Reduction of Mutual Coupling in UWB/MIMO Antenna Using Stub Loading Technique

Adamu Halilu Jabire* (Lecturer, Taraba State University, Jalingo, Nigeria),
Anas Abdu (Lecturer, Federal University Dutse, Jigawa, Nigeria),
Sani Saminu (Lecturer, University of Ilorin, Ilorin, Nigeria),
Sani Salisu (Lecturer, Ahmadu Bello University, Zaria, Nigeria),
Abubakar Muhammad Sadiq (Researcher, Tianjin University, Tianjin, P. R. China),
Adamu Mohammed Jajere (Researcher, Tianjin University, Tianjin, P. R. China),
Yusuf Kola Ahmed (Lecturer, University of Ilorin, Ilorin, Nigeria)

Abstract – The research presents mutual coupling reduction between UWB-MIMO antenna elements using stub loading technique. The proposed $2 \times 2$ UWB antenna geometry consists of two circular-shaped monopole radiators with a partial ground for perfect impedance matching. Stubs of 20 mm $\times$ 0.2 mm are inserted between the two antenna elements in the ground plane to improve the isolation. The decoupling stub leads to a mutual coupling reduction of less than 20 dB. The farfield measurement at a selected frequency of 10 GHz confirms an omnidirectional radiation pattern. Different MIMO antenna metric such as channel capacity loss (CCL), mean effective gain (MEG), total active reflection coefficient (TARC), envelope correlation coefficient (ECC), and surface current are presented. Details of the design considerations and the simulation and measurement results are presented and discussed. The proposed MIMO antenna array can be well suited for UWB applications.

Keywords – Diversity antenna; Error correlation coefficient; MIMO antenna; Mutual coupling; Slotted stub; UWB antenna.

I. INTRODUCTION

Deployment of multiple antennas at both links gives the capability to exploit other advantages than MIMO/diversity gains. MIMO techniques can be characterised when numerous antennas are used at transmitting and receiving end [1], [2]. The main idea of using the MIMO system is that sampled signals in the spatial terrain at both terminals are integrated to elevate the data rate and enhance the communication quality. Electromagnetic interaction among the MIMO radiating element is one of the MIMO system challenges [3]. When several radiating features are situated close to each other, the fields generated by one antenna change the current distribution on the other antenna; therefore, each MIMO element impedance matching and radiation pattern are assigned based on the presence of other features [4]. This mutual coupling between the antenna elements subverts the performance of the MIMO system. All the radiating features have to be in a single aperture, making it a single multiport antenna design problem.

MIMO systems helps us combat multipath fading, providing improved signal-to-noise-ratio (SNR), thus achieving better system capacity.

II. RELATED WORK

Some researchers use a multiport decoupling or matching network to reduce the mutual coupling effect between the antennas. The authors in [6]–[8] utilised a defective ground structure. Study [9] used parasitic elements while the author in [10], [11] employed a neutralization line method to cancel the effect. Metamaterial structure in the form of an electromagnetic bandgap (EBG) is presented in [12], [13]. A rectangular loop resonator was employed in [14] to abate the mutual coupling. The author in [15] proposed the UWB-MIMO sense in which some diodes had been used for that purpose. The pin diodes are turned off with a reversed biased of 0 V for two varactor diodes. A band-notched UWB antenna with band rejection ability is presented in [16]. A letter is presented in [17] whereby the author embedded different slots and slits on the radiating element to achieve UWB frequency.

III. DESIGN EVOLUTION

The geometry and fabricated models of the proposed MIMO/UWB antenna are presented in Fig. 1. The MIMO antenna consists of two printed circular patches on top of the plane and a partial ground plane. Four slots were employed in both the upper and bottom layers to achieve perfect matching. Two perturbed stubs were utilised in the middle of the ground plane, which served as a decoupling structure for mutual coupling reduction. The total design space was 30 mm $\times$ 60 mm, with a separation distance of 18 mm between the two elements. The optimized dimension of the MIMO antenna is presented in Table I.
TABLE I
MIMO ANTENNA PARAMETERS

| Parameter | Size, mm | Parameter | Size, mm |
|-----------|----------|-----------|----------|
| \( D \)   | 18       | \( L_s \)| 20       |
| \( G_w \) | 3        | \( R_p \)| 9.35     |
| \( L \)   | 30       | \( R_s \)| 2.6      |
| \( L_1 \)| 11.05    | \( W \) | 60       |
| \( L_2 \)| 10       | \( W_1 \)| 2.5      |

IV. PARAMETRIC ANALYSIS OF THE DESIGN

The parametric examination is displayed utilising different \( R_s \) values: the radius of the slots from Fig. 1 to have an optimum amount that can give us a better exhibition of the antenna as far as the reflection coefficient, radiation attributes, and data transfer capacity. Fig. 2 shows \( S_{11} \) for the slots with various radii, as can be seen from the plot. When the value of \( R_s \) is 2.6 mm, the resulting \( S_{11} \) is perfect at that value. Therefore, we used 2.6 mm as the radius of the slots for both the two reception apparatus. Even though the remaining plots are also within the range of ~10 dB and can also have a good result. Still, with 2.6 mm as the value of the radius, the performance has improved. That is why the value is taken as the final value for the proposed reception apparatus design and analysis. It shows that the slot controls the input impedance matching of the MIMO antenna. Finally, low polarization diversity is also considered for having low mutual coupling.

Fig. 1. System model: (a) top view, (b) bottom view.

V. MEASUREMENT SETUP AND RESULTS

The proposed MIMO antenna with a decoupling structure was fabricated and measured using a vector network analyzer (N5244A). Two perturbed stubs are used as a decoupling structure between the antenna for proper isolation between them. The measured and simulated \( S_{11} \) is shown in Fig. 3, while Fig. 4 is the measured and simulated \( S_{21} \) of the MIMO antenna. The isolation between the two antennas was below ~20 dB. The stubs bring about the high isolation between the MIMO components. Figure 5 shows the measured and simulated voltage standing wave ratio (VSWR). The \( S_{21} \) with and without stubs is depicted in Fig. 6. The current distribution at 4.5 GHz and 5.8 GHz when port one is excited is shown in Fig. 7. The antenna gain is an essential parameter for describing the degree of enlargement and concentration of input power. It is used to measure the antenna ability to send and receive signals in a specific direction. The measured and simulated MIMO antenna peak gain is shown in Fig. 8. The antenna directivity was measured using an anechoic chamber; the measurement setup can be seen in Fig. 9, the \( xz \)-plane and \( yz \)-plane radiation characteristics for 10.6 GHz are shown in Fig. 10. The measured values are in agreement with the simulated values. The little shift is due to fabrication errors or connection issues.

Fig. 2. \( S_{11} \) plot for various radiusses \( R_s \) in mm.

Fig. 3. Measured and simulated \( S_{11} \).

Fig. 4. Measured and simulated \( S_{21} \).
Fig. 4. Measured and simulated $S_{21}$.

Fig. 5. Measured and simulated VSWR.

Fig. 6. $S_{21}$ without and with a stub.

Fig. 7. Surface current at (a) 4.5 GHz, (b) 5.8 GHz.

Fig. 8. Measured and simulated peak gain.

Fig. 9. Far-field measurement setup.
VI. MIMO SYSTEM METRICS

To verify the MIMO antenna capability, some merits are used to evaluate the envelope correlation coefficient, total active reflection coefficient, channel capacity loss, and diversity gain. They are estimated using the S-parameters that has been extracted from the electromagnetic solver. ECC and TARC are essential parameters to quantify signal interference between MIMO channels [18] to secure the MIMO antenna capability. TARC can be computed for a 2 × 2 MIMO antenna using Eqs. (1) and (2).

\[ \Gamma_a' = \frac{\sum_{i=1}^{N} |b_i|^2}{\sqrt{\sum_{i=1}^{N} |a_i|^2}} \]  

(1)

\[ TARC = \frac{\left| S_{11} + S_{12}e^{j\theta} \right|^2 + \left| S_{22} + S_{21}e^{j\theta} \right|^2}{2} \]  

(2)

The phase difference between the excitation difference of our MIMO antenna and the TARC plot of the MIMO antenna is given in Fig. 11, with a difference of 0° from 0° to 180° with an interval of 30°. The plot reveals that 0° ≤ θa ≤ 1°. The ECC is computed from the S-parameter as calculated in Eq. (3).

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

(3)

where \( S_{11}, S_{12}, S_{21}, \), and \( S_{22} \) are the parameters of the MIMO array. The proposed MIMO antenna ECC was calculated from 1 GHz to 12 GHz, as shown in Fig. 12. It can be observed that ECC value is less than 0.002 through the UWB bandwidth, which fulfills a good diversity standard for a MIMO system. Channel capacity can be defined as a data rate supported in a particular channel, and that channel is a fading environment [19]. Considering a high SNR value, CCL has been evaluated from simulated S-parameters using Eq. (4) below [20].

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

(4)

where \( \psi^R \) is the 2 × 2 correlation matrix in terms of S-parameters presented in Eqs. (5)–(9):

\[ \psi^R = \begin{bmatrix} \psi_{11} & \psi_{12} \\ \psi_{21} & \psi_{22} \end{bmatrix} \]  

(5)

\[ \psi_{11} = 1 - \left( |S_{11}|^2 + |S_{22}|^2 \right) \]  

(6)

\[ \psi_{22} = 1 - \left( |S_{11}|^2 + |S_{21}|^2 \right) \]  

(7)

\[ \psi_{12} = S_{11}S_{12}^* + S_{22}S_{21}^* \]  

(8)

\[ \psi_{21} = S_{22}S_{12}^* + S_{11}S_{21}^* \]  

(9)

The equations are based on the simulated and measured S-parameter, which is plotted in Fig. 13. The plot uncovers that the channel capacity loss is less than 0.35 over the whole UWB span because in practice CCL < 0.4 bps/Hz. The diversity gain of MIMO antennas can be computed from ECC using Eq. (10) [20].

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

(10)

In Fig. 14, the diversity gain of nearly 10 dB is depicted; this signifies that the antenna has low polarization diversity that can give low mutual coupling.
The antenna mean effective gain (MEG) is defined as the ratio of the average power received at the microwave circuit (antenna) to the sum of the average power of the vertically and horizontally polarized waves received by an isotropic antenna [21]. Figure 15 shows the MEG, which is less than −3 dB. It can be calculated as in Eq. (11):

\[
MEG = 0.5 \left[ 1 - \sum_{j=1}^{N} |S_{jj}|^2 \right],
\]

where \( N \) is the number of antenna elements. A definite comparison between the proposed and the UWB-MIMO antenna presented in the literature is classified in Table II. It is perceptible that the proposed MIMO antenna is compact with high isolation.
A compact, printed low-profile UWB MIMO antenna with a low mutual coupling has been proposed in this article. Good isolation has been realised by using a perturbed stub from the ground plane. The MIMO antenna exhibits a bandwidth of 2.6–12 GHz, covering the entire UWB spectrum. The ECC value is less than 0.01, $CCL$ is less than or equal to 0.35 bps/Hz, $TARC$ is less than 0 dB, and $MEG$ is less than $-3$ dB throughout the UWB band, fulfilling a good diversity performance for a wireless system.

FUNDING
This research is funded by the Nigerian Communication Commission under grant NCC/R&D/TU/001.

REFERENCES
[1] D. Gesbert et al., “From theory to practice: an overview of MIMO spacetime coded wireless systems,” IEEE Journal Selected Areas on Communication, vol. 21, no. 3, pp. 281–302, 2003. https://doi.org/10.1109/JSAC.2003.809458
[2] A. Paulraj, R. Nabar and D. Gore. Introduction to space-time wireless communication. Cambridge University Press, Cambridge, UK, 2003.
[3] T. Daba et al., “Mutual coupling reduction between elements of UWB MIMO antenna using small size unipolar EBG exhibiting multiple stopbands,” International Journal of Electronics and Communication, vol. 93, pp. 32–38, 2018. https://doi.org/10.1016/j.ijecommer.2018.05.033
[4] Q. Ke-Wei et al., “An LTCC interference cancellation device for closely spaced antennas decoupling,” IEEE Access, vol. 6, pp. 68255–68262, 2018. https://doi.org/10.1109/ACCESS.2018.2879569
[5] B. K. Lau et al., “Impact of matching network on bandwidth of compact antenna arrays,” IEEE Transaction on Antennas and Propagation, vol. 54, no. 11, pp. 3225–3238, 2006. https://doi.org/10.1109/TAP.2006.883984
[6] A. Ijbas et al., “Mutual coupling reduction using F-shaped stubs in UWB-MIMO antenna,” IEEE Access, vol. 6, 2755–2759, 2018. https://doi.org/10.1109/ACCESS.2017.2785232
[7] B. T. P. Madhav, Y. U. Devi and T. Anikumar, “Defected ground structured compact MIMO antenna with low mutual coupling for automotive communication,” Microwave and Optical Technology Letters, vol. 61, no. 3, pp. 794–800, 2019. https://doi.org/10.1002/mop.31626
[8] R. Kumar and G. Surushe, “Design of microstrip-fed printed UWB diversity antenna with tee crossed shaped structure,” Engineering Science and Technology, an International Journal, vol. 19, no. 2 pp. 946–955, 2016. https://doi.org/10.1016/j.ijestch.2015.10.006
[9] A. Akgul and A. Tohtas, “Design of wideband orthogonal MIMO antenna with improved correlation using a parasitic element for mobile handsets,” International Journal of Microwave and Wireless Technology, vol. 8, no. 1, pp. 109–115, 2016. https://doi.org/10.1002/mmte.201500243
[10] C.-H. Lee, S.-Y. Chen and P. Hsu, “Integrated dual planar inverted-F antenna with enhanced isolation,” IEEE Antennas and Wireless Propagation Letters, vol. 8, pp. 963–965, 2009. https://doi.org/10.1109/LAWP.2009.2029707
[11] A. Diallo et al., “Enhanced two antenna structure for universal mobile telecommunication system terminals,” IET Microwave Antenna and Propagation, vol. 2, no. 1, pp. 93–101, 2008. https://doi.org/10.1049/iet-map:20060220
[12] M. Li, B. G. Zongh and S. W. Cheung, “Isolation enhancement for MIMO patch antenna using near-field resonators as coupling mode transducers,” IEEE Transaction on Antennas and Propagation, vol. 67, no. 2, pp. 755–764, 2019. https://doi.org/10.1109/TAP.2018.2880048
[13] H. S. Farahani et al., “Mutual coupling reduction in patch antenna array using a UC-EBG superstrate,” IEEE Antennas and Wireless Propagation Letters, vol. 9, pp. 57–59, 2010. https://doi.org/10.1109/LAWP.2010.2042565
[14] A. H. Jabire et al., “Characteristic mode analysis and design of wideband MIMO antenna consisting of metamaterial unit cell,” Electronics, vol. 8, no. 1, pp. 1–14, 2019. https://doi.org/10.3390/electronics8010068
[15] X. Zhao, S. Riaz and S. Geng, “A reconfigurable MIMO/UWB, MIMO antenna for cognitive radio applications,” IEEE Access, vol. 7, pp. 46739–46747, 2019. https://doi.org/10.1109/ACCESS.2019.2909810
[16] S. P. Biswal and S. Das, “A low profile dual-port UWB-MIMO/diversity antenna with band rejection ability,” Int. J. RF Microwave Computer-Aided Engineering, vol. 28, no. 1, e21159, 2018. https://doi.org/10.1002/mmce.21159
[17] Z. Tang et al., “Compact UWB-MIMO antenna with high isolation and triple band-notched characteristics,” IEEE Access, vol. 7, pp. 19856–19865, 2019. https://doi.org/10.1109/ACCESS.2019.2897170
[18] Y. Li and G. Yang, “Dual-mode and triple-band 10-antenna handset array and its multiple-input multiple-output performance evaluation in 5G,” International Journal of RF Microwave Computer-Aided Engineering, vol. 29, no. 2, e21538, 2019. https://doi.org/10.1002/mmce.21538
[19] R. Gurjar et al., “A novel compact self-similar fractal UWB MIMO antenna,” International Journal of RF Microwave Computer-Aided Engineering, vol. 29, no. 3, e21632, 2019. https://doi.org/10.1002/mmce.21632
[20] R. Hussain, M. S. Sharawi and A. Shamim, “An integrated four-element slot based MIMO and a UWB sensing antenna system for CR platforms,” IEEE Trans Antennas Propag, vol. 66, no. 2, pp. 978–983, 2018. https://doi.org/10.1109/TAP.2017.2781220
[21] N. M. K. Al-Aini et al., “A design of MIMO prototype in C-band frequency for future wireless communication,” Advanced Electromagnetics, vol. 9, no. 1, 78–84, 2020. https://doi.org/10.7716/aem.v9i1.1333
Anas Abdu was born in Kiyawa Local Government, Jigawa State, Nigeria (720102). He received his B. sc. degree in Physics from Bayero University Kano, Nigeria, and M. sc. degree in Signal and Information Processing from Tianjin University of Technology and Education, PR China, in 2009 and 2014, respectively. He is currently pursuing his Doctoral degree in Electronics and Technology at Hebei University of Technology, PR China. His research interests include wireless body area network (WBAN), wearable and textile antennas, and millimeter-wave techniques. E-mail: anas.abdu@fud.edu.ng

Sani Saminu was born in Kano State, Nigeria (711101). He received his B. sc. degree in Electrical and Electronic Engineering from Kano University of Science and Technology, Wudil, Kano, Nigeria. He obtained M. sc. degree in Electrical and Electronic Engineering from Yasar University, Izmir, Turkey. He has been working with the Biomedical Engineering Department, University of Ilorin, Nigeria. He is currently a Doctoral candidate at the School of Electrical Engineering, Hebei University of Technology, Tianjin, China. His research interests are in the signal processing, wireless communication, and instrumentation, particularly in biomedical applications. E-mail: sansam4k@gmail.com ORCID iD: https://orcid.org/0000-0002-5182-7150

Sani Salisu was born in Zaria Local Government, Kaduna, Nigeria (810222). He attended the Nigerian Military School Zaria from 1999 to 2004 and headed to Ahmadu Bello University Zaria for the first degree where he obtained B. sc. in Electrical Engineering in 2010. He then proceeded to Kingston University London and obtained M. sc. degree in Renewable Energy Engineering in 2013. He then proceeded to Universiti Teknologi Malaysia in 2016 where he obtained a Doctoral degree in Electrical Engineering in 2020. He is currently a Senior Lecturer at the Department of Electrical Engineering of the prestigious Ahmadu Bello University Zaria. E-mail: sansalisu@abu.edu.ng

Abubakar Muhammad Sadiq was born in Yamaltu/Deba Local Government Area of Gombe State, Nigeria (760222). He received his B. sc. degree in Electrical and Electronic Engineering from the Abubakar Tafawa Balewa University, Bauchi, Nigeria, in 2014, and M. sc. degree in Signal and Information Processing from the Tianjin University of Technology and Education, Tianjin, China, in 2019. He is currently pursuing a Doctoral degree in Microsystems and Solid-state Electronics at Tianjin University (TJU), Tianjin, China. His current research interests include antennas in the new generation of mobile communication, magnetoelectric (ME) dipole antennas, reconfigurable antenna and antenna arrays, circular polarized antennas, multi-in-multi-out antenna, and Yagi-Uda antennas. E-mail: amsadiq32@gmail.com ORCID iD: https://orcid.org/0000-0002-0165-3914

Adamu Mohammed Jajere was born in Fune Local Government Area of Yobe State, Nigeria (620232). He received his B. sc. degree in Computer Engineering from the University of Maiduguri, Nigeria, in 2012, and M. sc. degree in Signal and Information Processing from Tianjin University of Technology and Education, Tianjin, PR China, in 2017. He is currently a Doctoral student at School of Microelectronics, Tianjin University, Tianjin, PR China. His research interest includes designing and analysing multi-functional antennas, signal and medical image processing, and modern wireless network design. Mr. Mohammed Jajere is a professional member of the Institute of Electrical and Electronics Engineers (IEEE), International Association of Engineers (IAENG), and also a registered engineer by the Council for the Regulation of Engineering in Nigeria (COREN). E-mail: mainajajere@tju.edu.cn ORCID iD: https://orcid.org/0000-0002-0374-5847

Yusuf Kola Ahmed was born in Kwara, State Nigeria (240212). He received his B. sc. degree in Electrical and Electronic Engineering from the University of Ilorin, Kwara State and M. sc. degree in Electrical and Electronic Engineering from the University of Ibadan, Oyo State, both in Nigeria. He joined the Biomedical Engineering Department of the University of Ilorin in 2015 and currently is a Lecturer. His research interests include bioinstrumentation and control, signal processing and telemedicine. E-mail: yusufahmed8519@gmail.com ORCID iD: https://orcid.org/0000-0002-1023-0307