FUOYE Journal of Engineering and Technology, Volume 7, Issue 2, June 2022 ISSN: 2579-0617 (Paper), 2579-0625 (Online)

Design of a Radio Frequency Energy Harvester Impedance Matching Circuit for 2.4 GHz Microstrip Patch Antenna

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Received: 02-MAR-2022; Reviewed: 12-APR-2022; Accepted: 21-APR-2022
https://doi.org/10.46792/fuoyejet.v7i2.814

ORIGINAL RESEARCH ARTICLE

Abstract- Energy Harvesting (EH) is the process of capturing energy from external sources and storing it for small wireless autonomous devices. Radio Frequency (RF) EH aims at capturing ambient energy with an antenna and transforms this energy into exploitable power. Different energy fields are available in nature from which energy can be harvested. An impedance matching circuit for an RF energy harvester was designed in this paper. The design is made up of the antenna circuit which captures the RF signals from the mobile and Wi-Fi bands in the atmosphere, and the impedance network that matches between the RF source and the load to capture the power. A Villard voltage multiplier was employed to rectify and step up the captured RF signal into a useable direct current output voltage. Due to the low output voltage obtained after rectification, the voltage was boosted to the power needed for the load. The output of the boost converter was then used to charge a lithium-ion battery. In this paper, Intelligent Schematic Input System proteus professional suite software was used in simulating the designed system. This was used to analyse the performance of each system's component and to evaluate the quality of the designed circuitry. RF energy harvesters convert electromagnetic waves into usable DC voltage. However, the harvested energy is relatively low to the required voltage. Different techniques have been proposed, but the complexity of energy harvesting persists. This discourages the use of low-power devices. Bridging this gap will improve energy harvesters' efficiency.

Keywords- Energy Harvesting (EH), Impedance Matching Circuit (IMC), Microstrip Patch Antenna, Radio Frequency (RF).

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1 INTRODUCTION

Energy Harvesting (EH) is a green energy technology used for the conversion of energy present in the environment into electrical energy to energize low-power devices or circuits. This is being used to replace the use of battery power because of its economic and practical benefits for the optimal use of energy (Sanislav *et al.*, 2021). One of the most serious challenges facing wireless sensor networks is how to harness EH technology. This is owing to the reason that sensor nodes have reduced energy capacity. Hence, the energy of low-power devices has to be effectively managed to extend the operation time of a communication system (Adoulie *et al.*, 2019).

The recent interest in Radio Frequency (RF) EH (RF-EH) is being driven by the progress in wireless communication systems that have availed a lot of freely propagating ambient RF energy (Nechibvute *et al.*, 2017). Energy from RF can be extracted and used in a variety of applications such as charging batteries, energizing multiple ranges of low-power electronic devices like wearable smart devices, Radio Frequency Identification tracking tags, and wireless sensor devices (Gaurav *et al.*, 2013; Schauwecker, 2016).

The antenna picks up the RF power sent out by the transmitting sources, the Impedance Matching Network (IMN) ensures maximum power transfer in the system and the rectifying circuit converts the RF power to a Direct Current (DC) voltage and then boosts the voltage to the level adequate for charging a lithium-ion battery (Bakkali *et al.*, 2016). This technology offers improved reliability and reduces the size and cost of devices (Din *et al*. 2012; Nechibvute *et al.*, 2017; Saeed *et al.*, 2018)

The remaining part of the paper is organized as follows; Section 1 established the background and motivation for RF-EH and stressed the significance of wireless power solutions for low-power applications. Section 2 outlined in chronological order a review of related works on RF-EH, including commonly targeted frequencies as well as common configurations used for RF signal filtering and rectification. Section 3 is the methodology, where discussions were made on circuit design. Section 4 presents and evaluates results obtained, while the concluding remarks were presented in Section 5.

2 RELATED WORKS

An outdoor RF power level survey was proposed by Piñuela *et al* (2013). The researchers found out that approximately 50% of the 270 stations in London tested were suitable locations for EH. The researchers proposed a single band harvesting circuit. A 40% end-to-end efficiency for the GSM 900 MHz band was achieved. Bakkali *et al* (2016) designed a dual-band antenna for RF-EH systems for a wireless-based network. The design centred on ambient RF energy available from commercial broadcasting stations to provide a system based on RF-EH. This incorporated a new receiving antenna design. The design sought at increasing system efficiency in the 2.45 GHz and 5 GHz Wi-Fi bands. This offers another

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Section B- ELECTRICAL/ COMPUTER ENGINEERING & RELATED SCIENCES
Can be cited as:
Tooki O.O., Olubolade O.T. and Odaba A. (2022): Design of a Radio Frequency Energy Harvester Impedance Matching Circuit for 2.4 GHz Microstrip Patch Antenna, *FUOYE Journal of Engineering and Technology* (FUOYEJET), 7(2), 157-161. http://doi.org/10.46792/fuoyejet.v7i2.814

energy source for powering sensors in extreme conditions where energy from other sources is unavailable.

Schauwecker (2016) investigated the processing circuitry for harvesting RF energy. The design presented was performed to process an RF energy signal received from an antenna that targets Wi-Fi bands at 2.4 and 5 GHz. The final design consists of two bandpass filters, two two-stage voltage doubler circuits and a boost converter that is designed to obtain a voltage output of 3.2 V to charge a Lithium-ion battery. The RF energy harvester was tested in an ambient environment using 2.4 GHz Wi-Fi signals and a 470 μF capacitor linked to the output. This demonstrated the circuit's ability to harvest significant energy. While the maximum measured voltage of 50 mV does not meet the design specification of 3.2 V.

Parna *et al*. (2016) suggested using a rectifier circuit for an RF-EH system. A rectifier system together with an IMN was implemented. The IMN was designed using two microstrip lines. The rectifier system was designed using a bridge rectifier. The results obtained from the designed rectifier system offer a maximum efficiency of 50%. The circuit simulator ADS 2015.01 was used for the system design. Performances of the system were analysed. This proposed rectifier along with the IMN was used for the design of an RF-EH system. Song *et al* (2016) proposed a novel six-band rectifier and antenna circuit. The design managed to harvest 96 μW with an input power level of -15 dBm. Also in 2017, Song *et al* presented an innovative approach for the rectenna system where the impedance of the antenna was matched to the impedance of the rectifier. The researchers tend to eliminate the requirement for an IMN and consequently reduced the complexity of the design. The researchers were unable to achieve this.

Starck (2018) checked if harvesting ambient radio waves could be a viable energy source. The researchers also want to determine where and when it is appropriate to want to determine where and when it is appropriate to use it. One circuit was constructed and two more were simulated, along with the circuitry needed to measure and display the quantity of harvested energy. The system was tested in the same places as the location where a survey of the signal strength was done. The maximum harvested energy was 35μW which was at a location inside a window facing a cellular transmitter at a distance of 100 m to 200 m away from a cellular transmitter. The value of the output was 1 μW, in a city environment, while the output from the harvester was 0 μW.

Kassem *et al* (2018), attempt to validate that RF-EH for mobile phones is valid. The system design consists of four main parts which are proposed and implemented in their detailed information and simulations with a plan of selecting part that gives better performance parts. The first component of the antenna circuit captures signals from the RF of the mobile, and at bands of the Wi-Fi in the atmosphere. In addition, the IMN matches the RF source and the load to obtain far more power. A rectification circuit was also implemented to convert RF signals to DC output voltage. A voltage converter was designed to step up the voltage to match the power needed load. The Nakagami-m fading model was used to obtain stochastic characteristics of the energy harvested as a constant stochastic process. Castro *et al* (2019), proposed the use of received signals in a large RF channel for a gamma-process. Some EH system performance indicators were obtained. Also, a transmission policy subject to different fading conditions was considered. Devi *et al.* (2012), the processing circuitry of the system is shown in Figure 1.

This paper has reviewed different matching techniques, adaptive, power-based and lumped elements; for the design of RF energy harvester. These methods are inadequate due to the identified limitations. However, this paper designed an Impedance Matching Circuit (IMC) for an RF energy harvester to overcome identified constraints.

3 RESEARCH METHODOLOGY

3.1 MATHEMATICAL ANALYSIS OF THE SYSTEM

- **Antenna Structure**

The width, W, of the rectangular microstrip patch antenna was calculated using (1).

$$Width = \frac{V}{2f_r}\left(\frac{E_r+1}{2}\right)^{-0.5} \qquad (1)$$

where V is the light's speed which is equal to $3 \times 10^8 m/s$; *fr* is the operating frequency in GHz. For this paper, *fr* = 2.4.

The effective dielectric constant is given by

$$E_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-0.5} \qquad (2)$$

where ε_r is the electric permittivity of the substrate material and h is the substrate's thickness.

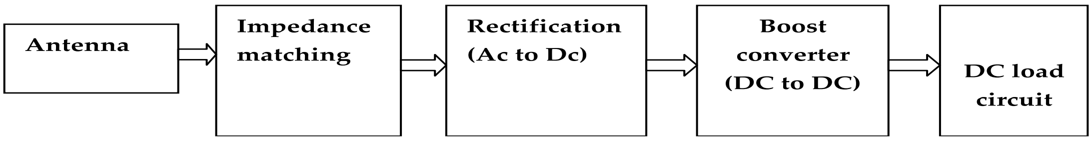

Fig.1: Block diagram of RF Processing Circuitry (Devi *et al*., 2012)

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The effective length E_{eff} of the patch is defined as follows

$$L_{eff} = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}\bullet\sqrt{\varepsilon_{eff}}} = \frac{V}{2f_r\sqrt{\varepsilon_{eff}}} \qquad (3)$$

The characteristics impedance of the rectangular microstrip antenna, *Z* was calculated using (4) and is based on the transmission line model (Siddik *et al.*, 2019).

$$Z = \frac{Z_0}{2\pi\sqrt{2(1+\varepsilon_r)}}\ln\left[1 + \frac{4h}{\omega_{eff}}\left[\frac{14+\frac{8}{\varepsilon_r}}{11}\frac{4h}{\omega_{eff}} + \sqrt{\left[\frac{14+\frac{8}{\varepsilon_r}}{11}\frac{4h}{\omega_{eff}}\right]^2 + \pi^2\frac{1+\frac{1}{\varepsilon_r}}{2}}\right]\right] \qquad (4)$$

where Z_0 is the impedance of free space, h is the thickness of the substrate, and W_{eff} is defined as:

$$W_{eff} = \omega + t\frac{1+\frac{1}{\varepsilon_r}}{2\pi}In\frac{4e}{\sqrt{\left(\frac{t}{h}\right)^2+\left(\frac{1}{\pi}\frac{1}{\frac{\omega}{t}+\frac{11}{10}}\right)^2}} \qquad (5)$$

where *t* is the thickness of the metallization. Using the equations above, the desired characteristic impedance is used in alignment with the specifications of the substrate. This was calculated for the trace width to obtain the impedance. Alternately, the trace width can be based on component size or parasitic inductance calculations, and use this value along with the substrate specifications to calculate the characteristic impedance of the microstrip transmission line. This can then be utilized in the design of the antenna and filtering circuitry.

Parasitic inductance resulting from copper traces is another element the designer must be mindful of when performing the Printed Circuit Board (PCB) layout. The inductive components of conductors resulted in reactance that increases as the signal frequency increases. The approximate inductance of the microstrip was calculated using (6);

$$L_{microstrip} = 0.0002\,{}^{*}\mathrm{L}\left[In\left(\frac{2^{*}L}{W+H}\right) + 0.2235^{*}\left(\frac{W+H}{L}\right) + 0.5\right]\mu H \qquad (6)$$

where *L* is the length of the microstrip, W is the width, and H is the height.

While this is an approximation method, it gives insight into the best methods for reducing parasitic inductance on the PCB. A decrease in the length of traces is used to reduce parasitic inductance, which requires the precise placement of components.

3.2 SYSTEM IMPLEMENTATION

This section explains the simulation of the developed system and measurements carried out at different stages. It consists of a microstrip antenna, voltage doubler and boosts converter sections. The set-up was simulated with the help of ISIS Proteus Professional 8.9. Voltage doubler circuitry was based on the Villard voltage multiplier. Double of the input signal voltage is obtained at the single output. This was cascaded to form a voltage multiplier. This circuit contains a signal generator designed to operate at a 2.4 GHz Wi-Fi band. The IMC has seven-stage voltage doubler circuits, a steering diode to direct the output voltage from the voltage doubler circuit to the input of the final stage, and the final boost converter circuit, which steps up the output voltage to the level capable of charging a Lithium-ion battery. Figure 2 is the Villard voltage multiplier circuit. It was derived from the function of the peak detector. The choice of the circuit was necessitated by the fact that it produces two times the input signal voltage towards the ground at a single output. The schematic for the designed RF processing circuit was also simulated. This is as shown in Figure 3. The output of each stage was measured with a DC voltmeter and observed on an oscilloscope. This was done to know the output voltage of each stage.

4 RESULTS AND DISCUSSION

Different stages of the processing circuitry were measured to assess the output of each stage. Using the animating time on the simulator, the time scale ranges between 0.000003528s and 0.000017229s. The oscilloscope was scaled for all measurements. This circuit contains a microstrip antenna, IMC, seven stages voltage doubler and steering diodes to direct the output voltages from the voltage doubler circuit to the input of the final stage. The final boost converter circuit was used to charge the Lithium-ion battery

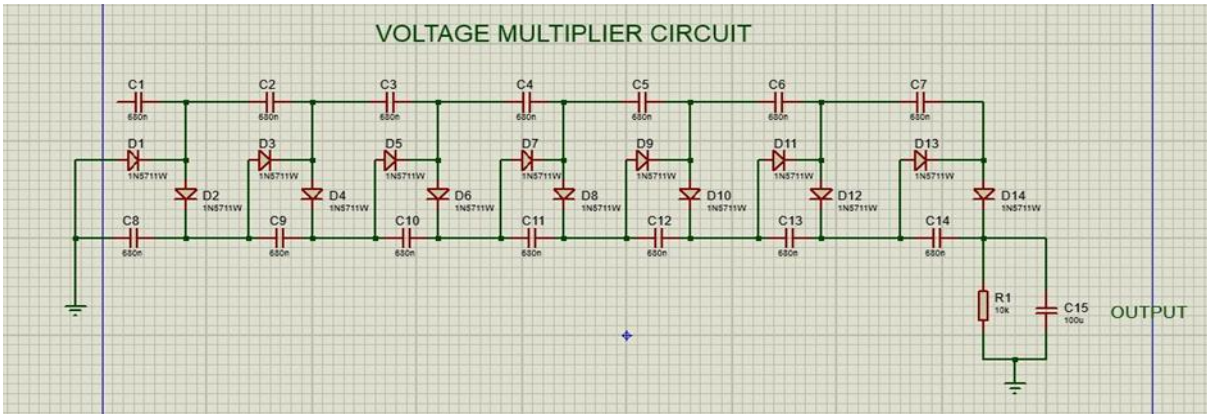

Fig. 2: Villard Voltage Multiplier

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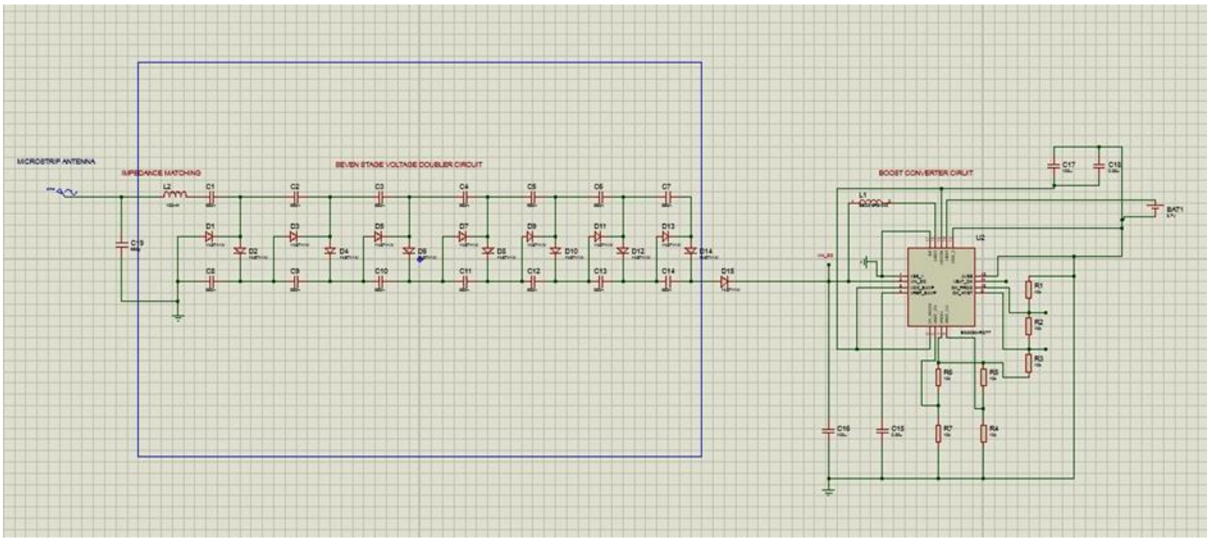

Fig. 3: Processing Circuitry Schematics for the RF Energy Harvester

The results of four stages were presented in this paper; stages 1, 3, 5 and 7 which corresponds to the results in Table 1, 2, 3 and 4, respectively. These stages determine the desired value of the output voltage. The capacitance obtained from the design is the amount of energy stored in the storage unit.

It was mentioned that the output voltage on the DC voltmeter increased as the stages increased while the output on the oscilloscope had amplitude differences. This observation is a result of the compounding voltages from each stage, as the processing circuitry itself is composed of a voltage doubler circuit. The results demonstrate a proof-of-concept of the RF energy harvester, as well as validate the ability of the processing circuitry to rectify the received RF signal. It was further noticed from the simulation that without the boost converter circuit gives an error message simulation not running in real-time due to excessive load. This is because the simulation of digital systems has always been a challenge added to the simulation that integrates the complexity of analogue systems. Real-time modelling of the entire system becomes extremely difficult. This is a limitation of the host system rather than the simulation software.

Table 1. Stage 1 Operating Point Information

Signal Freq.	Terminal Voltages	Relative Voltage	Instance Parameters
2.4 GHz	Anode(A) 3.52 V Cathode(K) 3.65 V	3.59 V	ID= -2.91 Power = 10.79 W Capacitance 2.009 pF

Table 2. Stage 3 Operating Point Information

Signal Freq.	Terminal Voltages	Relative Voltage	Instance Parameters
2.4 GHz	Anode(A) 3.62 V Cathode (K) 3.58V	3.88 V	ID=1.41 Power = 13.12 pW Capacitance 2.01 pF

Table 3. Stage 5 Operating Point Information

Signal Frequency	Terminal Voltages	Relative Voltage	Instance Parameters
2.4 GHz	Anode (A) 3.75V Cathode (K) 3.77V	3.76 V	ID= 3.6 Power = -11.57 pW Capacitance 2.01 pF

Table 4. Stage 7 Operating Point Information

Signal Freq.	Terminal Voltages	Relative Voltage	Instance Parameters
2.4 GHz	Anode (A) 3.68 V Cathode (K) 3.72 V	3.69 V	ID= 2.6 Power = 11.27 pW Capacitance 2.01 pF

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5 CONCLUSION

Inside this paper, a proof-of-concept for the processing circuitry for the RF energy harvester was designed, implemented and tested. As described in the early sections of this paper, an IMC was designed to harvest and process ambient RF energy to charge a lithium-ion battery. The designed processing circuitry differed from other methods since an IMC was incorporated. The design presented in this work gave better performance due to improved voltage values required to charge a lithium-ion battery. The application of the RF-EH circuit, to charge a battery, increases the effective lifetime of a battery. The designed circuitry is a viable solution that can be adapted to provide direct input for low-power devices.

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