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Mutual Coupling in a Collocated Dipole Antenna Setup: A Comprehensive Review

Ademola S ADESOYE
Department of Electrical and Electronics Engineering
Federal University of Technology, FUTA, Akure, Nigeria
ademoladesoye@gmail.com

Jide J POPOOLA
Department of Electrical and Electrical Engineering
Federal University of Technology, FUTA, Akure, Nigeria
jjpopoola@futa.edu.ng

Akinwale O FADAMIRO
Department of Computer Engineering
Federal University of Technology, FUTA, Akure, Nigeria
aofadamiro@futa.edu.ng

***Abstract*— The dipole antenna is one of the most important and frequently used radio frequency (RF) antennas. It is used on its own and integrated into many other RF antenna designs, where it serves as the driving element for the antenna. To save cost and ensure a wider reach for wireless communication users, wireless communication operators and users put their antennas in the same location in the base station mast or buildings, known as collocation and can also be put in an array system. The major problem with the collocation of antennas is that the antennas interact with one another by receiving signals from one another, known as mutual coupling. This reduces the overall performance of the antennas by lowering the gain, altering the radiation patterns and the antenna impedance when they are not properly placed from one another. This paper present review of different mutual coupling reduction techniques with past works of several researchers and concludes with the most efficient method to reduce mutual coupling in an antenna array or collocated system.**

Keywords—Mutual coupling; Dipole antenna; Interference; mutual impedance; Collocation

I. INTRODUCTION

An antenna is an electromagnetic device that is used to transmit and receive radio signals. Antennas consist of a conductor designed to work on a radio frequency of different shapes and sizes. An example of such an antenna is a dipole antenna [1].
A dipole antenna (likewise recognized as a doublet or dipole aerial) is a straight electrical conductor measuring half wavelength from end to end and coupled at the center to a radio frequency (RF) feed line. The dipole is any one of the varieties of antennas that produce a radiation pattern approximating an elementary electric dipole. Dipole antennas are the simplest and most widely used type of antennas. The finite length dipole antenna includes a half-wave dipole antenna, a full-wave dipole antenna, folded dipole antenna. The half-wave dipole antenna is used to operate at the frequency range of 3kHz to 300GHz and is used to feed or drive bigger antennas which are convenient for GSM, television cable system, satellite communication which is the most commonly used standard for wireless telecommunication [2].
The wireless access of information and telecommunication services has changed the operational dynamics of individuals and industries across the board. An increase in the users of smartphones, increased mobile communication services, increased number of cable television users, limited spectrum resources, and increased radio frequency service providers have led to frequency reuse in cellular network architecture [3]. To improve the quality of service in the network, this has led to a diverse range of challenges in the network architecture. One of such challenge is the placement of several radio frequency transceiver antennas at close proximity to one another (either on the same building or on the same network mast/tower); the concept is known as collocation.
Collocation is a wireless communication facility owned and operated by a communication service provider located on the same tower, building, accessory structure, or property as another telecommunication facility owned or operated by a different communication service provider. It is also a situation where two or more RF users share the same infrastructure in a particular site. The shared infrastructure could range from the site, tower, shelter, generator, and even the air conditioning system. New operators can lease antenna space on the tower, install their shelters within the site of an existing operator, and share the cost of running and securing the site [4] [5].
Sharing a common site has its economic advantages. Multiple service providers can consolidate to reduce maintenance costs, rental, logistics, and other recurrent expenditures. This allows mobile stations to have reduced filtering and dynamic range specifications [6]. In addition, it minimizes the stealing

of antenna equipment and increases the level of interference due to signals from surrounding antennas [5] [7] [8]. When multiple antennas are placed within a limited space, interference is bound to occur. Interference in modern communication networks is undesirable, limiting the benefits desirable from this communication [3].

Interference is when two or more waves superpose to form a resultant wave greater, lower, or the same in amplitude. It modifies or disrupts a signal as it travels along a channel between the source and the receiver, i.e., it is the addition of unwanted and wanted signals. Interference has been found to be high when two or more antennas are in close proximity due to interaction in signals between the antennas. This effect is known as mutual coupling.

Mutual coupling is the electromagnetic interaction between the antenna elements in an array. The current developed in each antenna element of an array depends on their excitation and the contribution from adjacent antenna elements. Mutual coupling between antenna elements is well known as an undesired effect, which degrades the performance of array signal-processing algorithms [9]. Various methods have been used to reduce or isolate mutual coupling and some would be discussed in this paper.

This paper aims to review the different techniques for reducing mutual coupling in a collocated antenna or array system.

II. DIPOLE ANTENNA

The dipole antenna consists of two straight electric wires separated by a small gap at the center, and the power is fed at the center gap. The electric cables should be electrically thin, i.e., the linear dimensions of its cross-section are much smaller than the wire length. It is an omnidirectional antenna, and its polarization is determined by the orientation of the wires, which can be horizontal, vertical, or at the slant [10].

Dipole antennas are widely used due to their simple characteristics and ease of implementation in an array configuration. Dipole antennas vary in shape and sizes, including short dipole antennas, half-wavelength dipole antennas, monopole antennas, V-shaped antennas, folded dipole antenna Yagi-Uda antenna, whip antenna, etc. An example of a simple dipole antenna application is given in Figure 1 [12].

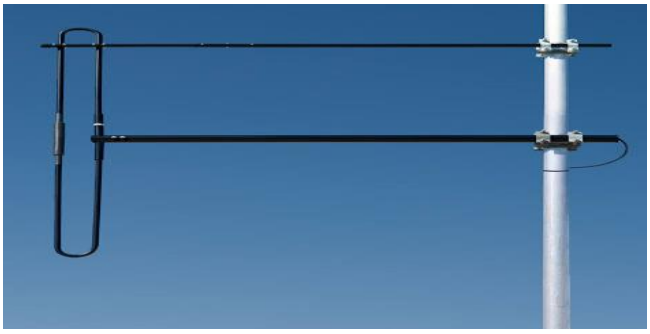


Figure 1: A Dipole Antenna [11]

III. APPLICATION OF DIPOLE ANTENNAS

Dipole antennas have been found to have various uses. Depending on its construction, it is either a directional or an omnidirectional antenna with a high frequency of 3kHz to 300GHz with high gain uses [15]. Dipole antennas have different applications across the world of wireless communication. It can be used as a radio receiver, a television receiver, and a radio frequency transmitter for mobile communication. When used with various antennas, it has a wide variety of applications [16]. The dipole antenna can be further constructed as a half-wave dipole antenna with various applications, which can also be constructed as a half-wave folded dipole antenna that can be used where optimum power transfer is needed and where large impedances are needed. The folded dipole antenna is used as the main element in the construction of the Yagi-Uda antenna [16] [17] for Television cable services. The application of the folded dipole is enormous as it is used as major radio receivers, parabolic antennas in base stations as GSM transmitting antennas, turnstile antenna that can be used as spacecraft antenna, log periodic antenna, phased and reflector array.

IV. DIPOLE ANTENNA ANALYSIS

The geometry arrangement and current distribution of a small dipole antenna are shown in Figure 2a and 2b, respectively [14].

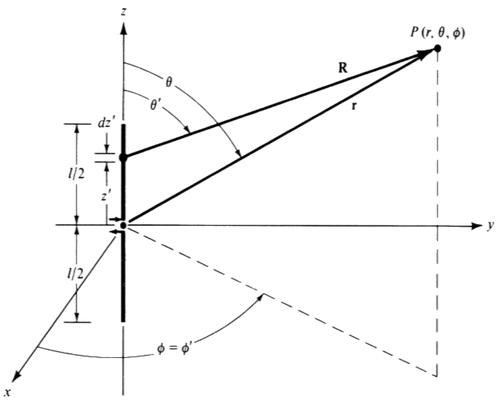


Figure 2a: A Dipole Geometry *[14]*

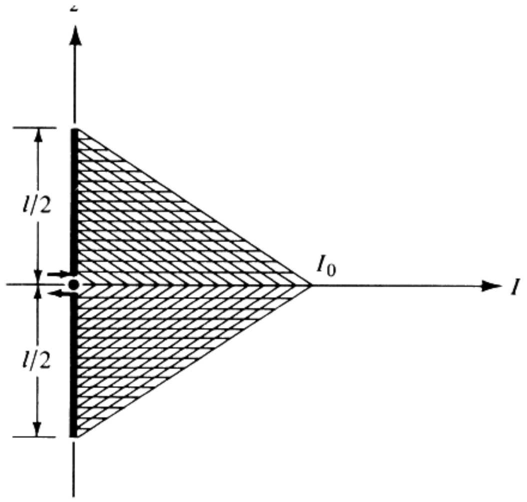


Figure 2b: Current Distribution *[14]*

The vector potential Ā for a dipole antenna can be written as [14];

$$\bar{A}_z = \frac{\mu}{4\pi}[\hat{a}_z \int_{-\frac{l}{2}}^{0} I_o \left(1+\frac{2}{l}z'\right)\frac{e^{-jkR}}{R}dz' + \hat{a}_z \int_{0}^{\frac{l}{2}} I_o \,(1 - \frac{2}{l}z')\frac{e^{-jkR}}{R}dz'$$

(1)

Where I_o is a constant
Because the overall length of the dipole is very small, the values of R for different values of z along the wire length are not much different from r. Thus, R can be approximated by R≈ r throughout the integration path. Performing the integration, equation (1) reduces to [14] [12]:

$$\bar{A} = \hat{a}_z \bar{A}_z = a_z \frac{1}{2}\left[\frac{\mu I_o l e^{-jkr}}{4\pi r}\right]$$

(2)

The field component of the dipole antenna can be determined using the vector potential $\bar{A}$. The magnetic field is determined using

$$\bar{H} = \frac{1}{\mu}\nabla \times \bar{A} = -\hat{a}_\phi \frac{1}{\mu}\frac{\partial \bar{A}_z}{\partial \rho}$$

(3)

Using the cylindrical coordinates to analyze equation (3), the magnetic field intensity of the dipole antenna is given as [14]:

$$\bar{H} = \hat{a}_\emptyset \bar{H}_\emptyset = -\hat{a}_\emptyset \frac{I_o}{4\pi j}\frac{1}{y}\left[e^{-jkR_1} + e^{-jkR_2} - 2\cos\left(\frac{kl}{2}\right)e^{-jkr}\right]$$

(4)

Where

$$r = \sqrt{x^2+y^2+z^2} = \sqrt{\rho^2+z^2}$$

(5a)

$$R_1 = \sqrt{x^2+y^2+(z-\frac{l}{2})^2} = \sqrt{\rho^2+(z-\frac{l}{2})^2}$$

(5b)

$$R_2 = \sqrt{x^2+y^2+(z+\frac{l}{2})^2} = \sqrt{\rho^2+(z+\frac{l}{2})^2}$$

(5c)

The corresponding electric field is found by using Maxwell's equation:

$$\bar{E} = \frac{1}{j\omega\varepsilon}\nabla \times \bar{H}$$

(6)

Where the component of the electric field radiated by the dipole are [14]:

$$\bar{E} = \hat{a}_\rho \bar{E}_\rho + \hat{a}_z \bar{E}_z = -\hat{a}_\rho \frac{1}{j\omega}\frac{\partial \bar{H}_\emptyset}{\partial z} + \hat{a}_z \frac{1}{j\omega\varepsilon}\frac{1}{\rho}\frac{\partial}{\partial \rho}(\rho \bar{H}_\phi) \quad (7)$$

$$\bar{E}_\rho = \bar{E}_y = j\frac{\eta I_0}{4\pi y}\left[\left(z-\frac{l}{2}\right)\frac{e^{-jkR_1}}{R_1} + \left(z+\frac{l}{2}\right)\frac{e^{-jkR_2}}{R_2} - 2z\cos\left(\frac{kl}{2}\right)\frac{e^{-jkr}}{r}\right]$$

(8)

$$\bar{E}_z = -j\frac{\eta I_0}{4\pi}\left[\frac{e^{-jkR_1}}{R_1} + \frac{e^{-jkR_2}}{R_2} - 2z\cos\left(\frac{kl}{2}\right)\frac{e^{-jkr}}{r}\right] \quad (9)$$

Equation vanishes when the overall length of the element is an integral number of odd half-wavelength ($l = \frac{n\lambda}{2}, n = 1,3,5,\ldots$), because $\cos\left(\frac{kl}{2}\right) = \cos\left(\frac{n\pi}{2}\right) = 0 \; for \; n = 1,3,5,\ldots$

Using a finite length dipole antenna (ideally zero diameter), with the antenna center-fed, the current vanishes at the endpoints ($z = \pm\frac{l}{2}$). The current distribution along the wire is given by [14]:

$$I_z = 2\pi a J_z = I_m \sin\left[k\left(\frac{l}{2} - |z'|\right)\right]$$

(10)

V. COLLOCATION

Wireless communication is made of a set of networks that transports the data necessary for telecommunication services. Each network requires building, operating, and maintaining an infrastructure made up of a combination of different types of assets. These assets include passive infrastructure assets, such as but not limited to masts, shelters, air conditioning equipment, active infrastructure assets, such as antennas, transceivers, microwave radio equipment, switches, and intangible assets like spectrum licenses [18] [19].
Collocation, otherwise known as infrastructure sharing in wireless communication, refers to the joint use of the assets necessary to provide wireless communication services to reduce network infrastructure building operation and maintenance. Sharing can be done at any of the wireless communication networks [18]. It is useful to build coverage quickly while saving cost, mainly when covering a substantial number of areas in a telecom start-up phase. Sharing of infrastructure can help in achieving this goal.
Due to the close proximity of antennas with other antennas in a collocated site, they are bound to receive unwanted signals from another antenna that are close by, causing degradation in the performance of the antennas. This phenomenon can be referred to as interference.

VI. INTERFERENCE

The term interference occurs when two waves leaving a source travel by different paths arrive at a point. This occurs in micro wave space propagation as this is one of the optical properties of radio wave propagation [20]. The optical effects such as diffraction, reflection, and interference can alter the ray wave front propagation from the normal space wave behavior in the earth's atmosphere [21].

Radio frequency interference is the reception of unwanted signal(s), which causes a detrimental effect on the reception of the desired signal. Technically, it can be defined as an electromagnetic disturbance due to the super-imposition of an unwanted signal on a wanted signal, producing a resultant signal having both wanted and unwanted signal [21]. Interference limits the overall performance of all communication systems by restricting the operation range, generation of error messages, and in dire cases, it prevents receivers from receiving desired signals.

A. TYPES OF INTERFERENCE

There are different types of interference in wireless communication systems. The common ones are;

i. Self-interference
ii. Multiple access interference
iii. Co-channel interference
iv. Adjacent channel interference

Self-Interference is induced by signals that are transmitted on a shared transmitter.

Multiple Access Interference is induced by transmission from multiple radios using the same frequency resource.

Co-channel Interference occurs when more than one user is using the same radio frequency at a time.

Adjacent Channel Interference occurs when a strong signal from a neighboring antenna affects the signal from other antennas.

B. INTERFERENCE MITIGATION

There are various types of interference mitigation techniques that are being used today. They would be discussed.

1) INTERMODULATION SOLUTION

The amplitude modulation of signals containing two or more frequencies in a signal with non-linearities is called intermodulation. Intermodulation between the frequencies brings about additional signals at frequencies that are not in harmonic frequencies with one another but also at the same sum and or difference frequencies of the original frequencies and their multiples [22].

The types of intermodulation in collocated base stations are; forward and reverse intermodulation (RIM). The forward intermodulation (FIM) components are produced in the victim's receiver and are of great concern when they affect the required signal. A knowledge-based filtering solution was proffered in [23] to eliminate the forward intermodulation components. This approach relies on the knowledge of collocated transceiver specifications antenna pattern. [24] proffered another approach that locates the jamming signal by scanning the spectrum with fast fourier transform (FFT), after which it would be removed with a tunable notch filter [25].

The reverse intermodulation (RIM) components are produced when high-powered transmission from a jammer radiates its signal into the antenna system of another jammer. The adaptive solution for reverse intermodulation is classified into transmitter-end solutions and interference cancellation using regenerated distortions. The transmitter-end solution involves placing multiple isolators at the power amplifier output [26].

2) FREQUENCY PLANNING TECHNIQUE

Frequency (channel) allocation in wireless communication is paramount in the world of telecommunication. With the increase of users using wireless technology, the frequency spectrum has remained fixed. This has given rise to frequency allocation problems, which are modeled as a multi-objective, multi-constraint optimization problem given several base stations with limited available channels [27]. It is then required to find an optimal frequency plan that can satisfy the demand for channels of wireless communication users and the interference constraint.

3) GENETIC ALGORITHMS

Evolutionary computation is an approach that models biological evolutionary principles to solve complex mathematical optimization problems. Evolutionary computation can be divided into; genetic programming, genetic algorithm, evolutional strategies, and computation. Evolutionary computations use biological, genetic concepts; hence, the terminologies used are mutation, crossover, patent, etc. are used quantitatively to define the processes involved in applying the evolutionary computation to optimization problems [28].

Genetic algorithm has been applied to channel assignment problems. The problem formulation is often viewed as, given an n number of radio cells and several available channels, it is required to find an optimal channel assignment that minimizes the interference constraints and maximizes the resources and spectrum available. In this genetic algorithm, several feasible solutions are first randomly generated and are called parent at the initial stage; offspring are then generated using crossover or mutation approaches on the parent [29]. Cross-over operators perform the cross between parents to exchange information to produce better offspring, while mutation operators combine random mutagens with each parent to form a new generation. This process is repeated iteratively until an optimal solution is found.

VII. ANTENNA COUPLING

Antenna to antenna mutual coupling can be described as the energy absorbed by one antenna's receiver when another antenna nearby is operating. This means that mutual coupling is undesirable because another antenna absorbs energy that should be radiated away. Also, a signal that could have been captured by one antenna would be absorbed by another nearby antenna. Mutual coupling can be described to reduce the antenna efficiency and the overall performance of antennas in both the transmitting and receiving modes. Figure 3 gives the graphical analysis of the antenna's mutual coupling.

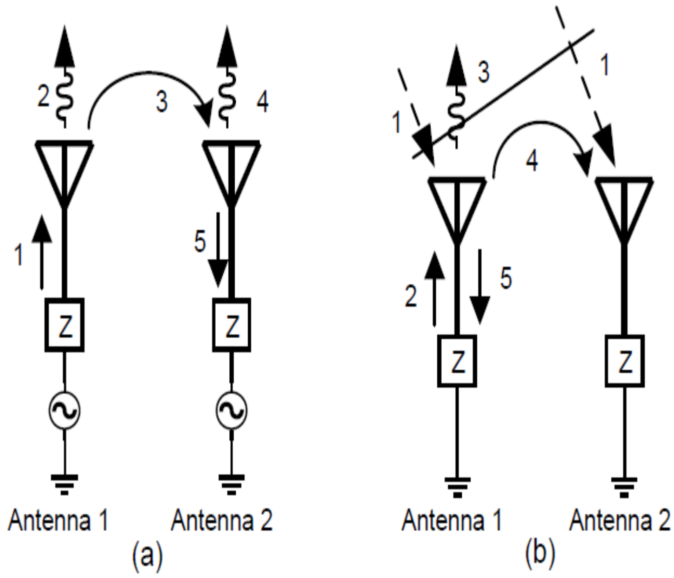


Figure 3 Mutual coupling of antenna arrays (a) Transmitting antenna array (b) Receiving antenna array

Figures 3a and 3b occur when antenna 1 is excited, generating an electromagnetic wave, a part of energy 2 as seen in the diagram is directly radiated into free space. Another part of energy 3 is coupled into the adjacent antenna 2. After antenna 2 receives energy 3, it generates a current and radiates a part of energy 4 into space. The energy 3 from antenna 1 can be seen as energy 5, which enters the signal source and is superimposed with the energy generated by antenna 2. This causes a mismatch in the antenna, thereby deteriorating the antenna's performance.
The mathematical analysis can be carried out by analyzing the antenna elements.

VIII. MUTUAL COUPLING BETWEEN ANTENNA ELEMENTS

The amount of mutual coupling between array elements depends on the relation characteristics of each antenna, the relative separation between the pair of antennas, and the relative orientation of each antenna. Conventionally, the mutual impedance is used to measure the mutual coupling effect.
When an antenna is in the presence of an obstacle or other element, its current distribution and the radiation field are altered. Because of this observation, the input impedance of the antenna varies. The interaction between elements is called driving-point impedance and is the combination of the self-impedance and the mutual impedance between the driven element and other obstacles or elements. The driving-point impedance depends upon the antenna type, the relative placement of the elements, and the type of feed used to excite the elements. Mutual coupling can be analyzed using either the traditional (conventional) mutual impedance method or the receiving mutual impedance method [14] [30].

IX. REVIEW OF DECOUPLING TECHNIQUES

Many decoupling techniques have been proposed to tackle mutual coupling in antenna arrays. Each method is based on a different principle and for various applications.

A. Open-Circuit Voltage Method

This method being discussed in [31] [32] [33] is one of the earliest methods used to analyze the effect of mutual coupling in antenna arrays. It was proposed by. In this method, the mutual coupling between two antennas was characterized by a mutual impedance whose parameters was taken from that used originally in circuit analysis, i.e., using the Z parameters in the network analysis. It treats the antenna array as an N-port network relating to the antenna terminal voltages $V_j(j = 1,2,3\ldots,N)$ to the open circuit voltages V_{ocj} through an impedance matrix that is represented as

$$\begin{bmatrix} 1+\frac{Z_{11}}{Z_L} & \frac{Z_{12}}{Z_L} & \cdots & \frac{Z_{1N}}{Z_L} \\ \frac{Z_{21}}{Z_L} & \frac{Z_{22}}{Z_L} & & \frac{Z_{2N}}{Z_L} \\ \vdots & & \ddots & \vdots \\ \frac{Z_{N1}}{Z_L} & \frac{Z_{N2}}{Z_L} & \cdots & 1+\frac{Z_{NN}}{Z_L} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} V_{0c1} \\ V_{0c2} \\ \vdots \\ V_{0cN} \end{bmatrix}$$

(11)

Where $Z_{ij}(i,j = 1,2,3\ldots,N)$ represents the mutual impedances between the antennas array elements, while Z_l represents the self-impedance of the antennas. The mutual impedance or self-impedance of the antenna is given as:

$$Z_{ij} = \frac{V_{0ci}}{I_j(0)} = -\frac{1}{I_i(0)I_j(0)}\int_0^l E_j(r).I_i(r)dl$$

(12)

Where $I_i(0)$ is the value of the current distribution $I_i(r)$ of the ith number antenna at the feed point. $I_j(0)$ is the value of the current distribution $I_i(r)$ of the jth number antenna at the feed point. $E_j(r)$ is the electric field radiation at the surface of the ith number antenna, which is being generated by the current distribution at the jth terminal. L is the length of the ith antenna. Equation 12 can be calculated by using the EMF method or the moment method. The EMF method is found by first getting the mutual impedance.

1) MUTUAL IMPEDANCE

The conventional mutual impedance of two antennas is evaluated by employing two-port (four terminal) networks [30]. Assuming the antenna system consist of two elements with one antenna in transmitting mode connected to a source and another is in receiving mode and open-circuited in Figure 4 and Figure 5, we can write;

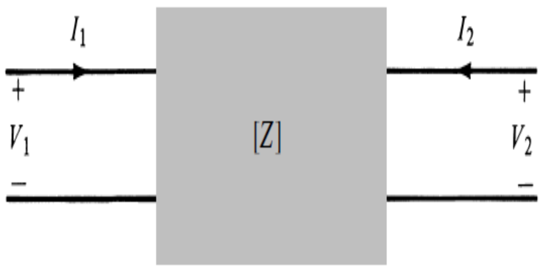


Figure 4: A Two-Port Network [14]

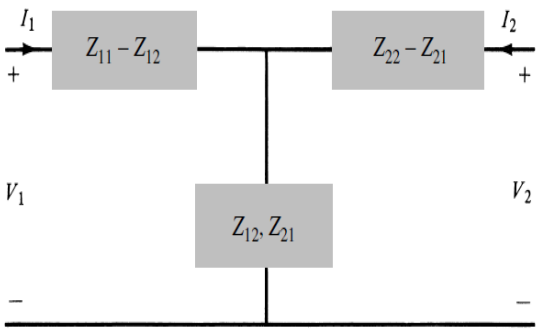


Figure 5: T-Network Equivalent [14]

For the two-port network in Figure 4, the current-voltage relationship [34]:

$V_1 = Z_{11}I_1 + Z_{12}I_2$
(13a)

$V_2 = Z_{21}I_1 + Z_{22}I_2$
(13b)

Where Z_{11} is the input impedance at port 1 with port 2 open-circuited;

$Z_{11} = \frac{V_1}{I_1}|_{I_2=0}$
(14)

Where Z_{12} is the mutual impedance at port 1 due to current at port 2 (with port 1 open-circuited);

$Z_{12} = \frac{V_1}{I_2}|_{I_1=0}$
(15)

Where Z_{21} is the mutual impedance at port 2 due to current at port 1 (with port 1 open-circuited);

$Z_{21} = \frac{V_2}{I_1}|_{I_2=0}$
(16)

Where Z_{22} is the input impedance at port 2 with port 1 open-circuited;

$Z_{22} = \frac{V_2}{I_2}|_{I_1=0}$
(17)

Equations (15) and (16) mean that the impedance Z_{11} and Z_{22} are the self impedances of antennas 1 and 2 respectively when in an isolated environment. Equations (15) and (16) are the mutual impedances Z_{12} and Z_{21}, which are reciprocal for conventional mutual impedance method that is $Z_{12} = Z_{21}$.

The conventional mutual impedance assumes that the same model is applicable in transmitting and receiving models. However, [34] introduced the new concept of mutual impedance, known as receiving mutual impedance, which is superior to the conventional mutual impedance.

The following points are the fundamental difference between the receiving and the conventional mutual impedance [34].

1. The receiving mutual is defined on a three-port system. It requires an external source to excite the two antennas, and hence one can consider the external source as the third port while the conventional mutual impedance is defined based on a two-port network system.
2. The receiving mutual impedance makes a reference to the external source where the conventional does not.

The consequence of these differences between the two methods is that the conventional mutual impedance satisfies the reciprocity theorem. $Z_{12} = Z_{21}$ Whereas the receiving mutual impedance does not, that is, $Z_{12} \neq Z_{21}$

2) THE INDUCED EMF METHOD

It is a classical method of computing the self and mutual impedances of an N-port network representation of an antenna array. The induced EMF method is used to calculate the mutual impedance for straight, parallel-in-echelon elements. It does not account for the radius of the antennas and the gaps at the feed [35].

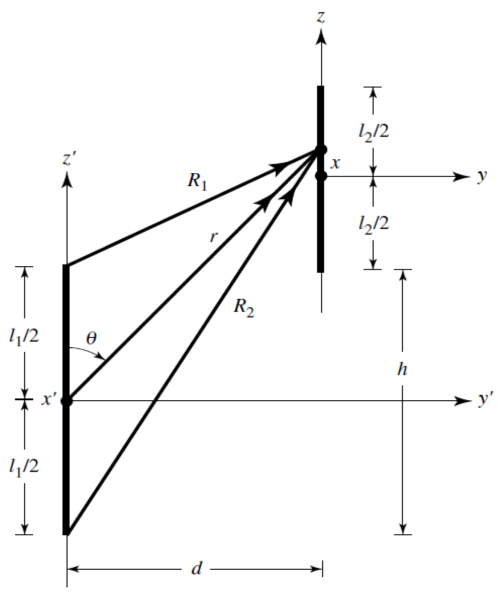


Figure 6: Dipole Positioning for Mutual Coupling for Induced EMF Method [14]

Using the figure 6 above, the mutual impedance Z_{21} (i.e. induced open circuit voltage in antenna 2, referred to its current at the input terminal, due to radiation from antenna 1) is given as [14]:

$$Z_{21} = \frac{V_2}{I_1} = -\frac{1}{I_{1i}I_{2i}}\int_{\frac{-l_2}{2}}^{\frac{l_2}{2}} E_{z21}(z')I_2(z')dz'$$
(18)

When

$E_{z21}(z')$ = Electric field radiated by antenna 1, which is parallel to antenna 2

$I_2(z')$ = Current distribution along antenna 2

Using the induced EMF method, the mutual impedance is based on the equation above, except that $I_2(z')$ is assumed to be the ideal current distribution of equation (10) while $E_{z21}(z')$ is the electric field of equation (9). This equation (18) can be expressed as;

$$Z_{21} = \frac{V_2}{I_1} = j\frac{\eta I_m I_{2m}}{4\pi I_{1i}I_{2i}}\int_{\frac{-l_2}{2}}^{\frac{l_2}{2}} \sin\left[k\left(\frac{l_2}{2} - |z'|\right)\right]\left[\frac{e^{-jkR_1}}{R_1} + \frac{e^{-jkR_2}}{R_2} - 2\cos\left(k\frac{l_1}{2}\right)\frac{e^{-jkr}}{r}\right]dz'$$
(19)

Where

$$r = \sqrt{x^2 + y^2 + z^2} = \sqrt{\rho^2 + z^2}$$
(20a)

$$R_1 = \sqrt{x^2 + y^2 + (z - \frac{l}{2})^2} = \sqrt{\rho^2 + (z - \frac{l}{2})^2}$$
(20b)

$$R_2 = \sqrt{x^2 + y^2 + (z + \frac{l}{2})^2} = \sqrt{\rho^2 + (z + \frac{l}{2})^2}$$
(20c)

With y = d, and $I = I_1, I_{1m}, I_{2m,} and\ I_{1i}, I_{2i}$ are the maximum and input currents for antenna 1 and 2, respectively. By referring to each of the maximum currents to those at the input and assuming free-space, equation (13) can is written as

$$Z_{21} = j\frac{30}{\sin\left(\frac{kl_1}{2}\right)sin\left(\frac{kl_2}{2}\right)}\int_{\frac{-l_2}{2}}^{\frac{l_2}{2}} \sin\left[k\left(\frac{l_2}{2} - |z'|\right)\right]\left[\frac{e^{-jkR_1}}{R_1} + \frac{e^{-jkR_2}}{R_2} - 2\cos\left(k\frac{l_1}{2}\right)\frac{e^{-jkr}}{r}\right]dz'$$
(21)

The mutual impedance referred to as the maximum is related to that at the mutual impedance referred to the input of equation (20) by

$$Z_{21m} = Z_{21i}\sin\left(\frac{kl_1}{2}\right)sin\left(\frac{kl_2}{2}\right)$$
(22)

For identical elements ($l_1 = l_2 = l$) , the equation reduces to

$$Z_{2m} = Z_{21i}\sin^2\left(\frac{kl}{2}\right) \quad (23)$$

The real and the imaginary parts of the mutual impedance are expressible as

$$R_{2m} = R_{21i}\sin^2\left(\frac{kl}{2}\right)$$
(24)

$$X_{2m} = X_{21i}\sin^2\left(\frac{kl}{2}\right)$$
(25)

B. S-Parameter Method

In [36] - [38] the s-parameter method, the receiving or transmitting antenna array was modeled as an N-port network. Then the mutual coupling between the antenna array elements was modeled using scattering parameters. When the s-parameters are determined, the decoupled signals are calculated from the coupled terminals signals. Though, in using this method, only the transmitting antenna array is modeled correctly with regard to handling the mutual coupling effect. For the receiving antenna array, due to the definition of s-parameters requiring that the antenna elements be driven by an active source that is connected at the terminals of one of the antennas in the array system, it, therefore, fails to correctly model the array of the antenna elements that are driven by an external source, which is outside of the array.

C. Full-Wave Method

The full-wave method in [39] [40] [41] is used to solve the entire boundary value difficultly of the EMF for the whole antenna array by using the moment method. It uses the parameters that are known, such as the terminal voltages with currents that come with mutual coupling, to calculate the incident of the array that is coupling free. But, only the terminal voltages or currents are known and not the entire current or voltage allocations on the antenna elements. This results in an undetermined system of equations. For the undetermined system to be solved, some approximations have to be made. For example, the current distribution would be assumed, which is a known coming path of the incident field, or by just solving the undetermined system straight by using a compromised method. The performance of this method depends on the approximations made, which can sometimes not be realistic, allowing its scope of application to be limited. Suppose the incident field is assumed to completely know. In that case, the full-wave method can be used as an accurate analysis tool in investigating the effect of mutual coupling in antenna arrays.

D. Decoupling by Antenna Design

Mutual coupling in antenna arrays can be minimized or reduced if there is a proper design of the antenna elements and/or the configuration of the antenna [42] [43]. As seen in a two-element planar Yagi-Uda antenna array shows a lower mutual coupling (< -22dB) when the antennas were aligned in a collinear form rather than the parallel form. That is, when the Yagi-Uda elements are in the collinear configuration, they are almost in the null radiation of the near field pattern of the close element, which results in low-level mutual coupling. In, the antenna array was designed to reduce the parasitic current on the antenna elements by changing the load impedances for the parasitic radiation field caused by the adjacent elements to be reduced. This results in the active element patterns of the antenna elements comparable to a single element pattern, which means the mutual coupling is reduced substantially.

E. THE RECEIVING MUTUAL IMPEDANCE

The two dipole antennas are configured as a linear array with their axes along the z-axis, as shown below. The two antennas are completely identical in all respect with length l and wire radius a. They are separated along the x-axis by a distance d. An external field coming from a direction φ azimuth plane excites the antennas. Both dipoles are connected to an external load Z_L as shown in Figure 7 below [34].

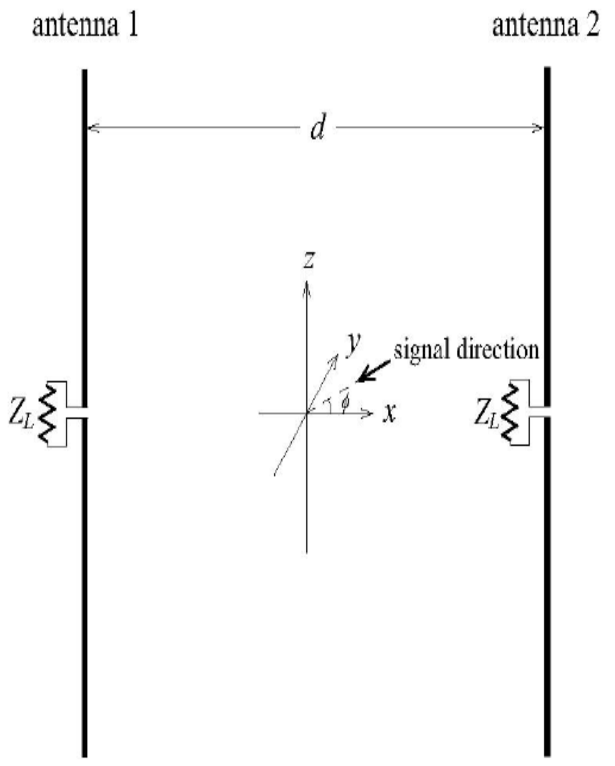


Figure 7: The Two Dipole Antennas and the External Excitation Source [14]

In receiving mutual impedance approach, the mutual impedance Z_{12} is defined as the ratio of the induced voltage V_1 across the terminal load of the antenna 1 to the current I_2 on the terminal load of antenna 2 when the array is excited by the external field:

$$Z_{12} = \frac{V_1}{I_2}$$
(26)

Which, V_1 on antenna 1 is that part of the induced voltage is solely due to the exciting current on antenna 2 and not due to the external source.

Z_{21} is defined similarly as Z_{12} but the position of antennas 1 and 2 are interchanged

$$Z_{21} = \frac{V_2}{I_1}$$
(27)

To find the receiving mutual impedance using theoretical method, the values of V_1 and I_2 in equation (13) can be calculated in the following manner [9].

First, the two dipoles are excited by the external source, and the terminal voltages and currents on the two dipoles are calculated and denoted as V_1', V_2', I_1 and I_2. Second, the terminal voltages on two isolated dipoles are calculated by removing one of the dipoles from the array when the terminal voltage, on the other hand, is being calculated. For example, the isolated terminal voltages are calculated to be $V_1''$and V_2''. Then according to the superposition principle, the terminal voltage on antenna 1.

$$V_1 = V_1' - V_1''$$
(28)

Z_{12} can be obtained by substituting equation (15) into equation (16) as;

$$Z_{12} = \frac{V_1' - V_1''}{I_2}$$
(29)

And Z_{21} as;

$$Z_{21} = \frac{V_2' - V_2''}{I_1}$$
(30)

F. Slots/Slits-Etching Approach

In this method, the ground has been detected by etching slots/slits in the ground plane. This approach is used to disturb the flow of the surface current distributions as it diverts the conducting paths that the current flows. Different works of literature have successfully carried out this approach, and some of them will be discussed.

The common slot etched in the radiator of an antenna helps minimize mutual coupling [44] - [46]. Along the line of neutralization, four slits were etched to the ground (Yang *et al.,* 2016) to reduce the mutual coupling between the antenna elements of a multiband multiple input multiple output (MIMO) antenna used for GSM and long term evolution (LTE) applications. Different slot representations have been used over time in other research that would be discussed extensively in the slot/slit-etching approach. This approach for reducing mutual coupling in antennas has not been very effective as it isolates only a small amount of the nearby signal from the neighboring antenna(s). Unwanted signals can still be received or transmitted with this method.

In [44], miniaturization was achieved by using different combinations of techniques, which includes a resonant stub connected to the ground, which shorts the excessive coupled energy before it reaches the other port and reduces coupling, slots that are etched in the radiator also helps to reduce mutual coupling.

In [45], an etched rectangular slot is introduced in the circular radiator to enhance the isolation between the two ports of an Ultra-wideband antenna, which results in a low mutual coupling between the ports of the antennas. The antenna orientation was not considered for this.

In [46], a U-shaped. I-shaped and S-shaped paired slot is etched to the ground between the two-port to enhance the antennas' isolation. The stub from the ground has an effect on both the bandwidth and the mutual coupling between the antennas. The bandwidth of the antennas was altered in this process, thereby not making it a very good method. This method does not work for multiband systems.

In [47], four 30mm long slits and two 2x12 mm^2 rectangles are cut from the ground plane's backside to reduce mutual coupling between antennas and also slightly improve the impedance matching. The gain with this method did not improve.

In [48], two planar inverted-F antennas are experimented upon, with a proper slot being introduced on the antenna plate to achieve a dual-band operation. Two slots were also used between the antennas to enhance the isolation between the antennas to reduce the mutual interaction between them. There was no actual reduction in the mutual interactions between these antennas, and it works only on one frequency.

In [49], a dual-band two-element multiple input and multiple outputs for wireless area network were worked on. A wide slot and a pair of narrow slots were used between the ports of the antennas to analyze and reduce the mutual coupling. The wide slot was to change the surface current distribution and also extend the path between ports 1 and 2 at the different antennas. The mutual coupling was reduced at 2.5GHz but was not reduced at other frequencies.

In [50], two different antennas were worked on for ultra wideband application. The antennas consisted of two monopole-antenna elements, a T-shaped ground stub, a vertical slot cut on the T-shaped ground stub to reduce mutual coupling. There was not much reduction in the mutual coupling between the input ports as there was an increase without the ground slot.

In [51] and [52], monopoles antennas were 90^o angularly parted with stepped semi-circular decoupling strips on the radiator and six slits which aids to diminish mutual coupling and also adds in the direction of impedance matching for wireless application. The different antenna configurations were not considered, which gives room for non-accurate results using another configuration.

In [53], a simple method was proposed to reduce mutual coupling between two closely spaced antennas using a miniaturized open-end T-shaped slot. The method relies on the bandstop effect of the slot, which suppresses the induced common ground and near field currents.

In [54], a T-shaped rectangular slot of 7.5mm x 2mm was etched to the ground. The rectangular slot diverts the direction of the surface currents and increases the distance between ports, which improves the isolation of the surface current to reduce the mutual coupling. This method cuts off part of the signal being sent from the antenna, making it ineffective.

In [55] tried reducing mutual coupling in extremely closed placed dual-element microstrip antennas positioned on a finite-sized ground plane for wide local area network (WLAN) application using a high isolation slot structure on the ground between the microstrip antenna. This proposed method was used to reduce mutual coupling through a half-wavelength slot antenna formed by the slot cut on the ground plane.

In [56], antennas consist of two L-shaped slot antenna elements and a narrow slot on the ground plane. The antenna elements were placed perpendicularly to each other to obtain high isolation, and a narrow slot is added to reduce further mutual coupling of the antenna elements in the low frequency band.

In [57], a T-shaped slot impedance transformer was applied to reduce mutual coupling. For specific sizes of the ground plane, the formed T-shaped slot can be excited to reduce mutual coupling. The T-shaped must always be dimensionally accurate for the different ground planes.

In [58], two antennas were collinearly placed with an edge-to-edge spacing of 0.09 λ with two symmetric stepped open L-shaped slots etched in the ground plane to reduce mutual coupling. The slots obstruct the current flowing through the common ground plane between the two radiators.

In [59], six pairs of slits were etched into the middle of the ground plane to reduce mutual coupling of the upper band frequency between a C-shaped slot antenna with a T-shaped antenna. This does not work for the lower band frequencies.

In [60], an E-shaped slot was inserted in the radiating patch to increase the current isolation and thereby reducing the mutual coupling between the antenna elements at a low frequency band. To further reduce the mutual coupling, a narrow slot was inserted into the ground plane.

In [61], n-section rectangular slits were placed in between the antennas to be investigated to isolate surface current, and that in turn reduces the mutual coupling between the antennas. The effect of the reduction of the mutual coupling was negligible as the current wasn't properly isolated.

In [62], a dual slot line defected ground structure (DGS) was placed between the adjacent antennas to improve the isolation of surface and current and reduce mutual coupling between the adjacent antennas considerably.

In [63], a parasitic T-shaped strip was placed between the two radiating antenna elements as a decoupling structure to suppress the mutual coupling. A notched band was at 5.5GHz is realized by etching a pair of L-shaped slits on the ground. A low mutual coupling was achieved with a low envelope correlation coefficient. This method works only for very high frequency bands and not for low frequencies.

In [64], a paired H-shaped slit was inserted in the patch of the radiating antenna with a narrow slot etched to the antenna's ground plane to reduce the mutual coupling between the antennas. This method reduced the mutual coupling but also did not affect the gain of the antenna as it was reduced due to the mutual coupling of the antenna

In [65], a decoupling slot was introduced on the ground of two unsymmetrical dumbbell slot antenna elements to reduce the mutual coupling between the antenna elements. This method successfully reduced the mutual coupling between the antennas, but a deviation of the radiation pattern was observed.

In [66], a triangular slot that acts as a band stop filter to help in reducing the mutual coupling and a meshed metal strip are introduced in the ground plane. As the ground plane width approached $\lambda/_{2}$, minimum surface current density occurs near the edge of the ground plane, which reduces the mutual coupling due to the surface waves. This method work for ultra-high frequency bands.

G. Protruding Ground Stub Structures

This is similar to the slot/slits-etching approach method, and the protruding ground stub structures is another established method of reducing mutual coupling in antennas. It provides isolation, and sometimes it improves impedance matching and also helps achieve wider impedance bandwidth [67]. Some of the popular designs would be further discussed in the review of protruding ground stub structures. Among all of them, the T-shaped ground plane is widely used among the dipole antenna for Ultra wideband applications. A T-shaped. The decoupling stubs decompose the original coupling by creating another coupling path and therefore reducing the mutual coupling.

In [68], to reduce the mutual coupling between the antennas, a T-shaped stub formed by a horizontal strip of size ($L_{g1}\ X\ W_{g1}$) and vertical strip size ($L_{g2}\ X\ W_{g2}$) was fabricated to isolate the ground plane current distribution, redistribute them, and modify the ground plane. The isolation was achieved, and a good impedance matching was achieved, but the method cannot work for other antennas.

In [50] [69] - [79], the same T-shaped ground stub along with some variation like an etched slot in the T-shaped stub, stepped T-shaped stub and some similar structures were used in these publications to isolate excess current flowing into the antennas to reduce mutual coupling between the antennas. It significantly reduced the mutual coupling between the antennas but would be an expensive approach for commercial purposes.

In [80], mutual coupling was reduced by first etching a rectangular slot on one of the antennas that are circular, and after that, an inverted Y-shaped metallic stub was introduced to the ground plane. The rectangular slot acts as a quarter wavelength resonator at the lower frequency edge of the ultra-wideband, resulting in the reduction of mutual coupling. The reduction was small compared to the T-shaped stub.

In [81] [82], a decoupling stub was placed at 45^o between the two radiators of the antennas to ensure high isolation coupled with etching two split-ring resonators (SRR) slots on the respective radiators. The rectangular stub improved the scattering parameters, and it reduced the wideband mutual coupling by separating the radiation patterns of the two radiators.

In [83], an extended protruding rectangular stub was placed in between two heptagonal monopoles that are orthogonally and symmetrically aligned to have extended ground planes. This altered the antenna propagation of the antennas.

In [84], a simple Y-shaped defected ground structure was etched to the ground plane, and a protruded stub to achieve band rejection to reduce the mutual coupling between the antennas. The antennas elements were arranged orthogonally and fed perpendicularly to obtain polarization and reduce mutual coupling. To further reduce the mutual coupling, the Y-shaped defected ground structure was etched in the ground between the closely spaced antenna element to suppress the coupling current. This method extends the distance between the antennas.

In [85], antennas for Wireless Local Area Network (WLAN) application were worked on as a folded Y-shaped stub isolator element was introduced between the isolator element and the radiators of the meandered monopole antennas at the lower band. The folded Y-shaped isolator also presents an additional coupling path between the radiators resulting in the cancellation of mutual coupling between the antennas. This system is not sustainable as it affects the propagation of signals.

In [86] [87], an inverted pair of L-shaped rectangular strips were etched to the ground plane to reduce mutual coupling in the antennas. The effect of reduction of the mutual coupling was minute.

In [88], two orthogonal T-shaped asymmetric microstrip antennas closely placed were worked for mutual coupling reduction. The microstrip antennas were isolated with an inverted L-type ground strip embedded at the left corner, followed by the square strip. A modified meandered line (MML) was embedded with the square strip, and also a split ring resonator (SRR) was placed at the back of the antenna to reduce mutual coupling. The MML, SRR, and inverted L-type ground strip reduced the mutual coupling to a reasonable extent and obtained a circular polarization.

In [89], two circular arc-shaped protruding grounded stubs were placed on the ground plane to reduce the mutual coupling of two closely placed dipoles with a distance of 0.5λ between them. This method was not very effective as there was still a disturbing amount of coupling between the antennas.

In [90], two capacitively extended curved ground stubs were used to back two monopole antennas to reduce the mutual coupling. The stubs were a quarter wavelength long at a lower operating band than the antennas. The stub intercepted the antenna's current and diverted to reduce the mutual coupling, but the diversion could cause a major collapse in the overall system.

In [91], a partial ground T-shaped isolating stub structure was introduced into the antenna system to control the space and degrading factors of mutual coupling between the antennas due to the close coupling of the radiating elements. A reduced mutual coupling was achieved, but it was minimal as there was still a distortion in the radiating antennas as signals were being sent.

In [92], reduction of mutual coupling between two ports was made by a metal branch stub being extended on the ground plane and etching a T-shaped slot to the ground to increase isolation between the two antennas. The metal stub decreases the current on the ground flowing between the two antennas. Reduction of mutual coupling was achieved at the cost of antenna gains.

In [93] [94], two F-shaped stubs, were placed in between two antennas on the same shared ground plane to reduce mutual coupling. The two F-shaped stubs acted as a reflector to separate the radiation of the antennas. This system was not effective for reducing mutual coupling but good for antenna gain.

In [95], a decoupling structure consisting of two inverted L-shaped branches and a rectangular slot with one circular end etched to the ground plane was presented to reduce the mutual coupling between the antenna elements. The inverted L-shaped branches combined with the etched slot to block the current from flowing from the exciting port to the coupled port. This was an effective way to reduce the mutual coupling, but the decoupling structure affected the antenna's performance.

In [96], a cross-shaped unconnected stub was introduced into the ground plane to reduce mutual coupling. The characteristics mode was also tuned by observing modal significance and characteristics currents, which helps to reduce the mutual coupling more. Mutual coupling was significantly reduced, but this works on antennas with high frequency bands.

In [97], a stepped stub was extended from the modified ground plane as a decoupling element between the radiators of the antennas to realize good isolation to reduce the mutual coupling between the antennas. The direct ground current was broken when the stepped stub was used. This reduced the mutual coupling, but the redirected current can cause more harm to the antenna system if not properly redirected.

In [98], metallic and slot stubs with properly shaped arms were inserted between two adjacent radiating antennas to reduce mutual coupling. The tilted stubs (one metallic and one slot) were attached to the corners of the antenna ground arms. While the metallic stub by virtue of currents induced on it blocks the spread of electric field into the antennas, the slot stub limits the ground plane currents from spreading to other ports. This reduced the mutual coupling between the antennas and also blocked radiating signals.

H. Parasitic Element/Structures

In a single antenna system, the parasitic elements/structures are used to achieve multi resonance, which enhances the impedance bandwidth (IBW). In a collocated antenna setup, they are inserted between the resonating antenna, either as a reflector or resonator, to reduce mutual coupling between the antenna elements. Generally, parasitic elements/structures are not connected to the ground, unlike those connected to the ground to form a resonator [99]. Parasitic elements/structures generate a coupling opposing the original coupling created by the excited antenna elements. The resulting coupled field would be out of phase with the unreceptive antenna at that moment as it would help reduce the effect of mutual coupling from one radiating element to another. These parasitic elements are specifically modeled or designed to control the bandwidth of isolation and the level at which the mutual coupling would be reduced.

In [100], a modified serpentine structure (MSS) with a width of 3mm was designed to reduced mutual coupling in an antenna array. The antenna array was constructed using square patch radiators and designed to work at 2.45GHz with a spacing of $\lambda_0/_{20}$ used for wireless communication. The proposed MSS acts like a band-reject filter working along with resonators to reduce the mutual coupling between the radiators in the antenna array. The surface current on the ground from the radiating antenna are captured by the intermediate resonators along with the serpentine structures, therefore providing enhanced isolation. Mutual coupling was reduced with the proposed MSS design but can have an effect on the antenna radiation.

In [101], a central reflector was placed at the center of two groups of four elements of dielectric resonator antennas (DRAs) in a 4x4 antenna configuration for wireless access point application. The reflector element was proposed to tilt the radiated beam patterns to reduce the field correlations, as a result of this reducing mutual coupling for the antenna system. It was able to reduce mutual coupling, but it caused a minimal effect on the efficiency of the antenna, the bandwidth of operation, and impedance matching.

In [102], a metal strip reflector was placed in between two antenna elements placed in a parallel configuration to act as an efficient tool to reduce mutual coupling in the band of operation for wireless application. The decoupling structures help to block the migrating current or attenuate it, reducing the mutual coupling effect between the two antennas. This was effective for of 4.5GHz, but the influence of the decoupling structure waned for frequencies greater than 7.5GHz

In [103], an asymmetrical H-shaped strip that acted as a reflector was placed in between the antenna elements to reduce mutual coupling between the antenna elements. The effect of the reflector did not mean much as there was just a small reduction in the mutual coupling between the antennas.

In [104], a rotated "+" shaped rectangular strip reflector structure was introduced in between the antenna elements configuration to reduce mutual coupling. On the introduction of the slot reflector to a diagonal antenna configuration, there was a significant improvement in the reduction of mutual coupling, but on introducing the slot reflector to an adjacent configuration, the effect was minimal. This method works well for antennas placed diagonally.

In [105], a rectangular parasitic element was embedded between the monopole antennas at the substrate backside on which the antennas were placed to reduce mutual coupling between the monopole antennas. By wise tuning of the position and dimensions of the parasitic elements, high current isolation is achieved for more reduction in the coupling of the antennas. This method was effective for low frequency bands but less effective for high frequency bands.

In [106], a linearly arranged patch antenna array is being presented for mutual coupling reduction. The antennas were arranged in close space with edge-to-edge separation of 0.096 λ and center-to-center spacing of 0.29λ. Two separate rectangular shapes and T-shaped parasitic elements, were used to cancel the surface current to reduce mutual coupling. These parasitic elements were placed in between the antennas with an extension of the T-shaped element towards the boundary of the patches. There was a reduction in the mutual coupling between the antennas, but it only works for antennas in a parallel configuration.

In [107], a cross-shaped metallic fence was placed in between two antennas to reduce mutual coupling between them to avoid loss of a degree of freedom (DOF) being used for Robust navigation. The metallic fence provided a medium of blocking interactions between the antennas which helps for power coupling between the antennas. This method is only effective for miniaturized antenna systems.

In [108], a stepped cross-shaped metallic reflector strip was placed in between antenna elements reflector to reduce mutual coupling. The reflector strip was specifically designed for this cognitive radio antennas system for 5G applications. This was effective for this application as it reduced the mutual coupling to an allowable extent, but it is not certain it can work for other antenna setups.

In [109], a compact high ultra-wideband antenna comprising of two monopole antennas with a circular parasitic element at the backside of the radiating patch to reduce mutual coupling. This parasitic element creates a reverse coupling in order to counter the effect of the mutual coupling for it to be reduced. The circular parasitic element was introduced at the center of the antennas to act as an isolator to reduce the coupling. The mutual coupling was reduced considerably but effective for this type of antenna.

In [110], a novel reversed S-shaped wall was used to provide high isolation between antenna elements in closed space with the edge-to-edge distance being 1mm in order to reduce mutual coupling. Mutual coupling was able to be reduced with this method, but it works for smaller antenna systems.

In [111], a decoupling metallic strip loaded with an inductor was used to reduce mutual coupling between two mobile ad-hoc networks (MANET) antennas for MANET communication, satellite navigation, and satellite communication application. To decrease the mutual coupling between the two MANET antennas, an isolation strip with an inductor loaded was introduced in between the antennas. More energy was coupled to the isolation strip at the resonant frequency of the isolation strip. The coupling between the two antennas at that frequency was reduced compared to the case without isolation.

In [112], two modified L-shaped slots, a rectangular ground plane structure, and a rectangular parasitic structure for increased isolation were all used to reduce mutual coupling between two square monopole antennas. The parasitic element was embedded between the monopole antennas on the backside, and it showed a reduced mutual coupling of an acceptable level of -20dB.

In [113], octagonal notches and diagonal parasitic element was used to reduce mutual coupling between two closely placed antennas. The parasitic element was chosen in a diagonal position between the ground planes to reduce mutual coupling and to achieve high return loss. It was not an effective method to reduce mutual coupling as it was slightly reduced.

In [114], a Minkowski fractal parasitic stub along with a Minkowski fractal grounded stub was placed at 45^0 between the monopole antennas to reduce mutual coupling between them, which in turn establishes high isolation between the radiators. The Minkowski fractal shaped parasitic element creates a dissipative coupling to reduce mutual coupling and a rectangular stub extended from the ground plane symmetrical with respect to the ground plane at 45^0 to extend the effective current route, which in turn enhances the wideband isolation. The Minkowski fractal parasitic element captures the interfered signal and converts it to surface current resulting in reduced mutual coupling. The mutual coupling was reduced at ultra-high frequencies.

In [115], a new approach was used to reduce mutual coupling between two closely-spaced planar monopole antennas. The approach employs either two parallel metallic strips or a single strip with a meander-shaped slotted pattern that is symmetrically positioned between the two antennas. Their edges are separated by 4mm and 8mm, respectively. The decoupling structures were not only confined in the space shared by the two planar monopoles antenna edges but are rather extended above the partial ground plane on one end and to the edge of the substrate on the other end. This method effectively reduced the mutual coupling of the antenna but might not be realistic.

In [116], the use of resistor-loaded paired parallel-coupled resonator (PCRs) was proposed to reduce mutual coupling in an antenna array system with 0.125 λ_0 center-to-center spacing for wireless local area network (WLAN), long-term evolution (LTE), and possibly fifth-generation (5G) communication. The mutual coupling was significantly reduced with little signal overlap.

In [117], a parasitic fragment-type element was used in suppressing mutual coupling between two antennas that are $\lambda/_4$ in length at a frequency of 2.45GHz for

WLAN application. The parasitic fragment-type element was used to perform specific isolation of the antennas from coupling with one another. This was effective for the antenna design but might not completely work for other antenna designs.

I. Defected Ground Structures (DGs)

Defected ground structures are of the most popular techniques, particularly in the reduction of between wideband and ultra wideband antenna elements. DGs are a defect in the ground plane, introduced on purpose to the ground plane, which strongly disturbs the surface current distribution on the ground plane. This impedes the total transmission line between the different antennas to change, resulting in lower mutual coupling between them. [118] [119] [120] [121] discussed DGs and their importance when designing antennas.

In [122], a ring-shaped ground plane was modified by introducing four slots in each corner of the ground plane close to the antennas to reduce mutual coupling between the antennas. Since the four antenna ports were connected to the same ring-shaped ground plane, the slots could divert the current across the L-corners of the ground plane to decrease it. This reduced the mutual coupling among the antennas slightly.

In [123], a V-shaped modified ground structure between the adjacent dipole antenna elements was used to reduce spatial mutual coupling between the dipole antennas for Wireless Local Area Network (WLAN) and World Interoperability for Microwave Access (WiMAX). The dipole antennas were first placed in an orthogonal configuration which reduces mutual coupling by 5dB a little, and the V-shaped ground structure blocks the spatial coupling. This was not an effective method to reduce mutual coupling.

In [124], an interdigital structure (ID-DGs) was incorporated into the ground plane for modification to reduce mutual coupling in the antenna system. The ID-DGs were etched to the ground, which reduced the surface wave of the antennas, thereby reducing the mutual coupling by 12.5dB.

In [125], two decoupling structures consisting of a meandering resonant branch and an inverted T-shaped slot etched to the ground to defect the ground plane to reduce mutual coupling between antennas. The spacing between the antennas was smaller than $\lambda/_2$ with the T-shaped slot of about $\lambda/_4$ in length was etched to the ground, with U-slits being etched to the feedlines for effective isolation. The isolation was improved by up to 15dB and worked for compact antennas.

In [126] [127], a ring-shaped structure was placed in the ground plane, which behaves like a defected ground structure to reduce mutual coupling by behaving like a band-reject filter for the surface current. This ring-shaped structure cancels the current at the spiral slot's edges, minimizing the mutual coupling between the antenna element. It reduced the mutual coupling slightly, which was not very effective.

In [128], a funnel-shaped ground plane with an open-ended slot was used to reduce mutual coupling between the antennas for Wireless Local Area Network (WLAN) design. The funnel-shaped ground plane dissipated the surface current in the ground plane, which reduced the mutual coupling up to -21dB between the antennas.

In [129], a dumbbell-shaped defected ground structure (DB-DGs) was worked on as a bandstop filter to stop the flow of surface current in a $\lambda/_4$ microstrip line. This was modeled and fabricated, giving a stopband of -19dB. That is, when applied to an antenna array system, it can reduce the mutual coupling to an acceptable limit.

In [130], the combination of a spade-shaped radiation patch, a rectangular defected ground structure, and a windmill-shaped decoupling structure was used to reduce the mutual coupling in a super-wideband antenna system. The mutual coupling was effectively reduced by -17dB with a good envelope correlation coefficient.

In [131], a rectangular slot and a T-shaped slot were etched to the ground to cause a defect in the ground plane to reduce mutual coupling between the antennas. The T-shaped slot reduces the surface current on the ground plane between the two ports of the antennas and the rectangular acts as an isolation barrier to effectively reduce the mutual coupling of low frequencies by -16dB. This effect depreciates at high frequencies.

In [132] [133], a simple string of H-shaped ground structure was used to reduce mutual coupling in an antenna system. The H-shaped ground structure decreased the direct coupling path among the antenna's closely spaced (edge-to-edge gap of 0.038λ) paths, thereby reducing the mutual coupling between the antennas.

J. Antenna Placement and Orientation Approach

Antenna placement and their orientation are usually sufficient enough to achieve the minimum required isolation for the reduction of mutual coupling to -10dB or lower. The further away the antennas are placed from one another, the lesser the mutual coupling between them, but antennas cannot be totally apart when they are in a collocated system or when in an array setup. Therefore, there is the need to get the right position for which they can be placed from one another for lower mutual coupling between them.

In [134], four antennas were placed in an orthogonal configuration to reduce mutual coupling between them. This configuration allows isolation of the different orthogonal ports to reduce the exciting current distribution in the antennas. This was able to reduce the mutual coupling by -15dB.

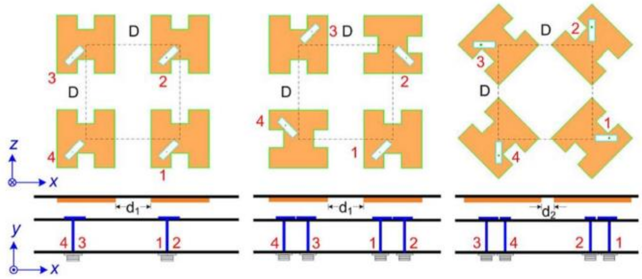
In [135], the feeding structures and the two antennas were orthogonally placed with no extra decoupling structure to reduce the mutual coupling between the antennas. This was able to reduce the mutual coupling by -15dB, brings features of pattern diversity, dual-polarization and also saves space in the antennas system.

In [136], L-shaped slot antennas were placed orthogonally with a spacing of 0.05λ from one another with L-shaped slits to provide further isolation and reduce mutual coupling between the antenna elements. This was able to reduce the mutual coupling between the antennas slightly due to the separating distance.

In [137], four inverted F-antenna elements were arranged in a rotational symmetry configuration along with a square substrate's four corners to reduce mutual coupling between the antenna elements. Decent isolation was achieved with this configuration without additional decoupling measures, which leads to a decent reduction in mutual coupling between the antenna elements.

In [143] [144] [145], a different form of orthogonal configuration for two antenna placements on the ground plane was used for isolation to reduce mutual coupling. For each orthogonal element, the pattern lies in a place with a different tilt in angle orientation of the antenna. The mutual coupling was slightly reduced with this method

In [138] [139] [140] [141] [142], the same orthogonal configuration arrangements were used for four antenna elements to reduce mutual coupling between the antennas. The distance between two dipoles was λ/4 [139]. The orthogonal configuration provided good isolation for the movement of surface current to reduce mutual coupling. This was effective as it improved the antenna gain and radiation efficiency. There was an additional offset of antenna orientation of 135^o and H orientation in [138] from the conventional sequential rotational array (SRA) orthogonal configuration, which provided further isolation and therefore had a better reduction in mutual coupling between the antennas.



(a) (b) (c)

Figure 8 (a) Non-rotated orthogonal array, (b) H-oriented SRA, (c) 135^o angular offset [138].

X. CONCLUSION

In this paper, reducing mutual coupling in a collocated antenna system or antenna array is significant problem. There is an increase in mutual coupling between antennas when the separating distance between the antennas is very small due to limited space. This reduces the performance of the antennas in the collocated system or antenna array. Different methods have been discussed in this paper on isolation and reduction of mutual coupling. The antennas placement and orientation is still one of the most cost effective and efficient way to reduce mutual coupling in a collocated antenna system or antenna array.

REFERENCES

[1] S. Rahmatia, D. E. Fransiska, N. I. H. Pratama, P. Wulandari and O. N. Samijayani, "Designing dipole antenna for TV application and rectangular microstrip antenna working at 3 GHz for radar application," in *In 2017 5th International Conference on Cyber and IT Service Management (CITSM)*, Denpasar, Indonesia, 2017.

[2] S. Pradhan and P. K. Singhal, "HALF WAVE WIRED DIPOLE ANTENNA FOR WIRELESS APPLICATIONS," *International Research Journal of Engineering and Technology (IRJET),* vol. 7, no. 05, pp. 1211-1213, 2020.

[3] Y. A. Adediran, H. Lasisi and O. B. Okedere, "Interference management techniques in cellular networks: A review," *Cogent Engineering,,* vol. 4, no. 1, pp. 1-10, 2017.

[4] J. J. Gavan and M. N. Shulman, "Effects of densensitization on mobile radio system," *EEE Transactions on Vehicular Technology,* vol. 33, no. 4, pp. 285-290, 1984.

[5] S. Roberts, "Radio Frequency Interference and Antenna Sites," 2011. [Online]. Available: http://www.unisite.com.

[6] S. Ahmed, "Interference mitigation in wireless system," *School of Engineering and Science Faculty of Health Engineering and Science,* 2012.

[7] F. E. Idachaba, "Telecommunication Cost Reduction in Nigeria through Infrastructure Sharing between Operators," *The Pacific Journal of Science and Technology,* vol. 11, no. 1, pp. 272-276, 2010.

[8] T. Peng, "RFI prevention for collocated antennas," *TDA Engineering Office,* vol. 13, no. 4, pp. 135-144, 1980.

[9] H. S. Lui, H. T. Hui and M. S. Leong, "A note on the mutual-coupling problems in transmitting and receiving antenna arrays," *IEEE Antennas and Propagation Magazine,* vol. 51, no. 5, pp. 171-176, 2009.

[10] T. K. Wang, "Antenna Model for Electromagnetic Compatibility Analyses," *U.S Deoartment of Commerce,* 2012.

[11] T. Inc, "Telewave Inc," 2020. [Online]. Available: https://www.telewave.com.

[12] T. A. Milligan, Modern Antenna Design, A John Wiley & Sons Inc, 2005.

[13] J. J. Carr, Practical Antenna Handbook, McGraw-Hill Company INC, 2001.

[14] C. A. Balanis, Antenna Theory: Analysis and Design, Canada: Wilety, 2005.

[15] L. Zhang, L. Hu, F. Hu, Z. Ye, X. Li and S. Kumar, "Enhanced OLSR routing for airborne networks with multi-beam directional antennas," *Ad Hoc Networks,* vol. 102, no. 5, pp. 102-116, 2020.

[16] S. Kumar, K. Harish and S. Nipun, "Theory of antennas, Its advantages and appliocation in communication systems," *Internation Journal of Engineering Development and Research,* vol. 6, no. 1, pp. 925-930, 2018.

[17] R. O. M. G. P. E. M. &. H. B. Kullock, "Electrically-driven Yagi-Uda antennas for light," *Nature communications,* vol. 11, no. 1, pp. 1-7, 2020.

[18] G. Marino and T. Kelly, "The economics and policy implications of infrastructure sharing and mutualisation in Africa," 2015.

[19] O. F. Ehiagwina and O. A. Fakolujo, "Mobile cellular network infrastructure sharing models among GSM network operators: A technical review," in *In Proceedings of the International Academic Conference for Sub-Sahara African Transformation and Development.*, Ilorin, Nigeria, 2015.

[20] L. E. Frenzel, Principles of electronic communication systems, McGraw-Hill, 2016.

[21] G. I. Ighalo and A. Osaigbovo, "Study of interference between the ondo state radio/television cooperation (OSRC) Akure, and independent television (ITV) Benin city," *Internation Journal of Engineering Development and Research,* vol. 4, no. 4, pp. 647-661, 2013.

[22] T. B. Iliev, I. S. Stoyanov , G. Y. Mihaylov and E. P. Ivanova, "Study the influence of intermodulation products on navigation signals," in *In IOP Conference Series: Materials Science and Engineering*, Coimbatore, India, 2021.

[23] F. German, K. Annamalai, M. Young and M. C. Miller, "Simulation and data management for cosite interference prediction," in *In 2010 IEEE International Symposium on Electromagnetic Compatibility*, Fort Lauderdale, USA, 2010.

[24] I. Demirkiran, D. D. Weiner, A. Drozd and I. Kasperovich, "Knowledge-based approach to interference mitigation for EMC of transceivers on unmanned aircraft," in *In 2010 IEEE International Symposium on Electromagnetic Compatibility*, Fort Lauderdale, USA, 2010.

[25] Q. Liu, B. Tang and Y. Wang, "Analysis and Elimination of Common Interference in Satellite Communications," in *In Journal of Physics: Conference Series*, Shanghai, China, 2020.

[26] S. Ahmed and M. Faulkner, "Mitigation of reverse intermodulation products at colocated base stations," *IEEE Transactions on Circuits and Systems I: Regular Papers,* vol. 60, no. 6, pp. 1608-1620, 2012.

[27] G. L. Stüber, "Frequency Planning Techniques. In Principles of Mobile Communication," *Springer, Cham,* vol. 60, no. 5, pp. 529-562, 2017.

[28] I. Khatami and M. Y. A. Jamalabadi, "Optimal design of microphone array in a planar circular configuration by genetic algorithm enhanced beamforming," *ournal of Thermal Analysis,* vol. 145, no. 4, p. 1817–1825, 2020.

[29] S. K. Mohanty and S. K. Udgata, "Minimizing the maximum receiver interference in wireless sensor networks using probabilistic interference model," *Engineering Applications of Artificial Intelligence,* vol. 91, no. 5, pp. 1-14, 2020.

[30] P. S. Carter, "Circuit relations in radiating systems and applications to antenna," *Proceedings of the Institute of Radio Engineers,* vol. 20, no. 6, pp. 1004-1041, 1932.

[31] I. Gupta and A. Ksienski, "Effect of mutual coupling on the performance of adaptive arrays," *IEEE Transactions on Antennas and Propagation,* vol. 31, no. 9, pp. 785-791, 1983.

[32] K. C. Lee and T. H. Chu, "Mutual coupling mechanisms within arrays of nonlinear antennas," *IEEE Transactions on electromagnetic compatibility,* vol. 47, no. 4, pp. 963-970, 2005.

[33] H. Rogier and E. Bonek, "Analytical spherical-mode-based compensation of mutual coupling in uniform circular arrays for direction-of-arrival estimation," *AEU-International Journal of Electronics and Communications,* vol. 60, no. 3, pp. 179-189, 2006.

[34] H. T. Hui and S. Lu, "Receiving mutual impedance between two parallel dipole antennas," in *In TENCON 2006-2006 IEEE Region 10 Conference*, Hong Kong, China,

2006.

[35] A. M. Wyglinski and S. D. Blostein, "Mutual coupling and scattering effects on cellular CDMA systems using smart antennas," in *In Vehicular Technology Conference Fall 2000. IEEE VTS Fall VTC2000. 52nd Vehicular Technology Conference (Cat. No. 00CH37152)*, Boston, USA, 2000.

[36] D. Segovia-Vargas, R. Martin-Cuerdo and M. Sierra-Perez, "Mutual coupling effects correction in microstrip arrays for direction-of-arrival (DOA) estimation," *IEE Proceedings-Microwaves, Antennas and Propagation,* vol. 149, no. 2, pp. 113-118, 2002.

[37] J. W. Wallace and M. A. Jensen, "Mutual coupling in MIMO wireless systems: A rigorous network theory analysis," *IEEE transactions on wireless communications,* vol. 3, no. 4, pp. 1317-1325, 2004.

[38] K. M. Pasala and E. M. Friel, "Mutual coupling effects and their reduction in wideband direction of arrival estimation," *IEEE Transactions on Aerospace and Electronic Systems,* vol. 30, no. 4, pp. 1116-1122, 1994.

[39] H. Yuan, K. Hirasawa and Y. Zhang, "The mutual coupling and diffraction effects on the performance of a CMA adaptive array," *IEEE transactions on vehicular technology,* vol. 47, no. 3, pp. 728-736, 1998.

[40] R. S. Adve and T. K. Sarkar, "Compensation for the effects of mutual coupling on direct data domain adaptive algorithms," *IEEE Transactions on Antennas and Propagation,* vol. 1, pp. 86-94, 2000.

[41] C. E. Lau, R. S. Adve and T. K. Sarkar, "Minimum norm mutual coupling compensation with applications in direction of arrival estimation," *IEEE Transactions on Antennas and Propagation,* vol. 52, no. 8, pp. 2034-2041, 2004.

[42] Y. Qian, W. R. Deal, N. Kaneda and T. Itoh, "A uniplanar quasi-Yagi antenna with wide bandwidth and low mutual coupling characteristics," in *In IEEE Antennas and Propagation Society International Symposium. 1999 Digest. Held in conjunction with: USNC/URSI National Radio Science Meeting (Cat. No. 99CH37010)*, Orlando, USA, 1999.

[43] J. D. Fredrick, Y. Wang and T. Itoh, "Smart antennas based on spatial multiplexing of local elements (SMILE) for mutual coupling reduction," *IEEE Transactions on Antennas and Propagation,* vol. 52, no. 1, pp. 106-114, 2004.

[44] M. S. Khan, A. D. Capobianco, A. Iftikhar, R. M. Shubair, D. E. Anagnostou and B. D. Braaten, "Ultra-compact dual-polarised UWB MIMO antenna with meandered feeding lines," *IET Microwaves, Antennas & Propagation,* vol. 11, no. 7, pp. 997-1002, 2017.

[45] G. Srivastava, B. K. Kanuijia and R. Paulus, "UWB MIMO antenna with common radiator," *International Journal of Microwave and Wireless Technologies,* vol. 9, no. 3, pp. 573-580, 2017.

[46] J. Y. Zhang, F. Zhang, W. P. Tian and Y. L. Luo, "ACS-fed UWB-MIMO antenna with shared radiator," *Electronics letters,* vol. 51, no. 17, pp. 1301-1302, 2015.

[47] Z. X. Yang, H. C. Yang, J. S. Hong and Y. Li, "A miniaturized triple band-notched MIMO antenna for UWB application," *Microwave and Optical Technology Letters,* vol. 58, no. 3, pp. 642-647, 2016.

[48] R. Addaci, K. Haneda, A. Diallo, P. Le Thuc, C. Luxey, R. Staraj and P. Vainikainen, "Dual-band WLAN multiantenna system and diversity/MIMO performance evaluation," *IEEE transactions on antennas and propagation,* vol. 62, no. 3, pp. 1409-1415, 2013.

[49] S. Nandi and A. Mohan, "A compact dual-band MIMO slot antenna for WLAN applications," *IEEE antennas and wireless propagation letters,* vol. 16, no. 3, pp. 2457-2460, 2017.

[50] L. Liu, S. W. Cheung and T. I. Yuk, "Compact MIMO antenna for portable UWB applications with band-notched characteristic," *IEEE Transactions on Antennas and Propagation,,* vol. 5, pp. 1917-1924, 2015.

[51] N. Jaglan, B. K. Kanaujia, S. D. Gupta and S. Srivastava, "Dual band notched EBG structure based UWB MIMO/diversity antenna with reduced wide band electromagnetic coupling," *Frequenz,* vol. 71, no. 11-12, pp. 555-565, 2017.

[52] N. Jaglan, S. D. Gupta, E. Thakur, D. Kumar, B. K. Kanaujia and S. Srivastava, "Triple band notched mushroom and uniplanar EBG structures based UWB MIMO/Diversity antenna with enhanced wide band isolation," *AEU-International Journal of Electronics and communications,* vol. 90, no. 4, pp. 36-44, 2018.

[53] J. Park, J. Choi, J. Y. Park and Y. S. Kim, "Study of a T-shaped slot with a capacitor for high isolation between MIMO antennas," *IEEE Antennas and Wireless Propagation Letters,* vol. 11, no. 3, pp. 1541-1544, 2012.

[54] C. R. Jetti and D. R. Nandanavanam, "Trident-

shape strip loaded dual band-notched UWB MIMO antenna for portable device applications," *AEU-International Journal of Electronics and Communications,* vol. 83, no. 4, pp. 11-21, 2018.

[55] J. OuYang, F. Yang and Z. M. Wang, "Reducing mutual coupling of closely spaced microstrip MIMO antennas for WLAN application," *IEEE Antennas and Wireless Propagation Letters,* vol. 10, no. 2, pp. 310-313, 2011.

[56] J. Ren, W. Hu, Y. Yin and R. Fan, "Compact printed MIMO antenna for UWB applocations," *IEEE antennas and wireless propagation letters,* vol. 13, no. 6, pp. 1517-1520, 2014.

[57] S. Zhang, B. K. Lau, Y. Tan, Z. Ying and S. He, "Mutual coupling reduction of two PIFAs with a T-shape slot impedance transformer for MIMO mobile terminals," *IEEE Transactions on Antennas and Propagation,* vol. 60, no. 3, pp. 1521-1531, 2011.

[58] S. P. Biswal and S. Das, "Two-element printed PIFA-MIMO antenna system for WiMAX and WLAN applications," *IET Microwaves, Antennas & Propagation,* vol. 12, no. 14, pp. 2262-2270, 2018a.

[59] Y. T. Wu and Q. X. Chu, "Dual-band multiple input multiple output antenna with slitted ground," *IET Microwaves, Antennas & Propagation,* vol. 8, no. 13, pp. 1007-1013, 2014.

[60] V. Bhanumathi and G. Sivaranjani, "High isolation MIMO antenna using semi-circle patch for UWB applications," *Progress in Electromagnetics Research,* vol. 92, no. 7, pp. 31-40, 2019.

[61] M. A. U. Haq and S. Koziel, "Ground plane alterations for design of high-isolation compact wideband MIMO antenna," *IEEE Access,* vol. 6, no. 3, pp. 48978-48983, 2018.

[62] R. Hussain, A. Raza, M. U. Khan, A. Shammim and M. S. Sharawi, "Miniaturized frequency reconfigurable pentagonal MIMO slot antenna for interweave CR applications," *International Journal of RF and Microwave Computer‐Aided Engineering,* vol. 29, no. 9, pp. 1-5, 2019.

[63] L. Kang, H. Li, X. Wang and X. Shi, "Compact offset microstrip-fed MIMO antenna for band-notched UWB applications," *IEEE Antennas and Wireless Propagation Letters,* vol. 14, no. 3, pp. 1754-1757, 2015.

[64] M. Ikram, M. S. Sharawi, A. Shamim and A. Sebak, "A multiband dual-standard MIMO antenna system based on monopoles (4G) and connected slots (5G) for future smart phones," *Microwave and Optical Technology Letters,* vol. 60, no. 6, pp. 1468-1476, 2018.

[65] Z. Yang, F. Li and F. Li, "A compact slot MIMO antenna with band-notched characteristic for UWB application," in *In 2018 International Conference on Microwave and Millimeter Wave Technology (ICMMT)*, Chengdu, China, 2018.

[66] P. C. Nirmal, A. Nandgaonkar, S. Nalbalwar and R. K. Gupta, "Compact wideband MIMO antenna for 4G WI-MAX, WLAN and UWB applications," *AEU-International Journal of Electronics and Communications,* vol. 99, no. 1, pp. 248-292, 2019.

[67] A. Kumar, A. Q. Ansari, B. K. Kanaujia, J. Kishor and S. Kumar, "An ultra-compact two-port UWB-MIMO antenna with dual band-notched characteristics," *AEU-International Journal of Electronics and Communications,* vol. 114, no. 7, pp. 1-7, 2020a.

[68] R. Chandel and A. K. Gautam, "Compact MIMO/diversity slot antenna for UWB applications with band-notched characteristic," *Electronics Letters,* vol. 52, no. 5, pp. 336-338, 2016.

[69] A. Bhattacharya, B. Roy, S. K. Chowdhury and A. K. Bhattacharjee, "An isolation enhanced, printed, low-profile UWB-MIMO antenna with unique dual band-notching features for WLAN and WiMAX," *IETE Journal of Research,* vol. 22, no. 5, pp. 1-8, 2019.

[70] L. Liu, S. W. Cheung and T. I. Yuk, "Compact MIMO antenna for portable devices in UWB applications," *IEEE Transactions on antennas and propagation,* vol. 61, no. 8, pp. 4257-4264, 2013.

[71] H. F. Huang and S. G. Xiao, "Compact triple band-notched UWB MIMO antenna with simple stepped stub to enhance wideband isolation," *Progress in Electromagnetics Research Letters,* vol. 56, no. 4, pp. 59-65, 2015.

[72] R. Mathur and S. Dwari, "Compact planar reconfigurable UWB-MIMO antenna with on-demand worldwide interoperability for microwave access/wireless local area network rejection," *IET Microwaves, Antennas & Propagation,* vol. 13, no. 10, pp. 1684-1689, 2019a.

[73] A. Toktas, "G-shaped band-notched ultra-wideband MIMO antenna system for mobile terminals," *IET Microwaves, Antennas & Propagation,* vol. 11, no. 5, pp. 718-725, 2017.

[74] L. Wu, Y. Xia, X. Cao and Z. Xu, "A miniaturized UWB-MIMO antenna with quadruple band-notched characteristics," *International Journal of Microwave and Wireless Technologies,* vol. 10, no. 8, pp. 948-955, 2018.

[75] L. Wu, H. Lyu and H. Yu, "A novel compact UWB-MIMO antenna with quintuple notched-band characteristics," *Wireless Personal Communications,* vol. 108, no. 3, pp. 1827-1840, 2019.

[76] L. Wu, H. Lyu, H. Yu and J. Xu, "Design of a Miniaturized UWB-MIMO Antenna with Four Notched-Band Characteristics," *Frequenz,* vol. 73, no. 7-8, pp. 245-252, 2019.

[77] D. Yadav, M. P. Abegaonkar, S. K. Koul, V. N. Tiwari and D. Bhatnagar, "Two element band-notched UWB MIMO antenna with high and uniform isolation," *Progress In Electromagnetics Research M,* vol. 63, no. 3, pp. 119-129, 2018.

[78] C. Yang, Y. Yao, J. Yu and X. Chen, "Novel compact multiband MIMO antenna for mobile terminal," *International Journal of Antennas and Propagation,* vol. 45, no. 6, pp. 50-62, 2012.

[79] Y. Zhao, F. S. Zhang, L. X. Cao and D. H. Li, "A compact dual band-notched MIMO diversity antenna for UWB wireless applications," *Progress In Electromagnetics Research C,* vol. 89, no. 5, pp. 161-169, 2019.

[80] G. Srivastava and B. K. Kanuijia, "Compact dual band-notched UWB MIMO antenna with shared radiator," *Microwave and Optical Technology Letters,* vol. 57, no. 12, pp. 2886-2891, 2015.

[81] B. P. Chacko, G. Augustin and T. A. Denidni, "Uniplanar polarisation diversity antenna for ultra-wideband systems," *IET Microwaves, Antennas & Propagation,* vol. 7, no. 10, pp. 851-857, 2013.

[82] P. Gao, S. He, X. Wei, Z. Xu, N. Wang and Y. Zheng, "Compact printed UWB diversity slot antenna with 5.5-GHz band-notched characteristics," *IEEE Antennas and Wireless Propagation Letters,* vol. 13, no. 4, pp. 376-379, 2014.

[83] H. K. Yoon, Y. J. Yoon, H. Kim and C. H. Lee, "Flexible ultra-wideband polarisation diversity antenna with band-notch function," *IET Microwaves, Antennas & Propagation,* vol. 5, no. 12, pp. 1463-1470, 2011.

[84] J. Zhu, B. Feng, B. Peng, S. Li and L. Deng, "A dual notched band MIMO slot antenna system with Y-shaped defected ground structure for UWB applications," *Microwave and Optical Technology Letters,* vol. 58, no. 3, pp. 626-630, 2016a.

[85] M. S. Khan, M. F. Shafique, A. Naqvi, A. D. Capobianco, B. Ijaz and B. D. Braaten, "A miniaturized dual-band MIMO antenna for WLAN applications," *IEEE antennas and wireless propagation letters,* vol. 14, no. 3, pp. 958-961, 2015.

[86] R. Chandel, A. K. Gautam and K. Rambabu, "Tapered fed compact UWB MIMO-diversity antenna with dual band-notched characteristics," *IEEE Transactions on Antennas and Propagation,* vol. 66, no. 4, pp. 1677-1684, 2018.

[87] M. S. Khan, A. D. Capobianco, S. M. Asif, D. E. Anagnostou, R. M. Shubair and B. D. Braaten, "A compact CSRR-enabled UWB diversity antenna," *IEEE Antennas and Wireless Propagation Letters,* vol. 16, no. 7, pp. 808-812, 2016.

[88] A. Kumar, A. Q. Ansari, B. K. Kanaujia and J. Kishor, "Dual Circular Polarization with Reduced Mutual Coupling Among Two Orthogonally Placed CPW-Fed Microstrip Antennas for Broadband Applications," *Wireless Personal Communications,* vol. 107, no. 2, pp. 759-770, 2019.

[89] R. Mathur and S. Dwari, "Compact 4-port UWB-MIMO slot antenna with dual polarization and low correlation for spatial diversity application," *Frequenz,* vol. 72, no. 11-12, pp. 503-509, 2018b.

[90] S. P. Biswal and S. Das, "A compact printed ultra-wideband multiple-input multiple-output prototype with band-notch ability for WiMAX, LTEband43, and WLAN systems," *International Journal of RF and Microwave Computer-Aided Engineering,* vol. 29, no. 6, pp. 1-7, 2019.

[91] L. Malviya, R. K. Panigrahi and M. V. Kartikeyan, "2× 2 MIMO antenna for ISM band application," in *In 2016 11th International Conference on Industrial and Information Systems (ICIIS)*, Roorkee, India, 2016.

[92] C. X. Mao and Q. X. Chu, "Compact coradiator UWB-MIMO antenna with dual polarization," *IEEE transactions on antennas and propagation,* vol. 62, no. 9, pp. 4474-4480, 2014.

[93] A. Iqbal, O. A. Saraereh, A. W. Ahmad and S. Bashir, "Mutual coupling reduction using F-shaped stubs in UWB-MIMO antenna," *IEEE access,* vol. 6, no. 1, pp. 2755-2759, 2017.

[94] Z. Wani and D. K. Vishwakarma, "An

ultrawideband antenna for portable MIMO terminals," *Microwave and Optical Technology Letters,* vol. 58, no. 1, pp. 51-57, 2016.

[95] S. Shoaib, L. Shoaib, N. Shoaib, X. Chen and C. G. Parini, "Design and performance study of a dual-element multiband printed monopole antenna array for MIMO terminals," *IEEE Antennas and Wireless Propagation Letters,* vol. 13, no. 4, pp. 329-332, 2014.

[96] H. V. Singh and S. Tripathi, "Compact UWB MIMO antenna with cross-shaped unconnected ground stub using characteristic mode analysis," *Microwave and Optical Technology Letters,* vol. 61, no. 7, pp. 1874-1881, 2019.

[97] S. P. Biswal and S. Das, "A low-profile dual port UWB-MIMO/diversity antenna with band rejection ability," *International Journal of RF and Microwave Computer-Aided Engineering,* vol. 28, no. 1, pp. 1-6, 2018b.

[98] R. R. Krishna and R. Kumar, "A dual-polarized square-ring slot antenna for UWB, imaging, and radar applications," *IEEE Antennas and Wireless Propagation Letters,* vol. 15, no. 3, pp. 195-198, 2015.

[99] M. S. Sharawi, "Printed MIMO antenna systems: performance metrics, implementations and challenges," in *In Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)*, Dhahran, Saudi Arabia, 2014.

[100] H. Arun, A. K. Sarma, M. Kanagasabai, S. Velan, C. Raviteja and M. G. N. Alsath, "Deployment of modified serpentine structure for mutual coupling reduction in MIMO antennas," *IEEE antennas and wireless propagation letters,* vol. 13, no. 8, pp. 277-280, 2014.

[101] M. S. Sharawi, S. K. Podilchak, M. U. Khan and Y. M. Antar, "Dual-frequency DRA-based MIMO antenna system for wireless access points," *IET Microwaves, Antennas & Propagation,* vol. 11, no. 8, pp. 1174-1182, 2017.

[102] T. K. Roshna, U. Deepak, V. R. Sajitha, K. Vasudevan and P. Mohanan, "A compact UWB MIMO antenna with reflector to enhance isolation," *IEEE Transactions on Antennas and Propagation,* vol. 63, no. 4, pp. 1873-1877, 2015.

[103] W. T. Li, Y. Q. Hei, H. Subbaraman, X. W. Shi and R. T. Chen, "Novel printed filtenna with dual notches and good out-of-band characteristics for UWB-MIMO applications," *IEEE microwave and wireless components letters,* vol. 26, no. 10, pp. 765-767, 2016.

[104] S. Singhal, "Four element ultra-wideband fractal multiple-input multiple-output antenna," *Microwave and Optical Technology Letters,* vol. 61, no. 12, pp. 2811-2818, 2019.

[105] N. Hatami, J. Nourinia, C. Ghobadi, M. Majidzadeh and B. Azarm, "High inter-element isolation and WLAN filtering mechanism: A compact MIMO antenna scheme," *AEU-International Journal of Electronics and Communications,* vol. 109, no. 9, pp. 43-54, 2019.

[106] F. Faraz, Q. Li, X. Chen, M. Abdullah, S. Zhang and A. Zhang, "Mutual coupling reduction for linearly arranged MIMO antenna," in *In 2019 Cross Strait Quad-Regional Radio Science and Wireless Technology Conference (CSQRWC)*, Taiyuan, China, 2019.

[107] S. Caizzone, "Miniaturized E5a/E1 antenna array for robust GNSS navigation," *IEEE Antennas and Wireless Propagation Letters,* vol. 16, no. 1, pp. 485-488, 2016.

[108] S. R. Thummaluru, M. Ameen and R. K. Chaudhary, "Four-port MIMO cognitive radio system for midband 5G applications," *IEEE Transactions on Antennas and Propagation,* vol. 67, no. 8, pp. 5634-5645, 2019.

[109] J. Ghimire, K. W. Choi and D. Y. Choi, "Bandwidth enhancement and mutual coupling reduction using a notch and a parasitic structure in a UWB-MIMO antenna," *International Journal of Antennas and Propagation,* vol. 30, no. 4, pp. 56-69, 2019.

[110] F. Wang, S. Li, Q. Zhou and Y. B. Gong, "Compact wideband quad-element MIMO antenna with reversed S-Shaped walls," *Progress In Electromagnetics Research M,* vol. 78, no. 5, pp. 193-201, 2019.

[111] L. Y. Nie, X. Q. Lin, B. Wang and J. Zhang, "A planar multifunctional four-port antenna system for sub-urban mobile tablet," *IEEE Access,* vol. 7, no. 7, pp. 56986-56993, 2019.

[112] B. Azarm, J. Nourinia, C. Ghobadi, M. Majidzadeh and N. Hatami, "On development of a MIMO antenna for coupling reduction and WiMAX suppression purposes," *AEU-International Journal of Electronics and Communications,* vol. 99, no. 5, pp. 226-235, 2019.

[113] S. Chouhan, D. K. Panda and V. S. Kushwah, "Modified circular common element four-port multiple-input-multiple-output antenna using

diagonal parasitic element," *International Journal of RF and Microwave Computer-Aided Engineering,* vol. 29, no. 2, pp. 1-7, 2019.

[114] P. Debnath, A. Karmakar, A. Saha and S. Huda, "UWB MIMO slot antenna with Minkowski fractal shaped isolators for isolation enhancement," *Progress In Electromagnetics Research M,* vol. 75, no. 5, pp. 69-78, 2018.

[115] A. A. Isaac, H. Al-Rizzo, S. Yahya, A. Al-Wahhamy and S. Abushamleh, "Decoupling of Two Closely-Spaced Planar Monopole Antennas Using Two Novel Printed-Circuit Structures," *Microwave and Optical Technology Letters,* vol. 60, no. 12, pp. 2954-2963, 2018.

[116] J. D. Park, M. Rahman and H. N. Chen, "Isolation enhancement of wide-band MIMO array antennas utilizing resistive loading," *IEEE Access,* vol. 7, no. 9, pp. 81020-81026, 2019.

[117] L. Wang, G. Wang and Q. Zhao, "Suppressing mutual coupling of MIMO antennas with parasitic fragment-type elements," in *In 2016 46th European Microwave Conference (EuMC)*, London, UK, 2016.

[118] G. Breed, "An introduction to defected ground structures in microstrip circuits," *High Frequency Electronics,* vol. 7, no. 11, pp. 50-54, 2008.

[119] M. K. Khandelwal, B. K. Kanaujia and S. Kumar, "Defected ground structure: fundamentals, analysis, and applications in modern wireless trends," *International Journal of Antennas and Propagation,* vol. 11, no. 5, pp. 1-7, 2017.

[120] L. H. Weng, Y. C. Guo, X. W. Shi and X. Q. Chen, "An overview on defected ground structure," *Progress In Electromagnetics Research B,* vol. 3, pp. 173-189, 2008.

[121] J. G. Webster, M. S. Bhuiyan and N. C. Karmakar, Defected ground structures for microwave applications, Wiley encyclopaedia of electrical and electronics engineering, 2014.

[122] A. MoradiKordalivand, T. A. Rahman and M. Khalily, "Common elements wideband MIMO antenna system for WiFi/LTE access-point applications," *IEEE Antennas and Wireless Propagation Letters,* vol. 13, no. 2, pp. 1601-1604, 2014.

[123] H. Wang, L. Liu, Z. Zhang, Y. Li and Z. Feng, "A wideband compact WLAN/WiMAX MIMO antenna based on dipole with V-shaped ground branch," *IEEE Transactions on Antennas and Propagation,* vol. 63, no. 5, pp. 2290-2295, 2015.

[124] A. Ramachandran, S. Mathew, V. P. Viswanathan, M. Pezholil and V. Kesavath, "Diversity-based four-port multiple input multiple output antenna loaded with interdigital structure for high isolation," *IET Microwaves, Antennas & Propagation,* vol. 10, no. 15, pp. 1633-1642, 2016.

[125] J. Deng, J. Li, L. Zhao and L. Guo, "A dual-band inverted-F MIMO antenna with enhanced isolation for WLAN applications," *IEEE Antennas and Wireless Propagation Letters,* vol. 16, no. 8, pp. 2270-2273, 2017.

[126] G. Irene and A. Rajesh, "Review on the Design of the Isolation Techniques for UWB-MIMO ANtenna," *Advanced Electromagnetics,* vol. 7, no. 4, pp. 46-70, 2018a.

[127] G. Irene and A. Rajesh, "A penta-band reject inside cut koch fractal hexagonal monopole UWB MIMO antenna for portable devices," *Progress In Electromagnetics Research C,* vol. 82, no. 7, pp. 225-235, 2018b.

[128] A. K. Gautam, A. Saini, N. Agrawal and N. Z. Rizvi, "Design of a compact protrudent-shaped ultra-wideband multiple-input-multiple-output/diversity antenna with band-rejection capability," *International Journal of RF and Microwave Computer-Aided Engineering,* vol. 29, no. 9, pp. 1-12, 2019.

[129] A. Kumar, A. Kumar and M. V. Kartikeyan, "Design and studies of bandstop filters using modified CSRR DGS for WLAN applications," in *In Optical and Wireless Technologies*, Springer, Singapore, 2020b.

[130] C. Yu, S. Yang, Y. Chen, W. Wang, L. Zhang, B. Li and L. Wang, "A super-wideband and high isolation MIMO antenna system using a windmill-shaped decoupling structure," *IEEE Access,* vol. 8, no. 2, pp. 115767-115777, 2020.

[131] Z. Li, C. Yin and X. Zhu, " Compact UWB MIMO vivaldi antenna with dual band-notched characteristics," *IEEE Access,* vol. 7, no. 4, pp. 38696-38701, 2019.

[132] A. M. Abbosh, "Analytical closed-form solutions for different configurations of parallel-coupled microstrip," *IET microwaves, antennas & propagation,* vol. 3, no. 1, pp. 137-147, 2009.

[133] j. Acharjee, K. Mandal and S. K. Mandal, "Reduction of mutual coupling and cross-polarization of a MIMO/diversity antenna using a string of H-shaped DGS," *AEU-International Journal of Electronics and Communications,* vol. 97, no. 11, pp. 110-119, 2018.

[134] H. Huang, Y. Liu, S. S. Zhang and S. X. Gong, "Compact polarization diversity ultrawideband MIMO antenna with triple band-notched characteristics," *Microwave and Optical Technology Letters,* vol. 57, no. 4, pp. 946-953, 2015.

[135] J. Tao and Q. Feng, "Compact UWB band-notch MIMO antenna with embedded antenna element for improved band notch filtering," *Progress In Electromagnetics Research C,* vol. 67, no. 3, pp. 117-125, 2016.

[136] R. Karimian, M. Soleimani and S. M. Hashemi, "Tri-band four elements MIMO antenna system for WLAN and WiMAX application," *Journal of Electromagnetic Waves and Applications,* vol. 26, no. 17-18, pp. 2348-2357, 2012.

[137] W. J. Liao, C. Y. Hsieh, B. Y. Dai and B. R. Hsiao, "Inverted-F/slot integrated dual-band four-antenna system for WLAN access points," *IEEE Antennas and Wireless Propagation Letters,* vol. 14, no. 5, pp. 847-850, 2014.

[138] K. L. Chung and S. Kharkovsky, "Mutual coupling reduction and gain enhancement using angular offset elements in circularly polarized patch array," *IEEE Antennas and Wireless Propagation Letters,* vol. 12, no. 1, pp. 1122-1124, 2013.

[139] Y. Luo, Q. X. Chu, J. F. Li and Y. T. Wu, "A planar H-shaped directive antenna and its application in compact MIMO antenna," *IEEE Transactions on Antennas and Propagation,* vol. 61, no. 9, pp. 4810-4814, 2013.

[140] D. Sarkar and K. V. Srivastava, "Compact four-element SRR-loaded dual-band MIMO antenna for WLAN/WiMAX/WiFi/4G-LTE and 5G applications," *Electronics Letters,* vol. 53, no. 25, pp. 1623-1624, 2017.

[141] Nirdosh, M. Tan C and M. R. Tripathy, "A miniaturized T-shaped MIMO antenna for X-band and Ku-band applications with enhanced radiation efficiency," in *In 2018 27th Wireless and Optical Communication Conference (WOCC)*, Hualien, Taiwan, 2018.

[142] K. Srivastava, A. Kumar, B. K. Kanaujia, S. Dwari and S. Kumar, "A CPW-fed UWB MIMO antenna with integrated GSM band and dual band notches," *International Journal of RF and Microwave Computer‐Aided Engineering,* vol. 29, no. 1, pp. 1-11, 2019.

[143] M. Aminu-Baba, M. K. A. Rahim, F. Zubir, A. Y. Iliyasu, M. F. M. Yusoff, K. I. Jahun and O. Ayop, "Compact patch MIMO antenna with low mutual coupling for WLAN applications," *ELEKTRIKA-Journal of Electrical Engineering,* vol. 18, no. 1, pp. 43-46, 2019.

[144] S. Chu, M. N. Hasan, J. Yan and C. C. Chu, "Tri-band 2X2 5G MIMO Antenna Array," in *In 2018 Asia-Pacific Microwave Conference (APMC)*, Kyoto, Japan, 2018.

[145] N. Ojaroudi, N. Ghadimi, M. Mehranpour, Y. Ojaroudi and S. Ojaroudi, "A new design of triple-band WLAN/WiMAX monopole antenna for multiple-input/multiple-output applications," *Microwave and Optical Technology Letters,* vol. 56, no. 11, pp. 2667-2671, 2014.