Rectifier and Reconfigurable Impedance Matching Network Analysis for Wireless Sub-6 GHz 5G/Wi-Fi 6/6E Energy Harvester

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Abstract. This paper presents the design and analysis of different rectifier configurations using the SMS7630 Schottky diode in RF energy harvesting applications. This study focuses on achieving maximum power transfer between the antenna and the rectifier by employing a reconfigurable impedance-matching circuit. The designed impedance matching circuit successfully achieved a reflection coefficient (S11) below -10dB across a range of frequencies from 1.5GHz to 5.6GHz. The performance and effectiveness of the rectifier designs and the impedance matching circuit were evaluated using advanced design system (ADS) software. The results demonstrate the feasibility and effectiveness of the proposed approach in optimising power transfer efficiency for RF energy harvesting systems within the specified frequency range.

Keywords: 5G/6G, Rectenna, Rectifier, Reconfigurable Impedance Matching, RF Energy Harvesting, Schottky Diode, Voltage Doubler.

1 Introduction

Sustainability is one of the world's significant challenges today, and the increasing use of fossil fuels to generate electricity exacerbates the situation. As a result, carbon-free energy generation methods have been investigated. Energy harvesting is a modern technology that collects and converts energy from the environment, such as wind turbines, solar cells, and electromagnetic waves in the ambient environment [1], [2]. Energy harvesting has gained significant attention in recent years as a promising solution to address the ever-increasing demand for power in wireless devices and systems. Amongst the various ambient energy sources, wireless energy harvesting technology has risen rapidly due to the popularity of wireless communications, such as TV, radio, cellular, satellite, and Wi-Fi signals, particularly since the early 1990s [3],

[4]. One avenue of exploration within this domain is RF energy harvesting, which involves the conversion of ambient electromagnetic radiation into usable electrical energy [5] [6].

The rapid population growth and the emergence of new communication technologies increased the demand for modern wireless communication technology, particularly mobile and television, which expanded base stations. As a result, RF energy distribution in the environment is becoming more widespread. The promising features of 5G/6G technology, such as high speed, low latency, enhanced capacity, and increased bandwidth, have advanced the use of indoor low-power devices such as IoT and sensors [7].

Rectenna, an essential component in energy harvesting systems, consists of a receiving antenna, bandpass filter, rectifying diode and DC-pass filter, allowing for the reception and conversion of RF power into usable DC power [3], [8]. Their significance lies in their ability to capture ambient electromagnetic energy, particularly in the radio frequency spectrum, and convert it into electrical power for various applications. Despite the widespread availability of radio waves for broadcasting and wireless communication, their power output could be improved, making it challenging to generate high voltage. To overcome this limitation, rectifiers can be employed in the RF energy harvesting circuits to increase the output power.

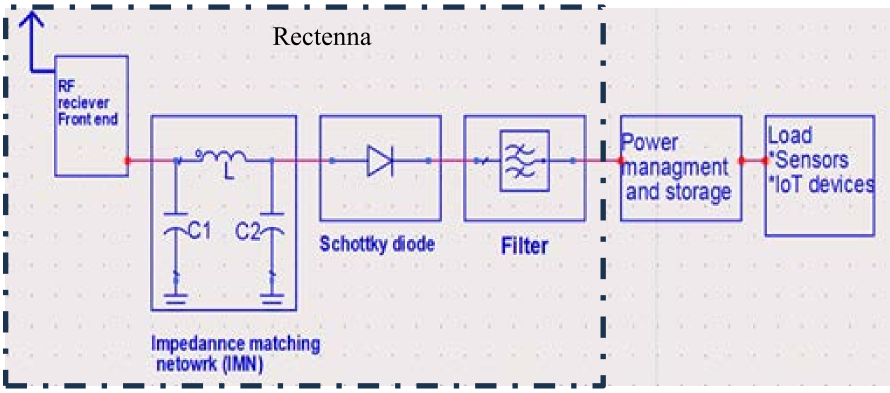

Fig. 1. RF Energy Harvesting block diagram.

Fig. 1 depicts the block diagram of an RF energy harvesting system comprising the antenna, matching network, rectifier, and load. The matching network maximises power transfer while the rectifier efficiently converts RF to DC. Consequently, the performance and efficiency of the system, represented by the obtained DC voltage value and the conversion efficiency (the ratio between DC power and RF power), are directly influenced by the nonlinear devices present in the rectifier, matching structure, and load. Moreover, the characteristics of the RF signal also impact the performance of the RF/DC conversion system.

Reconfigurable matching circuits provide several advantages, including expanding the frequency bands beyond those achievable with passive components and providing a broader available bandwidth [4-8]. When subjected to varied hostile environments that affect the frequency response of the antenna, reconfigurability is also vital for tuning the frequency bands of operation [5-9].

2 Modeling And Selecting RF Schottky Diode

The main challenge in designing an RF energy harvesting is operating with low RF power. For a typical 50 Ω antenna, the average RF power can be as low as -25 dBm (3.2uW) and generate a peak AC voltage of 5.7 mV; this requires a typical diode with a threshold much higher than the peak voltage. Additionally, these diodes must have a faster switching time than traditional ones, as RF energy harvesting operates at high frequencies. Therefore, Schottky diodes are a good candidate for these designs [4], [10].

RF Schottky diodes are high-frequency semiconductor devices widely used in microwave circuits, signal detection, and mixing. These diodes are ideal for RF applications due to their low forward voltage drop and fast switching speed. The maximum frequency of operation, forward voltage drops, reverse breakdown voltage, and noise characteristics are all important considerations when choosing an RF Schottky diode. Schottky diode efficiency can vary from 30% to 80%, depending on the device and operating conditions [9-14].

The most used RF Schottky diodes for this application are listed below, based on the application's unique criteria, such as frequency range, power level, and sensitivity. Table 1 summarises the determining characteristics of RF Schottky diodes. Despite having a relatively high forward voltage drop, the SMS7630 diode from Skyworks Solutions Inc. was used in all designs in this paper due to its market availability and wide operation frequency (up to 24 GHz). This diode has a peak current of 150 mA and a low turn-on voltage, and it is conveniently available in surface mount 0201 packages.

Table 1. Parameters of RF Schottky diodes.

Parameters	Unit	MA4E2054	SMS7630	SMS3922
Reverse leakage current, Is	A	3E-8	5E-6	3E-8
Series resistance, Rs	W	11	20	9
Emission coefficient, N	-	1.05	1.05	1.08
TT	sec	0	1E-11	8E-11
Zero bias junction capacitance, C_{JO}	pF	0.13	0.14	0.7
M	-	0.5	0.40	0.26
EG	eV	0.69	0.69	0.69
Breakdown voltage, Bv	V	5	2	20
Reverse bias current, IBV	A	1E-5	1E-4	1E-5
Junction voltage, Vj	V	0.4	0.34	0.595

3 Rectifier Design and Analyse

When selecting a diode for RF rectification, the most important criteria are its forward voltage drop (Vf) at the expected operating frequency and current level. The forward voltage drop is the voltage that the diode must overcome before the current can flow forward through it. As a result, limiting the forward voltage drop is critical since it decreases the amount of power wasted as heat in the diode and boosts the rectifier's efficiency. Furthermore, a low forward voltage drop reduces the diode's impact on the RF signal being rectified.

The SMS7630 RF Schottky diode was modelled in ADS using the parameters provided in Table 1. Several rectifiers, such as voltage doubler, Delon doubler, Delon tripler, Delon quadrupler, two-stage charge pump, three-stage charge pump and five-stage charge pump rectifiers, have been designed and analysed on ADS using the selected diode model (SMS7630). The output voltage and efficiency of each rectifier were compared, and it was found that the voltage doubler rectifier (Fig. 2) had the highest values. This can be attributed to the voltage doubler utilising only two diodes for rectification. On the other hand, the five-stage charge pump design employed ten diodes, resulting in the lowest output voltage and efficiency among the other designs. A diode was added in series to the load (50Ω) in the rectifier circuit to improve the sensitivity of the design by acting as a voltage booster, rectifying and stacking multiple RF cycles to increase the output voltage. In Fig. 2, a power generator tool from ADS (P_TONE) replaced the antenna and was set to generate input power.

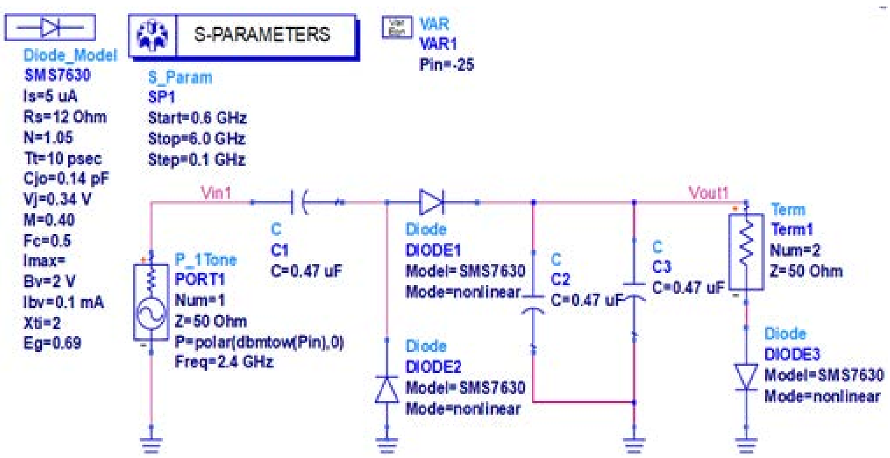

Fig. 2. The selected voltage doubler rectifier.

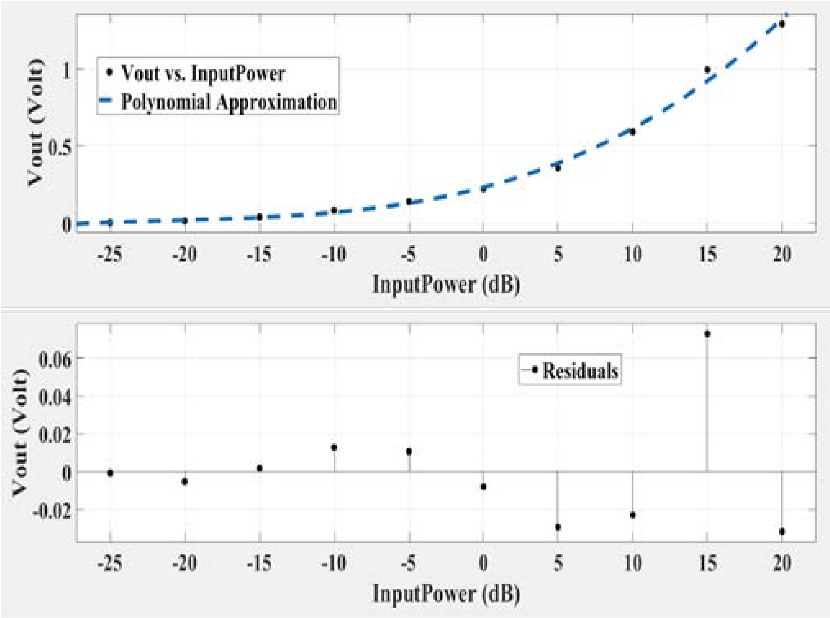

Fig. 3. Residual Plot of Output voltage (V) against the Input Power (dB).

$$\text{Output Voltage, Vout} = \sum_{n=0}^{N} C_n\,(P)^n \tag{1}$$

Here the coefficient bounds are as follows: $C_1 = 1.77e\text{-}05$, $C_2 = 0.001$, $C_3 = 0.025$, $C_4 = 0.233$.

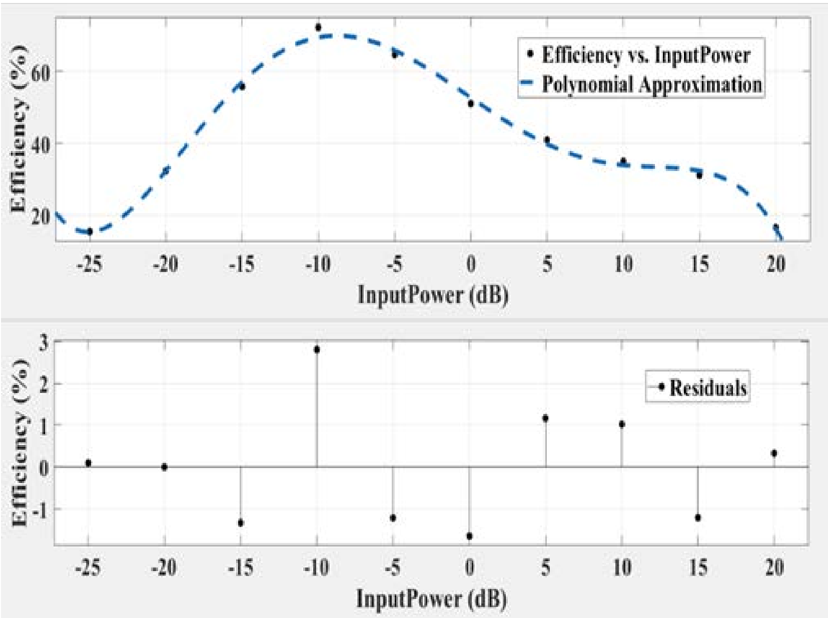

Fig. 4. Residual Plot of Efficiency (%) against the Input Power (dB).

$$\text{Efficiency}, \varepsilon\ (\%) = \sum_{n=0}^{N} K_n (P)^n \tag{2}$$

Here the coefficients bounds are as follows: $K_1 = -1.73e\text{-}05$, $K_2 = -0.0002$, $K_3 = 0.013$, $K_4 = 0.01$, $K_5 = -2.92$, $K_6 = 52.75$.

The output voltage and efficiency of the voltage doubler rectifier can also be expressed using polynomials (1) and (2), respectively. These polynomial approximations were based on the data presented in Figs 3 and 4, respectively, along with their corresponding residual plots.

The voltage doubler rectifier's output voltage and output current are given in Figs 5 and 6, respectively.

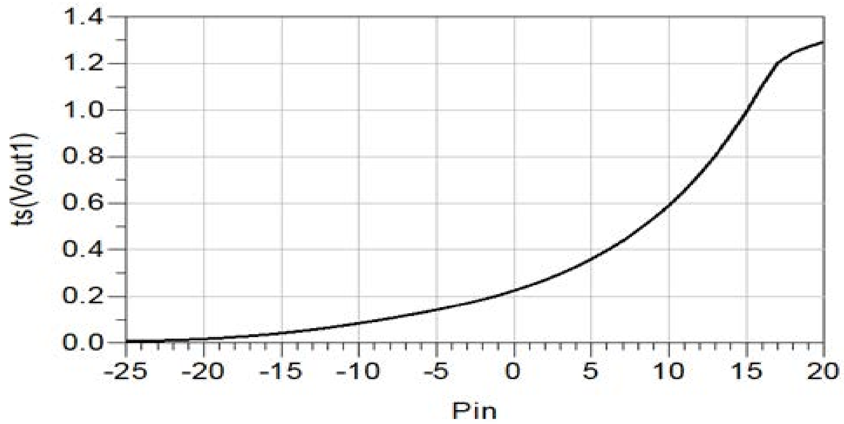

Fig. 5. Voltage doubler, output voltage (Vout1) in V vs Input power (Pin) in dBm.

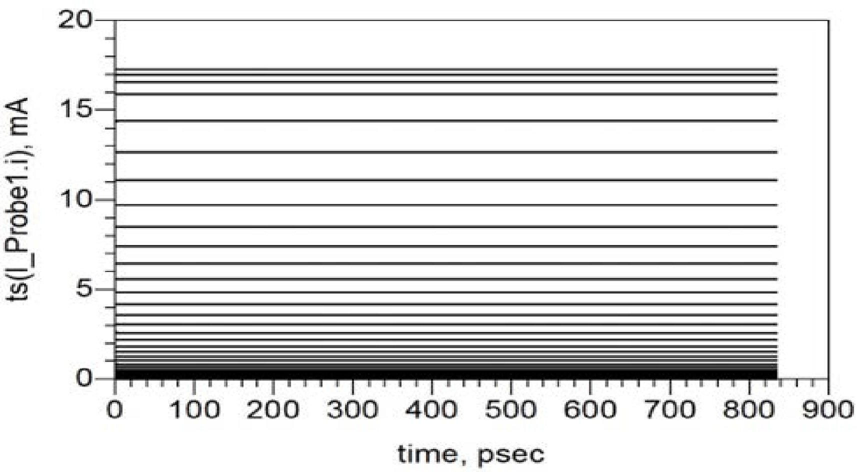

Fig. 6. Voltage doubler rectifier, output current in mA vs time.

The RF-DC conversion efficiency of a rectifier was calculated using the ratio of the output DC power (which depends on the output voltage and load) to the input power. In this report, the efficiency of each rectifier was calculated using (3).

$$\eta_{RF-DC} = \frac{V_{cap}^2}{2 * R_L * P_{in}} * 100 \quad (3)$$

Where; P_{in} = Input power, Vcap = Output voltage and R_L = Load resistance.

4 Matching Circuit Topologies and Reconfigurability

Impedance matching circuits are essential in RF energy harvesting technologies to ensure efficient power transfer and minimise signal reflection. These circuits are used to match the complex impedance of the antenna with the rectifier at specific frequencies. Different matching circuits can be implemented using distributed elements like transmission lines or discrete lumped elements such as capacitors and inductors. Each matching circuit must be designed and tested individually for a specific antenna and frequency range. While discrete lumped element circuits are more practical in size, low noise Figure, and good power handling capabilities, they are commonly used in RF and microwave applications up to 20GHz [7], [15] [16]. On the other hand, distributed element circuits are considered more feasible for matching networks in microwave applications, although they may pose challenges in predicting reflection for short wires [4], [16].

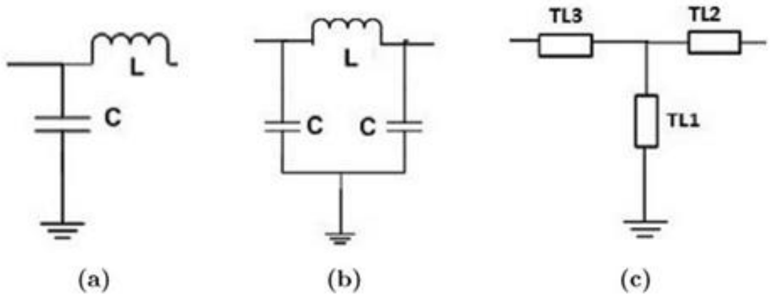

Fig. 7. Impedance matching topology (a)L (b) Π and (c) T.

The choice of network topology significantly impacts the reconfigurable network's effectiveness. Possible options include L, Π, and T structures (Fig. 7) and transmission line topology. Π and T structures offer similar reconfigurability across different frequencies; however, Π-structure proves to be less sensitive and facilitates the implementation of tuneable elements [8], [15]. Hence, Π-topology in series to an inductor was practised in this paper.

Various virtual antennas have been researched and investigated; however, a non-resonant cellular embedded IoT antenna from ignion, RUN mXTEND™, has been selected for this work. This antenna is compact (12.0 x 3.0 x 2.4 mm), has a 698 – 5875 MHz operating frequency, and can be used for applications such as wearable, IoT sensors and medical devices. It also has an omnidirectional radiation pattern, linear polarisation and less VSWR [17]. This antenna is a reliable, off-the-shelf product and compatible with multiple regionals. The library file of the antenna was downloaded from the ignion website [17], and the S-parameter file (. s1p) was imported into the ADS. The S-parameter of the selected antenna and rectifier circuit were extracted at various frequencies using ADS with the aid of the SP-Probe tool. The Smith chart (ADS tool) was used to analyse and adjust the impedance values of the antenna and rectifier at 2.4 GHz. Then, the impedance-matching circuit was adjusted to match different frequencies by varying the variable capacitor (C2), 0.3 – 6.2 pF. The reconfigurable impedance matching (RIM) circuit diagram with the value of the capacitors and inductors is given in Fig. 8.

Fig. 9 describes the simulation results of S11 when the RIM circuit was adjusted by varying the variable capacitor's value. It demonstrates that the RIM circuit effectively matched the impedance of both the antenna and the rectifier at multiple frequencies. The horizontal dashed line represents the maximum allowable value (-10dB) for the reflection coefficient (S11), and the graph indicates that the design achieved a satisfactory match at frequencies where S11 was below the dashed line (-10dB). Fig. 9 illustrates that the design achieved a good match (S11≤-10dB) across different frequency ranges (1.5 – 5.6 GHz) by adjusting the variable capacitor. Fig. 9 was produced by combining the S11 data below -10dB for each C2 value. Some value of C2 is shown in the figure; for instance, when the variable capacitor was set to 1.7pF, the reconfigurable impedance matching circuit successfully matched the antenna and the rectifier at 2.4 GHz, yielding a reflection coefficient of -14dB.

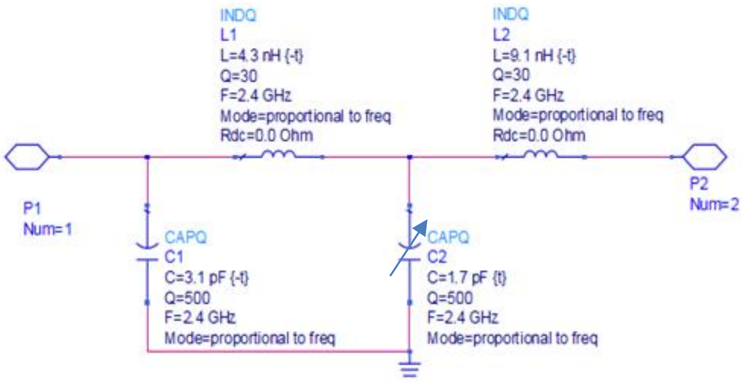

Fig. 8. Reconfigurable Impedance Matching (RIM) circuit diagram.

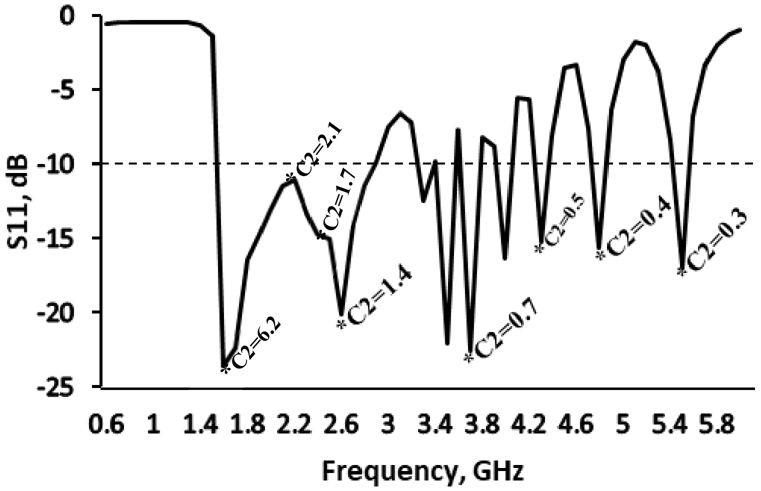

Fig 9. The design's reflection coefficient (S11) at different frequencies by manually tuning the capacitor, C2, (pF) of the designed RIM network.

5 Conclusion

The proposed architecture comprises an antenna, a reconfigurable impedance-matching network, and a rectifier. All the rectifier designs have been designed and evaluated in Keysight ADS software. However, only the selected rectifier is presented in this paper due to commercial sensitivity and page limit. The proposed design had an output voltage of 1.3 V and an efficiency of 70%. It also had an S11≤ -10dB and VSWR ≤ 2 for a wide range of frequencies. The proposed RF energy harvesting design had a sensitivity of -25dBm.

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