A 5.2 GHz RF Energy Harvester System Using Reconfigurable Parallel Rectenna

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***Abstract*— This paper presents a 5.2 GHz band, 67 % efficiency at the input power of +20 dBm RF Energy Harvester (EH) for IoT/wearable devices. In order to keep the high efficiency over the wide RF input range, the reconfigurable 6-parallel rectenna is proposed. The configuration of rectenna is automatically changed depending on the RF input power level. Also, adaptive matching is proposed to adjust the matching network automatically depending on the number of stages of rectenna, RF input frequency, and load current. Each RF-DC converter in rectenna is implemented by two Schottky diodes in a package and with a harmonic control scheme to produce a reasonable output DC voltage. Buck-boost converter is integrated to provide a constant voltage to the IoT/wearable devices. By using reconfigurable structure, different values of efficiency and the output DC voltage can be achieved. The measured efficiency of RF EH is 67 % with an output DC voltage of 6.1 V when the RF input power level is +20 dBm at the frequency of 5.2 GHz single-tone signal. It can charge the wearable devices such as G Watch, Mi band, and SmartThinQ.**

Keywords—RF energy harvester; Rectenna; IoT/wearable devices; reconfigurable; DC-DC converter

I. INTRODUCTION

The Internet of Things (IoT) and Bluetooth Low Energy (BLE) devices have been a major interest for designers because the number of IoT devices is increasing drastically and resulting in the availability of billions of them in the market. IoT devices have been equipped with several sensors and abled to communicate with other devices. Interrupt-free operation and consequently long battery life based on load conditions are demanding requirements for these devices. We have considered that Energy Harvester (EH) and low power devices cannot be installed under normal conditions and we cannot exchange their batteries easily [1], [2]. Low power and high efficiency power management integrated circuit (PMIC) is important for having higher battery life and sustaining a system without any need to recharge. In addition, smaller chip area, smaller external components like inductors and capacitors, and finally higher efficiency are required. Power loss factors such as parasitic element loss, Printed Circuit Board (PCB) loss, line loss, etc. are the targets of reduction and a recent trend is the integration of an energy harvester power management system, especially RF EH system with an IoT/wearable or RF Transceiver system [3], [4].

Inconvenience in portable wireless devices is caused by battery replacement or its recharging. Therefore self-powering based on energy harvesting in dense communication network is increasing as a critical demand for these wireless devices. Many solutions to construct remote charging through EH from renewable sources along with optimized processing techniques have been proposed [1-7]. Beside of thermal, solar and wind energy sources for EH, recently the presence of radio frequency (RF) signals in the ambient became appealing source for EH in portable devices. RF signals are capable of carrying information in wireless devices which introduces the concept of simultaneous wireless information and power transfer (SWIPT) that brings fundamental changes for the field of communication system design to facilitate efficient energy and information reception and self-powered by RF EH system.

Fig. 1 shows a system block diagram of an RF energy harvester system in IoT/wearable devices. The RF EH system consists of an antenna to receive RF energy, a rectifier, a DC-DC converter, and a load. The efficiency of the RF EH system is highly dependent on the RF-to-DC conversion efficiency of the rectifier and the efficiency of the DC-DC converter. Depending on the output DC voltage of the rectifier, either a buck-boost DC-DC converter or a buck DC-DC converter can be used. If the output DC voltage of the rectifier is sufficiently high, a relatively simple and efficient buck DC-DC converter can be selected instead of a buck-boost converter. Thus, it is necessary to design a rectifier with high output DC voltage as well as high conversion efficiency to improve the overall efficiency of the RF EH system.

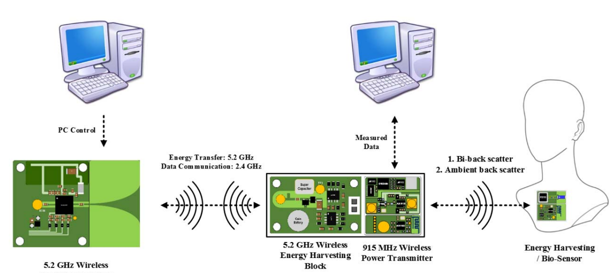


Fig. 1. System configuration of long-range high-power RF energy harvester.

II. ARCHITECTURE AND BUILDING BLOCKS OF THE RF ENERGY HARVESTING

A. Architecture

Fig. 2 shows the system budget of RF EH system. The maximum achievable power at the Rx module side is given by

$$P_R = P_T + G_T + G_R - \textit{Path loss} \quad (1)$$

where P_T is the Tx module output power, G_T is the Tx module antenna gain, G_R is the Rx module antenna gain, *path loss* is air loss of measured environment, and P_R is the received power at the Rx module detector. Considering a perfect system configuration, the distance between Tx and Rx module, and the Free Space Path Loss (FSPL) equation, the system budget illustrated in Table I, 6-array antenna compensating for air loss is designed in Rx module part to maximize the RF power for RF-DC converter. The configuration of the rectenna is automatically changed depending on the RF input power level.

Fig. 3 illustrates a block diagram of the proposed RF EH system. It comprises of a 2 x 3 array patch antenna, 6-parallel RF-DC converter in the front side, DC-DC converter, BLE module, and USB connector in the back side of Rx module PCB board, respectively. The front view of the PCB has rectenna composed of five RF-DC converters and five patch antennas, and also one RF-DC converter and one patch antenna is configured for the pilot signal only. The proposed RF-DC converter of each rectenna is fabricated based on a Dickson charge pump structure. A six array rectenna with two Schottky diodes was adopted to produce high efficiency and high-output DC voltage. It has an optimized third harmonic source termination for an improved conversion efficiency, and the implemented RF-DC converter includes series transmission lines and open-stubs for the third harmonic inductive termination and fundamental impedance matching. The simulated third harmonic contour using the harmonic source-pull simulation shows an optimum region near jX75 Ω with a maximum efficiency of 69.45%. The optimum third harmonic impedance is inductive due to the junction capacitance of the Schottky diodes, and the input capacitance and inductive source impedance produce parallel resonance for an appropriate Class-F third harmonic termination. Compared to the efficiency of the rectifier without harmonic control, the proposed rectifier with harmonic control exhibits a 5.2% higher efficiency at an input power of about +20 dBm. Using the optimum third harmonic termination, the voltage waveforms across the Schottky diodes of RF-DC converters become closer to the square waves of an ideal RF-DC converter. The rectenna is the first block at the input of the Rx module to rectify RF signal. A combining capacitor at the output of the rectenna is also used as a low-pass filter to remove ripples at the output. The output of the rectenna is fed to buck-boost converter. In order to eliminate voltage variation; buck-boost converter is used to produce constant output voltage. When the input voltage level reduces due to the weak RF signals, the boosting operation of the buck-boost converter is performed to maintain output voltage level and vice-versa. Low drop-out (LDO) regulator can be used to keep constant output voltage. A super capacitor is connected at the output of buck-boost converter to store energy and provides power for IoT/wearable devices and charger of the battery.

The RF energy harvester is implemented based on a RF-35 (front side) and FR4 (back side) with 4-layers using the commercial devices in order to maximize power efficiency. The 6-parallel rectenna is implemented and its configuration is automatically selected depending on the input power level. The Input range of the RF EH system is from 0 dBm to +30 dBm and the measured peak efficiency is 67 % when the RF input power level at the RF-DC converter input node with respect to the air losses is +20 dBm at the frequency of 5.2 GHz. It can charge the IoT/wearable devices at a distance of 78cm with a single 5.2 GHz Tx antenna charging station of transmit power 1 W, and 5.5m with 48-array antenna charging station of transmit power 3.6 W [8].

B. Tx, and Rx Antenna Design

The antenna is designed to receive 5.2 GHz RF signal from the Tx power amplifier and feed it to the energy harvester system and storage unit. A Koch fractal patch antenna with high-gain, low-return loss, and an inter-element spacing equal to 0.5λ (at the design frequency of 5.2 GHz, λ is the wavelength in free space) as a compact size for the Rx module side is implemented as shown in Fig. 4.

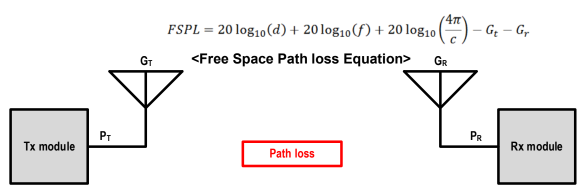


Fig. 2. System budget.

TABLE I. SYSTEM BUDGET

Distance (m)	*P_T (dBm)*	*G_T (dBi)*	*G_R (dBi)*	*Path Loss (dB)*	*Received Power (dBm)*
10	48	7.317	13 (6 array rectenna)	-66.75	0.967
5				-60.73	6.987
1				-46.75	21.067

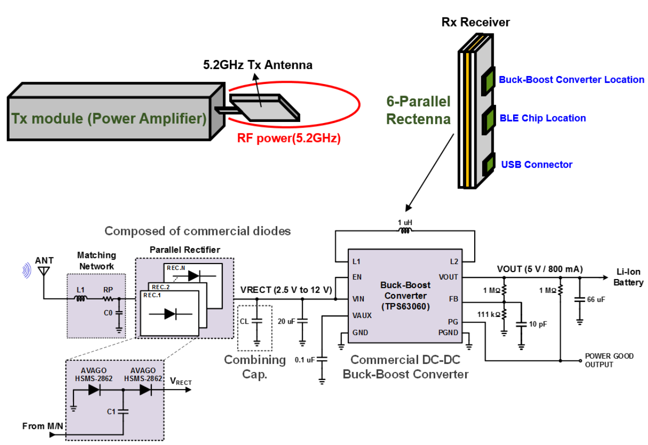


Fig. 3. Block diagram of the proposed RF energy harvester system.

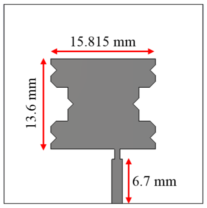
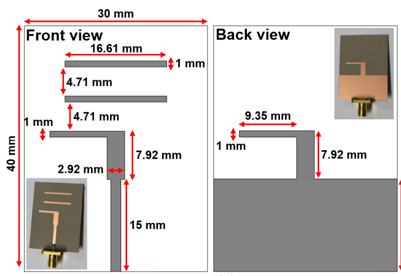
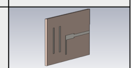


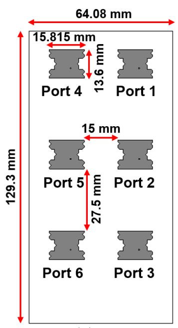
Fig. 4. Koch fractal patch antenna.



	Tx antenna
Figure	
Size	0.76 × 30× 40 (mm^3)
Substrate	RF-35 (ε_r = 3.5)
Bandwidth	5045 – 5312 MHz (about 267 MHz)
Gain	7.317 dBi

(a) (b)

Fig. 5. Configuration of the Quasi-Yagi Tx antenna, (a) photograph of fabricated Tx antenna, and (b) its specification.



Rx antenna	Broadside gain (dBi)
Port 1	6.00
Port 2	6.44
Port 3	5.64
Port 4	6.17
Port 5	6.21
Port 6	5.53

(a) (b)

Fig. 6. (a) 2x3 Rx module antenna arrangement, and (b) its specification.

Fig. 5 (a) and (b) illustrates a 5.2 GHz Quasi-Yagi antenna configuration on the substrate of Taconic RF-35 (0.76 mm) to transmit a total power of 3W, used as wireless power transmitter and its specification, respectively. An Rx module designed by 2x3 array antenna is located at a distance up to around 1m (distance can vary to harvest more RF input power) away from the transmitter to harvest the transmitted power as shown in Fig. 6 (a). Broadside gain of each port Rx antenna is shown in Fig. 6 (b).

III. Implementation and Experimental Results

Fig. 7 (a) and (b) shows the implemented RF EH module using reconfigurable and third harmonic control circuit schemes, and its PCB layer information, respectively. The 6-parallel rectenna exhibited a conversion efficiency of 67 % and an output DC voltage higher than 6.1 V at an input power of +20 dBm, which is four percentage points higher in terms of conversion efficiency than that of the RF-DC converter without the third harmonic control circuit. Using the proposed RF-DC converter, both high output DC voltage and conversion efficiency can be simultaneously achieved to obtain simpler system configuration and higher overall conversion efficiency of the total RF EH system. Fig. 8 (a), (b), and (c) shows measurement environments of RF EH systems. The transmitted 5.2 GHz RF signal via power amplifier and Tx antenna can charge the wearable device, chip LED, and mobile phone in distance of 65 cm, 80 cm, and 90 cm with transmission power of 34.77 dBm, respectively. Fig. 9 (a) and (b) shows the measured reflection coefficient (S11) of Tx antenna and Rx antennas, respectively. The measured power conversion efficiency results of the RF EH system are illustrated in Fig. 10. The proposed rectenna showed the highest output DC voltage of 6.1 V and high conversion efficiency in the frequency band above 5 GHz. As the number of parallel stages increases, the efficiency at higher input power is high (the operation of breakdown area of diode at high power is dominant in the efficiency decrease). The maximum achievable efficiency is 67 % at +20 dBm input power level when only a single rectenna is used.

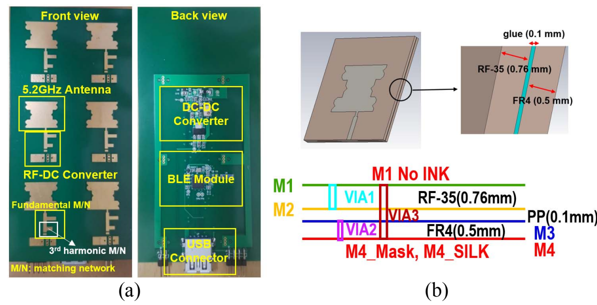


Fig. 7. (a) Fabricated RF energy harvester module front (6-parallel rectenna) and back (Rx receiver) sides, and (b) Its PCB layer information (4-layer).

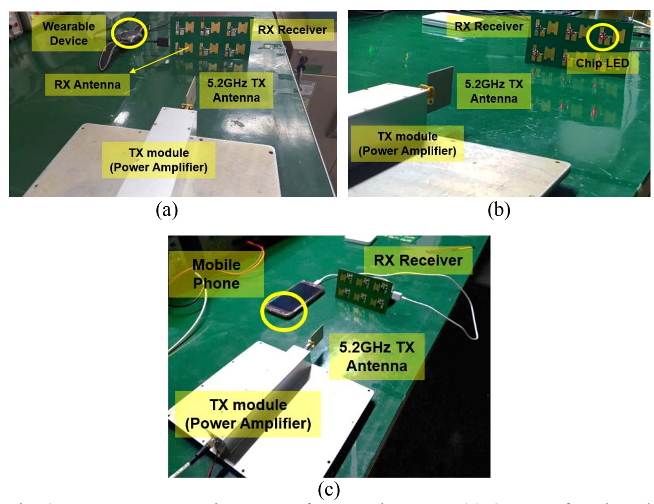


Fig. 8. Measurement environment of RF EH harvester (a) Output of Rx board connected to G Watch, (b) Chip LED, and (c) Mobile phone.

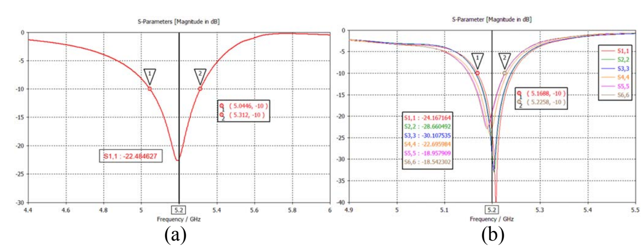


Fig. 9. Measured reflection coefficient of (a) Tx antenna, and (b) Rx antenna.

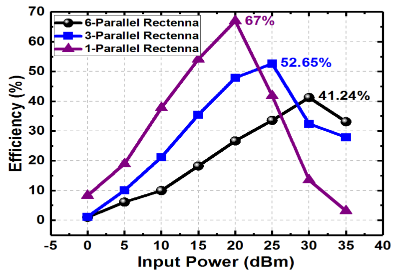


Fig. 10. Measured power conversion efficiency results of the RF EH system.

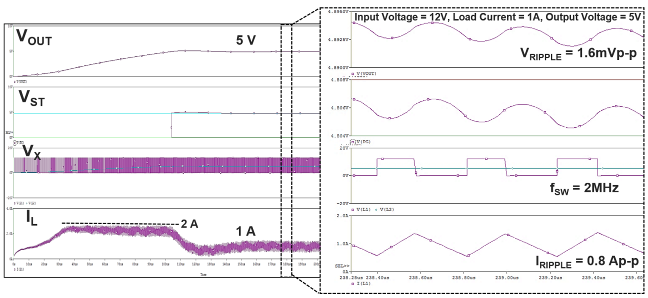


Fig. 11. Simulated results of buck-boost DC-DC converter.

The testbench has been configured for 12 V input, 5 V output at 1 A load. The efficiency of buck-boost converter is up to 93 % with switching frequency of 2 MHz. The simulation results of buck-boost converter is shown in Fig. 11. The performance metrics of the implemented RF EH system including key features, components used in Rx module board, and PCB board type are summarized in Table II. The performance of RF EH system is summarized in Table III when the USB connector is connected to IoT/wearable devices such as LG G Watch, Mi band, and LG SmartThinQ.

IV. Conclusion

In this paper, a 5.2 GHz RF energy harvester system was implemented using the reconfigurable parallel rectenna structure with third harmonic control circuit scheme. The implemented RF-DC converter uses a 6-parallel rectenna and it achieved both good efficiency and high output DC voltage. The latter allows deploying a simple buck DC-DC converter after the RF-DC converter to drive the IoT/wearable devices and BLE chip. The system exhibited a power conversion efficiency of 67 % and an output DC voltage of 6.1 V at an input power level of +20 dBm. Using the proposed architecture, different DC output voltage and efficiency can be obtained to power-up variety of IoT/wearable devices.

TABLE II. Performance Summary

Parameter	***Test Board***
RF-DC converter type	6-parallel rectena
Key features	1. Diode reliability considered 2. Parallel rectenna structure 3. Reconfigurable structure 4. Implementation for large input power
Diode	AVAGO HSMS-2862
Buck-boost converter	TI TPS63060
PCB board type	Taconic RF35 (Front: EH system) + FR4 (Back: BLE, DC-DC converter)
Peak efficiency	67% @20 dBm, 5.2 GHz

TABLE III. Performance Summary of IoT/wearable Devices

Parameter	***LG G Watch (Wearable Device)***	***Mi band (Wearable Device)***	***LG SmartThinQ (IoT, Sensor)***
Battery capacity	400 mAh, 1.52 Wh	45 mAh, 0.17 Wh	300 mAh, 1.11 Wh
Battery Life[a]	24 hour	30 day	90 day
Power Consumption	63mW	0.24mW	0.51mW
Distance	25cm	25cm	25cm
Transmission Power	30dBm	30dBm	30dBm
Antenna Gain	20dBi	20dBi	20dBi
Free Space Path Loss	-33.69dB	-33.69dB	-33.69dB
Received Power	16.31dBm	16.31dBm	16.31dBm
Battery charging time[b]	use time increased by 158%	8 hour	36 hour
Duration and use time aspects	use time increased by 158%	Continuous use without battery reduction when Tx Power is supplied	Continuous use without battery reduction when Tx Power is supplied

a. Battery Life = (Battery capacity [Wh] / Power Consumption [W])

b. Battery charging time = (Battery capacity[mAh] / Charger output current[mA]) x Charging factor(1.2)

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