A Review on Different Techniques of Mutual Coupling Reduction Between Elements of Any MIMO Antenna. Part 1: DGSs and Parasitic Structures

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Key Points:

- Multiple-Input-Multiple-Output (MIMO) patch antenna is required for high data rate transmission without additional bandwidth requirement
- Mutual coupling reduction among antenna elements is a significant challenge while designing a compact antenna array system
- Defected Ground Structures and Parasitics elements/structures for mutual coupling reduction have been discussed thoroughly in this article

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A Review on Different Techniques of Mutual Coupling Reduction Between Elements of Any MIMO Antenna. Part 1: DGSs and Parasitic Structures

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Abstract This two-part article presents a review of different techniques of mutual coupling (MC) reduction. MC is a major issue when an array of antennas is densely packed. When the separation between the antennas is $<\lambda_0/2$, i.e., half of the free-space wavelength, the antenna parameters suffer from the surface wave, and the space wave coupling effect between the antenna elements. To reduce the MC influence, several techniques have been discussed in the scientific literature. This part of the review paper will discuss strategies: antenna placement and orientation approach, Defected Ground Structures (DGSs), slots/slits-etching approach, protruding ground stub structures, and parasitic elements/structures. This article concludes with feasibility, applications, and comparison of the techniques mentioned above. Simultaneously, the applications and possibilities of the remaining methods are discussed in part two of the article.

Plain Language Summary A comprehensive two-part review article with more than 330 references is proposed.

1. Introduction

With the advancement in the high data rates wireless transmission, the demand for high channel capacity planar antennas, especially for handheld devices, has shown a significant market. Multiple-Input-Multiple-Output (MIMO) antennas can fulfill the top requirement. MIMO antenna helps in increasing data throughput and link coverage without sacrificing additional bandwidth or increased transmit power (Kumar et al., 2018a, 2018b). The MIMO antenna's other advantages are: high data throughput and link range without additional spectrum requirement, increased transmit power, spatial diversity and pattern diversity, and less signal dropout (Kumar et al., 2019a). In MIMO, multiple antennas radiate simultaneously and act as a transmitter or receiver depending upon its purpose. Multiple antennas placed on a single substrate sharing at least one standard radiating frequency will be considered an MIMO antenna. The MIMO antenna should have a common ground, easing the integration with monolithic integrated circuits (ICs) (Kumar et al., 2020a). However, sometimes the MIMO antenna does not have a common ground plane, but such cases should be avoided for better integration purposes and standard voltage levels.

MIMO antenna should be more compact to have a reduced form factor. The MIMO antenna's compactness is another primary concern when multiple antennas are placed on a single substrate. If the antenna element spacing is less than the $\lambda_0/2$, i.e., half of the free-space wavelength, then the antenna suffers from the surface wave and the space wave coupling effect between the antenna elements (Dama et al., 2011). For that reason, as the compactness increases, the chances of MC effect increase, resulting in degradation in the MIMO antenna performance due to power losses in a rich scattering environment. Therefore, an effective isolation technique is a must in the design of a compact MIMO antenna. Besides this, pattern and spatial diversity need to be taken care of while introducing any isolation techniques: it should not disturb the antenna far-field radiation pattern and the impedance matching at large.

This two-part article deals with a thorough description of the existing isolation techniques for minimizing the MC between patch antennas present until the to date literature. It clearly states the MC reduction techniques' purpose and significance between the patch antennas in an array configuration. Several methods have been introduced and published in the literature. Still, each one has its kind of resemblance and advantage depending upon the antenna's design and working under consideration and the given application. Some more specific parameters, especially of the MIMO antenna, have been thoroughly discussed (Chen, 2015; Nadeem & Choi, 2019; Paulraj et al., 2004; Stjernman, 2005; Thuwaini, 2018; Vaughan & Andersen, 1987). Many review papers (Chouhan et al., 2018; Irene & Rajesh, 2018a, 2018b; Malviya et al., 2017; Nadeem & Choi, 2019) have already been published, citing various techniques of MC reduction. However, the main objective is to have closely spaced MIMO antenna elements with high isolation between them. The techniques we will discuss in part one of the two-part articles are tabulated in Table 1.

Table 1
Mutual Coupling Reduction Techniques With references

Techniques	References
Antenna placement and orientation approach	Aminu-Baba et al. (2019), Chu et al. (2018), Chung and Kharkovsky (2013), Huang et al. (2015a, 2015b), Karimian et al. (2012), Khan et al. (2020), Liao et al. (2015) Luo et al. (2013), Mathur and Dwari (2018a), Nirdosh et al. (2018), Ojaroudi et al. (2014), Rekha et al. (2020), Sarkar and Srivastava (2017), Srivastava et al. (2019), and Tao and Feng (2016)
Defected Ground Structures (DGSs)	Abbosh (2007), Abdalla and Ibrahim (2013), Abid et al. (2018), Acharjee et al. (2018), Anitha et al. (2014), Asghar et al. (2018), Breed (2008), Chen and Chang (2016), Deng et al. (2017), Dhar and Sharawi (2014), Elsheakh et al. (2010), Gao et al. (2020), Gautam et al. (2019), Ghouz (2015), Habashi et al. (2011), Hussain et al. (2018), Irene and Rajesh (2018a, 2018b), Jamal et al. (2020), Khandelwal et al. (2017), Kim et al. (2008), Kumar et al. (2020b), Li et al. (2018, 2019), Lu et al. (2018), Malviya et al. (2016b), MoradiKordalivand et al. (2014), Numan et al. (2013), Ramachandran et al. (2016), Singh et al. (2015), Wang et al. (2015), Wang et al. (2014), Webster et al. (2014), Wei et al. (2016a, 2016b, 2017), Weng et al. (2008), Wu et al. (2019), Y et al. (2020), Yang et al. (2014), Yang et al. (2020), Zhang et al. (2020) and Zhu et al. (2016)
Slots/slits-etching approach	Addaci et al. (2014), Ayatollahi et al. (2012), Bhanumathi and Sivaranjani (2019), Biswal and Das (2018b), Chiu et al. (2007), Fritz-Andrade et al. (2020), Gangwar et al. (2020), Huang et al. (2015a), Hussain et al. (2019), Ikram et al. (2018), Jaglan et al. (2018, 2017), Jetti and Nandanavanam (2018), Kang et al. (2016), Khan et al. (2017b), Li et al. (2009), Liu et al. (2015), Lu et al. (2011), Marzudi et al. (2015), Nandi and Mohan (2017), Nirmal et al. (2019), Ouyang et al. (2011), Park et al. (2012), Ren et al. (2014), Sharawi et al. (2012), Sonkki and Salonen (2010), Srivastava et al. (2016), Srivastava and Mohan (2015), Ul Haq and Koziel (2018), Wang et al. (2020), Wu and Chu (2014), Zhou et al. (2012), Yang et al. (2016), Yang et al. (2018), Zhai et al. (2013), Zhang et al. (2015), Zhang et al. (2012), and Zuo et al. (2010)
Protruding ground stub structures	Ban et al. (2014), Bhattacharya et al. (2019), Biswal and Das (2018a, 2019), Chacko et al. (2013), Chandel and Gautam (2016), Chandel et al. (2018), Dong et al. (2020), Gao et al. (2014), Gautam et al. (2018), Govindarajulu et al. (2020), Hong et al. (2008), Huang et al. (2015a), Huang and Xiao (2015), Iqbal et al. (2017), Khan et al. (2015), Khan et al. (2017a), Krishna and Kumar (2016), Kumar et al. (2019b, 2020a, 2020c, 2020d), Kumar et al. (2018c), Li et al. (2013a, 2013b), Liu et al. (2013), Malviya et al. (2016a), Mao and Chu (2014), Mathur and Dwari (2018b, 2019a, 2019b), Mchbal et al. (2018), Saxena et al. (2017), Sharawi et al. (2011), Shoaib et al. (2015, 2014), Silveira et al. (2009), Singh and Tripathi (2019), Singh et al. (2013), Srivastava and Kanuijia (2015), Toktas (2017), Wani and Vishwakarma (2016), Wu et al. (2018), Wu, Lyu, & Yu (2019); Wu, Lyu, Yu, & Xu (2019), Yadav et al. (2018), Yang et al. (2012, 2016), Yoon et al. (2011), Zeng et al. (2012), Zhang et al. (2009), Zhao et al. (2019), and Zhu et al. (2016a, 2016b)
Parasitic elements/structures	Addaci et al. (2012), Alsultan and Ögücü Yetkin (2018), Arun et al. (2014), Azarm et al. (2019), Caizzone (2017), Chouhan et al. (2019), Debnath et al. (2018), Faraz et al. (2019), Ghimire et al. (2019), Ghosh (2016), Ghosh and Parui (2014), Alsath et al. (2013), Hatami et al. (2019), Hwang et al. (2010), Isaac et al. (2018), Kang et al. (2015), Kang and Wong (2010), Kumar et al. (2018b, 2019a), Lee et al. (2009), Lee et al. (2012), Li et al. (2012, 2016), Mak et al. (2008), Min et al. (2005), Minz and Garg (2010), Nie et al. (2019), Park et al. (2019), Payandehjoo and Abhari (2014), Roshna et al. (2015), Sharawi et al. (2017), Sharawi (2013), Singhal (2019), Thummaluru et al. (2019), Vasu Babu and Anuradha (2020), Wang et al. (2019), Wang et al. (2016), Wen and Xin-Liang (2018), Wu et al. (2017), Liu et al. (2018), Yu et al. (2020), and Zhu et al. (2016)

Before going into the details of different isolation techniques' performance, we should know some basic diversity performance parameter check discussed in the next section.

2. Mutual Coupling and Diversity Performances

2.1. Mutual Coupling

Mutual coupling (MC) is a physically complex phenomenon that refers to the electromagnetic interaction or the reaction between different antenna elements in a proximity configuration, as happens, e.g., in an array system. Even if all antennas are transmitting, they will simultaneously receive part of each other's transmitted energy.

A schematic diagram has been shown in Figures 1a–1c to explain the different paths through which the waves travel from one antenna to the other radiators. Figure 1a shows the various pathways through which the energy interchanges indirectly via scattering (transmission coefficients like S_{ji} where ith is the transmitting and jth is the receiving antenna) between four antenna elements placed in closed proximity, resulting in MC's manifestation. Similarly, in Figure 1b, Antenna m is radiating as it is connected to an active source, but the Antenna n is terminated (passive) with a characteristic impedance of 50 Ω. Antenna m can produce electromagnetic waves and radiate in free-space denoted by 2 in Figure 1b. Some portion of the radiated energy is received by the passive Antenna n characterized by 3. Some energy is reflected back to the port represented by 1. In contrast, some part of the rescatter energy is again received by the Antenna m as depicted by 4, thus expressing that the total energy is not coming from the exciting Antenna m only but also from the passive Antenna n. Therefore, MC needs to be checked to increase the performance and save the rescattering of energy. The unwanted incident radiation induces a current in the passive antenna elements due to coupling and will disturb its radiation characteristics. According to the reciprocity theorem, the same holds in the opposite direction (inverting the transmitter and receiver antennas) since MC is a symmetric phenomenon. The energy will also be wasted if some part of the radiating patch antenna gets transferred or induced to the nearby elements. Figure 1c shows the traveling of surface wave currents through the metallic patch placed on the top. It will radiate only when there is some discontinuity, curve, or truncation in the path. There will be some decay constants based on the permittivity of the substrate's dielectric constant, which decides the direction of the surface wave currents along the substrate and will radiate along the edges, as shown in Figure 1c. This impact will be severe in an antenna array, and so the surface current distribution needs to be checked and should be prevented from reaching the nearby antenna elements. So, proper isolation of the radiating antenna elements on the same substrate should be guaranteed to improve the radiation efficiency and preserves the spatial and pattern diversity of the individual antenna elements in an antenna array system.

The MC problem frequently arises in patch antennas when >1 antenna element is placed closer than $\lambda_0/2$ on a single substrate. Usually, these antenna elements are located in an array configuration, i.e., the dif-

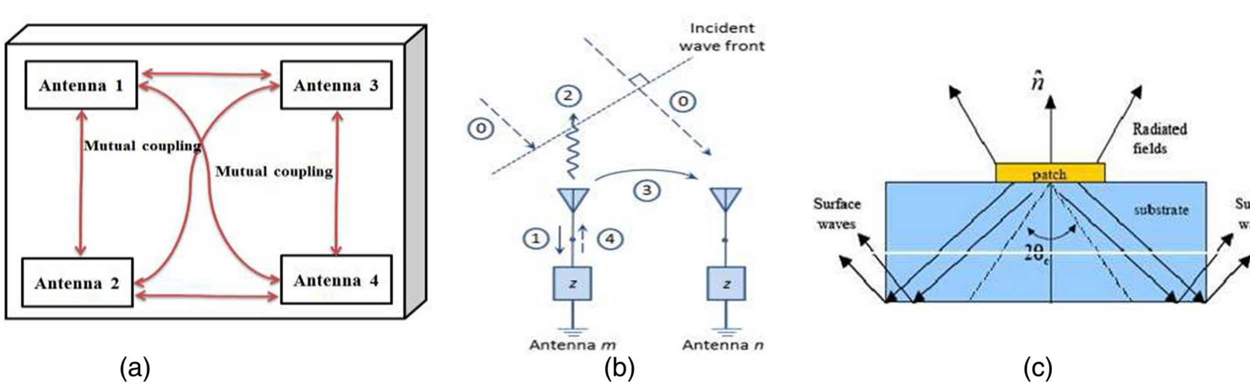

Figure 1. A schematic diagram illustrating the MC phenomena between compact antenna elements of any MIMO antenna (Thuwaini, 2018). MC, mutual coupling; MIMO, Multiple-Input-Multiple-Output.

ferent radiators have the same effective height. Antenna array plays a vital role in MIMO Systems (Smart Antenna Technology).

Strong MC causes:

- poor port isolation
- degradation of the spatial and pattern diversity
- reduction of antenna efficiency
- reduction of the antenna gain
- high correlation among radiators

So, we have some diversity performance check mentioned below to ensure the MIMO antenna systems' better performance.

2.1.1. Diversity Performances

To justify MIMO antennas performance, some of the diversity parameters, such as ECC (envelope correlation coefficient) (Chen, 2015; Kumar et al., 2018a, 2019a), DG (diversity gain) (Kumar et al., 2020a), MEG (mean effective) (Kumar et al., 2018a, 2019a), TARC (total active reflection coefficient) (Kumar et al., 2018a) and CCL (channel capacity loss) (Kumar et al., 2018a), have to be calculated and verified.

2.1.1.1. ECC and DG

The ECC describes how one antenna is correlated with other antennas present in their region of interference. Part of interference is considered an area that is coming under $\lambda_0/2$ distance from the concerned antenna resulting in MC among the antennas, and hence, it degrades the antenna performance (Dama et al., 2011). If the gap between the adjacent antennas is more than $\lambda_0/2$, it will not affect the nearby antennas; however, to achieve compactness; generally, two antennas are placed tightly. A general equation to compute ECC (Kumar et al., 2018a) is given below

$$\rho e\left(i,j,N\right) = \frac{\left|\sum_{n=1}^{N} S_{i,n}^{*} S_{n,j}\right|^{2}}{\Pi_{k=(i,j)}\left[1-\sum_{n=1}^{N} S_{i,n}^{*} S_{n,k}\right]} \tag{1}$$

Here, i and j are antenna elements (radiators) and N is the total number of antennas taken under considerations.

The approach of calculating ECC through S-parameters becomes more reliable by considering the antenna elements' radiation efficiencies (Nadeem & Choi, 2019), as shown in

$$\rho_{ij.\max} = \frac{-\sum_{n=1}^{N} S_{ni}^{*} S_{nj}}{\sqrt{\left(1-\sum_{n=1}^{N}|S_{ni}|^{2}\right)\left(1-\sum_{n=1}^{N}|S_{nj}|^{2}\right)\eta_{rad.i}\eta_{rad.j}}} + \sqrt{\left(\frac{1}{\eta_{rad.i}}-1\right)\left(\frac{1}{\eta_{rad.j}}-1\right)} \tag{2}$$

where $\eta_{rad.i}$ and $\eta_{rad.j}$ are the radiation efficiencies of ith and jth antenna elements of an MIMO antenna system. But for lower efficiency antenna, the above relation gives higher values. This method is also not suitable for pattern shape or a tilted beam (Nadeem & Choi, 2019). ECC should be as low as possible, with an acceptable limit of 0.05 (Kumar et al., 2018a).

ECC of the MIMO antenna has also been calculated using the equation based on the antennas' far-field radiation patterns (Kumar et al., 2019a, 2020a), as described in 3. Envelope correlation ρ_{ij} compares how the radiation pattern of the ith antenna element of an MIMO system is correlated with the jth antenna element. The calculation of ECC based on correlation coefficients from S-parameters gives shallow values. The computation of ECC using the S-parameter approach will provide you with port isolation value and is acceptable for the narrowband antenna. Still, for a wideband antenna, this approach is not so accurate. So, in general, it is better to compute ECC from far-field radiation patterns parameters (Kumar et al., 2019a) as given in 3. The lower will be the value; the better will be the radiation pattern diversity.

In the computational approach of ECC based on far-field radiation pattern mentioned in Equation 3, XPR is the measure of the cross-polarization rate of the incident field, which is defined as P_V/P_H, where P_V and P_H are the average power along the vertical and horizontal axis of the antenna, respectively, i.e., along with the spherical coordinates θ and Φ respectively. $E_{\theta i}$ and $E_{\Phi i}$ are the complex envelopes of θ and Φ components of the radiated far-field, respectively, when only the ith port is excited, and other ports are terminated with 50 Ω loads. P_θ and P_Φ are the probability of distributions of the incident power on the antenna in θ and Φ directions, respectively. The solid angle Ω is the two-dimensional angle in the three-dimensional radiation pattern defined by θ in elevation and Φ in azimuth. We will consider the reference of an isotropic environment where the P_V and P_H are almost equal, so $XPR = 1$ and $P_\theta = P_\Phi = 1/4\pi$. While calculating ECC from far-field, value <0.5 is widely accepted, unlike 0.05, in the case of S-parameters

$$\rho_{ij} = \frac{\left|\int \Omega\left[XPR \cdot E_{\theta i}E^*_{\theta j}P_\theta + E_{\phi i}E^*_{\phi j}P_\phi\right]d\Omega\right|^2}{\int \Omega\left\{XPR \cdot E_{\theta i}E^*_{\theta i}P_\theta + E_{\phi i}E^*_{\phi i}P_\phi\right\}d\Omega \times \int \Omega\left\{XPR \cdot E_{\theta j}E^*_{\theta j}P_\theta + E_{\phi j}E^*_{\phi j}P_\phi\right\}d\Omega} \tag{3}$$

Another method to compute ECC by utilizing far-field radiation is given in 4, where η_{max} is the maximum efficiency. It depends on the power distribution of the radiating elements. In this method, $\eta_i\ \eta_j$ is the total efficiency of the radiation elements

$$\left|\rho_{ij}\left(e\right)\right|^2 = 1 - \frac{\eta_{\max}}{\eta_i \eta_j} \tag{4}$$

Diversity gain states the amount of improvement obtained from MIMO compared to SISO (Single Input Single Output). It can be computed using the following relation (Kumar et al., 2020a), as given in 5. The maximum diversity gain is 10 at the 1% probability level with maximum-ratio combining, and e_p is the diversity gain reduction factor due to correlation between the signals on the two antennas (ρ_e is the envelope correlation coefficient)

$$DG = 10 \times e_p = 10 \times \sqrt{\left(1 - \left|0.99\rho_{ij}\right|\right)^2} \tag{5}$$

2.1.1.2. MEG

MEG is one of the characterization parameters of the MIMO antenna. MEG is the figure of merit of the antenna that measures the amount of power received by the antenna elements in an MIMO environment as compared to an isotropic antenna in a fading environment (Kumar et al., 2018a, 2018b, 2019a, 2020a). If we consider the statistical environment to be uniform Rayleigh with equal vertical and horizontal power densities, then MEG can be computed using the following relation 6 (Kumar et al., 2018a). Also, the difference between any two *MEGi* should be <3 dB 7 (Kumar et al., 2018a, 2018b, 2019a, 2020a)

$$MEG_i = 0.5\left[1 - \sum_{j=1}^{N}\left|S_{ij}\right|^2\right] \tag{6}$$

also

$$MEG_i - MEG_j \mid < 3\text{db} \tag{7}$$

MEG is also calculated from the far-field radiation pattern given in 8 (Kumar et al., 2019a, 2020a), which is considered more reliable than the S-parameters approach. In Equation 8, G_θ and G_Φ are the power gain patterns of the antenna elements when θ is varied, and Φ is constant in case of G_θ and vice versa for G_Φ (Kumar et al., 2019a, 2020a)

$$MEG = \int_0^{2\pi}\int_0^{\pi}\left[\frac{XPR}{1+XPR}G_\theta\left(\theta,\phi\right)P_\theta\left(\theta,\phi\right) + \frac{1}{1+XPR}G_\phi\left(\theta,\phi\right)P_\phi\left(\theta,\phi\right)\right]\sin\theta d\theta d\phi \tag{8}$$

In an outdoor uniform propagation environment (Kumar et al., 2019a), MEG has been calculated for $XPR = 0$. Theoretically, MEG's maximum possible value is −3 dB when antenna efficiency is 100% (Kumar et al., 2020a). The difference in MEGs in dB should be close to unity and should not exceed 3 dB, as shown in 7 for better diversity performance.

2.1.1.3. TARC

TARC is an important parameter to characterize MIMO antenna frequency bandwidth and radiation performance under the diverse nature of MIMO antennas (Kumar et al., 2018a, 2018b, 2019a, 2020a). It signifies the importance of impedance bandwidth and nonvarying resonance frequency even when the input signal phase θ changes for all the input ports. A generalized equation of TARC has been defined for multiple-port MIMO antenna combining all scattering parameters when the antenna is linearly polarized after considering the TARC formulation given in 9 (Irene & Rajesh, 2018a, 2018b; Kumar et al., 2018a)

$$TARC = \frac{\sqrt{\sum_{i=1}^{N}\left|S_{i1} + \sum_{m=2}^{N} S_{im}e^{j\theta_{m-1}}\right|^2}}{\sqrt{N}} \tag{9}$$

2.1.1.4. CCL

CCL is one of the vital diversity performance check-up parameters for MIMO antennas. CCL helps in signifying the maximum attainable limit of message transmission rate up to which signal can be transmitted continuously over the communication channel with a loss of fewer than 0.4 bits/s/Hz over the operating frequency range (Kumar et al., 2018a, 2018b, 2019a, 2020a). It can be computed using the following Equation 10:

$$C_{loss} = -\log_2 \det\left(\alpha^R\right) \tag{10}$$

where $\alpha^R = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} & \alpha_{14} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & \alpha_{24} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \alpha_{34} \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & \alpha_{44} \end{bmatrix}$

where $\alpha_{ii} = 1 - \left(\sum_{j=1}^{N}\left|S_{ij}\right|^2\right)$ and $\alpha_{ij} = -\left(S_{ii}^{*}S_{ij} + S_{ji}^{*}S_{ij}\right)$

3. Isolation Techniques Discussion

3.1. Antenna Placement and Orientation Approach

On several occasions, antenna placement and their orientation are sufficient enough to achieve the minimum required isolation of 10 dB or more. But sometimes, the only disadvantage is the wastage of the substrate area and the antenna area due to an orthogonal or diagonal arrangement of the antenna elements. Like in Huang et al. (2015b) as represented in Figure 2a, the orthogonal arrangement resulted in >20 dB similarly 15 dB isolation (Tao & Feng, 2016) over the entire ultrawideband (UWB) frequency range, without any isolation/decoupling structure. Again, in Karimian et al. (2012), orthogonally placed four antenna elements achieved polarization diversity along with minimum isolation of 16 dB with the additional help of slits etched in the ground plane. In Liao et al. (2015), the four inverted-F antenna elements are arranged in a rotational symmetry as represented in Figure 2b along the square substrate's four corners to

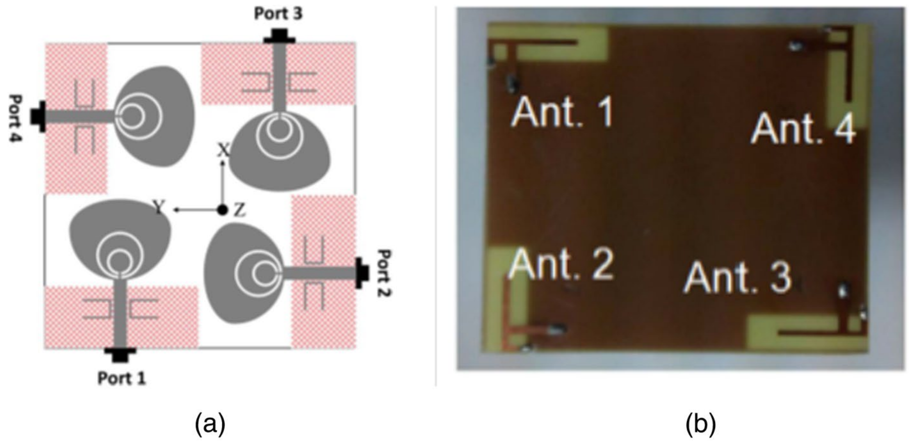

Figure 2. (a) Orthogonal arrangement (Huang et al., 2015b) and (b) rotational symmetry (Liao et al., 2015).

achieve decent isolation. Similar orthogonal arrangements of four elements have been shown in Chung and Kharkovsky (2013), Luo et al. (2013), Mathur and Dwari (2018a), Nirdosh et al. (2018), Sarkar and Srivastava (2017); and Srivastava et al. (2019), while in Chung and Kharkovsky (2013), there is an additional offset of 135° from the conventional sequential rotational array (SRA) for better isolation as represented in Figures 3a–3c. Some more examples of the orthogonal arrangement of two antenna elements have been shown (Aminu-Baba et al., 2019; Chu et al., 2018; Ojaroudi et al., 2014).

In Table 2, all antenna elements are orthogonally placed, minimizing the MC and attaining spatial and pattern diversity. Among all (Srivastava et al., 2019) is the most compact MIMO antenna with better isolation considering the four antenna elements.

3.2. Defected Ground Structures (DGSs)

Defected ground structures are the most popular technique, especially in MC reduction between wideband and ultrawideband MIMO antenna elements. Several review papers (Breed, 2008; Khandelwal et al., 2017;

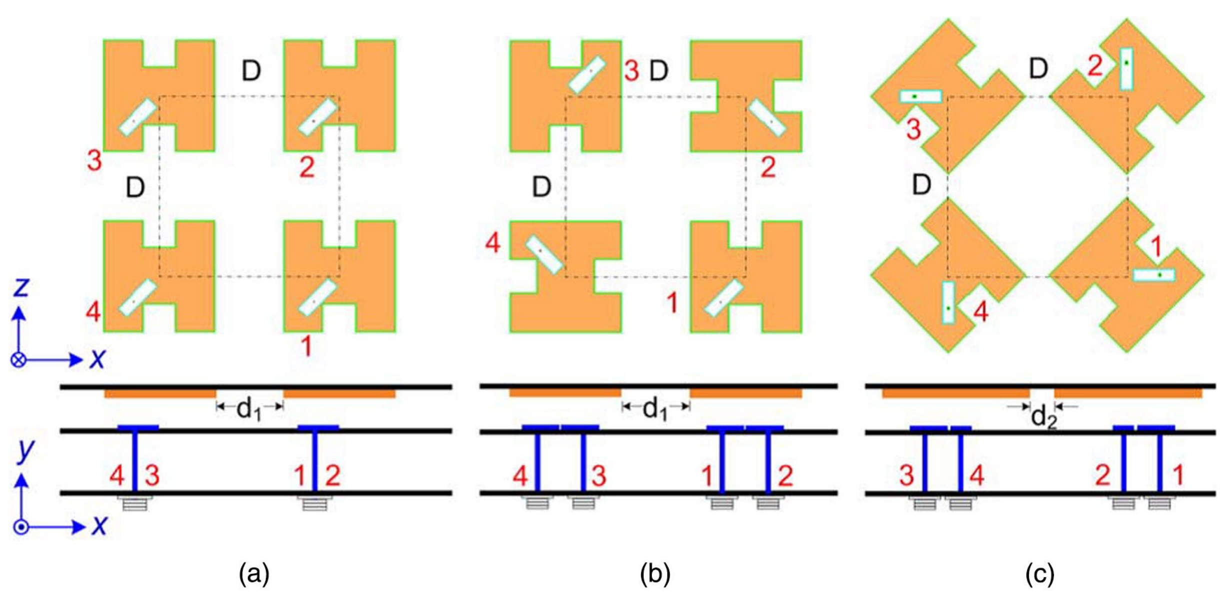

Figure 3. (a) Nonrotated array, (b) normal-H oriented SRA, (c) 135° angular offset. (Chung & Kharkovsky, 2013). SRA, sequential rotational array.

Table 2
Comparison Between Orthogonal Antenna Elements in an MIMO Antenna Design

Reference	Substrate area (l × b) mm^2, $\lambda_0 \times \lambda_0 = \lambda_0^2$	Min. isolation (dB)	Max. ECC value and computation approach	Antenna orientation	No. of antenna elements
Huang (2015b)	60 × 60, 0.56 × 0.56 = 0.31	20	0.035, *S*-parameters	Orthogonal	4
Karimian et al. (2012)	84 × 76, 0.67 × 0.61 = 0.41	16	0.05, *S*-parameters	Orthogonal	4
Liao et al. (2015)	50 × 50, 0.41 × 0.41 = 0.17	16	0.0576, far-field	Orthogonal	4
Sarkar and Srivastava (2017)	40 × 40, 0.32 × 0.32 = 0.10	14	0.05, —	Orthogonal	4
Luo et al. (2013)	42 × 42, 0.71 × 0.71 = 0.50	17	—	Orthogonal	4
Srivastava et al. (2019)	87 × 81, 0.22 × 0.21 = 0.05	20	0.10, *S*-parameters	Orthogonal	4
Mathur and Dwari (2018a)	36 × 36, 0.37 × 0.37 = 0.14	15	0.03, —	Orthogonal	4
Nirdosh et al. (2018)	25 × 25, 0.65 × 0.65 = 0.42	15	0.14, *S*-parameters	Orthogonal	4
Chu et al. (2018)	20 × 20, 1.87 × 1.87 = 3.50	—	0.0015, *S*-parameters	Orthogonal	2
Aminu-Baba et al. (2019)	58 × 45, 0.46 × 0.36 = 0.17	32	—, —	Orthogonal	2

where λ_0 is the free-space wavelength at the lowest operating frequency.

Webster et al., 2014; Weng et al., 2008) are available on DGSs in the existing literature to showcase its importance during MIMO antenna designing. DGS indicates a defect in a ground plane, introduced at will, which intensely disturbs the surface current distribution on the ground plane. As a result, the impedance of the equivalent transmission line between the different antennas will change.

A rectangular ground slot has been modified in MoradiKordalivand et al. (2014) by introducing four slots, one in each corner, while a V-shaped ground branch has been introduced in (Wang et al., 2015) to decrease the spatial coupling. As represented in Figure 4a, four interdigital structures have been etched in the ground to achieve isolation of about 28 dB between the four-port MIMO antenna (Ramachandran et al., 2016). Similarly, in Deng et al. (2017), a meandering resonant branch and an inverted T-slot, as represented in Figure 4b, have been etched in the ground plane to achieve isolation in the higher and the lower bands, respectively.

A fragmented type ground plane (Wang et al., 2014) as represented in Figure 4c, a modified dumbbell-shaped DGS (Numan et al., 2013), three rectangular slots etched in the ground plane (Irene & Rajesh, 2018a, 2018b), Y-shaped DGS (Zhu et al., 2016), partially connected two rectangular slots in one case, while two crossed rectangular slots in another trial (Ghouz, 2015), modified π-shaped strip and two shorted T-shaped strips (Wu et al., 2019) as represented in Figure 5a, a funnel-shaped ground plane with an open-ended slot (Gautam et al., 2019) as depicted in Figure 5b, dumbbell-shaped modified CSSR DGS (Kumar et al., 2020b), as

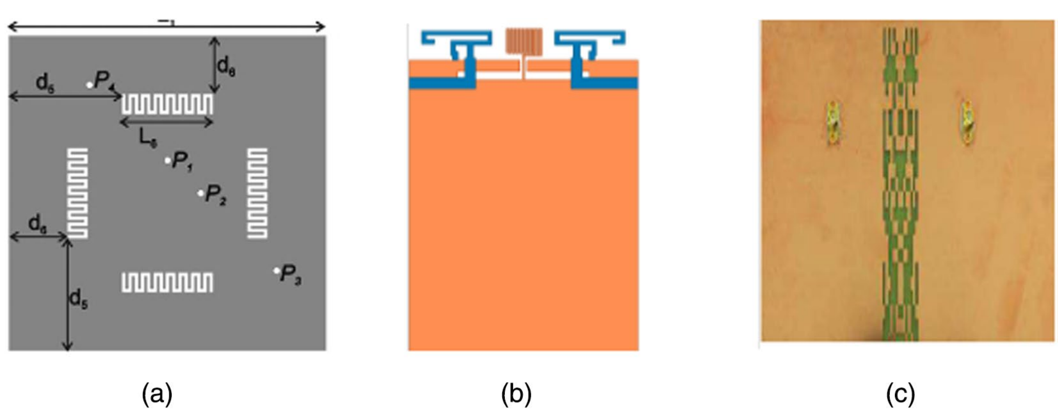

Figure 4. (a) Interdigital loaded ground plane (Ramachandran et al., 2016), (b) Meandering Branch and inverted T-shaped ground structure (Deng et al., 2017), and (c) fragmented type ground plane (Wang et al., 2014).

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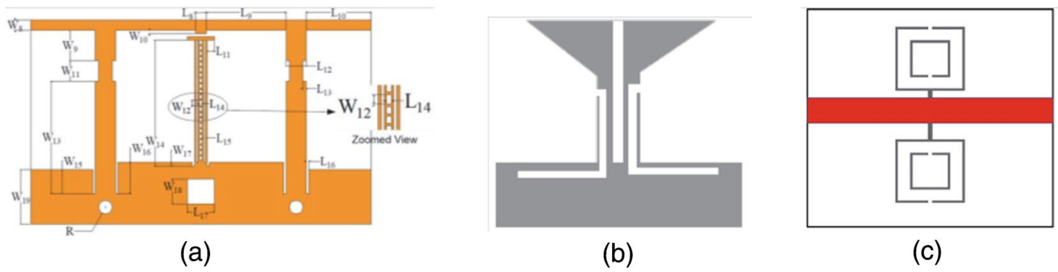


Figure 5. (a) Shorted T-shaped and π-shaped DGS (Wu et al., 2019), (b) funnel-shaped DGS (Gautam et al., 2019), (c) dumbbell-shaped complementary-split-ring resonator (CSRR) DGS (Kumar et al., 2020b). DGS, Defected Ground Structures.

represented in Figure 5c, T-stub loaded DGS (Y et al., 2020), U-shaped modified ground plane embedded with T-shaped slot (Li et al., 2019), a novel fractal DGS (FDGS) (Wei et al., 2016a) as represented in Figure 6a, partially stepped ground (PSG) (Malviya et al., 2016b), H-dumbbell-shaped DGS (Abbosh, 2007; Acharjee et al., 2018) shown in Figure 6b, a ladder-shaped modified ground plane (Asghar et al., 2018) shown in Figure 6c, compact DGS filtering structure (Abdalla & Ibrahim, 2013), square ring DGS (Anitha et al., 2014), meandered DGS (Chen & Chang, 2016; Dhar & Sharawi, 2014), different shapes of DGSs (Elsheakh et al., 2010) as represented in Figure 7, slotted ground plane (Abid et al., 2018), two columns of folded split-ring resonator (FSRR) etched in the ground plane Habashi et al. (2011) as represented in Figure 8a, annular slots etched DGS (Hussain et al., 2018), a $\lambda/4$ stub filter along with supplemental ground structure (Kim et al., 2008), fragmented structured DGS (Lu et al., 2018), shorted meandered line type DGS (Li et al., 2018) as represented in Figure 8b, forked shaped etched slot DGS (Singh et al., 2015), S-shaped periodic DGS (Wei et al., 2016b) as depicted in Figure 8c, another periodic spiral-shaped DGS (Wei et al., 2017)

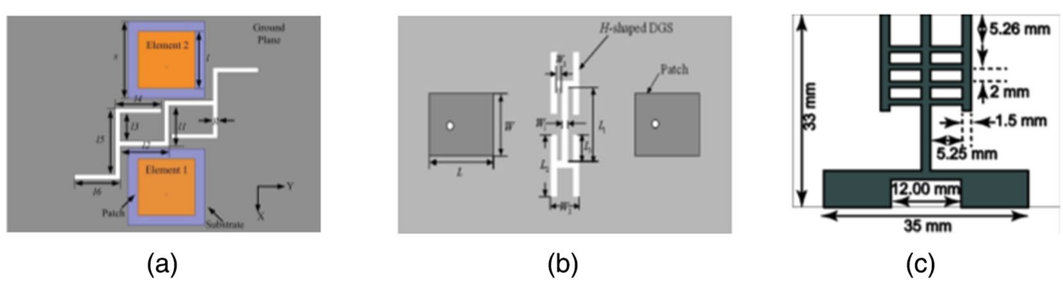


Figure 6. (a) FDGS (Wei et al., 2016a), (b) H-dumbbell-shaped DGS (Abbosh, 2007; Acharjee et al., 2018), and (c) ladder-shaped DGS (Asghar et al., 2018). FDGS, fractal Defected Ground Structures.

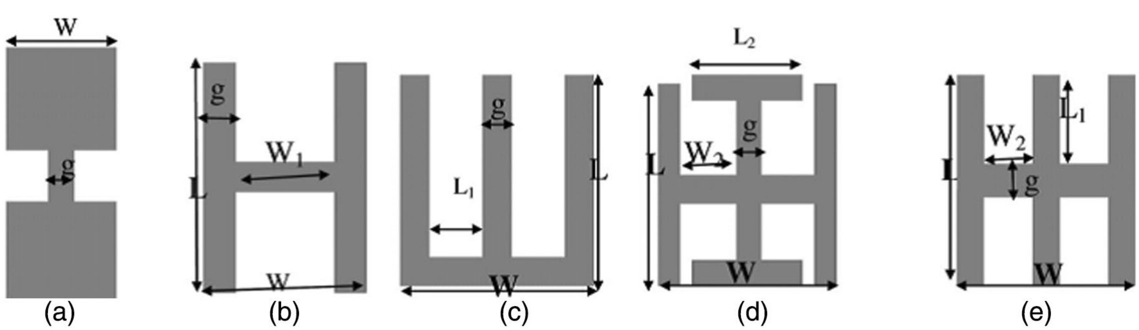
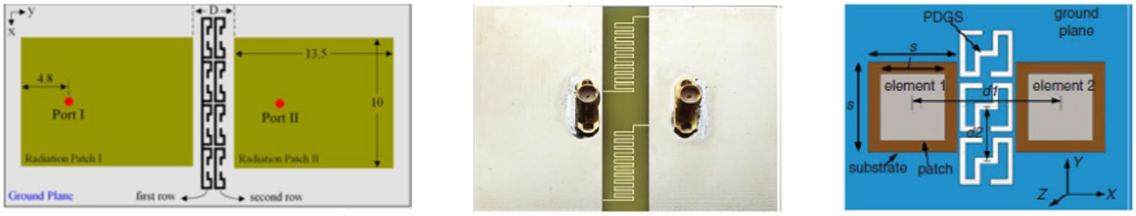


Figure 7. Different shapes of DGSs (Elsheakh et al., 2010). DGSs, Defected Ground Structures.



(a) (b) (c)

Figure 8. (a) Two columns of FSRRs (Habashi et al., 2011), (b) shorted meandered (Li et al., 2018), and (c) S-shaped DGS (Wei et al., 2016b). FSRRs, folded split-ring resonators.

and slotted CSRR etched DGS (Yang et al., 2014) have been used in the existing literature to isolate the elements of the tightly packed MIMO antenna.

As reported in Table 3, most wideband/UWB-MIMO antennas find difficulty in isolation than the narrowband counterpart. Among all, the MIMO antenna (Gautam et al., 2019) is the most compact one having a substrate area of 0.035 λ_0^2 only.

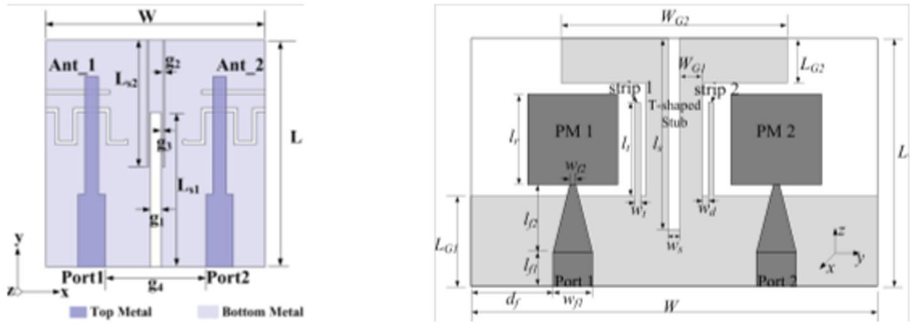
We can also observe that the maximum ECC value is 0.3, which is calculated from the far-field patterns irrespective of the lowest ECC value, 0.01 computed with *S*-parameters' help. The far-field computational ECC reflects pattern/spatial diversity irrespective of only port isolation when computed with *S*-parameters. So, ECC calculated from far-field is considered more accurate and reliable, especially in the wideband/UWB-MIMO antenna.

3.3. Slots/Slits-Etching Approach

Slots/slits-etching approach is one of the cases of DGSs. The ground has been detected by etching slots/slits in the ground plane. This approach is disturbing the flow of the surface current distributions by diverting

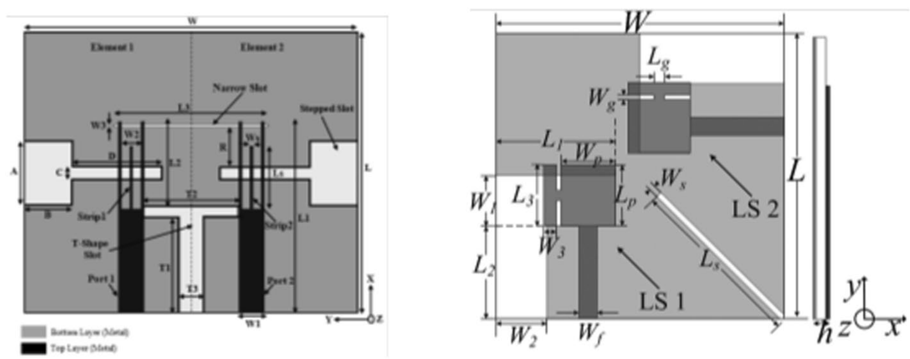
Table 3
Comparison of MIMO Antennas Based on DGSs

References	Substrate area (l × b) mm^2, $\lambda_0 \times \lambda_0 = \lambda_0^2$	Min. isolation (dB)	Max. ECC value and computation approach	Type of defects in the ground plane	No. of elements	Narrowband/wideband/UWB
Webster et al. (2014)	40 × 40, 0.31 × 0.31 = 0.10	10	0.266, far-field	V-shaped	4	Wideband
Ramachandran et al. (2016)	61 × 61, 0.50 × 0.50 = 0.25	28	0.300, far-field	Interdigital structure	4	Narrowband
Deng et al. (2017)	77.5 × 52, 0.62 × 0.42 = 0.26	15	0.200, far-field	Meandering Branch and inverted T-shaped	2	Narrowband (dual-band)
Wang et al. (2014)	120 × 197, 0.38 × 0.62 = 0.24	47	~0, *S*-parameters	Fragmented type	2	Narrowband
Wu et al. (2019)	50 × 30, 0.39 × 0.24 = 0.09	24	0.027, *S*-parameter	π-shaped DGS	2	Narrowband (dual-band)
Gautam et al. (2019)	15 × 26, 0.14 × 0.25 = 0.04	21	0.01, *S*-parameter	Funnel-shaped	2	UWB
Kumar et al. (2020b)	32 × 34.25, 0.26 × 0.27 = 0.07	28	Acts as band-stop filter	Dumbbell-shaped CSRR	2	Narrowband
Abbosh (2007)	50 × 86, 0.88 × 1.52 = 1.34	30	Acts as band-stop filter	H-dumbbell-shaped DGS	2	Narrowband
Asghar et al. (2018)	33 × 45.5, 0.34 × 0.47 = 0.16	15	—, —	Ladder-shaped DGS	2	UWB
Elsheakh et al. (2010)	53 × 53, 0.84 × 0.84 = 0.71	20	—, —	H-shaped DGS	4	Narrowband
Habashi et al. (2011)	50 × 68, 0.87 × 1.18 = 1.03	56	—, —	FSRRs	2	Narrowband
Li et al. (2018)	78 × 60, 1.30 × 1.00 = 1.30	39	—, —	Shorted meandered line	2	Narrowband



(a) (b)

Figure 9. (a) One wide and two narrow slots (Nandi & Mohan, 2017) and (b) vertical slot in T-shaped stub (Liu et al., 2015).



(a) (b)

Figure 10. (a) One T-shaped slot and two-stepped slots (Jetti & Nandanavanam, 2018) and (b) narrow diagonal slot (Ren et al., 2014).

the conducting path. Numerous such kind of practice has been successfully reported in the existing literature. Here, some of them are going to be discussed. Even the slot etched in the common radiator helps in minimizing the MC (Khan et al., 2017b; Srivastava et al., 2016; Zhang et al., 2015). Along with the neutralization line, four slits have been etched in the ground (Yang et al., 2016) to reduce MC between the elements of the multiband MIMO antenna working for GSM, DCS, and long term evolution (LTE) indoor applications. Two slots (Addaci et al., 2014), a wide slot and a pair of narrow slots (Nandi & Mohan, 2017) as represented in Figure 9a, six slits (Jaglan et al., 2017, 2018), simple wide slot (Ouyang et al., 2011), a vertical slot along with T-shaped ground stub (Liu et al., 2015) as represented in Figure 9b, inverted T-shaped slot along with a capacitor (Park et al., 2012), one T-shaped slot and two-stepped slots (Jetti & Nandanavanam, 2018) as described in Figure 10a, a narrow slot (Ren et al., 2014) as represented in Figure 10b, slitted pattern (Chiu et al., 2007), two symmetric stepped "L"-shaped open ground slots (Biswal & Das, 2018b), T-shaped slot impedance transformer (Zhang et al., 2012), two $\lambda/4$ slots (Zuo et al., 2010), E-shaped slot on the radiator and narrow ground slot (Bhanumathi & Sivaranjani, 2019), slot line based DGS (Hussain et al., 2019), six pair of slits (Wu & Chu, 2014), n shaped slot etched below the feed-line (Ul Haq & Koziel, 2018), meandered slot (Ayatollahi et al., 2012), L-shaped slot (Huang et al., 2015a), series of slits (Li et al., 2009), four slots etched (Ikram et al., 2018), H-shaped slot (Kang et al., 2016), as represented in Figure 11a, quasi-cross-shaped slot (Lu et al., 2011), two T-slots, and a rectangular slot (Marzudi et al., 2015), as described in Figure 11b, triangular slots and meshed metal strip (Nirmal et al., 2019), again a pair of slits (Sharawi et al., 2012), two $\lambda/2$ slots (Sonkki & Salonen, 2010), cross-shaped slot and a sickle-shaped metallic strip (Srivastava & Mohan, 2015), two U-shaped slots (Zhou et al., 2012) as represented in Figure 12a, two asymmetric dumbbells

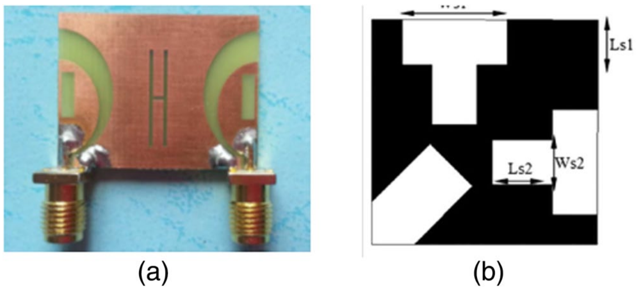


Figure 11. (a) H-shaped slot (Kang et al., 2016) and (b) two T-slots and one rectangular slot (Marzudi et al., 2015).

shaped slot, and one decoupling slot (Yang et al., 2018) as depicted in Figure 12b while a P-shaped slot and two F-shaped strips (Zhai et al., 2013) have been inserted in the ground plane to reduce MC.

The comparison in Table 4 shows that the slots/slits-etching process is another way of creating DGSs, which is more suitable for wideband and UWB-MIMO antenna. The maximum isolation achieved is mostly around 20 dB, unlike the cases mentioned in Table 2, where the DGSs help achieve isolation >56 dB (Habashi et al., 2011), but this holds for a narrowband MIMO antenna. Again, it has been certified that achieving better isolation in the UWB-MIMO antenna and compactness is a more significant challenge than for the narrowband MIMO antenna.

Among all, the mentioned MIMO antennas in Table 4 (Nandi & Mohan, 2017) is the most compact ($0.042\,\lambda_0^2$) UWB-MIMO antenna with 20 dB isolation.

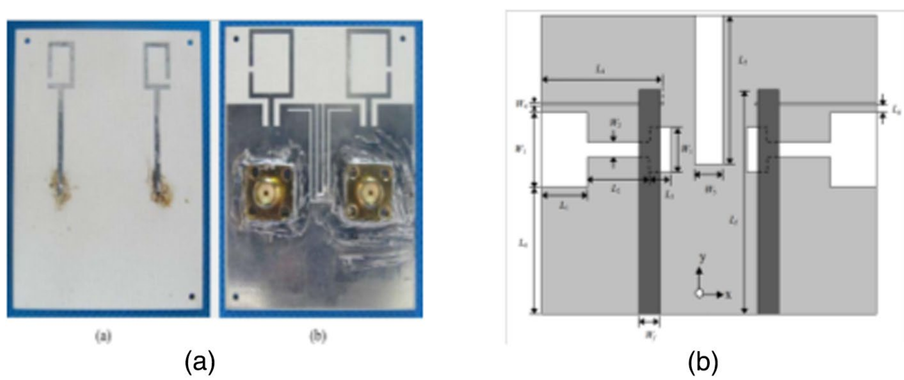
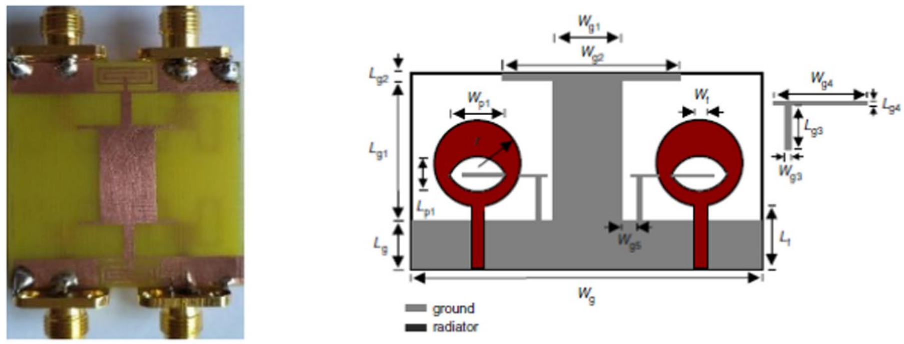


Figure 12. (a) U-shaped slots (Zhou et al., 2012) and (b) two dumbbells shaped and one decoupling slot (Yang et al., 2018).

Table 4
Comparison of MIMO Antennas Based on Slots/Slits-Etching Approach

References	Substrate area (l × b) mm^2, $\lambda_0 \times \lambda_0 = \lambda_0^2$	Min. isolation (dB)	Max. ECC value and computation approach	Type of slots/slits etched	No. of elements	Narrowband/ wideband/ UWB
Nandi and Mohan (2017)	24 × 25, 0.20 × 0.21 = 0.04	20	0.004, *S*-parameters	One wide and two narrow slots	2	Narrowband (dual-band)
Liu et al. (2015)	22 × 36, 0.23 × 0.37 = 0.09	15	0.1, far-field	Vertical slot in T-shaped ground stub	2	UWB
Jetti and Nandanavanam (2018)	22 × 26, 0.23 × 0.27 = 0.06	20	0.03, *S*-parameters	One T-shaped slot and two-stepped slots	2	UWB
Ren et al. (2014)	32 × 32, 0.33 × 0.33 = 0.11	15	0.02, *S*-parameters	Narrow diagonal slot	2	UWB
Kang et al. (2016)	28 × 22, 0.27 × 0.21 = 0.06	20	0.03, *S*-parameters	H-shaped slot	2	UWB
Marzudi et al. (2015)	30 × 30, 0.23 × 0.23 = 0.05	14	~0, *S*-parameters	Two T-slots and one rectangular slot	2	Wideband
Zhou et al. (2012)	63 × 50, 0.36 × 0.28 = 0.10	15	0.01, *S*-parameters	U-shaped slots	2	Wideband (dual-band)
Yang et al. (2018)	24 × 20, 0.25 × 0.21 = 0.05	18	0.025, *S*-parameters	Two dumbbells shaped and one decoupling slot	2	UWB



(a) (b)

Figure 13. (a) Shorted T-shaped stub and CSRR (Kumar et al., 2018) and (b) T-shaped ground plane (Chandel & Gautam, 2016).

3.4. Protruding Ground Stub Structures

Similar to the slots/slits-etching method, protruding ground stub structures is another prevalent method of creating DGSs. It provides isolation and sometimes improves matching, and helps achieve wider impedance bandwidth (Kumar et al., 2020a). This method is prevalent in providing isolation among elements of an UWB-MIMO antenna. Some of the popular designs will be discussed here. Among all, the T-shaped ground plane structure is ubiquitous among the UWB-MIMO monopole antenna. Monopole antennas are designed with partial grounds. A T-shaped stub protruding in the middle of the MIMO antenna's ground helps to minimize the MC to a remarkable extent. Two shorted T-shaped stub and CSRR help achieve isolation of >18 dB throughout the operating frequency range, as represented in Figure 13a (Kumar et al., 2018). In Figure 13b, we can see a T-shaped ground responsible for isolation in the UWB-MIMO antenna (Chandel & Gautam, 2016). Similar to protruding almost T-shaped ground stub along with some variations like an etched slot in the T-shaped stub, stepped T-shaped stub, and more similar structures have been used in Bhattacharya et al. (2019), Huang and Xiao (2015), Kumar et al. (2020a), Li et al. (2013), Liu et al. (2013, 2015); Mathur (2019), Silveira et al. (2009), Toktas (2017), Wu et al. (2018), Wu, Lyu, & Yu (2019); Wu, Lyu, Yu, & Xu (2019); Yadav et al. (2018), Yang et al. (2012), Yang et al. (2016), and Zhao et al. (2019) for minimizing the MC among the elements of UWB-MIMO antenna. Along with a slit on the shared circular-shaped radiator, an inverted Y-shaped stub has been introduced in the ground plane at an angle of 45° (Srivastava & Kanuijia, 2015) to minimize the MC. Because of instrumental contributions of protruding ground stub structures in reducing MC particularly among wideband and UWB-MIMO antenna elements many such designs have been introduced, among those some popular designs are folded Y-shaped (Khan et al., 2015), diagonally integrated strip (Chacko et al., 2013; Gao et al., 2014), extended rectangular stub (Yoon et al., 2011), protruded I-shaped stub at an angle of 45° (Zhu et al., 2016), an inverted pair of L-shaped strips (Chandel et al., 2018; Khan et al., 2017a), an inverted L-shaped strip (Kumar et al., 2019b), tree-like stub (Zhang et al., 2009) as represented in Figure 14a, arrowhead-shaped stub at an angle of 45° (Zhu et al., 2016), an inverted L-shaped and I-shaped stub (Liu et al., 2013) as represented in Figure 14b, funnel-shaped stub (Gautam et al., 2018), circular arcs shaped stubs (Mathur & Dwari, 2018b), extended curved stub (Biswal & Das, 2019), partial ground T-shaped stub (Malviya et al., 2016a), inverted L-shaped stub integrated with T-shaped slot (Singh et al., 2013), etching T-shaped slot on the radiator and extended arrow-shaped stub (Mao & Chu, 2014), pair of extended I-shaped (Sharawi et al., 2011), a rectangular slot with one circular end embedded with two inverted-L-shaped branches (Shoaib et al., 2014), a cross-shaped stub (Singh & Tripathi, 2019), F-shaped stubs (Iqbal et al., 2017), a dual-inverted-L-shaped ground branch with a slot (Zeng et al., 2012), two protruded ground parts (Li et al., 2013), a stepped stub at an angle of 45° (Biswal & Das, 2018a), two inverted L-shaped and one I-shaped stub (Hong et al., 2008), a pair of L-stubs, spiral stubs, and L-slots (Huang et al., 2015a), narrow metallic and slot stubs (Krishna & Kumar, 2016), grounded stub along with two F-dual grounded circular ring resonator (Mathur & Dwari, 2019a) as represented in Figure 15a, two F-shaped stub and rectangular slots (Wani & Vishwakarma, 2016) as described in Figure 15b, a simple I-shaped stub (Mchbal et al., 2018), a rectangular vertical arm (Saxena et al., 2017), inverted L-shaped and slot (Shoaib et al., 2015),

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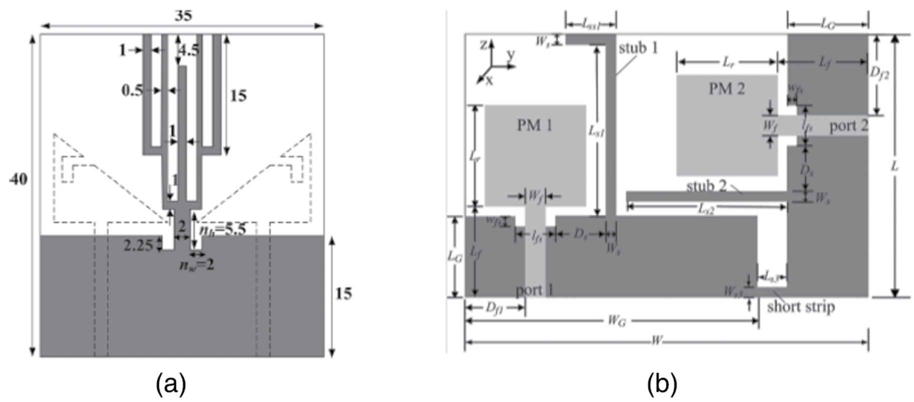

Figure 14. (a) Tree-like stub (Zhang et al., 2009) and (b) inverted L-shaped and I-shaped stub (Liu et al., 2013).

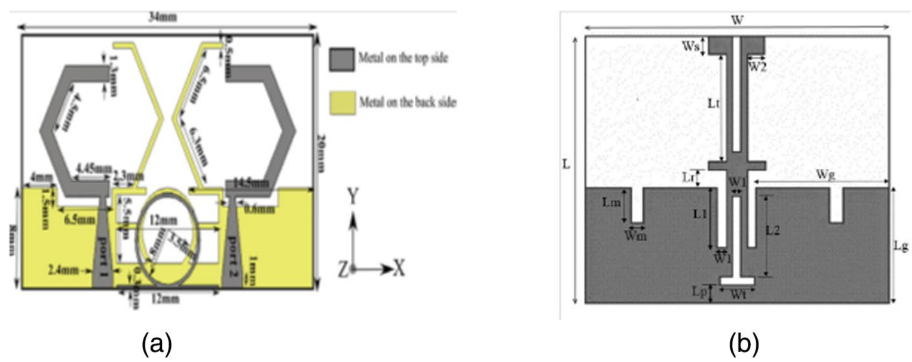

Figure 15. (a) Stub along with dual grounded circular ring resonator (Mathur & Dwari, 2019a) and (b) F-shaped stubs and rectangular slots (Wani & Vishwakarma, 2016).

I-shaped protruded stub (Ban et al., 2014) have been introduced in the ground plane to minimize MC and enhance the isolation among the elements of the proposed MIMO antenna.

Table 5 shows how the protruding ground stubs help in designing compact UWB-MIMO antenna having substrate area (total antenna area) almost $<0.06\,\lambda_0^2$ in most of the cases. We can also notice the lower ECC values computed by *S*-parameters than the far-field computation.

3.5. Parasitic Elements/Structures

In a single antenna system, the parasitic scatters are used to achieve multiresonance, which will enhance the impedance bandwidth (IBW). While in the MIMO antenna system, they are inserted between the resonating antenna as a reflector or resonator to reduce the MC between the antenna elements. Generally, parasitic elements are not connected to the ground, unlike those connected to form a sort of resonator (Sharawi, 2013). Parasitic elements will generate a coupling that will oppose the original one created by the excited antenna element. The resultant coupled field will be out of phase with the passive antenna at that moment, helping curb the effect of MC from one radiating patch to another. These elements are specifically designed to control the bandwidth of isolation and the extent of MC reduction. Many research articles have been published citing the importance of parasitic elements/structures, few we will discuss here.

A modified serpentine structure (Arun et al., 2014) occupying a width of only 3 mm, as represented in Figure 16a, has been inserted between two square patch antennas to achieve isolation as high as 34 dB at the resonating frequency of 2.45 GHz. A central metallic reflector has been placed in the center of two groups of four-elements of dielectric resonator antennas (DRAs) (Sharawi et al., 2017), as represented in

Table 5
Comparison of MIMO Antenna Based on Protruding Ground Stubs

References	Substrate area (l × b) mm^2, $\lambda_0 \times \lambda_0 = \lambda_0^2$	Min. isolation (dB)	Max. ECC value and computation approach	Type of protruding ground stub	No. of elements	Narrowband/ wideband/ UWB
Kumar et al. (2020a)	19 × 30, 0.20 × 0.31 = 0.06	18	0.13, far-field	T-shaped	2	UWB
Kumar et al. (2018)	32 × 38, 0.25 × 0.29 = 0.07	18	0.03, *S*-parameters	Shorted T-shaped stub and CSRR	2	UWB
Chandel and Gautam (2016)	18 × 36, 0.17 × 0.35 = 0.06	20	0.012, *S*-parameters	T-shaped ground plane	2	UWB
Chandel et al. (2018)	18 × 34, 0.18 × 0.33 = 0.06	22	0.01, *S*-parameters	Inverted L-shaped stubs	2	UWB
Khan et al. (2017a)	23 × 29, 0.23 × 0.29 = 0.07	15	0.15, far-field	Inverted L-shaped stubs	2	UWB
Zhang et al. (2009)	35 × 40, 0.36 × 0.41 = 0.15	16	0.01, *S*-parameters	Tree-like stub	2	UWB
Liu et al. (2013)	26 × 40, 0.27 × 0.41 = 0.11	15	0.2, far-field	Inverted L and I-shaped Stub	2	UWB
Iqbal et al. (2017)	50 × 30, 0.42 × 0.25 = 0.11	20	0.04, *S*-parameters	F-shaped stubs	2	UWB
Li et al. (2013)	20 × 34, 0.20 × 0.34 = 0.07	20	0.3, far-field	Stub along with dual grounded circular ring resonator	2	UWB
Wani and Vishwakarma (2016)	35 × 30, 0.36 × 0.31 = 0.11	22	0.005, *S*-parameters	F-shaped stubs and rectangular slots	2	UWB

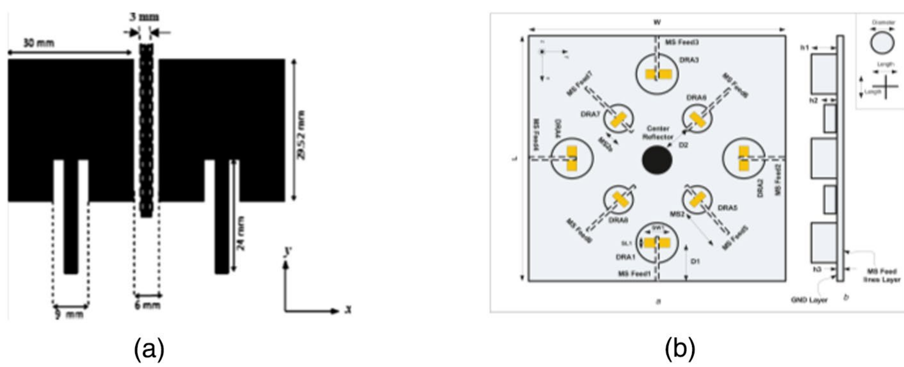

Figure 16. (a) Modified serpentine structure (Arun et al., 2014) and (b) center metallic reflector (Sharawi et al., 2017).

Figure 16b for isolation and tilting the radiation pattern of one group resonating at 5.8 GHz by 45° as compared to another group resonating at 2.45 GHz. Similarly, a simple metallic strip (Roshna et al., 2015), T-shaped parasitic strip (Kang et al., 2015), a modified interdigital capacitor (Kumar et al., 2018b), a novel ITI-shaped parasitic structure (Kumar et al., 2019a), parasitic inverted L-element with an open stub (Lee et al., 2012), H-shaped strip (Li et al., 2016), floating parasitic decoupling structure (Khan et al., 2014), a rotated "+" shaped rectangular strip pair (Singhal, 2019) as represented in Figure 17a, a rectangular parasitic element is embedded at the substrate backside (Hatami et al., 2019), two separate rectangular shapes and T-shaped parasitic elements (Faraz et al., 2019), as represented in Figure 17b, cross-shaped metallic fence (Caizzone, 2017), stepped cross-shaped reflector strip (Thummaluru et al., 2019), a circular parasitic element at the backside of the radiating patch (Ghimire et al., 2019), a novel reversed S-shaped walls (Wang et al., 2019), a decoupling metal strip loaded with an inductor (Nie et al., 2019), an optimized parasitic element (Addaci et al., 2012) as represented in Figure 18a, slotted meander-line resonator (SMLR) (Alsath et al., 2013) as represented in Figure 18b, a simple rectangular parasitic structure at the back (Azarm et al., 2019), diagonal parasitic strip at the back (Chouhan et al., 2019), Minkowski fractal-shaped isolators (Debnath et al., 2018) as represented in Figure 19a, a complementary pattern (CP) comprised of meandered transmission lines (Hwang et al., 2010), a group of six parasitic elements (Min et al., 2005), as represented in Figure 19b, two parallel strips, or a single strip embedded with patterned meander-shaped slot (Isaac et al., 2018) as represented in Figures 20a and 20b, two parasitic monopole providing a decoupling path

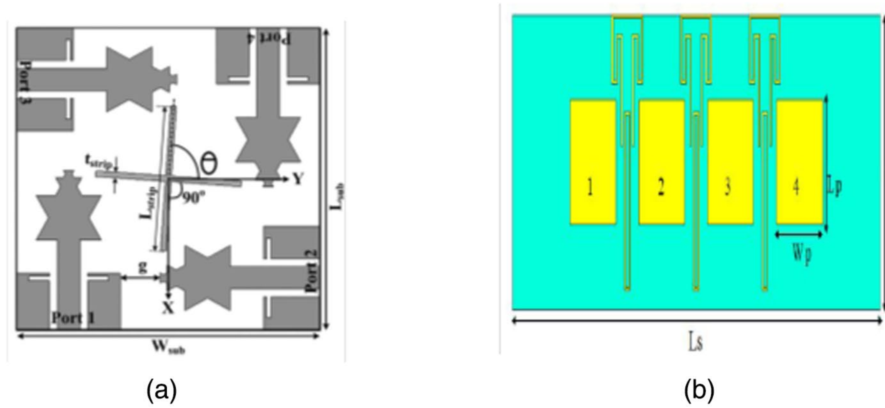

Figure 17. (a) Rotated “+” shaped rectangular strip pair (Singhal, 2019) and (b) two separate rectangular shape and T-shaped parasitic elements (Faraz et al., 2019).

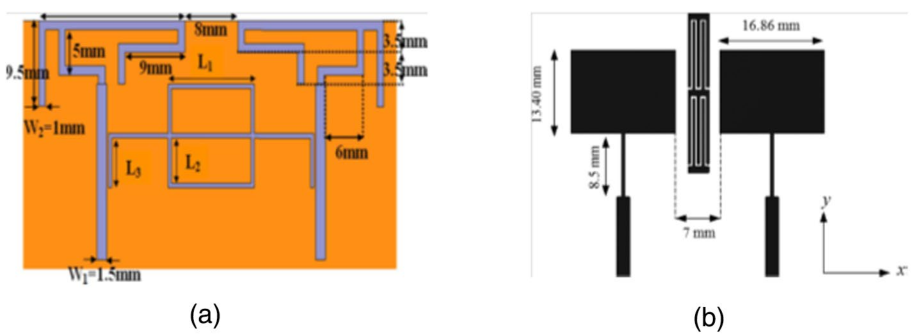

Figure 18. (a) Optimized parasitic element (Addaci et al., 2012) and (b) slotted meander-line resonator (SMLR) (Alsath et al., 2013).

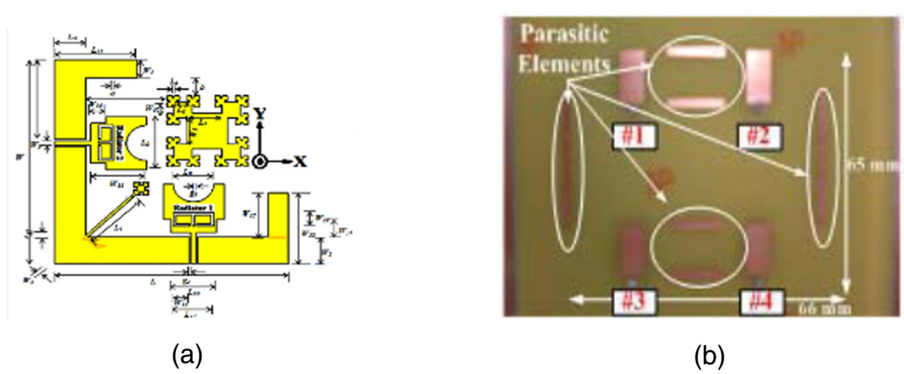

Figure 19. (a) Minkowski fractal-shaped isolators (Debnath et al., 2018) and (b) a group of six parasitic elements (Min et al., 2005).

(Li et al., 2012) as represented in Figure 21a, a novel H-shape parasitic element embedded in the ground plane (Liu et al., 2018) as represented in Figure 21b, a T-shaped coupling element providing an additional decoupling path (Mak et al., 2008) as represented in Figure 22a, 2 × 3 matrices of the C-shaped resonator is proposed (Alsultan & Ögücü Yetkin, 2018) as represented in Figure 22b, parasitic fragment-type isolation element (Wang et al., 2016) as represented in Figure 23a and a periodic paperclip-shaped structure (Wen & Xin-Liang, 2018) as represented in Figure 23b have been employed among patch antennas to minimize the MC between them. Further, Payandehjoo and Abhari have presented a comprehensive investigation

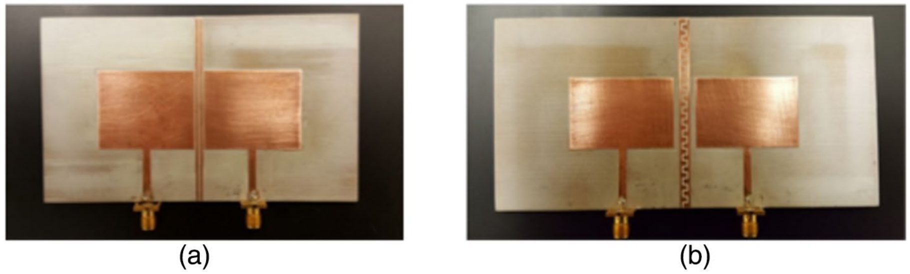

Figure 20. (a) Two parallel metallic strip and (b) single strip embedded with a meander-shaped slot pattern (Isaac et al., 2018).

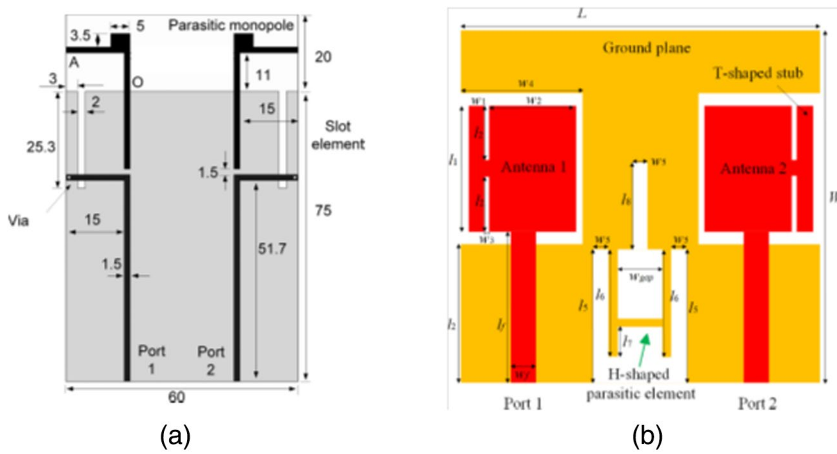

Figure 21. (a) Two parasitic monopole (Li et al., 2012) and (b) novel H-shaped parasitic element embedded in the ground plane (Liu et al., 2018).

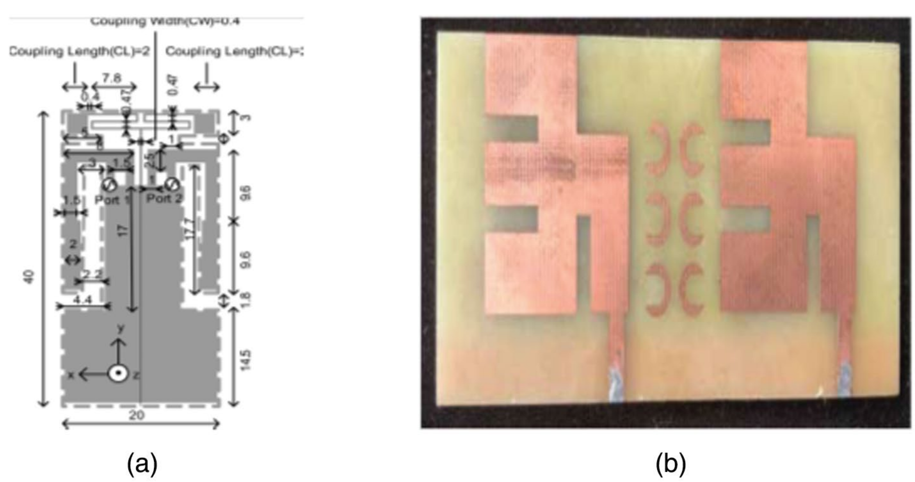

Figure 22. (a) A T-shaped coupling element (Mak et al., 2008) and (b) 2 × 3 matrix of C-shaped resonator (Alsultan & Ögücü Yetkin, 2018).

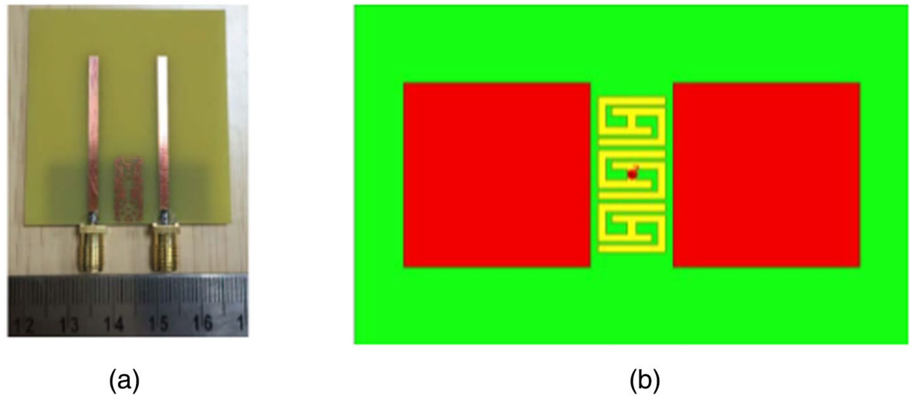

Figure 23. (a) Parasitic fragment-type isolation element (Wang et al., 2016) and (b) periodic paperclip-shaped structure (Wen & Xin-Liang, 2018).

of parasitic elements for coupling reduction in multiband antenna for handheld devices (Payandehjoo & Abhari, 2014).

In many cases, the parasitic elements/structures will act as a resonator, which will scatter the signal coming from one antenna and thus reduces MC like two resonators have been placed between the two planar inverted-F antenna (PIFA) (Minz & Garg, 2010), a diamond-shaped patterned ground resonator has been printed

Table 6
Comparison of MIMO Antenna Based on Parasitic Elements/Structures

References	Substrate area (l × b) mm^2, $\lambda_0 \times \lambda_0 = \lambda_0^2$	Min. isolation (dB)	Max. ECC value and computation approach	Type of parasitic elements/structures	No. of elements	Narrowband/ wideband/ UWB
Kumar et al. (2018b)	30 × 50, 0.31 × 0.51 = 0.16	16	0.01, *S*-parameters	Modified interdigital capacitor	2	UWB
Kumar et al. (2019a)	56 × 70, 0.42 × 0.52 = 0.22	24	0.036, far-field	A novel ITI-shaped parasitic structure	2	Wideband (multiband)
Arun et al. (2014)	—, —	34	~0, *S*-parameters	Modified serpentine structure	2	Narrowband
Singhal (2019)	27 × 27, 0.43 × 0.43 = 0.18	15	0.005, *S*-parameters	Rotated "+" shaped rectangular strip pair	4	UWB
Faraz et al. (2019)	30 × 80, 0.58 × 1.55 = 0.90	15	—, —	Two separate rectangular shape and T-shaped parasitic elements	4	Narrowband
Alsath et al. (2013)	54 × 45, 0.86 × 0.72 = 0.62	16	—, —	Slotted meander-line resonator (SMLR)	2	Narrowband
Debnath et al. (2018)	46 × 46, 0.48 × 0.48 = 0.23	17	0.02, *S*-parameters	Minkowski fractal-shaped isolators	2	UWB
Li et al. (2012)	95 × 60, 0.61 × 0.38 = 0.23	20	—, —	Two parasitic monopole	2	Narrowband
Liu et al. (2018)	36 × 35, 0.23 × 0.22 = 0.05	15.4	0.14, far-field	Novel H-shaped parasitic element	2	Wideband
Mak et al. (2008)	40 × 20, 0.32 × 0.16 = 0.05	30	—, —	A T-shaped coupling element	2	Narrowband
Alsultan and Ögücü Yetkin (2018)	41 × 100, 0.68 × 1.67 = 1.14	18	0.0001, *S*-parameters	2 × 3 matrix of C-shaped resonator	2	Wideband
Wang et al. (2016)	50 × 50, 0.41 × 0.41 = 0.17	16	~0, *S*-parameters	Parasitic fragment-type isolation element	2	Narrowband
Wen and Xin-Liang (2018)	25 × 40, 0.42 × 0.67 = 0.28	36	0.0006, *S*-parameters	Periodic paperclip-shaped structure	2	Narrowband

on the PCB between the two inverted-F antenna (IFA) (Wu et al., 2017), an additional folded resonator having an electrical length of half guided wavelength has been placed above connecting shorted metallic strip between two PIFA (Lee et al., 2009), and optimally designed resistor-loaded paired parallel-coupled resonators (PCRs) (Park et al., 2019), an I-shaped $\lambda/2$ resonator between microstrip array (Ghosh & Parui, 2014), dumbbell-shaped resonator between dual-trace dual-column coaxial microstrip array (Zhu et al., 2016), inverted U-shaped resonator and line resonator (Ghosh, 2016) and dual-band strip resonator as a wave trap (Kang & Wong, 2010) have been used to suppress the MC.

From the data in Table 6, the parasitic elements/structures help achieve high isolation for all the cases: narrowband; wideband; UWB; with an ultracompactness of $0.05\lambda_0^2$ (Mak et al., 2008; Liu et al., 2018). This approach is the most popular and straightforward to implement among so far discussed in the existing literature.

4. Conclusions and Future Scope

In all the above cases, it has been found that the isolation or suppressing of MC is a significant problem in the lower frequency range as the λ increases with the decrease of the frequency. Also, the impact of MC increases as the distance between the two microstrip antennas becomes much lesser than $\lambda_0/2$. The more the antenna is compact, the less will be the distance between the microstrip antennas. Hence, it will deteriorate the MIMO antenna's performance, especially at a lower frequency: consequently, more concern should be considered at a lower frequency. ECC is the most crucial diversity parameter when discussing spatial/pattern diversity if computed with far-field radiation patterns. We find relatively higher values but <0.5 compared to the *S*-parameters approach of calculating ECC, which is generally significantly lower than 0.05 and focused mainly on port isolation. Protruding ground stubs, DGSs, slots/slits-etching, and parasitic elements/structures are widely suitable for reducing MC in wideband and UWB-MIMO antennas.

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