Wireless Personal Communications
https://doi.org/10.1007/s11277-021-08463-7

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Performance Evaluation of RF Energy Harvesting Circuit with DRA and Planar Antennas

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Accepted: 28 March 2021

Abstract

In this study, a rectenna (antenna + rectifier) performance is compared with two different types of antennas; planar and DRA. The CST Microwave Studio and Advance Design System (ADS) is used to perform co-simulation. In this, first a .S2P is generated using two similar antennas keeping at a far-field distance in CST, afterward it is imported in ADS and tested with a typical rectifier circuit. Further, two experimental methods are performed in indoor and outdoor environments to validate the simulation results. In the indoor environment, a horn antenna excited with a signal generator is used as an RF power transmitter. In contrast, in the outdoor environment, the horn antenna is replaced with an ambient power source like a mobile base station. In both methods, at receiving side rectenna (antenna + rectifier) is kept in the far-field region. Here, both planar metallic and dielectric resonator antennas are use done after another with the rectifier circuit to test the rectenna system. From the simulation and experiments performed in indoor and outdoor environment method, it is confirmed that the rectenna system tenders the best performance with dielectric resonator antenna.

Keywords RF energy harvesting · DC voltage · Planar antenna · Dielectric resonator antenna

1 Introduction

Rapid advancement in wireless technology and associated devices require more efficient and powerful batteries to drive and function properly. However, these batteries need to be recharged frequently and to be replaced after some time due to their limited capacity and life cycle. Furthermore, this process is very hectic, time consuming and less practical at some instants and limits the performance of the device. It is possible to overcome partial or full battery replacement problems through the advancements in the RF energy harvesting

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techniques and circuits also termed as rectenna systems. However, despite these advancements, factors like multipath fading, low RF signal level and path loss due to the spatial separation between the RF source and the device severely affect the rectenna performance.

Therefore, to improve the rectenna performance in these circumstances, it is essential to collect more and more RF signals from the surrounding environment, which is possible through high gain and efficient antenna and rectifier circuit design.

In literature, many researchers have been reported a comparative analysis of RF energy harvesting circuits in terms of different matching techniques [1], diode selection and rectifier topologies [2], but not in terms of different antennas like planar and dielectric resonator antenna. Due to absence of metallic losses, DRA yields few noticeable features like broad impedance bandwidth, high gain and radiation efficiency compared to planar antennas [8], which shows its suitability as a receiving element for an efficient RF energy harvesting circuit. In the past, different types of antennas like planar and dielectric resonator antennas have been reported for RF energy harvesting, but a comparative analysis that may help the researchers to choose an appropriate antenna is not available yet. Previously, very few researchers have provided an idea of DRA application in rectenna system [3–7]. But, none of them compared the harvesting circuit performance with the planar antennas. In [7], a dual-band rectenna system using a broadband DRA is proposed and compared with the earlier reported rectenna systems employing planar antenna as an receiving element. However, the comparison was not fully justifying the superiority of DRA over the other existing planar antenna as they differ in terms of physical size, operating frequency and substrate.

To demonstrate the significance of DRA over planar antenna, this paper presents a comparative study of the RF energy harvesting circuit with the earlier reported planar and dielectric resonator antenna. The rectenna performance is compared in three different ways: (1) Co-simulation using CST Microwave Studio and Advance Design System (ADS) (2) Indoor environment, where a horn antenna is connected to the RF signal source worked as an RF power transmitter and the rectenna system kept in the far-filed. (3) Outdoor environment, where RF transmitter is replaced with the mobile base station. From all methods, it is concluded that compared to a planar antenna, DRA could be a potential candidate for RF energy harvesting to get higher DC voltage and RF to DC conversion efficiency.

2 Simulation Setup for Rectenna Performance Analysis

In order to estimate the rectenna performance, co-simulation has been performed using CST Microwave studio and Advance Design System (ADS), where a.S2p file is first generated by simulating an antenna system as a two-port network in CST environment and then exported in ADS. Figure 1 depicted the schematic diagram of the CST environment, where two same antennas (DRA) are placed in front of each other at a far-field distance *d*. Once the simulation is completed, a 2×2 scattering matrix is generated, which is then exported as a touchstone file (.s2p) in ADS, where it is integrated with matching network and rectifier circuit and simulated further for different RF power levels and corresponding DC output. Here, it is worth mentioning that the same simulation setup is followed for both types of antennas, DRA and planar. Indeed, this 2×2 scattering matrix is a touchstone file with extension.s2p contains spectral characteristics such as reflection coefficient and transmission coefficient of two-port antenna system where transmitting antenna (first antenna) modeled as RF source and 2^{nd} antenna acts as receiving antenna to collect RF signals. The two-port system/network can be characterized using four scattering parameters viz S11,

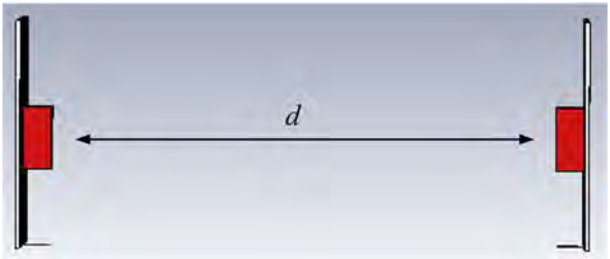


Fig. 1 Photograph of the DRA simulated in CST Microwave Studio as a two-port circuit

S21, S12 and S22 correlate incident, reflected and transmitted signal from its ports. Since both antennas are identical it is expected to have S11 and S22 same.

As seen in Fig. 2, the.S2P file consists of two ports, where one is connected to the input RF source and another one is connected to the rectifier circuit. It can be noticed that a full-wave rectifier configuration is made by a three terminal Schottky diode (HSMS-2852) from Avago technology of threshold voltage (V_{th}) 0.15 V. Though, the diode is a nonlinear device therefore, the rectenna system itself exhibits nonlinearity with incoming signal's power and frequency. However, the nonlinearity effect comes into the picture when RF power level is high, which is not the case here. Thus the impedance is varying with frequency only and to transfer maximum RF power to the load, the impedance of RF source should match with the rectifier circuit.

To obtain impedance matching, single stub matching networks are designed at different frequencies (0.9, 1.8, 2.1 and 2.4 GHz) and inserted between rectifier and antenna (RF source). The single stub matching network is chosen because of the easy optimization and fabrication process. The optimized layout and photographs of fabricated rectifier circuits at different frequencies are depicted in Figs. 3 and 4, respectively.

The rectenna's simulated dc output voltage with planar antenna [11] and DRA [7] is depicted in Fig. 5 at four different frequencies. As seen, at each operating frequencies rectenna achieved enhanced performance while uses the DRA than the planar antenna. Moreover, it can be noticed that the output voltage difference is gradually increased from 33 to 81%, while changing the operating frequency from 0.9 to 2.4 GHz. Although both DR and planar antenna are almost of the same dimensions and yield wideband characteristics, but due to the higher operating frequency, the conductive loss might be higher in planar antenna, which results in degraded performance as compared to DRA.

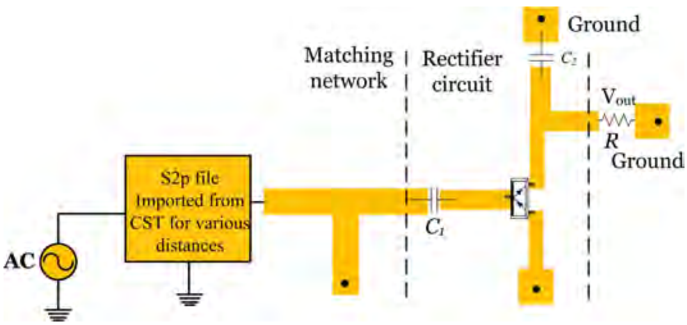


Fig. 2 Simulation setup in ADS environment for rectenna system

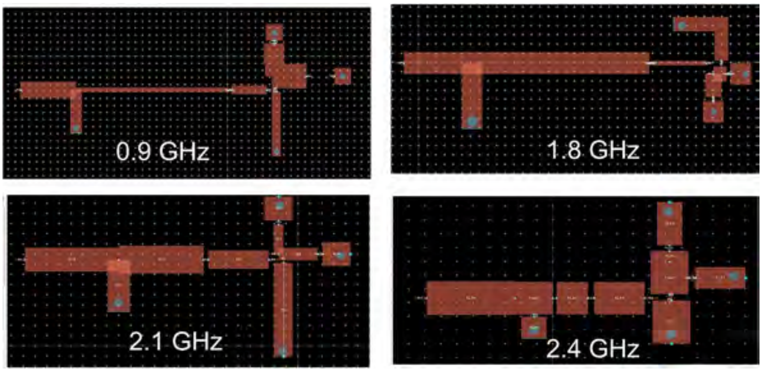


Fig. 3 Rectifier circuit layout at four different frequencies

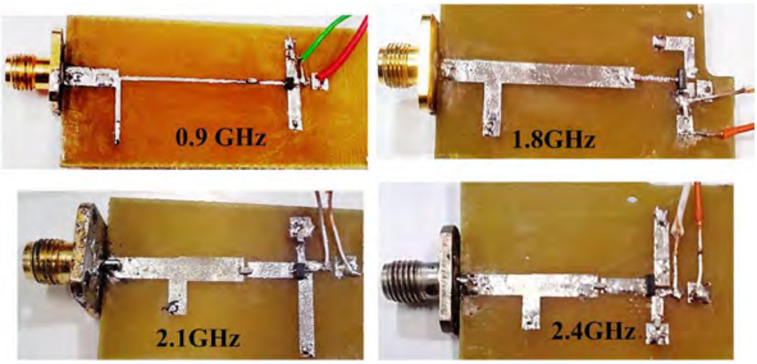


Fig. 4 Fabricated rectifier circuits at four different frequencies

3 Experimental Setup for Rectenna Performance Analysis

Figure 6 depicts the indoor rectenna/RF energy harvesting system performance measurement setup. Here, the sub-figure is showing the rectifier topology. As illustrated that a horn antenna, which is excited with a fixed power supply through a RF signal generator (N9937A) is used as a transmitting antenna. At the receiving end, the rectenna is kept at 1 m distance (to meet far-field region criteria) from the transmitter. Here, all the rectifier circuits shown in Fig. 4 are connected one by one with each antenna (depicted in Table 1) to form a rectenna system. The antennas which are used to receive the incoming RF power are summarized in Table 1.

Figure 7 shows the photograph of the indoor measurement setup. It can be seen that at the transmitting site, the horn antenna is connected to a signal generator (N9937A), whereas the receiving node situated at a distance of d comprises a multiband antenna (depicted in Table 1) connected to a rectifier circuit (shown in Fig. 4) whose output is measured at multi-meter. Figure 8 illustrates the rectenna's output voltage at four different frequencies. As seen, for each frequency DRA based rectennas [6, 7] outperform the planar rectennas [9–11] as DRA offers higher gain than the other planar metal antennas as shown in Table 1. Moreover, the output voltage difference of rectenna using planar and DRA is

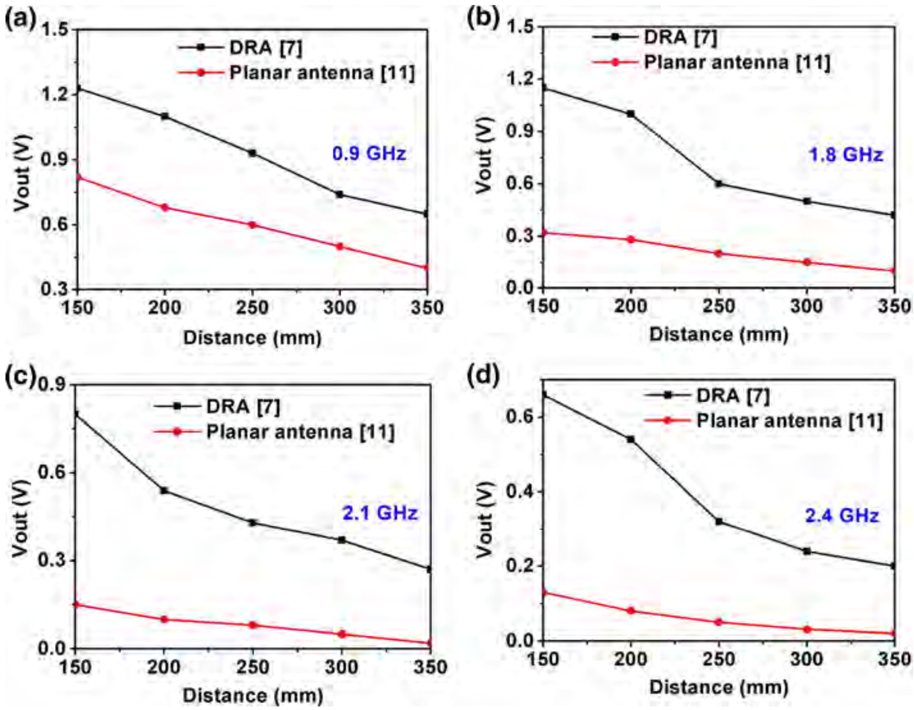


Fig. 5 Output voltage comparison of rectenna system with DRA and patch antenna at four different frequencies

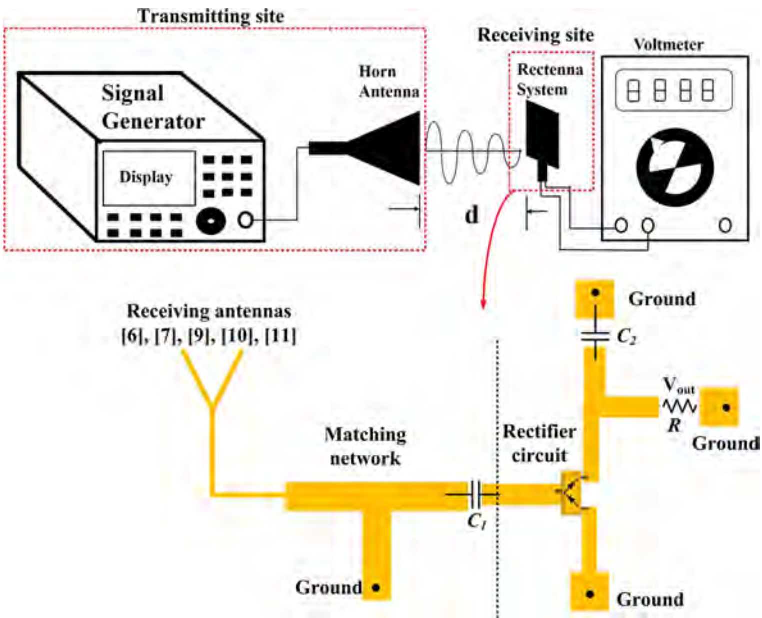
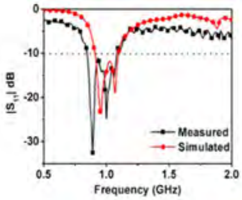
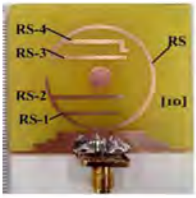
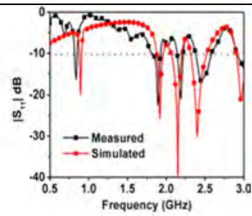
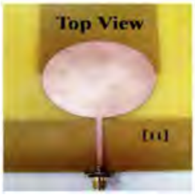
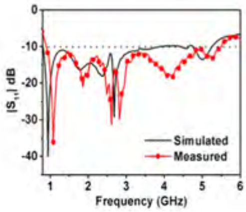
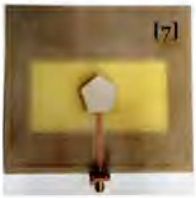
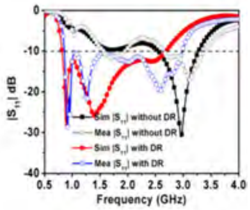
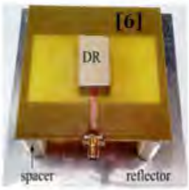
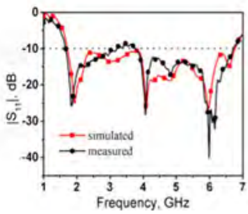


Fig. 6 Indoor rectenna performance measurement setup

Table 1 Antenna design selected for rectenna performance measurement

Antenna Design	Type/ Impedance bandwidth	Gain dBi	Radiation efficiency	Reflection coefficient
	Single-band 0.85-1.1 GHz (25%)	3.3	90-93% 0.85-0.95 GHz	
	Quad band 0.9, 1.8, 2.1, 2.4 GHz	1.72-2.72	60-70%	
	Wideband 0.89-5.53 GHz (144.5%)	1.93-4.3	Above 93% From (0.89-2.5 GHz)	
	Wideband 0.86-3 GHz (110.8%)	3.5-6.8	Above 95% 9.4-2.4 GHz	
	Wideband 1.67-6.7 GHz (120%)	7.5-9.9	Above 95% (1.7-2.5 GHz) Above 85% (2.6-6 GHz)	

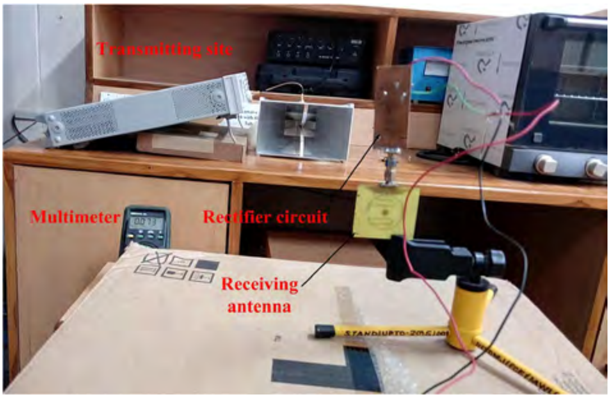


Fig. 7 Photograph of indoor rectenna performance measurement setup

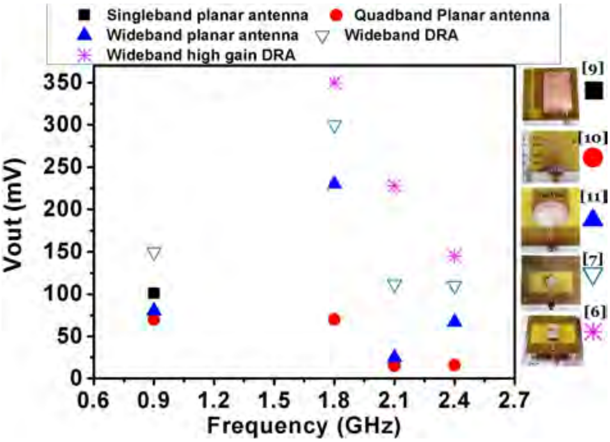


Fig. 8 Indoor rectenna performance measurement with earlier reported antennas

increased with frequency. This may be because of metallic losses, which are increased with frequency in the planar antenna.

In order to measure the rectenna performance in the open environment with the selected antenna designs, the cellular base station was selected in such a way that no surrounding obstacle and irrelevant radiating sources can influence the measurement. Figure 9 depicts the outdoor measurement setup to validate the different rectenna designs experimentally. Here, each rectenna performance is evaluated at a fixed distance of 20 m from the cell tower. All the rectennas are properly aligned and kept in line of slight to the base station to get maximum dc output voltage. Since the signal strength in GSM 900 MHz band is more, therefore, a rectifier circuit operating in the same frequency range is selected to convert the incoming RF power to DC voltage. Furthermore, four antennas [7, 9, 10, 11] working

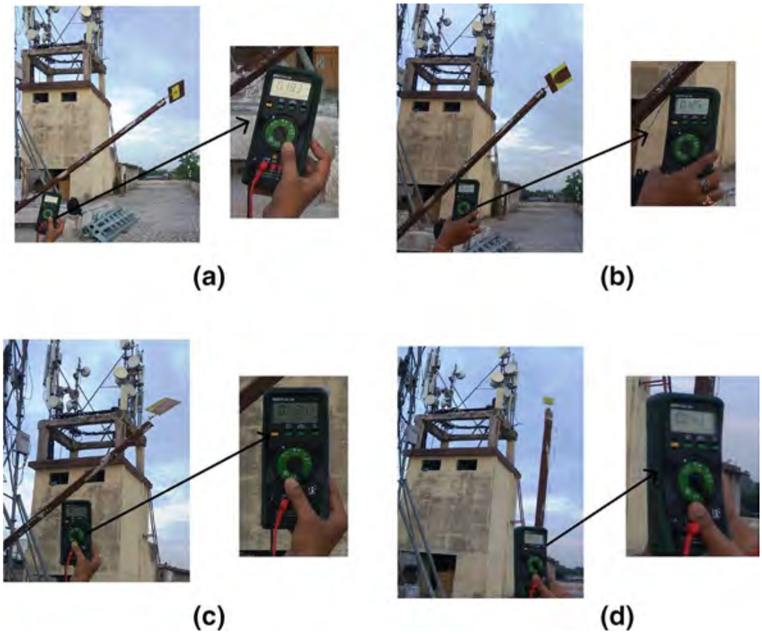


Fig. 9 Outdoor rectenna performance analysis with earlier reported antenna of **a** Ref. [7], **b** Ref. [11], **c** Ref. [9] and **d** Ref. [10]

on GSM-900 are chosen for comparison. Each rectenna's output is measured across the load impedance value of 4.7 kΩ. Here, it is worth mentioning that the same rectifier circuit (shown in Fig. 4) is repeatedly used with all antennas. In Fig. 9, the voltmeter reading shows that the rectenna system exhibits improved performance with DRA as a receiving antenna as compared to planar antennas. For clarity, the output voltage of all the rectennas shown in Fig. 9 is summarized in Table 2.

4 Conclusion

In this paper, a comparative study of a rectenna system with planar and dielectric resonator antennas are examined. Three different methods simulation, indoor and outdoor has been presented to evaluate the rectenna performance with DRA and planar antennas. From all methods, it is verified that a rectenna system offers enhanced performance with DRA than a planar patch antenna. This study suggests that for better RF DC conversion efficiency DRA based rectenna systems may be preferred over planar metallic antennas.

Table 2 Outdoor rectenna performance measurement with different types of antennas

Antenna type	Wideband DRA [7]	Wideband planar antenna [11]	Single band planar antenna [9]	Multiband planar antenna [10]
Output voltage (V)	0.193	0.125	0.131	0.043

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