

Original Article

# 3-Element Microstrip Yagi-Array Rectifier Antenna (RECTENNA) for Receiving Digital Television Signals on Ultra High Frequency Channels

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**Abstract** - This study examines the need for efficient Radio Frequency (RF) energy harvesting as a renewable alternative energy source. This study's main objectives are to design, produce, and test a rectenna system that combines a seven-stage voltage multiplier rectifier with a microstrip Yagi-Uda three-element antenna. The purpose of the rectenna is to transform received radio frequency energy into DC power that may be used by low-power electronic equipment. Experiments in the form of circuit design using NI Multisim, antenna design using CST Studio Suite, fabrication, and testing are all part of the study technique. With particular goals for strength ( $\geq 5$  dBi), VSWR ( $1 < VSWR \leq 2$ ), and return loss ( $< -10$  dB), the antenna is made to receive signals in the Ultra-High Frequency (UHF) band. Schottky diodes, which are perfect for converting RF frequencies to DC because of their low forward voltage and quick switching speed, are used in the rectifier. The antenna's efficacy has been validated through both simulation and experimental outcomes. These results indicate a return loss less than  $-10$  dB, a Voltage Standing Wave Ratio (VSWR) ranging from 1.1 to 1.8, and a gain exceeding 5 dBi, all of which signify acceptable signal integrity and impedance alignment. Investigations into the reception of digital television broadcasts, coupled with laboratory assessments, revealed that the rectenna functions effectively at varying proximities to the radio frequency emitter, generating a direct current output whose voltage escalates with increased input power. The system achieves its peak output of 1.696 V at a distance of 1 kilometer from the Digital Terrestrial Television (DTV) transmitter and 1.80 V when situated 25 centimeters away with an input power of 20 dBm. The system's capacity to energize Light-Emitting Diodes (LEDs) as a load underscores its potential for powering low-consumption apparatus.

**Keywords** - Rectenna, Antenna, Rectifier, Voltage Multiplier.

## 1. Introduction

Digital television transmitters, cellular services, and other communication devices emit Radio Frequency (RF) energy, which is extensively scattered in the atmosphere and mostly unutilized. Essentially, because receiving devices are unable to capture this energy, one such resource for powering low-power devices is radiofrequency energy [1]. The rectenna, a system that combines a receiving antenna with a rectifier circuit to convert RF energy into Direct Current (DC) voltage, is one technological advancement that makes it possible to use this energy [2, 3]. Typically, a rectifier circuit processes and transforms RF signals into usable electrical energy after an antenna receives and records the signals [4-6]. Numerous rectenna designs have been documented; nonetheless, the majority continue to achieve low RF-to-DC conversion efficiency and limited output voltage, especially when operating under low-power ambient signals. At a distance of 1 cm, a circular patch antenna-based rectenna design only

generated 11 mV [7], whereas a circularly polarized antenna with a voltage doubler circuit generated 63.7 mV [8]. At an input of 20 dBm, a microstrip slot antenna was used in another work to obtain about 2 mV [9]. A five-stage rectifier generated 22 mV, whereas a more intricate setup, including three antennas and three rectifier circuits, managed to reach 151.08 mV [10]. The majority of earlier research still generated voltages in the millivolt range, which is insufficient for real-world applications, even with the use of different antenna and rectifier approaches [11, 12]. These results point to two significant gaps in the field of rectenna research. First, most rectenna designs that have been described still have low conversion efficiency, which leads to DC output at the millivolt level—far below what low-power electronic devices need. Second, there is still a dearth of research on UHF antennas, especially for digital TV broadcast channels. Most of the research done so far has been on low-gain patch or slot antennas in labs, so their performance in real-world



transmitting situations has not been fully confirmed. Both of these points point to the necessity of creating UHF-frequency rectennas with improved antenna performance and more efficient rectifier designs.

To address these needs, this study introduces a rectenna based on a three-element microstrip Yagi-Uda antenna that has a directional radiation pattern and higher gain than a conventional patch antenna. The antenna is integrated with a seven-stage voltage multiplier rectifier circuit employing Schottky diodes. These diodes are recognized for their low forward voltage and rapid switching capabilities, which facilitate efficient operation at reduced radio frequency power levels [10]. The innovative aspect of this investigation resides in the synergistic combination of a directional Yagi-Uda antenna and a seven-stage rectifier, meticulously engineered for optimal energy harvesting from UHF digital television broadcast signals at a frequency of 642 MHz. This particular frequency range has been a subject of limited exploration in prior research endeavors.

The purpose of this study is to:

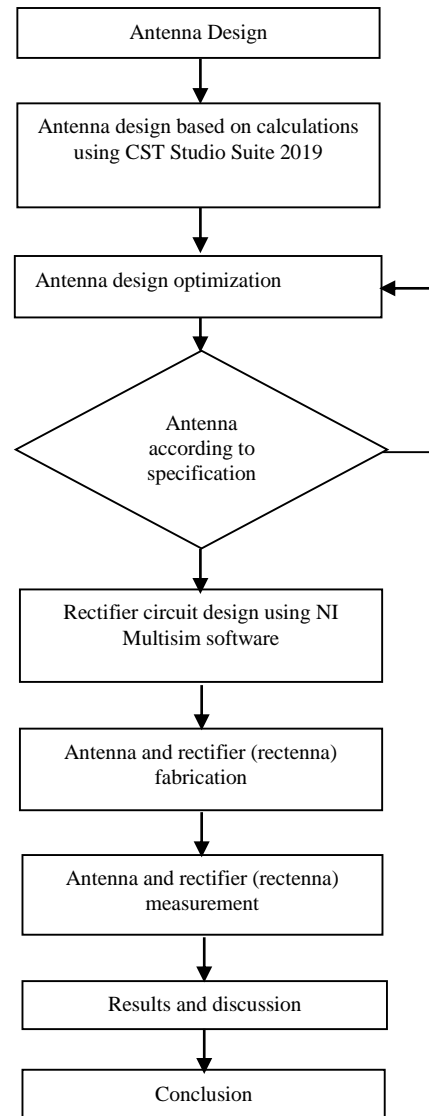
1. Create a three-element, 642 MHz, microstrip Yagi-Uda antenna.
2. Create a circuit for a seven-stage voltage multiplier rectifier using Schottky diodes.
3. Combine the two halves into a single rectenna system.
4. Measure the DC output voltage, gain, VSWR, and return loss to assess its performance.
5. To illustrate the advancements made, compare the results with those from earlier research.

This research employs multi-stage rectifiers and directional antennas to enhance the collection of radio frequency energy within the digital television UHF spectrum. Moreover, employing actual broadcast signals for testing, as opposed to solely signal generators, facilitates a more precise evaluation of performance. It is expected that this methodology will significantly advance the development of low-power radio frequency energy harvesting systems.

**2. Methodology**

The method of experimentation, a research approach employed in this study, aims to determine how one factor influences another within certain parameters. This strategy was chosen as it corresponds with the objective of the research, which is to understand the effectiveness of rectennas in harnessing radiofrequency energy and converting it into usable Direct Current (DC). The study data, derived from the design, practical testing, and simulation outcomes, were subsequently analyzed and compared with the established target specifications. The research process included several crucial stages, such as the design of antennas, the creation of rectifiers, the manufacturing of devices, and the testing of

rectennas. The initial stage focused on using CST Studio Suite software to develop a microstrip Yagi-Uda antenna consisting of three elements. To get parameters that satisfied the goal specifications, such as return loss  $\leq -10$  dB, VSWR in the range of 1 to 2, and gain  $> 5$  dBi, this stage entailed simulation. To confirm the circuit's reaction to the input signal, the second step was designing a seven-stage rectifier voltage multiplier using NI Multisim software. The next step is fabrication, which entails employing the PCB etching procedure to realize the planned antenna and rectifier on the FR-4 substrate. The antenna and rectifier are combined to create a rectenna system that is prepared for testing after the fabrication process is finished. Testing is the last step, during which signals from a UHF digital television transmitter with a splitter configuration are used to test the rectenna. The output voltage is measured using a digital multimeter, and the rectenna's performance is visually observed using an LED test load. Figure 1 shows the research flow.



**Fig. 1 Research process**

## 2.1. Antenna Design

In order to capture digital TV signals within the Ultra-High Frequency (UHF) range, a microstrip Yagi-Uda antenna consisting of three parts was designed. The proposed antenna comprises two sections of a Yagi-Uda array; each section includes one driver element, one reflector element, and one director element [3]. The active element of this antenna is built as an inverted J shape in its patch-driven configuration.

By reducing the size of the director element compared to the driven element and utilizing the ground plane as a reflector to direct signals towards the director, the overall gain of the antenna is enhanced [13, 14].

The substrate known as FR-4, commonly utilized in creating microstrip antennas, was employed in the design of the antenna. This choice was made because it is easily accessible and straightforward to manufacture. The specifications for the planned antenna are shown in Table 1.

**Table 1. Antenna Specifications**

No	Antenna Parameters	Value
1	Operating frequency	642 MHz
2	Return loss	≤ -10 dB
3	VSWR	1 ≤ VSWR ≤ 2
4	Input Impedance	50 Ω
5	Gain	≥ 5 dBi
6	Radiation patter	Directional

The initial design of this Yagi-Uda microstrip antenna with three elements relied on the calculations of a rectangular microstrip antenna [15], which was then modified as required.

### 2.1.1. Fundamental Wavelength

Prior to establishing the size of the antenna, the wavelength must initially be computed utilizing equation (1):

$$\lambda = \frac{c}{f_c} \quad (1)$$

### 2.1.2. Dimensions of the Driven Patch

#### Width of the Driven Patch

The measurement of the driven patch's width is determined using the operational frequency  $f_0 = 642$  MHz along with the substrate's dielectric constant of 4.3. Calculated using Equation (2) [16]:

$$Wp = \frac{c}{2f_0 \sqrt{\frac{\epsilon_r + 1}{2}}} \quad (2)$$

#### Driven Patch Length

To calculate the patch length, first determine the effective dielectric constant ( $\epsilon_{reff}$ ) using equation (3) [16]:

$$\epsilon_{reff} = \left(\frac{\epsilon_r + 1}{2}\right) + \left(\frac{\epsilon_r - 1}{2}\right) \left(1 + 12 \frac{h}{wp}\right)^{-1/2} \quad (3)$$

Then, the increase in length due to the fringing effect is calculated using equation (4) [16]:

$$\Delta L = 0,421h \frac{(\epsilon_{eff} + 0,3) \left(\frac{Wp}{h} + 0,264\right)}{(\epsilon_{eff} + 0,258) \left(\frac{Wp}{h} + 0,8\right)} \quad (4)$$

Next, calculate the effective patch length ( $L_{eff}$ ) using the equation(5) [16]:

$$Leff = \frac{c}{2f \sqrt{\epsilon_{reff}}} \quad (5)$$

Once the values are obtained, the length of the driven patch can be calculated using equation (6) [16]:

$$Lp = Leff - 2\Delta L \quad (6)$$

### 2.1.3. Distance Between Patch Elements

To maintain antenna performance, the distance between patch elements is set to half the wavelength, as shown in Equation (7):

$$d = \frac{\lambda}{2} = \frac{c}{2f} \quad (7)$$

### 2.1.4. Feed Channel Dimensions

#### Feed channel width

The width of the supply channel is calculated using Equation (8) [16]:

$$\frac{W}{h} = \frac{2}{\pi} \left[ B - 1 - \ln(2B - 1) + \frac{\epsilon_r - 1}{2\epsilon_r} \left( \ln(B - 1) + 0,39 - \frac{0,61}{\epsilon_r} \right) \right] \text{ untuk } \frac{Wf}{h} > 2 \quad (8)$$

Where h is the thickness of the substrate, and the value of B can be calculated using equation (9):

$$B = \frac{60\pi^2}{Z_0 \sqrt{\epsilon_r}} \quad (9)$$

### 2.1.5. Length of the Supply Line

The effective dielectric constant is calculated ( $\epsilon_{reff}$ ) using equation (10):

$$\epsilon_{reff} = \left(\frac{\epsilon_r + 1}{2}\right) + \left(\frac{\epsilon_r - 1}{2}\right) \left(1 + 12 \frac{h}{Wf}\right)^{-1/2} \quad (10)$$

Thus, the length of the feed line (Lf) is obtained using equation (11). Where is Nilia Phasa  $\phi = 90^\circ = \pi/2$

$$Lf = \frac{\phi(\pi/180)}{\sqrt{\epsilon_{reff}} \left(\frac{2\pi f c}{c}\right)} \quad (11)$$

### T-Junction Power Divider Dimensions

2.1.6. Power Divider Impedance

The impedance of the power divider for two elements is calculated using Equation (12) [17]:

$$Z = Z_0 \times \sqrt{N} \tag{12}$$

2.1.7. Power Divider Width

The width of the T-junction power divider can be calculated using Equation (13):

$$W = \frac{2h}{\pi} \left\{ B - 1 - \ln(2B - 1) + \frac{\epsilon_r - 1}{2\epsilon_r} \left[ \ln(B - 1 + 0.39 - \frac{0.61}{\epsilon_r}) \right] \right\} \tag{13}$$

2.1.8. Power Divider Length

Check the ratio between the width (W) and height of the substrate using equation (14):

$$W/h > 1 \tag{14}$$

Since  $W/h > 1$ , the dielectric constant value is calculated using equation (15):

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[ \frac{1}{1 + 12 \left( \frac{h}{W} \right)} \right] \tag{15}$$

Next, calculate the effective wavelength using Equation (16) [17]:

$$\lambda_0 = v/f \tag{16}$$

Based on the effective wavelength results, the effective length can be calculated using equation (17)[17]:

$$\lambda_g = \lambda_0 / \sqrt{\epsilon_{eff}} \tag{17}$$

Thus, the length (L) of the power divider is obtained using Equation (18) [17]:

$$L = \lambda_g/4 \tag{18}$$

The Width Of The Director (Wdr) was then made around 5% less than the width of the driven element to calculate the dimensions of the director and reflector in the suggested antenna design. Regarding the reflector's dimensions, it was built to be around 5% wider than the driving element, which serves as a ground plane in the suggested antenna [13]. The modified antenna was built on an FR-4 substrate measuring 424 mm by 150 mm. To guarantee impedance matching, the width of each element was kept constant at 3 mm. However, the antenna did not operate as expected. To achieve the desired specifications, optimization was done by adjusting the antenna parameter values [18].

Standards-compliant antennas have a return loss of  $\leq -10$  dB and a Voltage Standing Wave Ratio (VSWR) of  $\leq 2$ . The antenna design is shown in Figure 2.

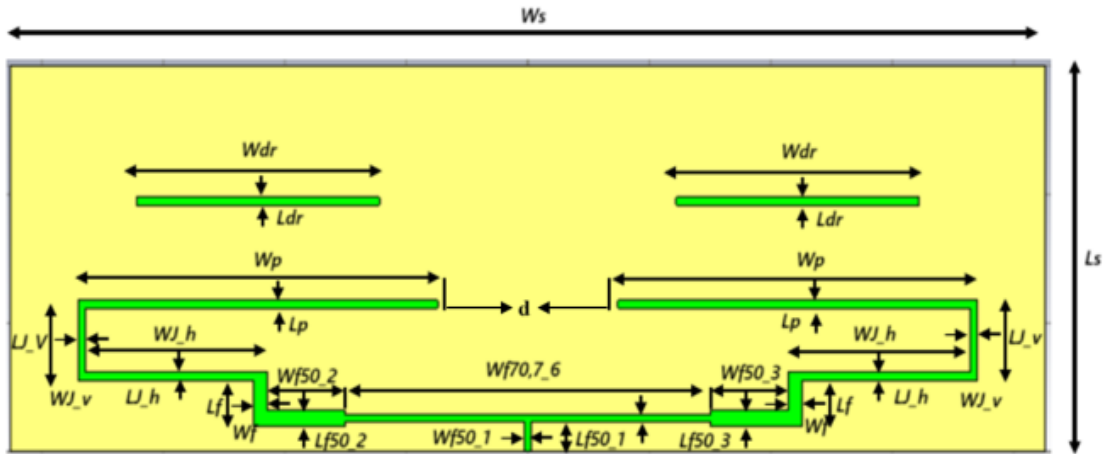


Fig. 2 Proposed Geometry of a 3-Element Microstrip Yagi-Array Antenna

Table 2. Dimensions of the Proposed 3-Element Microstrip Yagi-Array Antenna

No	Symbol	Value (mm)	Description
1	$Wp$	148	Driven Width
2	$Lp$	3	Length Driven
3	$Wf$	3.1020	Feedline width
4	$Lf$	2.81	Feedline length
5	$d$	90.6	Distance Between Elements
6	$Wd$	100	Director's width

7	$L_d$	3	Director of Length
8	$W_r$	426	Reflector Width
9	$L_r$	3	Reflector Length
10	$W_{f50\_1,2,3,4,5}$	3.0221	Width of the T-junction: 50 $\Omega$
11	$L_{f50\_1,2,3,4,5}$	3	Length of the T-junction: 50 $\Omega$
12	$W_{f70,7\_6}$	66.265	Width of the T-junction: 50 $\Omega$
13	$L_{f70,7\_6}$	3	Length of the T-junction: 50 $\Omega$
14	$W_s$	424	Width of Substrate
15	$L_s$	150	Length of Substrate
16	$h$	1.6	Thickness of Substrate
17	$p$	0.035	Copper Thickness

**2.2. Rectifier Circuit Design**

A seven-stage voltage multiplier rectifier based on Dickson topology is the rectifier circuit utilized. This topology was selected because it can generate a greater output voltage without requiring more complex components [19].

NI Multisim software was used to model the circuit with the following primary settings:

- The HSMS-2850 Schottky diode was chosen due to its low junction capacitance and low forward voltage, which

enhances the efficiency of RF–DC conversion.

- Each stage uses a 1 nF capacitor to minimize ripple and preserve output voltage stability.
- To reduce power reflection from the antenna, the input impedance is intended to be near 50  $\Omega$ .

To make sure the circuit could produce a DC voltage that rose in proportion to the input power, simulations were run. To ensure peak efficiency, factors such as input alignment, diode energy dissipation, and response to transients were observed.

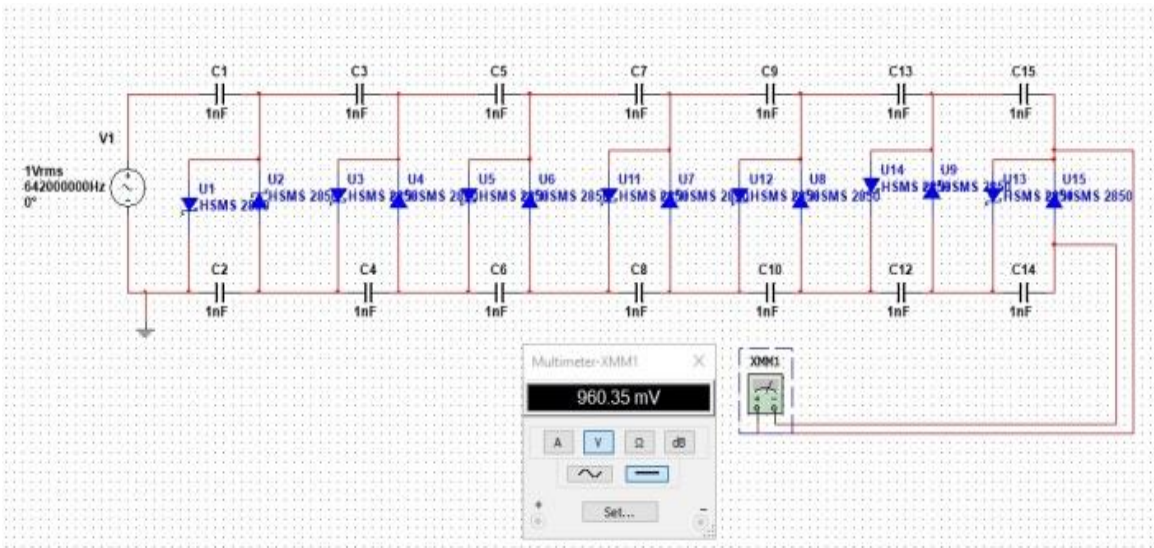


Fig. 3 Rectifier circuit simulation

**2.3. Antenna and Rectifier Fabrication**

An FR-4 PCB board was used to create the antenna and rectifier circuit once the modeling method yielded the ideal specifications. In accordance with the model developed by CST Studio Suite, the antenna configuration was implemented through the process of etching.

Schottky diodes and capacitors were carefully positioned in the rectifier circuit to reduce route losses and preserve circuit symmetry. A 50  $\Omega$  connector was used to integrate the antenna and rectifier, guaranteeing that the system impedance was at the proper level.

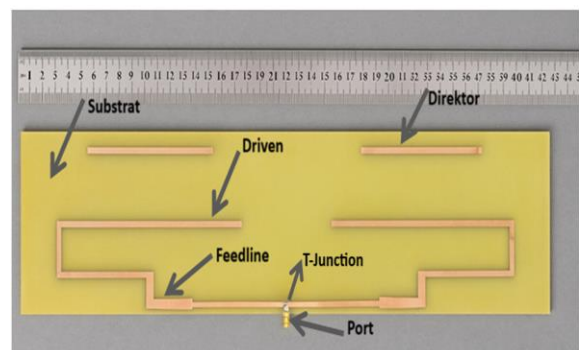


Fig. 1 3-element Yagi-array microstrip antenna

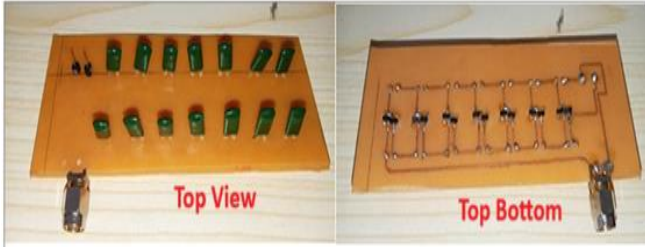


Fig. 5 Rectifier circuit

### 3. Results and Discussion

#### 3.1. Antenna Simulation Results using CST Studio Suite 2019 Software

Figure 6 presents the outcomes of the simulation for the three-element Yagi-Uda microstrip antenna. It illustrates the return loss (S11) graph in relation to frequency. If the return loss reading at the UHF operational frequency falls below -10 dB, this indicates that the antenna is capable of effectively transmitting most of the power, with minimal power being sent back to the source. This condition demonstrates that the

antenna meets the essential criteria required for receiving digital television. The chart shows that the VSWR range is from 1.1 to 1.8. This meets the required standards of  $1 \leq \text{VSWR} \leq 2$ , indicating that impedance is properly matched between the antenna and the transmission line. To guarantee that power from the RF source can be effectively transferred to the antenna without incurring considerable power reflection, this condition is crucial.

According to the simulation results, the antenna may greatly boost the strength of the signal received from a particular direction because its gain is greater than 5 dBi. Since this high gain is consistent with the design goal, it is thought that the antenna can enhance the rectenna system's overall performance. A distinct main lobe with a dominant direction and a comparatively tiny side lobe are visible in the radiation pattern. These features make the antenna directional and suitable for RF energy harvesting applications where concentrating on a single direction is necessary to optimize the power received.

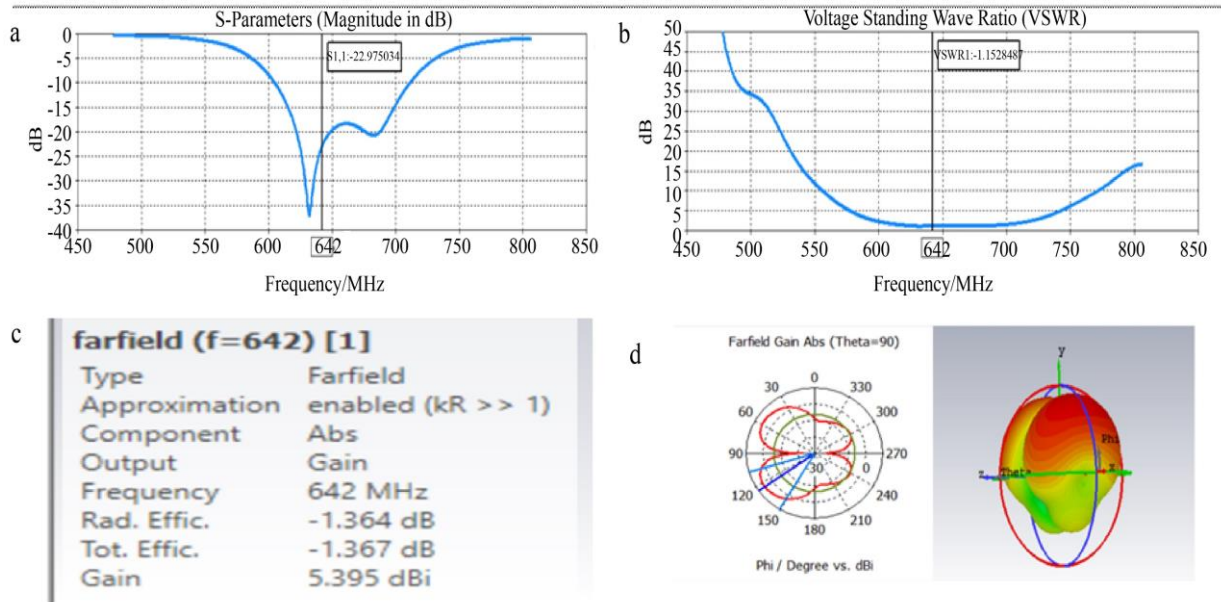


Fig. 6 Results of the 3-element microstrip yagi-array antenna simulation (a) Simulated antenna return loss, (b) Simulated antenna VSWR, (c) Simulated antenna gain, and (d) Antenna radiation pattern simulation.

#### 3.2. Antenna Measurement Results

After design and optimization, the three-element Yagi-Uda microstrip antenna was manufactured. The outcomes of the optimized antenna manufacturing are displayed in Figure 5. A Vector Network Analyzer (VNA) was then used to measure the manufactured antenna [20]. The antenna performance was then assessed by comparing the simulation and measurement findings. The more closely the simulation and measurement findings match, the more likely it is that the fabrication process was executed correctly and in compliance with the intended design. The return loss value of the simulation findings is superior to the measurement results,

according to the data in Figure 7. The antenna is still functioning correctly and meeting the requirements even though there is a difference between the two, because the return loss readings are still within the -10 dB minimum threshold.

Additionally, the simulated VSWR value performs better than the measured outcome. Nonetheless, the observed VSWR value can still be regarded as acceptable since it satisfies the antenna specifications, which are  $1 \leq \text{VSWR} \leq 2$ , indicating that the antenna has produced ideal impedance matching between the transmission system and the antenna.

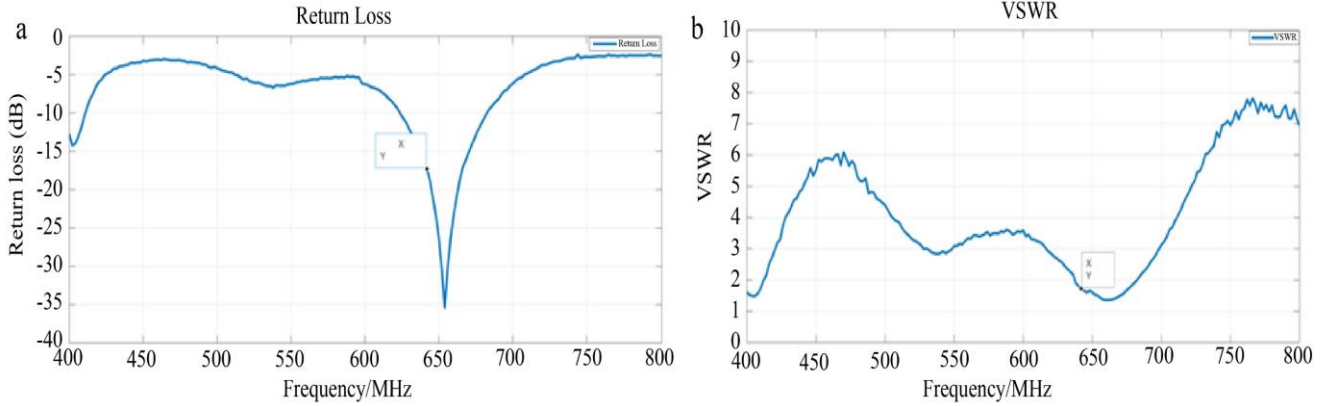


Fig. 7 Measurement Results of a 3-element microstrip yagi-array antenna (a) Measurement of antenna return loss, and (b) Antenna measurement VSWR.

By contrasting the transmitted power of the test antenna with that of a reference antenna, antenna gain measurements were carried out. A 500 MHz monopole antenna served as the transmitting antenna, and a 500 MHz dipole antenna served as the reference antenna for the measurements.

A signal generator was used to create a signal with a strength of 10 dBm and a frequency range of 600-700 MHz. Table 3 displays the results of the measurement.

Table 3. Receiving power comparison

No	Antenna	Power (dBm)
1.	Dipole	-60
2.	Mikrostrip Yagi-Array 3 Elemen	-54,38

The receiving power of a dipole antenna (watts) is calculated as follows:

$$P = -60 \text{ dBm}$$

$$P(\text{dBm}) = 10 \log\left(\frac{P(\text{watt})}{1\text{mW}}\right)$$

$$10^{-60/10} = \frac{P}{10^{-3}}$$

$$P = 1 \times 10^{-9} \text{ W}$$

Receiving power from a 3-element Yagi-Array antenna:

$$P = -54,38 \text{ dB}$$

$$10^{-54,38/10} = \frac{P}{10^{-3}}$$

$$P = 3,62 \times 10^{-9} \text{ W}$$

Therefore, the antenna gain is

$$\text{Gain (linear)} = \frac{P_{Yagi}}{P_{Dipole}} = \frac{3,62 \times 10^{-9}}{1 \times 10^{-9}} = 3,62$$

In decibels (dB):

$$G(\text{dB}) = 10 \log(3,62) = 5,58 \text{ dB}$$

### 3.3. Laboratory Characterization

The first tests of the rectenna's performance were carried out in an antenna laboratory. The testing apparatus employed a digital multimeter to measure output voltage and a transmitter antenna that was attached to a signal generator. The signal generator produced the RF signal at a frequency that was matched to the operating frequency of the receiving antenna. The equipment setup and signal flow during measurement are depicted in Figure 8.

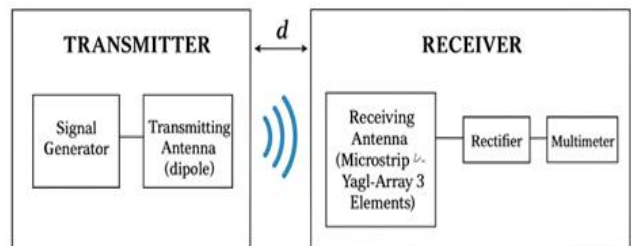


Fig. 8 Rectenna measurement block diagram

The measurements were made by changing the input power from -20 dBm to +20 dBm and the distance between the transmitting and receiving antennas from 25 cm to 100 cm. These alterations were made to ascertain how variations in signal power and distance affected the DC output voltage produced by the rectenna.

The measurement results are shown in Figure 9. Figure 9 shows that throughout all measurement distances, the rectenna produces a larger DC output voltage the more input power is supplied. The greatest voltage value of 1.80 V was attained at a distance of 25 cm with an input power of 20 dBm, while the lowest voltage of 0.01 V was recorded at a distance of 1 m with an input power of -20 dBm.

The RF input power and the distance between the transmitting and receiving antennas are the two primary elements that have a significant impact on the DC output voltage generated.

According to this data, the electromagnetic power received by the receiving antenna and transformed into DC voltage by the rectifier circuit increases with the rectenna's proximity to the transmitter. On the other hand, the voltage produced decreases as the distance increases. Wave

propagation theory, which states that signal power diminishes with increasing distance traveled, explains this occurrence [21]. Consequently, when the rectenna is placed closer to the transmitter, and the input power is high enough, the rectenna system performs better. The measurement results do, however, also show that the output voltage is not always constant. Losses in parts like diodes and variations in the signal generator's RF signal frequency can both contribute to this instability. Furthermore, because this system lacks a voltage regulator, the output voltage varies and is not kept constant.

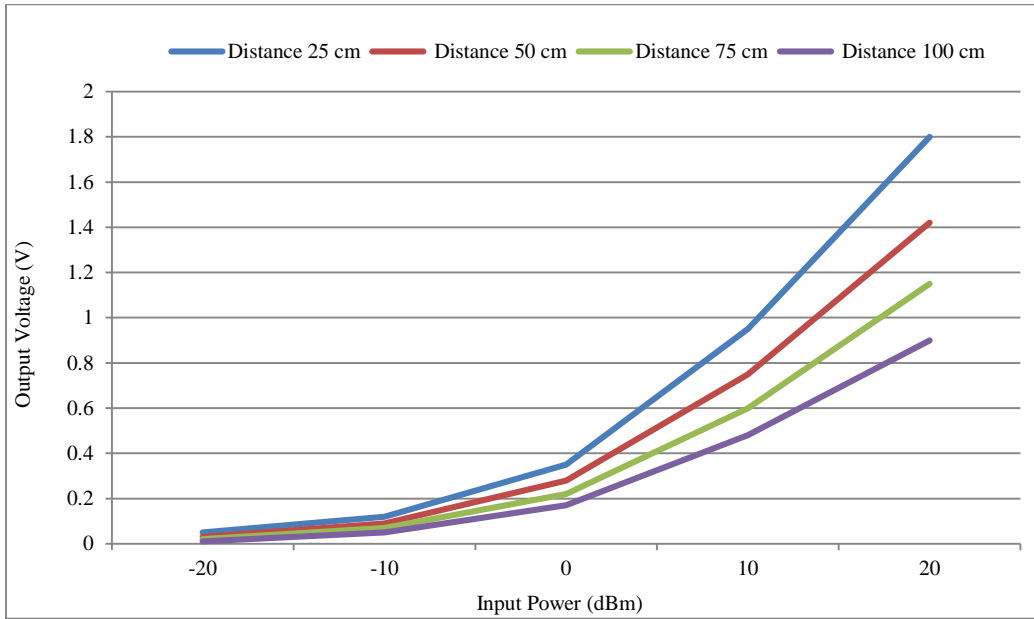


Fig. 9 Plot the DC output voltage with different input power levels and distances

### 3.4. Energy Harvesting from Digital Television Signals in the Surrounding Environment

The rectenna's ability to collect energy from digital television transmitter signals was then tested in the real world. Signals from a DTV transmitter station in West Sumatra Province, situated at coordinates of  $-0.8716983^\circ$  south latitude and  $100.3599383^\circ$  east longitude, were used to test the

rectenna. The distance was varied between 1 and 10 kilometers to take measurements. As seen in Figure 10, the Satfinder AR TV Dish Pointer application was used to calculate the measurement location and distance. A digital multimeter was used to monitor the DC voltage of the rectenna output, and an LED was attached as a load to watch the output's visual response.

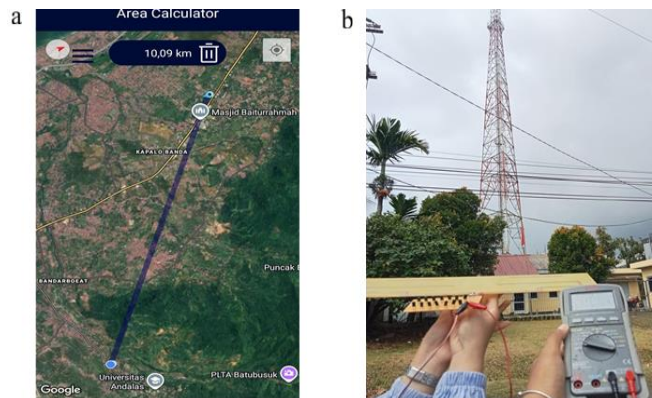


Fig. 10 Test area (a) Example of distance measurement from a transmission tower, and (b) DTV tower in west sumatra province.

Systematic measurements of the rectenna's output voltage were carried out at distances ranging from 1 km to 10 km from the transmitter station in order to assess how well the system harvested and converted Radio Frequency (RF) energy from Digital Terrestrial Television (DTV) signals into electrical energy. Because of its high gain and directional radiation pattern, the 3-element Yagi-Uda microstrip antenna was carefully positioned toward the transmitter based on application data to guarantee optimal signal reception. Figure 11 displays the rectenna's DTV energy harvesting results. The data indicate a steady drop in voltage with increasing distance. The findings show that as the distance from the transmitter

increases, the voltage produced by the rectenna steadily drops. At a distance of 1 km, where the signal strength is rather high, the voltage begins at 1.696 V, and at a distance of 10 km, it drops to a minimum value of 0.054 V. Indicating that the antenna successfully absorbed the RF energy from the DTV transmission and that the rectifier circuit transformed it into usable DC energy, the LED that was added as an indication load was able to light up during testing. As a result, the developed rectenna demonstrated the ability to provide an output voltage of up to 1.696 V, which is adequate to brilliantly illuminate the LED, making it a viable substitute power source for low-power devices.

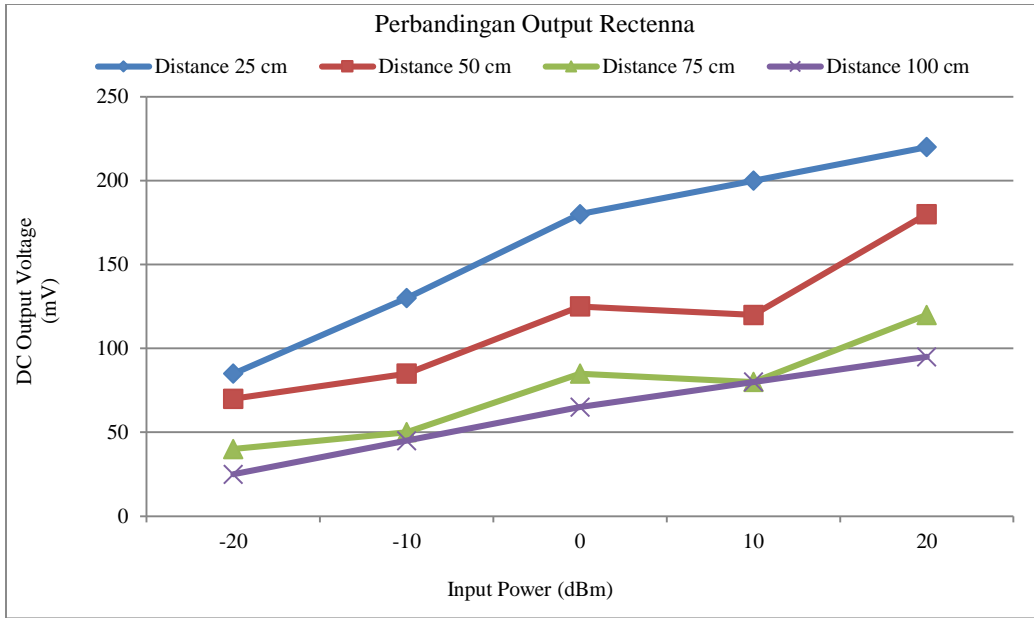


Fig. 11 DC Output voltage plot with digital TV Tower distance

According to the study's findings, the observed voltage dramatically drops with increasing distance between the transmitter source and the rectenna, which is consistent with the rules of electromagnetic wave propagation. These findings show how rectennas can be used for wireless energy harvesting in remote or rural locations with DTV transmitter signals. Increasing the sensitivity of rectifier circuits, incorporating Low-Noise Amplifiers (LNAs), or adding antenna elements to boost energy conversion efficiency at longer distances are just a few of the possibilities these discoveries present for future system design optimization.

#### 4. Conclusion

To harvest UHF Digital Television (DTV) energy at a frequency of 642 MHz, this study successfully designed, built, and assessed a rectenna system including a three-element Yagi-Uda microstrip antenna and a seven-stage Dickson rectifier circuit. All of the research goals were met: the measured gain was greater than 5 dBi, the rectifier circuit generated a significantly higher DC voltage than earlier studies, and the antenna demonstrated excellent impedance

matching with a return loss below -10 dB and a VSWR between 1.1 and 1.8. With a maximum value of 1.80 V at +20 dBm at a distance of 25 cm, laboratory testing demonstrated that the output voltage rose with increasing input power and proximity. At a range of one kilometer away from the DTV tower, practical testing with real broadcast signals resulted in voltages reaching 1.696 V, indicating that this rectenna is suitable for use in devices with low power consumption.

Even with the positive findings, multiple limitations were identified. The rectifier's output remains unstable due to the absence of a voltage regulating component, the choice of FR-4 substrate introduces dielectric losses that degrade antenna efficiency, and assessments were conducted solely at a single frequency without exploring multiband functionality. In addition, efficiency parameters, such as RF-to-DC conversion efficiency, have not been thoroughly investigated. Enhancing the effectiveness of conversions by utilizing substrates with minimal loss, along with the creation of multiband or wideband rectennas, the addition of impedance matching networks, the integration of voltage regulators, and the use of

energy storage components like supercapacitors should be the main emphasis of future research. To get more thorough performance validation, field testing at different distances and locations is also advised. Taking everything into account, the proposed rectenna holds significant potential for RF energy harvesting applications and establishes a solid basis for further advancement.

### Ethics, Approvals, Consent, and Data Privacy

There were no animals, human subjects, or other ethically questionable practices used in this study. All of the studies used electronic components, synthetic radio frequency

signals, and laboratory equipment. No personal information is gathered, stored, or processed in any way for this study. There is no need for approval or informed consent because this research has complied with institutional requirements regarding ethical standards for non-human experimental investigations.

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