Compact and Wide Bandwidth Microstrip Patch Antenna for 5G Millimeter Wave Technology: Design and Analysis

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Abstract. In this paper, a compact microstrip patch antenna for 5G Millimeter wave technology has been proposed. By developing wide bandwidth characteristics, long ranges of data transfer are covered with better quality of signal transmission in 5G communication system. Modification of antenna element; patch width structured has influenced the frequency bandwidth. The design, analysis and optimization of the proposed work along with parametric analysis were performed using CST Microwave Studio. A microstrip patch antenna has been designed with high bandwidth millimeter wave, compact dimension, consistent radiation patterns and relatively higher gain at 28 GHz (mm-wave) band. FR-4 substrate has been employed in this work with a dielectric constant value of 4.3, thickness value of 1.6 mm and loss tangent value of 0.025. The proposed antenna has achieved high bandwidth which is 14.674 GHz with a reflection coefficient of -40.14 dB, Voltage Standing Wave Ratio (VSWR) value of 1.1098 and maximum gain of 5.29 dB with high directivity of 7.465 dBi. The antenna results of this work proved to be useful in fulfilling the requirements of wider bandwidth and higher gain particularly at 28 GHz for 5G applications.

1. Introduction

Fifth Generation (5G) antenna design is currently the most researched subject within communication systems. As predicted, 5G will be accessible to nearly all countries by 2021[1]. The Fifth Generation (5G) technology is anticipated to focus on improving the fourth generation (4G) technology, enabling approaches to the 4G shortage such as limited bandwidth and data transfer rate [2]. The Malaysian Communications and Multimedia Commission (MCMC), in January 2020, designated 700 MHz, 3.5 GHz, and 26/28 GHz as the three bands for Malaysia's 5G official launch [3]. Among these three bands, the 26/28 GHz band is considered as a millimeter wave (mm-wave) band based communication system. With Industrial Revolution 4.0 (IR 4.0), there will be digital transformation in all sectors such as education, health care, military, logistics and so forth [4]. The primary focus of the Fourth Industrial Revolution would be digitizing the economy and 5G networks would be key asset in supporting this
growth. To accomplish this task, a reliable wide area of network with high data is very important and is possible using 5G networks [5]. Small-sized antennas are in demand in 5G network infrastructure as they are capable of high frequency applications, which, in turn, make microstrip patch antennas one of the most effective and convenient antennas available for use [6]. In recent years, the study of microstrip patch antennas has made major progress. Microstrip patch antennas have more advantages relative to other types of antennas. They are light weight, small volume, low cost, low profile, smaller in dimension and easy to fabricate [7]. The limited bandwidth and low gains, however, are the main disadvantages of the microstrip patch antennas. Nevertheless, the bandwidth can be improved using a thicker substrate that will increase the surface waves that move through the substrate and radiate the patch [7]. However, this method causes the antenna gain to decrease and this might affect the antenna’s overall efficiency. Moreover, using thicker substrate would enlarge the overall dimension of the antenna which is not desired in 5G technology.

Many types of antennas have been designed to meet the requirement of 28 GHz band for 5G technology. Several researchers have proposed microstrip patch antennas to operate at 28 GHz using FR-4 as the dielectric substrate where permittivity value of the substrate was 4.4 with different substrate thickness which are 0.8 mm and 1.6 mm [8-10]. In [8], the gain was achieved higher, 6.37 dB as compared to the other two substrates. The results were exactly opposite with regards to the bandwidth. The highest bandwidth of 4.1 GHz was achieved in [10] followed by 3.9 GHz in [9] and 2.48 GHz in [10]. In [11], the authors used FR-406 with a permittivity value of 3.93 and a thickness of 0.8 mm to design a Planar Inverted F-Antenna (PIFA) operating at 28 GHz. Here, the proposed antenna achieved a gain value of 3.75 dB with a bandwidth of 3.34 GHz. Another common dielectric substrate used for microstrip patch antenna is RT-5880 with a permittivity value of 2.2 to operate at 28 GHz [12-15]. The thickness of the substrate was 0.708 mm, 0.5 mm, 1.6 mm and 0.127 mm in [12], [13], [14] and [15] respectively. With regards to the gain performance, the highest gain value of 8.03 dB was achieved by the authors in [12] and subsequent gain value of 2.6 dB in [13], 3.7308 dB in [14] and 6.61 dB in [15]. From the literature review, it has been considerably observed that, performance of FR-4 based antennas specifically in term of bandwidth is much better as opposed to the RT-5880 based antennas. Moreover it is noticed that using thicker substrate with lower permittivity value increases the antenna’s overall efficiency however it leads to enlargement of antenna’s dimension. Therefore it is complex to balance the trade-off between antenna’s size and performance. Since, fifth generation technology particularly in 5G communication systems, wide bandwidth and smaller geometry are important undoubtedly.

Therefore, in this research paper, FR-4 is chosen to use as the dielectric substrate for the proposed antenna to achieve high bandwidth with compact antenna dimension compared to the references cited above. The key objective of this research is to investigate the performance variation of the antenna with varying parameter and propose an improved design with wide bandwidth, compact size and high gain for 5G applications at 28 GHz. To obtain these objectives, parametric analysis of the antenna is performed to identify which parameter plays a major role in antenna’s reflection coefficient, bandwidth and resonant frequency. After identification of antenna parameter, new shape antenna is proposed which perform wide bandwidth, high gain and resonance frequency of 28 GHz. The paper has been divided as follows: Section 2 summarizes the antenna design methodology. Section 3 elaborates on the parametric analysis, optimizations performed and the performance of the proposed antenna compared with recently published works. The conclusion of this research paper is set out in section 4.

2. Antenna Design Methodology
In designing the antenna, the desired design specification are considered important as it has an impact on the antennas overall performance. The antenna was designed to be a compact microstrip patch antenna at resonance 28 GHz. The antenna must have a reflection coefficient value (S11) of less than -10 dB, a Voltage Standing Wave Ratio (VSWR) of less than or equal to 2 dB at a line impedance match at 50 Ohms and a bandwidth greater than or equal to 400 MHz as shown in Table 1.
Table 1. Design Specifications of the Proposed Antenna

| Specification       | Values          |
|---------------------|-----------------|
| S11                 | Less than -10 dB|
| VSWR                | 1.2             |
| Input Impedance, Z  | 50 Ohms         |
| Copper thickness, mm| 0.035 mm        |
| Bandwidth           | ≥ 400 MHz       |
| Frequency           | 28 GHz          |

Once the dielectric substrate had been chosen and using the antenna geometric formulas, the dimensions of the antenna was calculated designed. In order to analyze the effect of the antennas dimensions on its performance, parametric analysis was conducted to determine optimum dimensions of the antenna. Simulation software, CST Microwave Studio (CST 2019) was used to carry out the parametric analysis and to design the antenna. After designing and optimizing the antenna, the simulated results for reflection coefficient (S11), Voltage Standing Wave Ratio (VSWR), gain and radiation patterns in Two dimensional (2-D) views and Three dimensional (3-D) views were analyzed and discussed. To evaluate the performance of the proposed antenna design, the performance of proposed antenna was compared with other recent published antenna design.

A microstrip patch antenna is comprises of a radiating patch, a dielectric substrate and a ground plane as illustrated in Figure 1(a). The length and width of the ground plane are labeled as “Lg” and “Wg”, while the length and width of the patch are indicated as “Lp” and “Wp” respectively. The width and length of the feedline are represented as “Wf” and “Lf” as shown in Figure 1(b). The patch is usually made from conductive materials such as copper or gold. The substrate provides mechanical strength to the antenna. The function of the feedline is to connect the antenna to a radio transmitter and receiver.

![Figure 1](image_url)

**Figure 1.** Microstrip patch antenna’s basic (a) Structure (b) Dimension [16]

The dielectric substrate used in this research is Flame retardant (FR-4) with permittivity of 4.3, standard thickness value of 1.6 mm and loss tangent of 0.025. To design the antenna shape, equation 1 to equation 9 of [16] were applied. Once the dimension of the antenna has been calculated, the antenna has been designed using CST simulation software as shown in Figure 2 and its dimension is tabulated in Table 2.
Table 2. Calculated Dimensions of the Proposed Design

| Parameter          | Notation | Calculated value (mm) |
|--------------------|----------|-----------------------|
| Ground Width       | Wg       | 12.884                |
| Ground Length      | Lg       | 11.287                |
| Patch Width        | Wp       | 3.289                 |
| Patch length       | Lp       | 1.687                 |
| Feedline Width     | Wf       | 3.13                  |
| Feedline Length    | Lf       | 4.8                   |

3. Results and Discussion

The simulated reflection coefficient (S11) result of the calculated antenna design is shown in Figure 3. As depicted in Figure 3, the calculated antenna achieved the S11 value of -8.1798 dB at 28 GHz whilst the main curve was at higher band far away from desired frequency. Since, the S11 curve has to be below -10 dB at exactly 28 GHz, optimization had to be carried out to achieve the optimum results at the desired frequency. The parametric analysis of the proposed design was carried to analyze the parameters of the antenna design with the reflection coefficient (S11), bandwidth and resonant frequency. The results and discussion of the optimized antenna after the parametric analysis are explained in this section as well.
**Figure 3.** The result of simulated S11 value of the calculated antenna

### 3.1. Parametric Analysis

In this part, four antenna parameters, namely, Ground Width (Wg), Ground Length (Lg), Patch Width (Wp) and Patch Length (Lp) were analyzed to determine the changes in the performance of the antenna when there are variations to the parameters. The frequency range set for parametric analysis was 0 GHz to 38 GHz. Results obtained beyond 38 GHz is labeled with “exceeds given range”.

#### 3.1.1. Effect of Ground Width (Wg)

In order to choose a suitable and optimum Wg, different values from 9 mm to 12 mm were tested while other parameters remained constant. As shown in Figure 4, variation in Wg resulted the reflection coefficient, bandwidth and resonant frequency of the antenna to change slightly. From Table 3, it can be seen as Wg increases, the bandwidth of the antenna decreases, reflection coefficient increases and the resonant frequency shifts to higher band. Since variations in Wg have a small effect on reflection coefficient, bandwidth and resonance frequencies, it is an effective and non-sensitive parameter to modify in the event minor changes are required to be made to the antenna.

![Figure 4.](image)

**Figure 4.** The Effect of Ground Width (Wg) on S11, Bandwidth and Resonant frequencies

| Wg, mm | Lg, mm | S11, dB | Bandwidth, GHz | Frequency, GHz |
|--------|--------|---------|----------------|----------------|
| 9      | 10     | -45.29  | 13.749         | 28.043         |
| 10     | 10     | -36.431 | 13.243         | 28.16          |
| 11     | 10     | -34.97  | 11.677         | 28.272         |
| 12     | 10     | -35.83  | 11.046         | 28.72          |

#### 3.1.2. Effect of Ground length (Lg)

Different values of Lg from 9 mm to 12 mm were tested while the other parameters remained constant. In Figure 5, it is noted that Lg has significant impact on the antennas performance. Small variation in Lg resulted in a large change in the antennas reflection coefficient, bandwidth and resonant frequency. While varying Lg from 9 mm to 12 mm, optimum results were achieved at 10 mm where the reflection coefficient was -40.1 and bandwidth was at 15.303 at the desired frequency of 28 GHz. Therefore, Lg has
to be carefully designed in order to achieve optimum values. The obtained results are shown in Table 4 below.

![Figure 5](image_url)

**Figure 5.** The Effect of Ground Length (Lg) on S11, Bandwidth and Resonant frequencies

| Lg, mm | Wg, mm | S11, dB | Bandwidth, GHz | Frequency, GHz |
|--------|--------|---------|----------------|----------------|
| 9      | 8      | -8.99   | exceeds given range | 35.80          |
| 10     | 8      | -40.1   | 15.303         | 28             |
| 11     | 8      | -10.07  | 6.51           | 24.72          |
| 12     | 8      | -10.01  | exceeds given range | 32.99          |

**Table 4.** Tabulation of results while varying Ground Length (Wg)

3.1.3. Effect of Patch width (Wp)
The third parameter tested was Wp where it has been observed that this parameter had a minor effect on the antennas performance. From Figure 6, it can be observed that while increasing Wp from 3.8 mm to 7 mm, the antenna achieved wider bandwidth to operate close to the desired frequency. In addition, increase in Wp resulted slight shifting of curve towards higher frequency bands. Hence, it is a very effective parameter to vary if small changes or modifications are needed in antenna performance. The overall simulated results of varying Wp is tabulated in Table 5.

![Figure 6](image_url)

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Figure 6. The effect of patch width (Wp) on S11, Bandwidth and Resonant frequencies

Table 5. Tabulation of Results while Varying Patch Width (Wp)

| Wp, mm | Lp, mm | S11, dB | Bandwidth, GHz | Frequency, GHz |
|--------|--------|---------|----------------|----------------|
| 3.8    | 2.22   | -31.725 | 10.472         | 27.8           |
| 4.8    | 2.22   | -53.02  | 13.293         | 27.93          |
| 6      | 2.22   | -31.037 | 14.903         | 28.6           |
| 7      | 2.22   | -27.161 | 15.226         | 27.96          |

3.1.4. Effect of Patch Length (Lp)

The last parameter tested was patch length (Lp) of the antenna in which the results are tabulated in Table 6. It can be seen Lp has large effect on the antennas performance. With small variations in Lp, there was a complete mismatch of impedance which made the antenna unreliable as depicted in Figure 7. Hence, similar to Ground Length, Lp needs to be carefully designed to achieve the desired results. This parameter has bigger effect on the performance of antenna.

Figure 7. The Effect of Patch Length (Lp) on S11, Bandwidth and Resonant frequencies

Table 6. Tabulation of results obtained while varying Patch Length (Lp)

| Lp, mm | Wp, mm | S11, dB | Bandwidth, GHz | Frequency, GHz |
|--------|--------|---------|----------------|----------------|
| 0.8    | 5.2    | -18.05  | Exceeds given range | 35 |
| 1.6    | 5.2    | -15.16  | Exceeds given range | 26.107 |
| 2.8    | 5.2    | -31.92  | Exceeds given range | 31.6 |
| 3.8    | 5.2    | -10.692 | 4.026           | 32.869         |

3.2 Final and Optimum Design

The final design was achieved after a series of parametric analysis and optimization. As opposed to the calculated dimensions illustrated in Table 2, the overall ground plane area was reduced to 8×10 mm² whilst the patch area was increased to 5.22×2.22 mm² and feedline area reduced to 3.4×4.8 mm² as shown in Table 7. The line impedance of the proposed design is 50.0267 Ω which matches with the SMA
port impedance of 50 Ω. As a result, with minimal reflection loss, maximum power will be transferred to the antenna from the port. The new dimension of the antenna is illustrated in Figure 8.

Table 7. Final Dimension of the Proposed Antenna

| Parameters       | Notations | Optimized value, mm | Remark         |
|------------------|-----------|---------------------|----------------|
| Ground Width     | Wg        | 8                   | Reduced by 37.9 % |
| Ground Length    | Lg        | 10                  | Reduced by 11.4% |
| Patch Width      | Wp        | 5.2                 | Increased by 36.75% |
| Patch length     | Lp        | 2.22                | Increased by 24% |
| feedline Width   | Wf        | 3.4                 | Increased by 7.9% |
| feedline Length  | Lf        | 4.8                 | Unchanged       |

Figure 8. Simulated final antenna design (a) Front View (b) Back View (c) Perspective View
3.2.1. Reflection Coefficient (S11), Bandwidth and Voltage Standing Wave Ratio (VSWR)

For antennas, one of the most important specifications is reflection coefficient or S11. Reflection coefficient refers to the amount of power which has been reflected because of the discontinuation which has taken place in the transmission line. The accepted value of S11 is less than -10 dB. From the simulation result as shown in Figure 9, the simulated resonance frequency of the antenna was at 28 GHz with a reflection coefficient (S11) value -40.14 dB. Since the proposed antenna has very low reflection coefficient value of -40.14 dB hence it proves that a considerable amount of energy has been delivered to antenna. Having such low reflection coefficient value also determines that there is very good match with the transmission line hence maximum power has been transmitted from the antenna towards the intended direction.

Furthermore from Figure 9, the antenna has bandwidth coverage between 21.227 GHz to 35.874 GHz (14.674 GHz) which is 52.4% of the operating frequency. Having such wide bandwidth helps an antenna to transfer signals easily and it is more secured. Moreover, having wider bandwidth requires low power and low cost for the antenna to transmit and receive signals. Thus, it is clear that the proposed antenna has the capacity to deliver higher signal strength even in poor and adverse conditions.

![Figure 9. Reflection coefficient and Bandwidth of the proposed antenna](image1)

The simulation work continued to evaluate the Voltage Standing Wave Ratio (VSWR) of the proposed finalized design. According to ITU Standards for 5G Communication Systems [17], an antenna must have a VSWR value less than or equals to 2 dB to avoid mismatch. As demonstrated in Figure 10, the antenna achieved 1.1098 dB at the desired frequency of 28 GHz which is within the accepted range. The obtained VSWR value indicated that the antenna port doesn't have any reflected power. When the antenna and transmission line are not perfectly matched, reflections at the port of the antenna migrate back to the source and eventually lead in a standing wave formation.

![Figure 10. VSWR at 28 GHz](image2)
3.2.2. Radiation Pattern

The three-dimensional (3D) view of the radiation pattern of the simulated antenna is illustrated in Figure 11(a). The 3D view depicts the antenna at 0 degrees and the gain achieved was 5.29 dB at 28 GHz. Having directional patterns helps the antenna to cover a long range in one direction. Besides that, an antenna's directivity is also another key point. The directivity value is 7.465 dBi for the proposed antenna design as shown in Figure 11(a), which can also be regarded as a good directivity because the microstrip patch antenna directivity theory varies between 5-8 dBi [18]. Moreover, it is also considered that higher the value of directivity, better the antenna's overall performance effectiveness. In addition, the two-dimensional (2D) view of the radiation pattern, also known as polar pattern, because the axis is independent. The angular is known as theta or Phi. The polar pattern of Phi values 0 degrees and 90 degrees is illustrated Figure 11(b) and Figure 11(c) respectively. Since the proposed antenna has achieved relatively higher gain value of 5.29 dB, directivity value of 7.465 dBi and it is directional hence the antenna has advantage of longer range and better signal quality.
Figure 11. Radiation Pattern of the Proposed Antenna (a) 3D View (b) 2D View at Phi = 0° (c) 2D View at Phi = 90°

Table 8 compares the performance of the proposed microstrip antenna with several other antennas. From the table above, it is evident that the proposed antenna has a much wider bandwidth and is compact in size and has relatively higher gains as opposed to published reference works.

| Reference | Antenna dimension, mm² (Wg × Lg) | Frequency, GHz | Reflection coefficient, S11 | Gain, dB | Bandwidth, GHz |
|-----------|----------------------------------|----------------|-----------------------------|----------|----------------|
| [8]       | 7 × 7                            | 28             | -39.37                      | 6.37     | 2.48           |
| [9]       | 10 × 10                          | 28             | -35.73                      | 5.54     | 3.9            |
| [10]      | 5.5 × 4.35                       | 28             | -42.25                      | 5.61     | 4.1            |
| [11]      | 7 × 3                            | 28             | Below -10                  | 3.75     | 3.34           |
| [12]      | 19 × 19                          | 28.1           | -24.5                       | 8.03     | 1.02           |
| [13]      | 11 × 8                           | 28             | -21                         | 2.6      | -              |
| [14]      | 30 × 40                          | 28             | Below -10                  | 3.7308   | 1.37           |
| [15]      | 39.3 × 30.65                     | 28             | Below -10                  | 6.61     | 0.470          |
| This work | 8 × 10                           | 28             | -40.14                      | 5.29     | 14.674         |

4. Conclusion
A new compact microstrip antenna for 5G applications at 28 GHz was designed, analyzed and simulated in this research. Parametric optimization was also analyzed and discussed for different antenna parameters such as Ground Width, Ground Length, Patch Width and Patch Length. The proposed 5G microstrip patch antenna’s optimized simulation result obtained a reflection coefficient of -40.1 dB and VSWR value of 1.1098 dB at 28 GHz. The bandwidth obtained was 14.674 GHz from between 21.227 GHz to 35.874 GHz which signified the usability and versatility of the proposed antenna. The bandwidth recorded percentage was 52.4 % along with maximum gain of 5.29 dB and directivity of 7.465 dBi. Moreover, the bandwidth performance of the antenna in this work is observed to be suitable for broadband applications and capable of transferring good quality signals too. However, the proposed antennas efficiency was 60.6% whereby further investigation shall be conducted to improve overall antenna efficiency while maintaining compact dimensions. To conclude, the proposed antenna proved to meet the requirements of having a wider bandwidth, is compact in dimension, has a stable radiation pattern and has relatively higher gain which indicates its potential for 5G applications especially when bandwidth and gain are major concerns.

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