Gain enhancement by using combination slot techniques for millimeter-wave 5G antenna

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Abstract. This research aims to increase the antenna gain by adding U-slot and Y-slot and using the air gap method at millimeter-wave frequency 28 GHz. In the previous studies have shown an increase in antenna gain by using additional slots on the microstrip patch antenna, such as the U-slot, V-slot or Y-slot method. The air gap arrangement on the double layer substrate antenna also has an impact on increasing the gain. For this reason, this study carried out the development of the design of the microstrip antenna structure with the addition of U-slots and Y-slots as well as the adjustment of the distance between the two substrates, so it is expected to significantly increase the antenna gain. This research was conducted using quantitative methods through calculating the design, simulation, and fabrication of the combination U-slot and Y-slot structures and arrangement the distance between two substrate layers. The antenna design uses the Rogers RT5880 substrate material with a dielectric constant ($\varepsilon_r$) = 2.2, and $h = 0.787$ mm with dimensions 18.5 x 31.5 mm. Simulation and measurement results show that the proposed combination method can increase the millimeter-wave antenna gain significantly and better than the results of previous studies.

1. Introduction
Cellular communication technology is now entering the fifth-generation (5G). The development of this technology will support high-speed broadband data in many applications, such as machine to machine communication, remote manufacturing industries using robotic applications and other applications using the internet of things (IoT) [1]. The 5G application is an advanced of 4G generation on the telecommunications network. The fifth-generation of cellular wireless communication is targeting to increase data rates higher than the previous generation [2,3]. The 5G application is designed at C-band frequency (3.5 GHz) and millimeter-wave frequency such as 28 GHz, 38GHz, and 72 GHz with a bandwidth of 500 MHz, 1 GHz, 2 GHz which corresponds to high data rates [4].

One important device in 5G technology is the 5G antenna technology. Various studies have been developed to improve the performance of 5G antennas, one of them is the development of microstrip antenna performance as one type of antenna that is widely used today. Microstrip antenna is also one type of antenna that has good performance in the millimeter-wave band. Microstrip antennas have several advantages over other types of antennas, such as simple shapes, relatively lightweight, easy to fabricate and can be designed according to certain communication devices [5].

However besides the advantages of microstrip antennas also has several of disadvantages, such as low efficiency, low directivity, and gain, having losses in the feeding network, and narrow bandwidth [6]. In general, to improve antenna performance can be done by making antenna array configurations,
but for microstrip antennas other problems such as surface wave effects also occur. The surface wave effects are waves that are generated and move inside the microstrip antenna substrate and will be reflected at the interface of the air substrate and the metal layer. The effect of this surface-wave will inhibit the increase in gain and bandwidth of the microstrip array antenna [7,8].

For this reason, many studies and solutions were given to overcome surface waves in microstrip array antennas, such as the addition of air gap techniques [9-13]. The air gap is a technique of giving air gap between the ground plane and the substrate. The air gap is applied to eliminate back-lobe and increase gain with the addition of the tapered peripheral slits method. The result shows that it can obtain a gain value of 3.01 dB at the UHF frequency of 435.6 MHz [14]. Meanwhile, the distance of the air gap affects the gain value on the antenna, the results obtained are Gain 8.6 dB with the co-axial probe feed technique [15]. However, the air gap technique can affect the antenna resonance frequency, so it is necessary to use strip-lines feed to improve antenna bandwidth performance [16].

Furthermore, several study results propose the addition of a slot method to improve the performance of a microstrip antenna [17-20]. The addition of slots on the antenna patch has an impact on increasing the antenna bandwidth, decreasing the value of return-loss, and increasing the gain on the antenna [21-25]. The slot method has several types such as C-slot, E-slot, Y-slot, and U-slot [23-28]. This slot method shows different performance and U-slot shows better performance compare to others [28]. Therefore, in this study will propose development through a combination of slot techniques and microstrip antenna air gap adjustment to get better bandwidth more than 2 GHz in the millimeter-wave frequency compared to previous studies (average less than 2 GHz).

2. Theoretical foundations

2.1. U and Y-slot method

U and Y-slot is considered as a combination of the U-slot and Y-slot. Y-slot consists of two vertical parallel rectangular slots, a horizontal rectangular slot, and a vertical rectangular slot cut below the horizontal slot. The additional U-slot is smaller than the Y-slot and cut in the middle of the Y-slot. The width of the slot must be relatively small to the slot length. The combination of U and Y-slot as shown in Figure 1.

![Figure 1. Design patch Antenna with U and Y-Slot.](image)

The U-slot structure design is calculated based on parameters C, D, and E as shown in Figure 1, with the following relationship [29].

\[
E = F = \frac{\lambda}{60}
\]  

(1)
Length of U and Y-slot

\[ \frac{C}{W} \geq 0.3 \]  \hspace{1cm} (2)

Outer width of U and Y-slot

\[ D = \frac{c}{\text{Flow}\sqrt{\varepsilon_{\text{eff}}}} - 2(L + 2\Delta L - F) \]  \hspace{1cm} (3)

Where,

\[ \varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \left[ \frac{\varepsilon_r - 1}{2} \left( \frac{1}{\sqrt{1 + \frac{12h}{W_F}}} \right) \right] \]  \hspace{1cm} (4)

Where \( W \) is the width of antenna patch, \( L \) is the length of antenna patch and \( \varepsilon_{\text{eff}} \) is effective dielectric constant of substrate antenna.

2.2. Air gap method

The air gap method is a technique of giving air gap between the ground plane and the substrate. By adding the air gap between the substrate and the ground plane can also increase efficiency and reduce the high loss on the substrate and it reduces the effective dielectric constant. The gap distance is explained in equation (5).

\[ G = 1 - \left| \frac{Z_0 \sqrt{\varepsilon_{\text{eff}} - Z_0}}{Z_0 \sqrt{\varepsilon_{\text{eff}} + Z_0}} \right|^2 \times \frac{16}{3\pi} \]  \hspace{1cm} (5)

Equation (5) shows that the effective dielectric constant is inversely proportional to the gain value which is the smaller of the effective dielectric constant will provide the greater the gain value [26].

2.3. Microstrip patch antenna

Microstrip antenna consists of patch as radiator, substrate material and ground plane. Radiation on patches and feed lines is usually engraved on the top side of the dielectric substrate. The patch antenna dimensions are obtained from equations (6) and (7).

\[ W_p = \frac{c}{2fr \sqrt{\varepsilon_r + 1}} \]  \hspace{1cm} (6)

\[ L_{\text{eff}} = \frac{c}{2 \times fr \sqrt{\varepsilon_{\text{eff}}}} \]  \hspace{1cm} (7)

Microstrip patch antenna has several feeding techniques such as microstrip line feeding, coaxial probe, aperture technique, and proximity coupled. Microstrip line feeding is designed to obtain impedance matching with antenna radiating elements [5].

3. Antenna design method

The antenna is designed using RT Duroid 5880 as the substrate which has a dielectric constant \( (\varepsilon_r) = 2.2 \) and a thickness \( h = 0.787 \text{ mm} \). Antenna design consists of U and Y-slot structure design and air gap design to get the best performance.
3.1. Array antenna design

The basic array antenna before adding the U and Y-slot techniques and the air gap adjustment with dimensions 18.41 x 37.22 mm as shown in Figure 2.

3.2. Design antenna with U and Y-slot and air gap

Antenna array design with the addition of U and Y-slot and the addition of air gap as shown in Figure 3. The design of this structure is based on equations (1) to (3) at the frequency 28 GHz. The air gap adjustment between substrates is calculated based on equation (5).

4. Results and discussion

The 2x2 microstrip array antenna design is simulated using CST Microwave Studio 2016 software to describe antenna performance, such as S-parameters and antenna radiation performance. The design construction for the 2x2 array antenna simulation uses simulation software as shown in Figure 2 and Figure 3 for the proposed antenna using a combination of U-slot and Y-slot and air gap settings. Simulation results for the comparison of S-parameter and bandwidth performance of the antenna design with the addition of a combination of slots and air gaps as shown in Figure 4.

The comparison results as shown in Figure 4 prove that the microstrip antenna design method using a combination of slots and air gap settings can significantly improve antenna performance. These results indicate an improvement in return loss at the center frequency from -31 dB to -40 dB. For comparison of bandwidth performance, it is obtained an increase in bandwidth of 1.807 GHz from 829 MHz to 2.636 GHz or around 217%. This result also shows an increase in bandwidth performance compared to the results of previous studies [25] - [27].
The main parameter performance observed in this study was the increase in antenna gain parameters. The software simulation results show an increase in antenna gain with the method of adding a combination of slots and setting the air gap as shown in Figure 5 and Figure 6.

![Figure 5. Gain of the conventional antenna.](image1)

![Figure 6. Gain of the proposed antenna design.](image2)

These results indicate that the proposed design using the slot combination method and the air gap setting can increase the gain performance by 4.2 dB from 9.1 dB on conventional antennas to 13.3 dB on the proposed antenna design. Through a 2x2 array configuration, these results also show significant improvements compared to the gains achieved in previous studies [25] - [27]. The best results in this study were obtained by iterating the combination of slot design and air gap spacing. The best results are obtained by using a dual U-slot with an air gap of 1.09 mm.

As a verification of the design simulation results, microstrip antenna fabrication was carried out to obtain the measurement results. Fabricated antennas as shown in Figure 7.

![Figure 7. Fabrication of the proposed antenna design.](image3)

Comparison of simulation and measurement results as shown in Figure 8. This comparison shows there are differences in bandwidth and return loss values at the center frequency. This is caused by fabrication factors at millimeter-wave high frequencies that are easily affected in the measurement. However, these results have illustrated that the results of simulations and measurements have the same trend. Thus it can be concluded that the proposed method results in improved antenna parameters.
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5. Conclusion
The method of adding a combination of slots to the microstrip patch antenna and air gaps has been described. Simulation and measurement results show that this method can increase the bandwidth performances to reach 2.636 GHz and gain enhancement to 13.3 dB. The observations in this study show improvements in antenna performance compared to conventional array antennas and several previous studies. The proposed method in this study can be used as a basis for further development of the 5G millimeter-wave antenna.

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References
[1] Bangerter B, Talwar S, Arefi R and Stewart K 2014 Networks and Devices for the 5G era IEEE Commun. Mag. 52 90–96
[2] Agrawal S 2013 Design and analysis of hexagonal shaped fractal Antennas (Doctoral dissertation)
[3] Bahl I J and Stuchly S S 1980 Analysis of a Microstrip Covered with a Lossy Dielectric IEEE Trans. Microw. Theory Tech. 28 104–109
[4] Ahmad W and Khan W T 2017 Small form Factor Dual band (28/38 GHz) PIFA Antenna for 5G Applications IEEE MTT-S Int. Conf. Microwaves Intell. Mobility, ICMIM 2017 21–24
[5] Balanis C A 2016 Antenna theory: analysis and design (John wiley & Sons)
[6] Alam S 2016 The Design of Triangular Microstrip Antenna for Wimax Application at 2.300 MHz and 3.300 MHz Frequency J. Tek. dan Ilmu Komput. 04 15 255–268
[7] Komanduri V R, Jackson D R, Williams J T and Mehrrota A R 2013 A General Method for Designing Reduced Surface Wave Microstrip Antennas IEEE Trans. Antennas Propag. 61 6 2887–2894
[8] Garg R, Bhartia P, Bahl I J and Ittipiboon A 2001 Microstrip antenna design handbook (London: Artech house)
[9] Kumar A N G and P. C 2016 Gain and Bandwidth Enhancement Techniques in Microstrip Patch Antennas - A Review Int. J. Comput. Appl. 148 7 9–14
[10] Sandi E, Diamah A, Iqbal M W and Fajriah D N 2019 Design of Substrate Integrated Waveguide to Improve Antenna Performances for 5G Mobile Communication Application Journal of Physics: Conference Series 1402 4 044030

Figure 8. S-Parameter comparison of the simulation and measurement result.
[11] Mrnka, I. M 2017 Perforated Dielectrics and Higher Order Mode Dielectric Resonator Antennas
[12] Ozenc K M, Aydemir E and Oncu A 2013 Design of a 1.26 GHz High Gain Microstrip Patch Antenna using Double layer with Airgap for Satellite Reconnaissance RAST 2013 Proc. 6th Int. Conf. Recent Adv. Sp. Technol. 499–504
[13] La Spada L, Haq S and Hao Y 2017 Modeling and Design for Electromagnetic Surface Wave Devices Radio Sci. 52 9 1049–1057
[14] Sujadi A, Setijadi E and Hendrantoro G 2012 Desain Antena Microstrip dengan Tapered Peripheral Slits untuk Payload Satelit Nano pada Frekuensi 436,5 MHz Jurnal Teknik ITS 1 1 A25–A30
[15] Singh S S and Bhujade S R 2015 Design and Evaluation of High Gain Microstrip Patch Antenna Using Double Layer with Air Gap Int. J. Recent Innov. Trends Comput. Commun. 3 3 1678–1681
[16] Mao Y, Padooru Y R, Lee K F, Elsherbeni A Z and Yang F 2011 Air gap tuning of patch antenna resonance IEEE International Symposium on Antennas and Propagation (APSURSI) 3088–3090
[17] Yadav S and Singh S 2018 Review Paper on Development of Mobile Wireless Technologies (1G to 5G ) Int. J. Comput. Sci. Mob. Comput. 7 5 94–100
[18] Talandage K and Sutar U S 2016 Design and Optimization of Broadband Double Psi Shape Patch Antennas for Bluetooth and WLAN Applications Int. Conf. Energy Syst. Appl. ICESA 437–440
[19] Liu Y, Si L M, Wei M, Yan P, Yang P, Lu H and Sun H 2012 Some recent developments of microstrip antenna International Journal of Antennas and Propagation
[20] Liu G and Jiang D 2016 5G: Vision and requirements for mobile communication system towards year 2020 Chinese Journal of Engineering
[21] Ghosh S, Ghosh A and Sarkar I 2018 Performance optimization of microstrip antenna with different slot configurations and various dielectric materials J. Electron. Sci. Technol. 16 4 379–384
[22] Sandi E, Diamah A, Iqbal M W and Fajriah D N 2019 Design of Substrate Integrated Waveguide to Improve Antenna Performances for 5G Mobile Communication Application Journal of Physics: Conference Series 1402 4 044032
[23] Ambresh P A, Hadalgi P M and Hunagund P V 2011 Effect of slots on microstrip patch antenna characteristics Int. Conf. Comput. Commun. Electr. Technol. ICCCET 239–241
[24] Gupta N 2017 Effects of Slots on Microstrip Patch Antenna Int. Res. J. Eng. Technol. 4 2 1132–1135
[25] Toğ içuoğlu N B, Albayrak Y, Saylik M N, Daye M A, Bal M, İmec M and İmec T 2017 Circular patch antenna with circular and rectangular slots 2017 25th Signal Processing and Communications Applications Conference (SIU) 1–4
[26] Sran J S and Sivia S S 2015 Rectangular Microstrip Patch Antenna with Triangular Slots Int. J. Comput. Appl. 1 27–29
[27] Bhardwaj R Y and Samii S 2014 A Comparative study of C-Shaped, E-Shaped, and U-Slotted Patch Antennas Microw. Opt. Technol. Lett. 56 3 748–753
[28] So K K, Luk K M and Chan C H 2018 A High-Gain Circularly Polarized U-Slot Patch Antenna Array [Antenna Designers Notebook] IEEE Antennas Mag. 60 5 147–153
[29] Al Nahian A 2014 Design and Performance Analysis of U-Slot, Y-Slot and U-Y Slot Microstrip Patch Antenna for Wireless Applications Des. Perform. Anal. U-Slot, Y-Slot U-Y Slot Microstrip Patch Antenna Wirel. Appl. 32 2 197–207