Periodically-Stub-Loaded Microstrip Line
Wideband Circularly Polarized Millimeter
Wave MIMO Antenna

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ABSTRACT This paper presents a wideband eight-port multiple-input-multiple-output (MIMO) circularly polarized antenna system for mm-wave applications. The proposed antenna element is an L-shape microstrip line with a series fishtail stubs on one side. The spacing between these stubs is adjusted to be a guided wavelength at the center frequency. These fishtail stubs are used to cancel the anti-phase magnetic currents to enhance the radiated fields from the microstrip line. A 90° phase difference between the fields of the two arms of the L-shape is obtained by shifting the feeding point from the center of the corner by one eighth guided wavelength. This 90° phase difference introduces the required circular polarization. The proposed antenna covers the frequency range from 27.5 up to 31 GHz, which is suitable for mm-wave N261 5G-band which cover the range from 27.5 to 28.35 GHz. These antenna elements are arranged on the four corners of a rectangular substrate to configure the proposed MIMO antenna system. Different parameters of this MIMO antenna are investigated by using numerical simulation and verified by experimental results.

INDEX TERMS Circular polarization, MIMO antenna, stub-loaded microstrip line.

I. INTRODUCTION
Planar microstrip antennas represent good candidates for many wireless communication systems due to their light weight, conformal structure and low cost. Microstrip antennas have many configurations and different feeding mechanisms. Microstrip line represents the simplest configuration of microstrip structures [1]. However, a microstrip line is a waveguiding structure, which is not directly suitable to be used as a radiating structure. The radiation mechanism of microstrip configurations can be mainly explained due to the fringing electric fields on the edges of the microstrip structure. These fringing electric fields are equivalent to magnetic currents parallel to the edges of the microstrip structure. For the case of a simple microstrip line, the equivalent magnetic currents on the two sides of the microstrip line are anti phase as shown in Fig. 1-a. Thus, the radiated fields from the two sides cancel each other. This property is useful when the microstrip line is used as a guiding structure to reduce the radiation losses and also to reduce the cross-talk between nearby microstrip lines. However, the microstrip line should be modified if it is required to be used as a radiating structure.

This can be done by extracting half of the magnetic currents in each half-wave alternately, as shown in Fig. 1(b). Thus, the total remaining magnetic currents would add in-phase. Physically, this can be obtained by introducing periodic short circuits on one side of the microstrip line as shown in Fig. 1-b. Thus, the remaining in-phase magnetic currents would introduce effective radiation. Physical short circuits would require introducing via holes in the substrate of the microstrip line. These via holes introduce manufacturing complexity of the microstrip structure. Equivalent short circuits can be obtained by using planar tapered stubs. This structure can be used to introduce a simple planar radiating structure based on simple microstrip line configuration. In addition, by shaping this microstrip line it would be possible to control the obtained polarization. A similar approach was used to design a traveling wave antenna in [2]. This antenna consists of ten cascaded half-width microstrip patches. This microstrip line-based antenna has an additional advantage that it can be directly fed by a simple probe feeding as shown in Fig. 1-b.

This simple configuration can be directly used to introduce linearly polarized (LP) antennas. Linearly polarized antennas are commonly used in different wireless communication systems. However, circularly polarized (CP) antennas have the advantage of being suitable for arbitrary orientation and the...
ability of multipath propagation. This is the reason that most satellite systems, wireless communication systems, RFID tags, sensors, and tracking devices use circular polarization.

On the other hand, spatial diversity has a significant importance in modern wireless communication systems [3]. Multiple-input–multiple-output (MIMO) antenna technology uses multiple antennas at transceiver ends to send and receive signals to get the advantage of multipath signal propagation. Compared to single antenna systems, the MIMO arrangement offers higher spectral efficiency, higher capacity, and more efficient communication between the transmitting and receiving terminals [4]. In addition, polarization/pattern diversity techniques can be used to minimize far-field correlation without increasing antenna size [5], [6]. Various CP MIMO antenna configurations for wireless local area network (WLAN), C-band, and satellite applications are proposed [7], [8]. For WLAN applications, a dual-port antenna with two resonating elements was proposed in [9]. In this case, a square patch with truncated corners introduces the required CP. The other part at the bottom is an interdigital radiator, which introduces a linear polarization (LP). A triple-port MIMO antenna comprised of two LP dipoles and one CP chamfered-edge square patch antenna was proposed for WLAN systems [10]. In [11], inverted-L strips were used in the ground plane to achieve a wide axial ratio bandwidth (ARBW). 5G Fabry-Perot CP MIMO antennas presented in [12] and [13] provide high gain and good isolation. However, they have complicated designs and mechanical issues due to the air gap between superstrate and radiator. A dual-band CP MIMO antenna with twelve ports for the 5G base stations is proposed in [14]. The antenna system provides both LP and CP radiations based on end-user requirements and the single-element antenna has a gain of 8 dBi with an AR bandwidth of only 3% (27.5 – 28.5 GHz).

In this paper, a novel method for designing a wideband CP MIMO mm-wave antenna is presented in the frequency range from 27.5 to 31 GHz for 5G applications. This antenna is suitable for mm-wave N261 5G-band which cover the range from 27.5 to 28.35 GHz. The proposed antenna is composed of a microstrip line loaded with fishtail stubs. These stubs are located periodically on one edge of the microstrip line to improve the radiation from the microstrip line. The antenna is simply fed by a coaxial probe, without the need of using complicated feeding networks. The microstrip line has an L shape and the feeding network is shifted from the corner to introduce the required circular polarization. Then, a MIMO antenna is designed based on this antenna element.

The paper is organized as follows: In Sec. II, the analysis and design of a CP periodically stub-loaded microstrip antenna is presented. In Sec. III, the designed antenna is used to construct a MIMO Antenna configuration. The MIMO performances are studied in section IV. Finally, the conclusion is presented in section V.

II. ANALYSIS AND DESIGN OF A CP PERIODICALLY Stub LOADED MICROSTRIP ANTENNA

The basic principle of the proposed antenna can be summarized into two main points. The first point is how to convert the microstrip line from a guiding structure to a radiating structure with a simple feeding configuration. The second point is how to convert this modified microstrip line structure to radiate a circular polarization.

For conventional microstrip line, the fringing electric fields from the two edges are equivalent to two opposite magnetic current sources as shown in Fig. 1-a. The net far-field radiation is due to the combination from the two opposite magnetic current sources cancel each other. In addition, this magnetic current source on each edge is alternating each half-guided wavelength. Thus, if it is possible to compensate the magnetic current source in one half guided wavelength along one edge and to compensate the magnetic current source on the other edge in the following guided wavelength, the resulting magnetic current sources would be in one direction as shown in Fig. 1-b. In this case, the radiated fields due to these equivalent magnetic current sources would add together to introduce a radiating structure. This can be obtained by adding periodic short circuits on one edge of the microstrip line. These short circuits can be implemented without the need to vias by using wide-open circuit stubs on one edge of the microstrip line as shown in Fig. 2 [15]. The periodic spacing between these periodic stubs should be one guided wavelength. By adjusting the size and the shape of these stubs, it would be possible to decrease the magnitude of the equivalent magnetic current source at the position of the stub. Thus, the total magnetic current sources would have

![Feed Point](image)
a net value in one direction. An appropriate shape for this stub is the radial bowtie shape which can be used to obtain localized zero-point impedance [16]. In this paper, a fishtail shape stub, which represents a modified bowtie shape, is used to introduce the required effective short circuits. This simple antenna configuration can be fed directly by using a vertical probe feeding as shown in Fig. 2. This simple configuration in Fig. 2 is quite useful to convert a simple microstrip line to a radiating structure with linearly polarized radiation.

The second point in the proposed design is how to convert this periodically stub-loaded microstrip line to a circularly polarized antenna. To do this, the stub-loaded microstrip line is bent in L-shape as shown in Fig. 3 such that the horizontal and longitudinal arms have the same length. Thus, these two arms radiate equal orthogonal field components. By adjusting the phase shift between these two orthogonal components to be ±90° it would be possible to generate RH/LH circular polarization. This phase shift can be obtained by moving the feeding point from the center of the stub loaded microstrip line by a distance \( \frac{\lambda}{8} \) as shown in Fig. 3.

The proposed antenna is designed on a Roger substrate with a substrate thickness of \( h = 0.787 \text{ mm} \) and a relative permittivity of \( \varepsilon_r = 2.2 \) with dimensions \( L \times W = 25 \times 25 \text{ mm}^2 \). The antenna configuration includes four identical radiating stubs, distributed on two arms of L-shaped transmission line.

The microstrip line length is \( L_1 = 15 \), \( w_3 = 5 \text{ mm} \) and width \( w_m = 2.1 \text{ mm} \). The dimensions of the fishtail stub are \( w_1 = 3.8 \text{ mm} \), \( w_2 = 2.8 \text{ mm} \), \( h_1 = 0.5 \text{ mm} \) and \( h_2 = 0.4 \text{ mm} \), the radius of coaxial feed is \( R = 0.4 \text{ mm} \).

Figure 4 shows the resulting current distribution along this L-shaped stub-loaded microstrip line fed by a coaxial probe at 30 GHz. It is very clear that the current on the horizontal arm almost perpendicular to the current on the vertical arm which causes the circular polarization. The resulting input reflection coefficient of the microstrip line antenna with and without the fishtail stubs is shown in Fig. 5. It can be noted that the microstrip line without the fishtail has much less radiated power. Thus, the incident power is mainly reflected as it is noted from the corresponding reflection coefficient. On the other hand, the stub loaded line has less reflection in the operating frequency band. The radiation pattern of this antenna with fishtail stubs is shown in Fig. 6 at 30 GHz. It can be noted that the radiation pattern has a dominant LH circular polarization at the broadside direction. The polarization purity of the proposed antenna is slightly low, this may be attributed to the coupling between the two arms of the proposed L shape structure. Thus, pure 90 degrees’ phase shift cannot be completely satisfied even with the displacement of the feeding point. The axial ratio of this antenna is shown in Fig. 7.

This antenna is fabricated and measured as shown in Fig. 8. The measured results for the reflection coefficient is shown in Fig. 9. It can be noted that the measured result agrees with the simulation result. This combination of two elements is the basic element for the MIMO antenna structure discussed in the following section.

### III. CIRCULARLY POLARIZED 5G MIMO ANTENNA BASED ON STUB LOADED MICROSTRIP ANTENNA

In the proposed CP-MIMO antenna, the series fed antenna elements are incorporated at the corners of a rectangular substrate with total dimensions of \( 135 \times 75 \text{ mm}^2 \) as shown in Figure 10. The proposed CP series fed MIMO antenna is properly fabricated on a \( 0.787 \text{ mm} \) Roger 5880 substrate, and its S-parameters are measured using Vector Network Analyzer (VNA) ZVA 67.
Figure 11 shows the simulated and measured reflection coefficients of the proposed antenna at the eight ports. It shows that the antenna has a $-10$ dB reflection band of 27.5–31 GHz. Figure 12 compares the CP series fed antenna’s simulated and measured isolation coefficient. It can be noted that the measured isolation between two feeding ports is better than $-20$ dB at the operating band. Both simulated and fabricated designs cover the N261 5G-band of 27.5–28.35 GHz. In addition, as shown in Fig. 13, the antenna has a large C feature that supports the entire antenna operation band. Figure 14 shows the simulated and measured radiation patterns of antennas in the E-plane ($\phi = 90$°) and the H-plane ($\phi = 0$°) at the resonance frequency of 28 GHz. The measured gain of the antenna is shown in Figure 15. The antenna achieves a maximum gain of 10 dBi at 28GHz and a minimum gain of 9 dBi at 31GHz. It should be noted that these radiation patterns of the MIMO antenna are performed with feeding a single antenna element while the remaining antenna elements are terminated with matched loads. This procedure represents the actual performance of MIMO system where the received/transmitted signals are treated for each element separately in the presence of the coupling with the remaining elements.

IV. ANALYSIS OF THE OBTAINED MIMO PERFORMANCE

To validate the efficiency of the designed MIMO antenna for diversity applications, the envelope correlation coefficient (ECC) and diversity gain (DG) are investigated. These parameters are used to determine how different radio
frequency (RF) signal propagation paths affect the signal’s ability to reach the receiving antenna. In other words, the higher the diversity benefit, the lower the correlation factor. The MIMO antenna’s ECC value should be less than 0.1. The lowest correlation corresponds to the better MIMO performance. The ECC in far-field for a multi-antenna model is expressed as [17]:

\[
\rho_e = \frac{\int \int \left| \frac{\vec{E}_1(\theta, \varphi)}{\Omega} \cdot \vec{E}_2(\theta, \varphi) \right|^2 d\Omega}{\int \int \left| \vec{E}_1(\theta, \varphi) \right|^2 d\Omega \cdot \int \int \left| \vec{E}_2(\theta, \varphi) \right|^2 d\Omega}
\]
where \( \Omega, \phi, \) and \( \theta \) are the solid, azimuthal, and elevation angles, respectively, and \( E \) is the far-field radiation pattern. The ECC can be calculated in terms of the S-parameters of the antenna elements as follows:

\[
ECC = \frac{|s_{11}^* s_{12} + s_{21}^* s_{22}|^2}{(1 - |s_{11}|^2)(1 - |s_{22}|^2)}
\]  

(2)

Although this calculation is simple, it is not as accurate as far field calculation. Figure 16 shows the ECC based on the far field of the designed MIMO antenna which is obtained in the previous section. It can be noted that the peaks of ECC are less than 0.015. These results indicate that the proposed design has an excellent ECC performance.

Another important parameter of MIMO antenna is the diversity gain (DG). The required value of the DG for the MIMO system should be around 10dB. The DG is a function of ECC and can be expressed as [17]:

\[
DG = 10 \sqrt{1 - ECC^2}
\]  

(3)

Figure 17 illustrates the DG to be approximately varied from 0.999 to 10 within the required band, which ensures good diversity performance of the proposed antenna.

For a MIMO antenna system, the total active reflection coefficient (TARC) is defined as the square of the ratio of total reflected power to total incident power as follows:

\[
\Gamma_{e} = \sqrt{\sum_{i=1}^{N} |b_i|^2}, \quad [b] = [S][a]
\]  

(4)

The incident and reflected signals are denoted by \( a_i \) and \( b_r \), respectively. The scattering matrix, excitation vector, and scattered vector of the antenna are represented by \([S],[a]\), and \([b]\), respectively.

The TARC curves are shown in Figure 18. When port #1 is fed by a source \( 1e^{j\theta} \) and the other ports have the same amplitude but with different phases. The operating BW of the proposed antenna is slightly influenced by the different excitation phases of the other ports. On the other hand, the channel capacity loss (CCL) is calculated as follows:

\[
CCL = -\log_2 \det (\psi^R)
\]  

(5)

where \( \psi^R \) is the correlation matrix which can be calculated as follows,

\[
\psi^R = \begin{bmatrix}
p_{11} & p_{12} & p_{13} & p_{14} 
p_{21} & p_{22} & p_{23} & p_{24} 
p_{31} & p_{32} & p_{33} & p_{34} 
p_{41} & p_{42} & p_{43} & p_{44}
\end{bmatrix}
\]  

(6)

The elements of the correlation matrix are calculated in terms of the S-parameters of the MIMO antenna as follows:

\[
\rho_{mm} = 1 - \left| \sum_{n=1}^{4} S_{mn}^* S_{mn} \right|,
\]

\[
\rho_{mp} = 1 - \left| \sum_{n=1}^{4} S_{mn}^* S_{np} \right|
\]  

for \( m, p = 1, 2, 3 \) or 4  

(7)

Figure 19 shows the calculated CCL for the proposed MIMO. It can be noted that the calculated CCL is less than 0.4 bits/s/Hz which ensures that the system work properly [18].

Table 1 presents a comparison between the obtained results for the proposed MIMO antenna and previously published ones. It should be noted that most of the previously published MIMO antennas in the 5G mmWave band are linearly polarized except in [12], [14], and [19]. These CP antennas have
TABLE 1. Comparison between the present MIMO antenna and previously published ones.

| Ref  | Antenna Type          | Freq (GHz) | -10 dB $|S_11|$ BW(%) | 3dB AR BW(%) | Max. gain (dB) | No. of ports | LP/CP |
|------|----------------------|------------|-------------|--------------|---------------|---------------|-------------|-------|
| [12] | Fabry-pecor          | 30         | 5           | 5            | 8             | 4             | CP          |
| [14] | Vivaldi              | 28/38      | 6           | 3            | 8             | 12            | CP          |
| [19] | Dipole               | 28         | 7.14        | -            | 6.1           | 4             | LP          |
| [20] | Patch                | 31         | 39          | -            | 10.6          | 4             | LP          |
| [21] | Series slot Fed antenna | 28     | 13.19       | 8.2          | 11.86         | 4             | CP          |
| [22] | Patch                | 25.2       | 15.6        | -            | 8.7           | 8             | LP          |

FIGURE 19. Channel capacity loss of the proposed MIMO antenna.

V. CONCLUSION

A stub-loaded microstrip line fed by a via probe is investigated as an antenna element. This periodic stub loading extracts half the equivalent magnetic current on the side of the stubs. Thus, the remaining equivalent magnetic current on both sides would add in phase to introduce radiating fields. By bending this configuration in L-shape and adjusting the location of the feeding point from the corner of this L-shape, it is possible to convert this stub-loaded microstrip line to a circularly polarized antenna. By using this configuration, a design of a CP antenna operating in the frequency range from 27 to 31 GHz is investigated. The input reflection coefficient of the designed antenna is less than $-10$ dB and the corresponding axial ratio is less than 3dB in the required operating frequency band. This antenna element is arranged on the corners of a rectangular substrate to introduce a MIMO antenna composed of eight antenna elements. The proposed antenna is designed to be operating in the frequency range from 27.5 to 31 GHz for mm-wave N261 5G applications. The MIMO parameters including ECC, DG, CLL, TARC are investigated for this configuration.

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**S. M. El-Nady, A. M. Attiya: Periodically-Stub-Loaded Microstrip Line Wideband CP Millimeter Wave MIMO Antenna**

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