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A Dipole Sub-Array With Reduced Mutual Coupling for Large Antenna Array Applications

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ABSTRACT The use of large array antennas in multiple-input multiple-output (MIMO) exploits diversity and reduces the overall transmission power making it a key enabling technology for 5G. Despite all the benefits, mutual coupling (MC) between elements in these array antennas is a concerning issue as it affects the antenna terminal impedance, reflection coefficients, etc. In this paper, a four-element printed dipole sub-array with reduced MC for S-band has been proposed. A balanced transmission line structure has been designed with two dipole arms on the opposite side of the substrate. Simulated and measured results are in good agreement making the design suitable for large array applications such as phased array radars. The proposed array exhibits good impedance matching with a reflection coefficient of −45 dB and resonating at the center frequency of 2.8 GHz. Moreover, isolation of −20 dB has been achieved for each element in a 2×2 planar array structure using out of band, parasitic elements, and planar shift by distributing the separation between the elements.

INDEX TERMS Balanced transmission line, mutual coupling (MC), printed dipole, array antennas, sub-array.

I. INTRODUCTION

With the development of wireless communication technologies such as massive multiple-input multiple-output (MIMO) and the introduction of 5G communication systems, the design of compact and efficient antenna arrays has been increasing. Such antenna structures have attracted significant attention in the academics and research industries as they can be used to deploy high spectrum efficient communication systems. The large-scale antenna arrays offer several advantages over the single antenna such as increased gain, high directivity, and beam-forming capability. These advantages, make these antennas highly useful in many applications that include military radar applications, sonar, mobile, and satellite communication. However, due to today's need for antenna miniaturization and compact design, it is essential to decrease the spacing between the radiating elements. Therefore, the antenna arrays are constructed by placing the antenna elements at a closer distance. As a result of such placement, a fundamental problem in large-scale array antenna known as mutual coupling (MC) arises.

The array efficiency of the antenna structure reduces due to the strong MC between the antenna elements. It creates the scan blindness issue in phased array antenna structures and decreases the packing density of the array structures. This MC, due to the unwanted generation of the surface waves in the antenna substrate, severely degrades the efficiency of the system. It has a significant impact on the performance of the antenna due to the electromagnetic interaction between the array elements [1]. Moreover, this effect changes the radiation pattern as the reactive impedance of the element increases, thus making it store more energy and radiate less.

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The reflection coefficient and the array gain are also degraded [2]. This problem can be resolved using multiple ways such as by adjusting the resonant length of the dipole, using near-field meta-material insulator or by increasing the isolation between the array elements [3]. The recent literature with the proposed MC reduction approach is summarized below in related work.

Several MC reduction methodologies are presented in the literature that provides ways to improve the isolation between the elements. A dual-polarized antenna array for massive MIMO proposed in [4] offers high gain and low MC between any two ports of the array. The design of the planar wave traps structure between multiple antennas using a back-to-back relay for isolation improvement is implemented in [5]. The technique in [5] increases the isolation between antenna elements by 20 dB for 18 MHz bandwidth. The bending of elements at different angles, such as inverted-V dipole is proposed in [6], which increases the linear isolation between the array elements by 19 dB. In [7], a transverse resonance technique for the suppression of surface waves has been used that entirely compresses the surface wave at a particular resonance frequency. The idea of using electromagnetic band gaps for planar wave-guide slot array antennas is proposed in [8]. The design utilizes a simple planar array antenna that increases the overall isolation by 10 dB. The authors in [9] used the similar concept of electromagnetic band gaps for enhancing the isolation. The idea of a coupled line resonator can be utilized in an efficient manner to mitigate the MC [10]. Another approach to decrease the MC effect between the array elements is by increasing the spacing between the elements. However, it has to be noted that the spacing between the elements cannot be increased beyond a specific limit, i.e., 0.6λ, because of the grating lobe. This technique also results in an increased size of the overall antenna array.

The large antenna array system has found many interesting applications in Wireless communication. Large array antennas are actively used in radar systems to work as illuminators for broadcasting stations, optics, radio frequency identification, human-machine interfaces, space probe communications, weather research usage, etc. [6]. There use in radar systems is significant, as it changes the mechanical steering of radars with an electronic one, thus improving the accuracy, reducing the blindsides and vibrations. Their possible arrangement may vary from linear to planar. The printed antennas have ease of fabrication and can be effectively used in large arrays [11]. Among them, the printed dipole antennas got their name because of its effectiveness in large phased array antennas, due to its small size and large bandwidth [12]. A Layered structure printed dipole design of [13], combines a high and a low dielectric substrate to decrease the size of each element in an array. In [14], the authors use the corrugated and truncated slots to reduce the MC in an ultra wide-band co-planar Vivaldi array. Two types of spatially separated augmented nested vector-sensor linear arrays that jointly reduce the inter-element coupling, and inter-polarization coupling is proposed in [15]. A graphene-based frequency selective surface is used in [16], which reduces the coupling effects in dense plasmonic nano-antenna arrays for multi-band ultra-massive MIMO systems. A reduced-complexity near-optimal detection technique known as an element-based lattice reduction algorithm, for hybrid beam-forming in mmWave communications and its performance under the presence of MC is investigated in [17].

The main contribution of this paper is a reduced MC dipole sub-array, suitable for large antenna array applications. Most of the work available in the literature proposed MC reduction techniques for the linear array as well as planar one being placed in XY-direction. To best of our knowledge, there is no work so far that have analyzed the MC reduction of antenna elements being placed in XZ-direction and together promising steady isolation between each element. The proposed antenna design is fabricated on Rogers's 5880 substrates to validate the simulated claim further. Using this model, standard isolation of −20 dB can be achieved for large array antennas. The mathematical analysis helps in finding the compensated lengths without much intense simulated parametric analysis. For this purpose, different types of dipole antennas have been studied and simulated for performance evaluation. Bending the dipoles in different shapes increases the linear isolation between the elements. The isolation is improved further using the concept of out-of-band parasitic elements for linear array and slanting the upper substrate in the center of a lower one for a planar array. In the end, lengths of the dipole are varied to adjust the resonance frequency and to re-tune the sub-array.

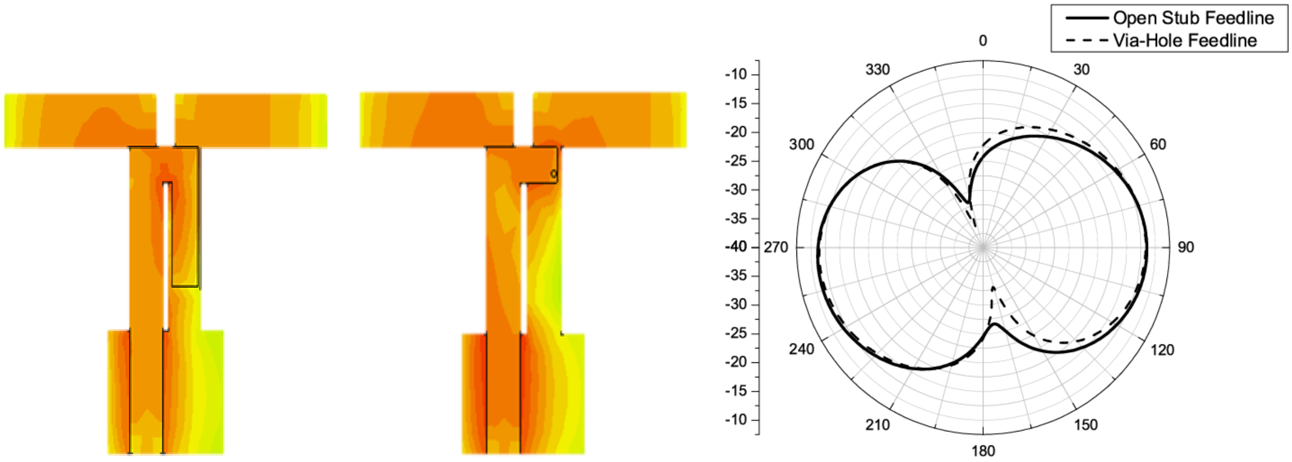
The remaining part of the paper is organized as follows: Section 2 describes the proposed antenna design, and the techniques incorporated to reduce the MC effect. Moreover, in section 2, more designs, available in the literature have been discussed with their drawbacks, which forbids them to be used in large array applications. Section 3 explains the simulated and measured results of the proposed antenna design and quantify the simulated results with the measured one. Furthermore, section 4 of this paper is based on mathematical analysis of the proposed technique, that verifies the compensated lengths obtained through simulated parametric analysis. In the end, the paper is concluded in section 5.

II. ANTENNA DESIGN

In this section, a detailed design analysis of proposed antenna has been discussed. A simple printed dipole antenna with integrated balun has been implemented on a single substrate. Initially, the antenna is fed through two different configurations using [18]–[20];

- Through via-hole feed.
- Open-stub coupled feed.

However, looking at the simulation results as illustrated in Fig. 1(a), a non-uniform current distribution is observed on the dipole surface suggesting that the two designs are unable to mitigate the effect of leakage current completely. The impact of the leakage current results in the squint of the



(a) *Surface current distribution* (b) *Radiation pattern*

FIGURE 1. **Simulated current distributions and radiation patterns of printed dipole with integrated balun using open-stub and via-hole feed.**

radiation pattern, which outcomes in a high MC as depicted in Fig. 1(b). The leakage currents can be visualized by looking at the surface current effect, as shown in Fig. 1(a). Therefore the designs proposed in [18]–[20], does not take into account the impact of leakage currents at the point of interconnection, which makes these techniques highly unsuitable for large antenna array applications.

A balanced microstrip feedline is connected with the dipole arms on different sides of the substrate [6], to overcome this problem. Different configurations of the printed dipole is available in the literature [6], [12]. We have adopted the same configuration of [6], and have bent the dipole arms into different shapes, to make it feasible for sub-array having reduced MC effect. Two shapes have been implemented along with the simple printed dipole antenna, are inverted-V dipole and the bending at right angle dipole, which can be seen in Fig. 2(a). The whole structure is backed with a ground wall at a distance of $\lambda/4$ to increase the gain and to make it feasible for phased array antenna applications. The ground wall is also used to minimize the sensitivity of the antenna from backward because of the presence of strong unwanted transmitters [12].

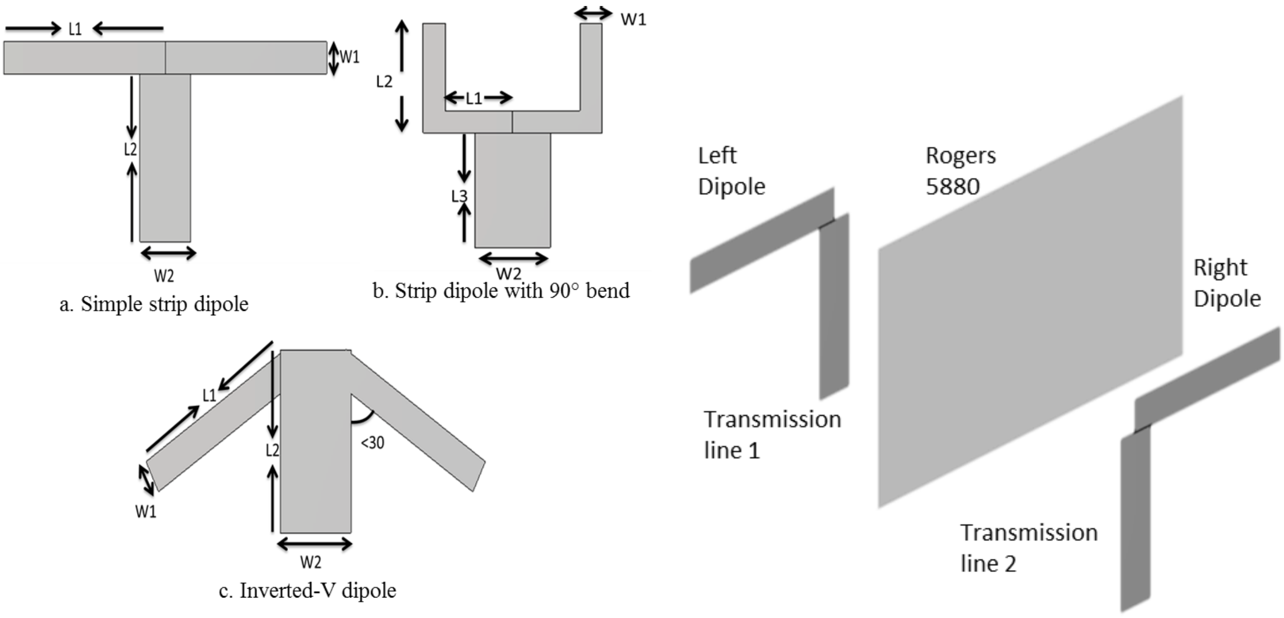
The balanced two-wire strip transmission lines are matched to the SMA connector at 50 Ω, by varying the width of the balanced transmission line. The length of dipoles is adjusted accordingly to make the antenna resonance at the said frequency, i.e., 2.8 GHz. The substrate that has been used in the construction of the printed dipole antenna is Rogers's 5880 and has ϵ_r of 2.2. A detailed comparison of each selected design has been done using various parameters, i.e., antenna gain, bandwidth, radiation pattern, and input match. With the designed SMA connector in CST and performing simulations in a dense mesh scenario, the variations in simulated and experimental results are minimized as much as possible. Figure. 2(b) shows the exaggerated view of the selected design. The detailed design parameters of each design are listed in Table. 1.

TABLE 1. **Design parameters of the selected printed dipole antennas design.**

Geometry Parts	Dimensions (mm)
Simple Dipole	Lengths $L_1 = 20.63$ $L_2 = 15.75$ Widths $W_1 = 3$ $W_2 = 6.52$
Bending at right Angle	Lengths $L_1 = 12.025$ $L_2 = 12.025$ $L_3 = 15.75$ Widths $W_1 = 3$ $W_2 = 10.15$
Inverted-V-Dipole	Lengths $L_1 = 19.3$ $L_2 = 15.75$ Widths $W_1 = 3$ $W_2 = 8.5$

To further compensate the effect of MC and to enhance the isolation, we have incorporated the out of band parasitic elements in the center of a linear array formed using the three selected dipole configurations. The width of parasitic elements is 1 mm, and we have used two elements back to back because of the presence of dipole arms on the different sides of the substrate. The idea is to experience better isolation by inserting parasitic elements in the direction of maximum radiation. Based on detailed simulation results, the inverted-V dipole configuration shows better improvement in linear isolation between the elements, while comparing with the other two designs. The inverted-V design shows an increase in linear isolation from -11 dB to -20 dB. A detailed analysis of each design in terms of linear isolation improvement, antenna gain, and bandwidth has been shown in Table. 2.

In light of the simulated results summarized in Table. 2, we have selected the inverted-V dipole for large array antennas considering the isolation effect. Moreover, in comparison to bandwidth, the inverted-V is not recommended. The bending of the dipole arms results in the low current distribution at



(a) *Geometry of the proposed antenna* (b) *Exaggerated view of the proposed antenna*

FIGURE 2. The proposed strip dipole antenna with balance micro-strip transmission line with different configurations.

TABLE 2. MC comparison of the selected configurations.

Tested Shapes	Before Isolation Improvement (dB)	After Isolation Improvement (dB)	Gain (dB)	Bandwidth (dB)
Simple Dipole	−11.678	−13.327	6.896	291
Bending at Right Angle	−14.502	−14.609	6.283	160
Inverted-V-Dipole	−20.385	−21.988	6.561	165

the bending edges, which varies the impedance and decreases the bandwidth. It can be noted that the overall electrical length remains the same. Since the majority of the current distribution is still in the center, so this impact is not very drastic. Since the scope of this paper is to propose a design with improving isolation and minimum MC, so the inverted V dipole is selected.

Furthermore, for planar isolation improvement, we have used the method of planar shift. The idea is to distribute better isolation between elements with poor isolation. For example, if the isolation between element 1 and element 4 is reasonable as compared to isolation between element 1 and element 3, split the better isolation between elements with the poor one, by introducing a planar squint. Fig. 3 shows the simulated isolation improvement arrangement model of this proposed method. As mentioned earlier, the MC effect changes the desired resonance frequency of the antenna. Although we have proposed techniques to reduce MC effect, one needs to re-tune the antenna parameters, i.e., resonance length to increase the overall performance of the antenna array. For this purpose, we have shown a comparison of MC compensated and non-compensated lengths in Table 3. Moreover, the compensated lengths are validated using the mathematical analysis provided in section 4 of this paper.

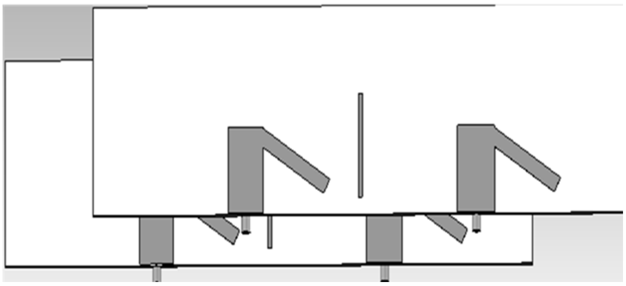


FIGURE 3. Isolation improvement design using planar squint and out of band parasitic elements.

III. SIMULATED AND MEASURED RESULTS

In this section, detailed simulation results of the proposed dipole sub-array have been discussed. All the simulations have been performed in CST. Moreover, the measured results have shown to support the simulated claim. Fig. 4 shows the combine far-field gain of the selected Inverted-V antenna design. From Fig. 4, it is quite evident that the flaw of

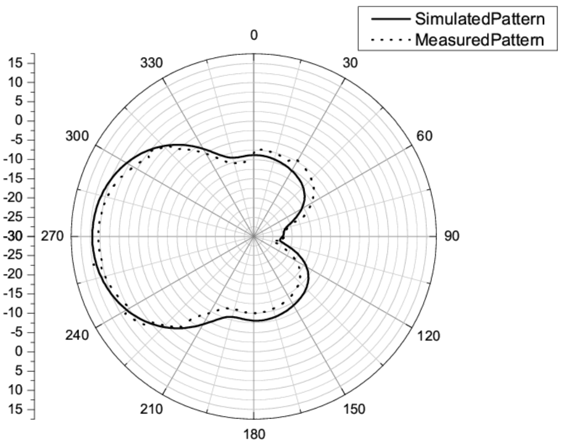


FIGURE 4. Comparative analysis of measured vs simulated radiation pattern of 2 × 2 planar configuration.

TABLE 3. Comparison of MC compensated and non-compensated lengths.

Inverted V-Dipole	Non-Compensated Lengths (mm)	Compensated Lengths (mm)
Element 1	38.37	38.55
Element 2	38.58	38.65
Element 3	38.37	38.54
Element 4	38.58	38.65

leaking surface current, which results in the squint of the radiation pattern is rectified. The maximum radiation pattern is towards 90° using a ground wall, for the selected inverted-V design. We have measured the radiation pattern of individual elements, and the combined pattern is calculated by inserting individuals in the classic array factor formulation (1). The following mathematical expression of the array factor is used

$$A_{rray}F_{actor} = \sum_{i=1}^{M} h_j e^{-jkr_j}. \tag{1}$$

Based on the above discussion, it is quite evident that the inverted-V dipole can be effectively used in our proposed MC minimization technique. Furthermore, the Fig. 5 shows a comparison of simulated radiation of each element in an array with a benchmark (ground backed single inverted-V dipole). Based on the comparison the radiation pattern of each element in decoupled form is quite similar to the benchmark. The prototype of the proposed design can be seen in Fig. 6(a) and Fig. 6(b), respectively. The comparison between simulated and measured S-parameter is depicted in Fig. 7. It can be seen that the measured results are in agreement with the simulation ones, and the proposed array antenna is working well on said 2.8 GHz resonance frequency. To further validate the design, the simulated envelop correlation coefficient (ECC) between each decoupled element is measured using s-parameters. From the results displayed in Fig. 8 it is quite evident that the proposed design is suitable for MIMO applications.

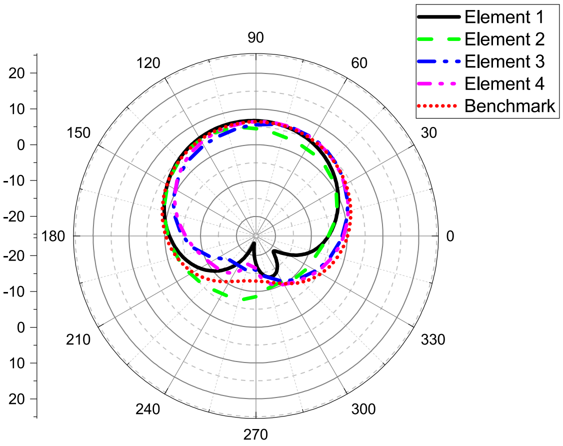


FIGURE 5. Comparison of simulated decoupled radiation pattern with the benchmark scheme.

In light of the simulation results, our proposed technique promises steady isolation of $-20\ dB$ for each element in a planar configuration. To validate that claim, we have measured the MC between each element, using the prototype, as shown in Fig. 6. The comparison of measured vs simulation MC between each element in 2 × 2 planar array can be seen in Fig. 5. The measured MC results are in agreement with the simulated one, which supports the claim of a steady MC. Overall, the side-by-side feed-line mechanism is simple and helpful in providing a balanced feed network to the radiating elements and hence making it feasible for large array applications, i.e. Radars.

IV. MATHEMATICAL ANALYSIS

The MC compensated lengths of the proposed design, found using parametric analysis can be further validated using some mathematical analysis. An induced EMF mechanism can be applied to estimate the mutual impedance between the two antenna elements [21]. In our case, we need to consider the following two cases, to calculate the MC from each element:

- Side-by-side configuration.
- Parallel with angle ϕ orientation.

A visual representation of the two orientations can be seen in Fig. 10 [22]. The mutual impedance for side-by-side configuration is mathematically formulated as [21]

$$Z_{21} = R_{21} \pm jX_{21}, \tag{2}$$

where, R_{21} is the real part of the impedance, i.e. resistive component, and X_{21} is an imaginary part of the impedance, i.e. reactive component. The resistive and reactive component, R_{21} and X_{21} are mathematically represented as

$$\begin{aligned} R_{21} &= 30\{2Ci(\beta d) - Ci[\beta(\sqrt{d^2+L^2}+L)] \quad \Omega \\ &\quad - Ci[\beta(\sqrt{d^2+L^2}-L)]\}, \end{aligned} \tag{3}$$

(a) *Prototype of proposed antenna with ground plane*

(b) *Front view of the proposed antenna design.*

FIGURE 6. **Prototype of the proposed antenna design.**

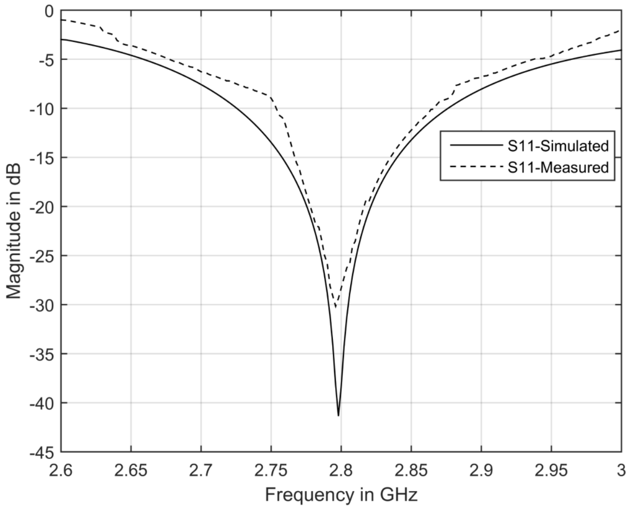


FIGURE 7. **Comparative analysis of measured vs simulated S-parameter.**

$$X_{21} = -30\{2Si(\beta d) - Si[\beta(\sqrt{d^2+L^2}+L)] \quad \Omega \\ - Si[\beta(\sqrt{d^2+L^2}-L)]\}, \tag{4}$$

where d is the port-to-port separation distance of the two elements and L being the length of each dipole. C_i and S_i can be represented as standard computing functions and are mathematically expressed as

$$C_i(x) = -\int_{-x}^{\infty} \frac{\cos y}{y} dy, \tag{5}$$

$$S_i(x) = \int_{0}^{x} \frac{\sin y}{y} dy, \tag{6}$$

using equation 3 and 4 in 2, we can express Z_{12} as follows

$$Z_{21} = 30\{2Ei(-j\beta d) - Ei[-j\beta(\sqrt{d^2+L^2}+L)] \quad \Omega \\ - Ei[-j\beta(\sqrt{d^2+L^2}-L)]\}, \tag{7}$$

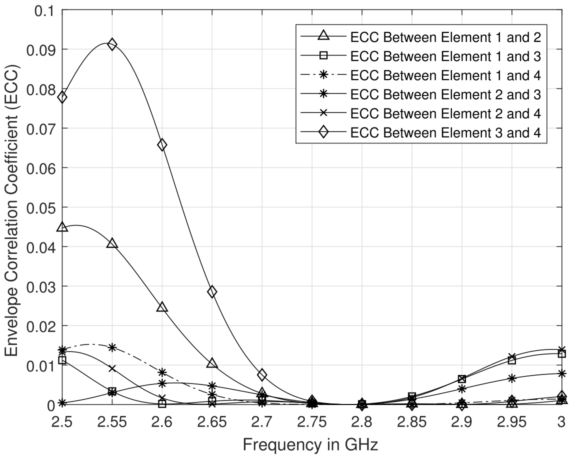


FIGURE 8. **Comparison of simulated ECC of each element in the proposed antenna design.**

where Ei is referred to as exponential integral and can be calculated using the following equation

$$Ei(\pm jy) = Ci(y) \pm jSi(y). \tag{8}$$

Based on above mathematical analysis and using the graphical representation of Fig. 10(b), we can formulate the mathematical expression of the mutual impedance of the parallel configuration with angle ϕ as follows

$$Z_{21} = \frac{V_{21}}{I_{21}} = \frac{60\pi L_{1\Lambda}}{R} sin\phi_1 \exp -j\beta r L_{2\Lambda} sin\phi_2. \quad \Omega \tag{9}$$

where $L_{1\Lambda}$ is the length of element 1, whereas $L_{2\Lambda}$ is the length of 2^{nd} element respectively. $sin\phi_1$ is inclination angle between element 1 and element 2, whereas $sin\phi_2$ is the orientation angle of element 2. β is wave number and R is the distance between the two elements.

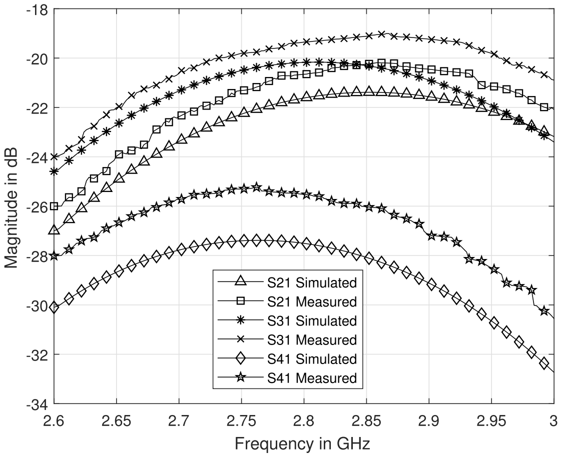


FIGURE 9. **Comparison of the measured vs simulated MC of the proposed antenna.**

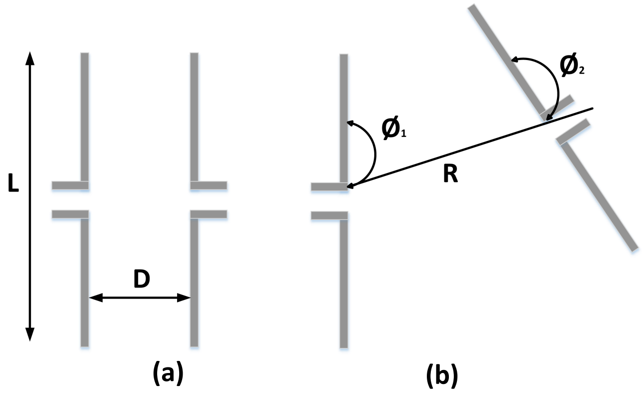


FIGURE 10. **Visual representation of two orientations of the proposed design.**

Overall, the mutual impedance between the two dipole elements can be calculated using the above mathematical analysis and helps in finding the MC compensated lengths for each element. It is noted that the out-of-band parasitic element hasn't been taken into account during the mathematical analysis, as it doesn't affect the resonance frequency.

V. CONCLUSION

This paper aims to propose a dipole sub-array with reduced MC for large antenna array applications. Firstly, we have performed some analysis using printed dipole with integrated balun having via-hole and open stub configuration. The two designs surfers from leakage surface current issue at the point of interconnection, which in-return increases the MC. The dipole antenna with balanced feed-line configuration was selected due to the simplicity in design, no surface current issue and can easily be handled in large arrays. Three different dipole shapes, i.e., simple dipole, inverted-V, and bending at a right angle, were analyzed. Based on simulation results, the inverted-V shows better isolation and reduced MC. The bending of dipole arms minimizes the current at ends but does not impact electrical length. The techniques of out-of-band parasitic elements for linear isolation and providing a planar shift has been used to minimize the MC. Moreover, the design was fabricated, and the results were compared with the simulated one. In the end, mathematical analysis has been provided to validate the findings further. The proposed sub-array design operating at S-band can effectively be used in larger array applications and promises steady isolation of −20 dB. In future, we are aiming to test this methodology on different antenna configuration, simultaneously enhancing it for massive MIMO and for mmWave frequency band, to make it more applicable for future wireless communication.

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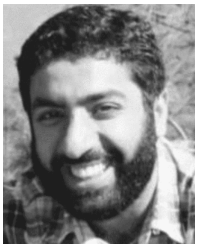

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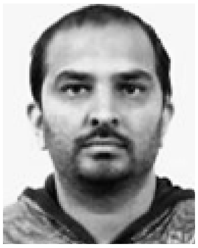

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