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Dual element MIMO planar inverted-F antenna for 5G millimeter wave application

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Abstract

This work presents a 28 GHz Dual Element Multiple Input Multiple Output (MIMO) Planar Inverted-F Antenna for millimeter wave 5G mobile terminal. The antenna design employs PIFA design concept as it is a common antenna type use for mobile phone as it provides wide bandwidth and good performance. The antenna design begins with a characterization of the single element PIFA design and then extended to Dual Element MIMO PIFA design. The single element PIFA design is enhanced to MIMO design by extending the ground plane and locate the second PIFA at the other end. Isolation between the antenna elements of the MIMO PIFA is analyzed by varying the gap distance between the antenna elements. The result for Envelope Correlation Coefficient, Diversity Gain and Multiplexing Efficiency is also presented. The simulation computed using Computer Simulation Technology (CST) Microwave Studio software.

Keywords: 5G, isolation, millimeter wave, PIFA

1. Introduction

The existing generations of cellular networks nowadays facing global bandwidth shortage. Increasing demand in higher data rates, higher frequency, and low latency require new frequency spectrum. The new generation of cellular networks, 5G utilizes millimeter wave spectrum. The utilization of millimeter wave spectrum has recently been proposed due to its large spectrum availability, higher bandwidth, high data rate and can handle larger user capacity compared with today's wireless systems [1, 2]. Millimeter wave spectrum used for mobile communication is Local Multipoint Distribution Service (LMDS) band. LMDS uses a cellular infrastructure, with multiple base stations supporting point-to-multipoint communication to small customer transceivers. Millimeter wave spectrum use by LMDS ranges between 28–32 GHz [3-5]. 28 GHz was chosen as the frequency of operation of the antenna design as defined by researchers in [6-9].

In order to increase the channel capacity, utilization of Multiple Input Multiple Output (MIMO) system is needed in 5G wireless communication systems at both the transmitter and receiver along with some complex signal processing [10]. Compared to single antenna, MIMO antenna has high Signal to Noise Ratio (SNR) resulted in higher data rate [11, 12]. Challenge in antenna design for the mobile terminal is limited space of mobile device and to fulfill the technical requirements for MIMO antenna which is low correlation and good efficiency. Multiple antenna in MIMO antenna design will introduce isolation. At present, several techniques employed to antenna design to improve the isolation. In [13], different orientations of antenna elements employed to the antenna design to improve the isolation. In [14] stubs and slots design employed to the antenna design to reduce mutual coupling between two adjacent antenna element. A compact decoupling network for enhancing the port isolation between two closely spaced antennas is proposed in [15].

This research works on dual element MIMO PIFA antenna design focus on the isolation improvement by varying the gap distance between the antenna elements. The proposed antenna design applied PIFA design, which is a common antenna used for mobile phone. PIFA has many advantages of the desired cross polarization, easy feeding, simple to fabricate

and easy to place in mobile terminal [16-18]. The single PIFA design has been extended to MIMO antenna by increasing the width of the ground plane. Meanwhile the second PIFA element is added to the other end of the ground plane. Isolation within the antenna element enhanced by placing the second element within acceptable gap distance. It is a simple method by adjusting the width of the ground plane to make the gap between the antenna elements wider.

The outline of this paper is as follows. Section 1 discusses the introduction of MIMO antenna for 5G technology, antenna isolation and parameter to characterize MIMO antenna. Section 2 presents the design methodology of the single element PIFA design and dual element MIMO PIFA design. Section 3 elaborates the results and discussion of this work and the parametric analysis of the proposed design. The objectives of this work are explained as:
- To propose a single PIFA for 28 GHz frequency.
- To produce Dual Element MIMO PIFA design for 28 GHz frequency.
- Investigate the effect of the gap distance between the antenna element.
- Evaluate results for envelope correlation coefficient (ECC), multiplexing efficiency (ME) and diversity gain (DG) a with a different gap distance of the antenna element.

2. Design Methodology
2.1. Single Element PIFA
The proposed Planar Inverted-F Antenna (PIFA) as shown in Figure 1 consists of the radiating patch, shorting plate and ground plane. RT/Duroid 5880 substrate with a thickness of 1.575 mm and permittivity, ε_r=2.2 is used in the proposed antenna. The dimension of the radiating patch is L_1 and L_2 and the ground plane is $L_g \times W_g$. The radiating patch place on top of the ground plane with height, h= 0.25 mm. The gap between the patch and the ground plane, h is filled with air substrate with permittivity, ε_r=1. The shorting plate is used to connect the antenna patch and ground plane. In the simulation, the 50 Ω discrete ports are used to feed in the bottom line of the rectangular patch. The distance of the feeding position to the shorting plate is 0.43 mm.
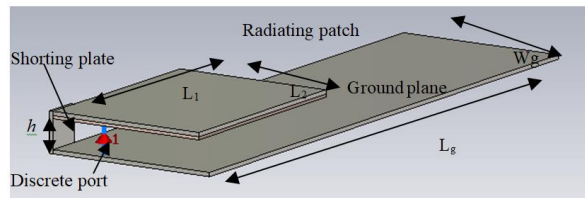

Figure 1. The geometry of the proposed PIFA

2.2. PIFA Design Calculation
The operating frequency of a microstrip patch antenna is inversely proportional to its physical dimension. In (1) shows that the resonant frequency is inversely proportional to the patch length. The length of the patch can be calculated using formula (2) and (3). The frequency of operation, *f* used in the calculation is 28 GHz as presented in [19, 20]. For a standard, probe feed, quarter wave microstrip patch antenna, the operating frequency can be approximately determined from the length of the antenna patch as follows:

$$f = \frac{c}{4(L_1+L_2)} \tag{1}$$

$$L_1 \approx \frac{\gamma_d}{4} = \frac{1}{4}\frac{c}{f\sqrt{\varepsilon_r}} \tag{2}$$

$$L_2 = \frac{c}{4f}\sqrt{\frac{2}{\varepsilon_{r+1}}} \tag{3}$$

in (4) can be used to find the total length [21]. The length and width, L_1 and L_2 of the patch that can be calculated as:

$$f = \frac{c}{4(L_1+L_2)}$$

$$(L_1 + L_2) = x$$

$$x = \frac{c}{4f} \qquad\qquad (4)$$

where c=free space velocity of light 3×10^8 m/s, f=frequency of operation and x is the total length of L_1 and L_2. Length of L_1 and L_2 approximately the same value. Thus, the calculated total length x is then divided by 2 for preliminary dimension of L_1 and L_2. The patch length and width are optimized by several simulations to 1.8 mm and 1.4 mm respectively. The size of the ground plane L_g and W_g is 5 mm$\times$1.5 mm.

2.3. MIMO PIFA Design

MIMO PIFA design is characterized by an extension of the ground plane width to the optimized value and the other PIFA is element placed at the other end of the design. The single element PIFA design is extended to be two elements PIFA. The second element is the mirror feature of the first element as shown in Figure 2. The optimized parameters for the proposed antenna as shown in Table 1. The width of the ground plane is extended to optimize while the length of the ground plane is similar with the length of the ground plane for the single element which is 5 mm. The second radiating patch is located at the edge of the ground plane. The dimension of the radiating patch for the MIMO design is optimized to 1.25$\times$1.85 mm. In order to implement the MMO design, the spacing between antenna elements needs to be optimized to provide good isolation characteristic. The calculation of the distance (D) between the two elements, which is half wavelength ($\lambda/2$) calculation is described as follows [22, 23]:

$$D = \frac{\lambda}{2} \qquad\qquad (5)$$

where λ= 0.011mm which is wavelength for 28GHz frequency.

For the optimization of the MIMO PIFA, the calculated value is used as the preliminary gap between PIFA 1 and PIFA 2. Element in MIMO antenna design has to keep apart to reduce the mutual coupling. Mutual coupling between antenna element will affect the antenna gain and efficiency [22]. The analysis and result of the simulation of the MIMO antenna with different gap distance will be discussed in Section 3.
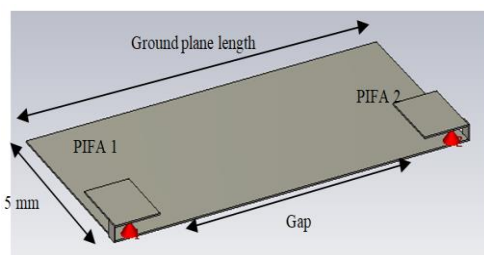

Figure 2. Geometry of dual element MIMO PIFA design

Table 1. Dimensions of Proposed Antenna

Parameters	Antenna	
	Singe PIFA	MIMO PIFA
$L_1\times L_2$	1.4 mm$\times$1.8 mm	1.25 mm$\times$.85 mm
$L_g\times W_g$	5 mm$\times$1.5 mm	5 mm$\times$8.0 mm

3. Results and Analysis

This section discussed the results or single element PIFA design and Dual Element MIMO PIFA design as shown in section 3.1, section 3.2 respectively. Section 3.3 shows the analysis of the Dual Element MIMO PIFA.

3.1. Single Element PIFA Result

The simulated return loss of the proposed antenna is shown in Figure 3. The proposed antenna resonate well within 28 GHz frequency and exhibit large bandwidth up to 2.68 GHz (26.3-29.3 GHz). The simulated 3D far-field view of the proposed antenna shown in Figure 4. The radiation pattern of the proposed antenna produced almost omnidirectional pattern. The far-field pattern showed upward radiation with 3.119 dB gain. The total efficiency of the antenna is 98%.
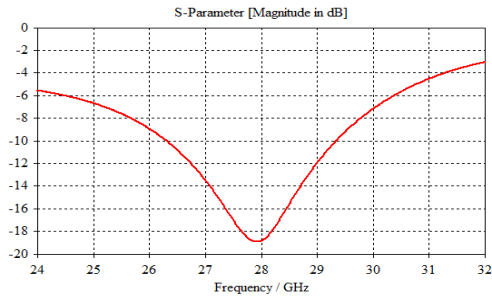

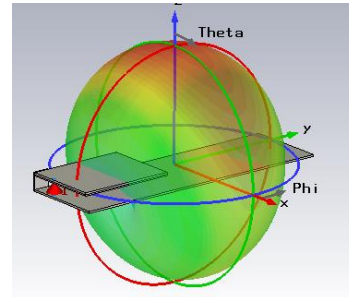Figure 3. Simulated S_{11}(dB) of the proposed single element PIFA at 28 GHz

Figure 4. The simulated far-field pattern of single element PIFA in 3D

3.2. Dual Element MIMO PIFA Result

This simulated results for scattering parameter are shown including gain, efficiency and 3D far-field pattern of the Dual Element MIMO PIFA for 5 mm gap distance. The 5 mm gap distance calculated from the previous section is as a preliminary value for the optimization of the gap. The 5 mm gap distance extended from the width of the ground plane of the single element which is 1.5 mm. The second antenna element placed at the edge of the extended ground plane is the mirror feature of the first antenna element.

Figure 5 shows the scattering parameter result of the Dual Element MIMO PIFA. The antenna resonates with wide bandwidth 26.41–30.18 GHz (3.77 GHz). It can be seen that the antenna has high isolation, with -14 dB at 28 GHz frequency. This is due to the close distance between the PIFA 1 and PIFA 2. 3D far-field pattern shown in Figure 6 (a) for PIFA 1 and Figure 6 (b) for PIFA2. The radiated far-field pattern shows upward radiation and away from each other. The antenna radiated outperformed with 4.684 dB gain and 96.6% efficiency.
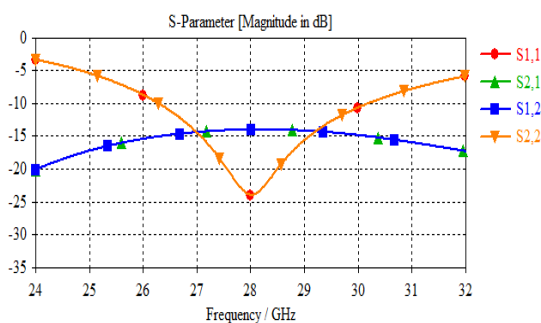

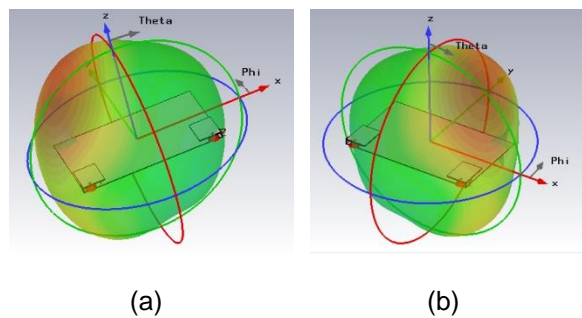Figure 5. Simulated scattering parameter for the dual element PIFA with 5 mm gap distance

Figure 6. 3D Far field pattern for the dual element PIFA with 5 mm gap distance
(a) far-field pattern for port 1
(b) far-field pattern for port 2

3.3. Analysis of Dual Element MIMO PIFA with Different Gap Distance

The analysis of the gap distance between MIMO PIFA elements is carried out from 5 mm to 40 mm with 5 mm increment Table 2 summarizes the 10 dB bandwidth of the Dual

Element MIMO PIFA. The configuration of the PIFA 1 and PIFA 2 are identical to each other, thus the results are similar. The 10 dB bandwidth for all gap distance approximately the same bandwidth indicates that the separation between the antenna element not affected to the antenna resonance. As presented in Figure 7, the gap distance affected to the mutual coupling between the antenna element. The gap between the antenna element is defined since the result is significant. Figure 7 shows the simulated transmission coefficient (S_{12}) of the Dual Element PIFA with different gap distance. Close gap distance between two antenna element will increase the mutual coupling, which is the electromagnetic interaction between the antenna elements that will affect the isolation value [24, 25]. It can be seen for the 5 mm gap distance, the antenna has poor isolation, which is -14 dB. Increasing the gap distance will improve the isolation value with the highest isolation value is -25 dB when the antenna elements keep apart with 40 mm gap.

Table 2. Result Summary for the Dual Element MIMO PIFA

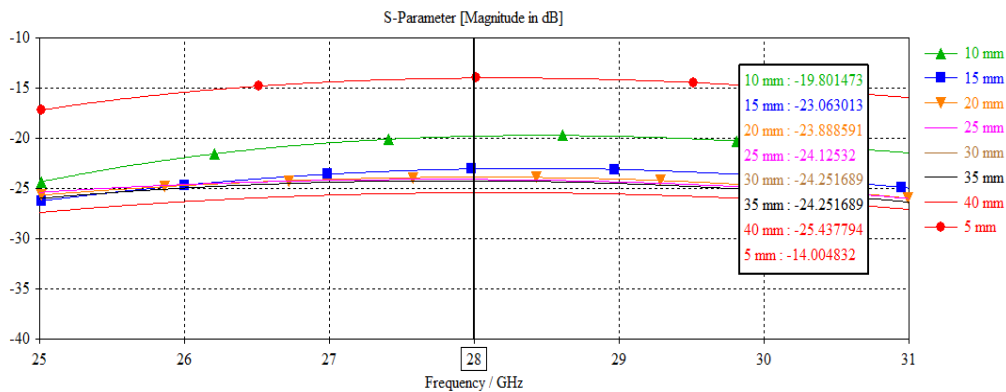| Gap Distance (mm)	Elements	10 dB Bandwidth (MHz)	Gap Distance (mm)	Elements	10 dB Bandwidth (MHz)
5	PIFA 1	3770	25	PIFA 1	3680
	PIFA 2	3770		PIFA 2	3680
10	PIFA 1	3720	30	PIFA 1	3750
	PIFA 2	3720		PIFA 2	3720
15	PIFA 1	3640	35	PIFA 1	3710
	PIFA 2	3640		PIFA 2	3710
20	PIFA 1	3710	40	PIFA 1	3766
	PIFA 2	3710		PIFA 2	3766

Figure 7. Simulated transmission coefficient (S_{12}) for the dual element MIMO PIFA with different gap distance

Figure 8 represents the gain and the efficiency of the Dual Element MIMO PIFA with different gap distance. As shown in Figure 8, from the 15 mm gap distance to 20 mm gap distance, the antenna gain rise up sharply approximately 1 dB increment and then slowly sustain the gain value. This situation similar to the antenna efficiency, where the efficiency rise sharply at the same gap distance. Increasing the gap distance improved the isolation and this also contribute to the enhancement of the antenna gain and efficiency. The maximum value of the gain is 6.730 dB and total efficiency is 99.9% achieved with 40 mm gap distance.

The simulated results for envelope correlation coefficient (ECC), diversity gain and multiplexing efficiency between PIFA 1 and PIFA 2 are presented in Table 3. The ECC is used to evaluate the diversity capability of multi-antenna system. The ECC value lower than 0.02 shows that the MIMO antenna having good diversity performance [26]. Based on the results, it can be seen that the value of the ECC approaching to zero represents the radiation pattern of PIFA 1 and PIFA 2 directed away from each other, which is nearly uncorrelated. From the correlation, a diversity gain (DG) of a MIMO antenna can be defined. For two uncorrelated antenna, the diversity gain will be approximately 10 dB. Multiplexing efficiency (ME) is defined from the envelope correlation and the gain of the two antenna element.
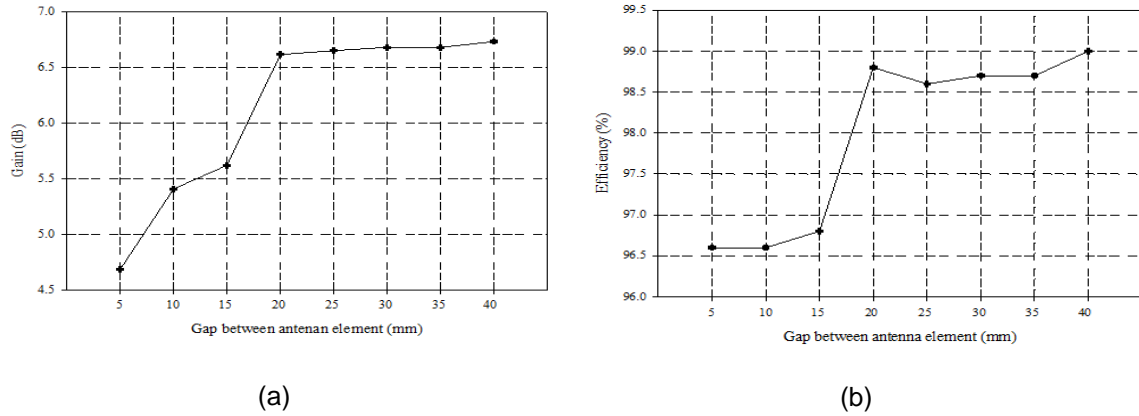
(a)   (b)

Figure 8. The simulated (a) gain amd
(b) efficiency for the proposed antenna with different gap distance

Table 3. Performance Characteristic of the Dual Element MIMO PIFA
with Different Gap Distance

Gap Distance	Envelope Correlation	Diversity Gain (dB)	Multiplexing Efficiency
5 mm	0.0006010	9.9986935	-0.212249
10 mm	0.0001378	9.9997007	-0.0849855
15 mm	0.0000185	9.9999598	-0.0701495
20 mm	0.0000108	9.9999764	-0.0762117
25 mm	0.0000121	9.9999531	-0.0946961
30 mm	0.0001369	9.9994289	-0.0918847
35 mm	0.0001369	9.9994289	-0.0918847
40 mm	0.0002630	9.9994280	-0.0937201

3.4. Simulated Return Loss and Radiation Pattern of the Antenna with 20 mm Gap Distance

From observation of the results for gain and efficiency of the proposed antenna, it shows that the antenna sustains the performance start form 20 mm gap distance Therefore, the proposed antenna decided to use 20 mm gap distance as the best optimization. Figure 9 shows the simulated scattering parameter with 3.71 GHz bandwidth and -23 dB isolation. Polar plot of the radiation pattern for PIFA 1 and PIFA 2 presented in Figure 10. The polar plot for both elements are identical to each other. The co-polarization components x-z plane ($\emptyset=0^0$) for both element showed in solid line while the cross polarization component y-z plane ($\emptyset=90^0$) showed in dashed line. The MIMO PIFA also simulated with both port excited. Both port excitation give combination of far-field from both elements. Gain of the MIMO PIFA with both port excite is 4.63 dB and the total efficiency is 99%. Figure 11 shows the 3D radiation pattern and the polar plot of the results.
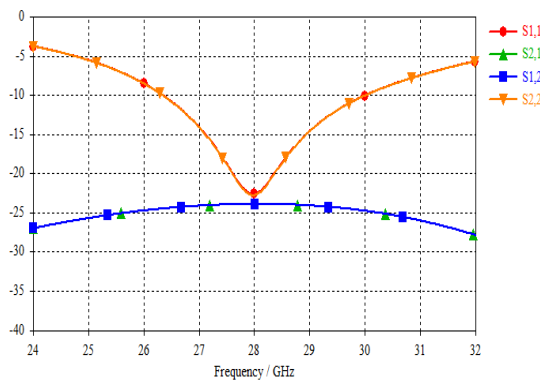

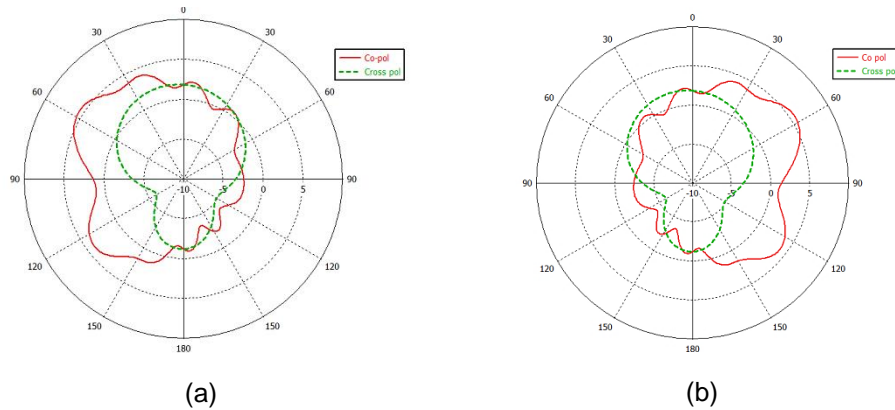Figure 9. Simulated scattering parameter for the dual element PIFA with 20 mm gap distance

Figure 10. Co-polarization and cross-polarization components of radiation pattern at 28 GHz for
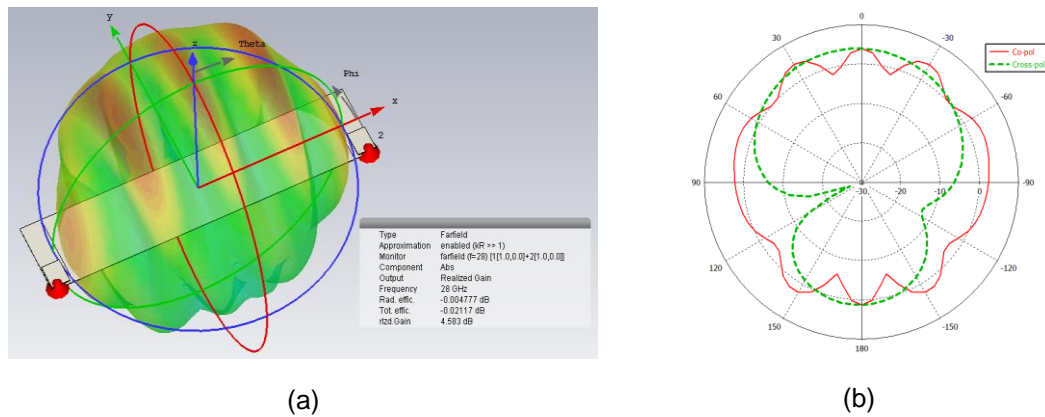(a) PIFA 1 and (b) PIFA 2

Figure 11. Far-field pattern of MIMO PIFA with both port excite
(a) 3D far-field pattern (b) co-polarization and cross-polarization

4. Conclusion

The dual element MIMO PIFA is a combination of two PIFA element. The analysis of the gap distance between the antenna element is to reduce the mutual coupling between the antenna element and improve the antenna isolation. ECC, MEC, and DG have been observed with different ground plane length which reflects the gap distance between PIFA 1 and PIFA 2. The results show that by improving the isolation of the antenna, the antenna gain and efficiency is enhanced. It has been proposed that the best antenna optimization of gap distance is 20 mm as the gain and the efficiency of the antenna start to sustain. The antenna has sufficient 3.71 GHz bandwidth at 28 GHz frequency with 6.6 dB gain and 98.8% efficiency.

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