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PAPERS

RF energy harvesting using a compact rectenna with an antenna array at 2.45 GHz for IoT applications

Subuh Pramono[1], **Dwiki Dimas Shidiq**[1], **Muhammad Hamka Ibrahim**[1], **Feri Adriyanto**[1], **Alfin Hikmaturokhman**[2]

This work addresses the design, fabrication, and implementation of an RF energy harvester 2.45 GHz using a compact rectenna. Our proposed rectenna focuses on development of an antenna array and rectifier circuit. The proposed rectenna is fabricated using FR4 substrate with its overall size of 12.24 cm × 18.17 cm with a thickness of 1.6 mm. The measured results show that a 10 dB bandwidth covering in 2374-2549 MHz (175 MHz) with center frequency 2415 MHz at S_{11} of -18.2 dB. There is a bandwidth enhancement of 57.6% compared to the single antenna. Gaining of the antenna array is 6 dB that is double a single antenna gain. Spatial diversity technique in antenna array yields a bigger antenna gain thereby increasing the received power level. Experimental measurements are carried out that the rectenna is placed indoor (LOS) at 5 m and outdoor (NLOS) at 15 m. Furthermore, we also explore the rectifier circuit that to maximize the output voltage. The received RF power that transmitted from WiFi router is -55 dBm ($0.15\,\mathrm{nW/cm^2}$) at 5 m and -59 dBm ($0.06\,\mathrm{nW/cm^2}$) at 15 m, respectively. The output voltages are achieved that 1092.5 mV at a distance of 5 m (LOS) and 5.48 mV at a distance of 15 m (NLOS). The highest RF-DC conversion efficiency of our proposed rectenna reaches 77.6%. The rectenna potentially meets all requirements to power up the IoT applications.

Keywords: RF, energy harvesting, rectenna, antenna array, IoT

1 Introduction

Nowadays, energy scavenging has attracted significant attention for self-powered devices in the realization of a smart environment that specifically focuses on the Internet of Things (IoT). However, powering the IoT devices remain a main issue that relates to the use and recharging of batteries will become restrictive and unsustainable for high density of devices. Energy harvesting is a promising technology to solve these challenges [1]. Harvesting ambient energy that is abundantly available in the form of vibration [2], thermal [3], solar [4], radio frequencies (RF) [5], magnetic and piezoelectric [6]. The idea of RF energy harvesting is converting ambient microwave energy to electrical energy introduced firstly by Nicola Tesla in 1890s [7]. RF energy harvesting is using rectifiers and antennas (rectenna) to extract energy from RF signals or ambient RF environment. It can provide mobility, lightweight, be scalable to many nodes and operate without light. RF energy harvesting is based on wireless power transfer including near-far field [8]. It harvests RF energy transmitted from dedicated existing sources such as WiFi and wireless cellular systems. Increasing number and widening deployment of wireless RF sources, ambient RF energy harvest is becoming feasible for the support of self-powered IoT devices. The main challenge in RF energy harvesting is the low power received caused by low RF power density of the ambient RF environment. In addition, the performance of wireless power transfer depends on the efficiency of the RF energy harvester [9]. In the receiver of the RF energy harvesting system, the transmitted RF waves are captured by the antenna which is the main part of the rectenna. First, the antenna converts the captured RF waves to the AC signals at its output. Then, the AC signals enter the rectifier. The rectifier changes the received AC signal to DC power. The DC power is used to charge directly the load or the battery. The receiving antenna is specifically designed based on the resonant frequency of the transmitting RF source. It is designed in such a way with high gain, broadband, high efficiency, and omnidirectional radiation pattern. Therefore, the receiving antenna can provide a high reception power. Moreover, an efficient compact rectifier should be designed for high-performance energy conversion.

Intensive research has been addressed towards antenna design and rectifier circuit development to boost high-efficiency performance with a compact size of rectenna. Several antenna configurations for various applications have been investigated such as single antenna, array antenna, slot antenna. We can utilize the different RF frequency bands. Previous works were including multiband such as dual-band [10], triple-band [11], four-band [12], and six-band [13] have been investigated for RF energy harvesting using a single patch antenna. However, it doesnt optimize the space diversity reception. Therefore, an array antenna configuration is one solution to

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overcome the limitations of a single antenna. An antenna array is a group of two or more antennas. It improves the overall performance over that of a single patch antenna by combines its signals. An antenna array is addressed to increase total gain, reduce the interference, provide space diversity reception, maximize the Signal to Interference plus Noise Ratio (SINR), and to measure the direction of arrival of incoming signals. The antenna elements transmit individually, while in array configuration the radiation pattern of all the elements sums up which has high gain, better performance, and high directivity. Also, there has been a lot of previous research including using different shaping/apertures dipole [14], rectangular [15], spiral [16], ring [16], slot [17], E-shaped patch, folded meandered-line antenna [18], groundplane modification [19][20], with linear and circular polarization.

Rectifiers are usually made of matching elements and diodes. The diodes play a key role in the rectifier circuit. Rectifiers have different topologies depending on the configurations of diodes used for rectification purpose, which include single series [21], single shunt [22], voltage doubler [23], and bridge type [24]. This work investigates a novel design of rectenna. It proposes a combination of antenna array structures and various rectifier circuits which is aimed to provide high output voltage and high RF-DC conversion efficiency.

2 Wireless power transfer

Tesla first introduced wireless power transfer (WPT) in 1890. This system connected the source to the load without using an electrical conductor. It has been continuously investigated by researchers over the last decades. Currently, the development of WPT is significantly increasing. It is potentially applied in modern industry in such as wireless sensor networks (WSN) [9], radio-frequency identification (RFID) [17], machine-to-machine (M2M) [17], wireless charger, internet of things (IoT) [4], and wireless communications. Previously, an inductive power transfer system was a basic system of power transfer. Nowadays, radiative WPT system and the wireless energy harvesting (WEH) from ambient RF fields using rectenna has become an interesting research topic. Specifically, industry 4.0 encourages new technology based on sensors and automations. Smart cities, smart agriculture, smart transportation, etc which using IoT platforms, self-sustainable low powering standalone devices. For example, RFID system applies wireless power transfer, where the incident RF waves transmitted by an RFID reader were harvested by a passive RFID tag for operating its system. Moreover, in an IoT or WSN system, the end nodes were randomly placed and unreachable that need continuous powering for transmitting the data to the head node. Rectenna will be a potential solution for this network, rectenna was embedded with the end node. The end node device automatically configures the network, collects and transmits the data to the head node that communicates with the server through a wireless mobile cellular network or wireline network (fiber optic). The WEH will become one of the promising solutions for continuously powering to low power devices. Rectenna harvests the ambient RF wave from the WiFi and mobile wireless cellular transmitters.

3 Radio frequency energy harvesting

Currently, WiFi technology and wireless mobile cellular are widely implemented both in urban, suburban, and rural areas. Their coverages are always maintained so that the transmitted RF wave will always be available. So far, it is just used as a wireless transmission medium in the communication system. The existence of RF waves has not been widely used. On the other side, the RF waves have the potential as an energy generator. The advantages of using RF waves energy are that the energy is low cost, non-depletable, and clean. The RF wave sources deliver continuous energy and are not obstructed by geographical aspects, weather conditions, day-night time. These things will not be found in other alternative energy sources such as wind, thermal, and solar. The transmitted RF waves reflect, diffuse, and scatter into the surrounding environment can be considered as ambient energy sources. However, getting a large amount of energy from ambient RF sources is still challenging which the transmitted RF waves are attenuated by wireless channels so the strength of the received signal is low [25]. The transmitted RF wave that is an energy source in the far-field propagation can be used for powering any small-standalone devices including an end node in IoT or WSN system. Figure 1 presents the basic structure of an RF energy harvesting system including the RF transmitter (WiFi router or mobile wireless cellular) as the RF energy sources and the rectenna as the receiver. The transmitter emits the RF waves with limited power. Attenuated RF waves are captured by an antenna which is the key part of the rectenna. The antenna produces AC signals at its output port. In the next stage, the AC signal will be converted to DC power by a rectifier. The DC power is used to directly power the load [6], [25]. An ambient RF energy harvesting system has some advantages and disadvantages. The advantages are including (a) power that can be harvested continuously over distance. Conversely, the disadvantages of the RF energy harvesting system such as (a) received RF power level is low, (b) free space loss/attenuation in a wireless channel is high that it is as a function of the distance and frequency, (c) limited power transmitter, (d) low efficiency.

The rectenna plays a key role in RF energy harvesting system. Figure 2 depicts a basic structure of rectenna that consists of receiving antenna, input filter, rectifier, and DC filter. The antennas receive incident RF waves, it should have a high gain and wide bandwidth. Next, the input filter has a role not only as impedance matching but also harmonics rejection. The third part is a rectifier-voltage multiplier that its configuration is determined

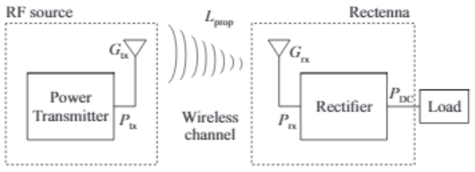


Fig. 1. The basic principle of RF energy harvesting

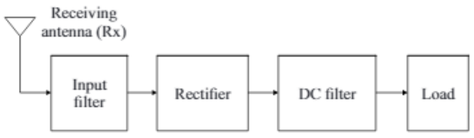


Fig. 2. Basic structure of a rectenna

Table 1. Material specification

	Thickness (cm)	Conductivity (S/m)	Dielectric constant
glass	0.5	10-12	3.0
wood	5	0.08	2.05
metal	5	107	N/A
concrete	16	0.05	5.5

Table 2. Dimensions of single antenna

Parameter	Value (mm)
W	37.26
L	27.87
L_{slot}	11.187
W_{grnd}	56
L_{grnd}	47
W_{slot}	0.3
W_{fline}	5.35
h (thickness)	3.2

based on the desired output voltage. It consists of multiple diodes. The last, DC filter performs to eliminate the unwanted voltage transient. Receiving antenna (Rx)

The ambient RF energy harvesting system is investigated in an indoor and outdoor environment that the room is equipped with a single WiFi router/transmitter. This room office is comprised of glasses, concrete walls, wooden tables-chairs, aluminum door-frame, partition board. The specific material properties are listed in Tab. 1.

The room is a rectangular shape. It sizes $10 \times 15\,\mathrm{m}^2$ with 3.75 m of height. It has one WiFi router/transmitter attached to the ceiling. WiFi router/transmitter is equipped with a 9 dBi omnidirectional antenna and the resonant frequency is 2.45 GHz. The transmitting power is 19 dBm (101.9 milliwatts).

4 Antenna design and fabrication

In rectenna, we use an array rectangular patch antenna for capturing the incoming RF wave emitted by the WiFi router/transmitter. Detail geometrical designs are shown in Fig. 3 and Fig. 5. Furthermore, specific design sizes are described in Tab. 2 and Tab. 3.

Design of the antenna proceeds as follows

- The width of radiator patch

$$W = \frac{c}{2f_{\mathrm{r}}}\sqrt{\frac{2}{\varepsilon_{\mathrm{r}}+1}}, \tag{1}$$

here, f_{r} is the resonant frequency, c is the speed of light $(3 \times 10^8 \mathrm{m/s})$, and ε_{r} is the dielectric constant of substrate.

- Effective dielectric constant

$$\varepsilon_{\mathrm{r,eff}} = \frac{\varepsilon_{\mathrm{r}}+1}{2} + \frac{\varepsilon_{\mathrm{r}}-1}{2}\left[1+12\frac{h}{w}\right]^{-1/2}, \tag{2}$$

where h is the thickness of substrate.

- The fringing length

$$\Delta L = 0.412h\frac{(\varepsilon_{\mathrm{r,eff}}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{\mathrm{r,eff}}-0.258)(\frac{W}{h}+0.8)}. \tag{3}$$

- The effective length of the radiator patch

$$L_{\mathrm{eff}} = \frac{c}{2f_{\mathrm{r}}\sqrt{\varepsilon_{\mathrm{r,eff}}}}, \tag{4}$$

with $L_{\mathrm{eff}} = L + 2\delta L$

We use an SMA connector with characteristic impedance of 50, hence the input impedance of the antenna

$$Z_{\mathrm{c}} = \frac{120\pi}{\sqrt{\varepsilon_{\mathrm{r,eff}}}\left[\frac{W_0}{h}+1.393+0.667ln(\frac{W_0}{h}+1.444)\right]}. \tag{5}$$

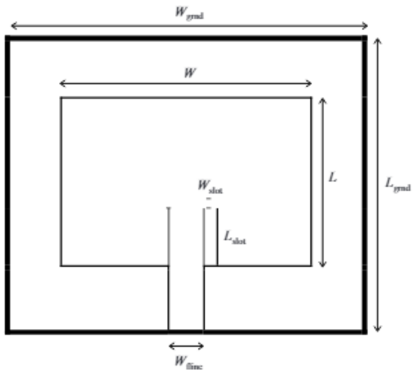


Fig. 3. Geometrical design of a single antenna

Table 3. Dimensions of antenna array 2 ×1

Parameter	Value (mm)
W	37.26
L	27.87
L_{slot}	11.187
W_{grnd}	56
L_{grnd}	47
W_{slot}	0.3
W_{fline}	5.35
h (thickness)	3.2

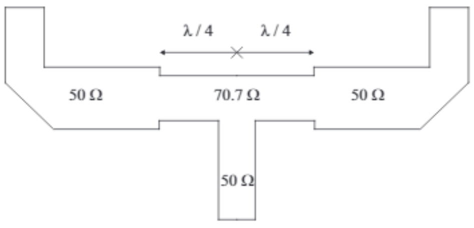


Fig. 4. T-junction

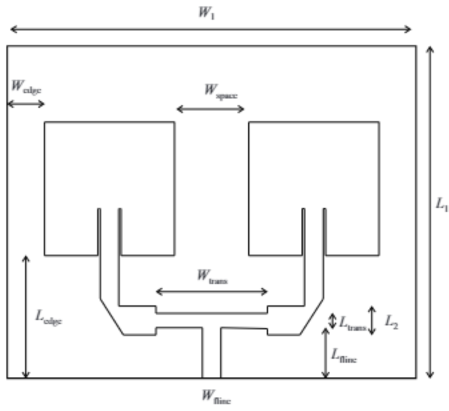


Fig. 5. Configuration of the proposed antenna array 2 ×1

After we design a single patch antenna. We use a T-junction to provide two elements array antenna. Microstrip line feed with transformer $\lambda/4$ is used to match the impedance, seen Fig. 4. T-junction technique divides the electric field distribution into two lines that have a characteristic impedance of 50Ω and 70.7Ω, respectively.

$$Z_{\mathrm{r}} = \sqrt{Z_1 Z_3} = \sqrt{50 \times 100} = 70.7, \tag{6}$$

where, Z_1 is the main feed line impedance, while Z_3 is the sum of the impedances of the two-line branches

The width of the transformer 4 line (70.7) can be determined from

$$W_{Z_0} = \frac{2h}{\pi}\Big\{B_{Z_0} - \ln(2B_{Z_0} - 1) + \frac{\varepsilon_{\mathrm{r}} - 1}{2\varepsilon_{\mathrm{r}}}\Big[\ln(B_{Z_0} - 1) + 0.39 - \frac{0.61}{\varepsilon_{\mathrm{r}}}\Big]\Big\}, \tag{7}$$

$$B_{Z_0} = \frac{60\pi^2}{Z_0\sqrt{\varepsilon_{\mathrm{r}}}}. \tag{8}$$

After we calculate and simulate the design of proposed antenna, we have to fabricate and measure it. Figure 6 shows the fabricated antenna.

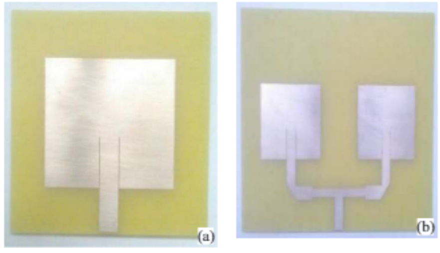


Fig. 6. Photograph of the fabricated antenna (a) single antenna (b) antenna array 2 ×1

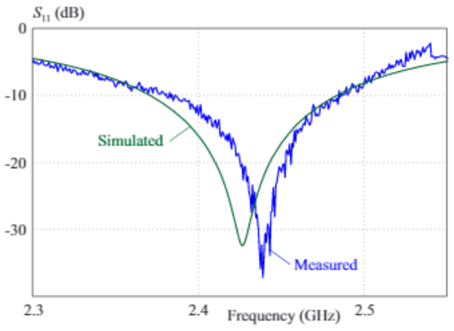


Fig. 7. Return loss of single antenna (simulated & measured)

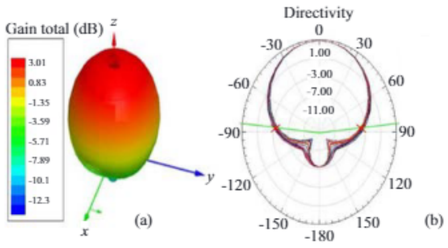


Fig. 8. (a) Gain (b) Radiation pattern of a single antenna (simulated)

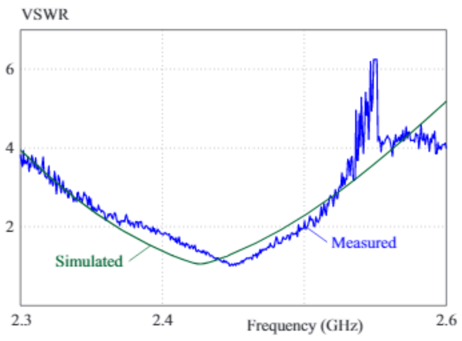


Fig. 9. VSWR of a single antenna (simulated & measured)

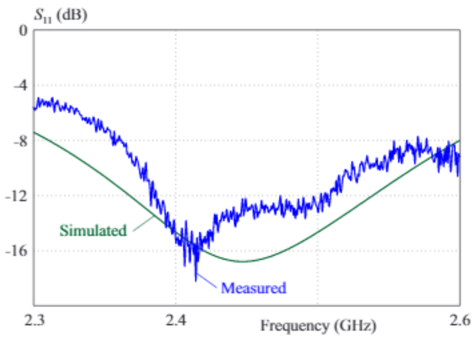


Fig. 10. Return loss performance of antenna array 2 × 1

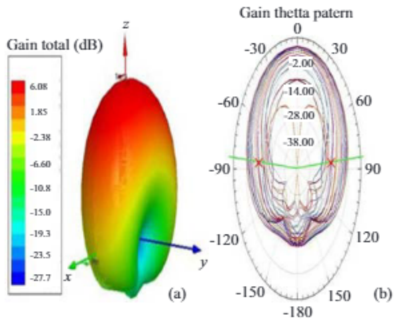


Fig. 11. (a) Gain (b) Radiation pattern of antenna array 2 × 1

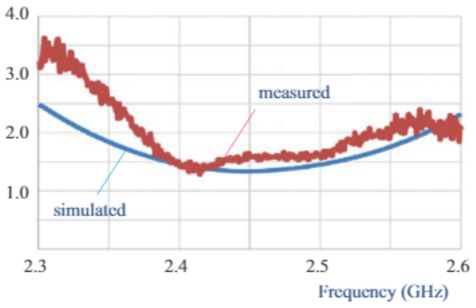


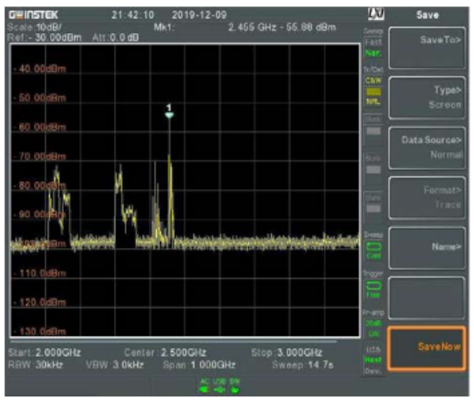
Fig. 12. VSWR of antenna array 2 × 1

Table 4. List of components model A

Component	Value
C	1 pF
L	2.2 nH
CS (junction)	150 pF
D_1	HSMS 2850/SMD
D $_2$	HSMS 2850/SMD
C_P (bypass)	150 pF
R_L	10 k

Figure 7 and Fig. 8 show the performance parameter of the S11 and radiation pattern of a single antenna. Based on figure 7, our proposed single antenna design generates a simulated -10 dB impedance bandwidth of 116 MHz (2371- 2487 MHz) with a center frequency of 2428 MHz at S11 of −32.08dB. The simulated result is confirmed by antenna measurement that the measured results yield a -10 dB impedance bandwidth of 111 MHz (2378 2489 MHz) with a center frequency of 2439 MHz at S11 of -37.16 dB. Figure 8 (b) depicts the radiation pattern of a single antenna with its −3 dB beamwidth (half-power beamwidth) of 156°. In addition, Fig. 8 (a) shows that the single antenna produces a maximum gain of 3 dB.

The second parameter, as pictured in Fig. 9, is investigated for VSWR (voltage standing wave ratio). Generally, VSWR a measure of how efficiently radio- frequency power is transmitted from a power source into a load through a transmission line. Our simulated result (red line) shows that the lowest VSWR is achieved of 1.049 at the frequency 2426 MHz while the measured result (blue line) exhibits that the lowest VSWR is measured of 1.032 at frequency 2448 MHz, it means that only a 1.57% of forwarding voltage to the load is reflected. A VSWR specification commonly adopted is a 2:1 VSWR, which means that the range of frequencies over which the VSWR is less than 2 is chosen as the bandwidth of operation. So, the simulated VSWR bandwidth (VSWR ¡ 2) is in the range of 2367-2489 MHz, while the measured result is in the range of 2380 2501 MHz. Purpose to enhance the performance of the antenna, we design, fabricate, and investigate an antenna array. Referring to Fig. 5, we investigate an antenna array 2x1. Utilizing space diversity in antenna array that to improve the performance of the antenna, enlarging the strength of received signal so that the rectenna output voltage is large, thereby increasing the rectenna efficiency.



21:42:10 2019-12-09
Scale:10dB/
Ref:- 30.00dBm Att:0.0 dB
Mk1: 2.455 GHz - 55.88 dBm
Start:2.000GHz Center:2.500GHz Stop:3.000GHz
RBW:30kHz VBW:3.0kHz Span:1.000GHz Sweep:14.7s

Fig. 13. Measurement of the WiFi working spectrum by spectrum analyzer using the proposed antenna

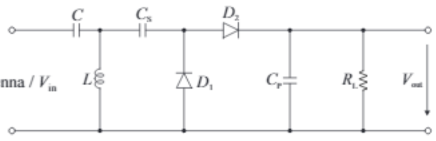


Fig. 14. Schematic configuration of rectifier circuit model A

Based on Fig. 10 shows that the antenna array yields better performance than a single antenna. This configuration gives a simulated -10 dB bandwidth in the range of 2342 2568 MHz (226 MHz) with a center frequency of 2442 MHz at S11 of -16.7 dB. Also, the measured result creates a -10 dB bandwidth covering in 2374-2549 MHz (175 MHz) with center frequency 2415 MHz at S11 of -18.2 dB. There is a bandwidth enhancement of 57.6% compared to the single antenna. Figure 11 informs us that the gaining of the antenna array is double that of a single antenna. There is a gain of 6 dB. It also has a wider half-power beamwidth of 164°.

Based on Fig. 12 that the lowest simulated VSWR of the antenna array is 1.33 at 2451 MHz. It has an ideal VSWR (VSWR 2) covering 2336 - 2568 MHz (232 MHz). Similarly, the lowest measured VSWR is 1.28 at 2417 MHz with its bandwidth (VSWR 2) covering 2369-2552 MHz (183 MHz). After we fabricated and investigated the performance of the antenna parameters, then we applied the antenna to receive ambient RF of WiFi router 2.4 GHz. We measured the strength of the received WiFi router RF using a spectrum analyzer as depicted in Fig. 13. The proposed antenna can operate and receive perfectly the WiFi RF that its working spectrum covering 2412-2495 MHz with a maximum received signal level of $-55.88\,\mathrm{dBm}$.

5 Rectifier design and fabrication

The RF energy harvesting system is mostly providing in a low power density that is caused by limited power transmit and high attenuation at the wireless channel. Therefore, the conversion efficiency of the rectifier plays a key role in generating targeted output power from the harvested ambient RF. A rectifier circuit, as well as an LC filter, consists of an inductor and capacitor components and diode component. In this research, we compare two types of rectifier circuits including model A and model B. Rectifier circuit model A that constructed based on a high pass filter (HPF). HPF passes high frequency with a minimum cut-off of 2.4 GHz. Configuration of rectifier circuit model A is depicted in Fig. 14 and detail components valued in Table 4. We use a single- stage Cockcroft-Walton voltage multiplier circuit with HSMS-2850 diode with a minimum forward voltage of 150 mV (IF = 0.1 mA) and 250 mV (IF = 1 mA), a breakdown voltage of 3.8 V, junction capacitance of 0.18 pF, parasitic series resistance of 25 , maximum reverse leakage current of 150 A. It has low forward bias voltage at high frequencies. It is suitable for low RF input power applications, tangential sensitivity $-56\,\mathrm{dBm}$ at 2.45 GHz. The Schottky HSMS-2852 diode was chosen because it has a low built-in voltage with fast switching response and high cutoff frequency.

The harvested RF by the antenna is converted to DC power through full-wave rectification. The rectifier is directly connected to the antenna port. The diode D1 operates negatively while the diode D2 is active positively. The capacitor C stores energy at a negative cycle. Fabricated rectifier circuit model A is shown in Fig. 15.

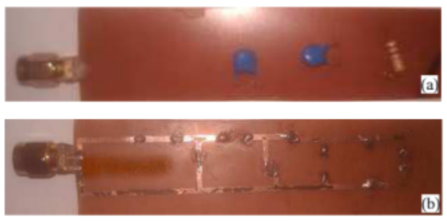


Fig. 15. (a) Front side (b) Backside of fabricated rectifier circuit model A

Furthermore, the rectifier circuit model B contains several components that are almost the same as model A. The difference is the LC filter configuration, in which the position of the inductor and capacitor is changed that the inductor L is serially connected to capacitor Cs. In addition, the load resistor has also been increased to $20\,\mathrm{k}\Omega$. The rectifier circuit model B configuration is based on a low pass filter (LPF) with a maximum cut-off frequency of 2.5 GHz. Detail components and their value are described in Fig. 16 and Tab. 5. The fabricated rectifier circuit model B is shown in Fig. 17.

Table 5. List of components model B

Component	Value
C	2 pF
L	2.2 nH
C_S (junction)	2 pF
D_1	HSMS 2850/SMD
D_2	HSMS 2850/SMD
C_P (bypass)	2.2nF
R_L	20 kΩ

Table 6. Power consumption of various sensors/devices

Device	Consumption
Wearable sensor	60 μW
Smoke detector	55 μW
Gas detector	5.12 mW
CO detector	1.5 mW
Smartwatch	31 mW
WiFi flash memory	210 μW
LED	60 mW

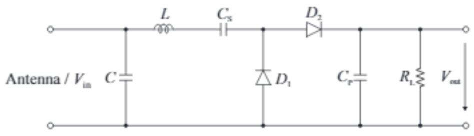


Fig. 16. Schematic configuration of rectifier circuit model B

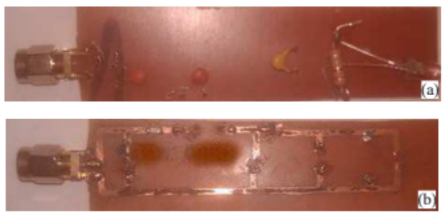


Fig. 17. Fabricated rectifier circuit model B: (a) – front side, (b) – backside

One of the important parameters in assessing the performance of a rectenna is the RF-DC conversion efficiency. The RF-DC conversion efficiency of a rectenna is influenced by the antenna performance, the impedance matching between the antenna and the rectifier, and power loss in the diodes. The RF-DC conversion efficiency is defined as the ratio of the amount of power delivered to the load to the amount of power received by the antenna. The RF- DC conversion efficiency is

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\,, \tag{9}$$

$$\eta = \frac{P_{\text{DC}}}{P_{\text{in}}} = \frac{V_{\text{DC}}^2}{R_{\text{L}}} \frac{1}{P_{\text{in}}}\,, \tag{10}$$

where P_{out} is the rectenna output DC power and P_{in} is the received RF power by the antenna. V_{DC} is the output voltage at the resistance, R_{L} is the resistance and P_{IN} is the received RF power by the antenna. In order to power up IoT and WSN devices, we need to know the power consumed by the sensors. The power consumption of different devices/sensors can be seen in Tab. 6.

6 Rectenna performance

The fabricated prototype of rectenna is shown in Fig. 18. The antenna is connected to the rectifier circuit through an SMA connector. The output voltage of rectenna is measured using a voltmeter.

We have four scenarios for analyzing performance of two types of antenna combined with two types of rectifier circuits. The measurements were taken at a distance of 5 and 15 meters from the WiFi router/transmitter, when the distance is 5 m that the rectenna is placed indoor with line of sight (LOS) propagation while the distance is 15 m that the rectenna is placed outdoor with non-line of sight (NLOS) thereby its higher attenuation. Wireless channel is a time- varying channel so the received power level has fluctuated.

Table 7. The measured output voltage of the rectenna at a distance of 5 m (LOS) & 15 m (NLOS)

No	Location Distance	Scenario (antenna & rectifier)	Lowest (mV)	Highest (mV)	Average (mV)
1	Indoor 5 m/LOS	A_1 & R_{A}	226	388	307
2		A_2 & R_{A}	451	605	528
3		A_1 & R_{B}	896	967	931.5
4		A_2 & R_{B}	982	1203	1092.5
1	Outdoor 15 m/NLOS	A_1 & R_{A}	0.47	0.50	0.485
2		A_2 & R_{A}	0.58	0.60	0.590
3		A_1 & R_{B}	3.71	4.32	4.015
4		A_2 & R_{B}	5.32	5.65	5.485

To determine the effect of changing the number of antennas and the rectifier circuit model on the rectenna, we apply four scenarios. Our scenarios are including A_1 combined with R_A, A_2 combined with R_A, A_1 combined with R_B, A_2 combined with R_B with A_1 is defined as a single antenna, and A2 is assigned two elements array antenna while RA represents rectifier circuit model A and R_B symbolizes rectifier circuit model B. The measured results are shown in Tab. 7. Both the distance of 5 and

Table 8. The RF-DC conversion efficiency at a distance of 15 m (NLOS propagation)

No	Scenario (antenna & rectifier)	Efficiency $\eta(\%)$
1	A_1 & R_{A}	48.68
2	A_2 & R_{A}	31.08
3	A_1 & R_{B}	58.31
4	A_2 & R_{B}	77.57

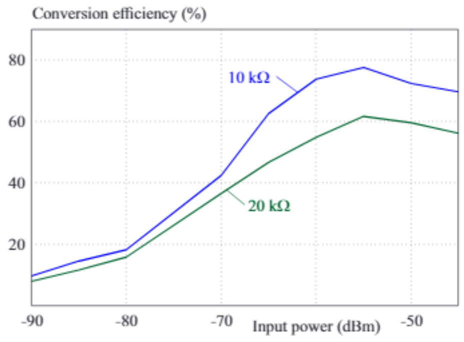


Fig. 18. Conversion efficiency of the proposed rectenna (with antenna array 2×1)

15 meters, the averaged lowest voltage is generated from the first scenario (A_1 combined with R_A) with a value of 0.485 mV at a distance of 15 m and 307 mV at a distance of 5 m while the highest voltage is yielded from the fourth scenario (A_2 combined with R_B) with a value of 5.485 mV at a distance of 15 m and 1092.5 mV at a distance of 5 m. By seeing the trend of measured results in Tab. 7, the presence of space diversity technique on the antenna array system creates a bigger antenna gain thereby increasing the received power level.

Based on our experimental measurement, when we use a single antenna that has an average received power of -59 dBm while using two elements array antenna that its average received power is 55 dBm. Referring the equations 11 and 12, by involving the received power level, resistance at the load, and output voltage of the rectenna, we can calculate the RF-DC conversion efficiency. There is a conversion efficiency for the distance of 15 m which is listed in Tab. 8.

By setting the distance between the WiFi router/transmitter and the rectenna so that the received RF power by the antenna has fluctuated. Thus, the fluctuated received RF power leads to the changing of RF DC conversion efficiency. Figure 19 shows the results of the conversion efficiency which is influenced by the input power. When we use a rectifier circuit model B (RB), the highest conversion efficiency (77.57%) is reached at a -55 dBm of input power.

7 Conclusion

In this work, we proposed, designed, fabricated, and tested a 2.45 GHz RF energy harvester for IoT applications. The proposed rectenna consists of a single or an array antenna, impedance matching, voltage multiplier, and DC filter. The rectenna is fabricated using FR4 substrate. To investigate the rectenna performance, there are four scenarios developed by combining two types of antennas (single and array antenna) and two types of rectifier circuits. Spatial diversity technique on array antenna yields a bigger antenna gain thereby increasing the received power level. Based on the experimental measurement, our proposed rectenna (the fourth scenario) produces a high output voltage of 1.092 V at a distance of 5 m (LOS propagation). It also has a 77.57% of conversion efficiency. The proposed rectenna with an array antenna and specific rectifier circuit is suitable for power up the IoT devices.

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REFERENCES

[1] S. Shen, Y. Zhang, C. Y. Chiu, and R. Murch, “An Ambient RF Energy Harvesting System Where the Number of Antenna Ports Is Dependent on Frequency”, *IEEE Transactions On Microwave Theory And Techniques*, vol. 67, no. (9), pp. 38213832, 2019.

[2] J. McCullagh, “An active diode full-wave charge pump for low acceleration infrastructure-based non-periodic vibration energy harvesting”, *IEEE Trans. Circuits Syst*, vol. 65, no. 5, pp. 17581770, 2018.

[3] F. Wei, “A novel thermal energy storage system in smart building based on phase change material”, *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 28462857, 2018.

[4] J. Bito, R. Bahr, J. G. Hester, S. A. Nauroze, A. Georgiadis, and M. M. Tentzeris, “A novel solar and electromagnetic energy harvesting system with a 3-D printed package for energy efcient Internet-of Things wireless sensors”, *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 5, pp. 18311842, 2017.

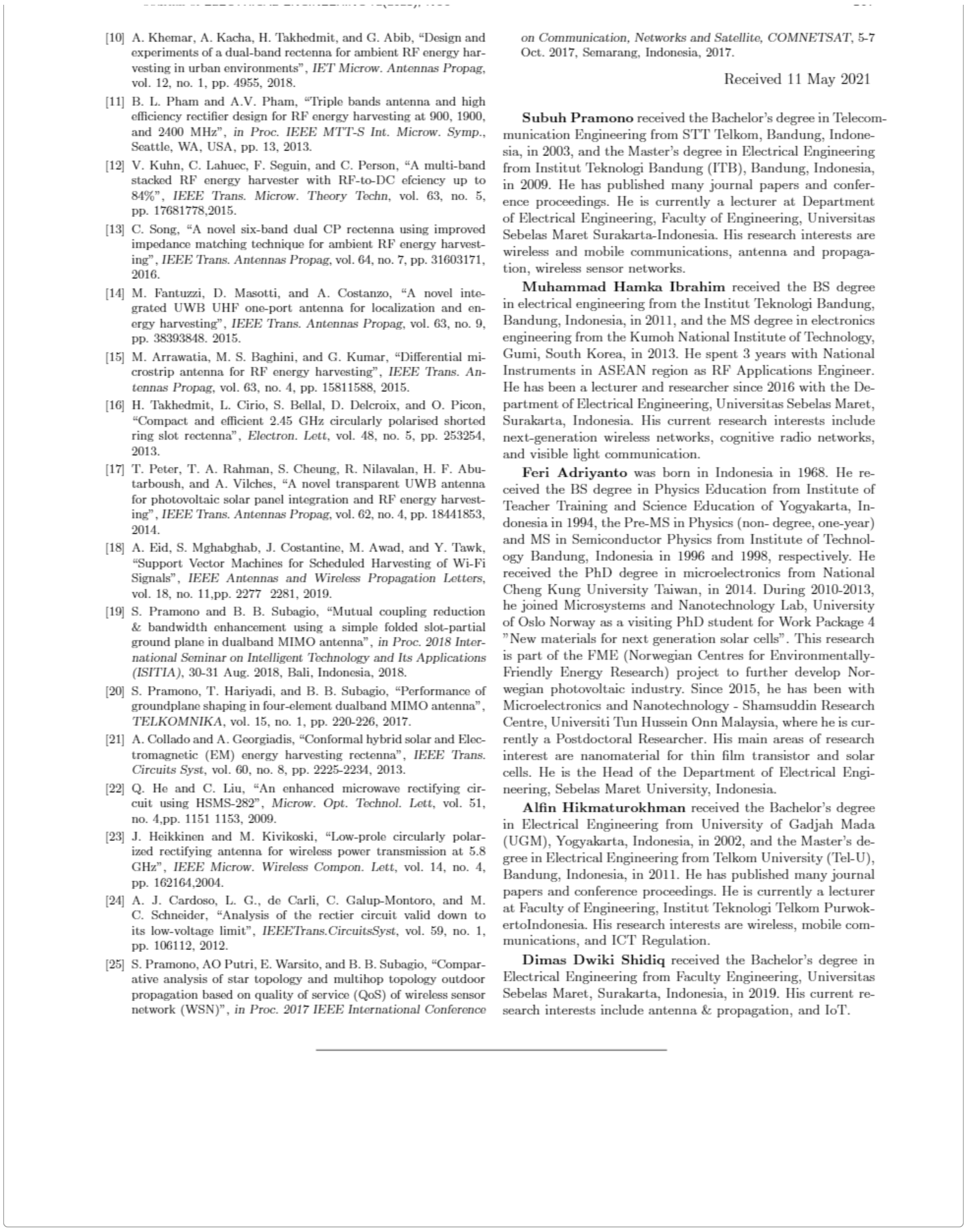
[5] S. Shen, C. Y. Chiu, and R. D. Murch, “Multiport pixel rectenna for ambient RF energy harvesting”, *IEEE Trans. Antennas Propag.*, vol. 66, no. 2, pp. 644656, 2017.

[6] A. Khaligh, P. Zeng, and C. Zheng, “Kinetic energy harvesting using piezoelectric and electromagnetic technologies state of the art”, *IEEE Trans. Ind. Electron*, vol. 57, no. 3, pp. 850-860, 2010.

[7] J. Garnica, R. A. Chinga, and J. Lin, “Wireless power transmission: From far-field to near-field”, *Proc. IEEE*, vol. 101, no. 6, pp. 1321 1331, 2013.

[8] Y. S. Chen, F. P. Lai, and J. W. You, “Analysis of Antenna Radiation Characteristics Using a Hybrid Ray Tracing Algorithm for Indoor WiFi Energy-Harvesting Rectennas”, *IEEE Access*, vol. 7, pp. 38833 38846, 2019.

[9] E. Vandelle, DHN Bui, TP Vuong, G. Ardila, K. Wu, and S. Hemour, “Harvesting Ambient RF Energy Efficiently with Optimal Angular Coverage”, *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 3, pp. 1862 1873, 2018.



[10] A. Khemar, A. Kacha, H. Takhedmit, and G. Abib, "Design and experiments of a dual-band rectenna for ambient RF energy harvesting in urban environments", *IET Microw. Antennas Propag*, vol. 12, no. 1, pp. 4955, 2018.

[11] B. L. Pham and A.V. Pham, "Triple bands antenna and high efficiency rectifier design for RF energy harvesting at 900, 1900, and 2400 MHz", *in Proc. IEEE MTT-S Int. Microw. Symp.*, Seattle, WA, USA, pp. 13, 2013.

[12] V. Kuhn, C. Lahuec, F. Seguin, and C. Person, "A multi-band stacked RF energy harvester with RF-to-DC efficiency up to 84%", *IEEE Trans. Microw. Theory Techn*, vol. 63, no. 5, pp. 17681778,2015.

[13] C. Song, "A novel six-band dual CP rectenna using improved impedance matching technique for ambient RF energy harvesting", *IEEE Trans. Antennas Propag*, vol. 64, no. 7, pp. 31603171, 2016.

[14] M. Fantuzzi, D. Masotti, and A. Costanzo, "A novel integrated UWB UHF one-port antenna for localization and energy harvesting", *IEEE Trans. Antennas Propag*, vol. 63, no. 9, pp. 38393848. 2015.

[15] M. Arrawatia, M. S. Baghini, and G. Kumar, "Differential microstrip antenna for RF energy harvesting", *IEEE Trans. Antennas Propag*, vol. 63, no. 4, pp. 15811588, 2015.

[16] H. Takhedmit, L. Cirio, S. Bellal, D. Delcroix, and O. Picon, "Compact and efficient 2.45 GHz circularly polarised shorted ring slot rectenna", *Electron. Lett*, vol. 48, no. 5, pp. 253254, 2013.

[17] T. Peter, T. A. Rahman, S. Cheung, R. Nilavalan, H. F. Abutarboush, and A. Vilches, "A novel transparent UWB antenna for photovoltaic solar panel integration and RF energy harvesting", *IEEE Trans. Antennas Propag*, vol. 62, no. 4, pp. 18441853, 2014.

[18] A. Eid, S. Mghabghab, J. Costantine, M. Awad, and Y. Tawk, "Support Vector Machines for Scheduled Harvesting of Wi-Fi Signals", *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 11,pp. 2277 2281, 2019.

[19] S. Pramono and B. B. Subagio, "Mutual coupling reduction & bandwidth enhancement using a simple folded slot-partial ground plane in dualband MIMO antenna", *in Proc. 2018 International Seminar on Intelligent Technology and Its Applications (ISITIA)*, 30-31 Aug. 2018, Bali, Indonesia, 2018.

[20] S. Pramono, T. Hariyadi, and B. B. Subagio, "Performance of groundplane shaping in four-element dualband MIMO antenna", *TELKOMNIKA*, vol. 15, no. 1, pp. 220-226, 2017.

[21] A. Collado and A. Georgiadis, "Conformal hybrid solar and Electromagnetic (EM) energy harvesting rectenna", *IEEE Trans. Circuits Syst*, vol. 60, no. 8, pp. 2225-2234, 2013.

[22] Q. He and C. Liu, "An enhanced microwave rectifying circuit using HSMS-282", *Microw. Opt. Technol. Lett*, vol. 51, no. 4,pp. 1151 1153, 2009.

[23] J. Heikkinen and M. Kivikoski, "Low-profile circularly polarized rectifying antenna for wireless power transmission at 5.8 GHz", *IEEE Microw. Wireless Compon. Lett*, vol. 14, no. 4, pp. 162164,2004.

[24] A. J. Cardoso, L. G., de Carli, C. Galup-Montoro, and M. C. Schneider, "Analysis of the rectifier circuit valid down to its low-voltage limit", *IEEETrans.CircuitsSyst*, vol. 59, no. 1, pp. 106112, 2012.

[25] S. Pramono, AO Putri, E. Warsito, and B. B. Subagio, "Comparative analysis of star topology and multihop topology outdoor propagation based on quality of service (QoS) of wireless sensor network (WSN)", *in Proc. 2017 IEEE International Conference on Communication, Networks and Satellite, COMNETSAT*, 5-7 Oct. 2017, Semarang, Indonesia, 2017.

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