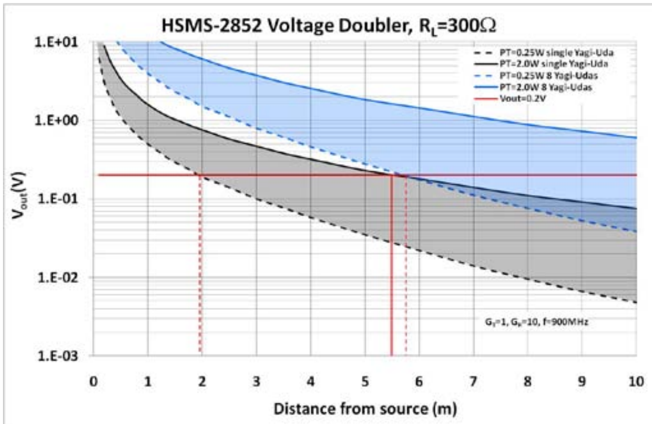

Fig. 8: Voltage doubler output voltage as a function of distance from a GSM-900 cell phone.

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