Inkjet-Printed GSM900 Band RF Power Harvester on Paper-Based Substrates

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***Abstract*—In this article the outcomes of an experimental investigation on the inkjet-printed power harvester for GSM900 band are presented. In this survey, a passive one-stage discrete rectifier and a planar antenna are fabricated on cardboard using inkjet-printing technology. For the rectifier a voltage doubler structure and for the antenna a broadband planar monopole antenna are utilized. Then, the functionality of the whole module is proven by measuring the output voltage in the real environment. The measurement results demonstrate appropriate absorbed voltage level for feeding a low power circuit by the presented power harvester. By the exploitation of the proposed idea, the fabrication of low-cost environmentally-friendly battery-less wireless modules is feasible.**

Keywords— battery less circuit; broadband planar monopole antenna; GSM900 band; inkjet printing technology; low cost fabrication method; paper based substrates; power harvester; voltage doubler;

I. INTRODUCTION

The lifetime of wireless portable devices are limited by the lifetime of the batteries [1]-[3]. Different investigations have been taken place in order to increase the lifetime of a battery and reduce the power consumption by the wireless equipment [4]-[6]. Alongside all these proposed ideas for increasing the lifetime of a battery, it is still finite. Therefore, it is tempting to utilize an alternative method to replace the finite time energy source like battery. Power harvesting is one of the appropriate solutions which is a set of techniques for obtaining electrical energy from the environment [7]-[8]. In power harvesting the required electrical energy for driving the low-power electronic circuits is collected from the ambient sources around us. The scavenged energy can be in the form of light, temperature, motion and electromagnetic [3]][8]-[9]. If the harvested power is from electromagnetic sources in the radio frequency (RF) range the method is so called RF power-harvesting [8]. The environment in which we live, is occupied by the RF signals from radio and television broadcasting, wireless LAN, mobile phone networks and communication devices [1][8]. The RF power is available at different frequency bands, radiation polarizations and levels in both indoor and outdoor environments.

The inkjet printing techniques provide the possibility to fabricate electronic circuits on unconventional substrates like paper [10]. The exploitation of paper based substrates not only decreases the production cost since paper is an ultra-low-cost substrate compared to the conventional laminate ones, but also ease the fabrication of environmentally-friendly circuits due to being compatible with recycling procedures [10]-[12].

In this project, Stora Enso packaging thin cardboard is utilized as the substrate and NPS-JL silver nanoparticle ink is used as the conductor for the fabrication of the RF electronic circuits. A Fujifilm Dimatix DMP-2831 material inkjet printer and 10 pL cartridges with 16 nuzzles in a single-row arrangement are utilized to print the circuit. The power harvester is designed in order to operate properly at GSM900 band due to the available power level in both indoor and outdoor environments. In the Section II and Section III the design, fabrication procedure and discussion on the measurement results of a one-stage rectifier and planar monopole antenna are investigated, respectively. Finally, the whole work is concluded in the Section IV.

II. DESIGN PROCEDURE OF POWER HARVESTER

Figure.1 illustrates the general block diagram of a RF power harvester consists of an antenna, matching circuit, a voltage multiplier and a charging control unit [8]. In this article the main focus is on the fabrication of the rectifier and antenna

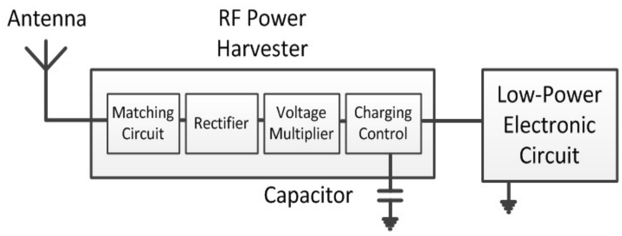
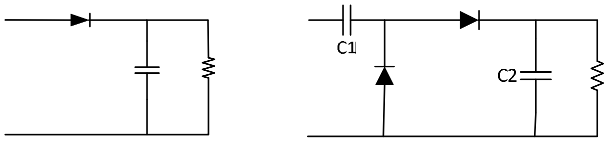


Fig. 1. The block diagram of a general power harvester.



(a) (b)

Fig. 2. (a) The schematic of the basic rectifier. (b) Voltage doubler.

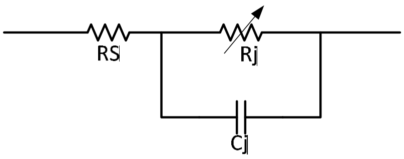


Fig. 3. The equivalent circuit of the schottky diode used in ADS.

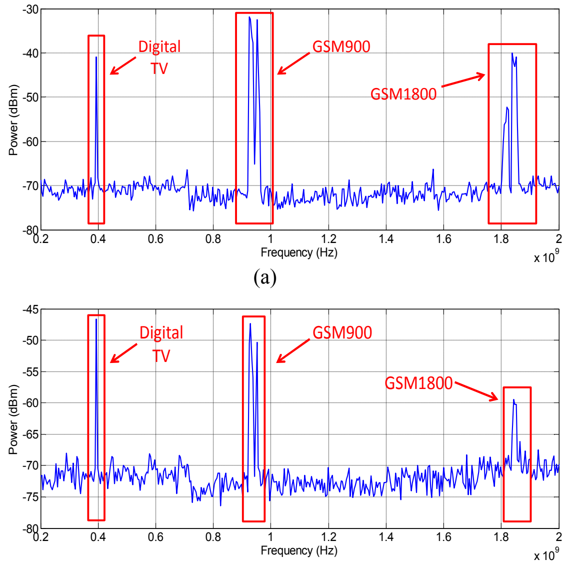
on paper-based substrate using inkjet-printing techniques. A rectifier is an electronic circuit which converts an input RF signal into a considerable DC voltage. The input RF signal can be converted to the DC signal based on the input-output characteristic of diode in the diode-based rectifiers. Fig.2 (a) and (b) illustrate the schematic of a basic rectifier and a voltage doubler, respectively. Based on basic rectifier structure, the voltage doubler is designed in two parts in each a schottky diode and a capacitor for performing rectification are utilized. The voltage stored in C_1 during negative half of the input cycle is transferred to C_2 during positive half. Hence, the output DC voltage is almost two times of the input rms voltage.

The exploited diodes are zero-bias schottky surface mount HSMS-2850 which are appropriate for low input power level up to 1.5 GHz. In addition, it provides a low forward voltage, low substrate leakage and high switching speed [13]. The circuit can perform properly, if the input voltage is higher than the diode forward voltage. The specific parameters of diode given by Agilent in datasheet are listed in Tab. I and used in Advance Design System (ADS) software to model the diode by its equivalent circuit shown in Fig. 3, where R_s is the series resistance, R_j is the junction resistance, and C_j is the junction capacitance.

The power harvester is designed in order to capture the ambient energy of GSM900 band since it has the highest

TABLE I. THE ELECTRICAL PARAMETERS OF THE SCHOTTKY DIODE [13].

Parameter	Value	Unit
B_v	3.8	V
C_{j0}	0.18	pF
E_G	0.69	eV
I_{BV}	3×10^{-4}	A
I_S	3×10^{-6}	A
N	1.06	
R_S	25	Ω
$P_B(V_J)$	0.35	V
$P_T(X_{TI})$	2	
M	0.5	



(a)

(b)

Fig. 4. The received power spectrum in (a) outdoor and (b) indoor environment.

available power level in both indoor and outdoor environment. The available power levels at different frequencies in indoor and outdoor environments at Tampere University of Technology are measured using a FieldFox N9912A RF Analyzer from 200 MHz to 2 GHz. Comparing the results shown in Fig. 4 it can be deduced that the maximum available power is in the GSM900 band. Thus, the frequency bandwidth is chosen to be between 930 MHz and 960 MHz. The circuit geometry depicted in Fig. 2 (b) is utilized for the rectifier while C_1 and C_2 are equal to 1nF and 1 μF, respectively.

Aforementioned, in this study the inkjet-printing technology is utilized for the implementation of the circuits. For this purpose a Fujifilm Dimatix DMP-2831 material printer, Stora Enso packaging thin cardboard, and NPS-JL silver nanoparticle ink with 55.5wt% metal content are used as the printer, substrate and conductor, respectively. In order to design a RF/Microwave circuit, the electrical properties of the substrate and conductor should be known. These parameters are characterized in the previous study [14] and summarized in Tab. II. 8 layers of silver ink are printed on cardboard in 4 cycles after surface treatment. In each cycle 2 layers are printed with 635 dpi resolution and sintered at 150 °C for one hour in a conventional oven. The surface treatment is done by printing 5 layers of primer (composed of tetrahydrofurfuryl acrylate, ethoxylated trimethylolpropane triacrylate, 2-hydroxy-2-methyl-1-phenyl-propan-1-one, and bisphenylphosphineox-

TABLE II. THE ELECTRICAL PROPERTIES OF THE SUBSTRATE AND CONDUCTOR TRACE [14].

Electrical properties	Values
Relative Permittivity of cardboard	1.78
Loss tangent of cardboard	0.025
Thickness of cardboard	560 μm
Conductivity of silver ink	2×10^7 S/m
Thickness of silver ink	3 μm

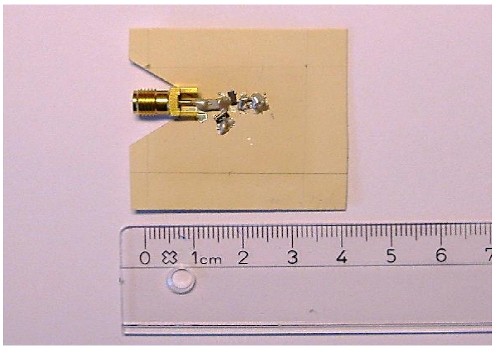


Fig. 5. The fabricated rectifier using inkjet printing technology on cardboard.

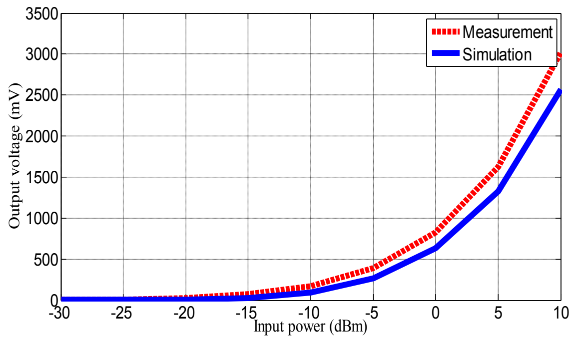


Fig. 6. The simulation and measurement results for the output voltage of the rectifier versus the input power.

ide [15]) with 1061 dpi resolution separately and cured with ultra-violet (UV) light for 15 minutes and then one hour at 150 °C [14]. The surface treatment is essential in order to make the fibrous substrate ink-proof and its surface smooth [14], hence increases the conductivity of the printed silver traces.

The fabricated rectifier on cardboard using inkjet-printing technology is shown in Fig. 5. As can be seen in Fig. 6, the simulation and experimental results of the output voltage versus input power level are in an appropriate agreement with each other. The main reason of the discrepancies can be related to the different practical values of the diode resistance compared to the simulation model [16]. The measurements are performed using a HP ESG-D3000A Digital signal generator at 950 MHz.

III. The Broadband Inkjet-Printed Planar Monopole Antenna

Alongside the studies has been done regarding the power

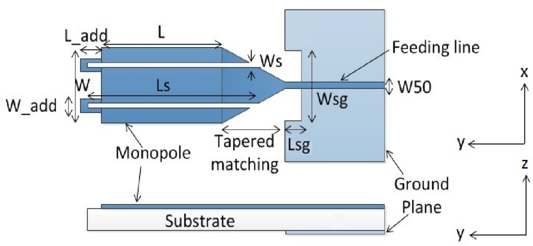


Fig. 7. The geometry of the proposed broadband planar monopole antenna.

TABLE III. The Length of Physical Dimensions

Physical parameter	Length (mm)
L	70
W	70
Tapered matching	60
W_{50}	1
L_S	66
W_S	1
L_{sg}	2
W_{sg}	10
L_{add}	30
W_{add}	9

harvester in this article, a broadband planar monopole antenna is also designed and implemented on cardboard by inkjet-printing technique. The proposed antenna is appropriate for power harvesting applications since its radiation pattern is omnidirectional in the H-plane, its bandwidth is broadband and the radiation pattern does not change with frequency.

The design is initiates from a rectangular planar monopole antenna and the appropriate performance is achieved by adding tapered matching and slits in the geometry of the antenna and the in the ground plane. The tapered matching decreases the reflection between the feeding line and the radiator. The slits in

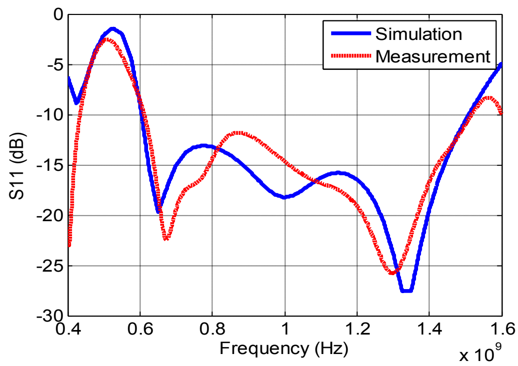


Fig. 8. The simulation and measurement results of S_{11} for the proposed antenna.

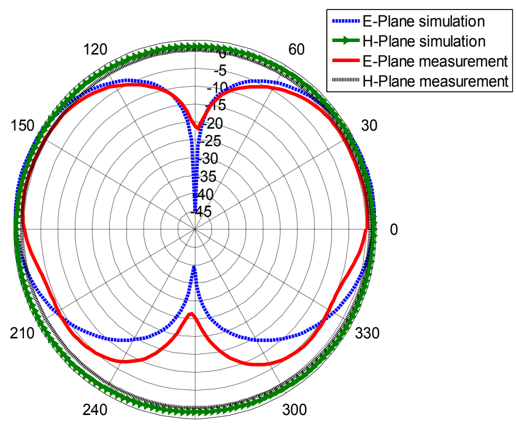


Fig. 9. The simulation and measurement results of the radiation patterns of the proposed antenna at 950 MHz.

the radiator and the ground plane improve the broadband performance of the antenna by disturbing the current distribution [17]. The final pattern and the physical dimensions of the proposed antenna are illustrated in Fig. 7 and Tab. III, respectively. The antenna is fabricated with the same procedure discussed in the Section II.

The simulation and measurement results of the input matching, and radiation patterns of the antenna are represented in Fig. 8 and Fig. 9, respectively. The gain and radiation patterns of the antenna stay constant in the whole frequency range of GSM900 band. In this range the maximum realized gain of the antenna varies between 1.9 dBi to 2.1 dBi. The antenna is simulated using the 3-D full wave electromagnetics simulator Ansys HFSS based on finite element method, the input matching is measured by an Agilent PNA E8358A two port vector network analyzer (VNA) between 400 MHz and 1.7 GHz, and the antenna parameters are acquired by the near-field measurement equipment Satimo Starlab. By comparing the simulation and experimental results, it can be deduced that the antenna performance is appropriate for the power harvesting application in the GSM900 band.

IV. CONCLUSION

In this study an inkjet-printed power harvester and antenna are proposed in order to power up low-power wireless circuits. Since the maximum available power in both indoor and outdoor environments is in GSM900 band the circuit is designed to cover this frequency range. The simulation and measurements for both the power harvester and for the antenna shows appropriate agreement and suitable output voltage particularly for high input power levels.

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