Wideband Three-Port Equilateral Triangular Patch Antenna Generating Three Uncorrelated Waves for 5G MIMO Access Points

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ABSTRACT A wideband three-port equilateral triangular (ET) patch antenna capable of generating three uncorrelated broadside-radiation waves for 5G MIMO access-point application is presented. The three-port ET patch antenna has a simple structure for easy implementation. To our best knowledge, using a simple ET patch antenna to generate three uncorrelated waves for MIMO application is reported for the first time. The ET patch is mounted 11.5 mm above the ground plane and has three L-strip capacitive feeds placed below the patch’s three triangular tips. Three isolated fundamental TM$_{10}$ modes polarized in three different directions can be excited to generate three uncorrelated waves at the same time. With a patch length of only 38 mm (0.48 $\lambda$ at 3.75 GHz), the three-port ET patch antenna covers 3.3-4.2 GHz (5G N77 band) with impedance matching $<-10$ dB and port isolation $>15$ dB. Details of the three-port ET patch antenna are presented.

INDEX TERMS Three-port single-patch antennas, equilateral triangular patch antennas, MIMO antennas, 5G antennas, MIMO access-point antennas.

I. INTRODUCTION
The wideband three-port patch antenna capable of generating three uncorrelated broadside-radiation waves has recently been reported for 5G mobile communication applications [1]–[3]. Such wideband three-port antennas are applicable as a building unit to achieve compact multi-input multi-output (MIMO) antenna arrays for outdoor base stations [1], [2] or indoor access points [3]. To achieve wideband operation in [1], two superimposed Y-shaped structures of different frequencies are used to obtain a fractional bandwidth of about 20%. Additionally, the antenna structure in [1], [2] is an all-metal structure with no substrate materials used, which is an advantage for practical applications to avoid substrate issues, such as the substrate’s ohmic losses and tolerance. In [3], the wideband circular patch antenna with three probe feeds spaced by 120° can generate three isolated TM$_{11}$ modes [4] to cover 3.3-4.2 GHz (5G N77 band) [5].

Note that, different from generating three uncorrelated broadside-radiation waves in [1]–[3], there are also three-port single-patch antennas reported to obtain three uncorrelated waves, such as generating three uncorrelated monopolar-like waves [6] or exciting two broadside-radiation waves plus one monopole-like wave [7]–[11] or achieving three directional quasi-Yagi waves with pattern diversity [12]. Most of the reported three-port patch antennas [3], [6]–[12] include using substrate materials in implementing the antennas. With an all-metal structure to avoid the substrate issues as shown in [1], [2], the multi-port patch antenna will be more attractive for practical MIMO antenna applications.

In this study, we present a wideband three-port equilateral triangular (ET) patch antenna to generate three uncorrelated broadside-radiation waves over a wide band of 3.3-4.2 GHz for 5G MIMO access-point application. The proposed antenna uses a simple ET patch and three L-strip capacitive feeds spaced by 120° below the patch to generate three isolated fundamental modes (TM$_{10}$ modes [13]). Three broadside-radiation waves polarized in three different directions can be generated in the proposed antenna.

In addition, very low envelope correlation coefficients (ECC $<0.01$) between the three generated waves are obtained in the desired wide band. Also, except that the ET patch is supported by a plastic post above the ground plane,
the proposed antenna is with an all-metal antenna structure to avoid the substrate issues [1], [2].

It is also noted that there have been many ET patch antennas reported in the open literature, to name a few in [13]–[19]. Very few of the reported ET patch antennas are for MIMO operation. In [19], the use of three separate ET patch antennas to generate three broadside-radiation waves for MIMO operation has been studied. However, since three separate ET patches are used, the total size of the three-port MIMO antenna is greatly increased [19]. It is to our best knowledge that using a simple ET patch antenna to generate three uncorrelated waves for MIMO application is reported in this work for the first time.

Additionally, by covering 3.3-4.2 GHz for 5G wideband MIMO application, the ET patch in the proposed antenna requires a patch length of only 38 mm (0.48λ at 3.75 GHz), similar to the conventional half-wavelength ET patch antenna operated in the fundamental TM$_{10}$ mode [13]. That is, with three uncorrelated waves obtained at the same time, the proposed three-port ET patch antenna has a similar size as the conventional ET patch antenna. Details of the three-port ET patch antenna are presented.

II. THREE-PORT EQUILATERAL TRIANGULAR PATCH ANTENNA

Fig. 1 shows the proposed wideband three-port ET patch antenna for 5G MIMO access-point application. To cover the wide band of 3.3-4.2 GHz (5G N77 band), the ET patch with a length of 38 mm (0.48λ at 3.75 GHz) is mounted 11.5 mm above the ground plane. That is, the antenna has an air substrate of thickness 11.5 mm. Three capacitive L-strip feeds (Ports 1-3) are placed 3.3 mm below the three tips of the ET patch and all face toward the patch center. Through the 3.3 mm coupling gap, each L-strip feed capacitively excite the TM$_{10}$ mode of the ET patch antenna [13]. In the study, the ET patch, L-strip feeds, and ground plane all use a 0.2 mm thick copper plate.

Each L-strip feed has a horizontal plate of $9 \times 9$ mm$^2$ and a vertical plate of $7 \times 7$ mm$^2$. The horizontal plate size can be varied to adjust the capacitive coupling for the TM$_{10}$ mode excitation. The width of the vertical plate can be varied to finely adjust the inductive reactance seen from each port. The selected dimensions of the L-strip feeds in the proposed antenna can excite three isolated TM$_{10}$ modes with the reflection coefficients ($S_{11} = S_{22} = S_{33}$, owing to symmetric structure of the antenna) lower than $-10$ dB and the transmission coefficients ($S_{12} = S_{13} = S_{23}$) lower than $-15$ dB in 3.3-4.2 GHz as shown in Fig. 2. The minimum value of the transmission coefficients is only about $-32$ dB at 3.65 GHz, which also occurs near the frequency with the lowest reflection coefficient. The simulated S parameters shown in Fig. 2 are obtained from the commercially available HFSS simulation tool [20].

In Fig. 2, the $S_{11}$ of the single-port case (Port 1 only, Ports 2 and 3 not present) is also shown for comparison. It is seen that the $S_{11}$ of the proposed three-port case and single-port case is almost the same. This indicates that the presence of Ports 2 and 3 has very small effects on the excited TM$_{10}$ mode of Port 1. This can confirm that the
three TM$_{10}$ modes excited in the three-port ET patch antenna can be considered to be isolated to each other.

Fig. 3 shows the input impedance seen at Port 1 of the three-port ET patch antenna. It is seen that both the real and imaginary parts of the input impedance are varied slowly in 3.3-4.2 GHz. In addition, the imaginary part of the input reactance is close to zero. The impedance characteristic confirms that the L-strip capacitive feeds can lead to good impedance matching of the TM$_{10}$ mode excitation over a wide operating band in this study.

The simulated vector surface current distributions on the ET patch and feed strips at 3.65 GHz for Ports 1-3 are also shown in Fig. 4. For Port 1 excitation in Fig. 4(a), the surface currents indicate that the excited TM$_{10}$ mode is mainly resonant from Point A toward its opposite edge BC. Similarly, for Port 2 excitation in Fig. 4(b), it indicates that the excited TM$_{10}$ mode is mainly resonant from Point B toward its opposite edge AC. Similarly, for Port 3 shown in Fig. 4(c), the TM$_{10}$ mode is excited and resonant from Point C toward its opposite edge AB. The results indicate that the three excited TM$_{10}$ modes are resonant in three different directions. This can lead to very low correlation of the three generated waves, which will be further discussed later in the next section. Also, the surface currents on the feed strips confirm good port isolation of Ports 1-3.

To explain the coupling mechanism of the capacitive L-strip feed in the proposed antenna, Fig. 5 shows an equivalent circuit of the L-strip feed which consists of a series inductance $L$ and a series capacitance $C$. The single-port case for the antenna is considered for simplicity. The series inductance $L$ can be adjusted by the L-strip’s vertical plate (size selected to $7 \times 7$ mm$^2$ here), whose equivalent inductance can be evaluated with the aid of the flat wire inductor calculator [21].

On the other hand, the series capacitance $C$ is a function of the L-strip’s horizontal plate (size selected to $9 \times 9$ mm$^2$ here) and the coupling gap (selected to 3.3 mm here) between the L-strip and the ET patch. By adjusting the equivalent series inductance and capacitance of the L-strip feed, smooth variation of the input impedance over a wide operating band is obtained as shown in Fig. 3.

Fig. 6 shows a comparison of the simulated $S$ parameters of the 3-port ET patch antenna with L-strip feeds (proposed) and direct feeds. In the direct-feed case, the feed strip has the vertical plate only (size selected to $7 \times 11.5$ mm$^2$) and is directly connected to the ET patch. Results show that the impedance matching is very poor (larger than $-9$ dB) over the desired wide band for the direct-feed case. The poor impedance matching is mainly owing to the excess equivalent inductance of the feed strip, although the feed strip has a wide strip width of 7 mm to decrease its equivalent inductance.

On the other hand, with the additional capacitance contributed by the equivalent series capacitance shown in Fig. 5, the input impedance seen at Port 1 of the three-port ET patch antenna. It is seen that both the real and imaginary parts of the input impedance are varied slowly in 3.3-4.2 GHz. In addition, the imaginary part of the input reactance is close to zero. The impedance characteristic confirms that the L-strip capacitive feeds can lead to good impedance matching of the TM$_{10}$ mode excitation over a wide operating band in this study.

The simulated vector surface current distributions on the ET patch and feed strips at 3.65 GHz for Ports 1-3 are...
III. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 7 shows the fabricated three-port ET patch antenna. In the experiment, the ET patch is supported above the ground plane using a plastic post placed between the patch center and the ground plane. To excite the antenna, the three L-strip feeds with Ports 1-3 are connected to three SMA connectors on the back side of the ground plane.

Fig. 8 shows the measured $S$ parameters of the fabricated antenna. Simulated results of Port 1 are included in the figure for comparison. Good agreement of the measurement and simulation is obtained. In the wide band of 3.3-4.2 GHz, the measured reflection coefficients are less than $-10$ dB and the measured transmission coefficients are less than $-15$ dB. Also note that at about 3.65 GHz where the minimum reflection coefficient occurs, the measured transmission coefficient is only about $-35$ dB.

The measured antenna efficiency and antenna gain are respectively shown in Fig. 9(a) and (b). Note that in Fig. 9(a), the presented antenna efficiency includes the mismatching loss and is the total efficiency. For comparison, the radiation efficiency for perfect matching condition is also included in the figure, which is larger than 97% in 3.3-4.2 GHz. The measured results also agree with the simulation prediction. The measurement is conducted in a far-field anechoic chamber and calibrated using a standard horn antenna. The measured antenna efficiency is larger than 82% and the measured antenna gain is about 6.3-7.4 dBi in 3.3-4.2 GHz.

The radiation patterns of Ports 1-3 are also measured. With the measured three-dimensional (3-D) radiation patterns [22], the ECC of the three generated waves is calculated, which is shown in Fig. 10. The calculated ECC is lower than 0.01 in 3.3-4.2 GHz. This indicates that the three generated waves can be considered to be uncorrelated. The HFSS simulated ECC shown in the figure is also very low and confirms
that three uncorrelated waves are generated in the proposed antenna.

Note that the ECC results shown in Fig. 10 are obtained based on the rigorous 3-D far-field radiation patterns with an expression given in [22]. The calculated ECC uses the measured amplitude and phase of the respective far-field electric fields excited by Ports 1-3 of the antenna. On the other hand, the HFSS [20] simulated ECC uses the simulated amplitude and phase of the far-field electric fields of Ports 1-3. The ECC$^{12}$ in the figure indicates the correlation between the two waves generated by Ports 1 and 2. Similarly, the ECC$^{13}$ is the correlation of the generated waves of Port 1 and 3, while the ECC$^{23}$ is the corresponding result related to Ports 2 and 3.

The measured and simulated two-dimensional (2-D) radiation patterns of Ports 1-3 at 3.65 GHz are shown in Fig. 11. The radiation patterns in the $\phi = 60^\circ$ plane for Port 1, in the $\phi = -60^\circ$ plane for Port 2, and in the $\phi = 0^\circ$ plane for Port 3 are respectively plotted in Fig. 11(a), (b), and (c). Broadside or near-broadside radiation is seen. The measured and simulated results are seen in agreement. For Port 1, its generated wave is slightly tilted away from the patch center (the $z$-axis) to the direction of Port 1. Similar characteristic is also seen for the generated waves of Ports 2 and 3. This characteristic can be seen clearer from the corresponding HFSS simulated 3-D total-power radiation patterns at 3.65 GHz for Ports 1-3 shown in Fig. 12. Since the three generated waves are polarized in three different directions and also slightly tilted away respectively from the $z$-axis to Ports 1-3, which may account for the very low ECC obtained in Fig. 10.

The HFSS [20] simulated coefficient (TARC) [22], [23] for the proposed MIMO antenna is also presented in Fig. 13.
The TARC results are obtained by considering that Ports 1-3 of the antenna are all excited with unity amplitude and same phases for transmitting three synchronized MIMO signals. In the operating bandwidth of interest (3.3-4.2 GHz), the TARC is seen to be less than $-10\, \text{dB}$.

IV. CONCLUSION

The wideband three-port ET patch antenna for 5G MIMO access-point application has been proposed and studied. With a simple structure and a patch length of only 38 mm (0.48λ at 3.75 GHz), the antenna can generate three uncorrelated broadside or near-broadside waves with very low ECC (<0.01) over the wide band of 3.3-4.2 GHz (5G N77 band). Details of the antenna structure and operating principle have been addressed. The experimental results of the fabricated antenna also verify the simulation prediction. The three-port ET antenna will be promising for indoor MIMO access-point applications.

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