2.4GHz WLAN RF Energy Harvester for Passive Indoor Sensor Nodes

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***Abstract*—this paper presents the design and measurement results of an RF Energy Harvester aimed to power sensor nodes like temperature, humidity, chemical, or radiation in an indoor industrial or residential environment. The harvester operates at 2.42 GHz WiFi-WLAN frequency band. It consists of multiple microstrip patch antennas, power combiner, voltage quadruple Greinacher rectifier circuit, and a super capacitor to store the harvested energy. All elements are designed using low-loss Rogers RO3206 substrate. The impedance matching of the power combiner with a rectifier is a non - trivial issue due to change in diode impedance with the input power. The peak efficiency is measured to be 57.8% at 6 to 8dBm input power. In the presence of realistic −10dBm continuous signal, the system can charge a 33mF super capacitor to 1.6V in 20 minutes. This collected energy is enough to power 10mW sensor node for a period of more than 4 seconds to perform wake up, sense and transmit functions, and put a sensor back to sleep mode.**

Keywords — Energy harvesting, WLAN energy harvester, self powered sensors, wireless power, indoor energy harvesting, multiple patch antennas, greinacher rectifier, greinacher quadrupler

I. INTRODUCTION

Modern industrial and residential buildings are installed with many different types of sensors for human safety and comfort. These sensors include temperature, humidity, light, smoke, chemical and radiation sensors. These sensors need two separate types of wiring, one for power delivery and another for signal transmission. Some of these sensors also use the batteries for uninterruptable power supply. These batteries are not being replaced with super capacitors. Super capacitors are similar storage capacity and more environmentally friendly compared to the batteries.

Electromagnetic (EM) power is omnipresent source of energy around us; countless communication devices transmit RF energy from a few MHz to several tens of GHz frequency range. The researchers have extensively measured the available power in the RF spectrum. It is concluded that the ambient RF energy density is so small that it is not possible to power a sensor which continuously dissipates power more than a quarter microwatt [1]. Most of these sensors mentioned above do not work in continuous mode. They read the desired variable after some predetermined interval or work on sense-on-demand principle.

Therefore, energy harvesters which can scavenge and store the energy and then provide this stored energy to power up the sensor node for a fixed duration, are suitable for above mentioned applications.

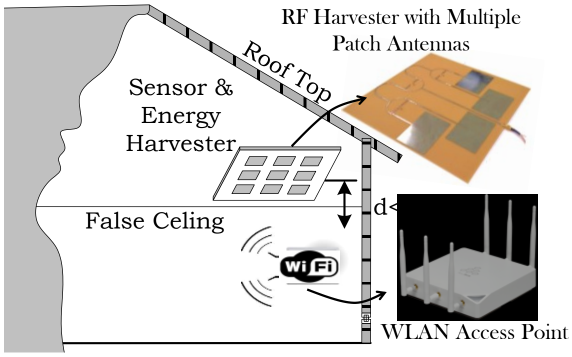


Fig. 1. Concept diagram of RF Energy Harvester

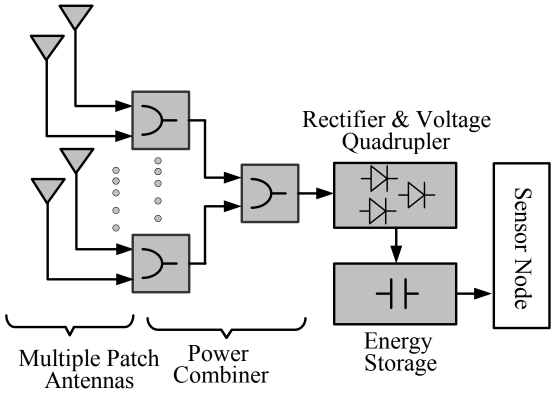


Fig.2 Block diagram of the implemented (gray blocks) energy harvester

Our lab measurements show that for indoor environment the most powerful signal available in close physical proximity of the sensor location is 2.42GHz WiFi signal compared to 100-108MHz FM and 900MHz GSM signal.

The modern MIMO type WiFi transceiver transmits the power of the 18-23dBm range from a single antenna [2], if the energy harvester is placed close to a transmitter at the distance less than 50cm as shown in Fig.1, we can receive the signal as powerful as 0dBm. The MIMO system transmits the different phase at different antennas in order to form a beam in a particular direction. The power added without compensating this phase delay using multiple input antennas is not always a linear sum. But for a harvest and store energy system, like ours, the instantiation received power is not as important as the long term average power. This average power over a time is proportional to received energy [3].

In recent literature, a large number of RF energy harvesting schemes are reported. In [4] two different strategies are discusses. In the first case, RF power is added and then rectified, while in the second case first the RF signals are rectified and then added to get the higher DC power. The reported rectifier has a peak efficiency of 68% for the input signal of -5dBm. In [5], an RF harvester design is presented which achieves an efficiency of 68% at 20dBm. Similar designs are also presented in reference [6] and [7]. None of these designs are suitable for indoor RF energy harvesting; the RF signal strength requirements are too high to be met by weak WLAN signals.

In this paper, we present an RF energy harvester to power up a passive sensor node as shown in Fig.1 and Fig.2. The energy harvester is placed close to the WiFi access point in order to receive the large amount of transmitted power. The energy harvester consists of multiple 2.42GHz microstrip patch antennas. The power from each antenna is added using a power combiner and then rectified using Greinacher voltage quadrupler rectifier to a useable DC signal as shown in Fig.2. This DC energy is stored in a super capacitor in order to energize the on-demand self-powered sensor nodes.

The paper is arranged as follows. In Section II, the design and measurement results of microstrip path antenna, power combiner and Greinacher rectifier circuit are discussed. An important issue is the change in input impedance of rectifier with input power. In Section III, the measurements results of a complete RF harvester are presented and last section concludes the paper.

II. Antenna, Power Combiner and Rectifier

The RF Energy Harvesting Device design consists of three sections; antenna for RF energy collection, power combiner for addition of energy, and rectifier circuit to convert the alternating RF signal to DC power. For a final circuit these elements have to be designed on a single PCB. For ease of testing and debugging we have designed them separately and combined them using the RF cables. The substrate used for all the PCBs is Rogers's low loss material RO3206 with dielectric constant (ε_r) of 6.5 and thickness of 1.6mm.

A. Microstrip Patch Antenna

Among several choices, the rectangular patch antennas are most suitable for a compact, space-saving design and can be easily manufactured on standard PCB. In order to match the impedance of the rectangular patch antenna with a 50-Ω port, an inset line feed was designed based on standard text book design procedure [8][9]. Fig.3 (a) shows the manufactured 48.8×45.1 mm^2 microstrip patch antenna on a standard 1.6mm thick PCB substrate. The measured and simulated S11 plots are shown in Fig.4. The slight shifts in frequency can be

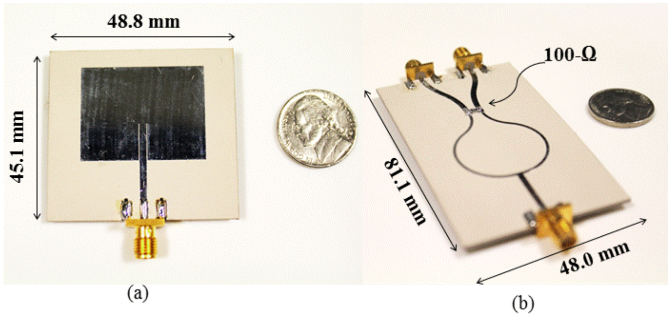


Fig. 3. (a) The photographs of manufactured microstrip antenna and (b) Wilkinson's power combiner on Rogers RO3206 substrate.

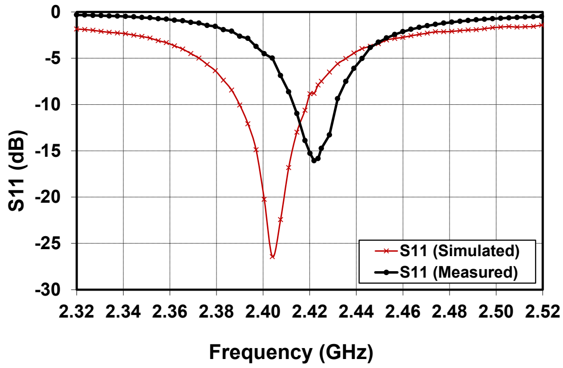


Fig.4. Microstrip patch antenna input reflection coefficient (S11)

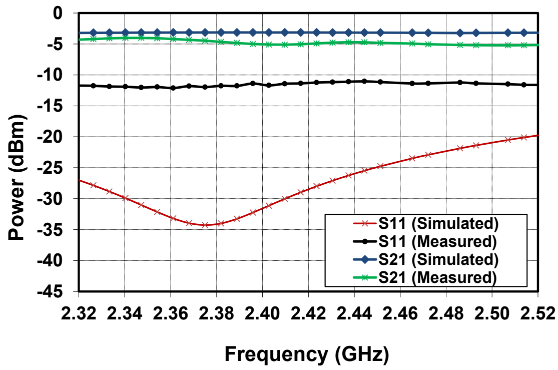


Fig.5. Wilkinson's Power Combiner input reflection coefficient (S11) an coupling coefficient (S21)

attributed to the PCB manufacturing tolerances and slightly misaligned manually soldered connector. Measurement results show the S11 of -16dB at 2.4GHz with 3dB bandwidth of more than 20MHz. These are acceptable values for a WLAN energy harvester front-end working at 2.4GHz.

B. Wilkinson Power Combiner

If a power harvested by a single patch antenna is -10dBm for example, then combing two of them, theoretically, will provide a power of -7dBm and four would provide -4dBm. Out of the many power combiners' types, Wilkinson power combiner was chosen due to its good port isolation, design flexibility, wide-bandwidth, and easy PCB based implementation.

Fig.3 (b) shows the manufactured standard Wilkinson's power combiner with 100Ω resistor which absorbs reflected power which in turn improves the port isolation [10]. The summary of measurement results is plotted in Fig.5. The measured value of S11 is better than -11dB in the 300MHz band from 2.32GHz to 2.52GHz. The coupling coefficient values of S21 (S12) are also plotted. After microstrip width and length optimization, ideal value of -3dB is obtained in simulations as shown in Fig.5. However the measured values deviate by −1.5 to 2dB from the simulated values. It is important to note that S21 value changes with the deviation in the physical soldering location of the 100Ω resistor on the PCB. Since we hand soldered the SMT components, the desired precision is not achieved, which is partially responsible for the discrepancy between the simulation and measurement results. Manufacturing tolerances are yet another factor contributing to this discrepancy. The S31 (& S13) curves are almost same as the S21 (& S12) curves; therefore, only S12 values are plotted.

C. Modified Greinacher Rectifier

A rectifier circuit is a core component which converts the RF signals to a useable DC voltage. Out of many options reported in literature, the Modified Greinacher Rectifier as shown in Fig. 6 was selected for this harvester for our application [4][7]. This circuit has unique ability that it works as voltage quadrupler, using two Greinacher cells of opposite polarities, and as a rectifier at the same time with a minimum number of diodes. The RF signals enter from the RF port, C1 and D1, shift this voltage up to node A then C2 and D2 rectify it to appear across the load. Similarly, C3 and D3 shift the voltage to node B while D4 and C4 rectify it to have a DC voltage across the load [4]. The dual HSMS285B zero bias Schottky diodes were used in this design as rectifiers. They are suitable for 2.4GHz operation. The series and back to back connect diodes are available in a single package, which makes the layout of rectifier simple and efficient due to small package parasitic capacitance. The s-parameter simulation models of these packaged diodes are available from the manufacturer's web page. The major issue in the design is a change in rectifier input impedance. In order to achieve the maximum power transfer, the impedance of the rectifier circuit must be matched with the impedance of input RF port. However, the rectifier circuit consists of nonlinear components and thus the overall impedance varies both with a power level and frequency. In order to match the rectifier impedance to the power combiner's 50-Ω port, the rectifier impedance was estimated under a −20dBm power level of input and then matched using a matching network of short-circuited stubs as shown in Fig.7.

These stubs are placed at both legs and the circuit was optimized for the operating frequency of 2.42GHz and input level of −20dBm. The final artwork work of designed rectifier and its PCB on RO3206 substrate is shown in Fig.7. Multiple samples of rectifiers are tested for input impedance matching with 50Ω with respect to frequency and power level. There is a minor discrepancy between the simulated and measured results (Fig.8 and Fig.9) and these results also changes slightly from sample to sample. The sample to sample variation points towards the fact that the major cause for this discrepancy is imprecise manual soldering not the PCB tolerances. As shown in Fig. 8, we get the best matching at 2.36GHz instead of

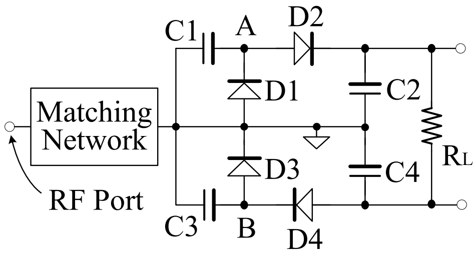
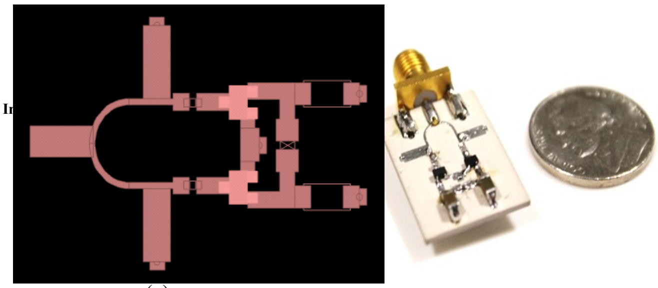
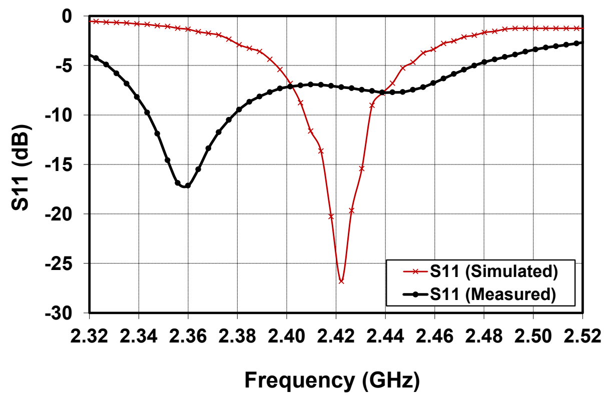


Fig.6 (a) Modified Greinacher Rectifier Circuit as depicted from [6].(b) Rectifier Circuit with a matching network and power combiner.



(a) (b)

Fig.7: (a) Modified Greinacher rectifier art work, a snap shot from ADS layout. (b) Photograph of manufactured rectifier PCB



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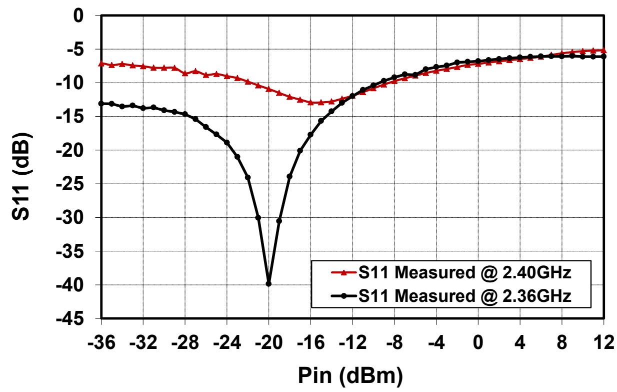

Fig.9. Measured reflection coefficient (S11) of rectifier circuit at frequency of 2.36GHz and 2.40GHz

desired simulated and optimized value of 2.42GHz; therefore the complete harvester testing was performed at 2.36GHz. In Fig.9, the rectifier's S11 is plotted with input power from −40dBm to 12dBm. The S11 changes from −25dB to −5dB with change in input power level of −20dBm to 0dBm. There is no simple solution to this mismatch problem which arises due to diode nonlinear characteristics, and inherent in all rectifier circuits; an adaptive input matching network is needed to overcome this problem.

III. COMBINED RF ENERGY HARVESTER

The final Energy Harvester under test consists of two patch antennas connected through a power combiner which is connected to a modified Greinacher rectifier. The rectifier charges a 33mF super capacitor. The complete measurement setup is shown Fig. 10. A 2.4GHz Yagi antenna is used to mimic the WLAN signal, this antenna is placed at the distance 104cm from an RF harvester's dual 2.4GHz patch antenna for initial testing. Fig.11 shows the comparison of power received by the single and dual patch antennas. It is obvious that received signal becomes powerful when two individual antenna signals are added using a power combiner.

Fig.12 shows the measured and simulated efficiency of the RF harvester with respect to incident signal on an antenna port. The peak measured efficiency is 57.8% at 6 to 8dBm input power. At high input power the measured and simulated curves depart due to increased mismatch between combiner and rectifier port. The rectifier input impedance deviated significantly from 50Ω with the increase in input power due to diode non-linear characteristics.

IV. CONCLUSIONS

A Radio Frequency Energy Harvester design was presented in this paper. Using two patch antenna and in presence of a −10dBm signal at antenna port of combiner the system can charge a 33mF super capacitor to 1.6V in 20 minutes. This sum up to the stored energy is around 42mJ, which is enough to power a 10mW sensor node for a period of 4 seconds. Since the signals as powerful as 0dBm are available in close proximity of a WLAN access point, this makes the presented RF harvester feasible for low power wireless sensor application.

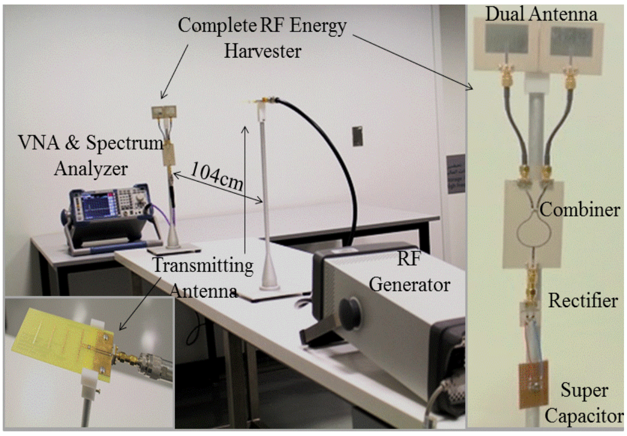

Fig.10. Complete RF energy harvester measurement setup. The inset pictures show the transmitting antenna and RF energy harvester hardware.

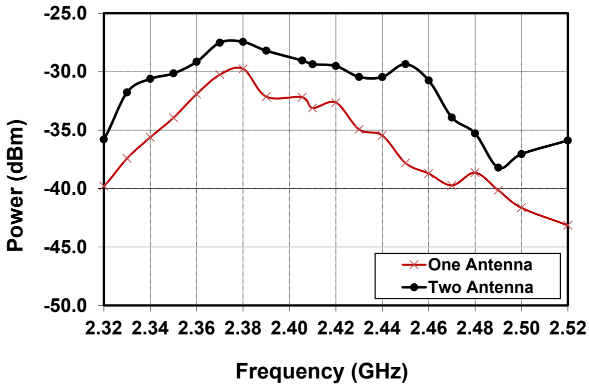

Fig.11: Power received by a single patch antenna and power received by two patch antenna and then added by a combiner.

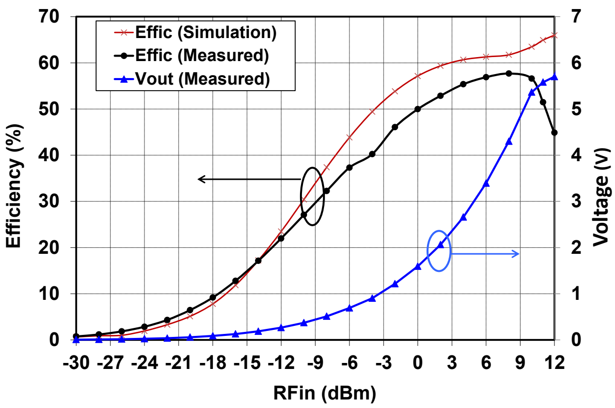

Fig.12. Left Side: Simulated and measured efficiency of the RF harvester; Right Side: The DC voltage level at the output versus RF input power.

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