Simple Adaptive Rectifier with High Efficiency over a Range of 21 dBm Input Power for RF Energy Harvesting Applications

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***Abstract*—This paper presents a novel simple adaptive and efficient rectifier for Radio Frequency (RF) energy harvesting applications. Traditional rectifiers have maximum RF-DC Power Conversion Efficiency (PCE) over a narrow range of RF input power due to diode breakdown voltage restrictions. The proposed adaptive design helps to extend the PCE over a wider range of RF input power at 2.45GHz using a simple design. Two alternative paths are controlled depending on the RF input power level. Low input power levels activate the first path connected to a single rectifier; low power levels make the diode operate below its breakdown voltage and therefore avoiding PCE degradation. High input power levels activate the second path dividing it into three rectifiers. This keeps input power at each rectifier at a low power level to avoid exceeding the diode break down voltage. Simulated PCE of this work is kept above 50% over a range of 21.4 dBm input power from -0.8dBm to 20.6dBm.**

***Index Terms*—RF energy harvesting, rectifier, power conversion efficiency**

I. Introduction

Energy harvesting techniques utilize energy from the surrounding environment such as (vibration, heat, wind, solar, and electromagnetic waves, etc.). Radio frequency harvesting (RFH) is counted as a promising harvesting technology due to the use of wireless technology as a vital aspect of our modern lifestyle. Radio Frequency (RF) energy is available in an extensive range of frequency bands used in our daily life as (mobile bands, Wi-Fi bands, radio, and TV bands). This encourages recycling these numerous surrounding free energies by harvesting and converting them into Direct Current (DC) power to replace energy sources for many low power applications such as Wireless Sensor Network (WSN) and Internet of Things (IOT). Fig. 1 shows a fundamental block diagram of RF energy harvester that contains rectenna including (antenna, impedance matching network, and rectifier), power management unit, and finally the load represented in the targeted application. The overall performance of RF harvester is measured by many parameters such as RF-DC Power Conversion Efficiency (PCE), sensitivity, operation distance, and output power [1]. Designing RF harvester faces many challenges, including the increase of PCE, which measures the ratio between harvester DC output power measured on the load terminals (P_{out}) and the power harvested by the antenna (P_{in}), and PCE is calculated using the following equations:

$$p_{out} = \frac{(V_{\text{dc}})^2}{R_{\text{load}}} \tag{1}$$

$$\text{PCE}=\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right)100\% \tag{2}$$

Several studies have been proposed to enhance PCE; for example, broadband harvester in [2] and [3], multiband harvester also discussed in [4] using a dual band rectifier, or quad band rectifier as in [5], and six band rectifier as in [6]. Other approaches have focused on enhancing the matching techniques to keep RF harvested power with minimum losses to avoid degrading in PCE [7], [8].

These studies and many others have achieved their maximum PCE over a narrow range of RF input power, available surrounding RF power can vary depending on its location from harvester and time during the day. It is fluctuated and keeps maximum PCE over a wide range of input power is a challenging target.

Increasing PCE over a wide range of input power has been discussed in several studies, e. g., Maximum Power Point Tracking (MPPT) method for increasing harvester dynamic range [9], the Resistance Compression Technique (RCT) [10], [11], and using dynamic input matching network [12]. In this paper we will propose a simple design to reach this target.

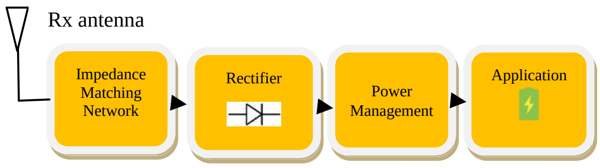

Fig. 1. Fundamental RF energy harvester block diagram.

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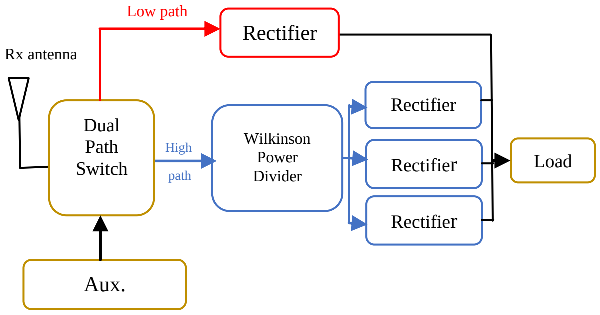


Fig. 2. Block diagram of proposed simple adaptive high PCE rectenna.

The relation between PCE and RF input power is highly nonlinear, specifically as RF input power increases. PCE increases to reach its maximum value then decreases significantly [13]. There is an optimal RF input power level leading to the maximum conversion efficiency, this maximum point is changeable depending on rectifier topology and rectifying element.

As shown in Fig. 2, this work proposes two paths for input RF power depending on its power level, a dual path switch selects the suitable path. The rectifier has its maximum PCE point at a specific input power range depending on diode breakdown voltage. This design tries to keep input power range at a level that avoids reaching diode breakdown voltage. The dual path switch selects a low path for the low-medium RF input power and selects a high path for the high RF input power, then power divider dividing the received high power equally into multiple rectifiers. Wilkinson divider is selected among many simple power divider designs because it is a very low loss divider when the output ports are matched and the isolation resistors used introduces minimal loss, especially when microstrip transmission lines are used along with low-loss PCB substrate material [14], [15].

This keeps the optimum power range at each rectifier input. This design keeps high PCE over a wide range of RF input power with a simple design.

This paper is arranged as follows. Section II involves a discussion of a novel simple adaptive circuit with high PCE using two different topologies. The simulation results of the proposed design are discussed in Section III, and Section IV presents the conclusion.

II. Simple Adaptive Rectifier

The PCE of a rectifier is the key to the proposed design, rectifier PCE maximum point depends on the selected diode, rectifier topology, and load resistance value. This section discusses the selection of diode and its effect on PCE. Two different rectifier topologies are used in the design of a simple adaptive rectifier.

A. Diode Selection

This study is concerned about Schottky diodes as a rectifying element due to its low turn-on voltage, each diode series as (HSMS285x and HSMS286x) has a different effect on maximum PCE point due to its breakdown voltage as illustrated in Spice parameters in Table I [16].

Table I: Spice Parameters of HSMS-285x and HSMS-286x Shottky Diodes

Parameter	Units	HSMS-285x	HSMS-286x
Bv	V	3.8	6
C_{J0}	PF	0.18	0.18
E_G	eV	0.69	0.69
I_{BV}	A	3x10E-4	10E-5
I_S	A	3x10E-6	5x10E-8
N		1.06	1.08
Rs	Ω	25	5.0
P_B(VJ)	V	0.35	0.65
P_T(XTI)		2	2
M		0.5	0.5

PCE of the rectifier increases directly with input RF power till it reaches diode breakdown voltage, then it decreases though increasing input RF power. To illustrate the effect of the breakdown voltage of diode on the PCE curve, two voltage doubler rectifiers are simulated. The simulation setup is created in the Agilent Advanced Design System (ADS) software because it is more suitable for microwave elements more than other simulation software like PSpice. First rectifier by using an (HSMS-2852) package and the second by using (HSMS-2862) package with a load resistance of 1KΩ applied on each of them. Fig. 3 shows the simulation results of DC output voltage and PCE curve at 2.45GHz, the maximum PCE point is at P_{in}=6.53dBm for the (HSMS-2852) diode package and P_{in}=11.44 dBm for the (HSMS-2862) diode package. To keep PCE at its maximum over a wider range of input power, the diode input voltage should be kept below the voltage of breakdown. The proposed design uses the (HSMS-285x) diode series due to its better performance in low power levels.

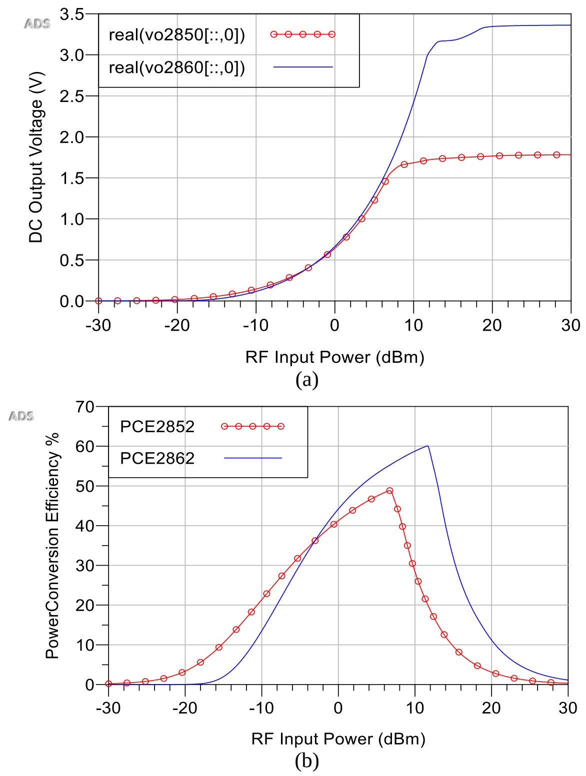
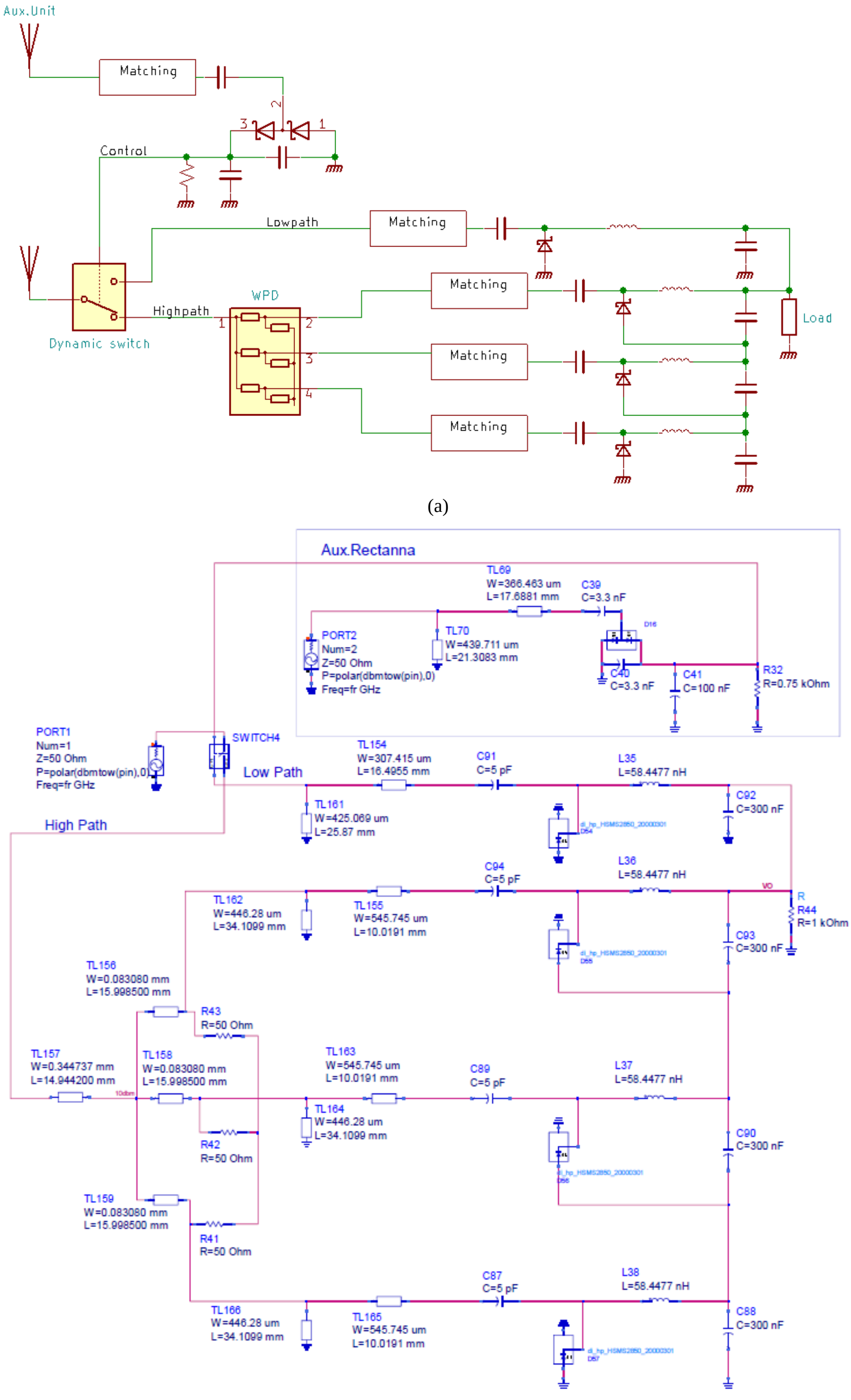


Fig. 3. Simulation results: (a) DC output voltage and (b) PCE of HSMS-2852 and HSMS-2862 diode packages.

B. Rectifier Topology and Proposed Circuit

There are many rectifier topologies presented in the RF harvesting research field. The difference between them depends on the position and number of used diodes. The simplest topologies used are series or shunt mounted single diode [17], and they show good performance in low power levels [18], [19]. Voltage multiplier or voltage doubler is also common in the literature to improve DC output voltage [20].

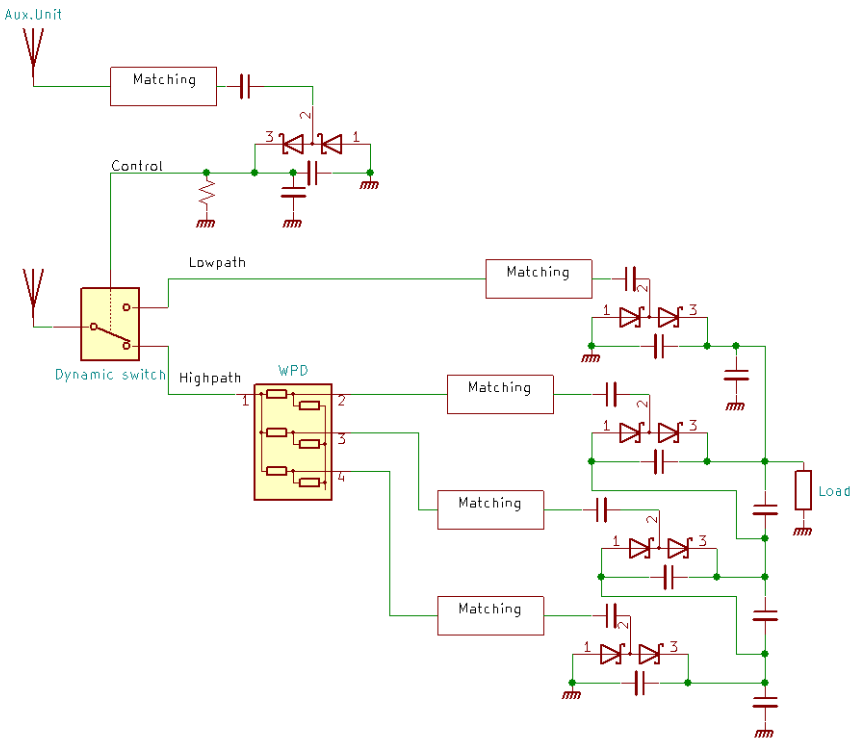
The proposed simple adaptive rectenna is designed using two different topologies; shunt diode topology as in Fig. 4, and voltage doubler topology as in Fig. 5.



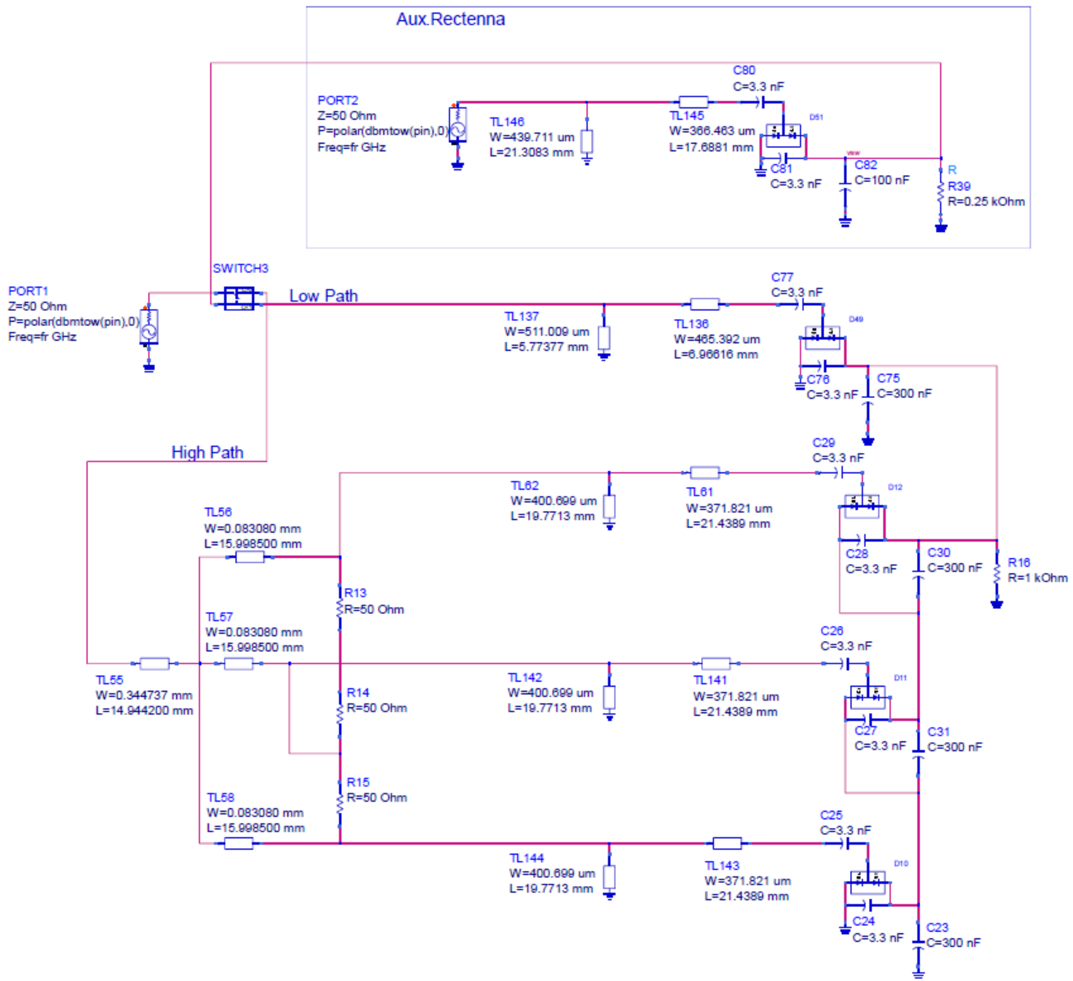
(a)

(b)

Fig. 4. Shunt diode topology: (a) Simplified schematic, (b) detailed schematic for simple adaptive rectenna using shunt model diode topology.



(a)



(b)

Fig. 5. Voltage doubler topology: (a) Simplified schematic, (b) detailed schematic for simple adaptive rectenna using voltage doubler topology.

TABLE II: DYNAMIC SWITCH RANGE OF USAGE

Control voltage (V)	R_1	R_2
$V_C > 2$	R_{on}	R_{off}
$V_C < 1$	R_{off}	R_{on}
$1 < V_C < 1.5$	R_{off}	Shifts from R_{on} to R_{off}
$V_C = 1.5$	R_{off}	R_{off}
$1.5 < V_C < 2$	Shifts from R_{off} to R_{on}	R_{off}

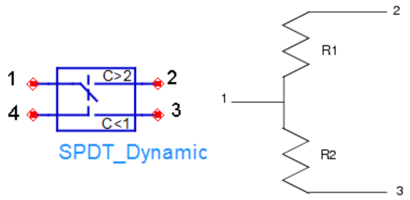


Fig. 6. Dynamic single pole double throw switch used in proposed design.

The designed operating frequency of each rectenna is 2.45GHz. The received antenna is modeled in simulation as a frequency source with 50Ω characteristic impedance. The simulation is conducted over a range of RF input power from –30dBm to 30dBm.

RF received signal is input to a dynamic single pole double throw switch SPDT shown in Fig. 6. Pin1 is the switch input, while pin 2 and pin 3 are the switch outputs connected to the high path and low path, respectively. Pin 4 is connected to the control voltage (V_C) supplied from an auxiliary rectenna. The dynamic switch has a range of usage [21] illustrated in Table II.

Auxiliary rectenna is designed using voltage doubler topology with the same operating parameters. When the RF input power level is low, its DC output is less than 1V and is supplied to the SPDT switch as a control voltage to select the low path rectenna. When the RF input power level is a high, auxiliary DC output is greater than 2V and supplied as a control voltage to let the switch select the high path.

The low path is connected to a short stub matching circuit. It is a simple matching technique to match a 50Ω antenna with the input impedance of rectifier, it is designed and optimized using Smith chart and optimization tools in ADS software. Matching stub is connected to the rectifier (shunt model diode topology or voltage doubler topology). The output DC increases directly with RF input power and achieves a maximum PCE at the optimum diode input power then DC voltage reaches to diode break down voltage which causes a dramatic decrease in PCE.

The high path is connected to a 3-way Wilkinson power divider designed as mentioned in [14], which divides the received high power equally between three rectenna cells to avoid reaching the breakdown voltage. Switching between low path in case of the low RF input power and high path in case of the high input RF power extends the maximum point of PCE over a wide range of input power and takes the advantage of available high power rather than missing it up. Each rectifier topology causes a shift in the maximum point of PCE. It is discussed in the next section with the result of the simulation for each rectifier topology.

III. SIMULATION RESULTS

Simulation is based on the use of RT/Duriod 6006 substrate from Rogers corporation [22], having a thickness of 0.254mm, the relative dielectric constant is 6.15, a dissipation factor (tanδ) is 0.0027, and a metal thickness of 35 μm.

First, the simulation is conducted by using LSSP (Large Signal S-Parameter) simulator because it considers the nonlinearity of the diode. It measures the input impedance of the rectifier and designs the matching stub. Next, the matching stub length is optimized to get a good value of input reflection coefficient S_{11} to be around –30dB and to ensure that rectifier input impedance matches with the 50Ω antenna characteristic impedance. Finally, a harmonic balance simulator (HB) is used to get the DC output voltage and rectifier PCE.

A static switch is used in the first simulation result then a dynamic switch is applied instead.

A. Shunt Diode Topology Simulation Results

The DC output voltage and rectifier PCE are shown in Fig. 7 using a static SPDT switch and Fig. 8 using a dynamic SPDT switch.

Results in Fig. 7 (b) show the shift of PCE maximum point in case of selecting the high path due to dividing the RF input power to three rectifiers. Fig. 8 shows the result when the circuit is automatically switched from the low path to high path depending on power level of the RF input signal using a dynamic switch.

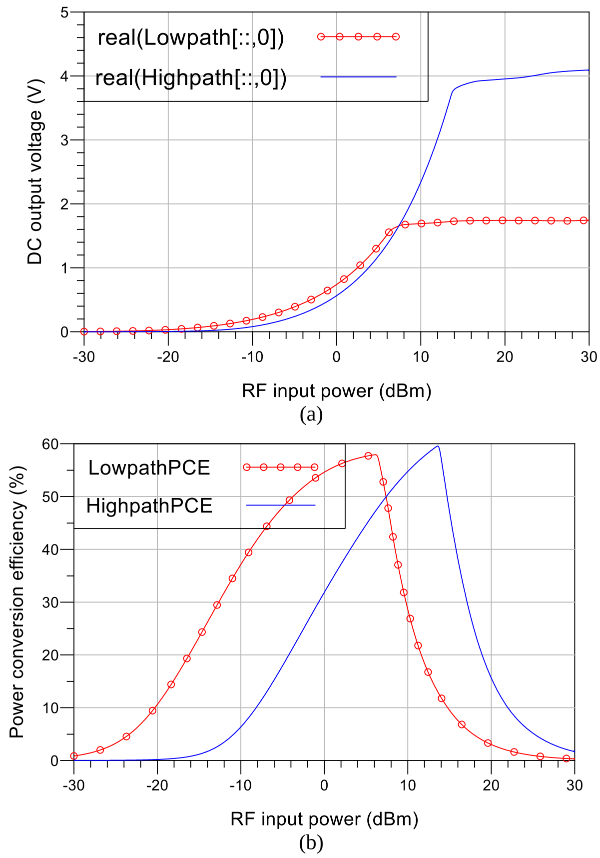


Fig. 7. Simulation results using static switch: (a) DC output voltage and (b) PCE of shunt diode topology.

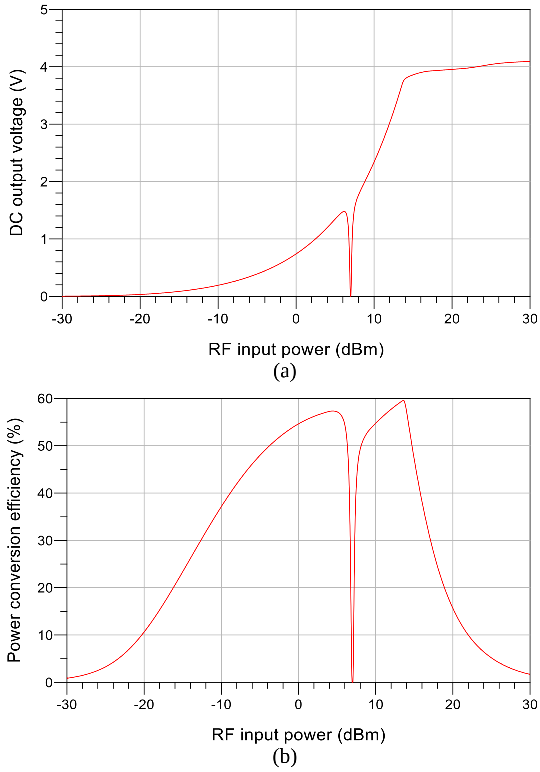


Fig. 8. Simulation results using dynamic switch: (a) DC output voltage and (b) PCE of shunt diode topology.

The proposed simple adaptive rectifier using the shunt diode topology achieves maximum PCE 59.5% at 13.6dBm. It keeps PCE above 50% over a range of input power from –3.7dBm to 14 .7dBm and keeps PCE above 20% from –16.2dBm to 18.9dBm. A drop is observed at 1.5V, as mentioned before in Table II. Control voltage (V_c=1.5V) turns the switch off (break before make). PCE drops at this voltage and can be avoided by using a more complex adaptive control circuit.

B. *Voltage Doubler Topology Simulation Results*

The DC output voltage and the rectifier PCE are shown in Fig. 9 using a static SPDT switch and Fig. 10 using a dynamic SPDT switch. The results show the maximum PCE is 65% at 10.5 dBm. It keeps PCE above 50% over a range of input power from –0.8dBm to 20.6dBm and keeps PCE above 20% from –11.7dBm to 24.82dBm.

Results show that PCE is above 50% over a range of 18.4 dBm of the input power for the shunt diode topology and 21.4 dBm of the input power for the voltage doubler topology.

Table III summarizes a comparison with previous works done to improve PCE over the range of RF input power. Martins and Serdijn applied MPPT to control the system in order to accommodate the variation of input power [9]. Barton *et al.* used the resistance compression technique to keep input impedance of the rectifier near constant [10]. Zeng *et al.* used multistage reconfigurable rectifier to switch the rectifier topology from series to parallel topology depending on power level [23]. Almansouri *et al.* proposed to control the conduction of transistors used in the rectifier and limit the reverse current with avoiding degrading in the forward current by applying a variable biasing technique [24]. Lu *et al.* adopted dual path CMOS rectifier with adaptive control circuit for auto-selection path, while this paper presents a promising simulation result for PCE using a simpler design [25].

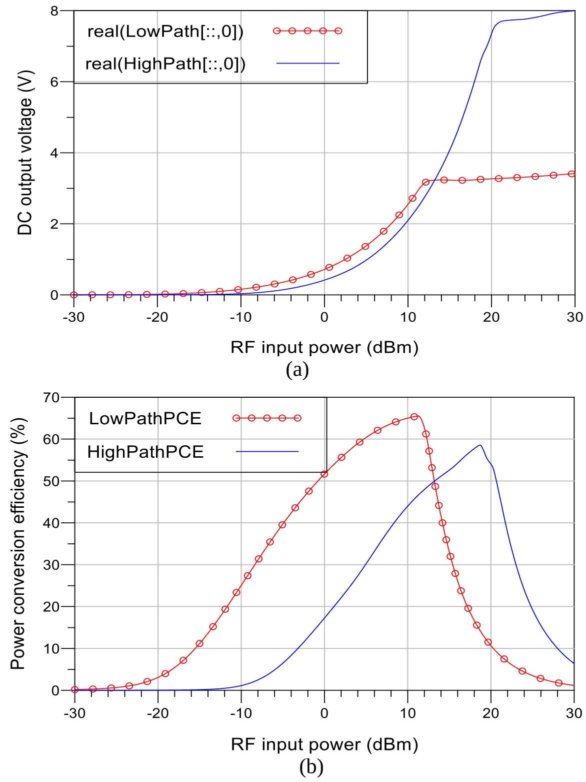


Fig. 9. Simulation results using static switch: (a) DC output voltage and (b) PCE of voltage doubler topology.

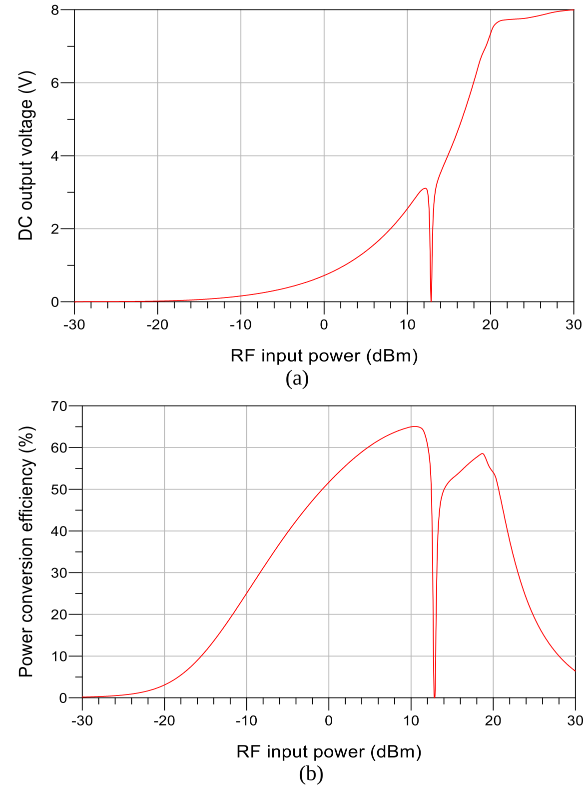


Fig. 10. Simulation results using dynamic switch: (a) DC output voltage and (b) PCE of voltage doubler topology.

TABLE III: COMPARISON WITH THE PREVIOUS WORK

Pub.	Methodology	Freq.	Peak PCE	PCE range	Result
[9]	MPPT	403.5 MHZ	49.1%	*13 dBm above 40%	simulated
[10]	RCT	2.45 GHZ	70%	*10 dBm above 50%	measured
[23]	reconfigurable rectifier stage	820 MHz	39%	14 dBm Above 20% PCE	measured
[24]	Variable biasing technique	433 MHZ	*70%	*13 dBm above 50%	simulated
[25]	Dual path for input power	900MHz	36.5%	11dBm Above 20% PCE	measured
This work	Dual path for input power	2.45 GHz	65%	21 dBm above 50% PCE	simulated

*Estimated from the figure.

IV. CONCLUSION

This paper introduced a novel adaptive rectenna based on a simple design for RF energy harvesting applications. It aims to keep high PCE over a wide range of RF input power. The proposed rectenna is simulated by using two different rectifier topologies, 50% PCE is achieved over a range of RF input power 21.4dBm using voltage doubler topology.

CONFLICT OF INTEREST

The authors do hereby declare that there is no conflict of interest whatsoever concerning this paper.

AUTHOR CONTRIBUTIONS

All the authors contribute equally to the implementation of such work, both for bibliographic research, the simulation and for drafting of the paper. All authors had approved the final version.

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