Demonstration of A Highly Efficient RF Energy Harvester for Wi-Fi Signals

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***Abstract*—This paper demonstrates a highly efficient radio frequency (RF) energy harvester to scavenge 2.45 GHz Wi-Fi energies from commercial available wireless routers. The measured Wi-Fi signal strength available in the normal working space is -44 to -18 dBm. In order to harvest and utilize such small signals, a complete system is designed to include a high gain antenna array, a high efficiency rectifier and a boost converter for voltage conditioning. The system can harvest a final DC power of 76.35 µW at a distance of 40 cm away from the wireless router. As the distance increases, the harvested power decreases gradually. A maximum working distance of 2.4 m is measured. The total RF to DC power conversion efficiency is measured to be from 9.76% at 2.4 m to 33.7% at 40 cm away from the router. The output DC voltage are in the range of 1.5 to 7.36 V, which is sufficient to supply various applications such as portable calculators, LED arrays and energy storage devices such as super-capacitors and batteries.**

I. INTRODUCTION

Today energy crisis becomes a global issue and has been raising attentions from both industry and academia. To address this great challenge, a significant amount of efforts has been spent on the two aspects: reducing power consumption, and finding renewable green energies. Related research topics includes but not limits to novel materials for batteries, highly efficient circuits and systems, ultra-low power ICs, and new ways to recycle wasted energies. Potential energy sources are in the form of vibration [1], heat gradient [2], light [3] and RF energy. These energy sources vary in terms of energy density, power level, availability, cost and etc., therefore they can be used for different applications. Among them, ambient RF energy has some advantages of easy access in modern society, immune to natural environment effects, and relative low cost although it may suffer from a low energy density problem. With the advancing IC technology and new circuit topologies, future electronic circuits will consume less and less DC energy. This makes ambient RF energy an excellent choice for the power supply to not only prolong the on-board battery lifetime but also replace the battery eventually. The resultant battery-less systems are light, compact, maintenance free and cost effective, which find numerous applications such as wireless sensor networks and imbedded biomedical devices. Some previous works have

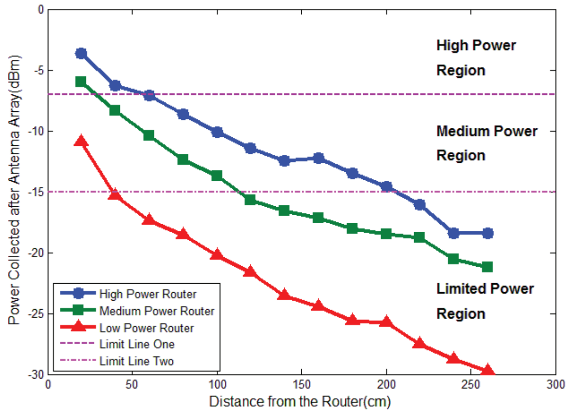

Figure 1. Measured available Wi-Fi signal power level from commercial wireless routers as a function of the radial distance away from the router.

been reported on the progress of microwave rectifiers [4], and rectennas for wireless power transfer [5]. While they focus on high energy density applications, this paper focus on a demonstration of harvesting very small RF energy at 2.45 GHz from daily used wireless Wi-Fi routers. The energy harvester in this paper is designed to work under the normal operation mode of the wireless router thus the available RF power level is less than one-tenth of that in [3]. To overcome these difficulties, a rectifier with a high efficiency is designed for very small RF power by properly selecting the Schottky diode and designing the impedance matching network. The boost converter is used to increase the output DC voltage level as well as serving as an emulated resistance required by the rectifier for high efficiency. A more accurate equation to determine the effective input resistance of the boost converter is derived.

II. DESIGN

Different from the wireless power transmission application where the transmitted RF power is fixed, the RF power to be scavenged from Wi-Fi routers varies significantly with different working modes and conditions. Therefore an accurate map of RF power level from a Wi-Fi router in a normal working space is desired and critical to the design of the following circuits. Two commercial available wireless Wi-Fi routers are selected for this study: TP-LINK TL-WR740N

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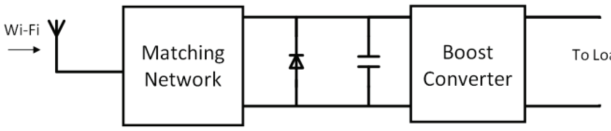


Figure 2. RF energy harvester circuit diagram

(low power mode) and ARGtek ARG-1210 that has two operating power modes (medium and high power modes). The measurement setup includes a 14 dBi directional patch antenna array and an RF power sensor (Mini-Circuits PER-6GHS). The measured Wi-Fi power level is from -29.72 dBm to -3.63 dBm within a radial distance of 2.4 m away from the router (Fig. 1).

To harvest and utilize such small RF signal, the proposed RF energy harvester is designed to include three main parts: a high gain antenna, a high efficient rectifier and a boost converter for voltage conditioning shown in Fig.2. The antenna is the same 14 dBi antenna array used in the Wi-Fi signal measurement. A simple shunt connected Schottky diode is used to convert RF power to DC power because it provides higher conversion efficiency compared with the rectifier using multiple diodes. Because the input RF power to the rectifier is very low, the Schottky diode with a low turn on voltage should be used. The matching network reduces power reflection due to impedance mismatching, therefore increases the RF power fed into the diode. The DC pass filter is implemented with capacitors with a capacitance of about 50 pF, which at the same time can effectively reduce the voltage ripples at the output port. Fig. 3 shows the simulation efficiency with input power ranging from -30 dBm to 3 dBm with a load resistor of 1500 Ω using (1).

$$\eta = \frac{P_{DC}}{P_{RF}} = \frac{V^2}{R \cdot P_{IN}} \tag{1}$$

From Fig. 3, it is shown that the rectified DC voltage is below 0.9 V that is usually too low to drive most application devices and storage components. Thus, a power management circuit is needed, which should have two major functions: 1) providing a fixed equivalent input resistance to the rectifier at various load conditions, and 2) providing a voltage gain to raise the output DC voltage usable for different applications. To meet these requirements, a boost converter with resistor emulation proposed in [5] is modified and used as the power management circuit in this work. For the boost converter shown in Fig. 4, the emulated input resistance is derived to be (2).

$$R = \frac{L \cdot T_{hf}}{t_1^2 \cdot d}\left(\frac{M-1}{M}\right) \tag{2}$$

where L is the inductance, T_{hf} is the period of the high frequency oscillator, t_1 is the time of working period within T_{hf}, M is the voltage gain, and d is the total pulse duty cycle

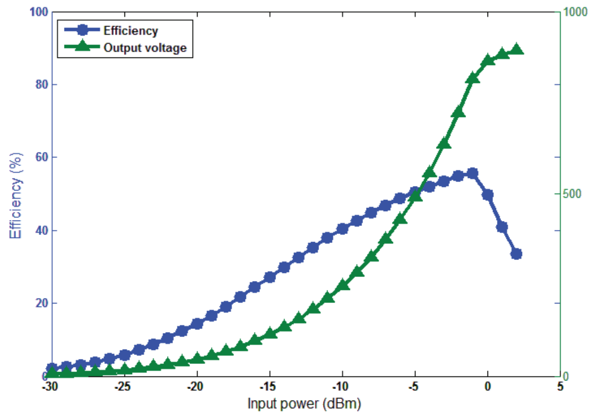
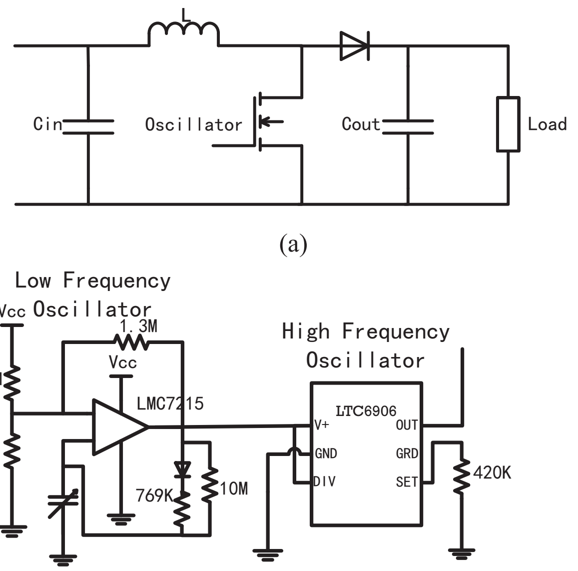


Figure 3. ADS simulated rectifier efficiency and output DC voltage under various input RF power levels.

with respect to the low frequency period, which is derived in (3).

$$d = \begin{cases} \frac{2(D\cdot T_{lf}-T_{set})}{T_{lf}} + \left\{\frac{D\cdot T_{lf}-T_{set}}{T_{hf}}\right\}\cdot\frac{2T_{hf}}{T_{lf}}, \\ \left\{\frac{D\cdot T_{lf}-T_{set}}{T_{hf}}\right\} < 0.5 \\ \left(\left[\frac{D\cdot T_{lf}-T_{set}}{T_{hf}}\right]+1\right)\cdot\frac{2T_{hf}}{T_{lf}}, \\ \left\{\frac{D\cdot T_{lf}-T_{set}}{T_{hf}}\right\} \geq 0.5 \end{cases} \tag{3}$$

where T_{lf} is the period of low frequency oscillator. Different from the results in [5], equation (3) is proved to be more accurate through experiment verification.



(b)

Figure 4. Circuit diagram of (a) the boost converter, and (b) the two-stage oscillator.

III. Fabrication

The RF rectifier is fabricated on a 32-mil-thick Rogers 4003C printed circuit board (PCB) with ε = 3.60 (shown in Fig. 5). A Skyworks Schottky diode (SMS-7630-079LF) is used due to its low turn-on voltage and small power consumption. A single-stub matching network is used before the rectifying diode for 50 Ω impedance match. After the rectifying diode, ten 5.6 pF high-Q RF capacitors from Murata are used as the DC pass filters. The boost converter circuit is fabricated on a 1.5 mm-thick FR4 board shown in Fig. 6. A low frequency oscillator is made up of a National Semiconductor comparator (LMC-7215) and a resistor capacitor (RC) loop circuit. The high frequency oscillator (LTC-6906) will provide high frequency control signal for the MOSFET. After the MOSFET, a Schottky diode (BAT43) is used to limit the reverse current from output to input. In the RC circuit part, a Vishay film dielectric trimmer (5.5 – 65.0pF) is used to fine-tune the capacitance value. A CR-1220 button cell is used to provide power for the boost converter.

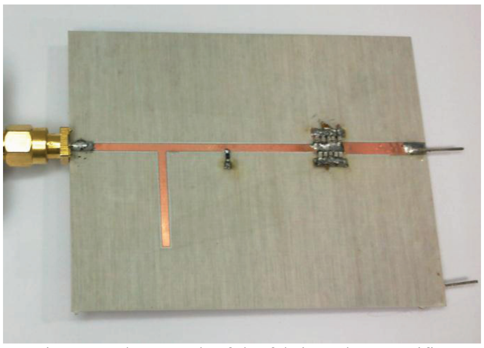


Figure 5. Photograph of the fabricated RF rectifier

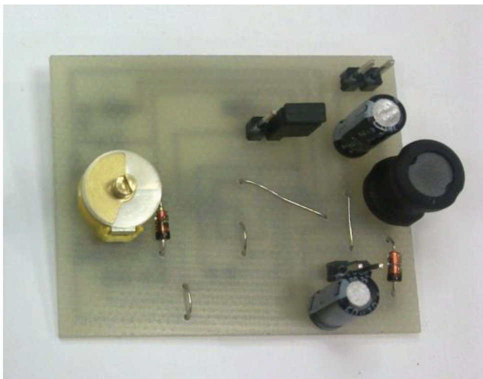


Figure 6. Photograph of the fabricated boost converter

IV. Results

In the measurement, the wireless router is placed in the center of an open space and set to work at its full speed. The RF energy harvester is placed at certain distance away from the router. The output voltages after the rectifier and the boost converter are measured using a multimeter and an oscilloscope. Detailed results are calculated and listed in Table I. The highest total system conversion efficiency is achieved when the harvester is placed at 40 cm away from the router. The received RF power before the rectifier is 226.55 μW that is finally converted to a DC output voltage of 7.36 V with a total efficiency of 33.7%. As the distance between the harvester and the wireless router increases, the available RF power drops gradually thus the scavenged DC voltage drops accordingly. At 2.4 m away from the router, the system can recycle a DC power of 1.74 μW at 1.5 V with a total efficiency of 9.76%. The measured rectifier efficiency agrees well with the simulation results, while the boost converter efficiency is maintained at 62%.

Since an on-board battery cell powers the boost converter, it is necessary to measure the total power consumption of the boost converter to justify the overall system efficiency. For a 3V battery, the DC current drawn from the battery is measured to be 11 μA when the boost converter is active, therefore the total power to operate the boost converter is about 33 μW. Taking this into consideration, the RF energy harvester can collect net positive energies when placed within 1 m from the router. When far away from the router, the harvested energy can be used to effectively prolong the lifetime of the on-board battery, which is still desirable for most applications in wireless sensor networks.

The above tests are under the condition that the wireless router transmits data at a full speed, however in real life, the wireless router may operate among different modes: sleep, low data rate, and high date rate. To test how the RF energy harvester behaves under these conditions, a 47 μF capacitor is connected to the boost converter as a final load, and the Wi-Fi signal is purposely interrupted by placing a metallic object in front of the router while keeping the router working at the full speed. Both the voltages after the rectifier and the boost converter are measured and plotted in Fig. 7. When there is Wi-Fi signal, the rectifier converts this RF signal to a relative constant DC output voltage, then the boost converter continuously charge the capacitor, which is indicated by the ramp-up voltage curve in Fig. 7. When there is no Wi-Fi signal, the rectified DC voltage drops to zero, while the capacitor starts to discharge due to the internal loss in the boost converter.

This RF energy harvester has very little impact on the normal usage of Wi-Fi signal. The energy it collects by the antenna is less than 1% of the total energy radiated from the router. According to the experiment, the downloading speed of computer is not affected when the harvester is working, and the reduction of RSSI that detected by the computer is less than 1% even the antenna array is placed just beside the computer.

TABLE I
MEASUREMENT RESULTS OF THE RF ENERGY HARVESTER

Distance From Router (cm)	Received Power (dBm)	Received Power (μW)	Rectifier Output Voltage (mV)	Converter Output Voltage (V)	Boost Times	Rectifier Efficiency (%)	Boost Converter Efficiency (%)	Total Efficiency (%)
40	-6.44	226.55	430	7.36	17.11	55.15	61.11	33.70
60	-7.46	179.58	360	6.88	19.11	48.76	63.71	31.06
80	-8.95	127.40	296	5.12	17.30	46.47	62.72	29.15
100	-10.18	95.94	220	4.96	22.55	34.09	62.34	21.25
120	-11.43	71.89	200	4.29	21.45	37.60	61.69	23.20
140	-12.34	58.29	175	3.76	21.49	35.50	63.43	22.52
160	-12.47	56.60	150	3.44	22.93	26.86	62.97	16.91
180	-13.84	41.31	100	2.60	26.00	16.36	62.01	10.14
200	-15.72	26.79	80	1.84	23.00	16.14	63.30	10.21
220	-15.93	25.49	68	1.68	24.71	12.25	63.56	7.79
240	-17.49	17.83	64	1.50	23.44	15.52	62.86	9.76

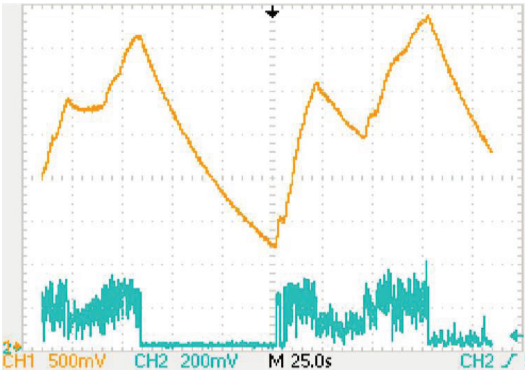


Figure 7. Measured output DC voltage of (a) the boost converter (upper yellow trace), and (b) the rectifier (lower blue trace) under different Wi-Fi router operational modes.

V. CONCLUSION

A complete 2.45 GHz RF energy harvester system has been demonstrated in this paper. This harvester can recycle wasted wireless power from Wi-Fi routers effectively. Within 2.4 m from the router, the harvester can produce a DC voltage from 1.5 V to 7.36 V with a system conversion efficiency of 9.76% to 33.7%. This output voltage is sufficient to power up various electronic applications and storage devices. This demonstration proves the usability and potential of utilizing the small Wi-Fi power wirelessly for many applications.

REFERENCES

[1] S. Roundy, P. K. Wright, and J. M. Rabaey, "Energy scavenging for wireless sensor networks with special focus on vibrations", Kluwer Academic Publishers, 2004.

[2] Tom Torfs, Vladimir Leonov, Chris Van Hoof. Bert gyselinckx "Body-heat powered autonomous pulse oximeter". In: *5th IEEE conference on sensors*; 2006. p. 427–30.

[3] V. Raghunathan, A. Kansal, J. Hsu, J. Friedman, and M. Srivastava, "Design considerations for solar energy harvesting wireless embedded systems," in *Proc. IEEE Int.Conf. Inf. Process. Sensor Netw.*, Apr. 15, 2005, pp. 457–462.

[4] J. McSpadden, L. Fan , K. Chang, "Design and experiments of a high-conversion-efficiency 5.8-GHz rectenna," *IEEE Trans. Microw. Theory Tech.,* vol. 46, pp. 2053-2060, 2002.

[5] T. Paing, J.Shin, R.Zane, Z.Popovic, "Resistor emulation approach to low-power RF energy harvesting," *IEEE Trans. Power Electronics*, vol. 23, pp. 1494-1501, 2008.