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Design and feasibility of quad band rectifier for RF energy harvesting technique for wireless technology

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ABSTRACT

The aim of this study is to investigate the feasibility of scavenging multiple RF energy sources from various wireless communication networks (WCN) in ambient environment. In such situations, the exact number of available RF frequency bands is unknown. Therefore, the initial objective of this research is to realize the realistic harvester operation at ambient RF energy levels obtained within rural and semi-urban atmosphere. In order to design highly sensitive multiband RF energy harvester, practical RF power spectral surveys are conducted at Multimedia University (MMU) within a semi-urban region in Malaysia. Based on this RF survey results, a quad-band rectifier circuit (including RF filter, matching section, signal converter, and low-pass filter (LPF)) is suggested over the available preferred frequency bands from the major RF power suppliers (GSM800, GSM1800, 3G and Wi-Fi) within the range of frequency (0.5-3 GHz) part of the RF spectrum. The novel impedance matching technique proposed in this research will increase the performance of the rectifier in an ambient environment. The maximum efficiency for RF to DC rectification is up to 84% for -10 dBm RF input levels and DC output voltage across the load of that rectifier is 11 V with 10 kΩ~20 kΩ load resistance.

Type of Paper:
Keywords: quad-band rectifier, matching network, ambient RF energy, RF survey, RF energy harvester

1. Introduction

Energy harvesting is referred to as the assembly of small amounts of ambient energy to power up the devices in the demanding sector for micro-electronics equipment such as wireless sensor networks (WSNs), inaccessible remote systems, and wearable electronics devices. In recent years, an impetuous advancement in communication networks (WCN) is maintained by self-sustaining devices that can be possible through energy harvesting technology. Compared to various harvesting approaches such as piezoelectric [1], turboelectric [2], nanogenerators, energy harvesting delivers relatively constant energy strokes due to the characteristic of facile accessibility, and low independence on the ambient environmental outcome.

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Smart design methodology of energy harvesting platforms is useful to decrease the dependence on frequent charging and may eradicate completely the necessity of battery in future [3]. Based on the snowballing demand related to daily life wireless applications, major development has been achieved in this energy scavenging sector. Previously, a large number of input independent energy harvesting concepts were developed [4–6]. The key problems of such energy harvesters are the low ability to harvest energy due to low incident power from desired operating frequency bands. In contrast with a single frequency application, multiband energy scavenging devices require a higher amount of dc voltage in order to harvest energy in various frequencies of operation. Nevertheless, the compensation can be trade-off between efficiency, performance, quality of service, and impedance matching at wireless application band [7], [8]. However, those topologies have various drawbacks such as increment of antenna number, circuit complexity, dimension and cost. Aiming to resolve the problems, a new smart approach consisting of multiband antenna stacked with RF filter, matching network, rectifier, low pass filter and load section is proposed in this paper. Moreover, to evaluate the feasibility of positioning RF energy scavengers, the existing RF power is planned to be analyzed in various locations. Based on those spectral surveys and clear knowledge of energy harvester performance, it can then be applied to identify the exact places whatever RF energy harvesting device that can be effectively installed. Many RF power spectral surveys, which analyze ambient power levels from different sources under common scenarios indoor, outdoor, train, bus etc. [9], [10]. Some of them used particular RF analyzers, however the proper position of every survey is not clearly identified and with ambient power density levels only being recorded under common scenarios (e.g., indoor, outside, highway, car, etc.) [11], [12]. Whereas being of hypothetical interest for health-related research [13], the scarcity of power density level and particular time frame or location information restricts their advantages for absorption in ambient RF power scavenging applications. In pursuance of demonstrating the usefulness for preliminary ambient RF energy harvesting, at first RF energy survey is conducted in MMU at Malaysia that is used to identify suitable positions and correlated frequency bands with adequate input RF energy levels for scavenging. Considering these justifications, the quad-band rectifier is designed and its efficiency, beneath ambient RF power harvesting procedure, was evaluated by indoor and outdoor field strength evaluation.

Mmu Rf spectral survey

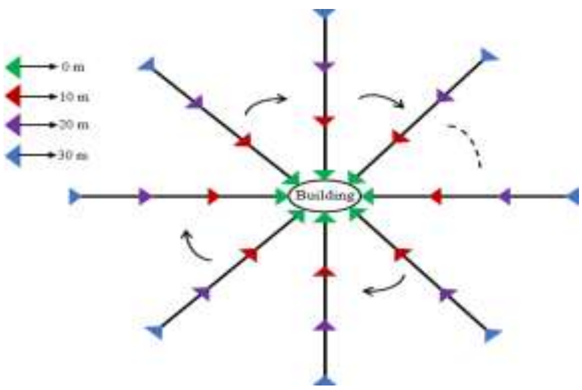

Fig. 1. Procedure for conducting RF spectral survey in each building. Distance is measured in meter (m).

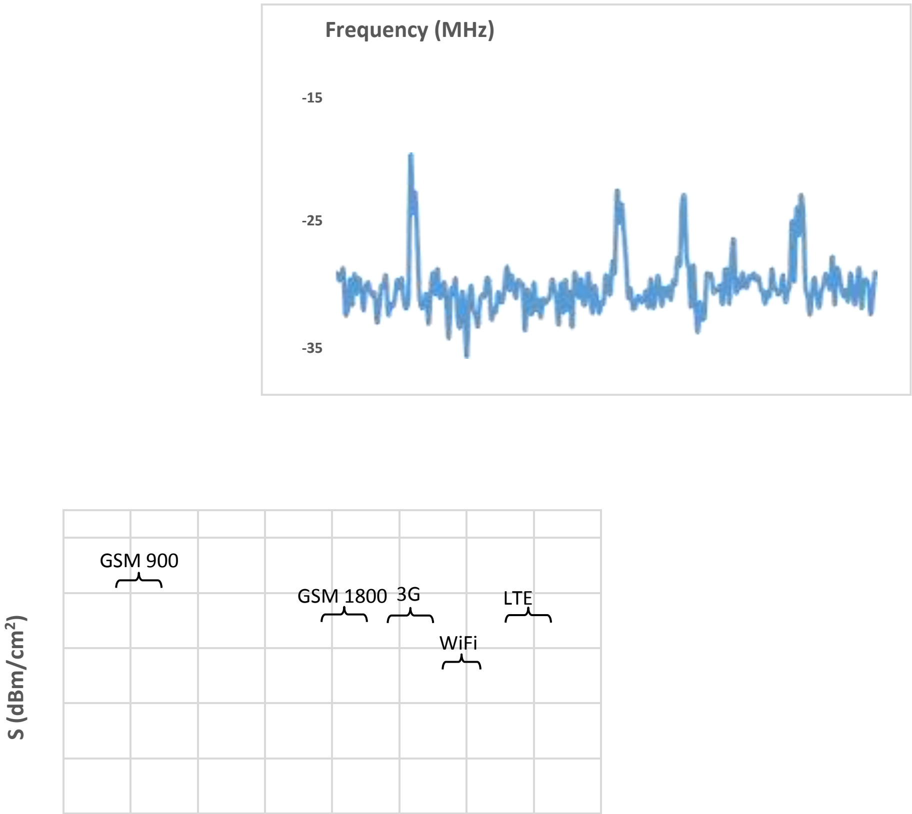

Fig. 2. Input RF energy density measurement inside MMU.

In order to determine input RF energy levels existing in an ordinary semi-urban zone, MMU RF spectral survey in the band of frequency (500 MHz-2600 MHz) portion of the frequency range was operated inside the university area. Many practical RF power analysis have earlier been carried out, but in general, only a small number of samples were considered, providing slight insight towards the semi-urban atmospheres [14], [15], and [16]. A comparative analysis of data collected from various locations at MMU campus (Faculty of Engineering (FOE), Digital Library (DL), Student Service Centre (STAD), Institute of Postgraduate Studies (IPS), and Faculty of Computing and Informatics (FCI)) was performed to identify the available frequency range and associated power level. By using a novel technique (Fig.1) the measurements were taken from the base point of the mentioned building to a remote location so that it maintains equal distance such as 0 m, 10 m, 20 m, and 30 m respectively and the rotation in each time 60- degree angle with clockwise direction. A TTi PSA6005 spectrum analyser with a calibrated 1.8 GHz isotropic antenna was used to measure RF power levels within 600 MHz to 3000 MHz frequency range. Fig. 2 illustrates the example of RF input power density levels measured inside the MMU where the range of frequency for GSM-900, GSM-1800, 3G, Wi-Fi, and LTE can be determined. The maximum power density levels in ambient environment from RF survey are shown in TABLE I, which works for a sensitive energy scavenger design preliminary facts as the RF energy level at every single band recapitulates the source impedance matching section of a harvester system especially for rectifier design. The proposed quad-band rectifier consists of a limited number of diodes, capacitors, and inductors. Simple series and voltage doubler configurations were used in earlier design multiband rectifiers.

Study Of Mmu Rf Power Survey Assessment

Brand Name	**Frq. Range (MHz)**	**Max. Power (dBm)**
GSM 900 (MTX)	880-915	-27.6
GSM 900 (BTX)	925-960	-22.5
GSM 1800 (MTX)	1710-1785	-44.9
GSM 1800 (BTX)	1805-1880	-17.8
3G (MTX)	1920-1980	- 43
3G (BTX)	2110-2170	- 43
WIFI	2300-2360	-38.6
	2390-2400	-25.6
LTE	2500-2700	-32.6

I. Suggested Rectifier Topology

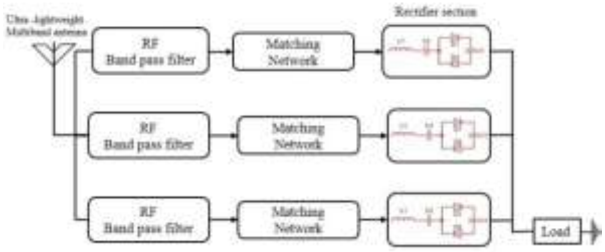

Fig. 3. Block diagram and symbolic schematic of multiband rectifier.

In this paper, the voltage doubler parallel configuration with novel matching network quad-band rectifier is proposed that is shown in Fig.3. The generated differential dc output voltage is double the amount of the RF input voltage which is suitable for quad band RF energy harvesting technique.

A. Unique Quad-Band Rectifier Design

Various types of topologies (e.g. series, shunt, voltage multiplier, bridge with various stages) and versatile comparisons between them were reported in [17] and [18]. Moreover, a multi-stage rectifier is able to reduce the extra losses, which are crucial for low-level RF input power in an ambient environment. In order to achieve a better comprehension of the non-linear behavior of source resistance in a multistage voltage doubler rectifier was simulated by ADS software. When sinusoidal signal is placed to the input section of the rectifier (Fig. 4), negative half cycle of the signal is converted by the parallel diode D2 and C2 is charged by this converted DC energy. Similarly, positive half cycle is rectified by another diode D1 and the C1 is charged by DC energy. For the period of the next full cycle the stored energy in C2 is transmitted to C1 and discharged through load impedance.

Here C1 acts as bypass capacitor refining the pure dc voltage. Thus the rectifier generated output V_{dc} voltage can be determined by

$$V_{dc} = 2RF_{@input} - 2V_f \quad (1)$$

Here, V_f is the forward voltage of the diode. The diode current I_D consists of DC and the harmonic components which can be expressed as

$$I_{DC} = I_S \left[B_0 \left(\frac{RF_{@input}}{mV_T} \right) \exp\left(\frac{-0.5V_{dc}}{mV_T} \right) - 1 \right] \quad (2)$$

Where, I_S , V_T , B_0 and m are the saturation current, the thermal voltage of the diode, the Bessel constant and the ideality factor respectively. The output DC voltage can be calculated by $V_{dc} = I_{DC} \times Load$ where the input resistance of

the diode is heavily influenced by the rectifier load section.

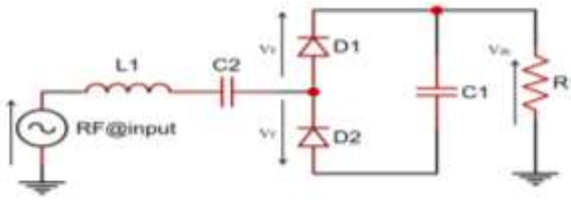

Fig. 4. Schematic view of the proposed rectifier section.

B. Impedance Matching Circuit Designed

The maximum power transfer theorem states that power transfer from the source to load is maximized when the internal complex impedances of the source are equal to the complex conjugates of the load impedances. The suitable matching between reactive source and load component depends on the Centre frequency of the matching network. Firstly, a single-band RF band pass filter impedance matching circuit is designed for suitable matching between 50 Ω input port and input impedance of a single branch rectifier. To achieve the band pass filter response and the single band impedance matching, the matching circuit should be made of a low pass (LP) filter matching topology (3rd order) at the starting frequency and a improved L-network (1st order) to cover the single frequency. Consequently, the proposed novel matching circuit is a fourth order lumped element matching circuit. In order to achieve proper synchronization between the antenna input impedance and the Centre frequencies of the rectifier, the filter circuit is operated as an adapter with T-network (Fig. 5). To achieve wider bandwidth and abate unwanted high frequencies near to the desired resonance Centre frequency, a capacitor placed parallel between two inductors with a resistor in the T-network [17] that looks like a shunt configuration. Moreover, the matching circuit is developed beside the band pass section so that it can easily eliminate the higher order harmonics outside the Centre frequency with the non- linear components that are capable of reducing the efficiency of RF to dc conversion. In addition, a matching network section which comprises a meander line, micro strip transmission line, short stub and shunt radial stub are developed. In order to design the suitable matching circuit to overlay four frequency ranges, matching circuits in each branch adapted in such a way that target frequencies are individually covered to 800 MHz, 1.8 GHz, 2.25 GHz, and 2.45 GHz. The rectifier performance parameters like reflection coefficient, dc conversion efficacy are analyzed for a wide range of criteria such as different RF input, quad-band Centre frequency ranges, and different value of load resistance. An electromagnetic (EM) solver in ADS was handled to investigate the different types of losses such as dielectric loss, an insertion loss of the substrate materials, micro strip transmission line, meander line, and radial stub.

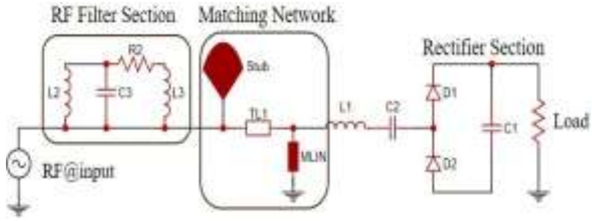

Fig. 5. Single branch complete topology.

TABLE I. The Optimized Parameters Of The Rectifier

Parameter name		Branch 1	Branch 2	Branch 3
L1		15 nH	12 nH	10 nH
C1		180 pF	147 pF	180 pF
R1		56 Ω	50 Ω	47 Ω
L2		15 nH	15 nH	15 nH
L3		14.4 nH	50 nH	13 nH
C2		3 pF	25 pF	2 pF
TL1	WTL1	0.70 mm	0.31 mm	0.73 mm
	LTL1	8.00 mm	6.00 mm	5.47 mm
Stub	WTL1	0.53 mm	0.72 mm	0.93 mm
	LTL1	3.17 mm	1.20 mm	5.70 mm
	Angle	70 (deg.)	38 (deg.)	30 (deg.)
MLIN	WTL1	0.50 mm	1.22 mm	0.55 mm
	LTL1	5.53 mm	11.1 mm	1.27 mm

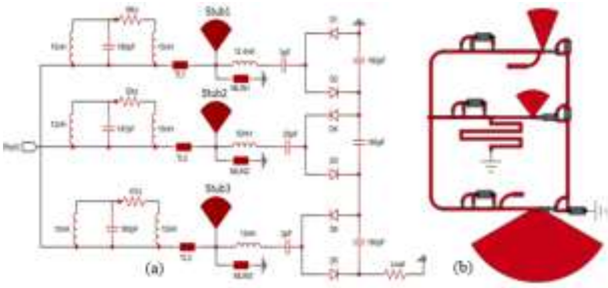

Fig. 6. (a) Schematic and (b) layout model of the suggested rectifier. The working area of the circuit is 2.7 × 2 cm^2.

The selected values in various SMD components (e.g. Avx and Murata) after optimization are shown in TABLE II. The schematic and layout structure of the suggested rectifier are shown in Fig.6 (a) and (b) respectively. The FR4 substrate material with a dielectric constant of 5.4 and substrate thickness of 1.6 mm is chosen in this work.

Rectifier Performance Analysis

The simulated scattering parameter (S11) at four RF input levels of the rectifier is shown in Fig.7. The 25 kΩ load resistor is chosen for the preliminary choice because it is mostly used in wireless applications [16], [18]. The outcomes of the rectifier recognize effectively at the frequency band nearby 780 MHz, 1820 MHz while the simulated scattering parameter (S11) at 2200 MHz and 2400 MHz is shifted to envelope frequencies among 2230 MHz and 2440 MHz is shifted to envelope frequencies among 2230 MHz and 2440 MHz. This frequency shifting may be caused by the unfamiliar parasitic effect of the practical components applied in the rectifier.

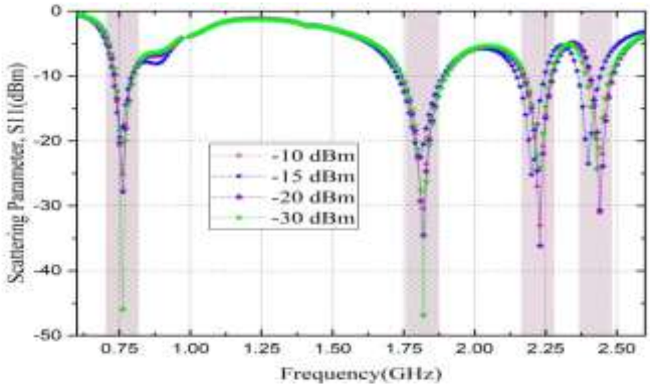

Fig. 7. The simulated, S11 for different ambient power levels.

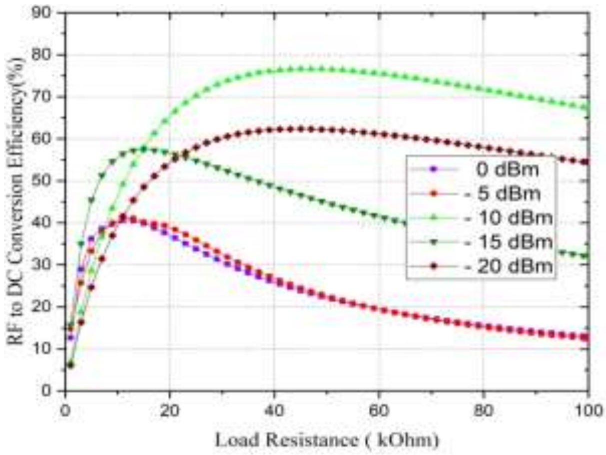

Fig. 8. The simulated conversion efficiency for different load values.

The rectifier RF to DC rectification efficiency can be determined by using the following equation:

$$\eta_{rf-dc}(\%) = \frac{V_{dc}^2 / R_L}{RF_{@input}} \qquad (3)$$

Where, V_{dc} is dc voltage against R_L load resistor and $RF_{@input}$ is the obtainable ambient RF input levels of the rectifier. Fig.8 illustrates the conversion efficiency at several RF input levels which is a function of frequency of suggested rectifier. The simulated rectification efficiencies at 0.8 GHz and 2.23 GHz are shown in Fig. 8 for different load values at 0 dBm, -5 dBm, -10 dBm,-15 dBm, and -20 dBm RF input levels. It is observed that maximum rectification efficiency attained at around 10 kΩ to 25 kΩ load resistance. The maximum efficiency is achieved at around 25 kΩ load resistance with a variation of RF levels between -10 dBm to - 15 dBm. The optimized load resistance is selected to be 25 kΩ to get the highest dc conversion efficiency reachable in the small input RF level. In Fig. 8, it is concluded that rectification efficiency does not deviate too much with the variation of load value (between 10 kΩ to 20 kΩ), because it is less sensitive in this range but extremely well for ambient energy scavenging in a wireless application. Fig.9 illustrates the simulated conversion efficiency of the multiband rectifier, which is a function of load resistance for different input levels. It is noticeable that with the value of load (e.g. 17 kΩ to 25 kΩ), it stabilizes the dc conversion efficacy with -20 dBm to -10 dBm input level and it upgrades from 74% to 84% with the variation of RF levels -15 dBm to -10 dBm. In addition, the overall conversion efficiency is improved with the increments of RF tone in

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source signals. As noticed in Fig. 10, the rectification efficiency is higher than 60% at about 800 MHz with RF energy level -10 dBm and finally increases above 83% at about 1800 MHz with -10 dBm input power for RL between 5 kΩ and 7 kΩ. The simulated rectification efficiency (ηrf-dc) is increased up to 20% (at 2230 MHz for -20 dBm source power) for RL= 12 kΩ to 17 kΩ. But with similar load value the conversion efficiency is increased a bit higher, above 35% (at 2400 MHz for -20 dBm source power). The simulated □□□ in each branch of the rectifier is depicted in Fig.11 for RF input energy levels provided by the power source.

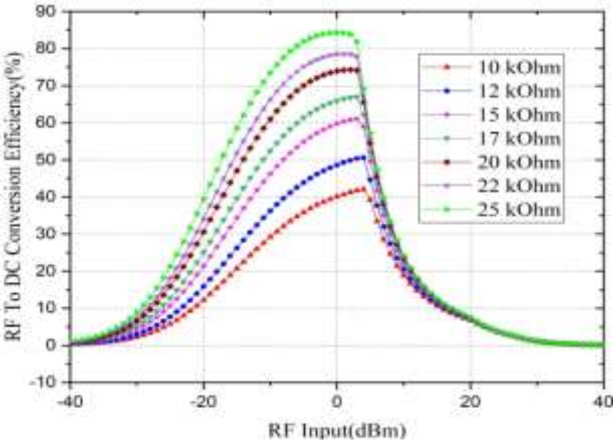

Fig. 9. The dc rectification efficiency for seven different *RL* values.

It can be observed that dc rectification efficiency of the rectifier increases with the increments of multiple RF sources. About 30% of rectification efficiency is progressed with all frequency bands produced by each source for increasing the number of RF sources from one to four. This improvement is due to the excellent impedance matching between antenna and quad-band rectifier as well as generated additional □□□ voltage across the load. It is extremely difficult to achieve maximum efficiency due to impedance mismatch that causes energy absorption from incident RF signals.

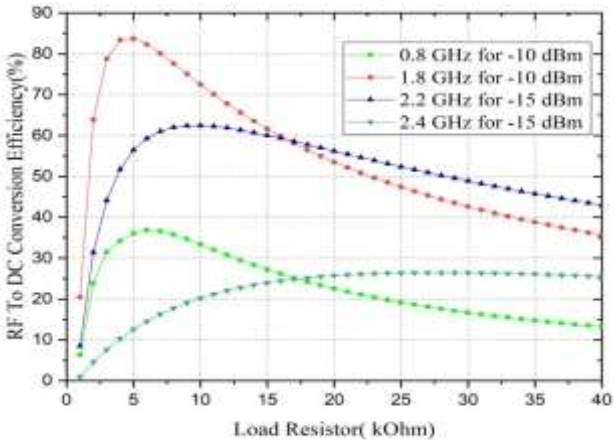

Fig. 10. The dc rectification efficiency for seven different *RL* values.

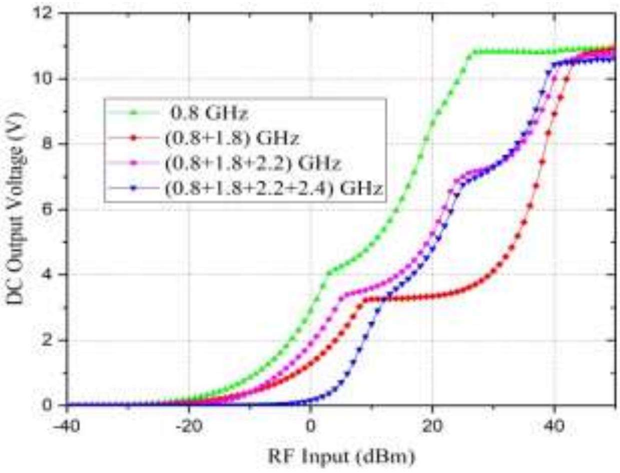

Fig. 11. The Simulated V_{dc} Value For Different Signal Tones.

TABLE II. Comparison Between The Suggested Rectifier And Previous Research

Ref.	**Topology Type**	**Resonance Frq. (GHz)**	**Input (dBm)**	**Efficacy (%)**	**Load (kΩ)**
[19]	Greinacher	0.9, 2.4	-10	4	0.5 ~ 3
[20]	Shunt	1.8,2.5	-35,-10	70	14.7
[13]	Series	0.5,0.9, 1.8, 2.4	-12	15	0.092 ~ 0.5
[21]	Series	0.9,1.75, 2.15, 2.45	-15	60	N/A
[15]	Shunt	0.9, 1.8, 2.1, 2.4	-25	65	11
[16]	shunt	0.55, 0.75, 0.9, 1.85, 2.15, 2.45	-30,-5	80	10~75
New	Shunt	0.8,1.8, 2.2,2.4	-10,-20	84	10~25

The comparison between the suggested rectifier and previous researches are shown in TABLE III. The proposed rectifier achieves outstanding performance in terms of efficiency compared to that of former researches in this area. A hexa-band rectifier with maximum achieved efficiency of 80% was proposed previously [16], that however had a higher load resistance. In another case, a quad-band rectifier was proposed by [21], it was defined that the efficiency is directly proportional to the exact number of frequency bands. Thus, it is clear that the proposed quad band rectifier is able to perform better in terms of efficiency than the rectifiers of greater number of resonance bands.

conclusion

In this paper a three branches quad-band rectifier is proposed by a novel impedance matching circuit. The upgraded impedance matching circuit offers exceptional performances in different broadband frequency range, RF sources and large value of load impedances. This design is very important for wireless harvesting application because the suggested quad band is able to offer 84% conversion efficiency with -10 dBm RF power at a single frequency (1.8 GHz). For successful operation the value of resistance has been considered carefully between 10 kΩ to 25 kΩ. It is proven that the simulated performance analysis of the proposed multiband rectifier can be an excellent candidate for ambient (e.g. outdoor and indoor) energy harvesting. In terms of dc rectification efficiency, dc output voltage, strong coverage of the preferred frequency ranges, and load value, the proposed design surpasses the previously-obtained performances by various researchers in this field. Thus, the suggested topology can be an excellent candidate for the RF energy harvesting applications and useful for a number of electric battery less demands in wireless application.

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