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TUTORIAL AND REVIEW PAPER

MIMO antennas with diversity and mutual coupling reduction techniques: a review

LEELADHAR MALVIYA, RAJIB KUMAR PANIGRAHI AND M. V. KARTIKEYAN

Multiple input multiple output (MIMO) antenna is at core of the presently available wireless technologies. The design of MIMO antennas over a limited space requires various approaches of mutual coupling reduction, otherwise gain, efficiency, diversity gain, and radiation patterns will be severely affected. Various techniques have been reported in literature to control this degrading factor and to improve the performance of the MIMO antennas. In this review paper, we have carried out an extensive thorough investigation of diversity and mutual coupling (correlation) reduction techniques in compact MIMO antennas.

Keywords: Smart antennas, Digital beam forming, MIMO, Antenna design, Modeling and measurements, Mutual coupling

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I. INTRODUCTION

Over the past few years, a remarkable development in indoor and outdoor wireless activities enhances the multiple input multiple output (MIMO) antenna technology. Most of the wireless work on MIMO antenna systems was reported and investigated for wireless local area network (WLAN)/world-wide interoperability for microwave access (WiMAX)/long term evolution (LTE) and other required applications. MIMO technology is a good candidate in non-line of sight (NLOS) communication to provide better quality of services. The idea of MIMO was started with the capacity theorem [1] and its application on wireless communication with pulse amplitude modulation signals [2], multivariate analysis over the Gaussian channel with memory [3], multi-channel digital transmission systems [4, 5], and directional digital transmission and reception using beam-forming signal-processing applications [6, 7]. The idea of using an array at the base station to improve channel characteristics for transmission and reception with space division multiple access invoked in minds of Richard Roy and Bjorn Ottersten [8]. The concept of gain enhancement using spatial multiplexing (SM) techniques in MIMO was proposed by Arogyaswami Paulraj and Thomas Kailath. They showed the concept of increasing data rate by dividing, transmitting, and receiving high-data rate signals into low-data rate signals [9]. A new concept of link through improvement of MIMO by using co-located antennas at the transmitter was carried out by Greg Rayleigh, Gerard J. Foschini, and Emre Telatar. The Bell laboratory first demonstrated a practically realizable prototype of SM to enhance the performance of MIMO communication systems [10–12].

Electronics and Communication Engineering Department, Indian Institute of Technology (IIT), Roorkee (U. K.)-247667, India
Corresponding author:
L. Malviya
Email: ldmalviya@gmail.com

The need of MIMO arises due to the drawbacks of single-input single-output (SISO) system established at the transmitter and receiver. The SISO places impossible bandwidth demands on the gigabit wireless system. Therefore, gigabit per second wireless links in NLOS communication networks using SISO are in general not feasible due to signal-to-noise ratio limits, average signal to interference with noise ratio limits, high-power/bandwidth requirements, and due to range reduction in practical receivers [9]. MIMO can be a integral part of present key technologies for the performance enhancement, i.e. gain, capacity, data rate, and efficiency, etc.

However, the compact and portable devices place a lower and upper bound on the space limits for the commercial/experimental wireless communication products. The close proximity of radiating elements in MIMO has compactness but at the cost of performance degradation. Another degradation is due to the shared ground effects. Such degrading effect is jointly known as a mutual coupling, which severely affects the diversity behavior and radiation characteristics. Various diversity techniques like space diversity, polarization diversity, and pattern diversity are having their merits and demerits to control the degrading effects of mutual coupling. Other techniques are also required along with diversity techniques to control the mutual coupling between radiators. The paper is discussed in three sections. Section II explains different diversity and mutual coupling reduction techniques with their merits and demerits. Section III shows the second aspect of Section II utilized for the miniaturization of MIMO antennas.

II. DIVERSITY AND MUTUAL COUPLING REDUCTION TECHNIQUES

An envelope correlation coefficient (ECC) is evaluated for the uncorrelated channels to find whether the channel is good,

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bad, or good enough. In real propagation world, even in line of site communication, finding a truly uncorrelated channel is impossible. Therefore, ECC is used for the measurement of such conditions. The *S* parameter approach as well as far-field analysis are considered to find the value of ECC. The effect of mutual coupling between any of the two ports of MIMO can be seen in terms of two scattering parameters, i.e. S_{12} and S_{21}. However, ECC involves all the scattering parameters of the designed MIMO to show their effects on the correlation coefficient (ρ). Lower the value of ECC means less correlation between antenna elements, while higher values of it shows the negative impact. For the good diversity behavior, the value of ECC must be <0.5 for mobile applications. The values of ECC [34] may be obtained using the formula given in equation (1). Here the values of $i = 1$ to n, $j = 1$ to n, and $N =$ number of radiating elements.

$$\left|\rho_e(i,j,N)\right| = \frac{\left|\sum_{n=1}^{N} S_{i,n}^{*} S_{n,j}\right|}{\sqrt{\left|\prod_{k(=i,j)}\left[1-\sum_{n=1}^{N} S_{i,n}^{*} S_{n,k}\right]\right|}}. \tag{1}$$

The ECC can be obtained using the far-field characteristics [104] of the radiating elements. Let the $\bar{F}_1(\theta,\phi)$ and $\bar{F}_2(\theta,\phi)$ are the field patterns of two radiating elements with respect to the θ and ϕ components, then ECC can be written in equation (2):

$$\rho_e = \frac{\left|\iint_{4\pi}\left[\bar{F}_1(\theta,\phi)\bullet\bar{F}_2(\theta,\phi)\right]\right|^2}{\iint_{4\pi}\left|\bar{F}_1(\theta,\phi)\right|^2 d\Omega \iint_{4\pi}\left|\bar{F}_2(\theta,\phi)\right|^2 d\Omega}, \tag{2}$$

where $\bullet$ is the Hermitian product operator and Ω is the solid angle.

The another way of utilizing the far-field characteristics to get ECC [39, 73], is given by equation (3):

$$\left|\rho_e\right|^2 = 1 - \frac{\eta_{max}}{\eta_1 \eta_2}, \tag{3}$$

where η_{max} is the maximum efficiency, η_1 is the total efficiency of radiating element 1, and η_2 is the total efficiency of radiating element 2. The η_{max} is the function of power distribution of the radiating elements. Therefore, the ECC is dependent on the efficiency and power distribution of the radiating elements.

Similarly, the diversity gain (DG) is also dependent on correlation (mutual coupling) [73], which is obtained in terms of maximum theoretical DG (10 dB) and ρ by using equation (4). Lower the value of correlation, higher will be the DG and vice versa.

$$G_{DG} = 10 \times \sqrt{1 - \left|\rho\right|^2}. \tag{4}$$

Similarly, the total active reflection coefficient (TARC) is also one of the parameter, which is dependent on the returnloss and correlation. The TARC involves random signals and their phase angles for diagonal/adjacent ports to compute the radiation performance of designed MIMO. It also investigates the actual behavior of the scattering parameters like S_{12} (between ports 1 and 2), S_{13} (between ports 1 and 3), and S_{14} (between ports 1 and 4) in case of four-port MIMO with required phase angle(s) between ports for better performance of design.

Let a_i is excitation vector, and b_i is scattering vector. The ratio of *b* and *a* for a particular port results in return-loss/isolation parameter (S_{ii} or S_{ij}). The formula of TARC [101] can be written in equation (5).

$$\Gamma_a^t = \frac{\sqrt{\sum_{i=1}^{N}\left|b_i\right|^2}}{\sqrt{\sum_{i=1}^{N}\left|a_i\right|^2}}. \tag{5}$$

The complete formula of TARC for any of the two adjacent/diagonal radiating ports can be shown in equation (6) as:

$$\Gamma_a^t = \frac{\sqrt{\left|(S_{ii} + S_{ij} * e^{jq})\right|^2 + \left|(S_{ji} + S_{jj} * e^{jq})\right|^2}}{\sqrt{N}}, \tag{6}$$

where θ is the phase angle between any of the two adjacent/diagonal ports.

Similarly, the performance of the MIMO is also characterized by the channel capacity [73], which is also dependent on the scattering parameters (i.e. returnloss and ρ) of the designed MIMO antenna. Let us consider a multipath transmission channel having multiple transmitting antennas (N_t) on one side and receiving antennas (N_r) on the other side. The formula of channel capacity may be written as shown in equation (7):

$$C = \log_2\left(I_{Nr} + \frac{P}{NN_t} HH^*\right), \tag{7}$$

where *P* is the signal power, *N* is the noise power (capacity of SISO is $C = \log_2(1 + (P/N))$), * denotes a complex conjugate transpose operation, *H* is the channel matrix and its transpose is H^*. The response of *H* is completely dependent on the correlation/mutual coupling between radiators, which is the function of channel parameters of the propagation environment, i.e. delay, gain, noise, interference, etc. The appropriate knowledge of channel and its parameters enable to find out the value of *H*. The channel matrix for two-port MIMO is shown in equation (8):

$$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}. \tag{8}$$

Similarly, in NLOS conditions, the directive gain is insufficient to deliver accuracy of results. Therefore, mean effective gain (MEG) is used in such conditions and is measured in an anechoic chamber for the far-field characterization. The MEG [101] includes efficiency and power patterns of the MIMO antenna. Let the cross-polarization ratio of the incident field is denoted by XPR. The probability distribution functions (pdf) of the incident wave are $p_{\theta j}$ and $p_{\phi j}$ for θ and ϕ components. The power gains of 2×2 MIMO antenna elements are $G_{\theta j}$ and $G_{\phi j}$. The value of *j* is 1–4 for four elements. The formula of MEG in two-dimensional plane is given by equation (9).

$$MEG_j = \oint\left(\frac{XPR}{1+XPR} P_{\theta j}(\Omega) G_{\theta j}(\Omega) + \frac{1}{1+XPR} P_{\phi j}(\Omega) G_{\phi j}(\Omega)\right). \tag{9}$$

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The above equation of MEG can also be written as shown in equation (10).

$$MEG_j = \frac{1}{2\pi}\int_0^{2\pi}\left[\frac{XPR}{1+XPR}G_{\theta j}\left(\frac{\pi}{2},\phi\right) + \frac{1}{1+XPR}G_{\phi j}\left(\frac{\pi}{2},\phi\right)\right]d\phi. \quad (10)$$

The maximum value of MEG with 100% efficiency is −3 dB. However, the efficiency also depends on the mutual coupling. For MIMO, each element should have equal value of MEG to get optimum diversity performance. The value of XPR(XPD) = 0 dB for outdoor uniform environment, and XPR(XPD) = 6 dB for indoor uniform environment. As MEG includes the effect of $G_{\theta j}$ and $G_{\phi j}$, which are the functions of the mutual coupling between radiators.

A thorough literature survey of diversity and mutual coupling reduction techniques are explored in details in literature.

A) Space diversity

The space diversity is the first kind of isolation enhancement technique between the closely packed radiating elements. The space variation is the key of this approach to achieve de-correlation or low mutual coupling between radiators. This is equally valid for all types of MIMO antenna structures such as monopole-, dipole-, conventional-shaped, planar inverted frequency antenna (PIFA), and fractal geometries, etc [13]. A reasonable distance between the radiating elements ensures the proper operation of the design and produces the desired performance parameters along with the limited coupling current, responsible for mutual coupling [14]. The close spacing between radiators is the major source of coupling (radiation emission) and common conductor (ground) emission [15]. The analysis of transfer function of a correlation coefficient revels the behavior of a designed MIMO. The separation, placement, and the orientation of radiating elements with the partial/stepped/full ground play a major role in deciding the value of mutual coupling [16].

The spacing constraint must be there to ensure the compactness of the overall size along with the proper treatment of degrading factors [17]. A space orientation (digonally placement, face to face, 180° face shifted, etc.) is also the prime requirement for controlling mutual coupling and enhancing diversity parameters of a designed MIMO [18, 19]. The space orientation has one of the important characteristics that it changes the direction of current flow, which in turn controls the correlation. The narrow/wide-band MIMO antennas were designed for WLAN/WiMAX/LTE applications with reasonable separation (space diversity) and space orientation for desired band of operations as shown in Fig. 1 [20, 21]. The value of isolation is more than 10 dB in this approach.

B) Polarization diversity

The space diversity technique at the base station is having a lot of space for implantation of MIMO antennas due to no space constraint there. However, at the mobile station, space constraint is required due to portability and mobility of devices. The polarization diversity on the other hand is simple and results in compactness of the overall MIMO antenna system. All the antennas are placed as a diversity branches, i.e. vertically and horizontally positioned [22, 23]. This in turn enhances capacity also due to the improvement in link quality. The placement of radiators and ground planes in 90° results in lower installation costs and better performance than space diversity. It can be equally incorporated with similar/desimilar or mixed radiating structures. Designers take the benefit of dielectric slabs placed between the radiators for the compactness of the overall design with polarization diversity. Experimentally, this verifies the improved performance of MIMO antennas in terms of compactness, gain, isolation (mutual coupling), and bandwidth [24].

Many times, feed probes are designed to ensure polarization diversity [25]. The link reliability along with the low mutual coupling can be achieved by the joint incorporation of polarization and pattern diversities in a MIMO antenna [26, 27]. The combination ensures enhanced diversity properties. A design related with this is shown in Fig. 2 [28, 29].

The undesired energy coupling can be limited in orthogonal polarization, since the field orientation is in cross-polarization due to the directional radiators [30]. MIMO with polarization diversity is also one of the approach used in cognitive radio communication for spectrum utilization [31]. Polarization diversity can also be realized if orthogonal

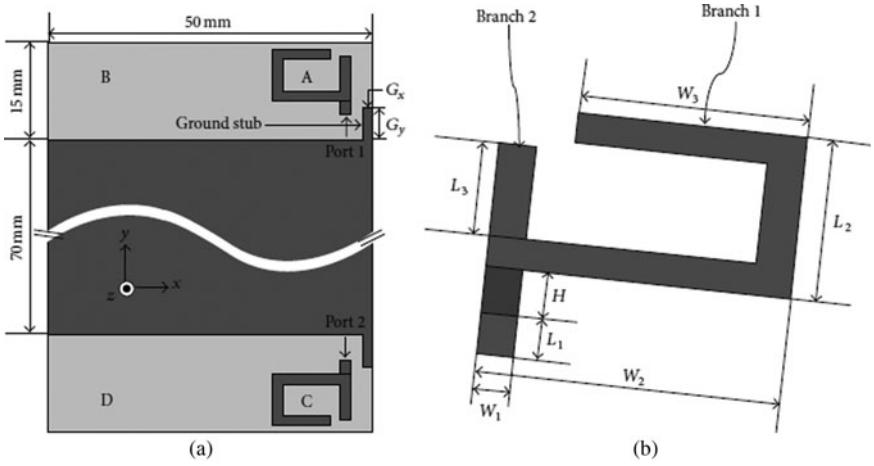


Fig. 1. Space diversity MIMO antenna © [20].

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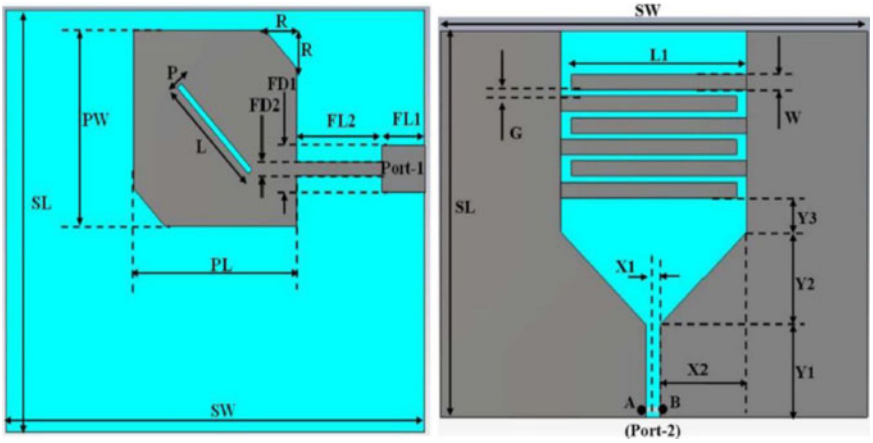


Fig. 2. MIMO antenna with pattern and polarization diversities © [28].

slot antennas (2 × 2) along with metal via to short ground plane are used as shown in Fig. 3 [32]. Similarly, a multi-layer approach enhances the bandwidth of a orthogonally placed PIFA elements (2 × 2) [33], whereas slotted strips in PIFA antenna aids certain amount of isolation (reduces mutual coupling) used for LTE and WiMAX applications [34]. MIMO antenna with crossed exponentially tapered slot (XETS) was also realized as an orthogonal polarization and used for the wireless applications [35]. The self-balancing radiation patterns (due to the design shown in Fig. 4) [36], port-to-port decoupling [37], diversion of ground linking current [38], better efficiency [39], and wider bandwidth responses with required in-band isolation [40] are certain advantages of the polarization diversity MIMO antennas. The port isolation in this approach is more than 15 dB.

C) Pattern diversity

To ensure the radio link reliability in multi-path environments, MIMO antenna radiators are designed to build radiation patterns in different directions. The patterns may be complementary (180° in phase reversal) symmetric or asymmetric depending on their orientation and placement. Such approach has benefit of getting equal amount of return-loss and mutual coupling between complementary symmetric case and vice versa at different ports [41]. A multi-mode and multi-layered MIMO antenna with pattern diversity and with stepped profile [42] was designed for bandwidth expansion, and reconfigurability of radiation patterns [43]. The pattern reconfigurability is the effect of ground current alteration [44]. An open-loop resonator with curved slots [45], and *I*-shaped conductor [46] approaches were implemented with pattern diversity technique.

D) Parasitic element/structure approach

In most of the cases, an indirectly connected metallic structure is introduced between the MIMO antenna radiators, which is known as a parasitic element. The location of a parasitic element ensures the diversion of certain unwanted field/current, and to enhance some specific characteristics such as bandwidth, isolation, and efficiency [47]. Also, a meandered line slot etched between the slotted radiating elements acts like a parasitic element [48] and serves the same purpose. A design with broadband technique used a parasitic structure as shown in Fig. 5 between the radiators to produce surface currents in existing coupling path to cancel out it and also to produce less ohmic losses [49]. A parasitic element showed in Fig. 6 cancel out the field by reverse coupling approach and limits the effect of correlation between the radiators [50, 51]. Similarly, an indirectly coupled, coupling element, as shown in Fig. 7, introduces an extra current

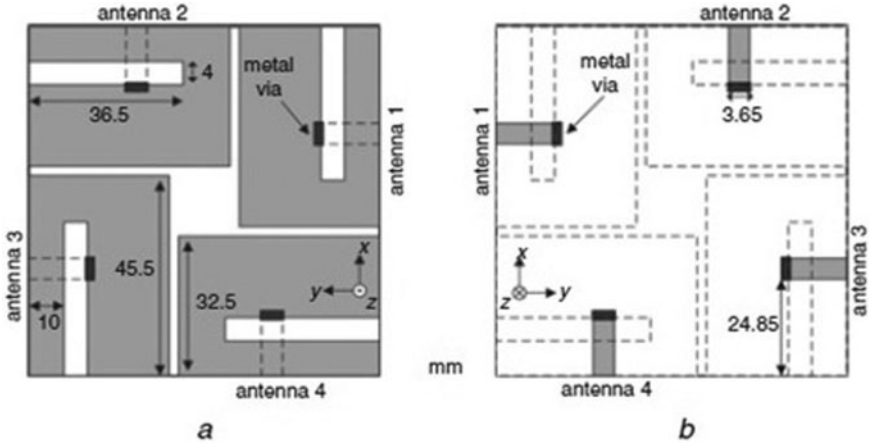


Fig. 3. MIMO using slot antennas with polarization diversity © [32].

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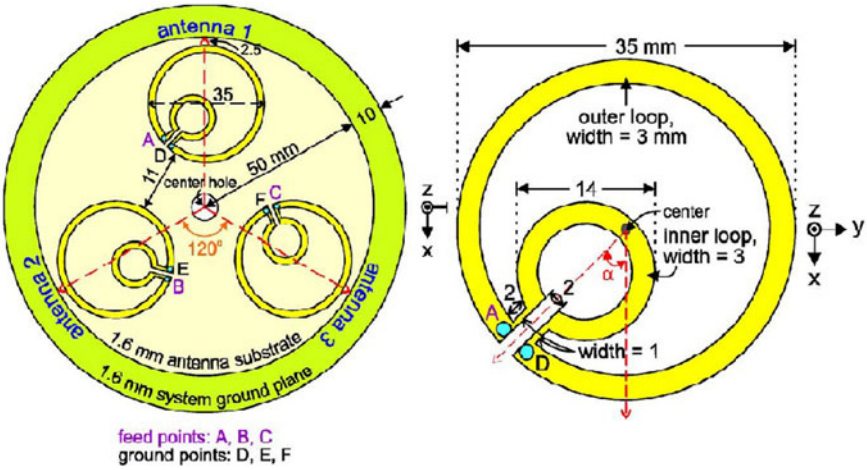


Fig. 4. Circular loop MIMO antenna for access point application © [36].

path and hence reduces coupling between the closely spaced antennas [52]. However, the parasitic element approach seems to be simple, and provides effective decoupling among radiators, yet very much sensitive to the position and placement of these elements. Parasitic element results in inductive loading and forms inductor–capacitor (LC)-equivalent circuit to shift mutual coupling from desired frequency band to out of band. The port isolation in this approach is more than 10 dB.

E) Neutralization line approach

A neutralization line is connected between the shorting/feeding strips to reverse the amount of coupling current and hence enhances the isolation. It can be placed between radiating elements or between ground plane and radiators. It results in inductive loading and forms LC circuit due to capacitive electromagnetic coupling between radiators to produce an open circuit at a desired frequency for mutual coupling reduction [53, 54]. A neutralization line is a kind of port decoupling technique implemented with short-circuited monopoles as shown in Fig. 8 [55], antennas with shorting posts for directive/rotational radiation patterns [56], and helps to achieve wide-band characteristics [57]. Similarly, a directly connected decoupling network is used as a neutralization line to get the dedicated radiation patterns for MIMO antenna elements. The direct connection of both radiators as shown in Fig. 9 allows the current to pass through the other (during the excitation of a single port) and protects the load from coupling current [58]. Although the neutralization line is an easy and simple approach of decoupling radiators, searching a low-impedance path for its placement is still challenging.

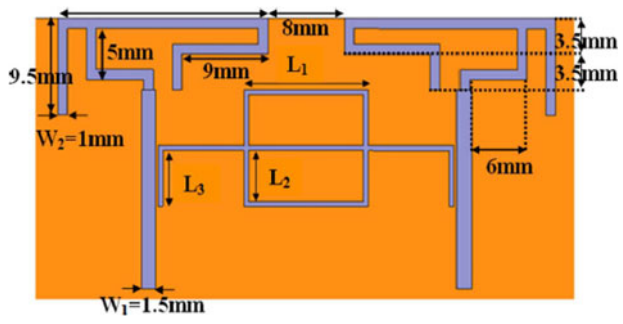


Fig. 5. MIMO antenna with parasitic element between radiators © [49].

F) Slit/slot-etching approach

The importance of slots and slits on different MIMO antenna designs with their advantages/disadvantages is described in this section. Different geometric shapes of slot etching into the radiating element and/or ground plane leads to the enhancement of specific characteristics like isolation (reduction in mutual coupling), wavelength shifting, and miniaturization, etc. The slot etching is a slow-wave structure technique to reduce the signal wavelength, which in turn reduces distance between the radiators and hence reduces correlation between them [59, 60]. Different slot structures play a role of isolation improver and multi-band creator [61, 62], i.e. *J*-shaped slot in ground [63]. Similarly, a slit etched in ground is a thought of a capacitive effect and helps in reducing mutual coupling between radiators [64]. The effect of slits and slots may induce back-lobe radiation. Though, they may help in improving efficiency and ensures compactness of the MIMO.

A PIFA antenna design with *C*-shaped ($\lambda/2$ wavelength) slots and *T*-shaped slits along with $\lambda/4$ wavelength resonator controls back-lobe radiation, reduces size, and enhances

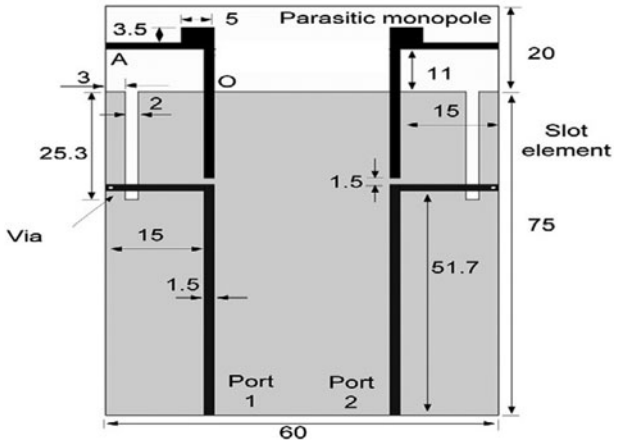


Fig. 6. MIMO antenna with parasitic element to enforce reverse coupling © [50].

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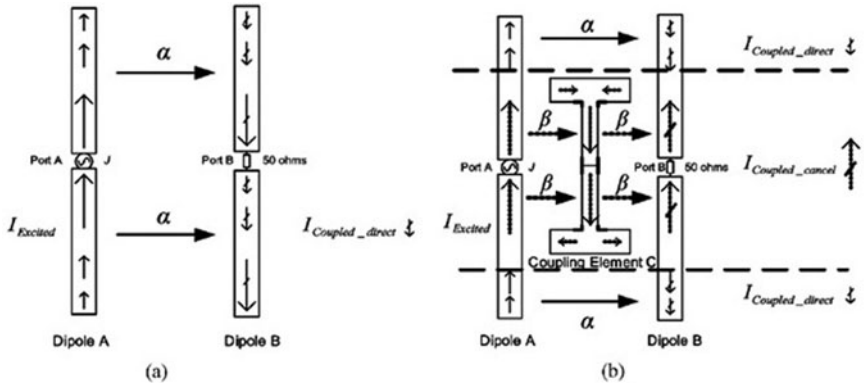


Fig. 7. MIMO antenna with *I*-shaped coupling element © [52].

efficiency. However, such design demands matching circuit to control mutual coupling [65]. While using slits and slots, the problem of matching can also be seen in case of proximity-coupled feeding. Sometimes, increasing the height of patch may solve the matching problem, likewise as shown in Fig. 10 [66]. The slits not only improve isolation, but sometimes are also used to widen the bandwidth [67]. MIMO antenna design with a pair of air-insulated $\lambda/4$ wavelength slots etched in a ground plane blocks the near-field radiations and some amount of coupling current to reduce mutual coupling [68]. A combined effect of XETS and intersecting square slot with parallel-piped cavity is also used for mutual coupling reduction and wide-band operation. A cavity is introduced in a design to reduce back radiations [69]. However, an indirectly excited slot in a cavity-backed slot array antenna acts like a parasitic element and distorts the radiation pattern by re-radiation of energy [70]. The port isolations in this approach is more than 20 dB.

A slot etching can be a form of defected ground structure (DGS) [71], like *H*-shaped slot [72] and fork-shaped slot (combination of *J*- and *L*-shaped slots) [73], to revert the direction of current flow for mutual coupling reduction. Similarly, a horn-shaped slot helps to achieve omnidirectional radiation patterns with enhanced bandwidth in a multi-antenna array system [74]. In elctromagnetically excited loops, decoupling can be achieved with *U*-shaped slot etched in a ground plane. Such technique helps to reduce mutual coupling and provides broadband features. The corresponding MIMO antenna design is shown in Fig. 11 [75]. Similarly, the slots etched at the corners of the ground are used to enhance the bandwidth and isolation between radiators. The design is shown in Fig. 12 [76]. Similarly, a MIMO antenna with a *T*-shaped open-ended slot and a chip capacitor as shown in

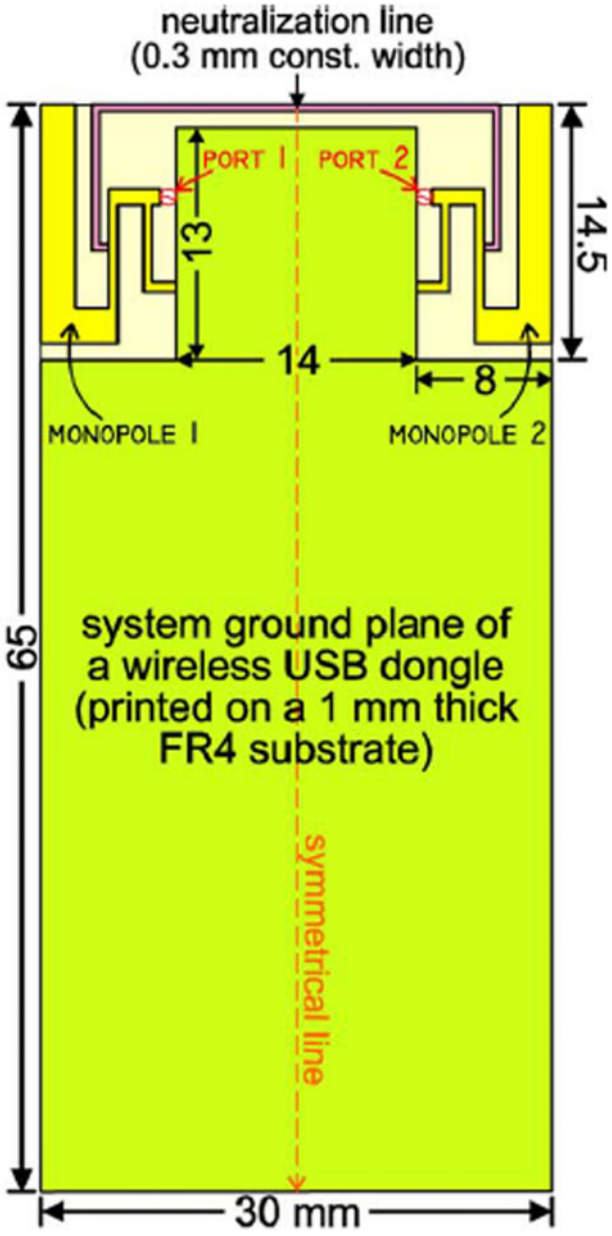


Fig. 8. MIMO antenna with neutralization line technique © [55].

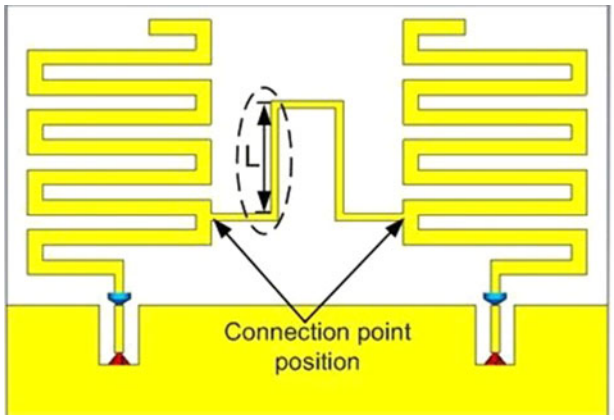


Fig. 9. MIMO antenna with directly connected decoupling network © [58].

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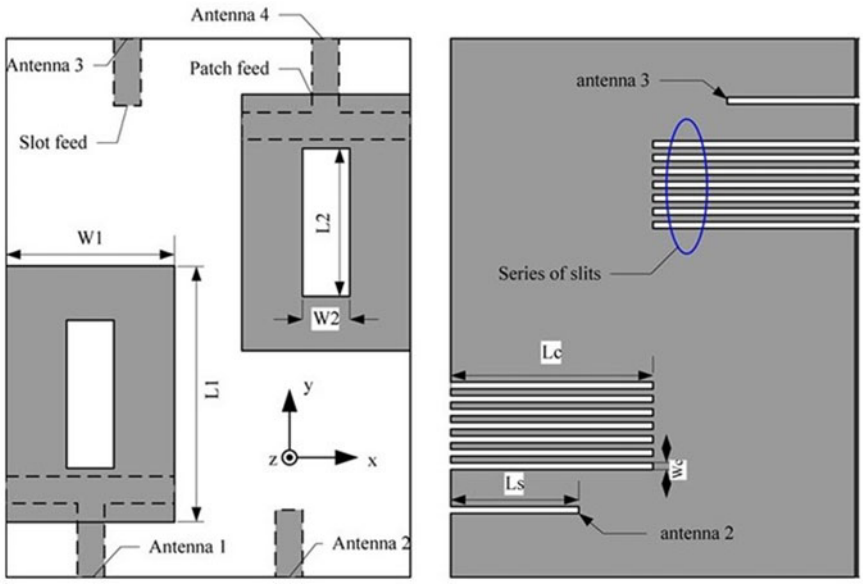


Fig. 10. MIMO antenna with slot in patches and slits in ground © [66].

Fig. 13 were combined for band rejection property and in turn reduces mutual coupling [77]. The combination of slot with ground branches as shown in Fig. 14 can be used to create multi-band operation and improves in-band isolation [78].

G) Coupling/decoupling structure approach

A through analysis of coupling/decoupling approaches has been included in this section with their advantages and disadvantages. A transmission line of $\lambda/4$ wavelength or submultiple of it is used for decoupling/descattering, and is placed at a point where the impedance is purely imaginary [79]. Similarly, a decoupling network converts the transadmittance of antenna ports into pure imaginary part [80]. Some designs use ring hybrid decoupling structure [81] to control mutual coupling. The combination of both the decoupling and matching networks are required in some designs to improve antenna characteristics [82]. A *T*-shaped ground arm also serves the purpose of port decoupling [83].

Similarly, a design uses a decoupling network with a chip capacitor and is connected to each feed line for the improvement of impedance matching and reduction of mutual coupling [84]. A transmission line with matching network is also used for decoupling purpose in some designs [85]. Similarly, a *U* section can also be used between the radiating elements to decouple them [86]. A reactive decoupling structure uses a *T*-shaped neutralization stub between the radiators for impedance matching and good isolation condition [87]. The effect of decoupling network using transmission line and matching stub as shown in Fig. 15 is utilized for decorrelation of antenna elements [88]. There are different types of decoupling networks and decoupling elements and are used according to the requirement in design [89, 90]. Similarly, the cross-shaped arms are used as a self-decoupling structure to generate orthogonal modes, which in turn enhances decoupling properties [91]. The decoupling level is more than 10 dB in this approach.

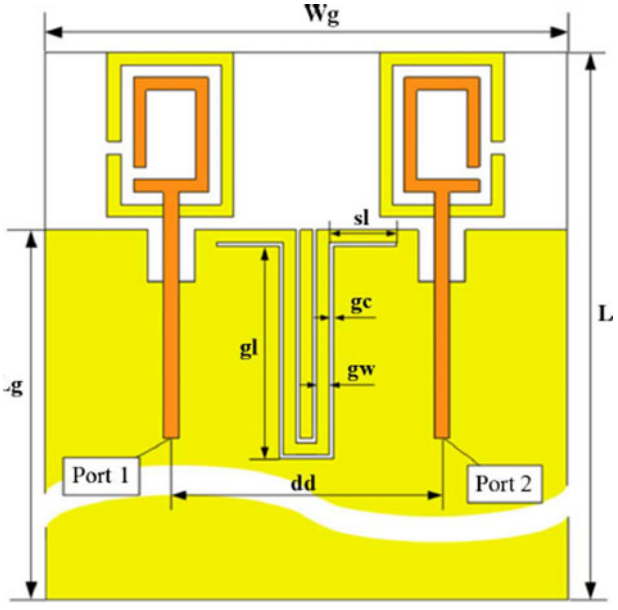


Fig. 11. Dual-loop MIMO antenna with dual *U* slots in ground © [75].

H) Meta-material approach/resonators

Different types of meta-material-inspired electromagnetic band gap (EBG) materials, along with their merits/demerits has been given in this section. These are specially used to control mutual coupling [92]. A meta-material-inspired element forms the LC-equivalent resonant circuit to shift the in-band mutual coupling elsewhere. Many of the EBG structures are available in antenna designs. These are also used to enhance certain properties of antennas to reserve the shape of radiation patterns, prevent back side reflection to increase DG, and reduces the loading effect of the adjacent antenna elements. The stacking of EBG layers offers a very low mutual coupling [93].

A meta-material-inspired broadband isolator is used to enhance in-band isolation [94]. A split-ring resonator (SRR)-loaded antenna utilizes the benefit of negative epsilon

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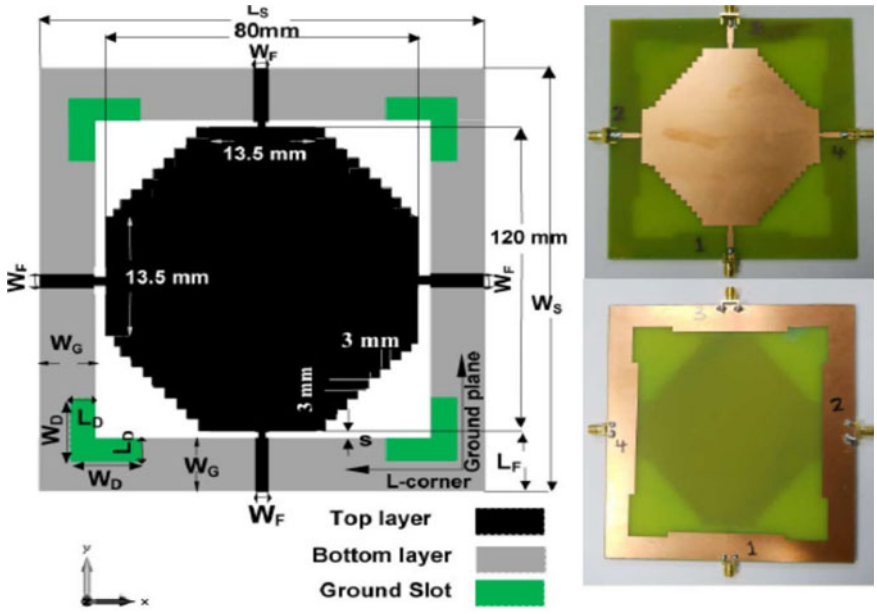


Fig.12. MIMO antenna with corner slots for isolation enhancement and wide banding © [76].

[95–97]. Similarly, a complementary split-ring resonator (CSRR)-loaded ground is used for size and mutual coupling reduction [98–100]. The SRR and CSRR structures are available in different shapes like an open-ended ring pair as shown in Fig. 16 [101, 102]. The capacitively coupled loop is also used for the reduction of mutual coupling [103]. The Babinet's principle can be applied to find out the field analysis of SRR/CSRR as shown in Fig. 17 [104]. The port isolation in this approach is more than 10 dB. The difference between the slot/slit etching in the ground and SRR/CSRR lie on their operation. As SRR/CSRR produces isolation, but results in narrow band operation, while slot/slit etching not only provides isolation, but also results in wide-band operation.

Similarly, a complementary pattern approach using a composite right/left-handed (CRLH) meta-material transmission line reduces mutual coupling and size of the radiators. The CRLH can be analyzed using a LC-resonant structure [105]. Similarly, a slotted meander-line resonator as shown in Fig. 18 is used to create defects between radiators, which in turn produces band notch operation to control the mutual coupling

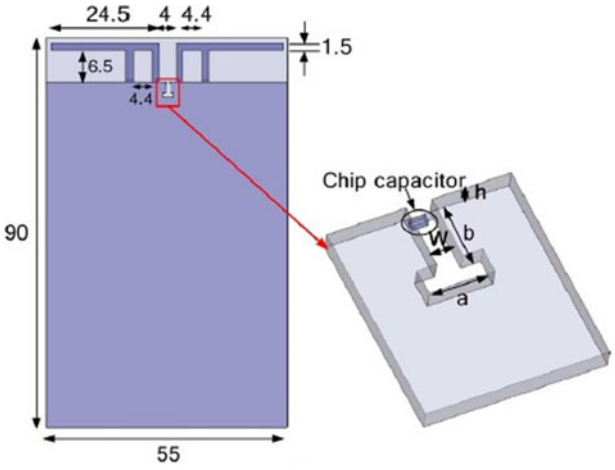


Fig. 13. MIMO antenna with *T*-shaped slot and capacitor © [77].

effects [106]. Also, to capture and control the surface currents of a radiator, a modified serpentine structure is inserted between the radiators [107]. A polarization diversity MIMO antenna utilizes the benefits of SRR by loading it between the radiators to offer multi-band operation with low mutual coupling, and reduction in size [108]. Having been enriched with many advantages, this approach results in slow wave structure, narrow band operation, as well as in low efficiency.

I) Metallic/shorting strips/stubs

In most of the MIMO antenna designs, a PIFA array antenna uses the shorting strips/posts for size and mutual coupling reduction [109]. The shorting pins/posts are used for the inductive loading, and in turn to form appropriate LC-equivalent circuit to control mutual coupling effects. The cross-polarization phenomena was seen in case of shorting pins/posts to distort co-polarization as well as gain pattern of the antennas. The effect of cross-polarization was reduced by meandering probe feeding of a *W*-shaped antenna structure. The design results in high bandwidth and was suitable for array application for LTE bands [110]. A broadside and conical patterns are also achieved with mode excitation by shorting posts and *L*-shaped probe feeds [111]. Thick circular patch with grounding pins/posts are also used in designs for specific characteristics [112]. A multi-branch MIMO antenna with a shorting strip and an isolation stub was utilized for portable wireless devices to divert the coupling current [113]. In such designs, the effect of shorting strip is to create the current loops, and in turn controls the direct-coupled currents [114, 115]. Although the approach seems to be beneficial for size reduction, gain enhancement, and mutual coupling reduction, the resulted structures become complex and increases the weight of overall structure.

J) Feeding networks

A common feed enhances radiation efficiency and gain, counter attacks on the channel fading due to multi-path propagation,

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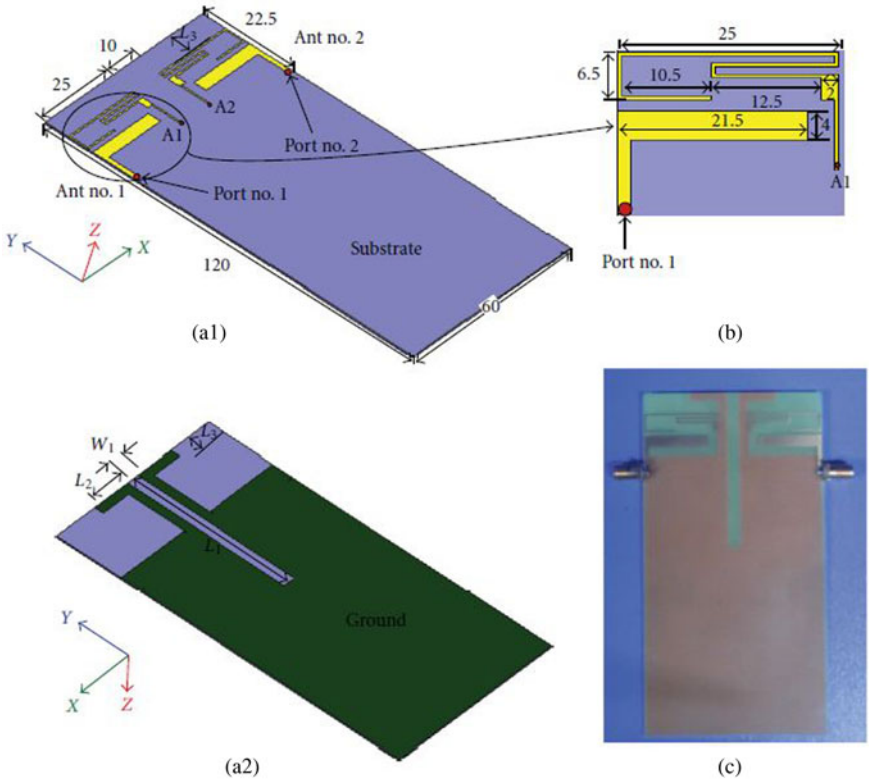


Fig. 14. MIMO antenna with ground slot and inverted *L*-shaped ground branches © [78].

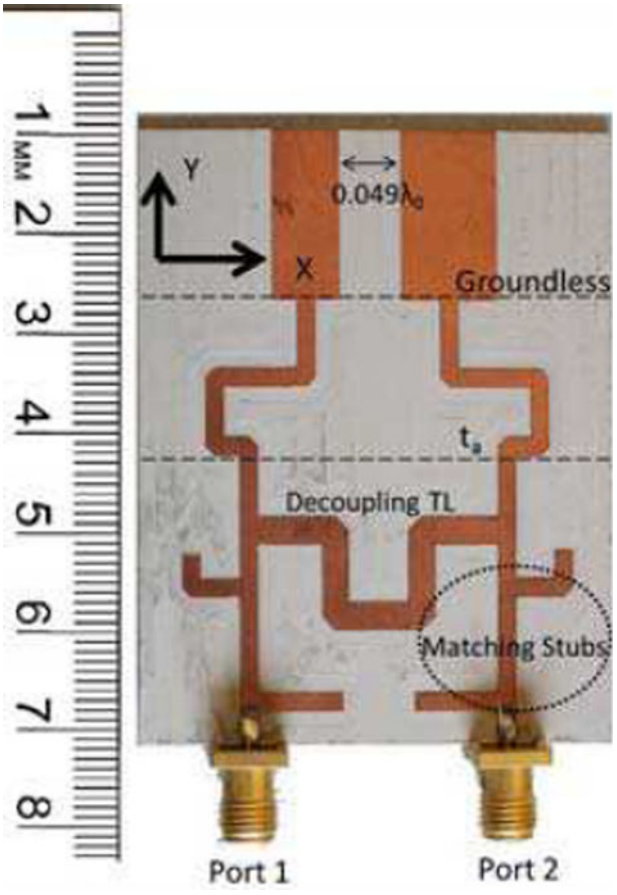


Fig. 15. MIMO antenna with decoupling network © [88].

and provides beam steering in radiation pattens [116]. A 180° asymmetrical *T*-shaped power divider (to avoid feed overlapping) [117], *U*-shaped folded feed line (power divider) structure [118], *L*-shaped feed structure [119], crossed feeding network [120], four-shaped feed structure [121], coupled feed [122], capacitive feed [123], and mixed micro-strip and coplanar feed [124] are used to control certain characteristics like mutual coupling between radiators. These feed structures also form the LC-equivalent circuits. Feeding networks with insufficient space between radiating elements result in inappropriate gain/isolation, and always have bigger sizes, though, these structures are easy to design and implement.

K) Ground branches/utilization

Different shapes of inverted/non-inverted *L* and *T* ground branches help in reduction of mutual coupling. Such branches have different effects on low/high frequencies [125, 126]. Similarly, a MIMO design has two isolation approaches, first that looks into the depth of the ground and other looks between the radiators in terms of partially extended ground arms as shown in Fig. 19 [127]. In many of the applications *L*/*T* ground branches are used with matching stubs [128, 129] for proper impedance matching as shown in Fig. 20 [130]. Few designs take the benefit of wide-band characteristics using *L*-protruded branches and *T*-shaped slots along with mutual coupling reduction as shown in Fig. 21 [131].

Similarly, the effect of multi-grounds in a MIMO design with inductive coil produces additional resonance and reduces mutual coupling effects [132]. A mutual coupling reduction and impedance bandwidth improvement approach uses embedded protruded ground arm between the radiators

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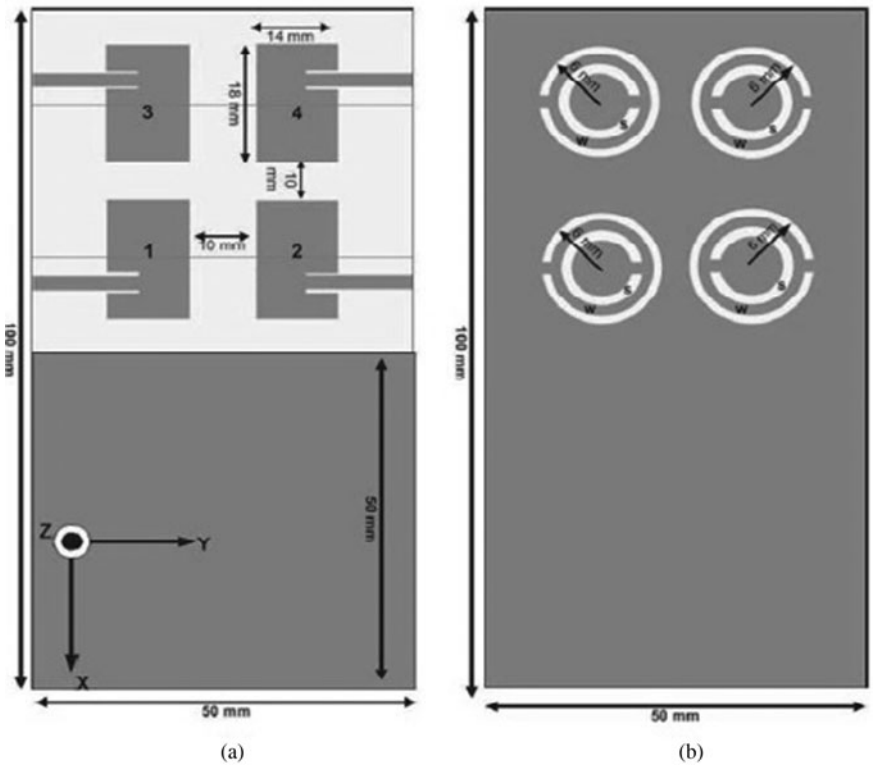


Fig. 16. A 2 × 2 MIMO antenna with CSRR © [101].

for MIMO antenna design [133]. The effects of mutual coupling may also be controlled by combining the effects of inverted *L* branches and a loop etched in a ground as shown in Fig. 22 [134]. The ground can be utilized as a reflector and to excite less surface currents in a directive multi-loop MIMO antenna design [135]. The port isolation in this approach is more than 10 dB. The ground branch approach is easy and simple, although placement on unwanted place may result in reduction of gain and enhancement in mutual coupling.

All the above diversity and mutual coupling reduction techniques are compared with their diversity performance using frequency bands/resonant frequencies, number of elements, size, isolation, and ECC as showed in Tables 1–3. The amount of isolation is dependent on the type of radiating elements, diversity technique, their placement, orientation, and the type of mutual coupling reduction technique used. For example, the ground branches/utilization approach is simple and suitable to design LTE operations such as 700, 800, and 900 MHz frequency bands using meander line or monopole radiators. The advantages and disadvantages of diversity and mutual coupling reduction techniques are compared in Table 4.

III. MIMO ANTENNA MINIATURIZATION

The miniaturization and space utilization are two of the important aspects of MIMO antenna designs and must be

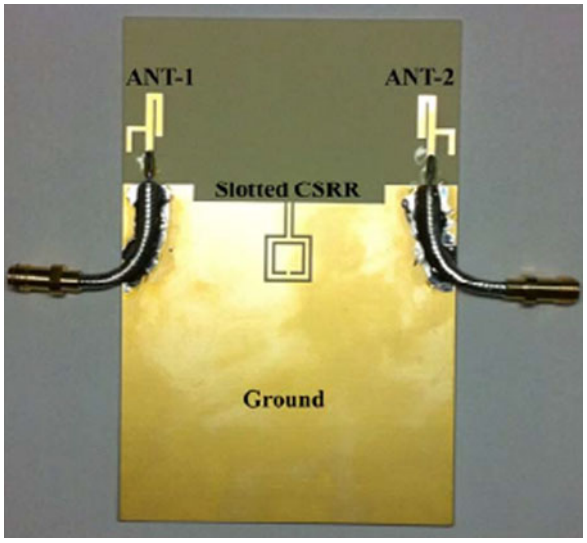


Fig. 17. MIMO antenna with slotted CSRR in ground © [104].

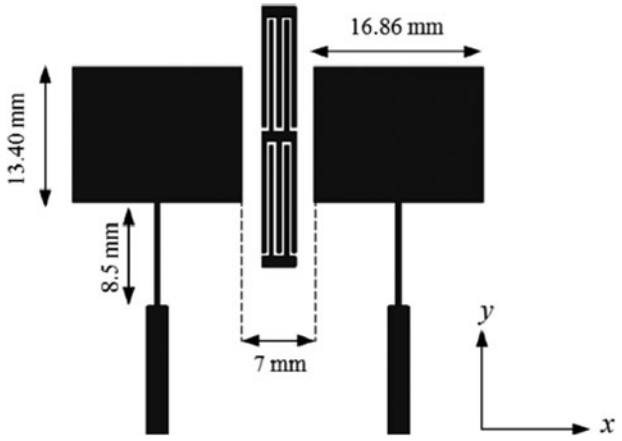


Fig. 18. MIMO antenna with slotted meander line resonator © [106].

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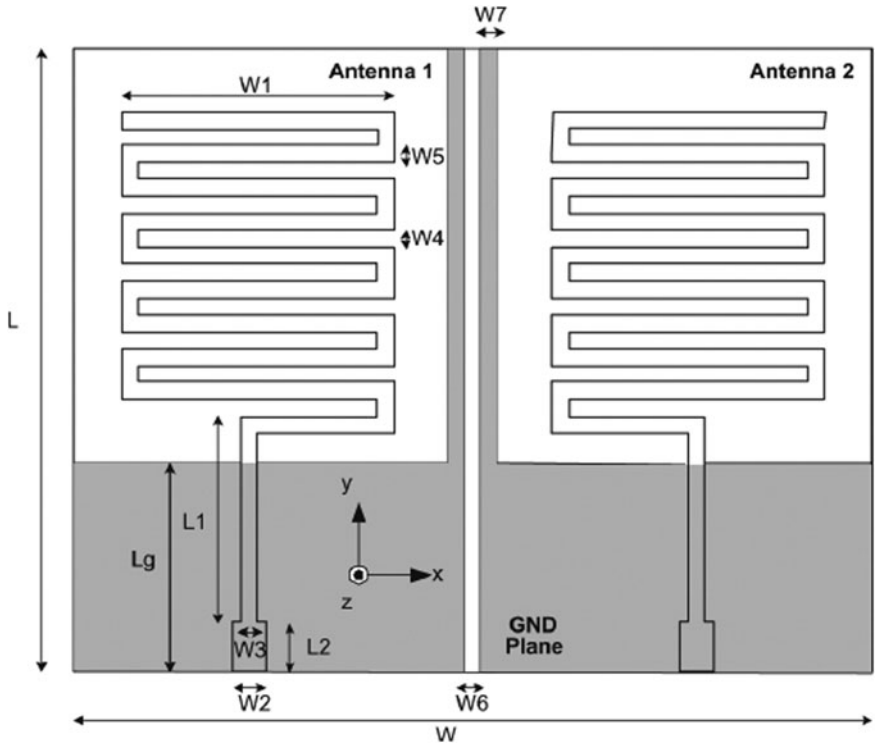


Fig. 19. MIMO antenna with ground split and ground arms © [127].

optimized for the present/future mobile communications [136]. As the antenna is an energy transformation device to transform the wave generated by the antenna into the radiating wave and vice versa. The reduction in the separation between MIMO antenna radiators affects transformation of energy and in turn discussed antenna parameters. The miniaturization of a MIMO antenna is concerned with the type of radiating element and ground. The most of the above discussed approaches of mutual coupling reduction serves the dual purpose. They not only help in reduction of mutual coupling, but also reduce the overall size of MIMO antennas for the present/future wireless communications. The first part of mutual coupling reduction approaches has already been presented thoroughly in previous section.

In first approach, high degree of miniaturization may be achieved with dielectric material loading, though such materials are very much expensive, and much care is needed in their designing and placement. Another disadvantage of this approach is that it has limited bandwidth [137, 138].

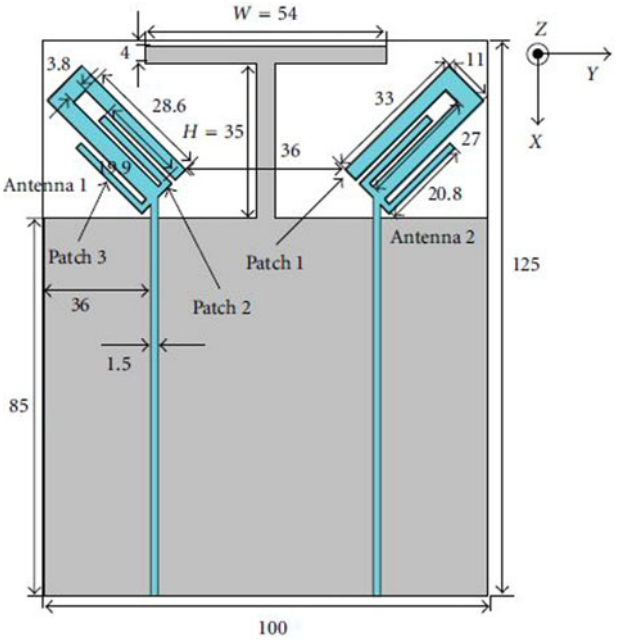


Fig. 20. MIMO antenna with *T*-shaped ground branch © [130].

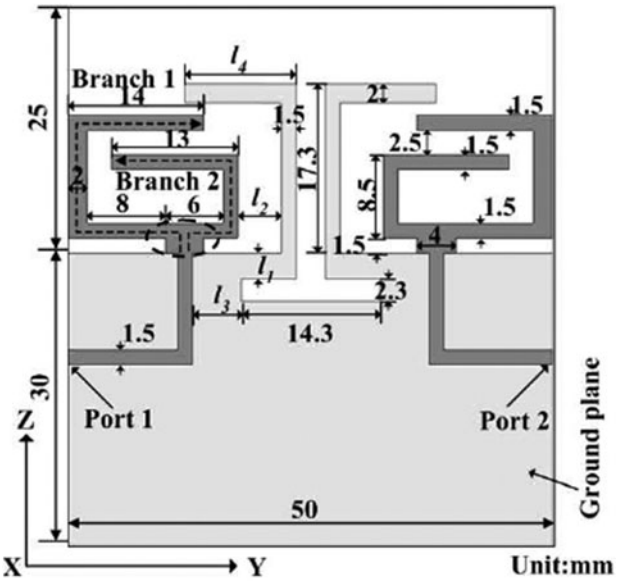


Fig. 21. MIMO antenna with *T* slot and protruded *L* branches in ground © [131].

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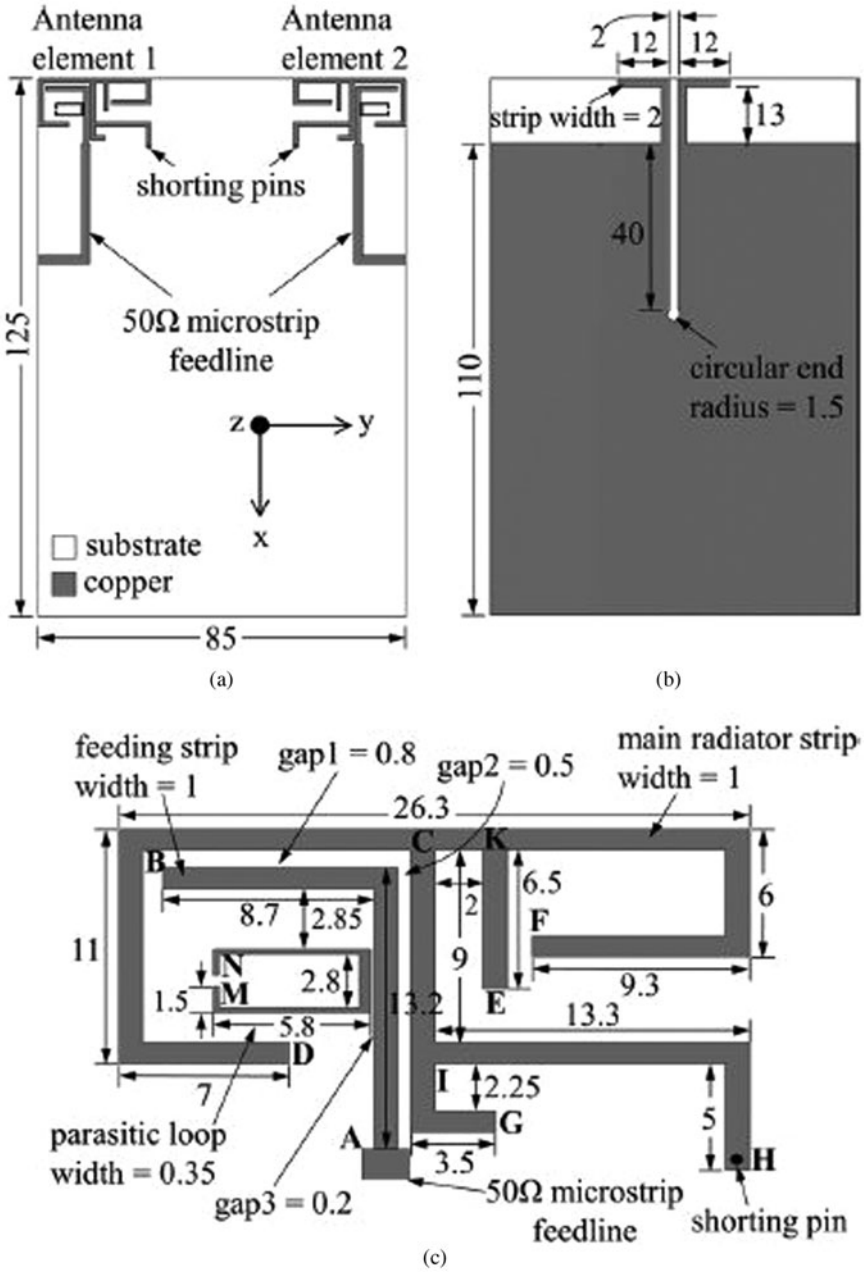


Fig. 22. MIMO antenna with ground slot and inverted *L* branches © [134].

Table 1. Comparison of considered references for WLAN band

Ref. no.	Frequency/bands (GHz)	No. of elements	Size (mm²)	Isolation (dB)	ECC	Gain (dBi)	Isolation approach
[27]	2.65	3	120 × 90	>20	<0.4	2.8	Polarization diversity
[31]	2.4	2	50 × 50	–	–	–	Polarization diversity
[35]	2.4–4.8	4	114 × 114	>10	–	5 (peak)	Polarization diversity
[39]	2.45	4	105 × 55	>10	$<10^{-2}$	2.15	Polarization diversity
[66]	2.4–2.5	4	80 × 60	>25	$<10^{-2}$	>2.84	Slit/slot etching
[72]	2.4	2	100 × 100	>40	–	>3.4	Slot etching
[95]	2.43–2.54	2	60 × 57	>30	$<10^{-3}$	2.57 (peak)	SRR
[99]	2.4	4	60 × 60	>22	<0.4	3.4 (peak)	CSRR
[101]	2.48	4	100 × 50	>10	<0.3	− 0.8	CSRR
[117]	2.4	2	60 × 90	>29	<0.2	–	Feed network
[120]	2.4	4	140 × 140	–	–	>1.8	Feed network

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Table 2. Comparison of considered references for WLAN/WiMAX bands

Ref. No.	Frequency/bands (GHz)	No. of elements	Size (mm²)	Isolation (dB)	ECC	Gain (dBi)	Isolation approach
[20]	2.02–2.93/5.10–6.45	2	100 × 50	>20	$<10^{-3}$	–	Space diversity
[23]	2.37–2.69/4.89–5.61	4	70 × 70	>17	$<10^{-2}$	>3.6	Polarization diversity
[49]	2.4–2.5/5.15–5.83	2	100 × 150	>15	0.1	–	Parasitic element
[61]	2.4–2.48/5.15–5.73	2	100 × 50	>25	–	–	Slot etching
[73]	2.45/5.8	2	100 × 50	>20	0.3	–	Slot etching
[104]	2.45/5.0	2	100 × 70	>18	$<10^{-2}$	–	Slit/slot etching
[114]	2.4/5.5	2	100 × 60	>26	$<10^{-2}$	4.84 (Peak)	Shorting strips

Table 3. Comparison of considered references for LTE bands

Ref. No.	Frequency/bands (GHz)	No. of elements	Size (mm²)	Isolation (dB)	ECC	Gain (dBi)	Isolation approach
[26]	0.45	2	182 × 204	>20	$<10^{-2}$	–	Polarization and pattern diversity
[37]	0.86	2	173 × 70	>40	$<10^{-2}$	>1.15	Polarization diversity
[60]	1.6–2.3	2	125 × 125	>30	–	8	Slot etching
[76]	1.8–2.9	4	140 × 120	>15	<0.1	>5.5	Slot etching
[111]	1.96–2.36	4	200 × 200	>24	–	>4	Shorting post
[122]	1.71–2.69	2	118 × 58	>12	<0.15	>1	Feed network
[124]	1.71–1.88	2	80 × 50	>15	$<10^{-2}$	>2.18	Feed network
[125]	1.88–2.20	4	95 × 60	>11.5	–	<1	*L*/*T* ground branches
[126]	1.7–2.9	2	110 × 65	>15	$<10^{-2}$	>1.21	*L*/*T* ground branches

Table 4. Comparison of diversity and mutual coupling reduction techniques

No.	Name of the technique	Advantages	Disadvantages
1	Space diversity	Simple	Consumes big space
		Enhanced isolation	Polarization mismatch
2	Polarization diversity	Improves capacity	Polarization mismatch
		Size reduction	
		Link quality	
		Better efficiency	
		Provides isolation	
3	Pattern diversity	Simple	Depends on other mutual coupling reduction techniques
		Link reliability	Polarization mismatch
		Complementary patterns (for exact case)	
4	Parasitic element/structure	Simple	Sensitive to the position/placement of parasitic elements
		Indirectly connected element	
		Produces less ohmic losses	
5	Neutralization line	Simple	Placement is still challenging
		Connected between the shorting/feeding strips	
6	Slit/slot etching	Reduces size	Back-lobe radiation
		Results in multi-band	
		Results in broad-band	
		Wavelength shifter	
7	Coupling/decoupling structure	Improves isolation	Placement dependent
		Placed at a point where impedance is imaginary	
		Converts trans-admittance into imaginary part	
8	Meta-material approach/ resonators	Size reduction	Narrow band operation
		Isolation enhancement	Reduces efficiency
		Wavelength shifter	Slow-wave structure
9	Metallic/shorting strips/stubs	Size reduction	Increases weight
		Gain enhancement	Placement dependent
		Isolation enhancement	
10	Feeding networks	Enhances isolation	Increases overall size
		Improves gain	
		Improves efficiency	
11	Ground branches/utilization	Improves isolation	Placement dependent
		Multi-band operation	

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The second approach of size reduction uses folding and shorting pins/posts. This approach provides four times of reduction in size, but has cost-effective solutions and non-planar structure with complex geometry. This approach also has no specific design rules. In a PIFA design, a meander line with the rectangular patch was combined for size reduction. A MIMO antenna with such design was utilized for SM transmission [139]. Similarly, a 2 × 1 MIMO miniaturization with the meander line was used to make electrically small antenna to operate at low-frequency band [140]. This approach takes the benefit of reactive impedance, exists due to the short circuiting (with via) in PIFA antennas [141], and also in inverted *F* antenna with stub loading [142].

n the third approach of size reduction, different patch shapes and slots are used, especially a fractal (having space-filling property) geometric patch provides eight times of miniaturization, and slots can provide wider bandwidths. This approach using fractal has complex geometry and has no standard design procedure [143, 144]. The reconfigurable slot antenna can be used to alter many of the required MIMO antenna characteristics and helps in miniaturization [145–147].

In the fourth approach of size reduction, ground is modified according to the requirement of MIMO antenna design. This approach also provides eight times of miniaturization, and is a planar and simple geometry, and also no standard design procedure is followed here. The drawbacks of this approach are that it provides increased the back-lobe level, and also reduces efficiency. In this approach, slots in the ground are also used for multi-banding and isolation enhancement. The slots in ground may be in the form of symmetric/asymmetric/square/rectangle shape [148, 149], and in the form of DGS to achieve matching conditions [150].

In the fifth approach of size reduction, meta-materials such as ϵ_r negative, μ_r negative, double negative, and meta-material-inspired resonators/techniques are used. This approach has high degree of miniaturization, but low efficiency, low bandwidth, and complex geometric structures, and no standard design procedure. These meta-materials are loading in ground plane/patch/both in the form of SRR [151] or CSRR [152].

IV. CONCLUDING REMARKS

The MIMO antennas are used to solve the problem of SISO antennas. On the other hand, their performance factors like gain, efficiency, MEG, and DG all are affected, due to the close proximity of MIMO antenna elements. The degradation in these parameters is due to the radiation and emission properties of radiators and ground, which is commonly encountered as a mutual coupling. A thorough literature review was presented to control the degrading factors of mutual coupling between the radiating elements. The impact of space/pattern/polarization diversity techniques was presented with their merits and demerits to control this factor. Similarly, the effect of parasitic element/structure, neutralization line, slits/slots, coupling/decoupling structures, meta-materials, metallic/shorting pins/stubs, feeding networks, and ground branches/utilization approaches was presented in depth with their utilizations in different designs to control mutual coupling.

Most of the considered techniques not only provides reduction in mutual coupling but also helps in miniaturization of the radiating elements. Therefore, these techniques are more important because these are capable in producing compact MIMO antennas for the present/future wireless communications. Each of the mutual coupling reduction technique loads a certain value of capacitance/inductance in between the radiating elements and forms a series/parallel resonance circuit to shift the in-band mutual coupling on the undesired frequency spectrum. The considered mutual coupling reduction techniques and their values are dependent on the type of radiating elements as well as orientation and placement of radiating elements.

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Leeladhar Malviya received his B.E. degree in Electronics and Telecommunication, from the Govt. Engineering College, Ujjain (MP), India, in 1998, M.E. degree in Electronics and Telecommunication, from Shri G. S. Institute of Technology and Science, Indore (MP), India, in 2008. Currently he is pursuing Ph.D. from Indian Institute of Technology Roorkee, India. His area of interest is MIMO antenna design for wireless applications.



Rajib Kumar Panigrahi received his Ph.D. degree from IIT Guwahati in 2011. He has received his M.Tech. degree in Electronics with specialization in microwave engineering from Cochin University of Science and Technology and B.E. degree in Electronics and Communication from Bangalore University (now VTU). Since 2012, he has been with the Department of Electronics and Communication Engineering, Indian Institute of Technology, Roorkee, where currently he is an Assistant Professor. His research interests include Radar-based remote sensing, SAR image denoising and segmentation and classification of SAR images.



M. V. Kartikeyan received the M.Sc. and Ph.D. degrees in Physics and Electronics Engineering from Banaras Hindu University, Varanasi, India, in 1985 and 1992, respectively. He was with Institut für Hochleistungsimpuls- und Mikrowellentechnik, Karlsruhe Institute of Technology, Karlsruhe, Germany, as an Alexander von Humboldt Fellow. He is a Full-Professor in the Department of Electronics and Communication Engineering, Indian Institute of Technology, Roorkee, India, since 2009. His current research interests include millimeter/THz wave engineering (high-power devices and allied components), microstrip antennas for communications, microwave-integrated circuits, and RF and microwave design with soft computing techniques.

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