ISSN 2714-7533

Design and construct a Yagi Antenna with Three Reflector Element to Strengthen 4G Signal in Rural Areas

Uzma Septima [a], Nasrul [a, 1, *], Firdaus [a], Rafika Uliana [a]

[a] Department of Electronics Engineering, Politeknik Negeri Padang, West Sumatera, Indonesia

[1] nasrulnawi0650@gmail.com
* corresponding author

ARTICLE INFO

Article history
Received June 30, 2023
Revised July 20, 2023
Accepted August 20, 2023

Keywords
Yagi Antenna
4G LTE
rural Areas
repeater

ABSTRACT

Rural areas are indicated to be still difficult to reach by 4G signals due to diverse topographical conditions and uneven landscapes, especially hilly areas that weaken the signal reception level in this region. To make the 4G signal accessible in this area, a repeater in the form of an antenna is needed to strengthen the signal. In this study, a yagi antenna is designed with three reflector elements at a working frequency of 1800 Mhz 4G LTE, expected to produce a minimum gain of 12 dBi and a more focused antenna radiation to strengthen the 4G signal in rural areas.

The antenna design was simulated using CST Studio Suite software, with optimized simulation results yielding a return loss of -22 dB, VSWR 1.167, and gain 12.40 dBi. From the measurements obtained, the yagi antenna with three reflector elements works well at a frequency of 1800 Mhz, with a return loss of -34.77 dB, VSWR 1.065, gain 12.96 dBi, and unidirectional radiation. With the optimal antenna parameters and the addition of three reflector elements, it's possible to increase the gain value, even though the gain increase isn't substantial, and it narrows the HPBW (Half Power BeamWidth) value. Moreover, testing the yagi antenna at 3 different distances demonstrated that the resulting gain value can enhance 4G signal speed in rural areas.

1. Introduction

Rural areas have diverse topographies and uneven landscapes. The presence of hills, valleys, and forests can hinder radio signal propagation, resulting in weak signal reception levels in these areas, particularly in regions with many hills. Another factor contributing to suboptimal signal reception in these areas is the large distance between the user and the transmitter because the further the distance between the two, the more the power level of the broadcasted signal decreases [1]. To address these issues, a Yagi antenna operating at 1800 MHz has been designed to enhance performance and strengthen 4G signal reception in rural areas. The use of a Yagi antenna is deemed suitable because it has unidirectional radiation. With this kind of radiation pattern, it can transmit signals over long distances [2]. Additionally, with a simple antenna design, a high gain can be achieved [3]. The construction of the Yagi antenna is relatively inexpensive in terms of cost because it uses aluminium, which is readily available.

Several studies have been conducted regarding the design of Yagi antennas to strengthen signal reception, including [4] Performance analysis of an 11-element Yagi antenna for GSM signal amplification, which works well at GSM uplink frequencies, [5] Designing a 5-element Yagi antenna for 4G signal amplification at 1800 MHz frequency, with average performance results indicating that 4G LTE can improve 4G signal quality, [6] A study was conducted on a three-element Yagi antenna for enhancing Yagi antenna performance with the addition of two reflector elements, which resulted in a gain increase of up to 6 dB. Based on the research [4] and [6] Based on the studies mentioned above, in this research, an 11-element Yagi antenna will be designed to operate at a frequency of 1800 MHz, with the addition of two reflector elements. It is expected to produce a minimum gain of 12 dBi, with a more focused and directed antenna radiation to enhance 4G signal reception in rural areas.

2. Research Methodology

A Yagi antenna consists of a few straight antenna elements, each tuned to a length approximately half of the electromagnetic wavelength it's designed to support. While it's true that it's a symmetrical type, it can become unbalanced if a balun isn't utilized at the transmission point where the driving element of the directional antenna is connected [7]. the Yagi-Uda antenna is a directional antenna equipped with several parallel straight cylindrical conductors. Only one of these conductors, known as the dipole, is powered, while the others serve as parasitic elements, namely directors and reflectors [8]. The reflector element is used to re-radiate the emission from the rear side towards the front [9]. In other words, the reflector element helps to reduce signal radiation in the backward directionthe Yagi antenna that will be designed aims to strengthen the reception of 4G signals at 1800 MHz frequency. The characteristics of the Yagi antenna are influenced by all the geometric parameters of the array. Typically, Yagi-Uda arrays have low input impedance and a relatively narrow bandwidth. Alterations in one aspect often come at the expense of others [3]. This Yagi antenna consists of 3 reflector elements, 1 driven element, and 9 directors, and uses a 1:1 balun as impedance matching between the antenna and the transmission line. In designing this antenna, it is necessary to determine the antenna specifications as a reference in the design. The required antenna specifications are as follows:

- Frequency : 1800 Mhz
- Return Loss : $\leq$ 10 dB
- VSWR : $1 \leq VSWR \leq 2$
- Input Impedance : 50 Ω
- Gain : > 10 dB
- Radiation Patern : Unidirectional

2.1. Yagi Antenna Calculation

Yagi antenna calculation is conducted to measure the length of the antenna elements and the spacing between antenna elements. To produce a good antenna, it's important to know the optimal dimensions of L_r ($\lambda/2$), L_a ($0.45\ \lambda$ -$0.49\ \lambda$) dan L_d ($0.4\ \lambda$ -$0.45\ \lambda$) [10]. to measure the length of the antenna elements, it is necessary to know the operating frequency of an antenna, after which the wavelength (λ) value can be determined. The calculation of the Yagi antenna will be described as follows:

1. Wavelength

The wavelength can be calculated using the following equation:

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

Where c is the speed of light in vacuum ($3x10^8$m/s) and f is frequency [11]. Therefore, the obtained wavelength is as follows:

$$\lambda = \frac{c}{f} = \frac{3x10^8\ m/s}{1800\ x\ 10^6\ Hz} = 0.167 \text{ m} = 167 \text{ mm}$$

2. Element Length and spacing between antenna element

Highest gain is obtained when the reflector is slightly greater than λ/2 in length and spaced at 0.25 λ from the driven element and when the length of the director less than with an optimal spacing of about 0.31 λ Therefore, the length of the elements and the spacing of the antenna are calculated using the equation [12]

a. The length of reflector

L_a= 0.475 (λ) (2)

L_a= 0.475 (λ) = 0.475 x 167 mm = 79.325 mm

b. The length of driven

L_r = 0.46 (λ) (3)

L_r = 0.46 (λ) = 0.46 x 167 mm = 76.82 mm

c. The length of director

L_d = 0.44 (λ) (4)

L_d = 0.44 (λ) = 0.44 x 167 mm = 73.48 mm

d. Spacing between elements

- Spacing between director and driving elemen

  S_L= 0.31 (λ) (5)

  S_L = 0.31 x 167 mm = 51.77 mm

- Spacing between reflector and driven element

  S_d= 0.25 (λ) (6)

  S_d = 0.25 x 167 mm = 41.75 mm.

3. Balun calculation

The driven element in a Yagi antenna is the part that is connected to the power and acts as the activator of the antenna, making it often considered a vital part of the antenna [13]. Therefore, the dipole made from copper wire should have an impedance matching the transmission line, and for this reason, a balun is used as an impedance matcher between the designed antenna and the transmission line. The type of balun to be used for this Yagi antenna design is a 1:1 balun. The balun configuration can be seen in Fig. 1. Based on the configuration in Fig. 1, the balun size can be calculated using the following equation [14]

- The length of balun = 0.25 (λ) (7)

  = 0.25 x 167 mm

  = 41.75 mm

- The length of feedline = 0.5 (λ) (8)

  = 0.5 x 167 mm

  = 83.55 mm

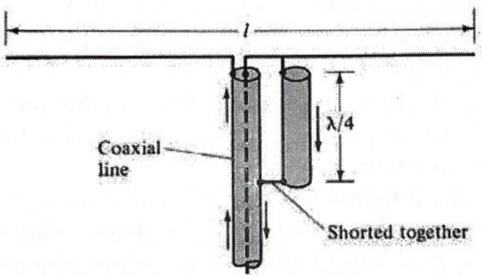


Figure 1. λ/4 coaxial balun (1:1) [15]

Here are the results of the Yagi antenna calculation shown in table 1

Table 1. The results of the Yagi antenna calculation

Yagi Antenna Elements	The Length of Elemens (mm)
Reflector 1	79.325
Reflector 2	79.325
Reflector 3	79.325
Driven	76.82
Director 1 – Director 9	73.48
Spacing between director and driven elemen	51.77
Spacing between reflector and driven elemen	41.75
Horizontal Spacing between reflectors	30^0 & 30^0
The length of balun	41.75
The length of feedline	83.55
Aluminum Diameter	2
Cooper Diameter	2

2.2. Antenna Yagi Design

The length of the Yagi antenna's director element is a little less than the length of the driven element, but the length of the reflector is longer than the length of the driven element [16]. The designed antenna uses aluminum for reflector and director elements, while the driven element uses copper wire with an antenna element diameter of 2 mm. The display of the antenna design results can be seen in Fig. 2.

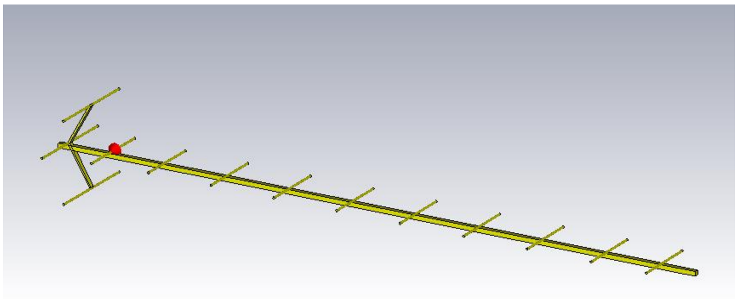


Figure 2. Yagi Antenna Design Results

2.3. Parametric Study

Parametric study was conducted to obtain optimal antenna parameter values in the simulation and to increase the gain was reached by modifying the geometry of element antenna [17]. This step is carried out by changing the lengths of the antenna elements. The antenna element that affects the operating frequency and input impedance of the Yagi antenna is the driven element [18]. the display of the return loss antenna parameter results is shown in Fig. 3. The return loss value at 1800 MHz frequency is -7.8 dB, which is still far from the required return loss value of below -10 dB. Optimization of simulation results is done by reducing the size of the driven, which initially was 76 mm, to 66 mm with the obtained return loss value of -7.8 dB. Then, when the driven size is increased to 70 mm, an optimal return loss result of -18 dB is obtained.

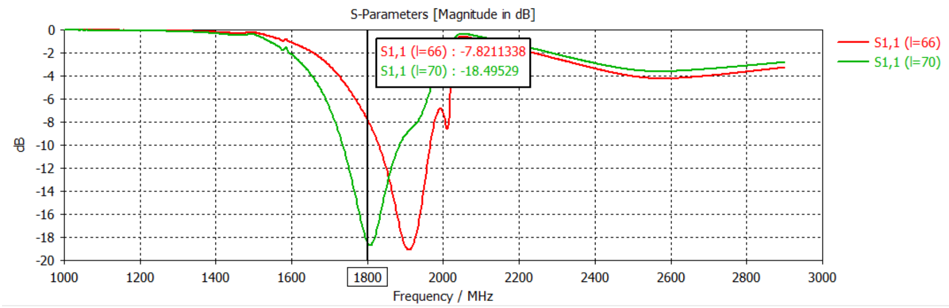


Figure 3. The Effect of driven length

Whereas the element that influences the increase in gain is the length of the reflector and directors [18]. to see the effect of the length of the reflector and director on the resulting parameter values, see Fig. 4. By enlarging the reflector size from the initial length of 79 mm to 90 mm and reducing the director size from the initial length of 73 mm to 60 mm, a more optimal return loss value of -22 dB was obtained compared to before. The power reflected by the antenna, also known as VSWR (Voltage Standing Wave Ratio), is a real number for the antenna. The antenna will be matched with the transmission line, which can deliver more power [19]. The resulting VSWR value of 1.16 is displayed in Fig 5.

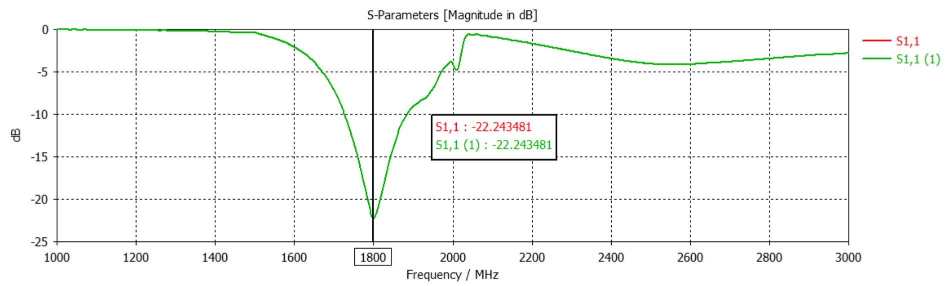


Figure 4. The Effect of Reflector and director

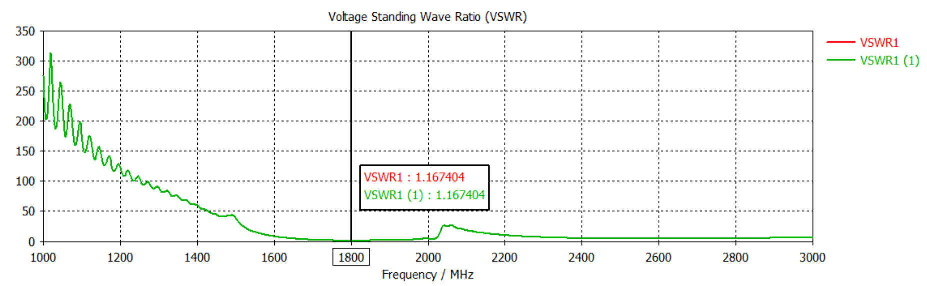


Figure 5. VSWR Results After Optimizations

Antenna design and optimization using CST Studio Suite, the length of elements and the spacing between elements are important design parameters in design [20]. the size of the antenna elements after conducting a parametric study will be different from the theoretical calculations. The antenna dimensions after optimization are what will be used for fabrication, as can be seen in Table 2 below.

Table 2. Yagi Antenna Calculation Results After Optimizations

Yagi Antenna Elements	The Length of Elemens (mm)
Reflector 1	90
Reflector 2	90
Reflector 3	90
Driven	70
Director 1 – Director 9	60
Spacing between director and driven elemen	51.77
Spacing between reflector and driven elemen	41.75
Horizontal Spacing between reflectors	30^0 & 30^0
The length of balun	41.75
The length of feedline	83.55
Aluminum Diameter	2
Cooper Diameter	2

The results of the Yagi antenna design after optimization can be seen in Fig. 5.

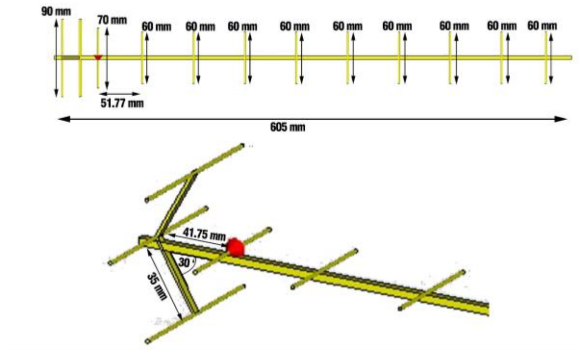


Figure 5. Yagi Antenna Design After Optimization

2.4 Yagi Antenna Fabrication

Once the antenna has achieved optimal results and meets the required antenna specifications, the next step is the fabrication process. The steps for fabricating the antenna are described as follows:

4. Antenna elements cutting

The main material in making a Yagi antenna is a 2 mm diameter aluminum pipe for the reflector and director elements, a 1x1 cm square aluminum for the boom, and a 2 mm diameter copper wire for the driven element. The aluminum pipe, square aluminum, and copper wire are cut according to their respective sizes as shown in Fig. 6.

Figure 6. Antenna Elemen

5. Antenna boom construction

For the construction of the boom, the top part of the aluminum will be coated with acrylic so that the installed antenna elements are not connected to the boom, as the function of the boom is just to arrange these antenna elements. The appearance of the boom can be seen in Fig. 7

Figure 7. Boom Antena

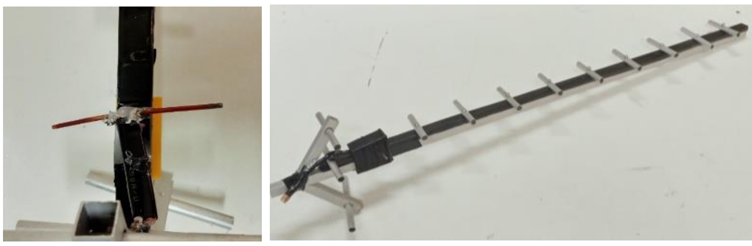
6. Construction of Driven Elements

The driven uses a dipole-shaped copper wire that is cut into 2 equal length parts. The driven element uses a 1:1 balun made from RG-58 coaxial cable. The ends of the copper wire that have been cut into 2 are first sanded so that their outer layer is open, then soldered to the coaxial cable. After that, the driven is coated with insulation to make it neater and safer. The following is Fig. 8, showing the driven element with a 1:1

Figure 8. Driven Elements with Balun 1:1

7. Installation Antena Elements

The director and reflector elements are mounted on the boom using bolts, while the driven element is installed last using glue. The antenna production results are shown in Fig. 9.



(a) (b)

Figure 9. (a) Driven installation (b) Yagi antenna fabrication results

3. Results And Discussion

3.1. Yagi Antenna Measurement Results

The Yagi antenna measurement was conducted in the G303 Antenna Lab of the Telecommunication Engineering Department at Politeknik Negeri Padang. The antenna parameters measured were return loss, VSWR, radiation pattern, and gain. The return loss and VSWR were measured using the Keysight Vector Network Analyzer. The results for the return loss parameter are shown in Fig 10. The measured return loss value was -34.78 dB at a frequency of 1800 MHz, while the optimized simulation result was -22 dB. Compared to the simulation results, the return loss obtained from the measurement was better. The use of a balun in the Yagi antenna greatly affects the return loss value. A previous measurement showed a return loss of -7 dB. This discrepancy was due to a soldering error between the balun and the dipole, which affected the resulting return loss value.

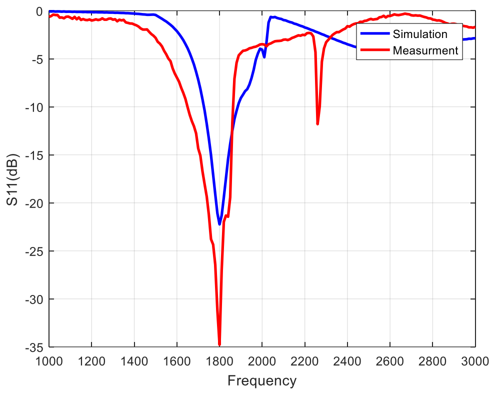


Figure 10. Return loss

The VSWR measurement resulted in a value of 1.047, whereas the optimized simulation result showed a VSWR value of 1.167, as displayed in Fig 11. The produced VSWR value meets the criteria and is in line with the antenna specifications. The designed antenna has already produced an optimal transmission system and antenna system.

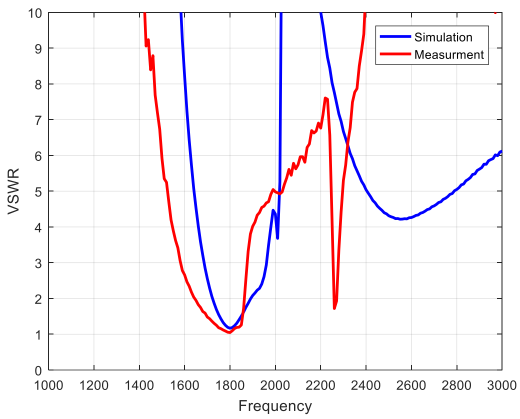
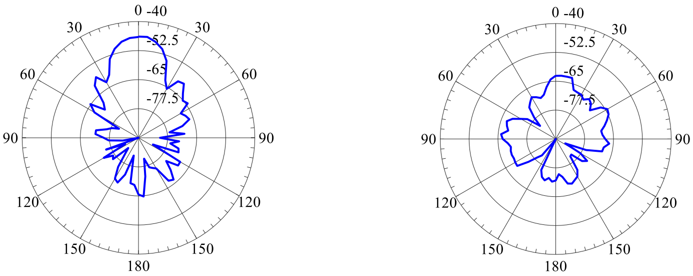


Figure 11. VSWR

Next, the radiation pattern measurement of the antenna used an RF Generator as the signal source, which was connected to a dipole antenna as the transmitter (Tx) and the Yagi antenna as the receiver (Rx) was linked to a spectrum analyzer, as shown in fig 12. The Yagi antenna measurement was performed both horizontally and vertically. The resulting radiation pattern measurement was unidirectional, as depicted in fig 12.

(a) (b)

Figure 12. (a) Tx Antenna is connected to the RF Generator (b) Rx Antenna is connected to the spektrum Analyzer



(a) (b)

Figure 13. (a) elevation (b) Azimuth

In fig 13, the resulting radiation pattern is unidirectional with a large main lobe and a small minor lobe. This ensures the Yagi antenna transmits power maximally to the front and minimally to the rear, with a maximum horizontal power level of -46.47 dBm. The radiation direction from the antenna is focused and extends far to the front, with no signal being transmitted to the rear. Subsequent gain measurements, using two dipole antennas, are shown in fig 14. The first dipole antenna serves as the transmitter (Tx), and the second dipole antenna acts as a reference antenna. The received power level of the reference dipole antenna is displayed in fig 15. The measurement results for the received power level of the reference dipole antenna and the Antenna Under Test (AUT), which is the Yagi antenna, are presented in table 3. The measured gain is 12.96 dBi, and the simulated gain is 12.40 dBi.

Figure 14. Dipole Antenna

(a)

(b)

Figure 15. (a) Measurement of the Received Power of the Reference Antenna (b) Measurement of the Received Power of the Yagi Antenna

Table 3. Received Power Level of the Reference Antenna and AUT Antenna

Antenna Type	Received Power (dBd)
Dipole Antenna 1800 Mhz (reference)	-55.31
Yagi Antenna 1800 Mhz (AUT)	-44.50

The Yagi antenna serves as a receiving antenna or the Antenna Under Test (AUT)

P_r AUT = -55.31 dBd, P_r *Dipole* = -44.50 dBd
G(dB) = P_r *Dipole* - P_r AUT
= -44.50 dBd - (-55.31 dBd) = 10.81 dBd
G (dBi) = G(dB) + 2.15 dBi
= 10.81 dBd + 2.15 dBi = 12.96 dBi

The measured gain value is 12.96 dBi, while the optimization result from the simulation is 12.40 dBi. The measured value is higher.

3.2. Yagi Antenna Testing Results.

The Yagi antenna was designed to enhance 4G signal reception in rural areas. Thus, a direct test was conducted in such an area. The Yagi antenna testing took place in Dusun Ladang Laweh, Desa Talago Gunung, in the Baringin sub-district of Sawah Lunto City. The coordinates for the location are latitude -0.540258 and longitude 101.443. With another set of coordinates at latitude -0.504825 and longitude 101.443. For the Yagi antenna testing, an induction system was used along with a Wi-Fi modem. Tests were conducted at distances of 200 m, 500 m, and 800 m. To determine the signal quality in the area, the Network Cell Info Lite application was used. The observed results included the received power level values, uplink, and downlink results.

A. Testing at a distance of 200 m

The first test was conducted using an induction system from the Yagi antenna to a mobile phone, measuring the received power level produced. Before using the Yagi antenna, the received power level was -121 dB, indicating a rather poor signal quality. However, after using the Yagi antenna, the received power level improved to -93 dB. In this case, there was an enhancement in signal strength when the Yagi antenna was used.

The second test involved a Wi-Fi modem. The Yagi antenna was mounted at a height of 2 meters and was connected to the Wi-Fi modem using an RG-58 cable. The measured values were the uplink and downlink speeds without the antenna and using the antenna, and each test was conducted three times. The results of these tests are presented in table 4.

Table 4. Antenna Testing Results at a distance of 100 m

Modem Wi-Fi 4G LTE without Yagi Antenna		
Experiment	Downlink (Mbps)	Uplink (Mbps)
1	12.7	0.0856
2	8.8	0.7948
3	11.2	1.2
Modem Wi-Fi 4G LTE with Yagi Antenna		
Experiment	Downlink (Mbps)	Uplink (Mbps)
1	16.7	3.1
2	16.6	1.2
3	23.4	4.4

In Table 4, the 4G LTE Wi-Fi modem, without using the Yagi antenna at a distance of 200 m, produced an average downlink speed of 10.9 Mbps and an uplink speed of 0.693 Mbps. However, when the 4G LTE Wi-Fi modem was connected with the Yagi antenna, it produced an average downlink speed of 18.9 Mbps and an uplink speed of 8.6 Mbps. The downlink and uplink speeds increased by 8 Mbps and 7.907 Mbps respectively.

B. Testing at a distance of 500 m

At a distance of 500 m, the received power level of the antenna without the Yagi antenna was -117 dB, indicating a rather poor signal quality. However, after using the Yagi antenna, the received power level improved to -81 dB. The speed test results for the 4G LTE Wi-Fi modem without the Yagi antenna produced an average downlink speed of 5.33 Mbps and an uplink speed of 0.528 Mbps. The signal speed decreased when compared to the results at 200 m. However, when the 4G LTE Wi-Fi modem was connected to the Yagi antenna, the average downlink speed was 25.86 Mbps and the uplink speed was 3.6 Mbps. The downlink and uplink speeds increased by 20.53 Mbps and 3.072 Mbps, respectively. The test results are displayed in Table 5 below.

Table 5. Antenna Testing Results at a distance of 500 m

Modem Wi-Fi 4G LTE without Yagi Antenna		
Experiment	Downlink (Mbps)	Uplink (Mbps)
1	5.3	0.7043
2	4.6	0.3932
3	6.1	0.4887
Modem Wi-Fi 4G LTE with Yagi Antenna		
Experiment	Downlink (Mbps)	Uplink (Mbps)
1	29.6	3.5
2	24.6	2.9
3	23.4	4.4

C. Testing at a distance of 800 m

At a distance of 800 m, the antenna's received power level was -114 dB, indicating a relatively poor signal quality. However, when compared to the two previous distances, the received power level started to improve. After using the Yagi antenna, the received power level improved to -71 dB. The speed test results for the 4G LTE Wi-Fi modem without the Yagi antenna at 800 m produced an average downlink speed of 8.13 Mbps and an uplink speed of 2.7 Mbps. As the distance between the modem and the BTS increased, the signal speed continued to decrease. However, when the 4G LTE Wi-Fi modem was connected to the Yagi antenna, the average downlink speed increased to 30.73 Mbps and the uplink speed reached 11.6 Mbps. The downlink and uplink speeds increased by 22.6 Mbps and 8.9 Mbps, respectively. Based on the test data from the Yagi antenna at the three different distances, it is evident that the Yagi antenna can enhance 4G signal reception in the area by increasing both the speed and the received signal's power level. The test results are displayed in table 6 below.

Table 5. Antenna Testing Results at a distance of 800 m

Modem Wi-Fi 4G LTE without Yagi Antenna		
Experiment	Downlink (Mbps)	Uplink (Mbps)
1	7.6	2.5
2	7.2	2.8
3	9.6	2.8
Modem Wi-Fi 4G LTE with Yagi Antenna		
Experiment	Downlink (Mbps)	Uplink (Mbps)
1	37.6	30.9
2	27.5	2.7
3	27.1	1.3

4. Conclusion

The Yagi antenna with three reflector elements performs well at a frequency of 1800 MHz, producing results of a return loss of -34.77 dB, VSWR of 1.065, a gain of 12.96 dBi, and a unidirectional radiation pattern. By adding three reflector elements, the antenna's performance improves with an increase in gain by 0.56 dBi and a narrower HPBW (Half Power Beam Width). Additionally, tests of the Yagi antenna at three different distances prove that the achieved gain can enhance the received power level and 4G signal speed in rural areas.

Acknowledgment

Thank you to Padang State Polytechnic and all parties who have assisted in this research.

References

[1] M. U. Jurusan, T. Elektronika, and P. N. Balikpapan, *Perhitungan Pathloss Teknologi 4g Long Term Evolution (Lte)*, *Journal Ecotipe*, vol. 3, no. 2, 2016.

[2] I. Gusti *et al.*, *Rancang Bangun Antena Yagi Pada Frekuensi 1800 MHz Untuk Penguatan Sinyal Modem*, *Teknologi Elektro*, vol. 16.

[3] Abdulhamid M. Analysis and design of 10-element Yagi-Uda Antenna. Zhurnal Radioelektroniki - Journal of Radio Electronics. 2020. No. 3. Available at http://jre.cplire.ru/jre/mar20/10/text.pdf. DOI 10.30898/1684-1719.2020.3.10.

[4] T. Silviati, D. Abdurrahman, A. M. Saad, and D. Bulgis, *Analisis Performansi Antena Yagi-Uda 11 Elemen Sebagai Penguat Sinyal Global System for Mobile Communication (GSM)*, 2018.

[5] S. Firas and S. Broto, *Rancang Bangun Antena Yagi 5 Elemen Sebagai Penguat Sinyal 4g Pada Frekuensi 1800 Mhz*, vol. 3, no. 1, 2020.

[6] G. M. Thakur, V. B. Sanap, and B. H. Pawar, Study of Radiation Patterns Using Modified Design of Yagi-Uda Antenna, *Advanced Engineering Technology and Application an International Journal Adv. Eng. Tec. Appl*, vol. 5, no. 1, p. 7, 2016, doi: 10.18576/aeta/050102.

[7] A. Haque *et al.*, "Design and Analysis of Sphere Yagi antenna at 915 MHz Band for LoRaWAN Application," in *Journal of Physics: Conference Series*, Institute of Physics, 2023. doi: 10.1088/1742-6596/2550/1/012015

[8] Meor Said, M. A., & Misran, M. H. (2021). *High Gain Design of Yagi Uda Antenna*.

[9] G. AbdelRahman M, H. Mohamed, H. Rehab, and Y. Ashraf, "Compact Super-Directive Yagi-Uda Antenna Based on Parabolic-Shaped Reflector for Wireless Communications," *International Journal of Electronics and Device Physics*, vol. 4, no. 1, Dec. 2020, doi: 10.35840/2631-5041/1706.

[10] C. Babu, K. V. Kumar, and M. N. Kumar, "Yagi-Uda Antenna Design With Gain And Bandwidth Improvement Of Arrays." [2022]. Available: www.irjmets.com

[11] Stutzman, Warren L. Antenna Theory and Design Third Edition, Virginia: Jhon Wiley & Sons Inc, 2012.

[12] G.S.N. Raju. Antennas and Wave Propagation, India, 2005.

[13] M. A. Haque et al., "Quasi-Yagi antenna design for LTE applications and prediction of gain and directivity using machine learning approaches," Alexandria Engineering Journal, vol. 80, pp. 383–396, Oct. 2023, doi: 10.1016/j.aej.2023.08.059.

[14] Firdaus, Monica, L., & Yustini. (2020). Study on Impedance Matching of 2.4 GHz Dipole Antenna. *IOP Conference Series: Materials Science and Engineering*, *846*(1).

[15] C.A.Balanis. Antenna Theory Third Edition, USA: Jhon Wiley & Sons Inc, 2012.

[16] M. A. Meor Said and M. H. Misran. (2021) "Design of Microstrip Yagi Antenna at 5 GHz for Wi-Fi Application,"

[17] Constantinescu, C., Pacurar, C., Giurgiuman, A., Munteanu, C., Andreica, S., & Gliga, M. (2023). High Gain Improved Planar Yagi Uda Antenna for 2.4 GHz Applications and Its Influence on Human Tissues. Applied Sciences (Switzerland), 13(11). https://doi.org/10.3390/app13116678

[18] A. E. Farahat and K. F. A. Hussein, "Dual-band (28/38 GHz) Yagi–Uda Antenna with Corrugated Radiator and Triangular Reflectors for 5G Mobile Phones," The Applied Computational Electromagnetics Society Journal (ACES), Nov. 2021, doi: 10.13052/2021.aces.j.361009.

[19] M. A. Ashraf, K. Jamil, A. Telba, M. A. Alzabidi, and A. R. Sebak,"Design and Development of Dual-Polarized Orthogonal Cross Yagi antenna for the frequency range of 50MHz to 500MHz," 2021

[20] M. Barshikar, A. Yenpure, O. Atre, S. Jagdale, and A. Lyengar, "Design and development of a wideband planar yagi antenna using tightly coupled directive element," *Micromachines (Basel)*, vol. 11, no. 11, Nov. 2020, doi: 10.3390/mi11110975.