Conical conformal antenna design using the CPM for MIMO systems

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Abstract- **In this article, the design of conformal antennas has been discussed using the characteristic modes (CM) method. For this purpose, the vector wave function(VWF) has been utilized to achieve a two-dimensional mapping of the conformal antenna. In designing and analyzing of cone-shaped antennas applicable for multi-input multi-output (MIMO) systems, the most important goal is to achieve a structure with the least correlation coefficient. In order to achieve this goal in these types of antennas, first an appropriate two-dimensional mapping has been selected using the vector wave functions and then its orthogonal characteristic modes have been obtained by the CPM method. In this way, a 4-port conical antenna, whose analysis had many computational problems, was designed; the results obtained from the simulation and the prototype as well as the measurement of this antenna also confirmed the low correlation coefficient (< 0.001), the gain of about 4.2 dB in a frequency of 5.5 GHz, and SWR < 1.22 in the frequency range of 4.6 to 6.6 GHz, indicating a broad bandwidth of around 32%.**

Index Terms- Multiple Input Multiple Output (MIMO) Systems, Characteristic Port Modes (CPM), Correlation Coefficient, Characteristic Modes methods (CMs), Vector Wave Functions(VWF).

I. INTRODUCTION

Today, the use of multi-input multi-output (MIMO) systems has been developed in order to improve the quality or increase the capacity in mobile telecommunication systems; in these systems, the orthogonal patterns can be exploited in order to achieve the minimum interference. To achieve this goal, the theory of characteristic modes has high efficiency. Hence in recent decades, this theory has been developed for the design of antennas. This method was first formulated by Garbacz for use in antennas [1]-[2]. CMs defined by Garbacz are related to Eigen vectors of a weighted Eigen value equation. These modes are accompanied by the useful feature of orthogonality. In 1971, Herrington and Mautz obtained the same

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modes defined by Garbacz by replacing the impedance matrix and its diagonalization [3]-[4]. In the following, another mode was proposed by Inagaki for radiation and dispersion of arbitrary continuous and discrete structures [5].

In the theory of CMs, surface currents are investigated and all calculations are based on the distribution of currents, in addition, the radiation fields are calculated based on these currents [6]. To create orthogonality, the emphasis is on this distribution of currents and the diversity pattern is used. In the CPM method, instead of emphasizing on the distribution of currents of the desired CMs, the calculated voltages are applied to the ports to create the orthogonality required in the CM method [7]-[8]. Regarding the design of the antenna using the CM method, Araghi investigated the triangular planar antennas and achieved the polarization diversity with this structure [9]-[10].

The field radiated or scattered from a perfect conductor body can also be expressed as a sum of vector wave functions(VWF) or modes. In the past, these vector wave modes have been used in radiation problems with standardized geometry. The equations governing the vector wave functions were first formulated by Tai [11]. In this regard, Antonino, Butler, and Cabedo performed investigations on these functions in cylindrical and spherical coordinates [11]-[12]. The results of these functions were used to analyze antennas that were similar to standard shapes [12]-[13]. In addition, this method was used in the field of broadband antennas and the creation of diversity patterns of antennas [14]-[16]. In this regard, the examinations on flat antennas were also associated with very good results [17].

In the present article, the CPM method has been used to accurately calculate and analyze the distribution of currents and optimally design the conformal antennas. Of course, the volume of computations is expected to be high in this method due to the use of the MoM for calculating currents, causing great complexity in these calculations and resulting in a significant increase in the time required for analysis. In order to reduce the computational time in the three-dimensional antennas, first the analysis of the vector wave functions has been performed to obtain the general structure of the released modes, then the conformal antenna is transformed into its flat equivalent using the mapping obtained from this analysis, so that the computation volume is reduced. In the next step, the optimal response for the released modes and the antenna supply can be obtained using the CPM method. The designed antenna has been simulated and constructed in the following, and finally the theoretical, simulation, and experimental results have been compared.

II. ANTENNA STRUCTURE

The antenna analyzed in this paper is a 4-port antenna with a slot supply on an incomplete cone with a height of 15 mm; the radius of bottom circle and top circle of the cone is 50 mm and 15 mm, respectively,

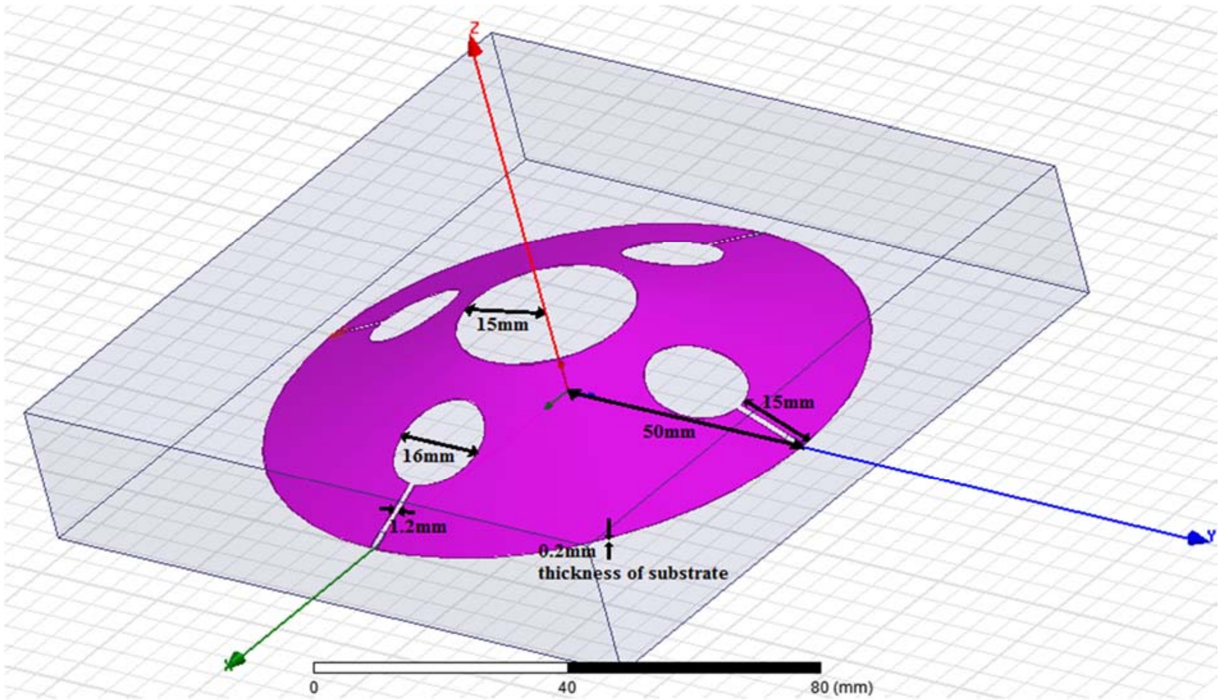


Fig. 1. Dimension and structure of antenna.

creating a cone with an apex angle of 67 degrees. In this antenna, slots with a width of 1.2 mm and a length of 15 mm are used to connect the supplies. In addition, in this antenna, circles with an 8-mm radius have been embedded at the ends of the slots to provide better matching and improve return losses; moreover, another task of the slots and circles is to eliminate the unwanted modes. Fig. 1 demonstrates the dimensions and specifications of the antenna.

To construct the prototype of the antenna, the RO4003 substrate with a dielectric coefficient, loss factor and thickness of respectively 3.55, 0.0027, and 8 mils (0.2mm) has been used and the board has been built on one side.

Symmetry is the important point in the structure of this antenna, which is highly important to create orthogonal patterns by the CPM method. Regarding the antenna supply, combination of the sum and the difference of input signals have been exploited using the Rate Race couplers to create orthogonality in radiation patterns and proper CMs. This method has been used to create a suitable matrix for supplying ports associated with the CPM method.

III. ANTENNA ANALYSIS AND SIMULATION

The analysis of the conical antenna presented in Fig. 1 using the theory of CMs has a very high computational volume due to its conformal structure, making the calculations of the CMs and associated

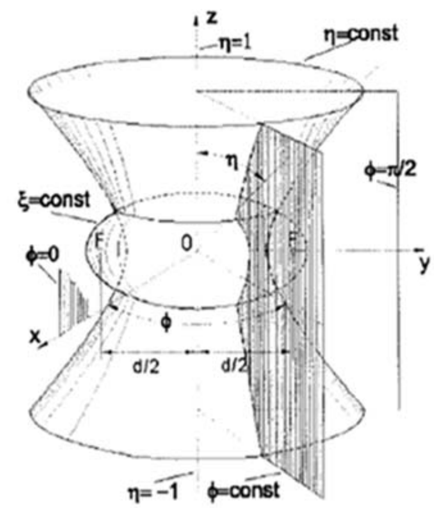


Fig. 2. Oblate spheroid coordinates

characteristic currents difficult. To overcome these problems, the solution proposed in the present article is the use of the vector wave functions method for the cone and to approximately obtain distribution of currents on the surface of the antenna. In the next step, using the mapping that converts this conformal antenna to its flat equivalent antenna, the CMs can be carefully calculated to achieve the distribution of currents on the surface of the antenna.

A. Antenna analysis using vector wave functions

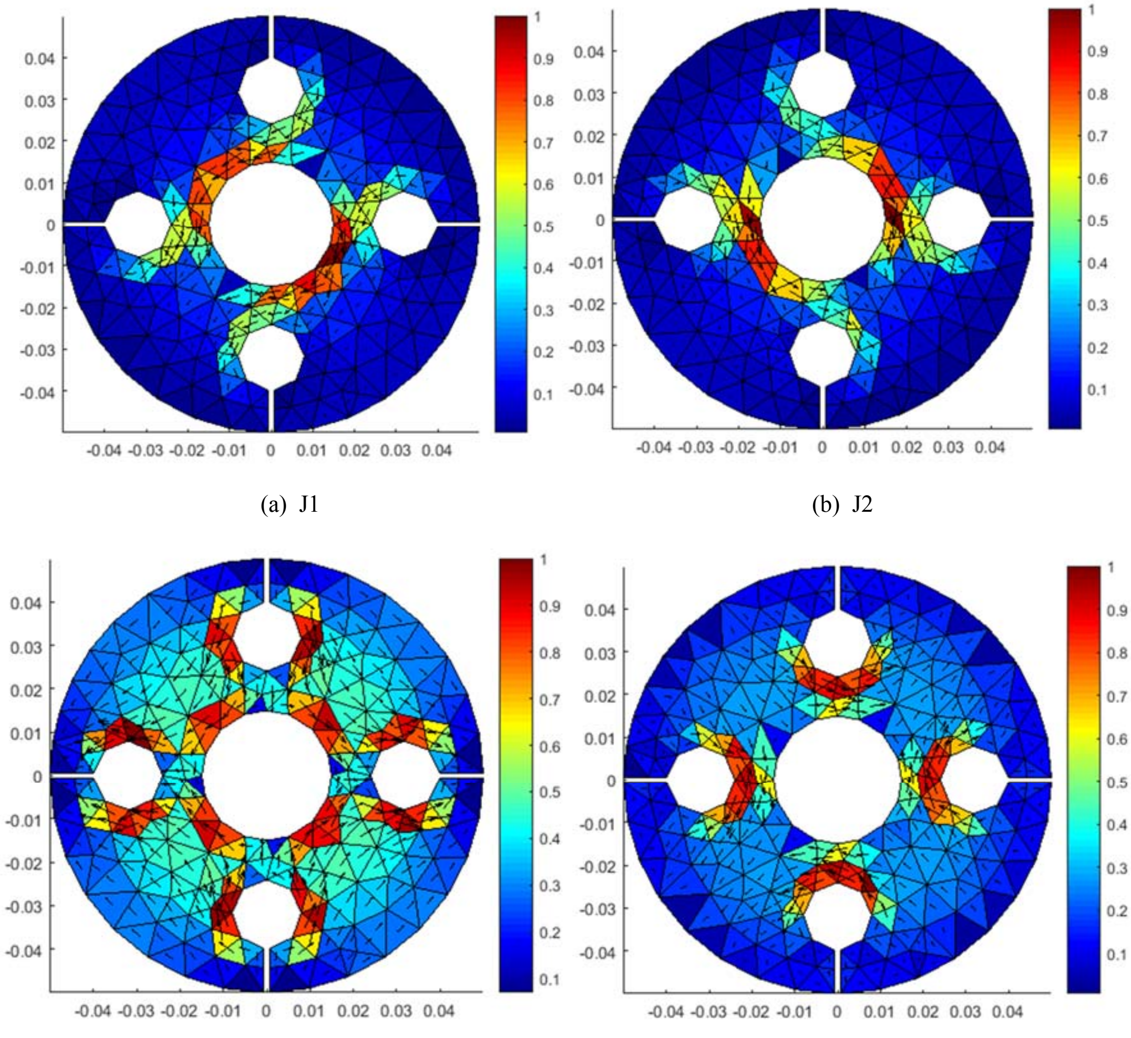
To calculate the approximate distribution of currents on the surface of the antenna, it is possible to start with radiation fields in the inclined spheroid coordinates using the vector wave functions. These coordinates have been introduced in Fig. 2 and equation (1).

$$x = \frac{d}{2}\sqrt{(1-\eta^2)(\xi^2+1)}\cos\phi \quad , \quad y = \frac{d}{2}\sqrt{(1-\eta^2)(\xi^2+1)}\, sin\phi \quad , \quad z = \frac{d}{2}\,\eta\xi \tag{1}$$

For analysis using the vector wave functions by the separation of variables method [11], the potential function is obtained as equation (2),in which $S_{mn}(-ic,\eta)$ is called The angular spheroidal function and $R_{mn}^{(i)}(-ic,i\xi)$ is called the radial spheroidal function [2]

$$\psi_{mn}^{e,o} = S_{mn}(-ic,\eta).\,R_{mn}^{(i)}(-ic,i\xi).\begin{Bmatrix} cos(m\varphi) \\ sin(m\varphi) \end{Bmatrix} \tag{2}$$

By calculating the magnetic fields, the track of this function can be used to obtain the analytical form of distribution of currents on the cone surface, and these currents are introduced in TM mode in equation (3) and (4).



(a) J1 (b) J2

(c) J3 (d) J6

Fig. 3. The distributions of currents created on the surface of the conical antenna using VWF

$$\bar{J}_{S,mn}^{TM\ e,o}(\mathrm{c};\eta,\xi,\varphi) = \frac{m.\xi}{\sqrt{(\xi^2+\eta^2)(1-\eta^2)}} S_{mn} R_{mn}^{(4)} \begin{Bmatrix} \sin(m\varphi \\ -cos(m\varphi) \end{Bmatrix} \hat{\phi}$$

$$- \frac{\sqrt{(\xi^2+1)(1-\eta^2)}}{(\xi^2+\eta^2)} \left[\xi \frac{\partial S_{mn}}{\partial \eta} . R_{mn}^{(4)} + \eta S_{mn} \frac{\partial R_{mn}^{(3)}}{\partial \xi} \right] . \begin{Bmatrix} cos(m\varphi) \\ sin(m\varphi) \end{Bmatrix} \hat{\eta} \qquad (3)$$

$$\bar{J}_{S,mn}^{TM\ e,o}(\mathrm{c};\eta,\xi=0,\varphi) = \frac{\sqrt{(1-\eta^2)}}{\eta} S_{mn}(-ic;\eta) \left. \frac{\partial R_{mn}^{(4)}(-ic,i\xi)}{\partial \xi} \right|_{\xi=0} . \begin{Bmatrix} cos(m\varphi) \\ sin(m\varphi) \end{Bmatrix} \hat{\eta} \qquad (4)$$

The reason for using these coordinates to express the cone is the simplicity of converting from a conformal shape to a two-dimensional and flat structure, so that the analysis of its CMs is simplified and the volume of calculations is reduced; for this purpose, the cone can be converted to a two-dimensional

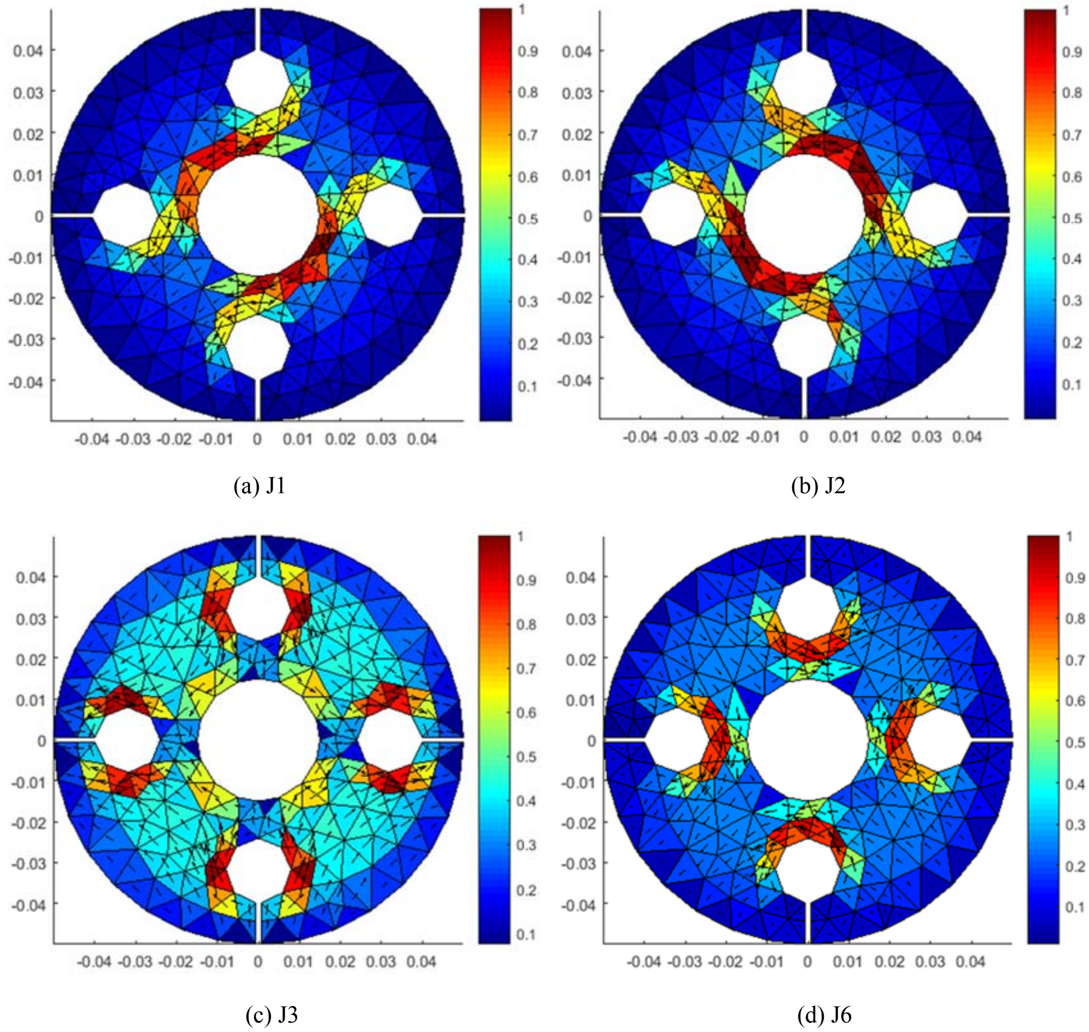


Fig. 4. The distributions of currents created on the surface of the conical antenna using CMs

surface through changing the value of ξ to zero, and the CMs, Eigen values, and resonance frequencies can be calculated for the antenna to accurately calculate the location of supplies and the shape and dimensions of slots related to the supplies. For calculation the current distribution on each element of method CM is used to; In this method, which is based on the method of the moment, the distribution of currents in the characteristic modes obtained from the analysis of the impedance matrix is calculated; We may obtain the characteristic currents on the circular plane of the antenna by using the method explained in the characteristic modes [3] and obtaining the characteristic values from the matrix equation (5).

$$X(\vec{J}_n) = \lambda_n R(\vec{J}_n) \quad (5)$$

Table I. Convergence study with change in N_k

<table>
<tr><td>Nk</td><td>321</td><td colspan="2">1284</td><td colspan="2">5136</td><td>20544</td></tr>
<tr><td>Condition(ZZ)</td><td>7.688</td><td colspan="2">3.065</td><td colspan="2">2.481</td><td>2.313</td></tr>
<tr><td>LSM</td><td colspan="2">0.1814</td><td colspan="2">0.0391</td><td colspan="2">0.0133</td></tr>
</table>

This matrix is used for the antenna surface covered with triangular elements(Nk), and λn Eigen values are matrix (for diagonalization), and Jn are Eigen vectors or characteristic currents on surface antenna. The resonant frequency is also the equivalent of the frequency at which the Eigen values are zero

B. Antenna analysis by CPM method

Due to the relationship between electrical currents on the cone on a two-dimensional surface and the mode analysis of the circular disk, it can be concluded that the four ports can be considered symmetrically to stimulate the first to fourth modes. To supply the four ports, the matrix introduced in equation (6) can be used to stimulate different modes at the resonance frequency of 5.5 GHz; the orthogonality of the vectors of this matrix is necessary to achieve the distribution of currents required for orthogonal patterns. Each column of this matrix is equivalent to a supply status, generating the distribution of currents from first to fourth modes.

$$[V_n] = \begin{bmatrix} 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & -1 \\ -1 & 0 & 1 & 1 \\ 0 & -1 & 1 & -1 \end{bmatrix} \quad (6)$$

The distributions of currents created on the surface of the conical antenna using the vector wave functions and CMs on the corresponding two-dimensional surface are very similar to each other, which confirms the strategy presented in this article. This similarity is visible in Fig. 3 and Fig. 4.

To verify the convergence of the proposed method, the condition of the impedance matrix generated in the CPM method can be investigated. Regarding that the antenna is used in Eigen values close to zero (resonance frequency), a good condition is not expected for the impedance matrix. To examine this parameter in singularity points, instead of the impedance matrix (Z), the product of the impedance matrix and its Transpose Conjugate matrix is used. For this purpose, Equation (7) has been used.

$$ZZ = [Z \,.\, ((Z)^*)^T] \quad (7)$$

The condition of this matrix for different values of the number of triangles is given in Table I; these results confirm the proper condition of the new matrix (ZZ), indicating the convergence of the method used in this article. Furthermore, by examining the error of calculation of the electrical currents on the

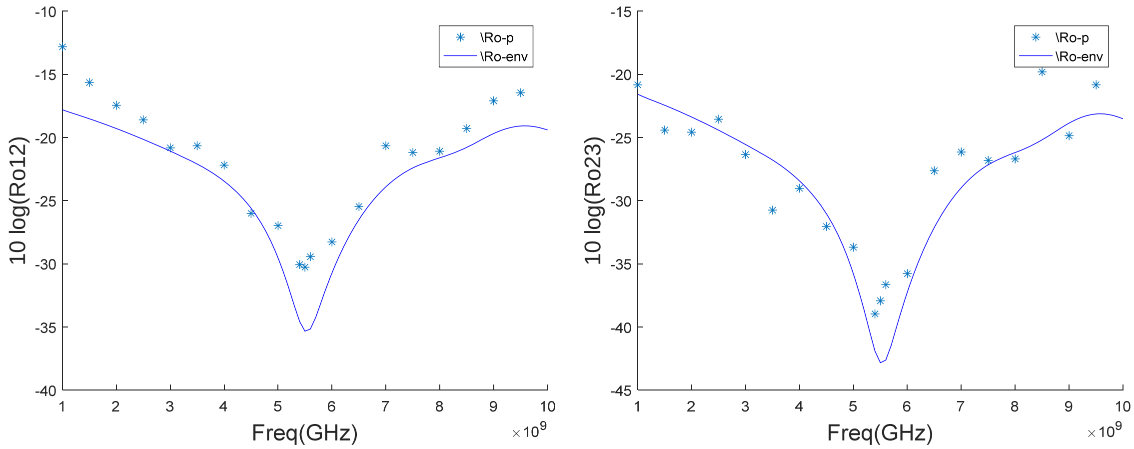


Fig. 5. Correlation coefficients in conical antenna for Ro12 and Ro23

antenna surface, the accuracy of the calculation and convergence of the proposed method can be achieved. For this purpose, the difference between the values of electrical currents on the surface of the antenna with the values calculated in the previous step was calculated by increasing the number of antenna meshing triangles. The results of these calculations are presented in Table I and as expected, this error rate is rapidly reduced by increasing the number of triangles; this error between two different Ns has been obtained through equations (8) and (9). In equations, Nk is the number of triangles created on the conducting surface; In each step we want to increase the accuracy, this number is quadrupled to indicate k (N1=321, N2=1284….), and Ink represent the electrical current of each element.

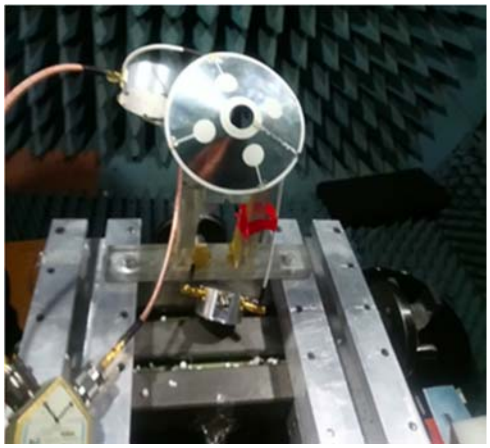
$$Imean_{N_{k+1}} = \frac{1}{4}\sum_{m=1}^{4} I_{N_{k+1}m} \quad (8)$$

$$LSM = \sqrt{\sum_{j=1}^{N_k}\left(Imean_{N_{k+1},j} - I_{N_k,j}\right)^2} \quad (9)$$

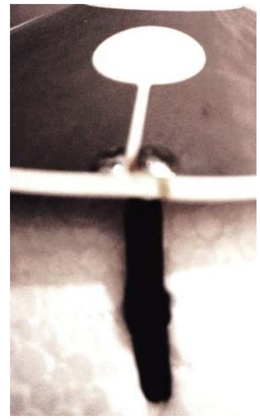
C. Diversity pattern

In antennas used in MIMO systems, spatial multiplicity, pattern, or polarization can be used. According to Fig. 4 regarding the distribution of currents of different modes, it can be concluded that the patterns generated by this distribution of currents have orthogonal radiation fields. To measure the correlation between the radiation fields of this distribution of currents, the envelope correlation coefficient defined by equation (10) is applicable.

$$\rho_P = \frac{\left(\iint_{4\pi}|F_i(\theta,\varphi)|\left|F_j(\theta,\varphi)\right|d\Omega\right)^2}{\iint_{4\pi}|F_i(\theta,\varphi)|^2 d\Omega \ \iint_{4\pi}\left|F_j(\theta,\varphi)\right|^2 d\Omega} \quad (10)$$



(a)



(b)

Fig. 6. (a) Photograph of the fabricated proposed antenna, (b) Feeder Connection

To obtain this quantity, radiation fields in the current distribution of J1, J2, J3, and J6 modes have been obtained separately at different frequencies, and by replacing in this relation, the value of this coefficient has been calculated at several frequencies. To calculate the value of this coefficient, the scattering parameters can be used instead of the radiation fields, which is acceptable assuming a loss-free antenna. The calculation procedure of the modal correlation coefficient of this method can be observed in equation (11).

$$\rho_{env}(i,j) = \frac{\left|\sum_{n=1}^{N} S_{i,n}^{*} S_{n,j}\right|^{2}}{\prod_{k=i,j}\left|\left(1-\sum_{n=1}^{N} S_{k,n}^{*} S_{n,k}\right)\right|} \tag{11}$$

To calculate the correlation coefficient from the fields, the antenna was first simulated using HFSS software; Then the radiation fields are calculated and this information is transmitted to the MATLAB environment, these coefficients were obtained using equation (10). Taking into account the fact that in this method, radiation fields should be obtained at a frequency in simulation, computations in the frequency domain were difficult, hence the correlation coefficients were calculated in several different frequencies, which is of course acceptably consistent with the results of using the scattering parameters in accordance with equation (11). The advantage of using the scattering parameters is that these coefficients can be calculated in the frequency domain and they are not limited to calculation in a few frequencies. However, considering that the values of the correlation coefficients are very low, they have been expressed in dB for the sake of simplicity of comparisons. The simulation results in the frequency range of 1 to 10 GHz have been presented for both methods in Fig. 5; in these graphs, the power correlation coefficient (ρ_P) and the envelope correlation coefficient (ρ_{env}) can be observed in terms of dB. Ro23 in the graphs indicates

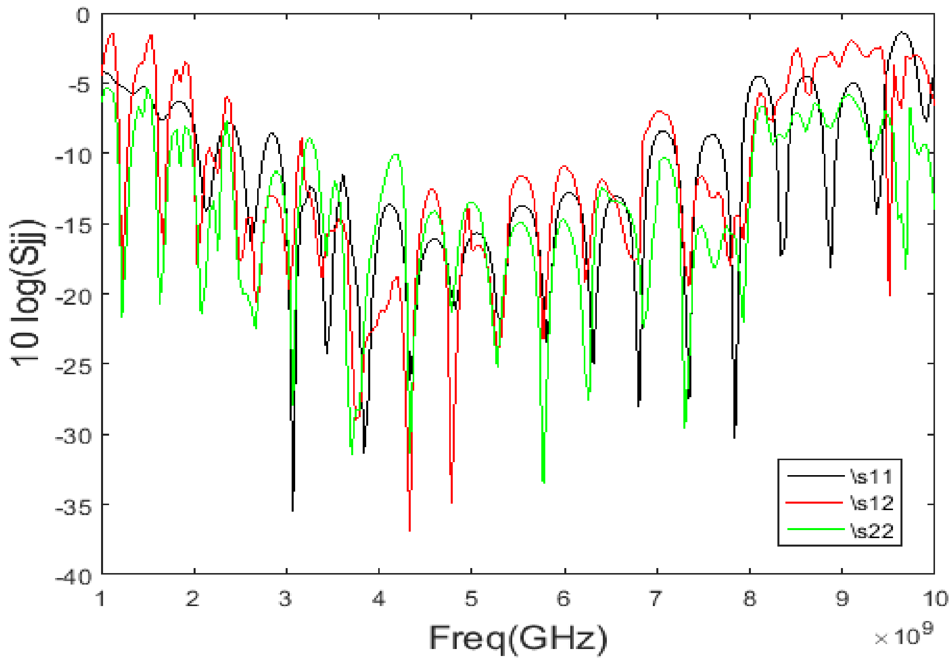


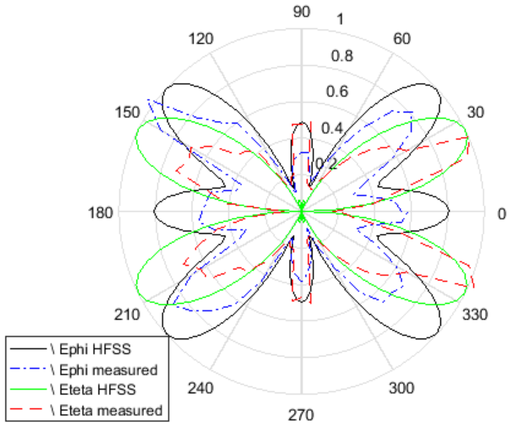
Fig. 7. Antenna scattering parameters

the correlation between the conditions of the supply 2 and supply 3; these different conditions can be assessed by the vectors introduced in the matrix equation (6), and each one stimulates one of the CMs.

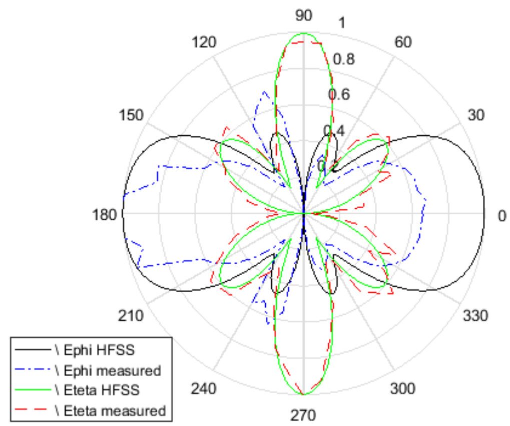
IV. RESULTS

The antenna was simulated using the HFSS software, and using the software, input matching and frequency bandwidth were optimized; a prototype of the designed antenna was also assembled. The antenna image in the test room is visible in Fig. 6(a). The supply in this antenna, given that the antenna has a conductive surface, is coaxially connected by a cable whose core is connected to one side of the gap and the shell to the other side, in addition, Bazooka BALUN has been used to counteract the return current on the shell; Fig. 6(b) shows how to connect the feeder to the antenna.

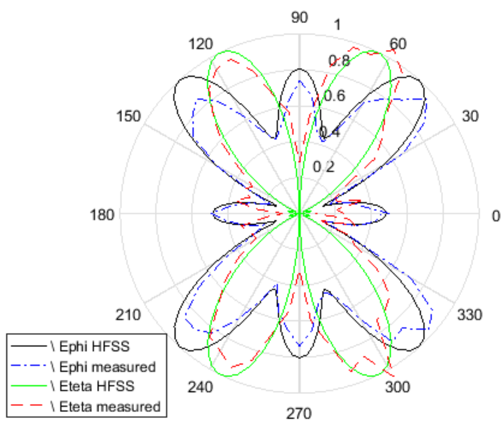
The antenna scattering parameters were measured by the Network Analyzer device, as presented in Fig. 7. In important point in the field of scattering parameters is the matching of impedance of antenna ports; according to the Fig. 7, it can be stated that the acceptable range for SWR < 1.22 requires a return loss of less than 10 dB, which is acceptable within the frequency range of 4.6 to 6.6 GHz. The results of the simulation along with the antenna test results indicate the acceptable accuracy in the construction of the antenna; of course, the low difference in the measured values and the simulation results are affected by the antenna test conditions and the constraints in the construction, which is in an acceptable level. The orthogonal pattern is the most important parameter for MIMO antennas. For this purpose, the antenna



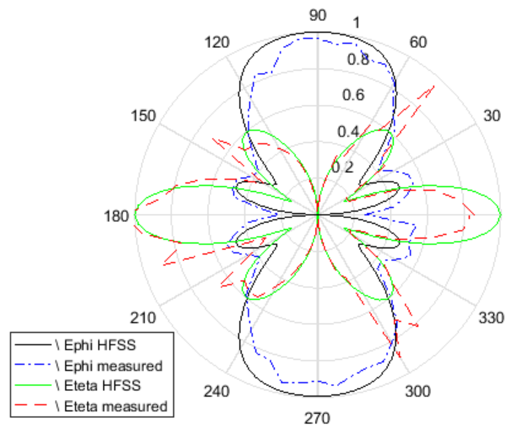
(a) J1



(b) J2



(c) J3



(d) J4

Fig. 8. Antenna radiation fields including E_θ (co-polar) and E_φ (cross-polar) measured and simulated in θ = 45° .

radiation fields including E_θ (co-polar) and E_φ (cross-polar) were measured at the angle θ of 45 degrees in the test room. These radiation patterns along with simulation results have been presented in Fig. 8.

The results obtained from the antenna and radiation patterns indicate a great orthogonality present between E_θ and E_φ radiation fields in different stimulation modes in this antenna. This orthogonality induces a very low correlation between different conditions of the antenna supply; these correlations can be observed in Fig. 5 as well. Moreover, the similarity of the experimental and simulation results confirms the accurate calculation of the antenna mods with the proposed method, and the similarity of the patterns obtained from the antenna test is also an affirmation of the consistency of reality with the performed calculations and simulation of the antenna in creating the multiplicity pattern.

The results of these investigations also indicate the improvement in the behavior of the antennas designed for MIMO systems. The results of comparison of the other antennas designed for MIMO systems using the CM method have been briefly presented in Table II. As shown in this Table, the

Table II. Comparison of important present antenna parameters with similar antenna

	Peak Gain (dBi)	Operating Bandwidth (GHz)	Fractional Bandwidth	Envelope Correlation Coefficient
Antenna1[10]	4.5	4.2 to 4.6	0.09	Less than 0.01
Antenna2[15]	5.5	1.8 to2.9	0.36	Less than 0.1
Antenna3[8]	---	2.2 to 2.65	0.18	Less than 0.05
Antenna4[17]	5.1	4.4 to 5.25	0.17	Less than 0.0001
Present Antenna	4.2	4.6 to 6.4	0.32	Less than 0.001

designed antenna has a very good correlation coefficient (< 0.001) with acceptable gain (about 4.2 dBi) and proper bandwidth (about 32%).

V. CONCLUSION

The final conclusion which can be derived from this article is that for the conformal antennas, a method with a lower computation volume and acceptable responses can be presented using the combination of two methods of VWF and CPM. In addition, the testing and simulation results for the proposed antenna are accompanied by orthogonal radiation fields and a very low correlation coefficient. This low correlation represents the creation of a diversity pattern in this structure, making it suitable for use in MIMO systems. Furthermore, the proposed antenna also has an acceptable gain and bandwidth.

REFERENCES

[1] R. J. Garbacz and R. H. Turpin, “A Generalized Expansion for Radiated and Scattered Fields,” *IEEE Trans. Antennas Propagat*., vol. 19, no. 3, pp. 348-358, May 1971.

[2] R. J. Garbacz and D. M. Pozar, “Antenna Shape Synthesis Using Characteristic Modes,” *IEEE Trans. Antennas Propagat*., vol. 30, no. 3, pp. 340-350, May 1982.

[3] R. F. Harrington and J. R. Mautz, “Theory of Characteristic Modes for Conducting Bodies,” *IEEE Trans. Antennas Propagat*., vol. 19, no. 5, pp. 622- 628, Sept. 1971.

[4] R. F. Harrington and J. R. Mautz, “Computation of Characteristic Modes for Conducting Bodies,” *IEEE Trans. Antennas Propagat*., vol. 19, no. 5, pp. 629-639, Sept. 1971.

[5] N. Inagaki, “Eigenfunctions of Hermitian Iterated Operator and its Application to Numerical Analysis,” *Dig. Int. Symp. Antennas Propagat.*, Japan, pp. 295-298, Sept. 1978.

[6] M. Cabedo Fabres, E. A. Daviu, A. V. Nogueira, M. F. Bataller, “The theory of characteristic modes revisited: A contribution to the design of antennas for modern applications,” *IEEE Antennas Propagat. Mag*., vol. 49, no. 5, Oct. 2007.

[7] J. Ethier, D. A. McNamara, “The Use of Generalized Characteristic Mode in the Design of MIMO Antennas”, *IEEE Trans. Magnetics,* vol. 45, no.3, pp. 1124-1127, March 2009.

[8] J. Ethier, D. A. McNamara, "An Interpretation of Mode-Decoupled MIMO Antennas in Terms of Characteristic Port Mode," *IEEE Trans. Magnetics*., vol. 45, no.3, pp. 1128-1133, March 2009.

[9] A. Araghi and G. Dadashzadeh, "Detail-Oriented Design of a Dual-Mode Antenna with Orthogonal Radiation Patterns Utilizing Theory of Characteristic Modes" *ACES Journal*, vol. 28, no. 10, pp. 952-955, Oct. 2013.

[10] A. Araghi and G. Dadashzadeh, "Oriented design of an antenna for MIMO applications using theory of characteristic modes," *IEEE Antennas and Wireless Propagat Letters*, vol. 11, no. 6, pp. 1040-1043, Sept. 2012.

[11] Chen-to Tai, *Dyadic Green's functions in electromagnetic theory*, 2rd Edition., IEEE Press, 1994, Ch. 3, pp. 161–244.

[12] M. Cabedo Fabres, E. A. Daviu, A. V. Nogueira, M. F. Bataller, "The theory of characteristic modes revisited: A contribution to the design of antennas for modern applications," *IEEE Antennas Propag. Mag*., vol. 49, no. 5, pp.52-68, Oct. 2007

[13] N. Belmar-Moliner, A. Valero-Nogueira, M. Cabedo-Fabres and E. Antonino-Daviu, "Simple design for cost-effective diversity antennas," *Microwave and Optical Technology Letters*, vol. 49, no. 4, pp. 994-996, April 2007.

[14] E. Antonino-Daviu; C. Suarez-Fajardo; M. Cabedo-Fabres and M.; Ferrando-Bataller, "Wideband antenna for mobile terminals based on the handset PCB resonance," *Microwave and Optical Technology Letters*, vol. 48, no.7, pp. 1408-1411, July 2006.

[15] Alishir MoradiKordalivand, Tharek A. Rahman, and Mohsen Khalily, "Common Elements Wideband MIMO Antenna System for WiFi/LTE Access-Point Applications," *IEEE Antennas and Wireless Propagat Letters,* vol. 13, pp. 1601-1604, Aug 2014.

[16] Qi I. Dai, J. W. Wu, L. L. Meng, W. Cho Chew "Large-Scale Characteristic Mode Analysis with Fast Multipole Algorithms," *IEEE Trans. Antennas Propagat*., vol. 64, no.7, pp. 2608 - 2616, Feb 2014.

[17] P. Mohamadi, G. R. Dadashzadeh, M. Naser-Moghadasi, "A New Symmetric Multimodal MIMO Antenna with Reduction of Modal Correlation Coefficient Using TCM," *IETE Journal of Research*., Published online:12 July 2018.