Systematic Design of 3-port Bug-like MIMO Antenna Based on Theory of Characteristic Mode

Dong-Woo Kim and Sangwook Nam
INMC, Dept. of Electrical and Computer Engineering, Seoul National University, Seoul, Korea
cb3403@snu.ac.kr

***Abstract*—In this paper, a 3-port bug-like multiple-input-multiple-output (MIMO) antenna design based on the theory of characteristic modes is proposed. This antenna has a compact size of 50 × 61.5 × 10 mm^3, and it operates in the 2.4-GHz ISM band. We present a novel design approach for the proposed antenna. First, as the antenna has a bilaterally symmetric structure, the characteristic currents can be decomposed into even/odd currents with respect to the axis of symmetry. Second, we define the characteristic current correlation for finding the optimal position of excitation for the antenna. Finally, we suggest a systematic design for the antenna with decoupling and feeding networks by using the antenna as a ground plane. The results show that the proposed 3-port MIMO antenna with a bilaterally symmetric structure is suitable for use in MIMO communication systems.**

***Index Terms*—MIMO antenna, characteristic mode, bilateral symmetry, characteristic current correlation**

I. Introduction

Multiple-input-multiple-output (MIMO) communication is one of the techniques used to increase the data rate. If antennas are uncorrelated and isolated, the channel capacity can be increased without broadening the bandwidth with respect to the number of inputs and outputs [1].

The theory of characteristic modes (TCM) provides the orthogonal properties of far-field patterns [2]; therefore, it is suitable for designing MIMO antennas with pattern diversity. Many researchers have already used the TCM to design such antennas. For example, a 2-port MIMO antenna has been proposed using an orthogonal set of currents [3]-[5]. Furthermore, shape optimization of an antenna has been used to design a 4-port MIMO antenna with symmetry [6]-[8]; however, such an antenna is restricted to a shape having two axes of symmetry. A limitation reported in previous studies is that designing a MIMO antenna with more than two ports requires a structure with only two orthogonal axes of symmetry if the electrical size of the antenna is not large enough [3]-[8].

In this paper, we design a 3-port bilaterally symmetric bug-like MIMO antenna. A Harvard research team has previously investigated the bug platform for a biomimetic robot [9]. In our laboratory, a single-mode bug-like antenna design was proposed using the TCM with the same bug platform as in a previous study [10]. However, this bilaterally symmetric structure is not suitable for designing a MIMO antenna with more than two ports when using previously proposed techniques. Therefore, we propose a systematic design method for the antenna with a mode decoupling network (MDN) by using the property of bilateral symmetry and defining the characteristic current correlation.

In section II, we review the TCM and apply it to a bug-like platform. In section III, we propose the novel design method, optimal position of excitation for a bilaterally symmetric 3-port MIMO antenna based on the characteristic current correlation, and systematic design for the MIMO antenna. In section IV, we discuss the simulation results of the designed antenna. In section V, we present the conclusions of this work.

II. Characteristic Mode Analysis of Bug-like Structure

The TCM provides a basis set of currents that can flow in a conductor. An arbitrary conductor has its own Z-matrix on a Rao-Wilton-Glisson basis. Let Z = R + jX, where Z is a complex symmetric matrix and R and X are real symmetric matrices. A basis set of currents can be obtained by solving the following generalized eigenvalue problem:

$$\mathrm{X}\mathbf{J}_{\mathrm{n}} = \lambda_{\mathrm{n}}\mathrm{R}\mathbf{J}_{\mathrm{n}} \tag{1}$$

where $\mathbf{J}_{\mathrm{n}}$ is the n$^{\mathrm{th}}$ characteristic current and λ_{n}, the eigenvalue of the n$^{\mathrm{th}}$ characteristic mode. As R and X are real symmetric matrices, all eigenvalues and eigenvectors are real, and the eigenvectors obtained from (1) have orthogonal properties of radiation.

From the TCM, the total current $\mathbf{J}$ flowing in the conductor can be decomposed into characteristic currents:

$$\mathbf{J}_{\mathrm{n}} = \sum_{\mathrm{n}} \alpha_{\mathrm{n}}\mathbf{J}_{\mathrm{n}} \tag{2}$$

where α_{n} is the modal weighting coefficient (MWC) of the n$^{\mathrm{th}}$ characteristic mode, and it is calculated as

$$\alpha_{\mathrm{n}} = \frac{<\mathbf{J}_{\mathrm{n}}, \mathbf{E}^{\mathrm{i}}{}_{\mathrm{tan}}>}{1 + \mathrm{j}\lambda_{\mathrm{n}}} \tag{3}$$

where $\mathbf{E}^{\mathrm{i}}{}_{\mathrm{tan}}$ is the incident tangential E-field. The numerator is called the modal excitation coefficient, and it is determined by how similarly a coupler excites the n$^{\mathrm{th}}$ characteristic current. The denominator is related to the modal significance, and it is determined by how well the n$^{\mathrm{th}}$ characteristic mode is resonated. Fig. 1 shows the bug-like structure whose characteristic modes are analyzed. Fig. 2 shows the eigenvalues of each mode; only three dominant

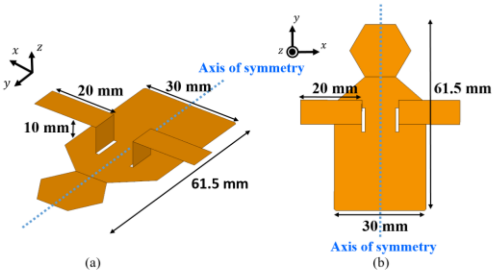

Fig. 1. Geometry of bug-like PEC structure.

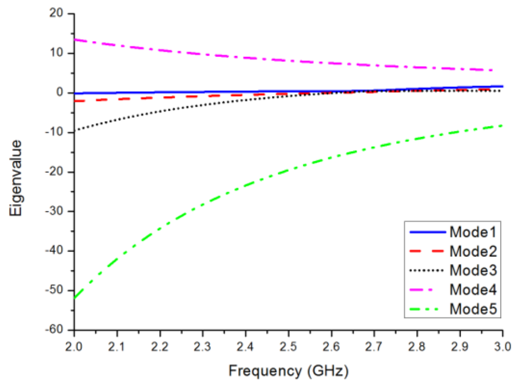

Fig. 2. Eigenvalue versus frequency for first five modes of bug-like platform. As seen in the figure, there are three dominant modes at 2.4 GHz, which are modes 1, 2, and 3.

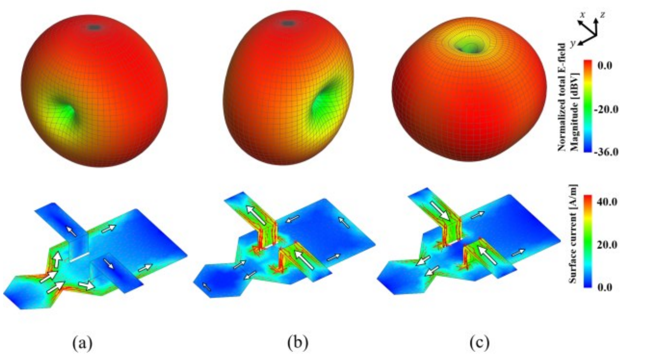

Fig. 3. Current distributions and far-field patterns of (a) mode 1, (b) mode 2, and (c) mode 3.

modes are found. Fig. 3 shows that modes 1 and 3 are even currents and mode 2 is an odd current with respect to the symmetric axis.

III. DESIGN OF BUG-LIKE MIMO ANTENNA

A. Excitation for 3-port Bug-like MIMO Antenna

The excitation of characteristic modes on the surface is an important issue in the design of a MIMO antenna. In this work, we placed three H-shaped inductive coupling elements (ICEs) [10] at the axis of symmetry, shown in Fig. 4. Fig. 4 shows the designed H-shaped ICE for the odd mode (mode 2) at the center among the three ICEs; the others are for even modes (modes 1 and 3). Specifically, by using bilateral

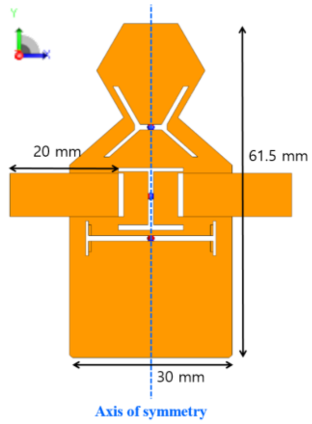

Fig. 4. Geometry of bug-like structure and positioning of H-shaped inductive coupling elements for 3-port MIMO.

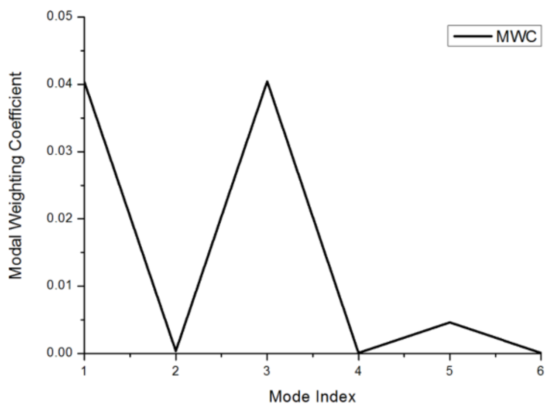

Fig. 5. Simulated modal weighting coefficient (MWC) for the excitation of one even port, with the others terminated by 50Ω. It is seen that modes 1 and 3 are excited together by only one port.

symmetry, it is easy to isolate odd currents from even currents if the ports for odd modes are virtually open to ports for even modes, and vice versa. Next, we have to isolate each even mode; however, even modes are correlated owing to the compact size of the antenna. Therefore, both modes are simultaneously excited from one H-shaped ICE as given by equation (4) and the MWC graph shown in Fig. 5:

$$\mathbf{J}=\sum_{n}\alpha_n\mathbf{J}_n \cong \frac{<\mathbf{J}_1,\mathbf{E}^{i}{}_{\tan}>}{1+j\lambda_1}\mathbf{J}_1+\frac{<\mathbf{J}_3,\mathbf{E}^{i}{}_{\tan}>}{1+j\lambda_3}\mathbf{J}_3$$
$$=\frac{<\mathbf{J}_1,\mathbf{E}^{i}{}_{\tan}>}{1+j\lambda_1}\mathbf{J}_1+\frac{|\mathbf{J}_3|}{|\mathbf{J}_1|}\rho_{1,3}\frac{<\mathbf{J}_1,\mathbf{E}^{i}{}_{\tan}>}{1+j\lambda_3}\mathbf{J}_3 \qquad (4)$$

where $\rho_{1,3}\equiv\frac{<\mathbf{J}_1,\mathbf{J}_3>}{|\mathbf{J}_1||\mathbf{J}_3|}$ is the characteristic current correlation.

Owing to the correlation between even currents, it is necessary to combine the signals from two H-shaped ICEs to separate the even currents. This implies that a systematic design using MDN is essential when the characteristic currents are correlated.

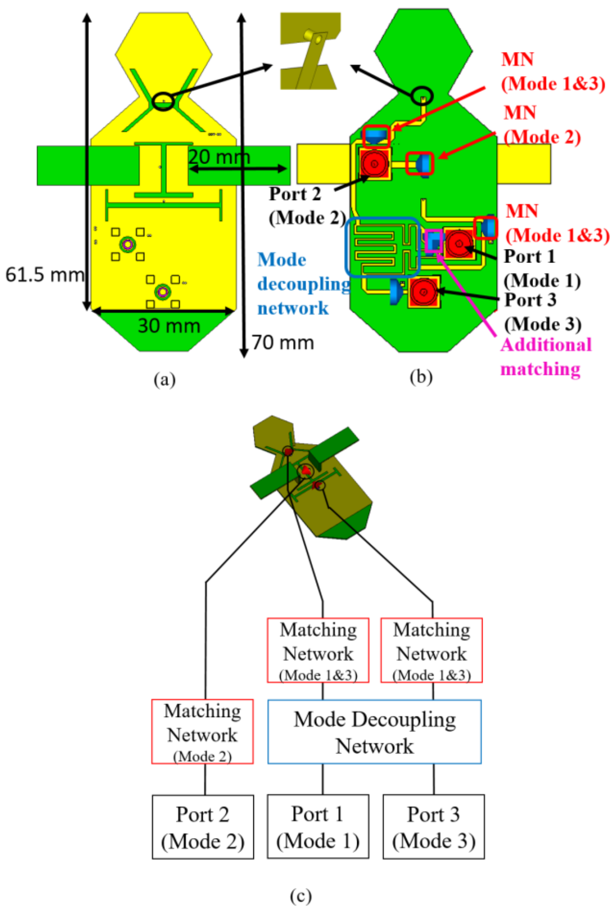

Fig. 6. Configuration of proposed bug-like MIMO antenna with feeding networks. (a) Top view, (b) bottom view, and (c) overall view.

B. *Systematic Design of 3-port Bug-like MIMO Antenna*

A systematic design is very useful when using TCM because we can use the antenna as the ground plane of the feeding signal line. Therefore, the size can be reduced by integrating the antenna and the feeding networks. We place the proposed antenna at the top of the substrate shown in Fig. 6(a). At the bottom of the antenna shown in Fig. 6(b), we design 180° hybrid coupler as the MDN to separate the even currents [11]. FR-4 with 0.5-mm thickness is used as the antenna substrate. As the H-shaped ICE is inductive, it is necessary to add matching networks for each ICE. Mode 2 has only a matching network because it is isolated from the even modes. Modes 1 and 3 consist of matching networks and 180 hybrid coupler. The matching networks are positioned between the antenna and the MDN because we need to match the input impedance of the rat-race coupler for ensuring the isolation of this coupler. An additional matching network is used after the MDN owing to fitting errors in the EM simulation results. Fig. 6(c) shows an overall view of the designed antenna.

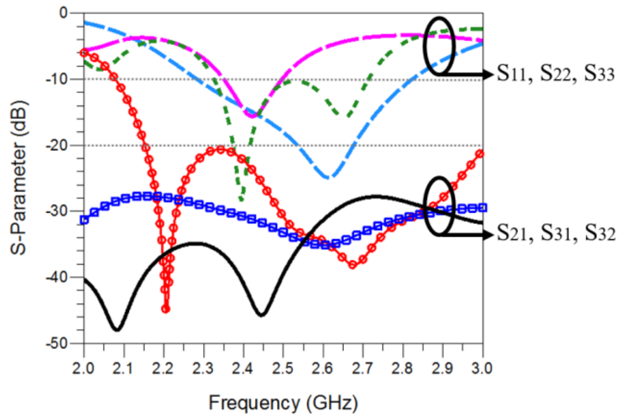

Fig. 7. Simulated S-parameter of systematic design of bug-like antenna shown in Figs. 6 and 7.

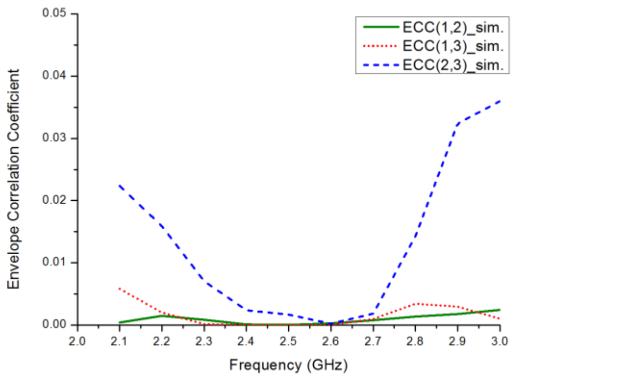

Fig. 8. Simulated envelope correlation coefficient (ECC) calculated based on far-field pattern.

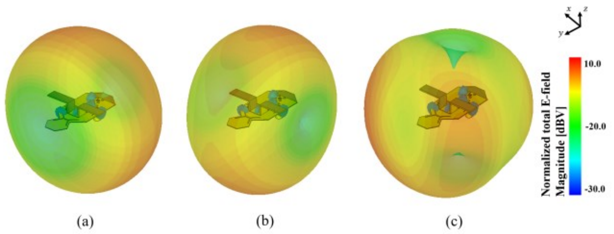

Fig. 9. Simulated radiated 3D far-field patterns for each port of the antennas. (a) Port 1 (mode 1), (b) port 2 (mode 2), and (c) port 3 (mode 3).

IV. SIMULATION RESULTS

To validate the design concept, a compact bug-like 3-port MIMO antenna was constructed in the EM simulator, as shown in Fig. 6. The Computer Simulation Technology 2016 program was used for the EM simulation [12].

Figs. 7 and 8 show the antenna characteristics as obtained from the EM simulation. Fig. 7 shows the simulated S-parameters of the proposed design. As seen in this figure, the impedance of the antenna is well matched at 50Ω in the 2.4-GHz ISM band, and the coupling between modes is under -20 dB. Fig. 8 shows the simulated envelop correlation coefficient (ECC) calculated based on the far-field patterns. As seen in this figure, the ECC values are below 0.05 over the entire band of interest, implying that the proposed 3-port antenna is suitable for diversity conditions. Fig. 9 shows the 3D far-field patterns for each port of the antenna, which are well-matched to the corresponding patterns of the characteristic mode.

V. CONCLUSIONS

A novel 3-port MIMO antenna with a bilaterally symmetric structure is designed based on the TCM. The simulated results of the proposed antenna show that all coupling values of the antenna are below -20 dB in the 2.4-GHz ISM band, and the envelope correlation coefficients between the antennas are below 0.05 in the operating band. In the future, measurement results of the proposed antenna will be presented, and a mathematical theory is being developed to enhance the proposed approach.

ACKNOWLEDGMENTS

This research was supported by a grant to Bio-Mimetic Robot Research Center funded by Defense Acquisition Program Administration(UD130070ID)

REFERENCES

[1] L. Zheng and N. C. Tse, "Diversity and multiplexing: A fundamental tradeoff in multiple-antenna channels," IEEE Trans. Inf. Theory, vol. 49, no. 5, pp. 1073–1096, May 2003.

[2] R. F. Harrington and J. R. Mautz, "Theory of characteristic modes for conducting bodies," IEEE Trans. Antennas Propag., vol. 19, no. 5, pp. 622–628, Sept. 1971.

[3] K. K. Kishor and S. V. Hum, "A pattern reconfigurable chassis-mode MIMO antenna," IEEE Trans. Antennas Propag., vol. 62, no. 6, pp. 3290–3298, Jun. 2014.

[4] H. Li, Z. Miers, and B. K. Lau, "Design of orthogonal MIMO handset antennas based on characteristic mode manipulation at frequency bands below 1 GHz," IEEE Trans. Antennas Propag., vol. 62, no. 5, pp. 2756–2766, May 2014.

[5] C. Deng and S. V. Hum, "MIMO mobile handset antenna merging characteristic modes for increased bandwidth," IEEE Trans. Antennas Propag., vol. 64, no. 7, pp. 2660–2667, July 2016.

[6] D. Manteuffel and R. Martens, "Compact multimode multi-element antenna for indoor UWB massive MIMO," IEEE Trans. Antennas Propag., vol. 64, no. 7, pp. 2689–2697, July 2016.

[7] B. Yang and J. J. Adamas, "Systematic shape optimization of symmetric MIMO antennas using characteristic modes," IEEE Trans. Antennas Propag., vol. 64, no. 7, pp. 2668–2678, July 2016.

[8] M. Bouezzeddine and W. L. Schroeder, "Design of a wideband, tunable 4-port MIMO antenna system with high isolation based on the theory of characteristic modes," IEEE Trans. Antennas Propag., vol. 64, no. 7, pp. 2679–2688, July 2016.

[9] R. J. Wood, "The first takeoff of a biologically inspired at-scale robotic insect," IEEE. Trans. Rob.,vol. 24,no. 2, 341–347, April 2008

[10] J. Won, S. Yoon, and S. Nam, "Design of antenna for bug robot using characteristic mode," in Radio Science Meeting (Joint with APS Symposium), 2015 USNC-URSI, 2015

[11] J. Coetzee and Y. Yu, "Port decoupling for small arrays by means of an eigenmode feed network," " IEEE Trans. Antennas Propag., vol. 56, no. 6, pp. 1587–1593, June 2008.

[12] CST Microwave Studio (MWS) 2016, CST Corporation [Online]. Available: http://www.cst.com.