TELKOMNIKA Telecommunication, Computing, Electronics and Control
Vol. 18, No. 5, October 2020, pp. 2572~2579
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v18i5.13666

Performance analysis of negative group delay network using MIMO technique

Yaqeen S. Mezaal[1], Marwah Al-Ogaidi[2]
[1]Department of Medical Instrumentation Engineering, Al-Esraa University College, Baghdad, Iraq
[2]Department of Laser and Optoelectronics Engineering, Al-Nahrain University, Baghdad, Iraq

Article Info

Article history:

Received Jul 22, 2019
Revised Mar 19, 2020
Accepted Apr 17, 2020

Keywords:

Bit error rate
MIMO antenna
MIMO wireless networks
Negative group delay
STBC mathematical equations

ABSTRACT

This study introduces comparative consequences that determine the bit error rate enhancements, resultant from adopting a proposed MIMO wireless model in this study. The antenna configurations for this model uses new small microstrip slotted patch antenna with multiple frequency bands at strategic operating frequencies of 2.4, 4.4, and 5.55 respectively. The S11 response of the proposed antenna for IEEE802.11 MIMO wireless network has been highly appropriate to be adopted with MIMO antenna system. The negative group delay (NGD) response is the most significant feature for projected MIMO antenna. The NGD stands for a counterintuitive singularity that interacts time advancement with wave propagation. These improvements are employed for increasing a reliability of instantly conveyed data streams, enhance the capacity of the wireless configuration and decrease the bit error rate (BER) of adopted wireless system. In addition to antenna scattering response, the enhancements have been analysed in term of BER for different MIMO topologies.

Corresponding Author:

Yaqeen S. Mezaal,
Medical Instrumentation Engineering Department,
Al-Esraa University College,
Baghdad, Iraq.
Email: yakeen_sbah@yahoo.com

1. INTRODUCTION

Since 1960s, wireless systems have promptly mounting segments with the potential for making available, swift and super information exchange among convenient devices placed somewhere in the world. The remarkable growth of wireless communication technology is because of a union of numerous aspects. Primarily, the requirement of the wireless connection has increased highly. Secondly, the spectacular advancement of VLSI machinery has activated low-power and compact implementing of complex code and signal processing. Thirdly, 2nd generation wireless communication standards, as in GSM, cause it achievable to broadcast voice with small volume of digital data. In addition, a 3rd generation of wireless systems has given clienteles higher service quality which accomplishes greater capacity and spectral efficiency [1].

Prospective applications activated by wireless systems consist of multimedia facilities on cellular phones, stylish homes, computerized highway systems, video chatting and self-directed sensor networks. On the other hand, there have been dual major technological challenges in sustaining these appliances: first challenge includes a fading occurrence, deviation time of the channel in consequence of a small-scale outcome of multipath fading along with large-scale influence as in pass loss by remote attenuation and obstacles shadowing. Moreover, as wireless sender and receiver require air communication with noteworthy interference among them. All challenges have been mainly due to restricted accessibility of radio frequency range and the complex time-varying wireless regulating.

At present, a main objective in wireless engineering is for upturning information rate and developing transmission dependability. Specifically, owing to the growing demand for superior bit rates, better-quality service quality, less faults, upper network capability and user coverage calls for inventive techniques which enhance spectral effectiveness and channel reliability, more and more wireless communication technologies have been initiated, like MIMO techniques [2]. In 1998, Alamouti built up diversity design using dual antennas in the transmit side and single antenna in the receive end. This design offers the identical diversity order like the maximal-ratio combining (MRC) in a receiver end, with single sending antenna and dual receiving antennas. Bandwidth extension in this design hasn't required. An entire coming response from receiving to sending antennas and its calculation complexity level have been identical to MRC [3]. Many categories of NGD network using RLC resonators were, in theory and experiments, proven in reported papers in [4-6]. Nevertheless, no one of them had employed transmission-type toplogy for NGD network by means of the parallel RLC resonator with a distributed transmission line due to an application inconveniency. Wilzeck et al. [7], proposed MIMO test-bed that uses two sending antennas and four receiving antennas receiver in "offline" mode, in which pre-processed data has been sent over-air and logged for upcoming processing. The receiving system permits 512 Mbytes of memory for every receive antenna and maximum sampling frequency of 100 MHz, which causes 2.68 seconds of logging time with 14-bit resolution. The test-bed has been in relation to Sundance's modular digital signal processing platform and plug-in radio frequency constituents produced through Mini-Circuits. Besides, bandpass filters using microstrip technique at 2.4 GHz resonant frequency have been used to prevent image bands and enhance the operation of adopted system. Lozano and Jindal [8], offered MIMO wireless network that has diversity principles.

This wireless system is based on the trade-off between spatial multiplexing and transmit antenna diversity. Bhatnagar et al. [9], showed MIMO OFDM wireless network using space time block coding (STBC) throughout Rayleigh channels by means of 2PSK as well as 4PSK modulations to conquer sub-channel interfering. Simulated output graphs showed that there is reduction in bit error rate amounts as SNR raises. On the other hand, the system throughput increases as SNR decreases. Premnath et al. [10], proposed a new rapid algorithm for antenna selection in wireless MIMO systems. This technique does comparable capacity as the most advantageous selection method and the rapid processing at more lessened computational costs. The applied uncomplicated G-circles process decreases the complication notably with a rational performance loss. It can be as well efficiently organized in correlation matrix-based on antenna selections. Multi band antennas for wireless systems have been presented in [11-18]. These devices are very important to operate in separated strategic bands for front ends of wireless systems especially for MIMO configurations. In this paper, the MIMO antenna configurations for IEEE802.11 model uses new microstrip slotted patch antenna with multiple interesting bands and significant NGD values. The return loss of the proposed antenna is suitable to be adopted with MIMO wireless configuration. By the influence of this antenna, the corresponding BER has been investigated using MATLAB simulator.

2. SPACE-TIME BLOCK CODES

Assume a wireless configuration has *N* sending antennas and *M* receiving antennas in a flat fading channel with a propagation gain $h_{mn,l}$. The parameter $h_{mn,l}$ is an independent complex Gaussian with variance 0.5 for every element in Rayleigh distributed random variable. Here, *n*, *m*, and *l* are indicators of sending antenna, receiving antenna and time, correspondingly. In STBC communication system, the code can be described by **C** matrix and STBC period by *L*. Supposing T is the symbol interval, a collected signal in a receive antenna *m* under *l*T time can be determined by [2, 19, 20]:

$$r_{m,l} = \sum_{n=1}^{N} h_{mn,l} c_{l,n} + n_{m,l} \tag{1}$$

$c_{l,n}$ represents the (*l*,*n*) part of the *L* by *N* code matrix **C**, while $n_{m,l}$ belongs to additive noise with variance σ^2 and zero-mean. In the case of quasi-static channel, the time index *l* in $h_{mn,l}$ is feasibly misplaced. Signify $(\cdot)^H$, $(\cdot)^*$ and $(\cdot)^T$ as a Hermitian transpose, a complex conjugate and a transpose, correspondingly. Through accumulating the vector form of received signal, as shown in (1) for quasi-static channel is expressed as:

$$R = CH^T + N \tag{2}$$

where R, H and N represent the L by M matrix with the (l,m) component $r_{m,l}$, the M by N channel matrix with the (m,n) element h_{mn}, and an L by M noise matrix.

It has been hard for implementing signal processing procedures to the matrix depiction in (2), because a code matrix **C** has not stated as a linear arrangement of STBC input symbols. Additionally, for not quasi-static channels, it is not possible to convert as shown in (1) into (2). Therefore, there is necessity to make an all-purpose expression form irrespective of code constitution or channel state. With the intention of applying signal processing techniques, linear superposition is required, as in (3);

$$\bar{r} = \bar{H}z + \bar{n} \tag{3}$$

Here, $\bar{\mathbf{r}}$ indicates the LM by 1 received signal vector, z has identified as the K by 1 sent signal vector $[z_1 \quad \cdots \quad z_K]^T$, $\bar{H}$ is the LM by K channel matrix, and $\bar{n}$ points to the LM by 1 noise vector. Various STBC schemes are feasibly changed into the linear superposition structure. A code matrix **C** used for Alamouti scheme [3] can be written as:

$$\boldsymbol{C} = \begin{bmatrix} z_1 & z_2 \\ -z_2^* & z_1^* \end{bmatrix}$$

The code is transformed into the linear superposition representation (LSR) in this following manner. Through determining the conjugating of 2nd half of the received signal, the LSR for Alamouti system has described by:

$$\begin{bmatrix} r_1 \\ r_2^* \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{2,1} \\ h_{2,2}^* & -h_{1,2}^* \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix}$$

where r_l, $h_{n,l}$, and n_l stand for M by 1 column vectors at time lT and have expressed as $[r_{1,l} r_{2,l} \cdots r_{M,l}]^T$, $[h_{1n,l} \quad h_{2n,l} \quad \cdots \quad h_{Mn,l}]^T$ and $[n_{1,l} \quad n_{2,l} \quad \cdots \quad n_{M,l}]^T$, correspondingly.

For quasi-static channels, the best possible discovery for the Alamouti method can be done by only multiplying the vector $\bar{r}$ by $\bar{H}^H$ and adjusting the symbol by symbol detector. A complete Maximum Likelihood (ML) search has denoted as the extensive exploration for equation solution, $min\|\bar{r} - \bar{H}z\|^2$, through inspection every probable sets of sent symbols. However, for wide-ranging STBC systems, it is not viable to generate a complex LSR for (3). For instance, for N=4 antennas configurations at a rate of 3/4, we assume C matrix [21] as:

$$\boldsymbol{C} = \begin{bmatrix} z_1 & z_2 & z_3 & 0 \\ -z_2^* & z_1^* & 0 & -z_3 \\ -z_3^* & 0 & z_1^* & z_2 \\ 0 & z_3^* & -z_2^* & z_1 \end{bmatrix} \tag{4}$$

This code matrix is not convertible to a complex LSR as achieved in the Alamouti code. But, if real and imaginary parts matrix facets are defined separately, the collected vector can be written in a real LSR. Ordinarily, by separating the real and imaginary components, each block code can be described. This is known as the lattice version.

3. LATTICE VERTION FOR STBC SCHEMES

A regular form of the lattice (higher orders) version for STBC can be constructed by dividing **C** matrix into dual components that are defined as $\tilde{C} = [C^R C^I]$ where C^R and C^I refer to real and imaginary elements of the vector or matrix, correspondingly. If $z_k = x_k + jy_k$ has been considered, presume that the (l,n) constituent of C represents $c_{l,n} = c_1 x_k + jc_2 y_k$, in which c_1 and c_2 stand for scalar constants. After that, the lth row vector of C^R and C^I has been symbolized by $c_l^R = [\cdots \quad c_1 x_k \quad \cdots]$, $c_l^I = [\cdots \quad c_2 y_k \quad \cdots]$ where $c_1 x_k$ and $c_2 y_k$ stand for the real and imaginary elements of $c_{l,n}$, respectively. At this point, $c_1 x_k$ and $c_2 y_k$ have been positioned at the nth location in $\mathbf{c}_l^R$ and $\mathbf{c}_l^I$. Such as the 2nd row vectors of matrix C^R and C^I as shown in (4) can be clearly acquired as $c_2^R = [-x_2 \quad x_1 \quad 0 \quad -x_3]$, $c_2^I = [y_2 \quad -y_1 \quad 0 \quad -y_3]$ [19]. By resembling the depiction lattice to transform a complex channel matrix equation into real lattice channel matrix $\widetilde{H}$ as stated in [14], the formation of $\widetilde{H}$ of the adapted code matrix $\tilde{C}$ will be:

$$\widetilde{H} = \begin{bmatrix} H_1^R & -H_2^I \\ H_1^I & H_2^R \end{bmatrix}$$

where the facets in H_1 and H_2 are calculated as a result of equivalent constituents of C^R and C^I. Namely, the *k*th column vector in the *l*th row block of the matrix H_1 (or H_2), $c_1 h_{n,l}$ (or $c_2 h_{n,l}$), has been evaluated using (*l*,*n*) part of C^R (or C^I), $c_1 x_k$ (or $c_2 y_k$). For instance, the 2nd row elements of H_1 and H_2 related to the row vectors c_2^R and c_2^I are gotten as $H_{1,2} = [h_{2,2} \quad -h_{1,2} \quad h_{4,2}]$ $H_{2,2} = [-h_{2,2} \quad h_{1,2} \quad -h_{4,2}]$. Accordingly, the size of real lattice channel matrix $\widetilde{H}$ has been 2*LM* by 2*K*. A lattice representation has lastly expressed as $\tilde{r} = \widetilde{H}\tilde{z} + \tilde{n}$ where;

$$\tilde{r} = \begin{bmatrix} r^R \\ r^I \end{bmatrix}, \tilde{z} = \begin{bmatrix} z^R \\ z^I \end{bmatrix}, \tilde{n} = \begin{bmatrix} n^R \\ n^I \end{bmatrix},$$

here, $r = [r_1 \quad r_2 \quad \cdots \quad r_L]^T$ and $n = [n_1 \quad n_2 \quad \cdots \quad n_L]^T$. After this representation rule, $\widetilde{\boldsymbol{H}}$ can be defined as:

$$\widetilde{\mathbf{H}} = \begin{bmatrix} \mathbf{h}_{1,1}^R & \mathbf{h}_{2,1}^R & \mathbf{h}_{3,1}^R & -\mathbf{h}_{1,1}^I & -\mathbf{h}_{2,1}^I & -\mathbf{h}_{3,1}^I \\ \mathbf{h}_{2,2}^R & -\mathbf{h}_{1,2}^R & -\mathbf{h}_{4,2}^R & \mathbf{h}_{2,2}^I & -\mathbf{h}_{1,2}^I & \mathbf{h}_{4,2}^I \\ \mathbf{h}_{3,3}^R & \mathbf{h}_{4,3}^R & -\mathbf{h}_{1,3}^R & \mathbf{h}_{3,3}^I & -\mathbf{h}_{4,3}^I & -\mathbf{h}_{1,3}^I \\ \mathbf{h}_{4,4}^R & -\mathbf{h}_{3,4}^R & \mathbf{h}_{2,4}^R & -\mathbf{h}_{4,4}^I & -\mathbf{h}_{3,4}^I & \mathbf{h}_{2,4}^I \\ \mathbf{h}_{1,1}^I & \mathbf{h}_{2,1}^I & \mathbf{h}_{3,1}^I & \mathbf{h}_{1,1}^R & \mathbf{h}_{2,1}^R & \mathbf{h}_{3,1}^R \\ \mathbf{h}_{2,2}^I & -\mathbf{h}_{1,2}^I & -\mathbf{h}_{4,2}^I & -\mathbf{h}_{2,2}^R & \mathbf{h}_{1,2}^R & -\mathbf{h}_{4,2}^R \\ \mathbf{h}_{3,3}^I & \mathbf{h}_{4,3}^I & -\mathbf{h}_{1,3}^I & -\mathbf{h}_{3,3}^R & \mathbf{h}_{4,3}^R & \mathbf{h}_{1,3}^R \\ \mathbf{h}_{4,4}^I & -\mathbf{h}_{3,4}^I & \mathbf{h}_{2,4}^I & \mathbf{h}_{4,4}^R & \mathbf{h}_{3,4}^R & -\mathbf{h}_{2,4}^R \end{bmatrix}$$

A different case we take in the consideration here, is the code, where some z_k's are joint in (*l*,*n*) element of **C** in the preservative form. Namely, z_k comes into view more than once in one row of **C**. This type of codes can be defined by adopting the linear superposition criteria. Accordingly, the code matrix will be [14]:

$$C = \begin{bmatrix} z_1 & z_2 & \frac{1}{\sqrt{2}} z_3 & \frac{1}{\sqrt{2}} z_3 \\ -z_2^* & z_1^* & \frac{1}{\sqrt{2}} z_3 & -\frac{1}{\sqrt{2}} z_3 \\ \frac{1}{\sqrt{2}} z_3^* & \frac{1}{\sqrt{2}} z_3^* & \frac{-z_1 - z_1^* + z_2 - z_2^*}{2} & \frac{-z_2 - z_2^* + z_1 - z_1^*}{2} \\ \frac{1}{\sqrt{2}} z_3^* & -\frac{1}{\sqrt{2}} z_3^* & \frac{z_2 + z_2^* + z_1 - z_1^*}{2} & -\frac{z_1 + z_1^* + z_2 - z_2^*}{2} \end{bmatrix}$$

A lattice channel matrix can be expressed as:

$$H_1 = \begin{bmatrix} h_{1,1} & h_{2,1} & \frac{1}{\sqrt{2}}\left(h_{3,1} + h_{4,1}\right) \\ h_{2,2} & -h_{1,2} & \frac{1}{\sqrt{2}}\left(h_{3,2} - h_{4,2}\right) \\ -h_{3,3} & -h_{4,3} & \frac{1}{\sqrt{2}}\left(h_{1,3} + h_{2,3}\right) \\ -h_{4,4} & h_{3,4} & \frac{1}{\sqrt{2}}\left(h_{1,4} - h_{2,4}\right) \end{bmatrix}$$

and

$$\boldsymbol{H}_2 = \begin{bmatrix} h_{1,1} & h_{2,1} & \frac{1}{\sqrt{2}}\left(h_{3,1} + h_{4,1}\right) \\ h_{2,2} & h_{1,2} & \frac{1}{\sqrt{2}}\left(h_{3,2} + h_{4,2}\right) \\ h_{4,3} & h_{3,3} & -\frac{1}{\sqrt{2}}\left(h_{1,3} + h_{2,3}\right) \\ h_{3,4} & -h_{4,4} & \frac{1}{\sqrt{2}}\left(h_{2,4} - h_{1,4}\right) \end{bmatrix}$$

In the circumstances of the quasi-static channel response, the equivalent channel matrix has been orthogonal in a case of orthogonal code matrix [19]. Consequently, a transpose of real lattice channel matrix $\widetilde{H}^T$ belongs to a matched filter. The symbol by symbol ML detection has been in a highly advantageous case and optimal after matched filtering. The outcome of the matched filtering for a symbol z_k has been:

$$\hat{z}_k = \gamma z_k + \hat{n} = \sum_{m=1}^{M} \sum_{n=1}^{N} |h_{mn}|^2 z_k + \hat{n}$$

where $\hat{n}$ represents a new term of additive noise with mean equals to 0 and variance equals to $\sum_{m=1}^{M} \sum_{n=1}^{N} |h_{mn}|^2 \sigma^2$, and γ is the channel response power. However, more in-depth STBC encoding and decoding information with the various number of transceiver antennas have given in [20-25].

4. MIMO SYSTEM MODEL OF IEEE 802.11

Alamouti scheme has been employed extensively in MIMO wireless systems. The typical adopted MIMO block diagram uses STBC signal processing at transmit and receive antennas as in Figure 1. We used applied wave research (AWR) electromagnetic package in designing and simulation of that MIMO antenna. This simulation software package provides schematic circuit technology with good performance in accuracy, capacity, convergence and speed. The microstrip antenna with uniform geometrical slot provides good performance of the antenna frequency response using dual via ports.

This MIMO antenna, as depicted in Figure 2, has been modelled based on FR4 substrate with dielectric constant of 4.4 and h of 1.6 mm. Dual via ports are positioned in the main microstrip resonator. The projected antenna substrate dimensions have overall of 31x31 mm^2. The consequent S11 (return loss) response has clarified in Figure 3. The S11 response in this graph has band frequencies of 2.4 GHz, 4.4 GHz, and 5.54 GHz. The subsequent input reflection values are 20.1, 18, and 15.2 dB for each band respectively, while the bandwidth ranges are 2.389-2.42, 4.314-4.47 and 5.545-5.61 GHz for the same band frequencies respectively. The new MIMO antenna has compact size and worthy frequency responses and multiple service bands that have been looked-for features for many MIMO wireless configurations as perceived by Figure 3. Table 1 explains the dimensions of proposed MIMO antenna.

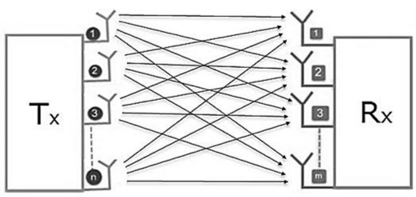

Figure 1. MIMO model

Table 1. Dimensions of the proposed MIMO antenna

Parameter	Value (mm)
Wg, Lg	31, 31
Wp1, Lp1	2.5, 30
p2	5
Wp3, Lp3	1, 5

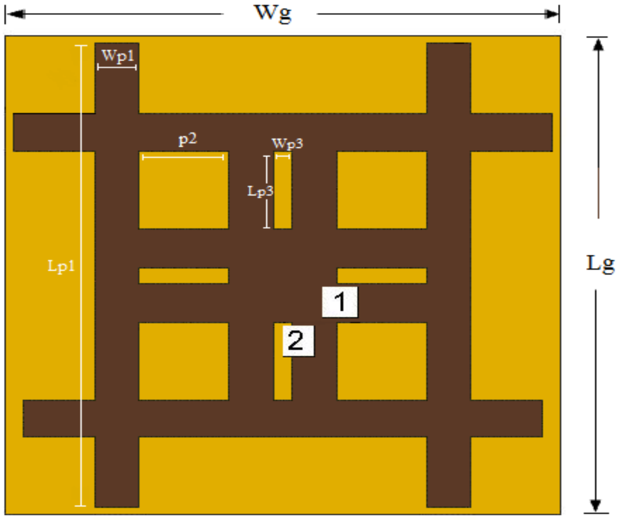

Figure 2. The modelled layout of multiband antenna

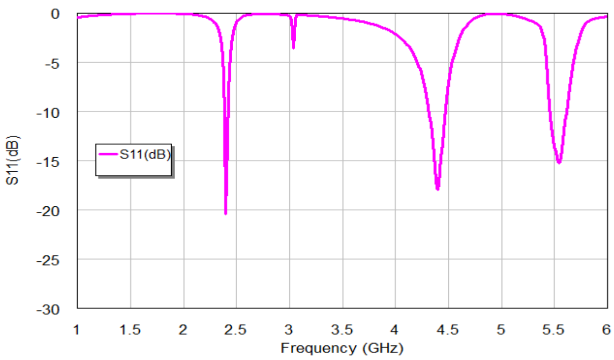

Figure 3. The S11 frequency responses of proposed MIMO antenna

With the intention of getting close by the angle response of S11 scattering parameter of the suggested microstrip MIMO antenna, simulation phase response at band resonant frequencies is depicted in Figure 4. This graph shows that the proposed antenna has good phase response linearity within 1 to 6 GHz sweeping frequency range. In Figure 5, group delay response of projected antenna has been presented. For this response, a positive group delay means that the pulse is shifted back in time as it passes through an antenna; whereas a negative group delay means it is shifted forward in time. The latter case doesn't necessarily violate causality, it just means that the antenna predicts where the pulse will be in the future, based on where it is now. The negative group delay (NGO) response is highly interested recently for RF and microwave devices including antennas [26]. Here, significant NGD values with -14.71, -3.2 and -1.507 ns are found in 2.4, 3.04 and 5.55 GHz. Using a suitable script to interface between AWR and MATLAB simulators, the used parameters in the simulated channel model have illustrated in Table 2. It has been essential here to reference that the entire bit error rate results in this paper are done with some transmitted bits of 10^6 bits and carrier frequency of f_c = 2.4 GHz related to the first band of employed antenna.

The channel code is employed for information encoding, and the encoded data has split into different data streams, all of them transmitted, based on numerous transmit antennas. The inward signal at every receive antenna is linear. Figure 6 illustrates BER responses with respect to signal to noise ratio (S/N) for 2PSK digital modulation in the case of Rayleigh channel. It explains as N and M are increased, the BER remains on declining and presents superior BER output as a result of spatial diversity. It has been important to indicate that (SIMO) antenna groupings (1x2 and 1x4) have higher quality BER results unlike (2x1 and 4x1) multiple input single output (MISO) antenna arrangements. This has been due to the received data from an active link makes antenna diversity order of 4 and 8, in which diversity order has been generally twofold a number of receiving antennas. For the number of symbols = 1000000 (transmitted), we can merely measure BER down to 10^{-5} consistently as in Figure 6. The most advantageous BER has been found in (4x4) antenna configurations.

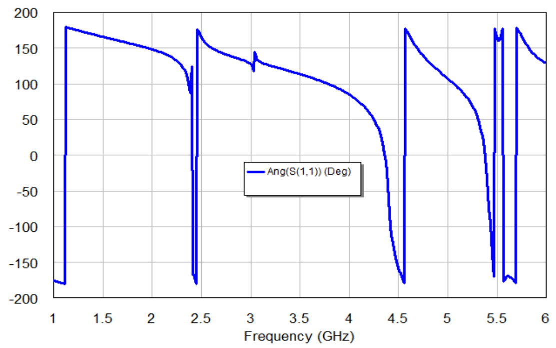

Figure 4. Phase responses of MIMO antenna

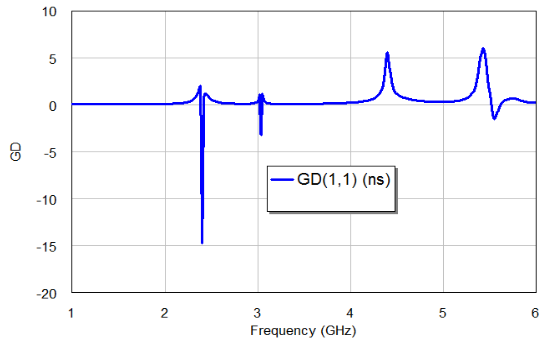

Figure 5. Group delay response of MIMO antenna

Table 2. The Simulated channel model parameters

Parameter	Magnitudes
Carrier frequency f_c	2.4 GHz
Sampling frequency f_s	10 KHz
Sent bits	10^6 bit
Modulation type	BPSK
N , M	1, 2,3,4

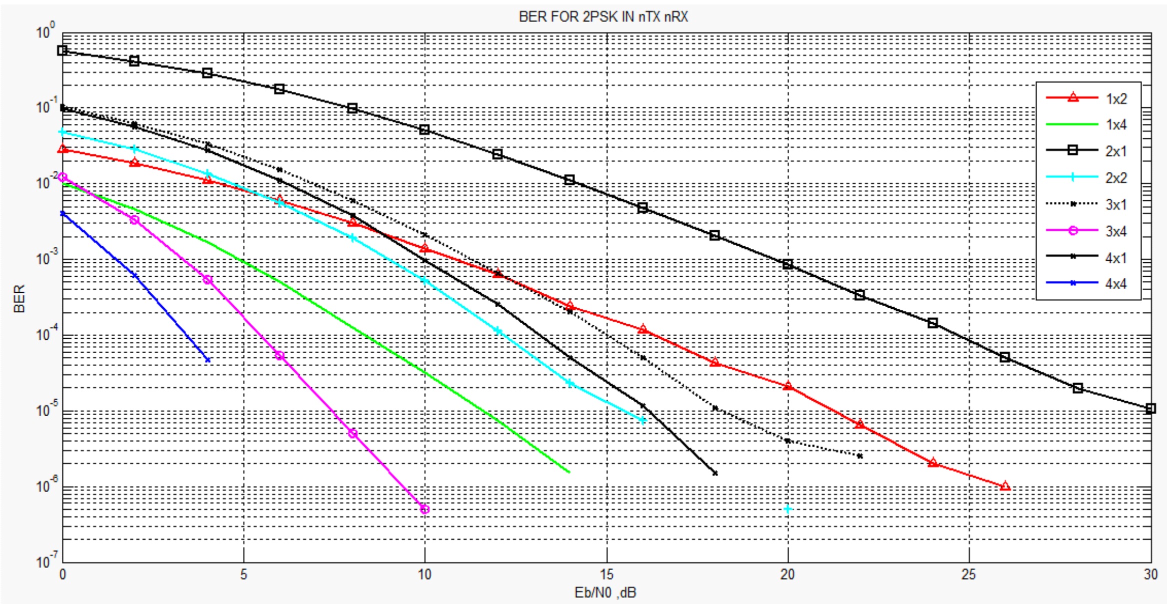

Figure 6. Bit error rate results of 2 PSK MIMO System with several antenna arrangements

5. CONCLUSION

The new implementation and characteristic of self-designed MIMO antenna was employed as multi band device. The proposed device provides frequency band responses at 2.4, 4.4, and 5.55 GHz respectively within (1-6) GHz frequency sweeping range with low insertion loss and high return loss magnitudes as well as the compactness property of the projected antenna. This antenna offers significant NGD magnitudes with -14.71, -3.2 and -1.507 ns at 2.4, 3.04 and 5.55 GHz. Simulation results of BER for 2 PSK MIMO NGD network with several antenna arrangements are tolerable. The enhanced IEEE802.11 wireless model has very good error rate performance, since it has the diversity gain by coding across time and space for accomplishing the reliable transmission.

REFERENCES

[1] U. Dalal, ”Wireless communication," Oxford University Press, Inc., 2010.
[2] Y. S. Mezaal, “Performance Enhancement of IEEE 802.11 Wireless Network Using MIMO Technique," *Proceedings 2nd international conference of southern technical university*, Basrah, Iraq, 2017.
[3] S. M. Alamouti, “A Simple Transmit Diversity Technique For Wireless Communications,” *IEEE Journal on Selected Areas in Communications*, vol.16, no. 8, pp. 1451- 1458, Oct 1998.
[4] G. Chaudhary, et al., “Compact negative group delay circuit using defected ground structure,” *Proceedings of the IEEE Asia-Pacific Microwave Conference*, pp. 22-24, November 2013.
[5] M. Kandic and G. E. Bridges, “Asymptotic limits of negative group delay in active resonator-based distributed circuits,” *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 58, no. 8, pp. 1727–1735, Aug 2011.
[6] Ramachandran, et al., “A compact triband quad-element MIMO antenna using SRR ring for high isolation,” *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 1409-1412, Dec 2016.
[7] A. Wilzeck, et al., “MIMO prototyping testbed with off-the-shelf plug- in RF hardware,” *IEEE Workshop on Smart Antennas*, Ulm, Germany, 2006.
[8] A. Lozano, et al., “Transmit diversity vs. spatial multiplexing in modern MIMO systems,” *IEEE Transactions on Wireless Communications*, vol. 9, no. 1,pp. 186-197, January 2010.
[9] P. Bhatnagar, et al., “Enhancement of OFDM system performance with MIMO technique," *International Journal of Computer Technology and Electronics Engineering (IJCTEE)*,vol. 1, no.3, 2011.
[10] S. P. Premnath, et al., “Performance enhancement of MIMO system using antenna selection algorithm,” *International Journal of Emerging Technology and Advanced Engineering*, vol. 3, no. 1, January 2013.
[11] Y. S. Mezaal and S. A. Hashim, “Design and simulation of square based fractal slot antennas for wireless applications,” *Journal of Engineering and Applied Sciences*, vol.13,no.17,pp. 7266-7270, Oct 2018.
[12] Y. S. Mezaal and D. A. Hammood, " New microstrip quasi fractal antennas: Design and simulation results," *IEEE 36th International Conference on Electronics and Nanotechnology (ELNANO)*, pp. 75-78, April 2016.
[13] Y. S. Mezaal, “New microstrip semi-fractal antenna: Design and simulation results," *IEEE 24th Signal Processing and Communication Application Conference (SIU)*, pp. 1601-1604, May 2016.
[14] K. V. Babu and B. Anuradha, “Design of multi-band minkowski MIMO antenna to reduce the mutual coupling,” *Journal of King Saud University-Engineering Sciences*,vol. 32, no. 1, pp. 51-57, January 2020.
[15] N. K. Maurya and R. Bhattacharya, “Design of compact dual-polarized multiband MIMO antenna using near-field for IoT,” *AEU-International Journal of Electronics and Communications*, vol. 117, April 2020.
[16] A. R. Saad, “Low-profile MIMO antenna arrays with left-handed metamaterial structures for multiband Operation,” *Progress In Electromagnetics Research*, vol. 89, pp. 1-11, 2020.
[17] V. Satam and S. Nema, “Six-element dual polarized high-gain MIMO antenna for multiband applications,” *Microwave and Optical Technology Letters*, vol.62, no. 1, pp. 217-225, 2020.
[18] C. K. Ghosh ,et al., “Mutual coupling reduction of microstrip MIMO antenna using microstrip resonator,” *Wireless Personal Communications*, pp.1-10, January 2020.
[19] W. Lee, et al., “Channel equalization technique for space time block codes in non quasi-static channels,” *Journal of Power Electronics*, vol. 60, no.3, pp. 2215-2219, September 2004.
[20] Y. Huang, et al., “System performance research and analysis of MIMO-OFDM based on space time block codes,” *International Conference on Intelligent Control and Information Processing*, pp. 414-417, August 2010.
[21] M. Jankiraman, “Space-time codes and MIMO systems,” Artech House, Boston, London, 2004.
[22] E. Biglieri, et al., “MIMO wireless communications,” Cambridge University Press, USA, 2007.
[23] M. Rintamaki, “Adaptive power control in CDMA cellular communication systems,” Helsinki University of Technology publisher, 2005.
[24] B. Vucetic, et al., “Space-time coding,” John Wiley & Sons Ltd, 2003.
[25] T. Ravibabu and C. D. Raj, “BER Analysis of spatial multiplexing and STBC MIMO-OFDM system,” *IEEE 4th International Conference on Devices, Circuits and Systems (ICDCS)*, pp. 110-116, March 2018.
[26] G Chaudhary, et al., “Realization of negative group delay network using defected microstrip structure,” *International Journal of Antennas and Propagation*, 2014.