Design and Simulation of Single and 2x2 MIMO Circularly Polarized Patch Antennas with a Pair of Chip Resistors for 5G Applications

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***Abstract*— This paper presents single microstrip antenna and MIMO structure with two equal length pairs of slits and two chip resistors as an antenna with circular polarization (CP) and broadside radiation for 5G mid-band portable devices. The two chip resistors are placed at a pre-calculated positions on a certain pair of slits to provide a slit length different from the other pair of slits in order to guarantee the presence of the CP. To obtain larger impedance bandwidth, the antenna is excited using the proximity-coupled feeding that results in simulated impedance bandwidth equal to 13.8% (3.38-3.88 GHz) with realized gain larger than 2dB along the operational band. By manipulating the antenna three-dimensional axial ratio pattern, the orientation of the CP is adjusted toward the broadside direction without defecting the antenna ground plane so that the back radiation of the proposed antenna is minimized. This process guarantees negligible undesired back radiation. The simulated 3dB axial ratio bandwidth (ARBW) in the broadside direction is equal to 4.65% (3.57-3.74 GHz). Moreover, 2x2 MIMO antenna structure, whose mutual coupling has values less than -20 dB, is also proposed in this paper to provide an antenna that is more convenient for the 5G handsets.**

Keywords—component, formatting, style, styling, insert (key words**)**

I. Introduction

The importance of the circular polarization (CP) significantly resides in its effective reduction for the polarization mismatching and the interference caused by multipath fading [1, 2]. These spectacular features have drawn the attention of many researchers toward the design of circularly polarized antenna with planar and nonplanar structures. Nowadays, CP is utilized for many wireless systems such as WLAN, WiMax, 5G applications, satellite applications [3], etc. As a result, antennas with CP are indispensable in such kinds of applications, so it is essential to propose some original structures that ensure the presence of broadside CP with reasonable bandwidth and compact size.

Many antennas are designed for multiband CP [4-6] and wideband CP [7-10] to extend the utilization of the CP to wider range of frequencies. Unfortunately, the mentioned designs have a noticeable back radiation that is not contributed in the CP communication. Consequently, many researchers have proposed single element and MIMO CP antennas with minimized back radiation to avoid the undesired back radiation. A patch antenna that is excited by a microstrip feed line [10] is designed for narrow band CP applications with major lobe to back lobe level (main/back) ratio equal to 4dB. The improvement of (main/back) ratio is enhanced in [11] to 30dB but with 3dB axial ratio bandwidth (ARBW) less than 1.5%. In [12], the proposed structure also has an enhanced (main/back) ratio but with narrow 3dB ARBW equal to 2.14%. The 3dB ARBW is improved to 7% with 10dB (main/back) ratio with the aid of non-planar and complicated designs of dielectric resonator antennas (DRA) [13, 14]. An ARBW equal to 3% with 16dB (main/back) ratio is obtained in [15] using large dimensional leaky-wave antenna. The ARBW improved to 6% in [16] using coaxial feeding, but the (main/back) ratio is heavily reduced to 3dB. The aforesaid works either improve the ARBW with toleration in (main/back) ratio or enhance the (main/back) ratio with reduced ARBW. However, a balance between the two is attained in [17] by a patch antenna with a proximity-coupled feeding and a patch with two pairs of unequal slits such that the ARBW is enhanced to 4.1% with (main/back) ratio equal to 20dB.

A microstrip antenna with CP and two equal-length pairs of slits and two chip resistors is presented in this work for mid-band 5G communication. The impedance bandwidth (BW) of the antenna is improved by using the proximity-coupled feed line. Furthermore, to reduce the unintended back radiation, the proposed patch antenna is analyzed using the 3D axial ratio pattern in such a way that the broadside CP is generated while keeping the antenna patch is entirely covered by the ground plane. The resulted antenna has an impedance BW and ARBW wider than those obtained in [17] with the same amount of (main/back) ratio. In addition, a 2x2 MIMO antenna with minimized mutual coupling is presented in this paper to be more suitable for the 5G handsets. The simulation results show a reasonable impedance BW and ARBW with a broadside power pattern and subtle back radiation.

II. Antenna Design

Figure 1 illustrates the overall dimensions of the proposed single-element antenna. It is important to notice that the ground plane covers the entire structure of the proposed antenna. In addition, the antenna has a double-layer structure and fed by a proximity-coupled feed line to improve the microstrip antenna bandwidth [2]. Figure 1(a) illustrates the top view of the proposed antenna which holds two equal length pairs of slits. Two of them is loaded by 1Ω chip resistors at distance (dr) from the shorted terminal of the slit. The presence of these chip resistors provides difference in length between the two pairs of slits because the resistor creates shorter current path through the slit. The difference in length results in a slightly separated resonant frequencies that produces circular polarization (CP) according to the criterion of generating CP in the single feed antennas [1]. The width of the slits (Ws) plays an important role in controlling the 3dB axial ration bandwidth (ARBW) and the orientation of the CP. The dimensions and the structure of the 50Ω proximity-coupled feed line is shown in Figure 1(b). The proximity-coupled feed line is placed on the second layer of the antenna. Figure 1(c) shows the antenna side view which consists of two $1.6mm$ thick FR4 dielectric substrates with dielectric constant of $(\varepsilon_r = 4.3)$ and loss tangent of 0.025.

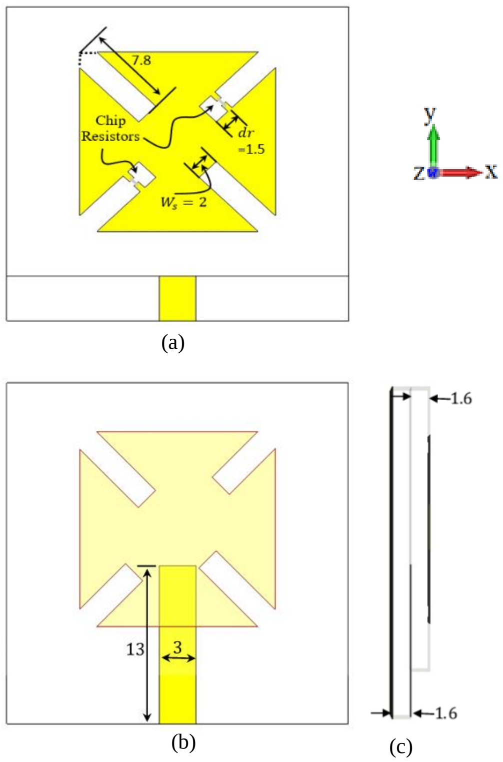


Figure 1: The structure of the broadband CP antenna with chip resistors with its optimized parameter values (a) top view, (b) the feed line structure, and (c) the side view. (All dimensions are in mm).

III. Broadside CP Generation Mechanism

In the beginning, it is important to notify that the simulation results of this design are acquired using CST Microwave Studio Simulation Suite.

The methodology of creating CP in single feed antennas can be summarized by: generating two current components passing through two perpendicular paths with slight difference in lengths to provide two slightly separated resonant frequencies [1]]. Meanwhile, the slits that are engraved on the antenna patch minimizes the antenna dimensions noticeably because they electrically elongate the current path [1]. This basic criterion was applied using narrow slots or slits and coaxial feeding that produced a very narrow ARBW in the broadside [1]. This concept is utilized as a first step in designing the proposed antenna then the ARBW and CP orientation is improved by using the proximity-coupled feeding, inserting the chip resistors, and controlling the slit width.

The reflection coefficient and the broadside axial ration (AR) as a function of frequency for the antenna with chip resistors at different values of (dr) are exhibited in Figure 2(a) and (b), respectively. As expected, increasing the value of (dr) directly affecting the separation between the two resonant frequencies of the antenna. The optimum value of (dr) is found to be equal to 1.5mm. This means that this value suitably separates the two resonant frequencies, so the surface current of the antenna is separated into two components passing through perpendicular paths with about 90o phase shift. At the optimum value of (dr) the CP bandwidth is equal to 4.65% extended along the frequency range (3.57-3.74 GHz). The improvement in the bandwidth comes from the effect of the proximity-coupled feeding and the chip resistors since they reduce the quality factor of the antenna, and the resulted impedance BW is 13.8% extended along the range (3.38-3.88 GHz)

As discussed in [17], it is not an easy task to attain a broadside CP in antennas with microstrip or the proximity-coupled excitation. However, it is noticed that antennas with these kinds of feeding structures can result in CP but at directions other than the broadside. Consequently, the key parameter that can justify the CP toward the antenna broadside direction should be found, and in this work it is found to be the slit width (Ws).

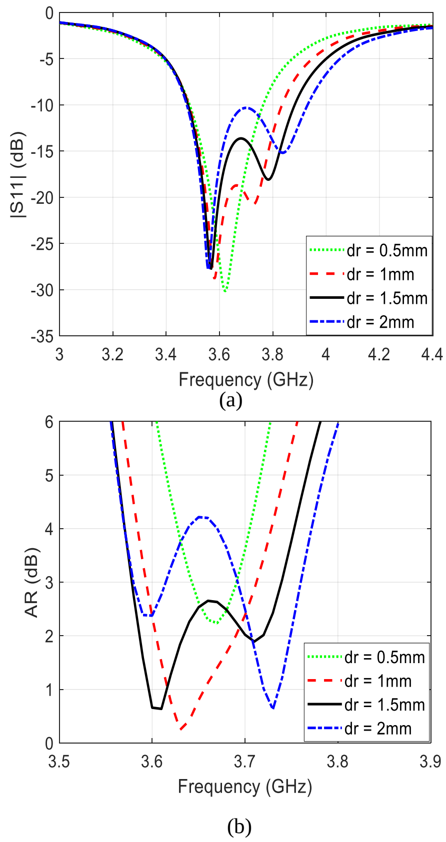
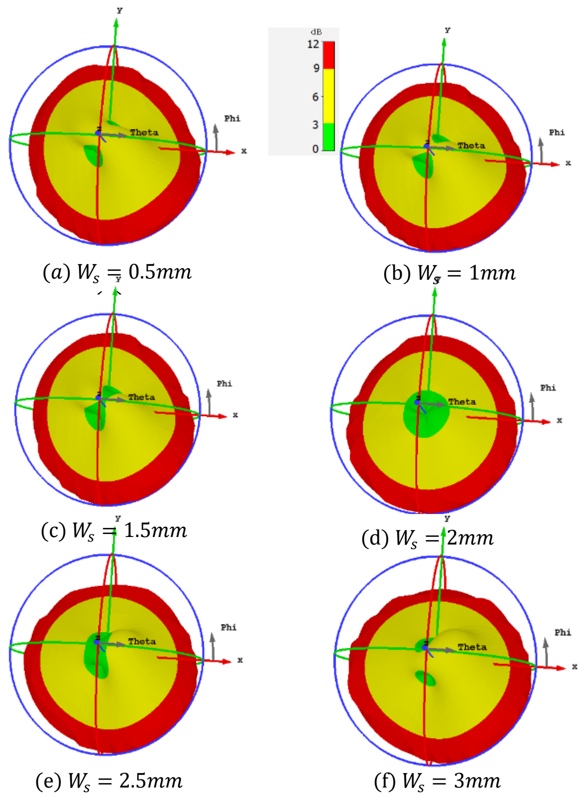


Figure 2: (a) Reflection coefficient and (b) broadside AR of the antenna with chip resistors at different values of dr.

The 3D AR pattern of the antenna with chip resistors at 3.6 GHz and different values of slit width is illustrated in Figure 3. In Figure 3(a), the broadside 3dB CP coverage is completely absent. However, a slit width equal to 1 mm results in two 3dB circularly polarized regions, which are shown as green spots in the 3D AR pattern, start to show up as illustrated in Figure 3(b). when the slit width increases to 1.5 mm 3dB circularly polarized regions comes closer to each other within the broadside direction as shown in Figure 3(c). For slit width equal to 2 mm, Figure 3(d) shows that the two circularly polarized regions are entirely overlapped in the broadside direction of the antenna patch. The reason of this overlapping resides in the fact that increasing the slit width forces the antenna surface current to be within central part of the patch of the proposed antenna. Consequently, the current rotation is concentrated in the central part of the antenna patch which causes a CP in the broadside direction.



(a) $W_s = 0.5mm$ (b) $W_s = 1mm$

(c) $W_s = 1.5mm$ (d) $W_s = 2mm$

(e) $W_s = 2.5mm$ (f) $W_s = 3mm$

Figure 3. The axial ratio pattern of the antenna with chip resistors for various values of slit width at 3.6 GHz.

Although the slit width has a negligible influence on the position of the resonant frequency (since it has no effect on enlarging the current path), additional increment in the slit width above 2 mm leads to a sensible frequency shifting. This results in deteriorating the separation of the resulted resonant frequencies, and the CP condition can be broken. This idea verified in Figure 3(e) and Figure 3(f), which show how the two 3dB CP regions detach from each other. Figure 4 exhibits the antenna reflection coefficient and the broadside AR as a function of frequency which reveals impedance BW equal to 13.8% and 3dB ARBW equal to 4.65% in case of slit width equal to 2 mm.

Finally, At $dr = 1.5mm$, $W_s = 2mm$, and $f = 3.6\,GHz$, the current distribution on the antenna patch at different time instants is shown in Figure 5. As expected, the current rotation is at the central part of the radiating patch, and the rotation is in the clockwise direction to form a LHCP. It is worth mentioning that the RHCP can be achieved by changing the position of the chip resistors to the other pair of slits.

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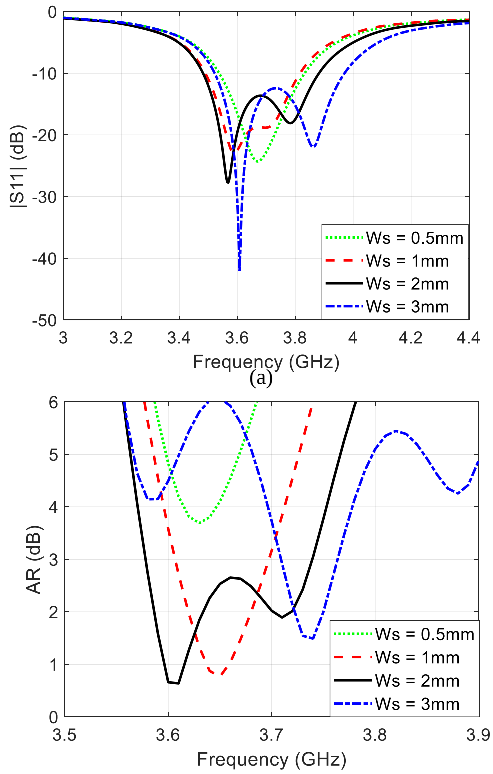
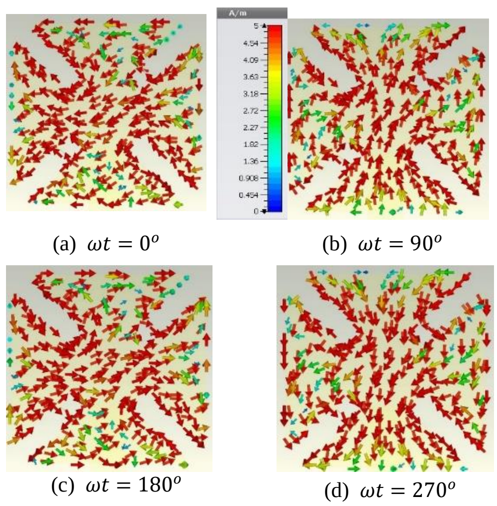


(a)

(b)

Figure 4: (a) Reflection coefficient and (b) broadside AR of the antenna with chip resistors at $dr = 1.5mm$ and different values of W_s.



(a) $\omega t = 0^o$ (b) $\omega t = 90^o$

(c) $\omega t = 180^o$ (d) $\omega t = 270^o$

Figure 5: The current distribution on the radiating patch of the antenna with chip resistors for different time instants at $f = 3.6GHz$.

IV. SIMULATION RESULTS

This section presents the simulation results of the proposed single element antenna and the 2x2 MIMO antenna structures.

A. Simulation results of single antenna

Figure 6(a) and (b) reveal the resulted reflection coefficient and the broadside axial, respectively, of the proposed single-element antenna. The results show that the -10dB BW of the proposed antenna is 13.8% along the frequency range (3.38-3.88 GHz), whereas the 3dB ARBW is 4.65% with the frequency span (3.57-3.74 GHz). The simulated realized gain of the proposed single element antenna as a function of frequency is shown in Figure 7. It is clear that the gain value is larger than 2dB along the entire operational band, which is very reasonable for 5G mid-band applications.

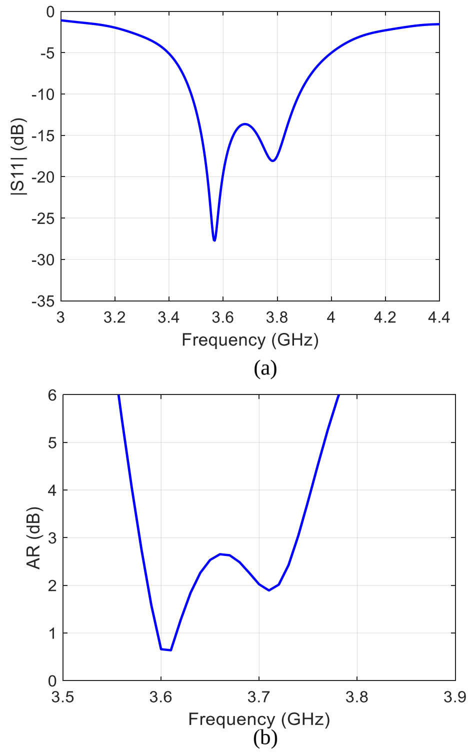


Figure 6: Simulated (a) Reflection coefficient and (b) broadside AR of the antenna with chip resistors.

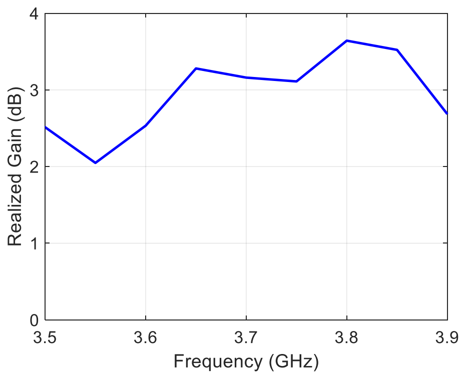


Figure 7: Simulated realized gain of the antenna with chip resistors as a function of frequency.

The absolute power patterns at $3.6GHz$ and $3.7GHz$ in the E-plane and H-plane directions are illustrated in Figure 8. The resulted pattern is directed toward the broadside direction of the antenna with trivial amount of back radiation. Consequently, the antenna with this design is convenient for 5G mid-band handsets with major lobe to back lobe ratio equal to 20dB.

B. Simulation Results of the MIMO Antenna

This paper utilizes the proposed single-element structure in designing the 2x2 MIMO structure shown in Figure 9. The dielectric substrate of the proposed MIMO structure is FR4 dielectric whose dimensions are equal the standard

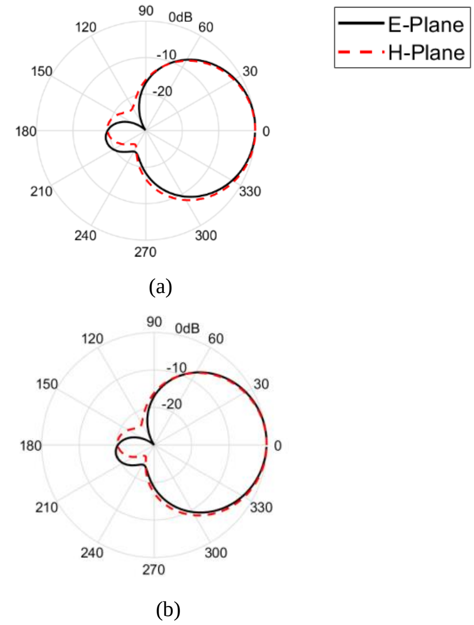


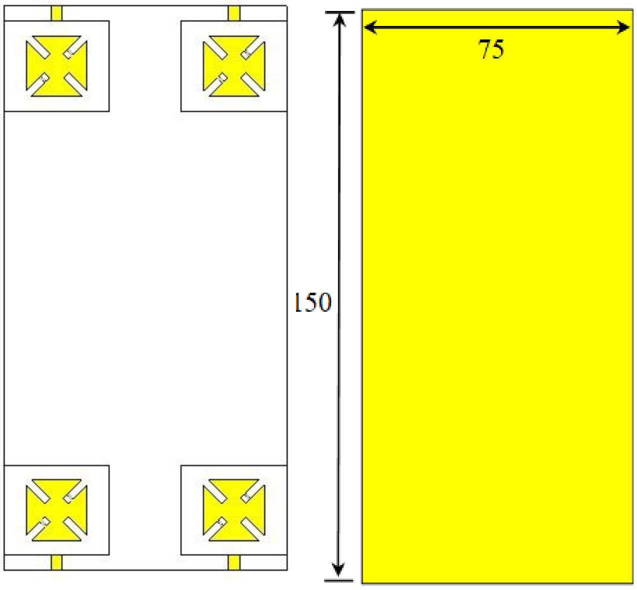
Figure 8: The power pattern of the antenna with chip resistors at (a) 3.6GHz and (b) 3.7GHz.

dimensions of the cellphones (150×75 mm). The elements of the MIMO antenna are placed at the corners of the dielectric substrate. Figure 9(a) exhibits the top view of the MIMO antenna system whose elements are with chip resistors, while Figure 9(b) shows the back view of the MIMO antenna system which includes a ground plane that covers the entire MIMO structure.

The mutual coupling between the four elements can easily be quantified by the transmission coefficients the MIMO antenna. Although, the forward and the backward transmission coefficients are important to be evaluated in non-symmetrical MIMO structures [18, 19], the forward transmission coefficient is enough in quantifying the mutual coupling the symmetrical MIMO structures. Figure 10(a) shows the simulated s-parameters of the proposed MIMO antenna. Since the proposed structure has |S21| less than -20dB, the antenna element isolation can be considered perfect such that there is no need to add an isolation elements between them. The Envelop Correlation Coefficient (ECC) between any two antenna elements (e.g. 1 and 2) is given by [20]:

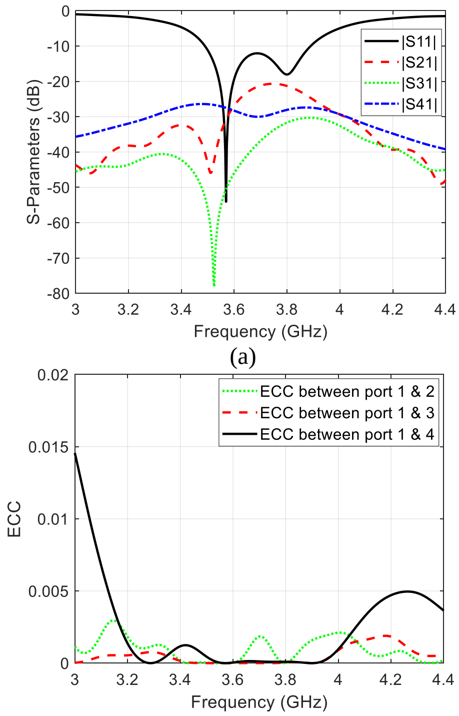
$$ECC = \frac{|S_{11}{}^{*}S_{12} + S_{22}S_{21}{}^{*}|^2}{(1-(|S_{11}|^2+|S_{21}|^2))(1-(|S_{22}|^2+|S_{12}|^2))} \quad (1)$$

Figure 10(b) illustrates the simulated ECC between every two elements of the proposed MIMO antenna. Generally, the value of the resulted ECC between any two antennas is less than 0.02, and this supports the idea of the perfect isolation between the elements.



(a) (b)

Figure 9: The proposed MIMO structure (a) top view and (b) the back view. (All dimensions are in mm).



(b)

Figure 10: (a)Simulated s-parameters and (b) the *ECC* of the proposed MIMO antenna systems.

For comparison purposes, a comparison between the proposed antenna and other some important papers in term of the BW, ARBW, and (main/back) ratio is given in Table 1. The proposed antenna has noticeable balance between the coverage of the ARBW and the level of the back radiation.

TABLE I. COMPARISON BETWEEN THE PROPOSED ANTENNA WITH OTHER DESIGNS.

Ref.	**Impedance BW %**	**ARBW %**	**(main/back) ratio %**
[10]	13.8 %	4.5 %	-4 dB
[11]	7 %	1.5 %	-30 dB
[12]	4.2 %	2.14 %	-20 dB
[14]	11.1 %	3 %	-16 dB
[16]	10.5 %	6 %	-3 dB
[17]	10.9 %	4.12 %	-20 dB
Proposed	13.8 %	4.65 %	-20 dB

V. CONCLUSION

A patch antenna with two pairs of equal length slits attached by two chip resistors for 5G mid-band applications with CP has been designed in this work. The proposed single element antenna is excited using proximity-coupled feed line to improve the impedance band width. With the aid of the 3D axial ratio pattern, the CP is adjusted in the broadside direction of the antenna while keeping the ground plane undistorted to obtain a negligible amount of back radiation. The simulated BW of the proposed structure is equal to 13.8% along the range (3.38-3.88 GHz), whereas the simulated ARBW is equal to 4.65% over the range (3.57-3.74 GHz. The (main/back) ratio of the antenna approaches to be 20 dB, which is considered as an evident for the weak back radiation. A 2x2 MIMO structure has also been presented in this paper, and it is found that the mutual coupling between the antennas is less than -20dB with ECC less than 0.02.

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