2.4GHZ RECTANGULAR MICROSTRIP PATCH ANTENNA AS WIFI TRAINER APPLICATION

Syahril Izwan bin Abdul Yamin*

Electrical Engineering Department, Tuanku Sultanah Bahiyah Polytechnic, 09700 Kulim, Kedah, Malaysia

*Corresponding author email address: syahril@ptsb.edu.my

ABSTRACT

The Rectangular Microstrip Patch Antenna (RMPA) is compatible with MMIC designs, low profile, conformable to planar and nonplanar surfaces, simple and inexpensive to manufacture using modern printed-circuit technology, mechanically robust when mounted on rigid surfaces, and very versatile in terms of resonant frequency, polarization, pattern, and impedance when the specific patch shape and mode are selected. The purpose of this study is to give exposure to students about the Flame Retardant 4 (FR4) used to produce RMPA, which is from various types of different dielectric constants, methods of transmission line feeds and the output result in terms of Return Loss at the minimum value desired frequency 2.4GHz. The process began with the creation of a single-element RMPA. The resonance frequency, material, and height of the substrate were all determined. For a good impedance-matching network, the patch dimensions were estimated using the transmission line model, and the single-element RMPA was excited using the inset-fed microstrip line approach and the quarter-wave transformer. The inset-fed microstrip line RMPA achieved gains of 10.29 dB, respectively, compared to the quarter-wave transformer RMPA gain of 5.26 dB. The results reveal that the inset-fed microstrip line of RMPA got better gain than the quarter-wave transformer RMPA. The antennas are suitable for usage in wireless local area networks, S-band communications, and advanced wireless communication systems.

Keywords: Microstrip Patch Antenna, Relative Permittivity, WIFI, Return Loss

1. Introduction

One of the most important sub-topics in DEP50043 Microwave Devices is Microstrip Patch Antenna (MPA). This antenna operated in microwave frequency range 1GHz to 100Ghz. Its application is mostly used as a radar antenna and mobile antenna. MPA also can be operating as a WIFI antenna in 2.4GHz and 5GHz frequency bands.

The IEEE802.x WLAN standard used now is 2.4GHz and 5GHz. Both frequencies have their advantages and disadvantages. It differs in terms of data transmission, data speed, operating distance, power consumption, and others. Wi-Fi, which is standard for wireless local area networking (WLAN), has become a need in our daily lives. Nearly 100 billion IoT devices, smartphones, tablets, laptops, desktops, smart TVs, video cameras, monitors, printers, and other consumer gadgets are connected to the Internet by more than a billion Wi-Fi access points, allowing millions of applications to be used by everyone, anywhere. One of the most important pieces of hardware in the

WIFI system is the antenna. There are several types of antennas were used such as an Omni-directional antenna, a dipole antenna, etc [1][2].

Antennas act as intermediaries between free-space electromagnetic waves and circuit-guided electromagnetic impulses. They are essential to the operation of wireless communication systems. Radiation can be defined as the transmission of electric energy. Antennas, which are conductive or dielectric structures, are used to efficiently launch waves into space. Although any structure can theoretically radiate electromagnetic waves, not all structures are effective radiation mechanisms [3].

As a result, engineers use a combination of theory, simulation, and experimental inquiry to arrive at a design that fits all of a given application's requirements. An antenna is a critical component in a wide range of applications, systems, and equipment, including aircraft, spacecraft, satellites, ships, biomedical systems, cellular phones, GPS, and radars [4].

Microstrip antennas are the most dynamic field of antenna theory used currently. Lightweight, compact size, low cost, conformability to host surface, and easy interaction with active devices are key advantages of MSAs. MSAs have two primary performance limitations: low gain and restricted bandwidth. As a result, increasing the gain and bandwidth of microstrip antennas is difficult. Many scholars have used a variety of strategies to construct MSAs with better performance. To improve the performance of microstrip antennas, some researchers have invented new designs or modified existing ones. Using alternative microstrip antenna array designs and microstrip slot antennas, the single-element MSAs' poor gain, narrow bandwidth, and limited power handling capacity have been improved [5].

There are various types of MPA shapes such as rectangles, circles, triangles, and others. This study uses a rectangular MPA as shown in Figure 1.

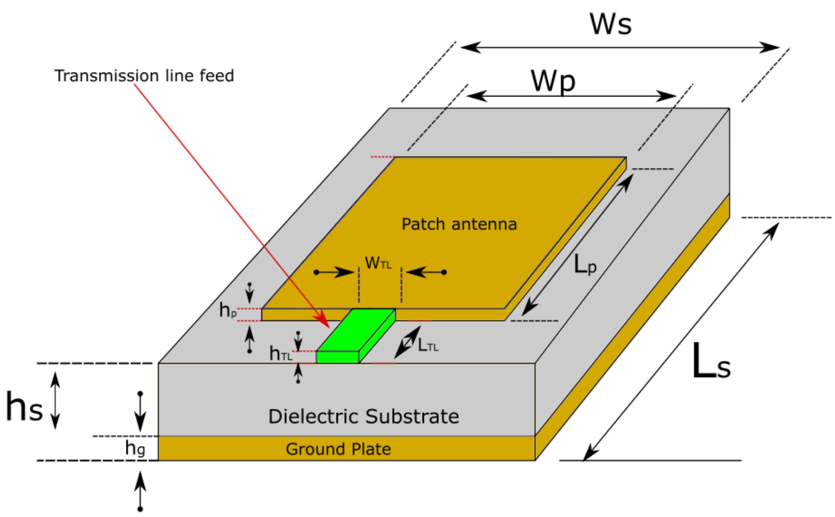


Fig. 1. Geometry Structure of MPA

The MPA description is as follows in table 1 below.

Table 1. MPA description

No.	Description	Specification
1	W_s	Width of the substrate
2	L_s	Length of the substrate
3	H_s	Height (thickness) of the substrate
4	W_p	Width of the patch
5	L_p	Length of the patch
6	H_p	Height(thickness) of the patch=0.035mm (standard of FR4 copper's height)
7	h_{TL}	Height(thickness) of the transmission line = h_p
8	W_{TL}	Length of the transmission line
9	H_g	Width of the transmission line

The purpose of this study is to give exposure to students about the material used to produce RMPA, which is from various types of materials where each material will have a different dielectric constant(relative permittivity, $\varepsilon_r = 3.3 - 4.8$) value such as FR4, Nylon610, Silicon, etc [6]. As a result, this value will be affected the output result, especially the return loss(S11) parameter. This study focused on FR4 material, which has various ranges of relative permittivity[6]. The RMPA's patch size and return loss at desired frequency will be affected accordingly by the relative permittivity $\varepsilon_r = 3.3 - 4.8$ [7].

2. Methodology

2.1 Rectangular Microstrip Patch Antenna (RMPA) Design.

RMPA design begins with several equations to determine the width and length of the patch radiation element. Then all the considerate parameters should be inserted into the CST Design Suite software with suitable values accordingly to the established equation. All the progress is shown in the block diagram in Figure 2.

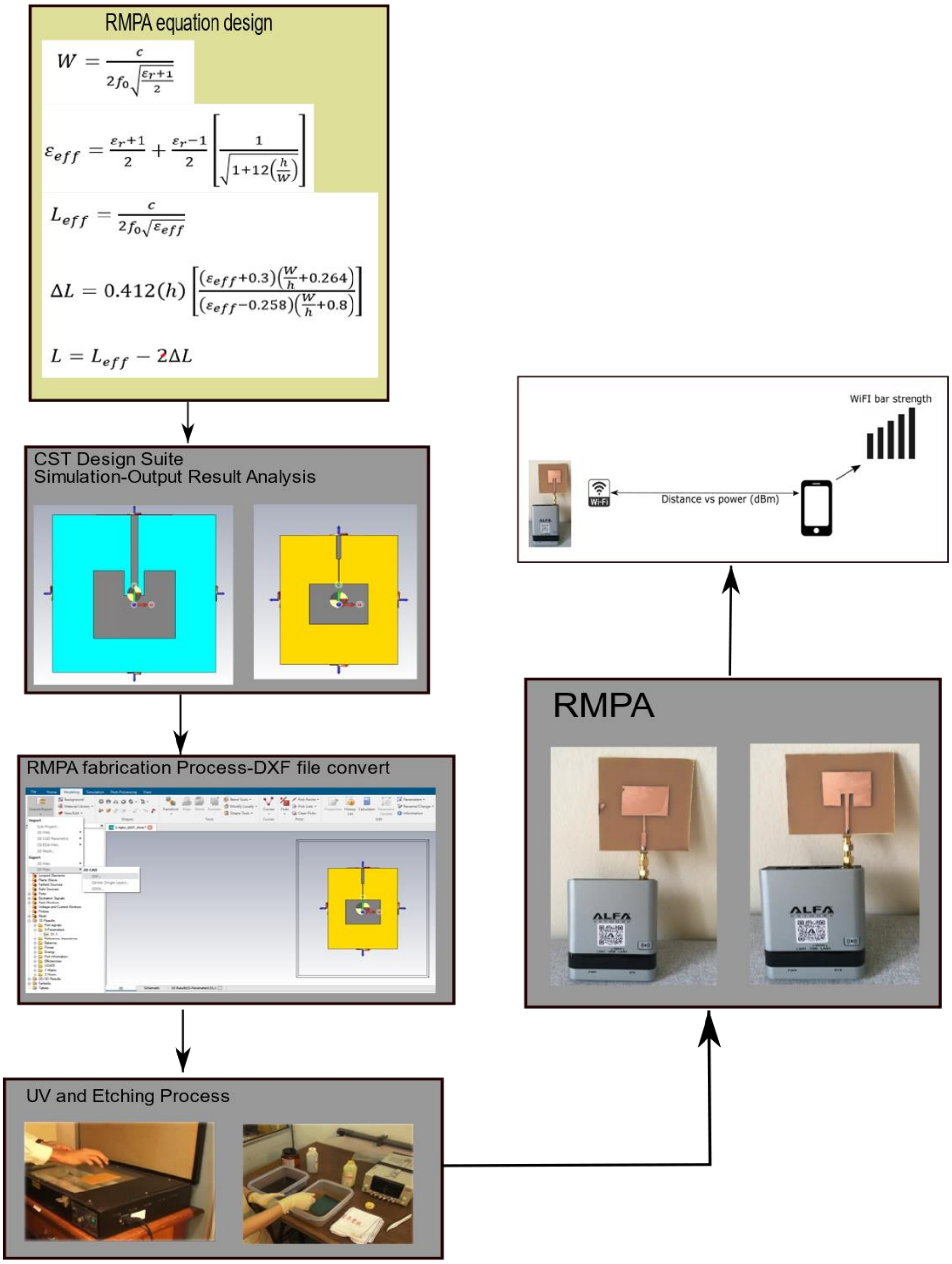


Fig. 2. RMPA design process

In this domain, a set of equations has been used to construct the desired antenna. The relevant geometry of the MPA structure is shown in Figure 3.

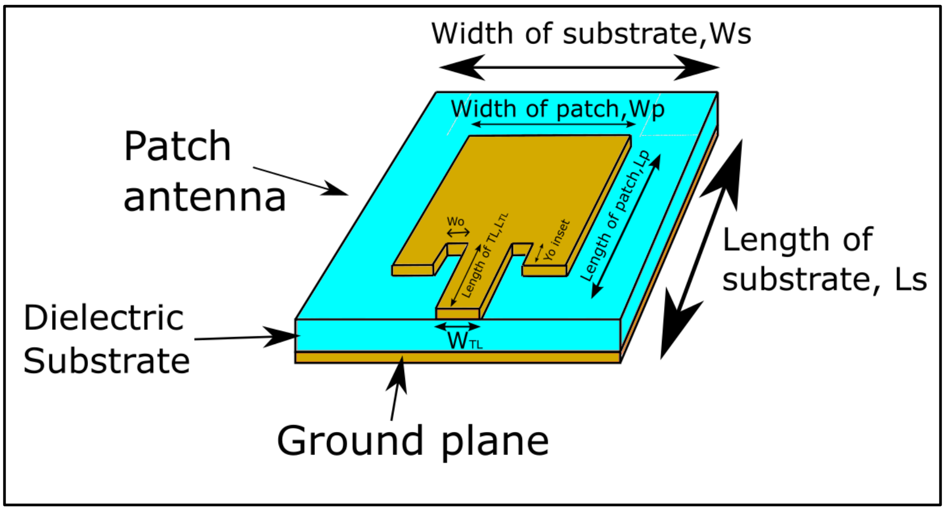


Fig. 3. Design parameters consideration

Each slot is equivalent to an analogous equivalent admittance (Y) with conductance (G) and susceptance (B). The equivalent circuit transmission model of an MPA is shown in Figure 4.

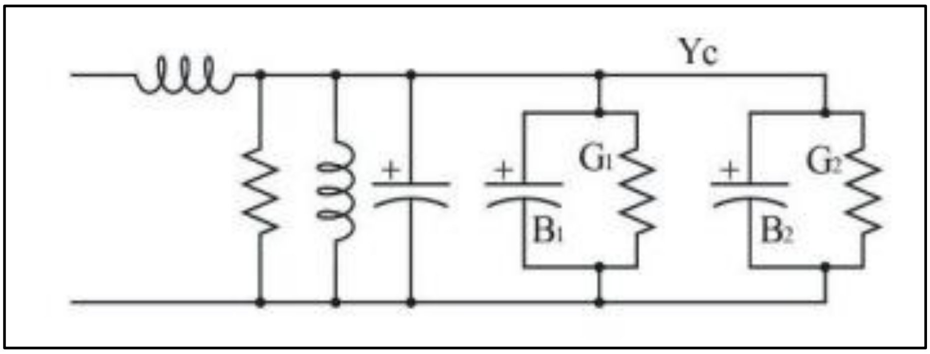


Fig. 4. Equivalent circuit of inset-fed MPA

The measurement of the Width (W) and Length (L) of the MPA is calculated from equations 1-5[8] with fixed parameters that are determined earlier such as resonant frequency, f_o=2.4GHz, a dielectric substrate, ε_r=4.0-4.5, and height of substrate, h_S=*1.6mm* and the height of the copper thickness, h_{TL}=0.035mm.

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}} \quad (1)$$

$$\text{Effective permittivity, } \varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}}\right] \quad (2)$$

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} \quad (3)$$

$$\Delta L = 0.412(h)\left[\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)}\right] \quad (4)$$

$$L = L_{eff} - 2\Delta L \quad (5)$$

Where (c) is the speed of light in vacuum taken as 299 792 458 m⁄s [12], (fr) is the resonant frequency, ($\varepsilon reff$) is effective dielectric constant, ($Leff$) is effective length, and (ΔL) is extended length [8].

Then the most important part is to determine the characteristic of the transmission line. The analysis of the transmission line is a separate part of the patch antenna. The load impedance, Z_L is the patch antenna, and the characteristic impedance, Z_0 is part of the transmission line as shown in Figures 5 and 6.

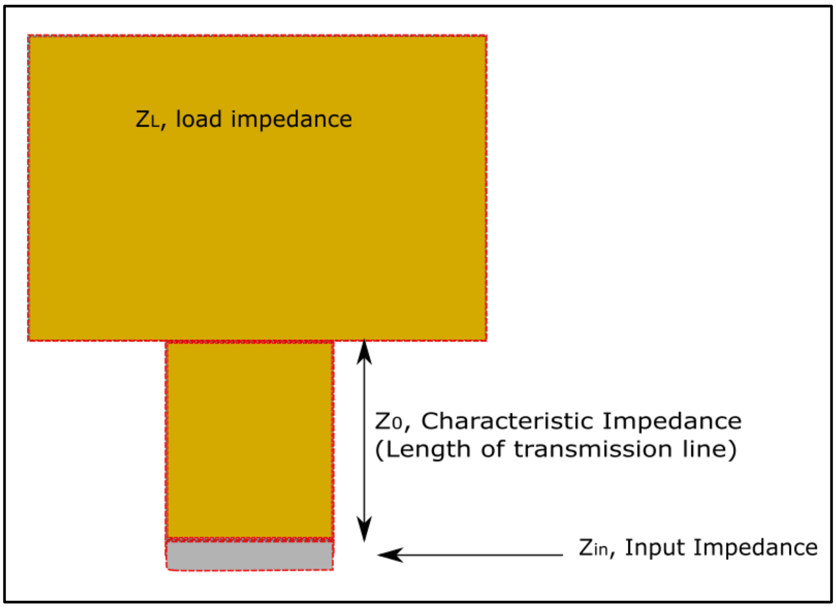


Fig. 5. Equivalent part of Patch antenna

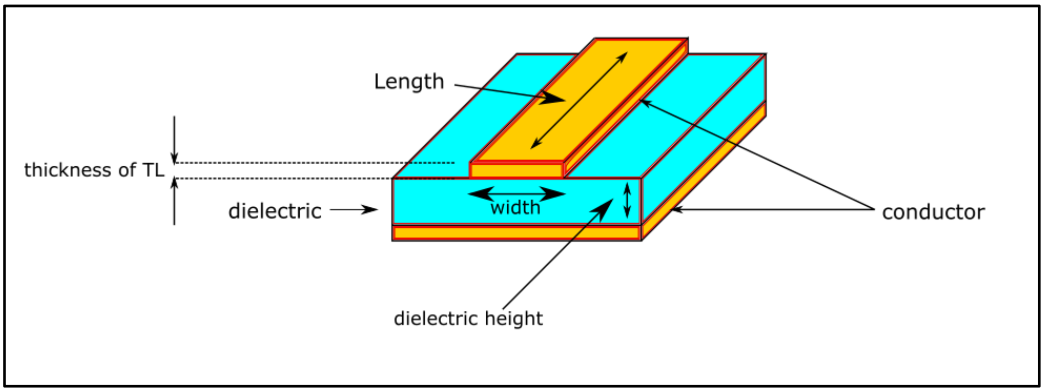


Fig. 6. Microstrip transmission line

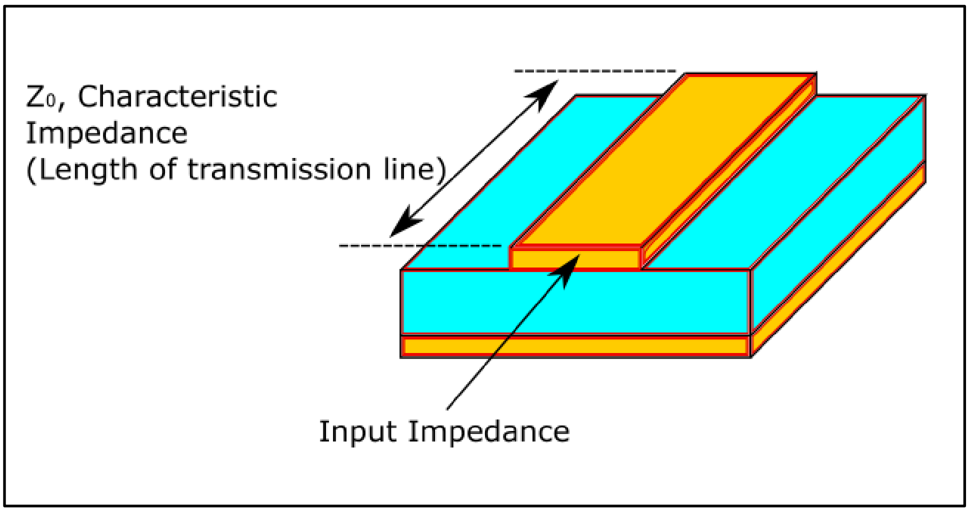


Fig. 7. Characteristic Impedance of the transmission line

The subsequent step is the analysis of transmission line characteristics. Equations 6 to 13 serve as references [4][3][9][10]. The first step to determine the width of the transmission line is according to equation (6) to find out the input impedance related to Figure 7.

$$Z_{in} = Z_0 \left[\frac{Z_L + jZ_0 tan(\beta\ell)}{Z_0 + jZ_L tan(\beta\ell)}\right] \quad (6)$$

Z_{in}= feed line input impedance (equal to 50Ω or 75Ω depends on generator)
Z_0 = characteristic impedance of the feed line
Z_L= impedance of the load(antenna or radiating element)

$$Z_L = 90\left(\frac{\varepsilon_r^2}{\varepsilon_r - 1}\right)\left(\frac{L}{W}\right)^2 \quad (7)$$

So, the $Z_{in} = \frac{(Z_0)^2}{Z_L}$.

Then the characteristic impedance, $Z_0 = \sqrt{Z_{in}Z_L}$. And now we have Z_0, so we can deduce the width of the transmission line, W_{TL} according to the following equations:

- If $\frac{W_{TL}}{h_s} \leq 1$;

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{eff}}} ln\left[\frac{8h_s}{W_{TL}} + \frac{W_{TL}}{4h_s}\right] \quad (8)$$

- $\frac{W_{TL}}{h_s} > 1$

$$Z_0 = \frac{120}{\left(\sqrt{\varepsilon_{eff}}\right)\left[\frac{W_{TL}}{h_s} + 1.393 + 0.667\, ln\left(\frac{W_{TL}}{h_s} + 1.444\right)\right]} \quad (9)$$

Choose either case $\frac{W_{TL}}{h_s} \leq 1$ or $\frac{W_{TL}}{h_s} > 1$ to determine the width of the transmission line, W_{TL}. If the value of the dielectric constant, ε_r are known, the ratio of $\frac{W_{TL}}{h_s}$ necessary to achieve. The characteristic impedance, Z_0 is given by;

$$\frac{W_{TL}}{h_s} = \begin{cases} \frac{8e^A}{e^{2A}-2} & \frac{W_{TL}}{h_s} < 2 \\ \frac{2}{\pi}\left[B - 1 - ln(2B-1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left(\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right)\right], & \frac{W_{TL}}{h_s} > 2 \end{cases} \quad (10)$$

Where;

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \quad (11)$$

$$B = \frac{60\pi^2}{Z_0\sqrt{\varepsilon_r}} \quad (12)$$

Assume $\frac{W_{TL}}{h_s} < 2$, use formula $\frac{8e^A}{e^{2A}-2}$. Then find the value of A.

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \quad (13)$$

The size of the antenna can be greatly reduced because most substrate materials have different permittivity levels; however, using these techniques lowers the antenna's radiation effectiveness and narrows its impedance bandwidth. A microstrip antenna typically has a bandwidth of 1% to 3%. Numerous optimization approaches have been devised to get around these restrictions. The radiating patch can be square, rectangular, circular, elliptical, triangular, dipole-shaped, or ring-shaped. When examining the performance and other antenna metrics, the patch's shape is crucial [11]. Microstrip Patch Antennas can be fed using a variety of techniques. The two types of these techniques are contacting and non-contacting. In contacting approaches, connecting components like a microstrip line are used to supply RF power directly to the radiating patch. In a non-contacting technique, the electromagnetic coupling is used to transfer power from the feed line to the path rather than directly feeding the patch with RF power. The most popular non-contacting feed techniques are proximity-coupled feed and aperture feed [11][12].

This typical RMPA may give a return loss lower than -10dB. So there two types of transmission line models were used to produce better return loss. For impedance matching purposes, this study was using the feed line technique and accordingly to the equation 14-18[4]. To determine the inset feed line, there are input impedance formula should be used as below in equation 14.

Input impedance, $R_{in(y=y_0)} = \frac{1}{2(G_1 \pm G_{12})} cos^2\left[\frac{\pi}{L}y_0\right]$

$$= R_{in}(y = y_0)cos^2\left[\frac{\pi}{L}y_0\right] \quad (14)$$

Inset feed length formula, $Y_{o.}$

$$y_o = 10^{-4}[0.001699\varepsilon_r^7 + 0.1376\varepsilon_r^6 - 6.1783\varepsilon_r^5 + 93.187\varepsilon_r^4 - 682.69\varepsilon_r^3 + 2561.9\varepsilon_r^2 - 404\varepsilon_r^1 + 6697]\frac{L}{2} \quad (15)$$

Inset feed width (Wo) = W_{TL}

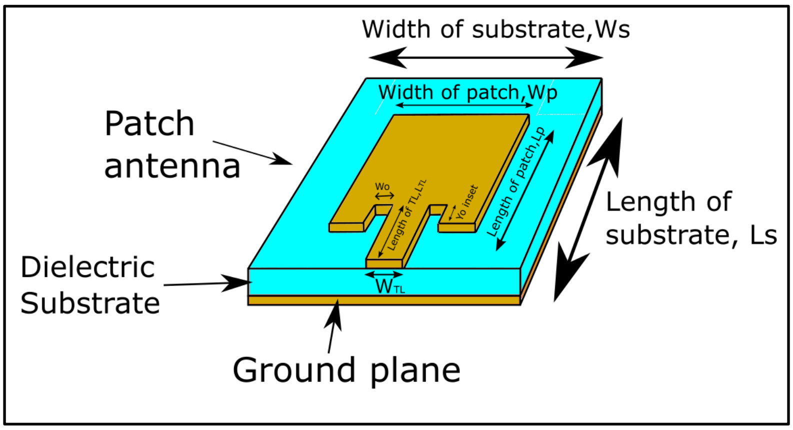


Fig. 8. Inset Feed of transmission line characteristic

The second method used the quarter-wave transformer, as shown in figure 9. Then all the parameters should be used in the designing process in terms of simulation, using CST Design Suite 2019 as shown in Figure 9.

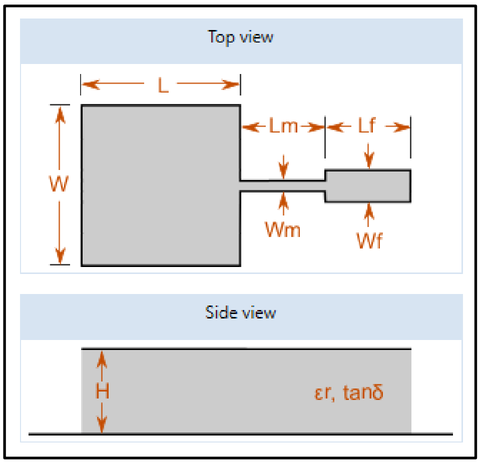
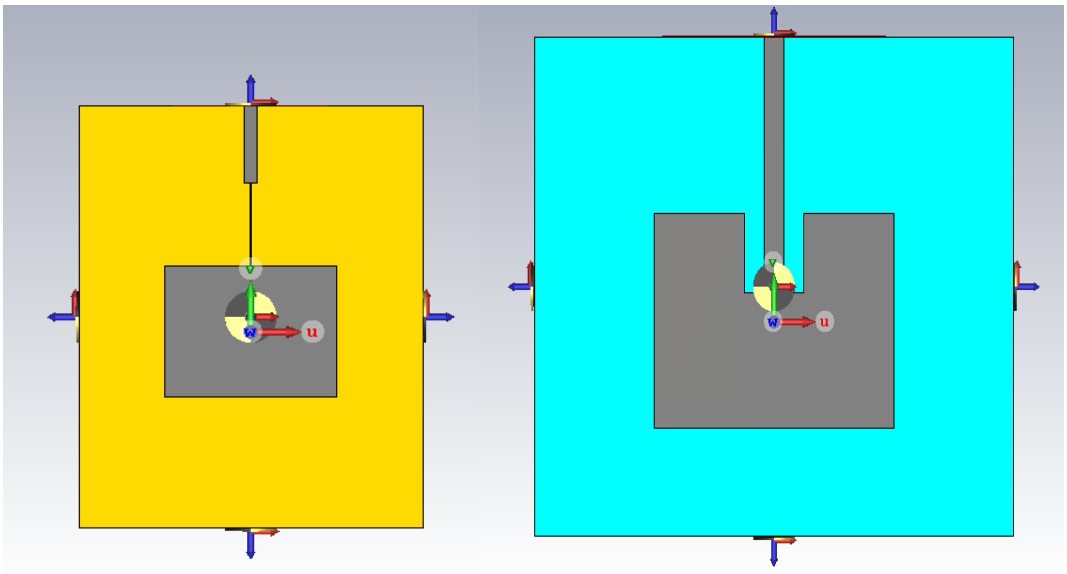


Fig. 9. Quarter-wave transformer transmission line feeding technique

Then both complete RPMA with transmission line feeding methods were simulated into the CST Design Suite 2019 before the real hardware of the antennas will be printed out.



(a) (b)

Fig. 10. RMPA with transmission line feeding methods were simulated in the CST Design Suite 2019. (a) quarter-wave transformer feeding technique. (b)Inset feeds technique.

2.2 RMPA Fabrication Process

Figure 11 shows the procedure for creating the microstrip patch antenna employed in this work. Utilizing CST Design Suite 2019, the initial phase is the computer-aided design of the antenna geometry. Then, it needs to be converted to a Gerber file or a DXF file so that a negative of this geometry printed on a transparent sheet can be used as a mask.

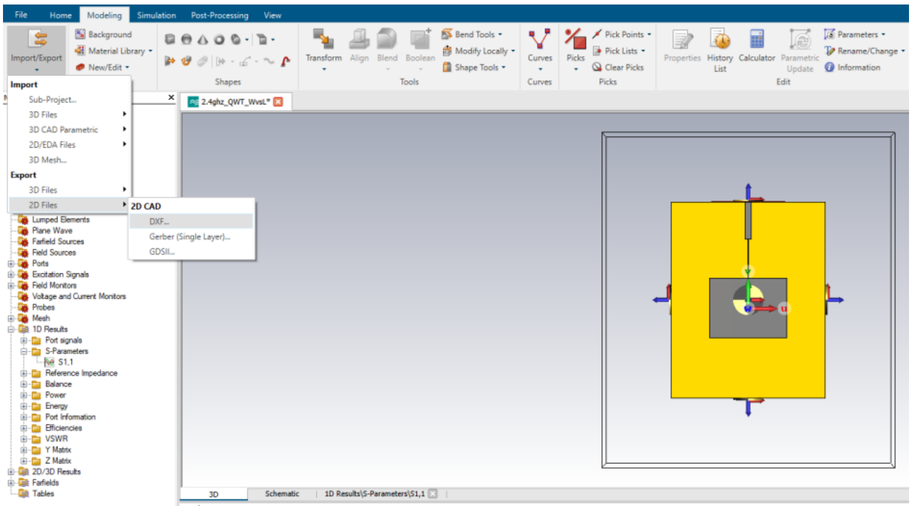


Fig. 11. CST Design Suite converts the design file to a DXF file

Then the printed RMPA mask used in the UV light and using acetone, a double-sided copper clad FR4 substrate with dimensions of 80 mm x 60 mm is completely cleaned. The etched pattern is disrupted by dust or other contaminants on the copper-clad surface, changing the resonance frequency. The second process involves laminating a negative photo-resist film to the dried and cleaned copper-clad substrate. The photo-resist laminated copper-clad substrate is firmly attached to the negative mask that was made in the first phase. UV light is shone upon the copper-clad substrate that has been masked and photoresist laminated.

Fig. 12. The UV exposure unit

The third stage is to develop the copper-clad substrate using UV-exposed photo-resist laminate. Unexposed photoresist remains light blue and dissolves in the developer solution, however, photoresist exposed to UV radiation hardens and turns a dark blue color. As a developer, sodium carbonate is employed. Finally, a solution of ferric chloride (FeCl3) is used to chemically etch the produced copper-clad substrate. Except for underneath the firm photoresist, the copper components disintegrate in FeCl3. To get rid of any remaining etchant, the etched substrate is rinsed under running water and dried. Use of sodium hydroxide is used to remove the hardened photoresist as shown in Figure 13.

Fig. 13. Etching Process and last result RMPA produced

3. Result and Discussion

The RMPA's design is based on a typical antenna that operates in the 2.4GHz band of the WiFi standard, uses FR4 ($\varepsilon_r = 4.7$), has a thickness (h) of 1.6 mm, and has an input impedance of 50. As seen in figure 14, a rectangular patch is used as the geometry with an inset fed. Improved impedance matching between the feed line and the element is the goal of inset feeding.

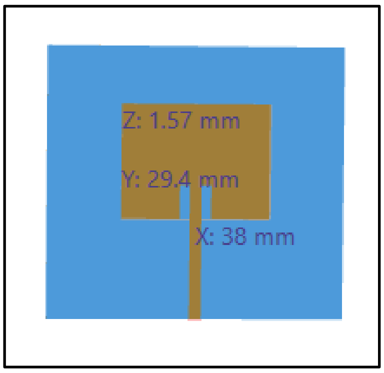


Fig. 14. Size and dimension of RMPA with inset feed transmission line.

Figure 15 illustrated the output result of the RPMA with an input inset feed transmission line. However, the output result as shown in the green line is still not accurate at the perfect desired frequency 2.4GHz. There are 2.371GHz at a minimum return loss of -9.516dB. The most important thing is the unacceptable value of -9.516dB, a considerable mismatch due to VSWR>2. Then the value of the RMPA's width, length, and size of inset feed Y_o and W_o should be optimized using a parametric sweep to determine the perfect value of output result return loss will be located at 2.4GHz with a minimum -10dB. As a result, shown in purple and blue line, this optimization is acceptable because it has -13.96dB at 2.403GHz.

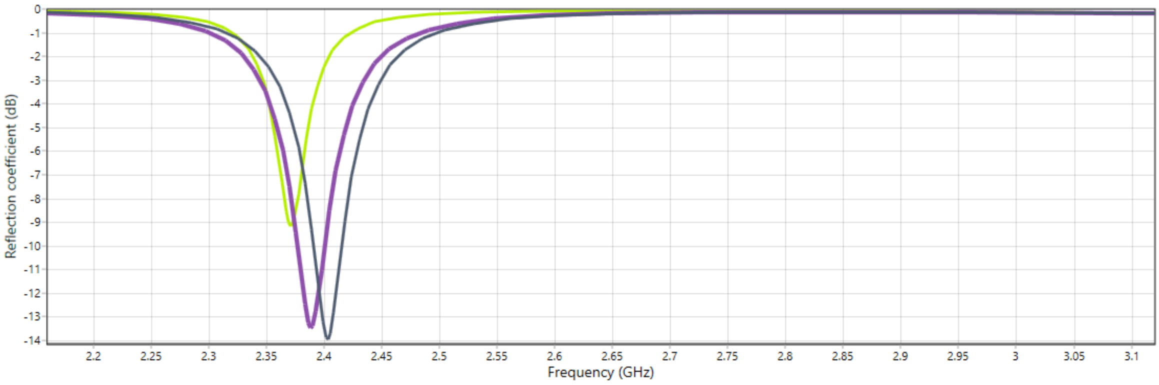
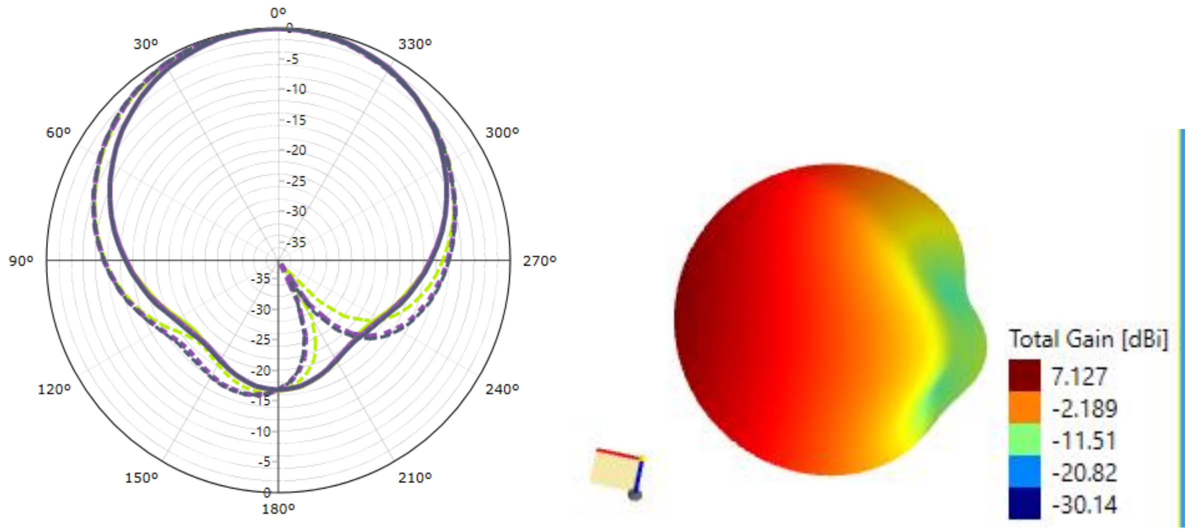


Fig. 15. Optimized Return loss versus frequency of RMPA.

Figure 16(a) shows the far field versus angle of RMPA at 2.4Ghz and (b) shows the radiation pattern of RMPA with 7.127dBi gain.



(a) (b)

Fig. 16. (a) Far-field versus angle of the antenna at 2.4Ghz shown the green line gives inaccurate result than the purple and blue line after the optimization.
(b) RPMA's radiation pattern

Secondly, RMPA design in terms of transmission line feed method using the quarter-wave transmission line with the same dimension of width and length 29.14mm and 38.19mm each as shown in Figure 17.

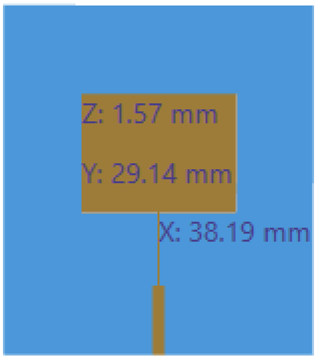


Fig. 17. Quarter-wavelength transformer diagram

This type of RMPA also has a non-optimized value of return loss which is -15.10dB at 2.274GHz, quite far from the 2.4GHz as illustrated in Figure 18.

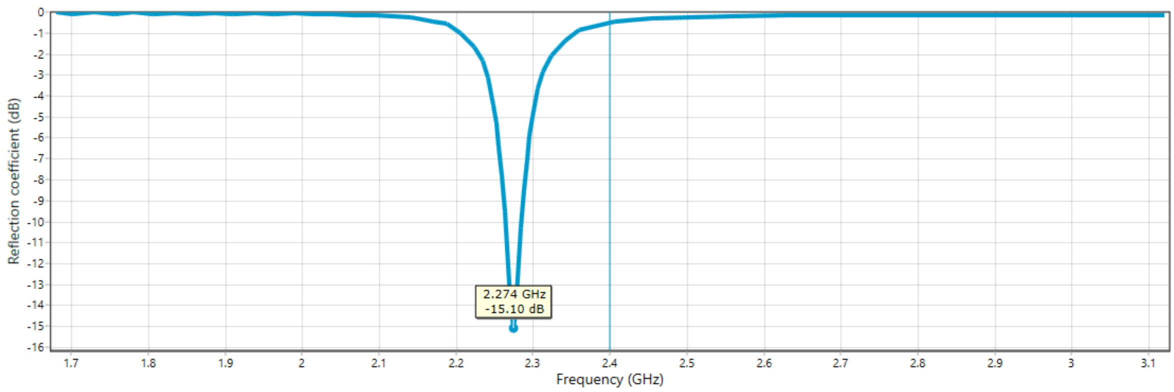


Fig. 18. RPMA output return loss at 2.274GHz with -15.10dB

Figure 19 illustrated the output result of the RPMA with input inset feed transmission line. However, the output result is still not accurate at the perfect desired frequency 2.4GHz. There are 2.274GHz at a minimum return loss of -15.10 dB. Then the value of the width, length, and size of inset feed Y_o and W_o should be optimized using a parametric sweep to determine the perfect value of output result return loss will be located at 2.4GHz with a minimum of -10dB. As a result, this optimization is acceptable because it indicated at -14.47dB at 2.4GHz perfectly.

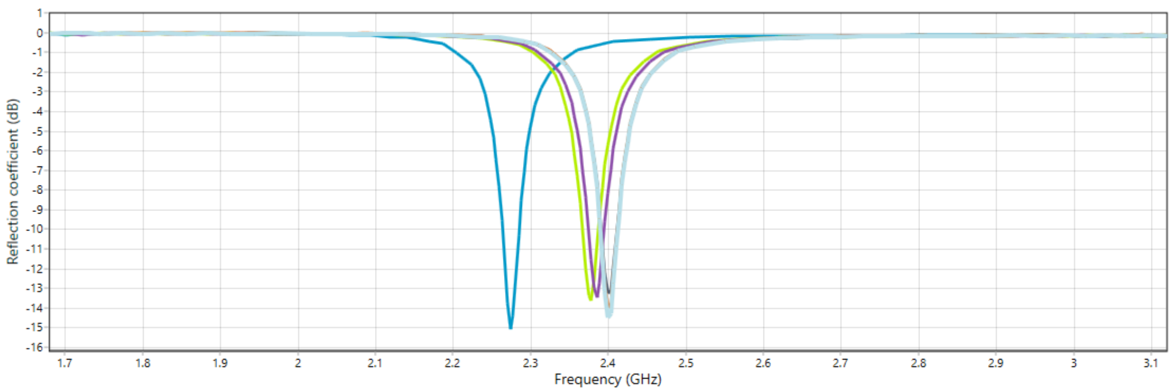


Fig. 19. Optimized Return loss versus frequency of RMPA.

This analysis provides evidence that the calculation theory for this antenna does not consider other factors such as substrate dielectric material, tangent loss, etc so there is the imperfect result of return loss did not perform at the minimal value of 2.4GHz.

To overcome this problem, a solution is used so that it achieves the original objective. By using the CST Design Suite software, a parametric sweep has been used. The desired frequency of an RMPA is influenced by rectangular size accordingly to the width and length. So the parametric sweep should be used to optimize the width and length value so the output result of the return loss will be perfectly located at 2.4Ghz. [13][6].

Result of the RMPA's parameters both of transmission line model inset feed and quarter-wave transformer shown in Table 2 with the same designated parameters:

(i) Resonant frequency = 2.4GHz
(ii) Substrate name = FR4

(iii) Substrate relative permittivity = 4.7
(iv) Port impedance Rin= 50Ω

Table 2. RMPA parameters with inset feed technique

No.	Description	Specification (millimeter)
1	W_s	Width of the substrate = 76
2	L_s	Length of the substrate =60
3	H_s	Height (thickness) of the substrate=1.57
4	W_p	Width of the patch=38
5	L_p	Length of the patch=29.4
6	H_p	Height(thickness) of the patch=0.035mm (standard of FR4 copper's height)
7	h_{TL}	Height(thickness) of the transmission line = h_p
8	W_{TL}	Length of the transmission line=35
9	H_g	Width of the transmission line=3.027
10	*Yo*	Length of inset feed =8.6
11	*Wo*	Width of space inset feed=2.5

Table 3. RMPA parameters with Quarter-wave transformer

No.	Description	Specification (millimeter)
1	W_s	Width of the substrate = 76
2	L_s	Length of the substrate =60
3	H_s	Height (thickness) of the substrate=1.57
4	W_p	Width of the patch=35.4
5	L_p	Length of the patch=27.4
6	H_p	Height(thickness) of the patch=0.035mm (standard of FR4 copper's height)
7	h_{TL}	Height(thickness) of the transmission line = h_p
8	W_{TL}	Length of the quarter-wave transmission line=18.25
9	H_g	Width of the quarter-wave transmission line =4um
10	*Lf*	Length of quarter-wave feed line =16
11	*Wf*	Width of quarter-wave feed line=3.027

The practical result measurement using router ALFA network R36A with WIFI frequency range 2.142GHz to 2.484GHz and smartphone using Android Application WIFI Analyzer to determine the signal strength as shown in Figure 21.

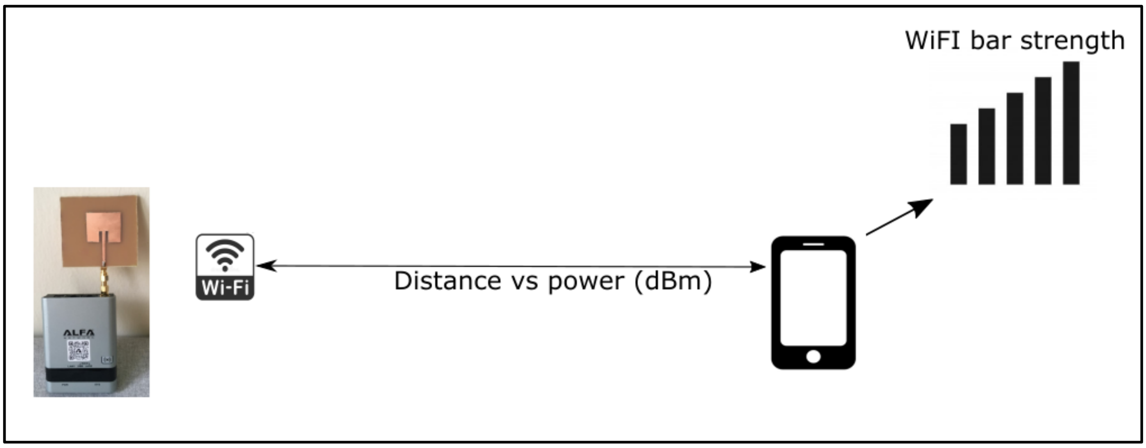


Fig. 20. Practical measurement RMPA WIFI signal strength inset feed technique.

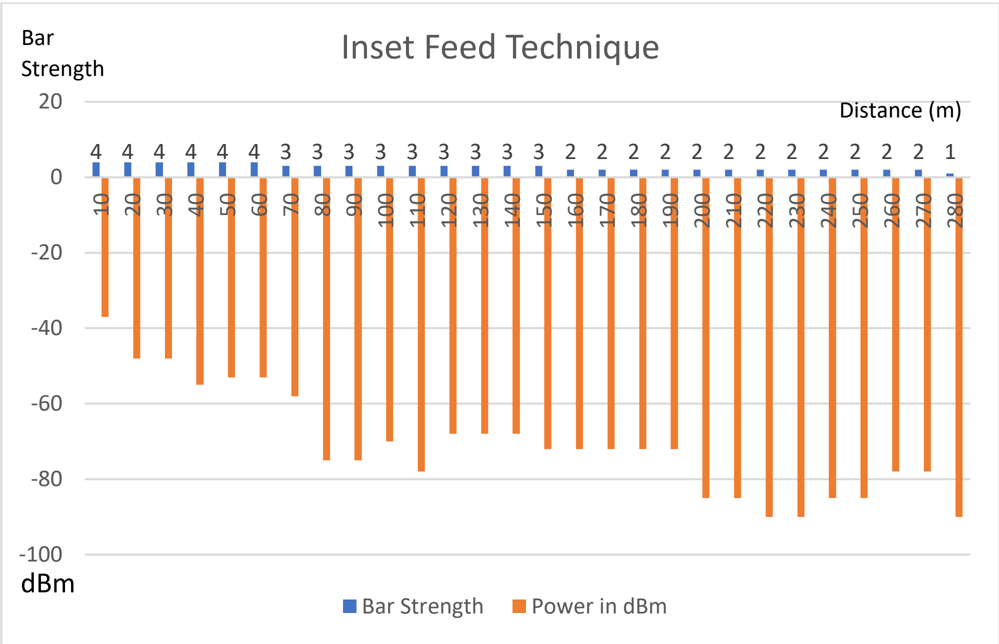


Fig. 21. Measurement result of the WIFI's signal strength using RPMA with inset feed technique.

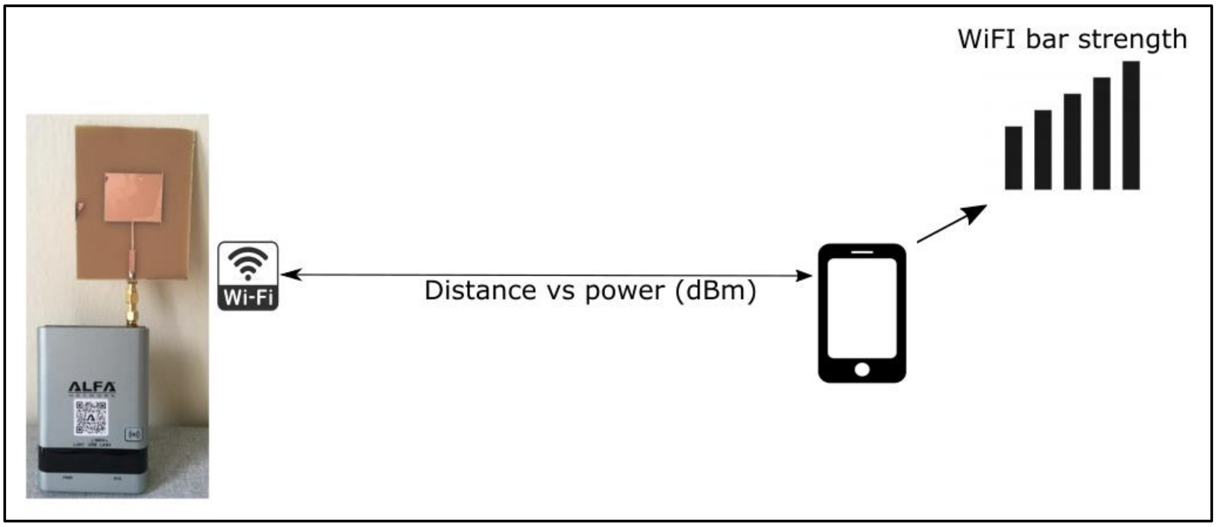


Fig. 22. Practical measurement RMPA WIFI signal strength Quarter-wave transformer Technique

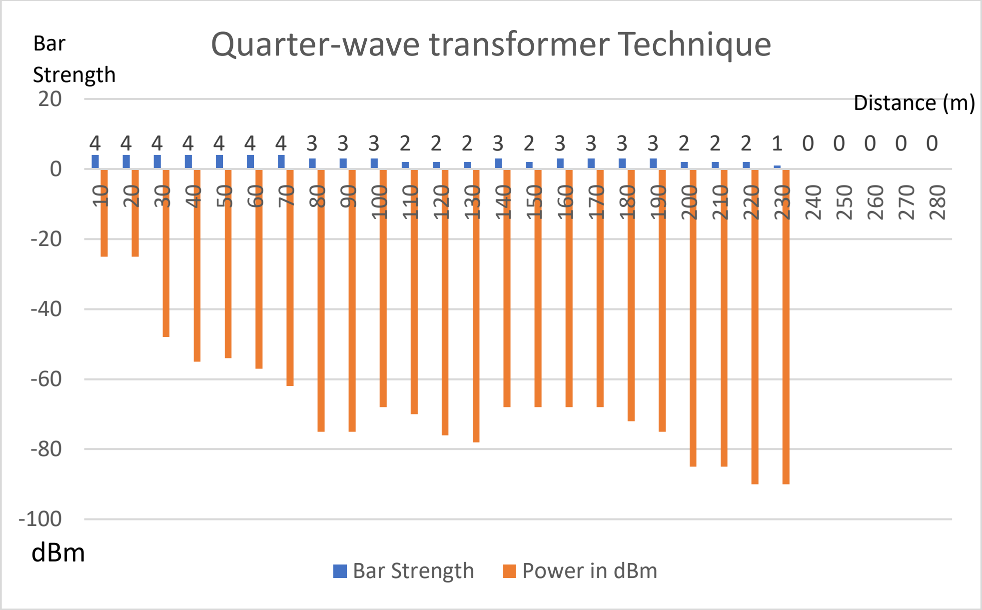


Fig. 23. Measurement result of the WIFI's signal strength using the RPMA Quarter-wave transformer Technique.

4. Conclusion

The conclusion of this project can be stated from the RMPA hardware itself. That is, several things affect the performance of this RMPA antenna, which are all related parameters such as relative permittivity, ε_r , the thickness of the copper, height of the dielectric(substrate). These are the fixed parameters that should not be changed. Only a few parameters can be changed, namely the size of the area of the rectangle and the area of the delivery line.

Apart from that, the RMPA design process also needs to consider the two transmission line feed techniques so that the Return Loss will be exactly at 2.4Ghz with the minimum dB being below -10dB. it is very significant to prevent SWR exceeding 1 to avoid signal loss.

Based on the results, it was found that the maximum distance at which WIFI can be accessed is different for each type of transmission feed technique, but the average signal strength is almost the same at each distance. Quarter-wave transformer feed technique loses the WIFI signal shorter than the inset feed technique.

The perfect measurement of these two RMPAs should be done by using Vector Network Analyzer to determine their Return Loss and minimum value of resonant frequency, VSWR, bandwidth at -10db, reflection coefficient, and others. All these parameters will be measured later with proper equipment.

References

[1] W. Lehr and L. W. McKnight (2003). Wireless Internet access: 3G vs. WiFi?," *Telecomm. Policy*, vol. 27, no. 5–6, pp. 351–370. DOI: 10.1016/S0308-5961(03)00004-1

[2] I. Al Shourbaji. An Overview of Wireless Local Area Networks. 1978.

[3] A. F. Alsager (2011). Design and Analysis of Microstrip Patch Antenna Arrays. *MSC. Thesis, Univ. Coll. Boras, Sch. Eng.*, no. 1, pp. 1–80.

[4] C. A. Balanis (2006). *Antenna Theory Analysis, And Design*, Third. John Wiley & Sons, Inc

[5] A. B. Obot, G. A. Igwue, and K. M. Udofia (2019). Design and Simulation of Rectangular Microstrip Antenna Arrays for Improved Gain Performance. *Int. J. Networks Commun.*, vol. 9, no. 2, pp. 73–81. DOI: 10.5923/j.ijnc.20190902.02

[6] E. Engineering. Design and Analysis of Antennas operating at different frequency bands using CST Pudu Atchutarao Design and Analysis of Antennas operating at different frequency bands using CST Master of Technology. May 2015

[7] J. Paleček, M. Vestenický, P. Vestenický, and J. Spalek (2013). Frequency dependence examination of PCB material FR4 relative permittivity. *IFAC Proc. Vol.*, vol. 46, no. 28 PART 1, pp. 90–94. DOI: 10.3182/20130925-3-CZ-3023.00020

[8] A. M. Abdulhussein, A. H. Khidhir, and A. A. Naser (2021). Design and Implementation of Microstrip Patch Antenna Using Inset Feed Technique for 2.4 GHz Applications. *Int. J. Microw. Opt. Technol.*, vol. 16, no. 4, pp. 355–361

[9] D. K. Naji (2018). Design of Compact Dual-band and Tri-band Microstrip Patch Antennas. *Int. J. Electromagn. Appl.* vol. 8, no. 1, pp. 26–34, 2018, doi: 10.5923/j.ijea.20180801.02

[10] K. Prahlada Rao, R. M. Vani, and P. V. Hunagund (2018). Planar microstrip patch antenna array with gain enhancement. *Procedia Comput. Sci.*, vol. 143, pp. 48–57, doi: 10.1016/j.procs.2018.10.350

[11] N. Kumar and N. Sharma (2019). The Various Feeding Techniques of Microstrip Patch Antenna Using HFSS. *Int. J. Electron. Commun. Eng.*, vol. 6, no. 6, pp. 23–29. DOI: 10.14445/23488549/ijece-v6i6p106

[12] G. Chaitanya, A. Arora, A. Khemchandani, Y. Rawat, and S. Singhai (2005). Comparative study of different Feeding Techniques for Rectangular Microstrip Patch Antenna. *Int. J. Innov. Res. Electr. Electron. Instrum. Control Eng.*, vol. 3, no. 5, pp. 2321–5526. DOI: 10.17148/IJIREEICE.2015.3509

[13] M. Sani Yahya, I. Abdul Dalyop, Y. Saleh, and M. Aminu-Baba (2018). Antenna for 5G mobile Communications Systems at 10 GHz. *Int. J. Eng. Technol.*, vol. 7, no. 3.36, p. 13. DOI: 10.14419/ijet.v7i3.36.29071