# Rectifier circuit design for 5G energy harvesting applications


Ioannis D. Bougas
Department of Physics
Aristotle University of Thessaloniki
Thessaloniki, Greece
impougas@physics.auth.gr

Maria S. Papadopoulou
Departmnt of Physics
Aristotle University of Thessaloniki
Thessaloniki,Greece
mpapa@physics.auth.gr

Achilles D. Boursianis
Department of Physics
Aristotle University of Thessaloniki
Thessaloniki, Greece
bachi@physics.auth.gr

Panagiotis Sarigiannidis
Department of Electrical and Computer Engineering
University of Western Macedonia
Kozani, Greece
psarigiannidis@uowm.gr

Spyridon Nikolaidis
Departmnt of Physics
Aristotle University of Thessaloniki
Thessaloniki,Greece
snikolaid@physics.auth.gr

Sotirios. K. Goudos
Department of Physics
Aristotle University of Thessaloniki
Thessaloniki, Greece
sgoudo@physics.auth.gr



***Abstract*— The need for electronic devices usage has risen significantly over the years. This has in turn generated greater demands for electricity and in addition for green energy sources. These include Radio-Frequency (RF) energy harvesting. In this concept we design a rectifier circuit for RF to DC conversion suitable for operation at sub-6 GHz 5G bands. Such a circuit can be used to supply low-power electronic devices. The proposed rectifier works at the frequency band FR1 of 5G cellular network and more specifically at 3.5 GHz. The most important problem in the RF energy harvesters is low system efficiency, something that limits the popularity of the power harvest. The proposed design is found to be highly efficient in its current form. Numerical results show that the system in a single-tone signal provides maximum power conversion efficiency equal to 42.5% when the load of the circuit is 1.1 KΩ and the input power reaches 9 dBm. The presented rectifier circuit performs better or equally with similar designs in the literature.**



***Keywords—radio frequency energy harvesting, wireless power transfer, impedance matching network, rectifier, voltage multiplier, power conversion efficiency, 5G, voltage doubler***


## I. Introduction

The ability to gather RF energy from ambient or dedicated sources would allow low-power devices to be charged continuously and could perhaps eliminate the need for a battery [1]. However, ambient RF energy harvesting has both advantages and disadvantages. An important advantage is that this energy is omnidirectional and is always available as a free energy source [1]. A notable disadvantage is that the power of this energy is very low. A rectenna is a system comprised of an antenna and a rectifier [2]. Fig. 1 illustrates a typical RF energy harvesting system that consists of a transmission antenna and a rectenna that is comprised of receiving antenna, an impedance matching network (IMN), and a rectifier. The antenna collects the RF signals, the rectifier converts the input signals into DC voltage and the impedance matching network (IMN) adjusts the impedance between the antenna and the rectifier.

RF energy harvesters are designed to operate at frequencies that are of particular interest for wireless communications and broadcast services. The new fifth generation of cellular communications (5G) operates among others in the Frequency zone 1 (FR1) in the n48, n77 and n78 bands with central frequency 3.5 GHz [3].

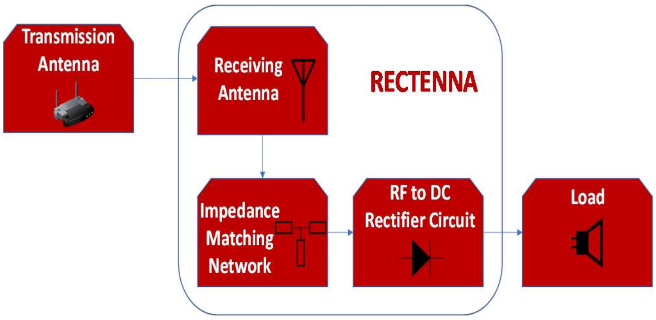


Fig. 1: Typical RF energy harvesting system

In [4], the authors designed a rectenna system that can harvest energy from WiMAX and Wi-Fi bands. Their half-wave rectifier (HW) is designed on Rogers RT/Duroid 5880 substrate and works at 3.5 GHz with efficiency 44% for 0 dBm input. Another half-wave rectifier we can find in [5]. This rectifier, having an input -10 dBm and using the SMS-7630 DIODE, achieves an efficiency of 42.5%.

If we want to take advantage of both halves of the input signal, we have to design full-wave (FW) rectifiers. In [6], the authors designed a full-wave bridge rectifier using HSMS-2820 Schottky diode, and achieved power conversion efficiency (PCE) at 3.84 GHz, 39.6%. A full-wave rectifier was designed in [7] and its conversion efficiency reached 29.72% at 3.5 GHz for input power 6 dBm. At the interesting frequency 3.5 GHz, the authors in [8] manufactured a Villard voltage doubler which has 14 dBm input power and reaches 42% power conversion efficiency. The authors in [9] designed a full-wave rectifier on Rogers RO3003 substrate that has 0 dBm input power. They use two Schottky diodes SMS7630-079LF and achieve PCE 42% at 3.5 GHz.

In this work, we present a rectifier circuit that works at the above-mentioned frequency bands of the 5G cellular network and more specifically at 3.5 GHz. The design methodology of the rectifier includes 4 steps, which are the selection of the appropriate substrate, the choice of the right energy harvesting circuit topology, the selection of the right diode, and the design of the impedance matching network [10].

The remainder of the paper is as follows. In Section II we present the design specifications and in Section III we present the numerical results. Finally, Section IV concludes the paper.

## II. RECTIFIER DESIGN SPECIFICATIONS

### A. Substrate Selection

The proposed circuit was designed on an RT/Duroid 5880 with substrate dielectric constant: 2.2, substrate thickness: 0.508 mm, dielectric loss tangent: 0.0009, thickness: 0.035 mm. RT/Duroid 5880 substrate presents a low dielectric constant and low dielectric loss. Hence, this substrate is appropriate for high-frequency applications like our rectifier that works at 3.5 GHz [11].

### B. Topology Selection

There are three basic types of rectifier topologies, the single diode, the voltage multiplier, and the bridge of diodes. In this work, we selected the Greinacher voltage multiplier because this type of rectifier circuit converts and amplifies the AC input to DC output [12]. This topology contains two Schottky diodes and two capacitors. Fig. 2 depicts the Greinacher topology. In this Fig. we distinguish two capacitors (C1, C2), two diodes (D1, D2), an AC source and the ground GND1.

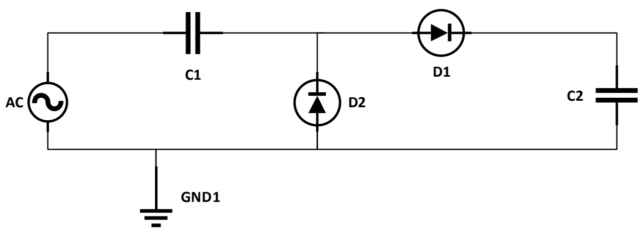

Fig. 2: Greinacher topology

### C. Diode Selection

In this design, we selected the HSMS-286C diodes. Diodes are the most important component in a rectifier circuit [7]. Using HSMS-286C we can achieve a high conversion efficiency thanks to their characteristics, which are maximum forward voltage $V_F$ = 250 mV–350 mV, typical capacitance $C_T$ = 0.25 pF, breakdown voltage $B_V$ = 7 V, series resistance $R_S$ = 6 Ω, barrier capacitance $C_{J0}$ = 0.18 pF [13].

### D. Impedance Matching Network Selection

The impedance matching is a technique to guarantee that power is transferred from the receiving antenna to the rectifier with minimum losses, in order for this circuit to ensure minimum signal power reflection back to the source [14]. Several configurations of impedance matching networks (IMNs) exist in the literature, and these can be designed either using lumped elements (capacitors, inductors) or distributed elements (stubs, microstrip lines) [10]. In our IMN we used distributed elements because these are ideal at microwave frequencies (3–300 GHz) while lumped elements are generally used at lower frequencies (below 3 GHz) [10]. Our IMN network is a T-type network with rectangular and radial stubs. We selected radial stubs because they need smaller chip space and give us better results. Fig. 3 illustrates the appropriate impedance matching network.

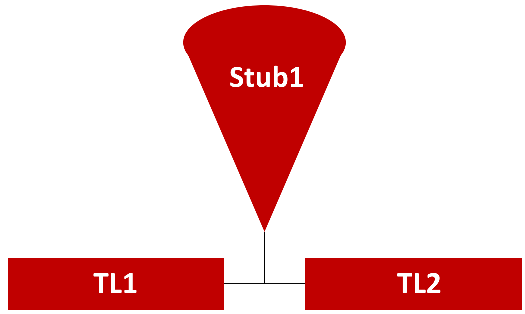

Fig. 3: Impedance matching network. TL1, TL2 and Stub1 are the rectangular and radial stubs accordingly

## III. NUMERICAL RESULTS

We designed a Greinacher Voltage doubler on RT/Duroid 5880 using HSMS-286C Schottky diodes. Our impedance matching network is a T-type network with rectangular and radial stubs. The two capacitors (C1, C2) of the design are equal to 100pF. In addition to that, the circuit contains various conductor lines of suitable width (W) and length (L) to connect all the other components (capacitors, diodes) and to help the impedance matching. Furthermore, the commercial software Advanced Design System (ADS) from Keysight Technologies 2022 (Student Edition) was applied to design and optimize this circuit. Fig. 4 depicts the total design of our circuit, included the output load (RL).

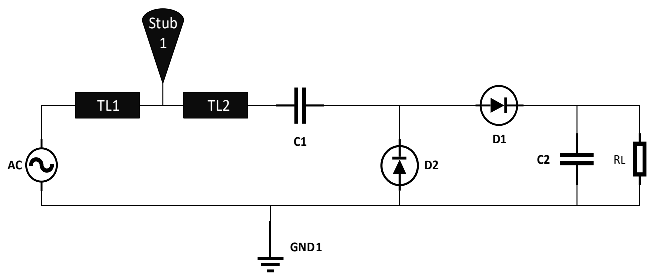

Fig. 4: Total design of proposed rectifier

To design this system, we considered that we have as an input an antenna port of $Z_A$= 50 Ω. Our goal is to match the impedance of the proposed rectifier, which was 10.609 – j17.032, with the impedance of the antenna which is 50 Ω. The result after the design of the IMN is 59.844 – j4.565 at 3.5 GHz. Fig. 5 depicts the reflection coefficient frequency response. The $S_{11}$ value at the design frequency of 3.5 GHz is -20.113 dB, which can be considered satisfactory. Moreover, the same Fig. shows that the $S_{11}$<-10dB bandwidth (BW) of this circuit is equal to 232 MHz.

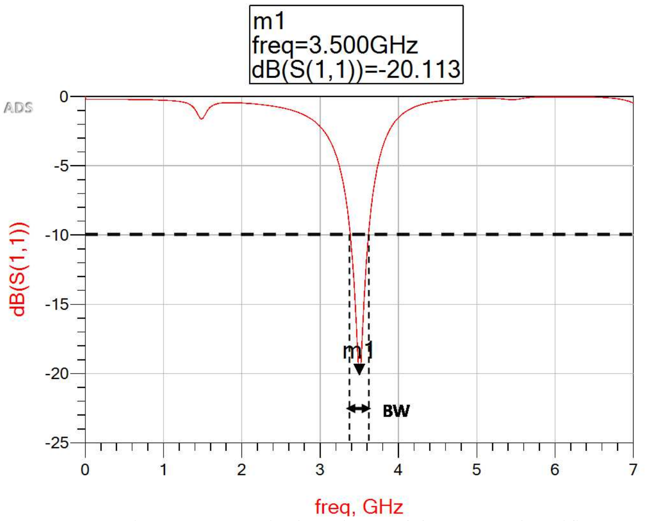


Fig. 5: S11 magnitude and BW of the proposed rectifier

At this point, we must refer that the most important part of the design of a rectifier is the output load. According to equation (1) below, the efficiency of the system decreases when the output load increases [10]. Hence the selection of the load is a very important design part.

$$n = \frac{P_{in}}{P_{out}}, P_{out} = \frac{V_{out}^2}{R_L} \qquad (1)$$

In the above equation we distinguish the $P_{in}$ which is the RF input power, the $P_{out}$ which is the output power, the $V_{out}$ which is the output voltage, and the $R_L$ which is the output load.

According to equation (1), we set as a goal the maximization of the efficiency n(%). So we made a harmonic balance simulation to see which $R_L$ and which $P_{in}$ gives us the better result. In Fig. 6, we observe that the proposed rectifier achieves maximum efficiency of 42.5% for input power equal to 9 dBm and for load value of 1.1 kΩ at 3.5 GHz.

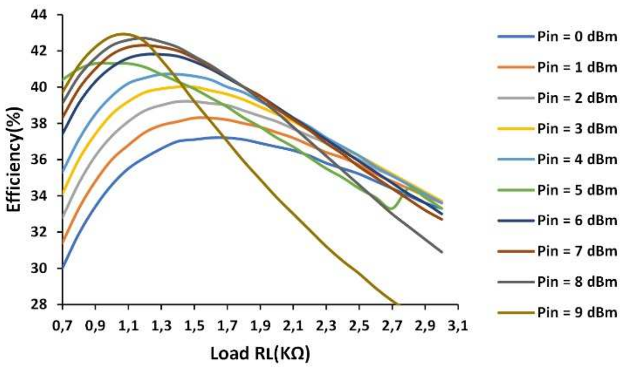


Fig. 6: Power conversion efficiency (%) - output load RL (KΩ) at 3.5 GHz for various Pin values

Fig. 7 illustrates the final result of harmonic balance simulation. We observe that we achieve better results for input power over 0 dBm.

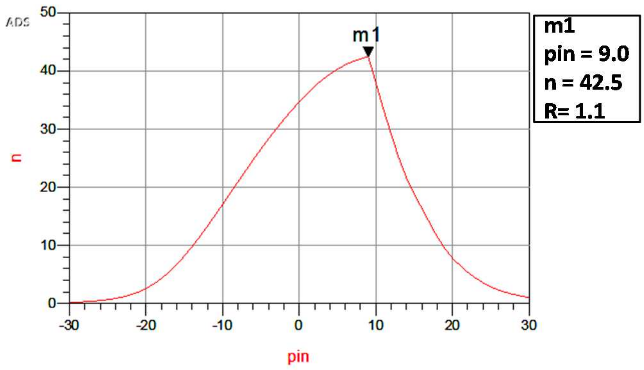


Fig. 7: Power conversion efficiency (%) - Pin (dBm) at 3.5 GHz for RL = 1.1KΩ

Finally, Fig. 8 depicts the Layout of the proposed rectifier.

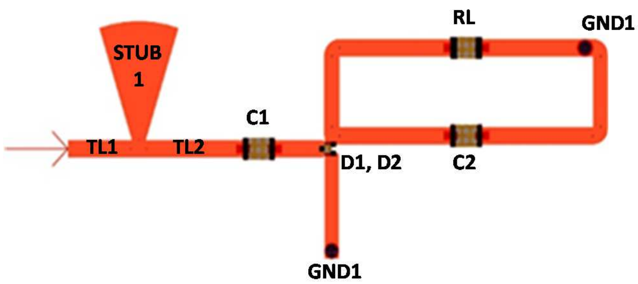


Fig. 8: Layout of the rectifier

Table I contains a comparison between our rectifier and previous works which are half and full-wave rectifiers that work at the frequency of 3.5 GHz. The presented circuit performs better or equally with other designs of the table.

TABLE I: COMPARISON BETWEEN PROPOSED RECTIFIER AND PREVIOUS WORKS

| Ref. | Characteristics of circuit designs | | | | | | |
|---|---|---|---|---|---|---|---|
| | ***Type of Rect.*** | ***Sub.*** | ***Diode*** | ***Freq. (GHz)*** | $P_{in}$ | $R_L$ **(KΩ)** | ***PCE @ 3.5 GHz*** |
| [4] | HW | RT/ Duroid 5880 | SMS 7630 | 3.5 5.8 | 0 dBm | 0.5 | 44 % |
| [5] | HW | FR-4 | SMS 7630 | 2.4 3.5 | -10 dBm | - | 42.5 % |
| [6] | FW | FR-4 | HSMS 2820 | 2.4 3.51 | 20 dBm | 50 | 39.6 % |
| [7] | FW | FR-4 | HSMS 2860 | - | 6 dBm | 1 | 29.72% |

| Ref. | Characteristics of circuit designs | | | | | | |
|---|---|---|---|---|---|---|---|
| | ***Type of Rect.*** | ***Sub.*** | ***Diode*** | ***Freq. (GHz)*** | ***$P_{in}$*** | ***$R_L$ (KΩ)*** | ***PCE @ 3.5 GHz*** |
| [8] | FW | FR-4 | HSMS 286C | 1.9 2.5 3.6 | 14 dBm | 3 | 42 % |
| [9] | FW | Rogers RO3003 | SMS 7630 -079 LF | - | 0 dBm | 2 | 42 % |
| **This Work** | FW | RT/ Duroid 5880 | HSMS 286C | 3.5 | 9 dBm | 1.1 | 42.5 % |

## IV. CONCLUSION

In this work, we have designed a full-wave rectifier for RF to DC conversion suitable for operation at sub-6 GHz 5G bands which can be used to supply low-power electronic devices. This circuit is designed to work within the 5G-FR1 bands and more specifically at those with central frequency 3.5 GHz. The substrate selected is the RT/Duroid 5880. The Avago HSMS-286C diodes were preferred for this design. The impedance matching network is a T-type network with rectangular and radial stubs. We selected radial stubs because they need smaller chip space and give us better results. The IMN network has been computed with the help of commercial software. Our design achieves maximum power conversion efficiency equal to 42.5% when the output load is 1.1 KΩ and the input power reaches 9 dBm. The proposed design operates equally or better than other similar found in the literature.

## REFERENCES


[1] N. Mirzababaee, F. Geran, and S. Mohanna, “A radio frequency energy harvesting rectenna for GSM , LTE , WLAN, and WiMAX,” *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 31, no. 6, Jun. 2021, doi: 10.1002/mmce.22630.

[2] W. C. Brown, "The History of Power Transmission by Radio Waves," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 32, no. 9, pp. 1230-1242, September 1984, doi: 10.1109/TMTT.1984.1132833.

[3] 3GPP: 5G-NR specifications series: https://www.3gpp.org/DynaReport/38-series.htm/, 2021, (accessed on 09 March 2022).

[4] M. C. Derbal and M. Nedil, “A HIGH GAIN DUAL BAND RECTENNA FOR RF ENERGY HARVESTING APPLICATIONS,” Prog. Electromagn. Res. Lett., vol. 90, pp. 29–36, 2020, doi: 10.2528/PIERL19122604.

[5] N. Eltresy, D. Eisheakh, E. Abdallah and H. Elhenawy, "RF Energy Harvesting Using Efficiency Dual Band Rectifier," 2018 Asia-Pacific Microwave Conference (APMC), 2018, pp. 1453-1455, doi: 10.23919/APMC.2018.8617347.

[6] C. Mohamed Zied, E.-R. Rashid, and A. Hareb, “Harvesting microwave energy from WiMax bands based on a Dual-Band Antenna,” IOP Conf. Ser. Earth Environ. Sci., vol. 227, p. 042044, Mar. 2019, doi: 10.1088/1755-1315/227/4/042044.

[7] O. M. A. Dardeer, H. A. Elsadek and E. A. Abdallah, "Compact Broadband Rectenna for Harvesting RF Energy in WLAN and WiMAX Applications," 2019 International Conference on Innovative Trends in Computer Engineering (ITCE), 2019, pp. 292-296, doi: 10.1109/ITCE.2019.8646386.

[8] S. S. Sarma, S. Chandravanshi and M. J. Akhtar, "Triple band differential rectifier for RF energy harvesting applications," 2016 Asia-Pacific Microwave Conference (APMC), 2016, pp. 1-4, doi: 10.1109/APMC.2016.7931295.

[9] S. M. K. Azam, Md. Shazzadul, A. K., and M. Othman, “Monopole Antenna on Transparent Substrate and Rectifier for Energy Harvesting Applications in 5G,” Int. J. Adv. Comput. Sci. Appl., vol. 11, no. 8, 2020, doi: 10.14569/IJACSA.2020.0110812.

[10] I. D. Bougas, M. S. Papadopoulou, A. D. Boursianis, K. Kokkinidis, and S. K. Goudos, “State-of-the-Art Techniques in RF Energy Harvesting Circuits,” Telecom, vol. 2, no. 4, pp. 369–389, Oct. 2021, doi: 10.3390/telecom2040022.

[11] RT/duroid ®5870/5880: High Frequency Laminates. Available online: https://rogerscorp.com/-/media/project/rogerscorp/documents/advanced-electronics-solutions/english/data-sheets/rt-duroid-5870---5880-data-sheet.pdf (accessed on 09 March 2022).

[12] I. D. Bougas, M. S. Papadopoulou, K. Psannis, P. Sarigiannidis and S. K. Goudos, "State-of-the-Art Technologies in RF Energy Harvesting Circuits – A Review," 2020 3rd World Symposium on Communication Engineering (WSCE), 2020, pp. 18-22, doi: 10.1109/WSCE51339.2020.9275507.

[13] HSMS-286x Series: Surface Mount Microwave Schottky Detector Diodes. Available online:

https://gr.mouser.com/datasheet/2/678/V02_1388EN0-1222339.pdf (accessed on 09 March 2022).

[14] AN5457: RF matching network design guide for STM32WL Series. Available online:

https://www.st.com/resource/en/application_note/an5457-rf-matching-network-design-guide-for-stm32wl-series-stmicroelectronics.pdf

(accessed on 09 March 2022).