Multiband Ambient RF Energy Harvesting for Autonomous IoT Devices

Hong Son Vu, Ngan Nguyen, Nam Ha-Van, *Member, IEEE*, Chulhun Seo, *Senior Member, IEEE*, and Minh Thuy Le, *Member, IEEE*

***Abstract*—This letter presents a novel multiband rectenna for the ambient wireless energy harvesting of an autonomous internet of thing (IoT) sensor. A bow-tie antenna with slits is proposed to obtain four frequency bands at 840 MHz, 1.86, 2.1, and 2.45 GHz, respectively. Furthermore, a multiband rectifying circuit combined of four single ring-loop rectifiers is designed with high conversion efficiency. Finally, a power management circuit with storing and converting the harvested voltage is proposed for smoothing dc output voltage. The energy harvester can be used in practical wireless sensor applications.**

***Index Terms*—Bow-tie antenna, multiband rectenna, power management circuit, radio frequency energy harvesting (RF-EH).**

I. Introduction

RECENTLY, radio frequency energy harvesting (RF-EH) techniques have become promising solutions to power the next generation wireless networks, such as the sensor nodes in wireless sensor network, and the autonomous internet of thing (IoT) devices [1]–[5]. The RF-EH technique exploits available ambient power that allows the wireless devices to harvest energy from the RF signal [6]–[8]. The ambient RF-EH is a green renewable energy solution, which has been attracting many researchers even though a big challenge of low incident power for RF-EH design. Fortunately, with the advancement in wireless and telecommunication domain, multiple RF energy sources are found in ambient, such as Wi-Fi, DTV, and GSM/3G/4G/5G. To improve the demanding power requirements of the ambient RF-EH system, multiband and broadband rectennas have been investigated for practical options concerning productivity [9]–[11]. A multiband and broadband rectenna is expected to effectively harvest the energy from the available frequency bands simultaneously in real ambient. However, most rectennas presented in the previous literature have been implemented using dedicated sources rather than ambient RF energy. Furthermore, RF sources in the environment are coded and modulated before transmitting. Therefore, the RF-EH system performance should be validated properly using the modulated signal instead of the sinusoidal sources.

Manuscript received June 24, 2020; revised August 13, 2020 and September 24, 2020; accepted October 2, 2020. This work was supported in part by the Vingroup Innovation Foundation (VINIF) under Project VINIF.2020.DA09. *(Corresponding author: Minh Thuy Le.)*

Hong Son Vu and Minh Thuy Le are with the Department of Instrument and Industrial Informatics (3I), School of Electrical Engineering, Hanoi University of Science and Technology (HUST), Hanoi 10000, Vietnam (e-mail: thuy.leminh@hust.edu.vn).

Ngan Nguyen, Nam Ha-Van, and Chulhun Seo are with the Department of Information and Telecommunication Engineering, Soongsil University, Seoul 06978, South Korea.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LMWC.2020.3029869

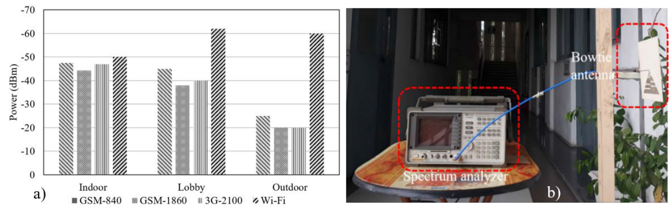

Fig. 1. (a) Input RF power density measurement in HUST. (b) Measurement configuration.

Due to a nonsinusoidal RF incoming signal, the actual rectenna dc voltage pattern appears as pulses [12]. Since the need for a smooth dc power supply for IoT devices, a power management module is required to convert pulse voltage. To control the incoming energy flow, harvest-use and harvest store-use method are utilized [1]. The harvested energy is immediately used to power the wireless devices leading to the amount of converted electricity that must be constantly exceeded the minimum power demand. Meanwhile, the device is equipped with a rechargeable battery or supercapacitor that stores the converted energy. The energy storage module then operates only if the harvested energy is still available after satisfying the need for the wireless device. However, owing to the low power density presented above, the harvest-use method is rather appropriate to this application. Therefore, power management is proposed to convert instantly harvested electricity to power IoT wireless devices.

In this letter, a new bow-tie antenna and multiband rectifier are proposed and described with the performance evaluation, as presented in Section II. The rectenna design and measurement are presented in the practical configuration. Finally, in Section III, a novel power management circuit is proposed to store and convert the pulse voltage due to the nonsinusoidal RF sources.

II. Antenna and Rectifier Design

A. Antenna Design

Fig. 1 shows the power level of ambient RF energy that is measured in Hanoi University of Science and Technology (HUST), Vietnam. The spectral bands for GSM and Wi-Fi band including GSM-840, GSM-1860, 3G-2100, and

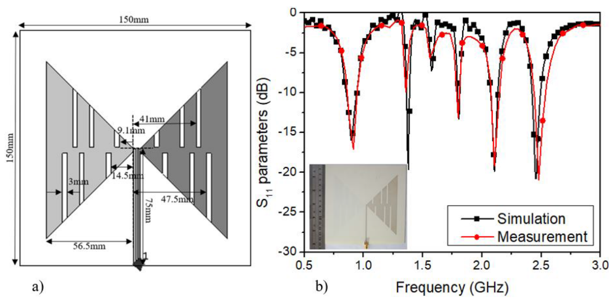

Fig. 2. (a) Proposed bow-tie antenna with its dimensions. (b) Comparison between simulation and measurement S_{11} parameters of the antenna. The inset illustrates the antenna fabrication.

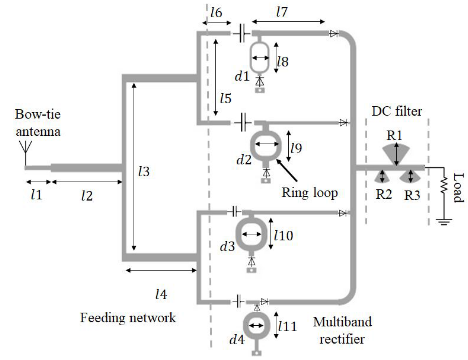

Fig. 3. Schematic of the multiband rectifier with ring loops. $l_1 = 10$, $l_2 = 24$, $l_3 = 63$, $l_4 = 23.5$, $l_5 = 31.8$, $l_6 = 10$, $l_7 = 27.6$, $l_8 = 9$, $l_9 = 6.5$, $l_{10} = 7$, $l_{11} = 5$, $d_1 = 5$, $d_2 = 7$, $d_3 = 6.5$, $d_4 = 5$, $R_1 = 8$, $R_2 = 4$, $R_3 = 4$, all units in mm.

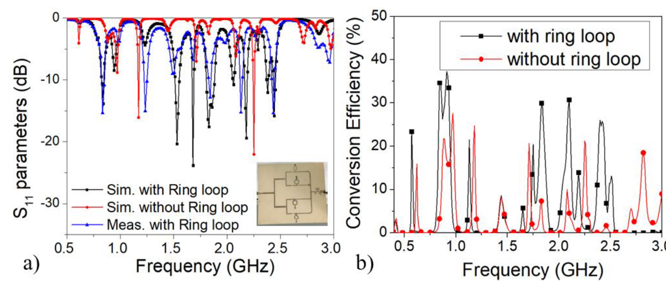

Fig. 4. (a) Reflection coefficient of the proposed multiband rectifier. (b) Conversion efficiency of the rectifier with and without ring loops.

Wi-Fi-2450 are identified, which can be exploited to design RF-EH circuits. In order to harvest energy from multi RF bands, a multiband antenna is required to cover these frequency bands. A new slotted bow-tie antenna with different numbers of slits and dimensions is proposed because of the advantages, such as wide bandwidth, high gain, low front to back ratio, low cross-polarization level, and compact size. The two fins of the bow-tie are placed on the two sides of the substrate, as shown in Fig. 2(a). Three slits-pairs are inserted on each arm of the bow-tie with a width of 3 mm and lengths depending on the slits-pair positions. By changing the dimensions as well as the positions of the slits-pairs, the resonant frequencies are controlled to desired frequencies. The antenna is designed using the Rogers 4003C substrate with a dielectric constant of 3.55 and a thickness of 0.8 mm. The simulated and measured S_{11} parameters of the antenna are shown in Fig. 2(b). It is obvious that the effect of the slits results in generating the resonant frequencies at 840 MHz, 1.86, 2.1, and 2.45 GHz, respectively. There is good agreement between simulation and measurement results of the reflection coefficient of the antenna.

B. Rectifier Design

For multiband RF-EH system, the multiband rectifying circuit is proposed to have an energy collection from the multiband bow-tie antenna. The multiband rectifier is composed of a one-in and four-out feeding network, a dc-pass filter, four rectifying elements corresponding to four frequency bands, and a load, as shown in Fig. 3. The single rectifier corresponding to each frequency band is necessary to achieve high efficiency with the same load. A crucial component of the rectifier is the diode, which is compatible with the low RF power density in ambient. After verifying the effect of the diode parameters on the conversion efficiency of the rectifier, the SMS-7630 Schottky diode is chosen with its junction capacitor, series resistance, voltage threshold, and breakdown voltage of 0.14 pF, 20 Ω, 0.34, and 2 V, respectively. It is suitable for ambient energy with a low threshold voltage.

The single rectifier consists of a pumping capacitor, a shunt diode with a ring loop, and a series rectifying diode. A conventional matching circuit of the rectifier is optimized for a fixed specific operating frequency. Therefore, a multiband matching network is extremely complex and enlarged. In this letter, a ring loop with more compact and better performance is proposed for the first time to adjust the imaginary part of the rectifying circuit impedance. When the ring loops are used, the rectifying circuits are matched at the desired frequencies than without rings. The dc-pass filter consists of three radial stubs, which prevents the RF signals and their harmonics conducive to reduce the ripple of the output dc power. The first radial stub is used to suppress for 1.8 GHz band, the second stub for 0.9 GHz, and the third stub for both 2.1 and 2.45 GHz. The multiband rectifier is fabricated using the Roger 4003C substrate with a dielectric constant of 3.55 and a thickness of 0.8 mm to feasibly integrate with the antenna. The inset on the left side of Fig. 4(a) illustrates the fabrication of the multiband rectifier. It can be seen that there is a slight difference between simulation and measurement of the reflection coefficient of the multiband rectifier with a ring loop, as illustrated in Fig. 4(a). The tolerance can be explained by the difference between the reference impedance of the port simulation and vector network analyzer (VNA). Fig. 4(b) shows the conversion efficiency obtained using the ring loop structure increases considerably. The peak efficiencies are 46%, 42%, 42%, and 36% at 0.84, 1.86, 2.1, and 2.4 GHz frequencies, respectively.

C. Rectenna Design

After optimizing the bow-tie antenna and the multiband rectifier, the rectenna was integrated and implemented, as shown in Fig. 5(a). The measurement of the proposed rectenna was conducted practically to harvest energy from Wi-Fi 2450 and

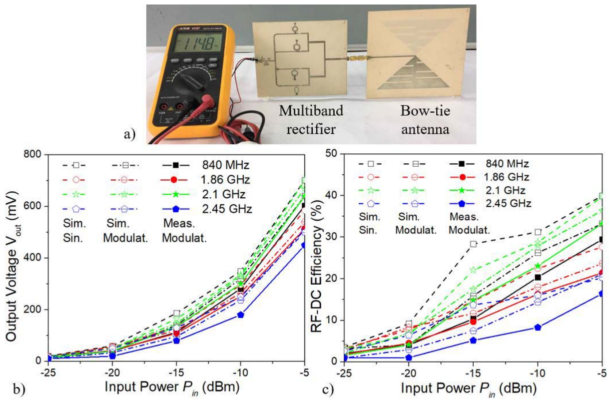

Fig. 5. (a) Rectenna measurement in ambient with a voltage meter. (b) Simulation and measurement output voltage results. (c) RF-dc efficiency of multiband rectenna at four desired frequency bands.

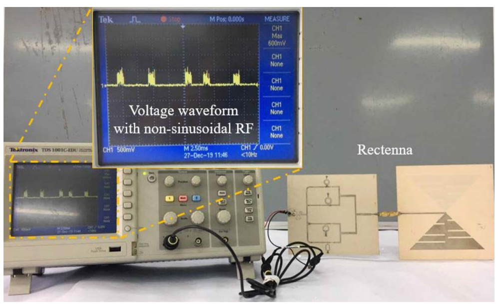

Fig. 6. Actual rectenna dc output voltage due to nonsinusoidal RF sources.

GSM/3G sources in the environment. First, a fabricated prototype antenna was used to receive the signals and measured using a spectrum analyzer. The rectenna was then placed in the same position of the tested antenna. The output dc voltage was measured by a voltmeter. The input power was verified from −25 to −5 dBm. The simulated and measured result comparisons of the output dc voltage and RF-dc efficiency at four frequency bands depending on the input power are demonstrated in Fig. 5(b) and (c), respectively. The simulation was implemented with the continuously sinusoidal signal and modulated signal as the input power source. It is obvious that the real modulated signal induces a degradation of output voltage and RF-dc efficiency. There is good agreement between the simulated and measured results of the modulated signal cases.

III. Multiband Rectenna With Power Management Circuit

The practical measurement of the RF harvesting system was made with the sources consisting of a phone call and an emitted Wi-Fi router. The experimental rectified voltage at the rectifier output due to nonsinusoidal RF sources is illustrated in Fig. 6. The voltage waveform involves the incoherent voltage pulses which are insufficient to directly power up low-power devices. Normally, a conventional power management circuit cannot solve this issue. For a practical RF-EH system, a power management circuit is required to store and convert pulse voltage. Therefore, a novel power management circuit with a buffered supper capacitor is proposed with the block diagram of power management is shown in Fig. 7(a). Normally, in an ambient RF power system, the harvested energy is first stored in a supercapacitor. Then, the voltage monitor module detects the desired voltage level of 0.9 V of the supercapacitor to boost the dc–dc converter circuit, which is used to convert the output voltage of rectenna to higher voltage. To monitor the voltage level, an IC voltage detector is used belonging to the NCP302 family of ON semiconductor which has a voltage range from 0.9 to 4.9 V. The output voltage of power management circuit is achieved at 3.36 V when the supercapacitor stores enough 0.9 V, as shown in Fig. 7(b). Table I summarizes the performance comparison between this work with the previous researches. This letter shows a compatible high efficiency of the ambient RF-EH system with power management to store and convert pulse voltage for the practical system.

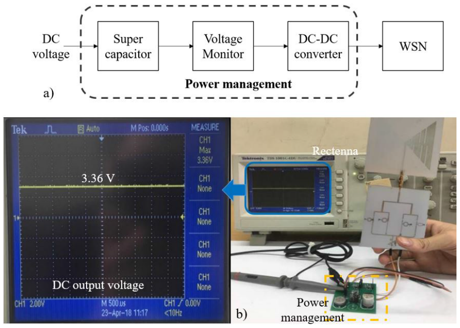

Fig. 7. (a) Block diagram of the power management. (b) Measurement of the rectenna with power management circuit.

TABLE I
Performance Comparison With Previous Researches

Ref.	Input Power	Freq. band	Peak eff.	Power manage.
[10]	-25 dBm ÷ -5 dBm	LTE 700 MHz GSM 850 MHz ISM 900 MHz	30% (indoor)	No
[12]	-20 dBm ÷ 0 dBm	GSM 900 MHz GSM 1800 MHz UMTS 2150 MHz Wi-Fi 2450 MHz	46% NA NA 16%	No
[13]	-15 dBm	GSM 900 MHz GSM 1800 MHz Wi-Fi 2450 MHz	45% 46% 25%	No
[14]	-17 dBm	ISM 915 MHz ISM (850 - 900 MHz)	40%	No
This work	-25 dBm ÷ -5 dBm	GSM 840 MHz GSM 1860 MHz UMTS 2100 MHz Wi-Fi 2450 MHz	30% 22% 33% 16.5%	Yes

IV. Conclusion

A proposed multiband rectenna with a power management circuit is presented in this letter. The bow-tie antenna operates at four frequency bands corresponding to ambient RF sources. The multiband rectifier with a ring loop is designed to rectifier the RF signals at four desired frequencies. Finally, a power management circuit with storing and converting the harvested voltage is designed for smoothing dc output voltage supplied to a practical IoT wireless device.

REFERENCES

[1] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 757–789, 2nd Quart., 2015.

[2] H. Nishimoto, Y. Kawahara, and T. Asami, "Prototype implementation of ambient RF energy harvesting wireless sensor networks," in *Proc. IEEE Sensors*, Nov. 2010, pp. 1282–1287.

[3] N. H. Nguyen *et al.*, "A novel wideband circularly polarized antenna for RF energy harvesting in wireless sensor nodes," *Int. J. Antennas Propag.*, vol. 2018, pp. 1–9, 2018.

[4] A. Bakkali, J. Pelegri-Sebastia, T. Sogorb, V. Llario, and A. Bou-Escriva, "A dual-band antenna for RF energy harvesting systems in wireless sensor networks," *J. Sensors*, vol. 2016, pp. 1–8, Jan. 2016.

[5] N. N. Yoon, N. Ha-Van, and C. Seo, "High-gain and wideband aperture coupled feed patch antenna using four split ring resonators," *Microw. Opt. Technol. Lett.*, vol. 60, no. 8, pp. 1997–2001, Aug. 2018.

[6] X. Zhang, H. Jiang, L. Zhang, C. Zhang, Z. Wang, and X. Chen, "An energy-efficient ASIC for wireless body sensor networks in medical applications," *IEEE Trans. Biomed. Circuits Syst.*, vol. 4, no. 1, pp. 11–18, Feb. 2010.

[7] Y. Hao, L. Peng, H. Lu, M. Hassan, and A. Alamri, "Energy harvesting based body area networks for smart health," *Sensors*, vol. 17, no. 7, p. 1602, Jul. 2017.

[8] M. Pinuela, P. D. Mitcheson, and S. Lucyszyn, "Ambient RF energy harvesting in urban and semi-urban environments," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 7, pp. 2715–2726, Jul. 2013.

[9] N. Shariati, W. S. T. Rowe, J. R. Scott, and K. Ghorbani, "Multi-service highly sensitive rectifier for enhanced RF energy scavenging," *Sci. Rep.*, vol. 5, no. 1, p. 9655, Sep. 2015.

[10] U. Muncuk, K. Alemdar, J. D. Sarode, and K. R. Chowdhury, "Multiband ambient RF energy harvesting circuit design for enabling batteryless sensors and IoT," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2700–2714, Aug. 2018.

[11] C. Song, Y. Huang, J. Zhou, J. Zhang, S. Yuan, and P. Carter, "A high-efficiency broadband rectenna for ambient wireless energy harvesting," *IEEE Trans. Antennas Propag.*, vol. 63, no. 8, pp. 3486–3495, Aug. 2015.

[12] D. Masotti, A. Costanzo, M. Del Prete, and V. Rizzoli, "Genetic-based design of a tetra-band high-efficiency radio-frequency energy harvesting system," *IET Microw., Antennas Propag.*, vol. 7, no. 15, pp. 1254–1263, Dec. 2013.

[13] S. Keyrouz, H. J. Visser, and A. G. Tijhuis, "Multi-band simultaneous radio frequency energy harvesting," in *Proc. 7th Eur. Conf. Antennas Propag. (EuCAP)*, Piscataway, NJ, USA, Apr. 2013, pp. 3058–3061.

[14] M. Stoopman, S. Keyrouz, H. J. Visser, K. Philips, and W. A. Serdijn, "Co-design of a CMOS rectifier and small loop antenna for highly sensitive RF energy harvesters," *IEEE J. Solid-State Circuits*, vol. 49, no. 3, pp. 622–634, Mar. 2014.