Chapter

Techniques for Compact Planar MIMO Antennas

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Abstract

MIMO Technology has promoted the developments of various antennas, then the planar antenna will be one of the main directions to satisfy the future compact requirement of the 5G+/6G communications. This chapter introduces different types of the planar antenna and summarizes the implicit compact techniques, where the related techniques like the diversity and the reconfigurable are not included owing to they are the inherent properties of the MIMO antennas. These antennas contain the patch antenna, slot antenna, dipole/monopole antenna, loop antenna, cavity antenna, Yagi-Uda antenna, fractal antenna, UWB antenna, PIFA etc., and their deformations to the specific purposes. On the contrary, the implicit compact techniques are not so explicit as the antenna configurations, but they are classified to be the close-spacing structure without decoupling, owing to the decoupling is not the necessary requirement of MIMO application, decoupling technique of spacing reduction, meandered line technique, multi-element method, co-radiator/co-location design, fractal antenna, and radiator-cutting antenna. Besides, the corresponding techniques for the compact design are also concluded, including the mode-cutting method, fractal technique, characteristic mode analysis, and the optimization algorithms.

Keywords: MIMO, 5G+/6G, planar antennas, compact techniques, integration

1. Introduction

Owing to the prominent advantages compared with the conventional single-input single-out (SISO) system, the MIMO technology has been extensively applied to many scenarios, in which the antenna with beamforming is one of the key features in order to realize the multiple path communications. Consequently, the multi-beam, the multi-polarization, or the related diversity or the reconfigurable techniques are the inherent properties of the MIMO antennas. To satisfy the requirement of MIMO communication, many antenna types have been employed, including the high-profile 3D antennas, such as the dielectric resonator antenna (DRA) [1–3], helix antenna [4], structure-loaded antenna [3, 5–7] or multi-element antenna [8, 9], and the other common 2D planar antennas. On the other hand, the 5G+/6G technology puts forwards the new compact, easy-fabricated and easy-integrated requirements for the antenna development resulting in the planar antennas will be one of the main directions in the future. Therefore, the focus of this chapter is on the introduction of planar antennas and especially the implicit techniques on how to design the compact structure.

Many planar antenna types have been proposed for the MIMO applications, but not all of them will be discussed in this chapter considering the related compact techniques. The planar antennas involved are patch antenna [10–22], slot antenna [23–30], dipole/monopole antenna [31–48], loop antenna [49–58], ultrawideband (UWB) antenna [59–71], Yagi-Uda antenna [72–77], cavity antenna [78–82], fractal antenna [83–90], and the planar inverted-F antenna (PIFA) [91–104]. These antennas do not appear in isolation, they often combine with other types for the specific purpose, such as, both the patch antenna and the dipole antenna were used to realize the linear and circular polarization design [11], the slot antenna [28] and the fractal antenna [83] also belong to the UWB antenna, and the radiator of UWB antennas [59–62] is monopole. However, we distinguish them according to their explicit features in this chapter as the above categories, and the relatively simple antenna structures are picked up from the similar works. Additionally, though these are planar structures, they can be used in the 3D situations [27, 43, 102] like in the mobile application. All selected types are the printed antennas, they will be good candidates for the future 5G+/6G applications from the view of easy fabrication and integration.

The compact design is always the research focus of MIMO antennas, many techniques have been employed to compress the volume of structure. However, we face a common problem that the antenna performance is affected because of coupling when they are close to each other. There are two general ways to solve this problem, one is that we need not care about the coupling but put them closer if the coupling is not too significant, which is because the MIMO antenna technique does not require the elements to work at the same time, the coupling will not affect the work status of MIMO system; the other is using the decoupling technique to realize the compact design, even so the antenna performance is also affected when the elements are close enough.

In addition to the above close-spacing compact techniques, changing the antenna shape is another conventional way to realize the compact design, such as, using meander line for the dipole/monopole or the slot antenna to save the spacing, and by the combinations with different antennas to change the shape, like the electric and magnetic dipoles, the patch and slot, the PIFA and slot etc. Besides, the fractal technique and the optimization algorithm with constraints are often implemented to change the antenna shape. And we can physically reduce the antenna size by performing the corresponding cutting based on the related modes.

In this chapter, we will focus on the introduction of the corresponding compact techniques of the planar antennas, including the close-spacing and the shape change methods. Therefore, the rest is organized as follows. Section 2 introduces the corresponding general compact methods implicit in different antenna types, including the close-spacing no-decoupling design, decoupling design, meander line method, multiple antenna structure, co-radiator/co-location design, fractal antenna, and the mode-cutting technique. The fundamentals for compact designs, including mode-cutting method, fractal technique, characteristic mode analysis (CMA), and optimization algorithm, are summarized in Section 3, which will be helpful to the future compact researches owing to the physical reduction of antenna size. Then, the conclusions are shown in Section 4.

2. Compact antenna techniques

Though different antenna types have been designed for the compact purpose depending on the present development trend, the compact techniques are similar accompanied by the types. We summarize the corresponding compact techniques in this section.

2.1 No-decoupling compact designs

The purpose of MIMO antenna is using the multiple path transmissions to realize the high-efficiency and high-capacity communication, which means the antenna may not work simultaneously and then the coupling is not a main concerned focus. In other words, we need not care about the mutual couplings among elements so seriously in some cases when we want to realize the compact design but put them closer. Moreover, the coupling can be reduced by properly arranging the positions of elements to form the orthogonal polarization etc.

In [101], even the cross line connected with four elements exists to improve the isolation, the minimum isolation is up to 9.7 dB. The similar phenomenon happens in [36, 80] where no-decoupling structures were used. The four-element 90 degrees rotated structure of [36] is shown in **Figure 1**, from which we know the coupling is significant and the authors gave that of about 12 dB. The shorting pins and the 90 degrees rotation also do not reduce the mutual coupling seriously at some frequencies in [80], which is about 13.3 dB, the corresponding configuration is shown in right subfigure.

When the spacings become larger, the coupling will be smaller [29, 35] where the orthogonal polarization techniques were employed as well. Using the shorting pins [78] or slot [81] to stop the current flowing to the neighbor element in the cavity antenna is an efficient way to reduce the coupling. And we can obtain the lower coupling by exciting the neighbor elements with the differential modes instead of additional decoupling structure [14, 46, 88].

2.2 Compact decoupling techniques

Generally, we should consider the mutual couplings in the MIMO antenna design which decreases the consequent undesirable problems of the related system. Except the above differential mode method, we often reduce the mutual coupling for the close-spacing elements from two aspects, one is from the source and the other in the transmission process. The decoupling techniques of patch antenna can illustrate these well [15–18]. When the spacing is large enough, the surface current on the ground plane affects the mutual coupling rarely so that a proper metamaterial absorber put between the patch is enough to stop the surface and the radiated waves in the decoupling process [17]. As the spacing becomes closer, the surface current on the

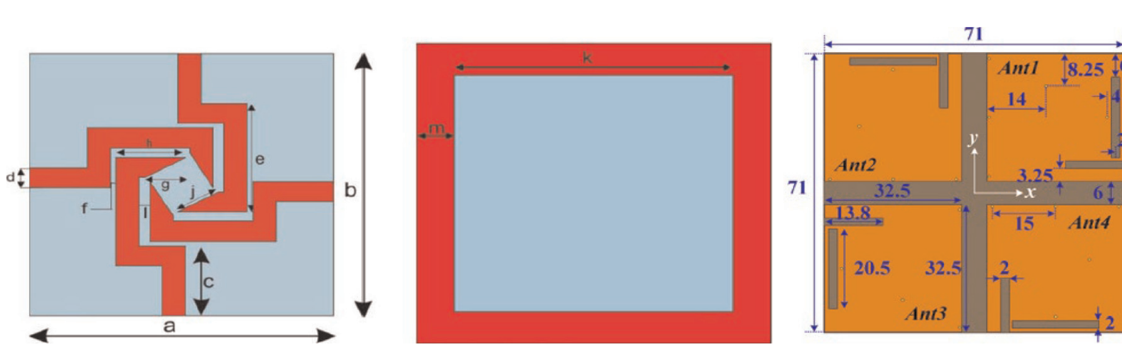

Figure 1.
No-decoupling MIMO antennas: [36] (left) and [80] (right).

ground plane diffuses to the neighbor element, and the near-field coupling to the other patch generates, so the defected ground structure (DGS) and/or resonator techniques between patches can reduce the couplings significantly [15, 16, 18]. **Figure 2** shows the simple decoupling structure in [15], in which the slot through the substrate and ground plane was curved. The surface current on the ground was cut off and the resonator was form between patches resulting in the reduction of mutual coupling. In order to reduce the mutual coupling of patches, literature [18] used another way, where the parasitic elements are put closer than the spacing between patches so as to induce the power to the parasitic metal rather than the neighbor patch. **Figure 3** shows the current distributions on the top layer of patch antenna before and after using parasitic technique. It is clear that the coupling to the neighbor element is suppressed.

The ideas were implemented into the PIFA antenna [92, 93, 96], loop antenna [49, 52, 53], slot antenna [69, 70], and UWB antenna [60, 62, 69, 70] and so on. **Figure 4** shows the corresponding antenna and the decoupling structures. Both the PIFA and the UWB suppress the coupling in the wave propagation process, and the other two cuts off the surface currents.

The neutral line technique is another normal method to reduce the coupling in the monopole [45] and UWB [60] antennas. It does not destroy the structure of ground plane but introduce the neutral line between elements. The decoupling structure of [60] is shown in **Figure 5**, where the circular disc of neutral line allows several

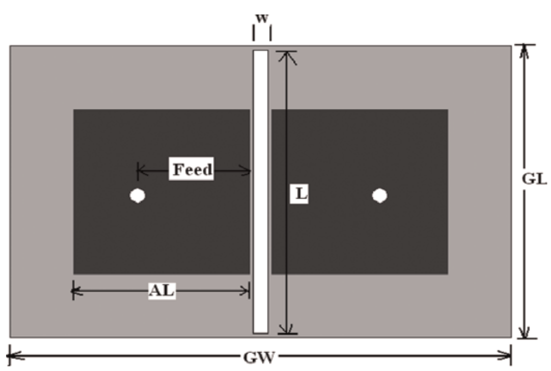

Figure 2.
DGS and resonator techniques to reduce the coupling [15].

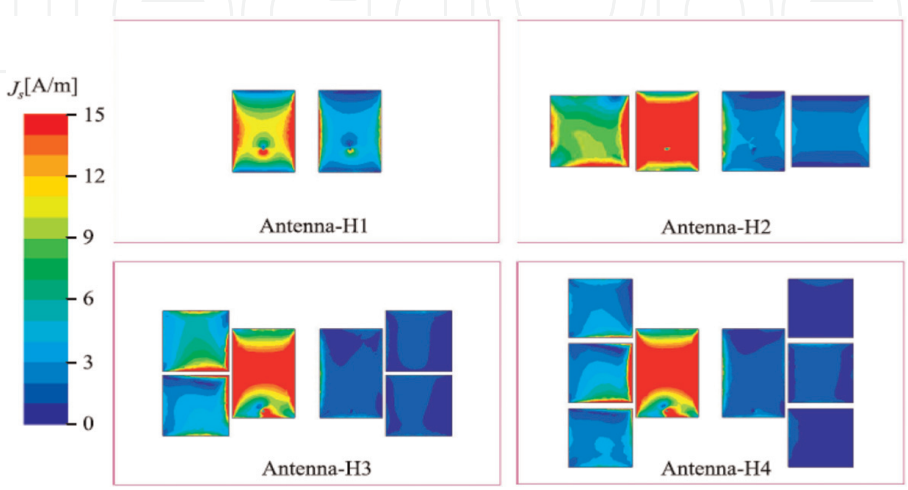

Figure 3.
The comparisons of current distributions on the top layer [18].

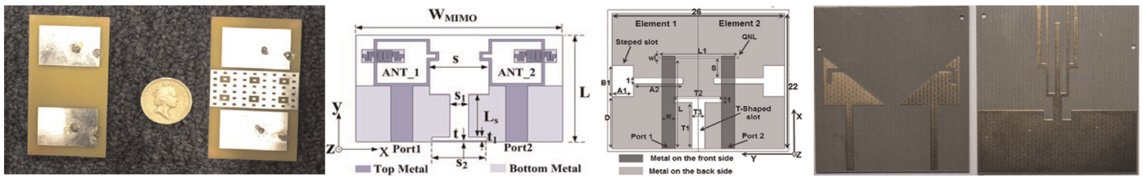

Figure 4.
The antennas and decoupling structures (from left to right): PIFA [96], loop [52], slot [69], and UWB [62].

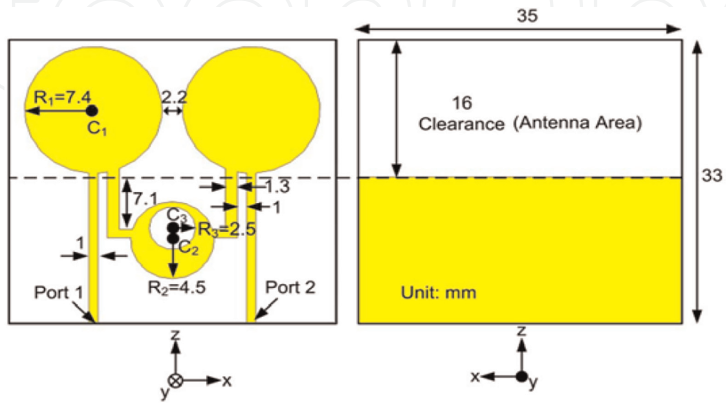

Figure 5.
The antennas and the neutral line decoupling structures of [60].

decoupling paths to cancel the coupling current on the ground so that the UWB decoupling is realized, and with the help of slot in the circular disc, the highest decoupling frequency can be tuned to 5 GHz.

If the cavity is cut properly, the antenna can realize the self-isolation without any additional structure. Such as in [81], the authors cut a slot symmetrically for the quarter cavity, the consequent 1/8 mode cavity antennas have good isolation. This self-isolated technique is also applied in the loop antenna, and the size is reduced by means of the introduction of two vertical stubs in the loop [53].

2.3 Meander line antennas

It is the conventional way to restrict an antenna to a fixed area by meandering the radiator. It is often adopted in the dipole/monopole, slot, and loop antennas, where the corresponding method is relatively simple, that is, we just adjust the meandered sections to resonate at the desired frequency as the straight one. We can find many meander line techniques employed in the MIMO antenna designs [25, 36, 38–40, 42, 47, 49, 56, 57, 67].

The dual-band is realized by two different length slots, the authors meandered the longer slot which makes the two slots have the similar length in the horizontal direction [25]. The arms of dipole/monopole are meandered as well for the compact design [36, 38–40, 42, 47, 67]. For the loop antenna, the authors put two loops on the different layers and the smaller one is embedded into the bigger one [49], while the loops meandered inward are implemented for the rectangular [57] and the Alford [56] loops, respectively.

2.4 Multiple antenna structures

Multiple antenna structure, or the hybrid structure with different antenna types, also can obtain the compact design for the MIMO antenna application. This combination not only saves the spacing, but also suits for the realization of multi-band or multi-polarization.

In [11], the patch antenna combines with the dipole antenna to realize the polarization diversity design, where the chamfered-edge square patch with an offset feed is used to obtain the circular polarization and the two dipoles are responsible for the linearly polarized radiation. Literature [32] also shows the combination of both patch antenna and the monopole antenna with the same ground, but the patch antenna is fed by the electromagnetic coupling.

Two pairs of slot antennas are etched in the patch to realize the dual-polarized radiation, and good isolation is obtained due to the proper feeding positions [19]. The authors put the IFA and the slot antenna together for different LTE bands in the mobile application [104]; and two slots with different lengths are put close for the dual-band radiation [25].

2.5 Co-radiator/co-location antennas

To some extent the co-radiator and the co-location antennas resemble the multiple antenna structure. For the co-radiator MIMO antenna, there exists one common radiator but excited by different ports, while the co-location antenna assembles different antennas in the fixed area. These two types are similar to some diversity antennas of one radiator but different feeds and the multi-band antenna with one radiator, respectively. In other words, the co-radiator/co-location antennas are not so unfamiliar things but they just have the common property for a kind of antennas.

The antenna of [105] shown in **Figure 6** explain the co-radiator antenna clear, where four ports excite the common radiator and the slot of ground plane is used to improve the isolation. The configuration of [106] resembles to this work, but use two ports to excite the co-radiator, the isolation is improved by means of the T-shape slot and the irregular stub extended from the ground plane.

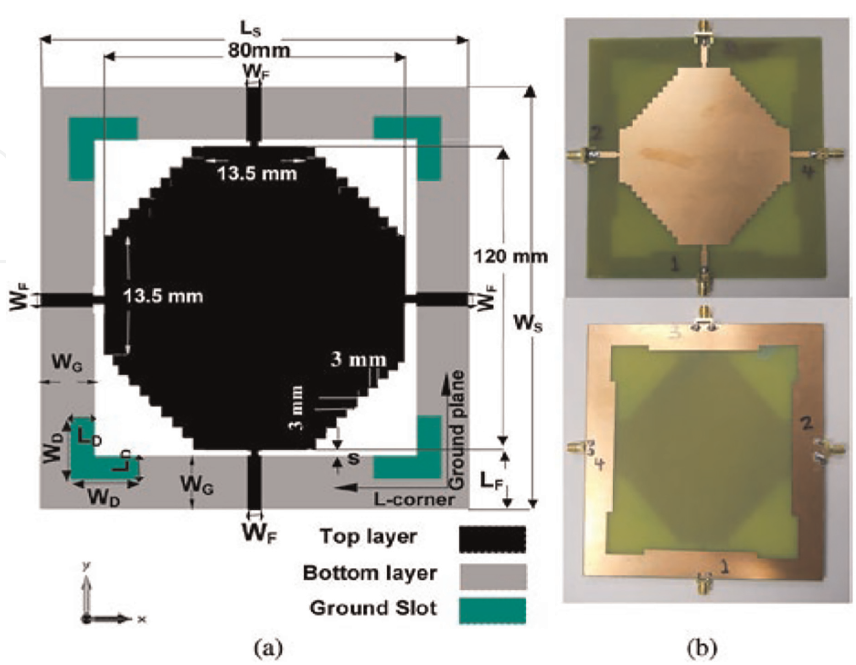

Figure 6.
Co-radiator antenna of [105]: (a) Geometry and (b) prototype.

The circular co-radiated patch is employed in [107], the configuration is shown in **Figure 7**. The authors analyzed the two close modes TM_{02} and TM_{11} with the monopole-like and patch-like radiations, respectively, and put several vias around the center to make sure the resonant frequencies are the same. Then, they used the center port to obtain the monopole-like radiation, the other two ports excite two orthogonal patch-like patterns.

The application of the co-radiator technique in the mobile terminal was investigated in [108], we repeat the configuration in **Figure 8**. The loop is the co-radiator of port 1 and port 2 as shown in **Figure 8c**. The two ports are put at the center of loop, and port 1 feeds the loop directly while port 2 feeds the loop by a microstrip line. Owing to the odd and even modes appear by the two ports, the high isolation is achieved in the design.

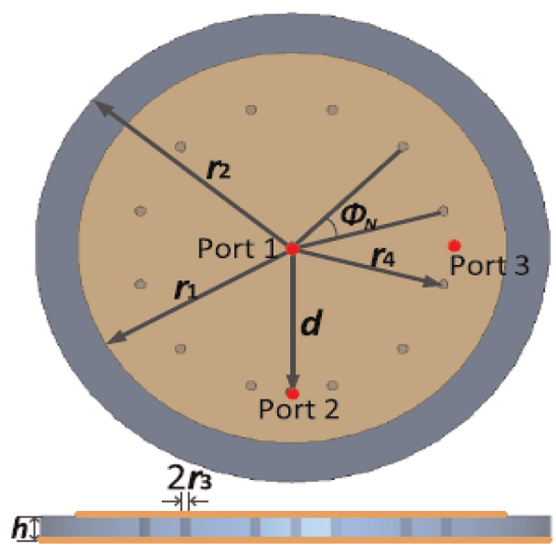

Figure 7.
Circular co-radiator antenna of [107].

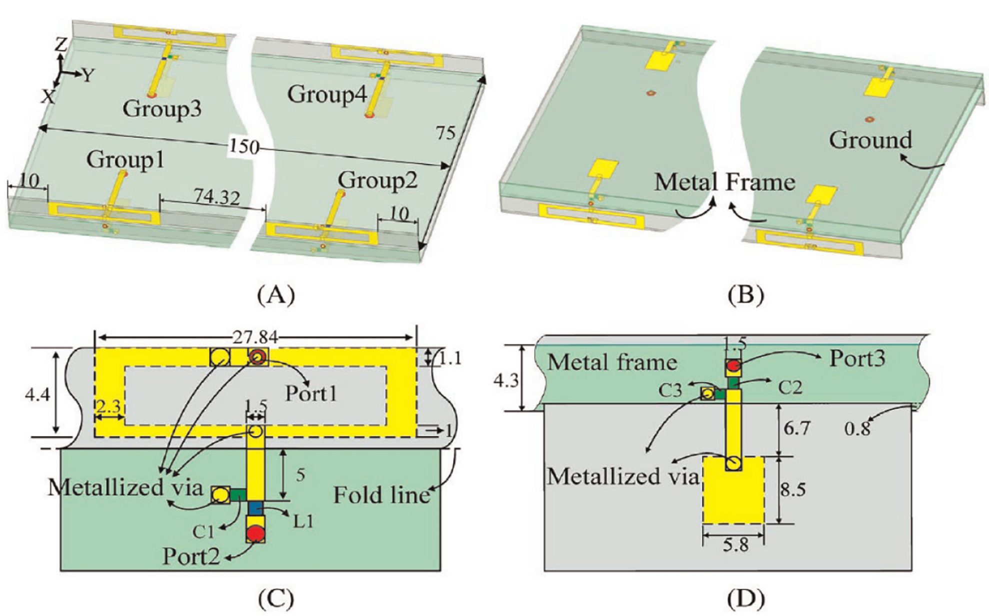

Figure 8.
Co-radiator antenna applied in mobile terminal [108]: (A) front view, (B) back view, (C) details of the upper structure, and (D) details of the lower structure.

The co-location antenna is the same as the co-radiator antenna in a way as in [107], where different radiation patterns are generated by the different ports at different positions but the radiator is not changed. However, we differentiate them in this section by introducing the co-location antenna with different radiators [30]. The corresponding antenna configuration and the current distributions at different frequencies are shown in **Figure 9**, where the two ports are placed on the top and left sides. When the lower frequency is excited at any port, the square-ring slot works, the edge branch radiates for the higher frequency.

2.6 Fractal antennas

The fractal technique is helpful to reduce the antenna size owing to the self-similar and space filling properties, thus it is used to design the MIMO antenna for the compact purpose.

In [83, 86, 88], the Koch fractal technique were adopted to design the MIMO antenna. The iteration process of [83] is shown in **Figure 10**. The initial shape is the octagon of **Figure 10a**, the fractal shape after first iteration is shown in **Figure 10b**, and the second iteration has satisfied the requirement of the UWB band. The corresponding MIMO antenna is shown in **Figure 11**. The C-shape slot is sliced on the

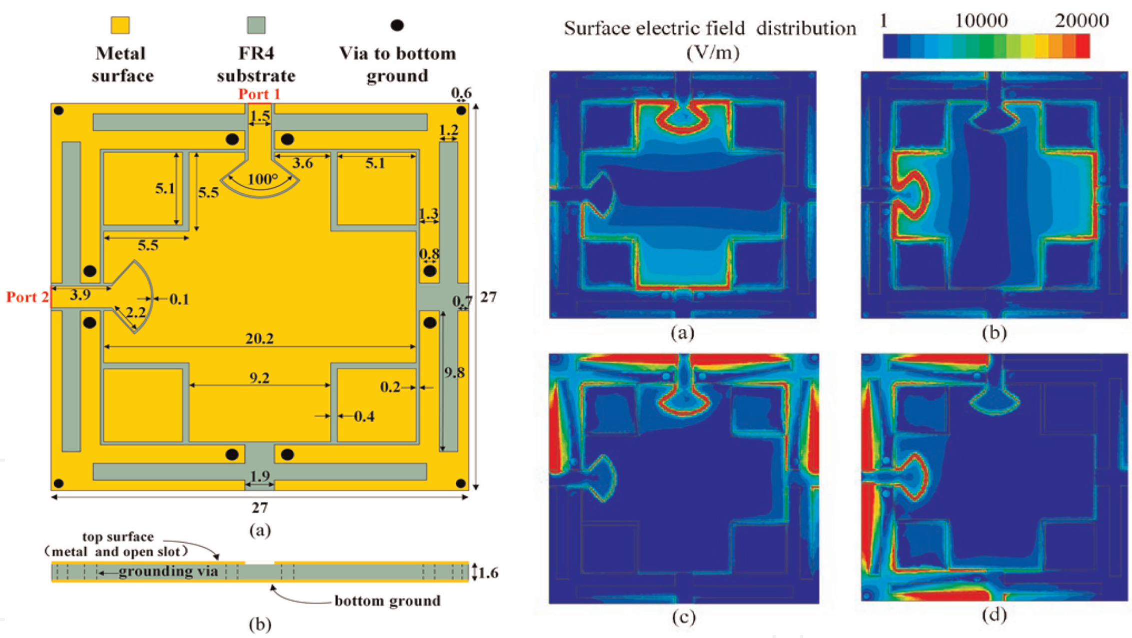

Figure 9.
Antenna configuration (left: (a) Top view and (b) cross-sectional view) and current distributions at different frequencies (right: (a) Port 1 excited at 3.4 GHz, (b) Port 2 excited at 3.4 GHz, (c) Port 1 excited at 3.8 GHz, and (d) Port 2 excited at 3.8 GHz) of [30].

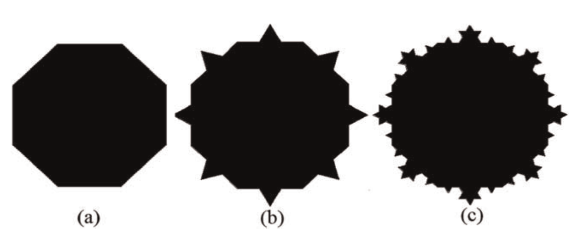

Figure 10.
Iteration process of Koch fractal [83]: (a) initiator, (b) first iteration, and (c) second iteration.

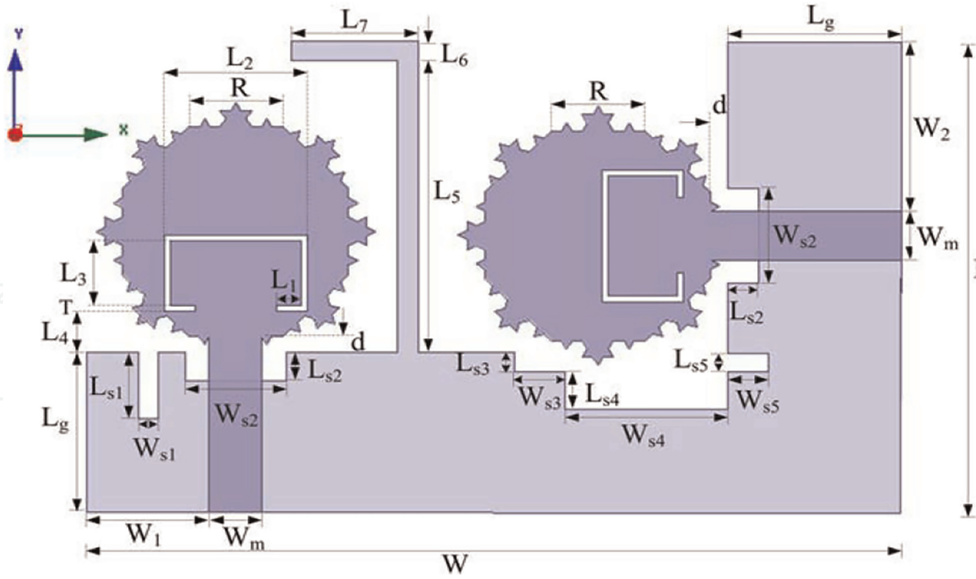

Figure 11.
Fractal MIMO antenna of [83].

fractal octagon to realize the rejection band, the orthogonal arrangement and a L-shape stub connected with the ground plane are used to increase the isolation.

The hybrid fractal technique is also used to design the UWB antenna [85], where both the Sierpinski and Koch fractal were applied, and a U-shape slot etched in the radiating element to notch the WLAN band. For the MIMO antenna design, the two antennas are put parallel, but the isolation is increased by both the stepped ground plane and the reflecting ground stub in between.

Using the similar idea as in [85], the authors in [87] combine the Koch and the Minkowski to get the dual-band MIMO antenna. The corresponding hybrid fractal idea and the MIMO antenna are shown in **Figure 12**. There is an initiator and a generator for the Minkowski fractal technique as shown in the left subfigure of **Figure 13**. This structure meets the dual-band requirements of 1.65–1.90 GHz and 2.68–6.25 GHz, and the high isolation is achieved with the help of the T-shape stub connected to the ground plane.

In contrast, the hybrid Quadric–Koch fractal antenna was designed in [89] for the multi-band requirement where the circular polarizations were obtained for the bands of 3.66–3.7 GHz and 5.93–6.13 GHz and the rest five bands are linear polarization. No additional structure was used in the MIMO antenna, where two elements are put symmetrically, and the isolation is better than 17 dB over the entire bands.

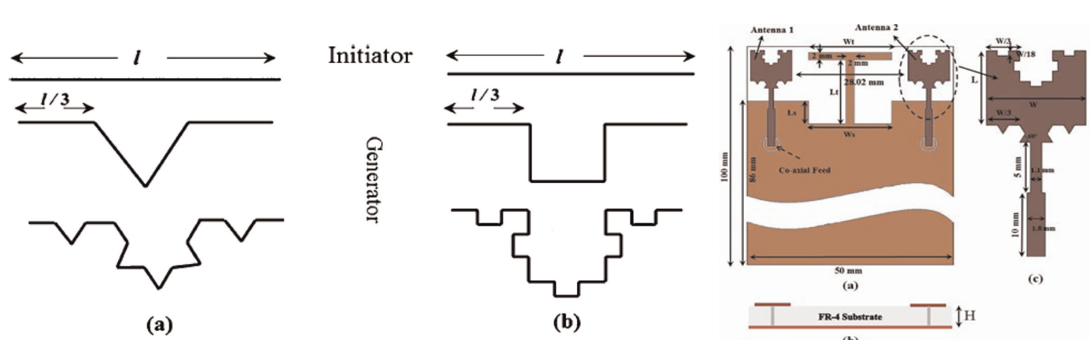

Figure 12.
Hybrid fractal MIMO antenna of [85].

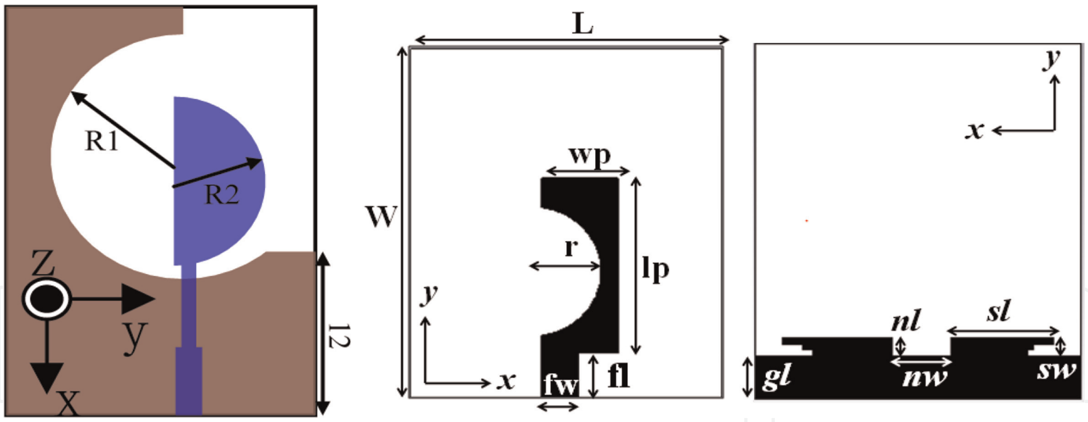

Figure 13.
The elements of MIMO antennas in [109] (left) and [110] (right).

The Hilbert fractal technique was employed in [90] to realize the dual-band property, the correlation coefficients lower than 0.1 when the two orthogonal-arranged antennas are put close.

2.7 Radiator-cutting antennas

Though the fractal technique reduces the antenna size significantly in physical, there is another way to reduce the antenna size physically, that is, by cutting the original antenna into a small piece. This method is suitable for the antenna with the symmetrical structure or the cavity antenna who has the symmetrical modes.

In the works of [109, 110], the radiator is cut into two pieces and leave one for the radiation. The corresponding element structures of the MIMO antennas are shown in **Figure 13**. It is clear that the antennas have no complete structures. It is the quasi-self-complementary monopole in [109] owing to the monopole has the semi-circle patch while the slot in the ground is not complete half-complementary structure. This cutting structure keeps the UWB property as that of the complete monopole. Through the symmetrical arrangement of two elements, the MIMO antenna has high isolation without any additional structure due to the asymmetry structure. While in [110], the rectangular monopole is not only cut into two pieces, but also a semi-circle slot is etched in the half-monopole to improve the optical transparency. However, the ground plane is modified by etching a slot and adding staircase stubs resulting in the improvement of the impedance bandwidth.

The non-integer order mode cutting technique is also adopted to reduce the antenna size physically. It is the same as the radiator-cutting method. That is because the complete structure has the integer mode, if we want to use its non-integer mode we have to cut the structure. In other words, the structure cutting means the mode cutting.

The non-integer mode structure of rectangular cavity in [80] has been shown in Section 2.1, where the length of the patch is half of the complete one so that the $TM_{1/2,0}$ mode etc. form. The same idea appears in [82], but one 1/8 mode is used for the circular cavity. While the semi-taper slot is etched on the top lay of the cavity in [111] in order to radiate the related power, where the four CPW-fed MIMO antenna is shown in **Figure 14**. The metallic vias are set to form five cavities, the outer four with the semi-taper slots are responsible for the radiation. The half mode of TM_{110} will generate by the proper feeding, and this MIMO antenna has high isolation owing to the orthogonal arrangement and the existence of the metallic vias.

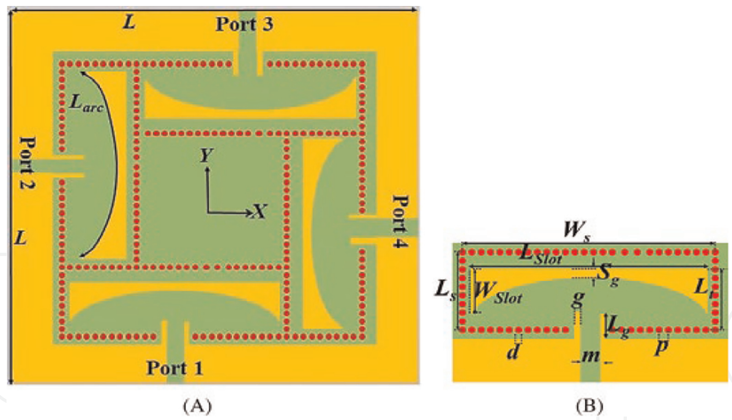

Figure 14.
MIMO antenna of [111]: (A) geometry and (B) unit.

3. Fundamentals of compact design

Section 2 has discussed the specific antennas and the corresponding compact techniques implicit in the design, but there are some methods leading to the compact design not only suit for one fixed structure, but also will be used into other types in the future. Thus, we discuss their applications in MIMO antennas and the related techniques in this section, including the detailed explanation of mode-cutting method, the fractal technique, the theory of characteristic mode, and the optimization algorithms.

3.1 Mode-antenna analyses

In Subsection 2.7, the mode-cutting methods for different antenna types has been shown, however, the cited references did not discuss the detailed modes so clear. Now we discuss the mode distributions according to the specific antenna types which have been studied in the MIMO antenna.

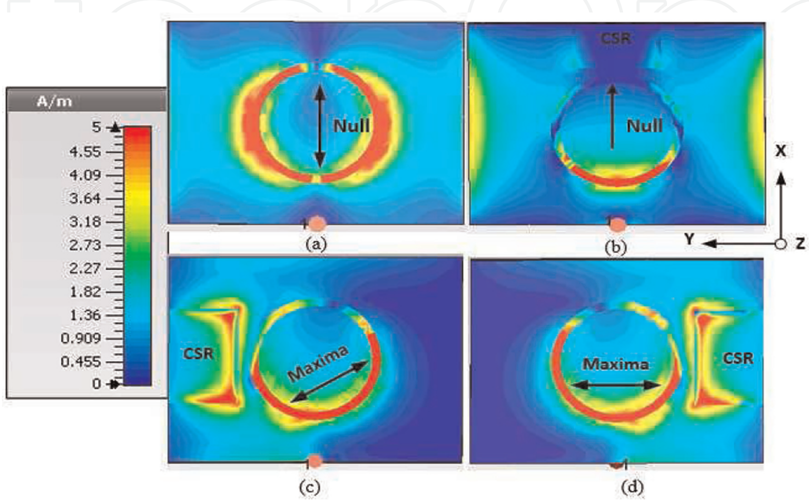

Figure 15.
Current distributions of complete slot of [112]: (a) without CSR, (b) CSR at position 1, (c) CSR at position 2, and (d) CSR at position 3.

If the mode-cutting method is implemented, the corresponding antenna has at least one integral modes, or we can say that the cutting method suits to the integral order mode of the related structures.

For the cutting of the semi-circle slot antenna, the authors in [112] discussed the current distribution of the complete slot as shown in **Figure 15**. Whether the complementary slot reflector exists or not, the current distributions are symmetrical. By optimizing the size and position of CSR, the cutting method can be implemented to get the half-loop slot, and the corresponding performances are affected rarely. Then, the two-element MIMO antenna is formed by symmetrical arrangement whose isolation less than 12 dB is achieved without any additional decoupling structure.

The literature [113] provides another way to design the cavity MIMO antenna which excites each sub-mode generated by the different shape cavities. The authors started the analysis for the closed circular cavity, then analyzed the characteristic modes for the open and sector cavities, and consequently obtained the methodology that the whole cavity can be divided into N sub-cavities. If a T-shape monopole is put at the proper position for each sub-cavity, the N-port MIMO antenna forms and high isolation is obtained. They took the 4-port circular open cavity as an example and fabricated an antenna prototype shown in **Figure 16**, whose measurements agree well with those of simulations. Thus, they continue discuss the related design for other shape cavity antennas.

3.2 Fractal techniques

The fractal technique has been employed in the MIMO antennas as in subsection 2.6 owing to it can reduce the size for the compact design. As we know the fractal technique needs several iterations, it is effective to reduce the size in finite iterations, but when the iteration reaches to a certain number, the size reduction will not so obvious until it does not work. That's because as the iteration increases, the length of fractal shape will become smaller and can not be comparable with the wavelength. Therefore, we have to consider the iteration number depending on the specific requirement. In this subsection, we introduce two common simple fractal techniques, the Koch and the Sierpiński fractals [114, 115].

1. Koch Fractal

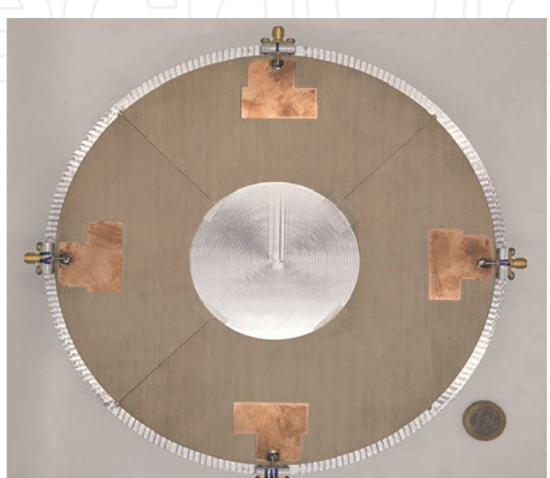

Figure 16.
4-Port MIMO antenna of [113].

The **Figure 12** has presented the 2nd iteration process for the line segment, we do not repeat here. The detailed iteration method is, (1) the line segment is selected as the initiator, (2) divide the segment into three equal portions, then rotate the middle portion ±60 degrees to form another two new subsegments, and (3) repeat the process of last step. The length will increase 1/3 times for each iteration.

2. Sierpiński Fractal

The Sierpiński iteration process of isosceles triangle is shown in **Figure 17** [114]. The coordinates for the next iteration can be obtained by

$$v_1(x,y) = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} \frac{1}{2} \\ \frac{\sqrt{3}}{2} \end{pmatrix} \tag{1}$$

$$v_2(x,y) = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} -\frac{1}{2} \\ \frac{\sqrt{3}}{2} \end{pmatrix} \tag{2}$$

$$v_3(x,y) = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \end{pmatrix} \tag{3}$$

This iteration process described by formulas (1)–(3) can be summarized as, find the midpoint of each segment and connect them to form four same isosceles triangles, then remove the middle triangle, we will get the final iteration shape.

3.3 Characteristic mode analysis

The CMA permits the researcher to know the antenna performance at the initial stage without considering the specific excitations so that the user can have an insight into the radiation essence, which is extensively used in the application of mobile handset antenna where the large metal chassis exists [116]. And the MIMO antennas are also extensively investigated for the mobile terminal application, there are a lot of works using the CMA [47, 117, 118].

In [47], a meandered dipole working at 3.5 GHz was studied by using the CMA. The first 10 modes are compared and the symmetrical reverse modal currents are

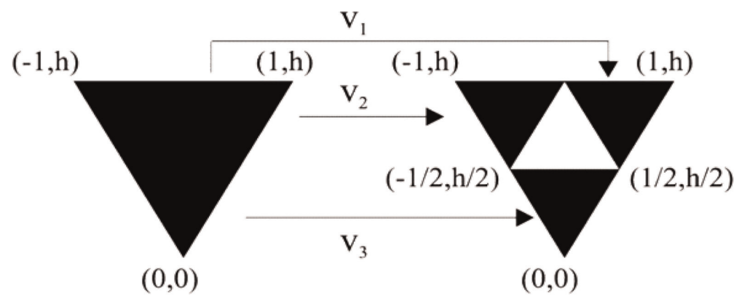

Figure 17.
Iteration process of Sierpiński fractal [114]: left is initiator and right is the 1st iteration.

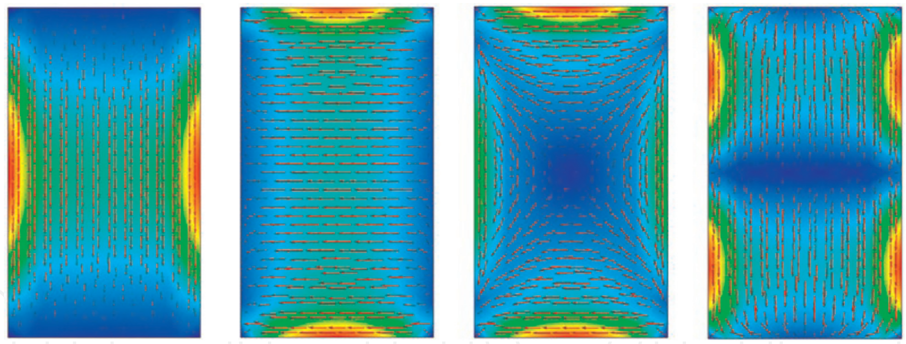

Figure 18.
First four modes at 2.2 GHz of [118].

excited to get the low SAR, and the isolation of 16 dB is achieved. On the contrary, the CMA is implemented on both the ground plane and the antenna in [117], but only on the chassis ground plane in [118]. The first four modes of [118] are shown in **Figure 18**. With the help of the current distributions, the antennas are put intensity-weak position of the corners for the MIMO antenna design.

Depending on the extensive application in MIMO antenna designs, we simply introduce the corresponding theory of the electric-field boundary conditions as follows [116, 117].

The related scattering field expression satisfy:

$$[L(\boldsymbol{J})]_{\tan} = \boldsymbol{E}^{i}_{\tan}(\boldsymbol{r}), \boldsymbol{r} \in S \tag{4}$$

where $L(\bullet)$ is the intetro-differential operator.

Owing to $L(\bullet)$ features with the impedance property, thus the formula (4) is rewritten as:

$$Z(\boldsymbol{J}) = [L(\boldsymbol{J})]_{\tan} \tag{5}$$

where $Z(\bullet)$ represent the tangential component of electric field related with $\boldsymbol{J}$.

The impedance matrix $\boldsymbol{Z}$ has the real and imaginary parts, we get the following related formulas:

$$\boldsymbol{Z} = \boldsymbol{R} + j\boldsymbol{X} \tag{6}$$

$$\boldsymbol{R} = (\boldsymbol{Z} + \boldsymbol{Z}^*)/2 \tag{7}$$

$$\boldsymbol{X} = (\boldsymbol{Z} - \boldsymbol{Z}^*)/2j \tag{8}$$

By means of Poynting's theorem, we get the straightforward relation for $\boldsymbol{R}$ and$\boldsymbol{X}$, which has clear physical meaning, as

$$\boldsymbol{X}\boldsymbol{J}_n = \lambda_n \boldsymbol{R}\boldsymbol{J}_n \tag{9}$$

where $\boldsymbol{J}_n$ and λ_n are the real eigenvector and eigenvalue of nth mode, respectively.

The orthogonality of modal currents is defined by:

$$<\boldsymbol{J}_m, \boldsymbol{R}\bullet\boldsymbol{J}_n> \; = \; <\boldsymbol{J}_m^*, \boldsymbol{R}\bullet\boldsymbol{J}_n> \; = \delta_{mn} \tag{10}$$

$$<\boldsymbol{J}_m, \boldsymbol{X}\bullet\boldsymbol{J}_n> \; = \; <\boldsymbol{J}_m^*, \boldsymbol{X}\bullet\boldsymbol{J}_n> \; = \lambda_n\delta_{mn} \tag{11}$$

$$<\boldsymbol{J}_m, \boldsymbol{Z}\bullet\boldsymbol{J}_n> = <\boldsymbol{J}_m^*, \boldsymbol{Z}\bullet\boldsymbol{J}_n> = (1 + j\lambda_n)\delta_{mn} \tag{12}$$

where $\delta_{mn} = 1, m = n$ or $\delta_{mn} = 0, m \neq n$.

Depending on the theory of characteristic mode, we get the induced currents on the PEC body and the resultant fields:

$$\boldsymbol{J} = \sum_n \alpha_n \boldsymbol{J}_n \tag{13}$$

By using the Z impedance operator, formula (13) becomes:

$$\sum_n \alpha_n Z(\boldsymbol{J}_n) = \boldsymbol{E}^i_{\tan}(\boldsymbol{r}) \tag{14}$$

Taking the inner product by the current $\boldsymbol{J}_m$ for (14), we have:

$$\sum_n \alpha_n < Z(\boldsymbol{J}_n), \boldsymbol{J}_m > = < \boldsymbol{E}^i_{\tan}(\boldsymbol{r}), \boldsymbol{J}_m > \tag{15}$$

Applying the orthogonality of currents, we will get under the condition of m = n:

$$\alpha_n(1 + j\lambda_n) = < \boldsymbol{E}^i_{\tan}(\boldsymbol{r}), \boldsymbol{J}_m > \tag{16}$$

so we know:

$$\alpha_n = \frac{< \boldsymbol{E}^i_{\tan}(\boldsymbol{r}), \boldsymbol{J}_m >}{1 + j\lambda_n} \tag{17}$$

where $< \boldsymbol{E}^i_{\tan}(\boldsymbol{r}), \boldsymbol{J}_m >$ **i**s called the modal excitation coefficient and the modal significance MS is defined as:

$$\text{MS} = \left|\frac{1}{1 + j\lambda_n}\right| \tag{18}$$

3.4 Optimization algorithms

The optimization algorithms are often used to reduce the antenna size, but for the MIMO antenna it becomes a multi-objective optimization problem due to we have to consider other parameters, like the effect of mutual coupling and the related position change etc. of antenna element. If we use the single optimization algorithm to optimize the MIMO antenna, it will take more time, so the hybrid algorithms are employed to process the complicated discrete and continuous mixed parameters [119–121].

In [119], both the antenna shape and the decoupling structure were considered, thus the hybrid algorithm of both the multiobjective evolutionary algorithm based on decomposition combined with differential evolution (MOEA/D-DE) and MOEA/D combined with genetic operator (MOEA/D-GO) were used, where the MOEA/D-DE is adopted to optimize the radiator while the MOEA/D-GO optimizes the isolated area shown in **Figure 19**. They divided the circle into 8 areas of the same size, each has the 45 degrees angle and divided into several small pieces. In the optimization process, "1" represents the existence of metal while "0" not. Literature [120] Integrates the particle

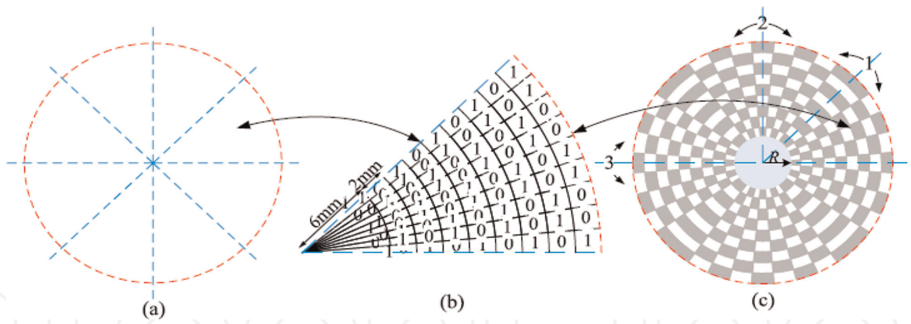

Figure 19.
Fragment-type isolation of [119]: (a) split method, (b) discretization and assignment of "0" or "1", and (c) frqgment-type structure.

swarm optimization (PSO) and binary PSO into multi-objective evolutionary algorithm based on decomposition (MOEA/D) to realize the optimization of antenna size and isolation, while the surrogate-based optimization was employed in [121].

Though different algorithms have been proposed to improve the optimization result, the corresponding optimization process is similar as in [119].

The optimized problem can be expressed as:

$$min\ F(X) = \left(f_1(X), f_2(X), \dots, f_n(X)\right)\ s.t. X \in \Omega \tag{19}$$

where $f_i(X)(i = 1, 2, \dots, n)$ indicates the corresponding optimized objective, X is a decision variable, and Ω is the design space.

The authors of [119] presented three optimized objectives due to the four-port MIMO antenna so that they have to consider the mutual coupling of different ports. We can simplify the optimized objectives by two ports, they are:

$$f_1(X) = max\ \left(Q_1 - min\left|(S_{11})_{dB}\right|, 0\right)\omega \in [\omega_1, \omega_2] \tag{20}$$

$$f_2(X) = max\ \left(Q_2 - min\left|(S_{12})_{dB}\right|, 0\right)\ \omega \in [\omega_1, \omega_2] \tag{21}$$

where $[\omega_1, \omega_2]$ indicates the frequency band, Q_1 is the desired minimum of return loss, which is set to be 10 dB, and Q_2 desired minimum isolation.

With these optimized objectives and the constraints, the iteration process can be implemented by the hybrid utilization of EM simulator and the proposed algorithm.

4. Conclusions

Depending on the development trend of 5G+/6G, we focused on the summaries of the planar MIMO antennas and the related compact techniques in this chapter owing to they are easily fabricated and integrated into a system. These planar antennas contain several common antenna types, including the patch, dipole/monopole, slot etc. Even so, they still can be designed into the 3D structure and there are specific applications like in the mobile terminal. The compact techniques implicit in the designs are dug up and summarized into seven categories, including the no-decoupling and the decoupling designs, multiple antenna structure, meander line technique, co-radiator design, and the fractal and radiator-cutting antennas. Then, in Section 3, we discussed the related fundamentals for the compact designs though the antenna types are conventional, and showed the corresponding simple design methods, they are mode analyses, fractal techniques, characteristic analysis, and the optimization algorithms.

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References

[1] Roslan SF, Kamarudin MR, Khalily M, Jamaluddin MH. An MIMO rectangular dielectric resonator antenna for 4G applications. IEEE Antennas and Wireless Propagation Letters. 2014;**13**: 321-324. DOI: 10.1016/s0014-5793(01) 03293-8

[2] Farahani M, Pourahmadazar J, Akbari M, Nedil M, Sebak AR, Denidni TA. Mutual coupling reduction in millimeter-wave MIMO antenna array using a metamaterial polarization-rotator wall. IEEE Antennas and Wireless Propagation Letters. 2017;**16**: 2324-2327. DOI: 10.1109/LAWP.2017.2717404

[3] Li M, Cheung S. Isolation enhancement for MIMO dielectric resonator antennas using dielectric superstrate. IEEE Transactions on Antennas and Propagation. 2021;**69**(7): 4154-4159. DOI: 10.1109/TAP.2020.3044683

[4] Chew M, Mavrakis S. Quadrifilar helix antenna for MIMO system. IEEE Antennas and Wireless Propagation Letters. 2004;**3**:197-199. DOI: 10.1109/LAWP.2004.832642

[5] Hassan T, Khan MU, Attia H, Sharawi MS. An FSS based correlation reduction technique for MIMO antennas. IEEE Transactions on Antennas and Propagation. 2018;**66**(9): 4900-4905. DOI: 10.1109/TAP.2018.2842256

[6] Boukarkar A, Lin XQ, Jiang Y, Nie LY, Mei P, Yu YQ. A miniaturized extremely close-spaced four-element dual-band MIMO antenna system with polarization and pattern diversity. IEEE Antennas and Wireless Propagation Letters. 2018;**17**(1):134-137. DOI: 10.1109/LAWP.2017.2777839

[7] Zhai G, Chen ZN, Qing X. Enhanced isolation of a closely spaced four-element MIMO antenna system using metamaterial mushroom. IEEE Transactions on Antennas and Propagation. 2015;**63**(8):3362-3370. DOI: 10.1109/TAP.2015.2434403

[8] Chiu C-Y, Yan J-B, Murch RD. Compact three-port orthogonally polarized MIMO Antennas. IEEE Antennas and Wireless Propagation Letters. 2007;**6**:619-622. DOI: 10.1109/LAWP.2007.913272

[9] Pan Y, Cui Y, Li R. Investigation of a triple-band multibeam MIMO antenna for wireless access points. IEEE Transactions on Antennas and Propagation. 2016;**64**(4):1234-1241. DOI: 10.1109/TAP.2016.2526082

[10] Qin P-Y, Guo YJ, Weily AR, Liang C-H. A pattern reconfigurable U-slot antenna and its applications in MIMO systems. IEEE Transactions on Antennas and Propagation. 2012;**60**(2): 516-528. DOI: 10.1109/TAP.2011.2173439

[11] Sharma Y, Sarkar D, Saurav K, Srivastava KV. Three-element MIMO antenna system with pattern and polarization diversity for WLAN applications. IEEE Antennas and Wireless Propagation Letters. 2017;**16**:1163-1166. DOI: 10.1109/LAWP.2016.2626394

[12] Narbudowicz A, Ammann MJ. Low-cost multimode patch antenna for dual MIMO and enhanced localization use. IEEE Transactions on Antennas and Propagation. 2018;**66**(1):405-408. DOI: 10.1109/TAP.2017.2767643

[13] Qian J-F, Chen F-C, Ding Y-H, Hu H-T, Chu Q-X. A wide stopband filtering patch antenna and its application in

MIMO system. IEEE Transactions on Antennas and Propagation. 2019;**67**(1): 654-658. DOI: 10.1109/TAP.2018.2874764

[14] Cheng B, Du Z. Dual polarization MIMO antenna for 5G mobile phone applications. IEEE Transactions on Antennas and Propagation. 2021;**69**(7): 4160-4165. DOI: 10.1109/TAP.2020.3044649

[15] OuYang J, Yang F, Wang ZM. Reducing mutual coupling of closely spaced microstrip MIMO antennas for WLAN application. IEEE Antennas and Wireless Propagation Letters. 2011;**10**: 310-313. DOI: 10.1109/LAWP.2011.2140310

[16] Ghannad AA, Khalily M, Xiao P, Tafazolli R, Kishk AA. Enhanced matching and Vialess decoupling of nearby patch antennas for MIMO system. IEEE Antennas and Wireless Propagation Letters. 2019;**18**(6): 1066-1070. DOI: 10.1109/LAWP.2019.2906308

[17] Garg P, Jain P. Isolation improvement of MIMO antenna using a novel flower shaped metamaterial absorber at 5.5 GHz WiMAX band. IEEE Transactions on Circuits and Systems II: Express Briefs. 2020;**67**(4):675-679. DOI: 10.1109/TCSII.2019.2925148

[18] Tran HH, Nguyen-Trong N. Performance enhancement of MIMO patch antenna using parasitic elements. IEEE Access. 2021;**9**: 30011-30016. DOI: 10.1109/ACCESS.2021.3058340

[19] Row J-S, Yeh S-H, Wong K-L. Compact dual-polarized microstrip antennas. Microwave and Optical Technology Letters. 2000;**27**(4):284-287. DOI: 10.1002/1098-2760(20001120)27:4<284::AID-MOP21>3.0.CO;2-L

[20] Wong K-L, Chen J-Z, Li W-Y. Four-port wideband annular-ring patch antenna generating four decoupled waves for 5G multi-input–multi-output access points. IEEE Transactions on Antennas and Propagation. 2021;**69**(5): 2946-2951. DOI: 10.1109/TAP.2020.3025237

[21] Wong K-L, Jian M-F, Li W-Y. Low-profile wideband four-corner-fed square patch antenna for 5G MIMO mobile antenna application. IEEE Antennas and Wireless Propagation Letters. 2021; **20**(12):2554-2558. DOI: 10.1109/LAWP.2021.3119753

[22] Qian J-F, Chen F-C, Chu Q-X, Xue Q, Lancaster MJ. A novel electric and magnetic gap-coupled broadband patch antenna with improved selectivity and its application in MIMO system. IEEE Transactions on Antennas and Propagation. 2018;**66**(10):5625-5629. DOI: 10.1109/TAP.2018.2860129

[23] Karimian R, Oraizi H, Fakhte S, Farahani M. Novel F-shaped quad-band printed slot antenna for WLAN and WiMAX MIMO systems. IEEE Antennas and Wireless Propagation Letters. 2013; **12**:405-408. DOI: 10.1109/LAWP.2013.2252140

[24] Soltani S, Lotfi P, Murch RD. A dual-band multiport MIMO slot antenna for WLAN applications. IEEE Antennas and Wireless Propagation Letters. 2017;**16**: 529-532. DOI: 10.1109/LAWP.2016.2587732

[25] Nandi S, Mohan A. A compact dual-band MIMO slot antenna for WLAN applications. IEEE Antennas and Wireless Propagation Letters. 2017;**16**: 2457-2460. DOI: 10.1109/LAWP.2017.2723927

[26] Hu H-T, Chen F-C, Chu Q-X. A compact directional slot antenna and its

application in MIMO array. IEEE Transactions on Antennas and Propagation. 2016;**64**(12):5513-5517. DOI: 10.1109/TAP.2016.2621021

[27] Sun L, Li Y, Zhang Z. Wideband integrated quad-element MIMO antennas based on complementary antenna pairs for 5G smartphones. IEEE Transactions on Antennas and Propagation. 2021;**69**(8):4466-4474. DOI: 10.1109/TAP.2021.3060020

[28] Ren J, Hu W, Yin Y, Fan R. Compact printed MIMO antenna for UWB applications. IEEE Antennas and Wireless Propagation Letters. 2014;**13**: 1517-1520. DOI: 10.1109/LAWP.2014.2343454

[29] Srivastava G, Mohan A. Compact MIMO slot antenna for UWB applications. IEEE Antennas and Wireless Propagation Letters. 2016;**15**: 1057-1060. DOI: 10.1109/LAWP.2015.2491968

[30] Hu W, Chen Z, Qian L, Wen L, Luo Q, Xu R, et al. Wideband back-cover antenna design using dual characteristic modes with high isolation for 5G MIMO smartphone. IEEE Transactions on Antennas and Propagation. 2022;**70**(7):5254-5265. DOI: 10.1109/TAP.2022.3145456

[31] Anitha R, Vinesh PV, Prakash KC, Mohanan P, Vasudevan K. A compact quad element slotted ground wideband antenna for MIMO applications. IEEE Transactions on Antennas and Propagation. 2016;**64**(10):4550-4553. DOI: 10.1109/TAP.2016.2593932

[32] Oliveira JGD, D’Assunção Junior AG, Silva Neto VP, D’Assunção AG. New compact MIMO antenna for 5G, WiMAX and WLAN technologies with dual polarisation and element diversity. IET Microwaves, Antennas & Propagation. 2021;**15**(4):415-426. DOI: 10.1049/mia2.12057

[33] Sarkar D, Srivastava KV. A compact four-element MIMO/diversity antenna with enhanced bandwidth. IEEE Antennas and Wireless Propagation Letters. 2017;**16**:2469-2472. DOI: 10.1109/LAWP.2017.2724439

[34] Wang H, Liu L, Zhang Z, Li Y, Feng Z. A wideband compact WLAN/WiMAX MIMO antenna based on dipole with V-shaped ground branch. IEEE Transactions on Antennas and Propagation. 2015;**63**(5):2290-2295. DOI: 10.1109/TAP.2015.2405091

[35] Darvish M, Hassani HR. Quad band CPW-Fed monopole antenna for MIMO applications. In: Dans: 2012 6th European Conference on Antennas and Propagation (EUCAP). IEEE: Prague, Czech Republic; 2012. pp. 1-4

[36] Chouhan S, Panda DK, Gupta M, Singhal S. Meander line MIMO antenna for 5.8 GHz WLAN application. International Journal of RF and Microwave Computer-Aided Engineering. 2018;**28**(4):e21222. DOI: 10.1002/mmce.21222

[37] Im Y-T, Lee J-H, Bhatti RA, Park S-O. A spiral-dipole antenna for MIMO systems. IEEE Antennas and Wireless Propagation Letters. 2008;**7**:803-806. DOI: 10.1109/LAWP.2008.2001395

[38] Shoaib S, Shoaib I, Shoaib N, Chen X, Parini CG. MIMO antennas for mobile handsets. IEEE Antennas and Wireless Propagation Letters. 2015;**14**: 799-802. DOI: 10.1109/LAWP.2014.2385593

[39] Sharawi MS, Iqbal SS, Faouri YS. An 800 MHz 2×1 compact MIMO antenna system for LTE handsets. IEEE Transactions on Antennas and

Propagation. 2011;**59**(8):3128-3131. DOI: 10.1109/TAP.2011.2158958

[40] Mahmood F, Kazim J-R, Karlsson M, Gong S, Ying Z. Decoupling techniques of compact and broadband MIMO antennas for handheld devices. In: Dans: 2012 6th European Conference on Antennas and Propagation (EUCAP). IEEE: Prague, Czech Republic; 2012. pp. 1-5

[41] Khan MS, Shafique MF, Naqvi A, Capobianco A-D, Ijaz B, Braaten BD. A miniaturized dual-band MIMO antenna for WLAN applications. IEEE Antennas and Wireless Propagation Letters. 2015; **14**:958-961. DOI: 10.1109/LAWP.2014.2387701

[42] Thummaluru SR, Kumar R, Chaudhary RK. Isolation and frequency reconfigurable compact MIMO antenna for wireless local area network applications. IET Microwaves, Antennas & Propagation. 2019;**13**(4):519-525. DOI: 10.1049/iet-map.2018.5895

[43] Cui L, Guo J, Liu Y, Sim C-Y-D. An 8-element dual-band MIMO antenna with decoupling stub for 5G smartphone applications. IEEE Antennas and Wireless Propagation Letters. 2019; **18**(10):2095-2099. DOI: 10.1109/LAWP.2019.2937851

[44] Ren Z, Zhao A, Wu S. MIMO antenna with compact decoupled antenna pairs for 5G mobile terminals. IEEE Antennas and Wireless Propagation Letters. 2019;**18**(7): 1367-1371. DOI: 10.1109/LAWP.2019.2916738

[45] Serghiou D, Khalily M, Singh V, Araghi A, Tafazolli R. Sub-6 GHz Dual-Band 8 × 8 MIMO Antenna for 5G Smartphones. IEEE Antennas and Wireless Propagation Letters. 2020; **19**(9):1546-1550. DOI: 10.1109/LAWP.2020.3008962

[46] Xu Z, Deng C. High-isolated MIMO antenna design based on pattern diversity for 5G mobile terminals. IEEE Antennas and Wireless Propagation Letters. 2020;**19**(3):467-471. DOI: 10.1109/LAWP.2020.2966734

[47] Zhang HH, Yu GG, Liu XZ, Cheng GS, Xu YX, Liu Y, et al. Low-SAR MIMO antenna array design using characteristic modes for 5G mobile phones. IEEE Transactions on Antennas and Propagation. 2022;**70**(4):3052-3057. DOI: 10.1109/TAP.2021.3121174

[48] Ye Y, Zhao X, Wang J. Compact high-isolated MIMO antenna module with chip capacitive decoupler for 5G mobile terminals. IEEE Antennas and Wireless Propagation Letters. 2022;**21**(5): 928-932. DOI: 10.1109/LAWP.2022.3152236

[49] Zhou X, Quan XL, Li RL. A dual-broadband MIMO antenna system for GSM/UMTS/LTE and WLAN handsets. IEEE Antennas and Wireless Propagation Letters. 2012;**11**:551-554. DOI: 10.1109/LAWP.2012.2199459

[50] Wang Y-Y, Ban Y-L, Nie Z, Sim C-Y-D. Dual-loop antenna for 4G LTE MIMO smart glasses applications. IEEE Antennas and Wireless Propagation Letters. 2019;**18**(9):1818-1822. DOI: 10.1109/LAWP.2019.2930726

[51] Rhee C, Kim Y, Park T, Kwoun S-s, Mun B, Lee B, et al. Pattern-reconfigurable MIMO antenna for high isolation and low correlation. IEEE Antennas and Wireless Propagation Letters. 2014;**13**:1373-1376. DOI: 10.1109/LAWP.2014.2339012

[52] Nandi S, Mohan A. CRLH unit cell loaded triband compact MIMO antenna for WLAN/WiMAX applications. IEEE Antennas and Wireless Propagation

Letters. 2017;**16**:1816-1819. DOI: 10.1109/LAWP.2017.2681178

[53] Zhao A, Ren Z. Size reduction of self-isolated MIMO antenna system for 5G mobile phone applications. IEEE Antennas and Wireless Propagation Letters. 2019;**18**(1):152-156. DOI: 10.1109/LAWP.2018.2883428

[54] Kulkarni AN, Sharma SK. Frequency reconfigurable microstrip loop antenna covering LTE bands with MIMO implementation and wideband microstrip slot antenna all for portable wireless DTV media player. IEEE Transactions on Antennas and Propagation. 2013;**61**(2):964-968. DOI: 10.1109/TAP.2012.2223433

[55] Ahn C-H, Oh S-W, Chang K. A dual-frequency omnidirectional antenna for polarization diversity of MIMO and wireless communication applications. IEEE Antennas and Wireless Propagation Letters. 2009;**8**:966-969. DOI: 10.1109/LAWP.2009.2030135

[56] Hu PF, Leung KW, Pan YM, Zheng SY. Electrically small, planar, horizontally polarized dual-band omnidirectional antenna and its application in a MIMO system. IEEE Transactions on Antennas and Propagation. 2021;**69**(9):5345-5355. DOI: 10.1109/TAP.2021.3061096

[57] Fernandez SC, Sharma SK. Multiband printed meandered loop antennas with MIMO implementations for wireless routers. IEEE Antennas and Wireless Propagation Letters. 2013;**12**: 96-99. DOI: 10.1109/ LAWP.2013.2243104

[58] Zhao X, Yeo SP, Ong LC. Planar UWB MIMO antenna with pattern diversity and isolation improvement for mobile platform based on the theory of characteristic modes. IEEE Transactions on Antennas and Propagation. 2018; **66**(1):420-425. DOI: 10.1109/ TAP.2017.2768083

[59] Liu L, Cheung SW, Yuk TI. Compact MIMO antenna for portable devices in UWB applications. IEEE Transactions on Antennas and Propagation. 2013;**61**(8): 4257-4264. DOI: 10.1109/ TAP.2013.2263277

[60] Zhang S, Pedersen GF. Mutual coupling reduction for UWB MIMO antennas with a wideband neutralization line. IEEE Antennas and Wireless Propagation Letters. 2016;**15**:166-169. DOI: 10.1109/LAWP.2015.2435992

[61] Wang Y, Zhu F, Gao S. Design of planar ultra-wideband antenna with polarization diversity and high isolation. In: Dans: 2016 IEEE International Conference on Ubiquitous Wireless Broadband (ICUWB). Nanjing, China: IEEE; 2016. pp. 1-3

[62] Zhang S, Ying Z, Xiong J, He S. Ultrawideband MIMO/diversity antennas with a tree-like structure to enhance wideband isolation. IEEE Antennas and Wireless Propagation Letters. 2009;**8**:1279-1282. DOI: 10.1109/ LAWP.2009.2037027

[63] Saleem R, Bilal M, Bajwa KB, Shafique MF. Eight-element UWB-MIMO array with three distinct isolation mechanisms. Electronics Letters. 2015; **51**(4):311-313. DOI: 10.1049/el.2014.4199

[64] Gautam AK, Yadav S, Rambabu K. Design of ultra-compact UWB antenna with band-notched characteristics for MIMO applications. IET Microwaves, Antennas & Propagation. 2018;**12**(12): 1895-1900. DOI: 10.1049/iet-map.2018.0012

[65] Li J-F, Chu Q-X, Li Z-H, Xia X-X. Compact dual band-notched UWB

MIMO antenna with high isolation. IEEE Transactions on Antennas and Propagation. 2013;**61**(9):4759-4766. DOI: 10.1109/TAP.2013.2267653

[66] Lee J-M, Kim K-B, Ryu H-K, Woo J-M. A Compact ultrawideband MIMO antenna with WLAN band-rejected operation for mobile devices. IEEE Antennas and Wireless Propagation Letters. 2012;**11**:990-993. DOI: 10.1109/LAWP.2012.2214431

[67] Deng J-Y, Guo L-X, Liu X-L. An ultrawideband MIMO antenna with a high isolation. IEEE Antennas and Wireless Propagation Letters. 2016;**15**:182-185. DOI: 10.1109/LAWP.2015.2437713

[68] Saxena S, Kanaujia BK, Dwari S, Kumar S, Tiwari R. A compact dual-polarized MIMO antenna with distinct diversity performance for UWB applications. IEEE Antennas and Wireless Propagation Letters. 2017;**16**:3096-3099. DOI: 10.1109/LAWP.2017.2762426

[69] Luo C-M, Hong J-S, Zhong L-L. Isolation enhancement of a very compact UWB-MIMO slot antenna with two defected ground structures. IEEE Antennas and Wireless Propagation Letters. 2015;**14**:1766-1769. DOI: 10.1109/LAWP.2015.2423318

[70] Liu Y-Y, Tu Z-H. Compact differential band-notched stepped-slot UWB-MIMO antenna with common-mode suppression. IEEE Antennas and Wireless Propagation Letters. 2017;**16**:593-596. DOI: 10.1109/LAWP.2016.2592179

[71] Roshna TK, Deepak U, Sajitha VR, Vasudevan K, Mohanan P. A compact UWB MIMO antenna with reflector to enhance isolation. IEEE Transactions on Antennas and Propagation. 2015;**63**(4):1873-1877. DOI: 10.1109/TAP.2015.2398455

[72] Capobianco A-D, Pigozzo FM, Assalini A, Midrio M, Boscolo S, Sacchetto F. A compact MIMO array of planar end-fire antennas for WLAN applications. IEEE Transactions on Antennas and Propagation. 2011;**59**(9):3462-3465. DOI: 10.1109/TAP.2011.2161557

[73] Hsu Y-W, Huang T-C, Lin H-S, Lin Y-C. Dual-polarized quasi Yagi–Uda antennas with endfire radiation for millimeter-wave MIMO terminals. IEEE Transactions on Antennas and Propagation. 2017;**65**(12):6282-6289. DOI: 10.1109/TAP.2017.2734238

[74] Jehangir SS, Sharawi MS. A miniaturized multi-wideband Quasi-Yagi MIMO antenna system. International Journal of RF and Microwave Computer-Aided Engineering. 2018;**28**(5):e21237. DOI: 10.1002/mmce.21237

[75] Jehangir SS, Sharawi MS. A wideband sectoral Quasi-Yagi MIMO antenna system with multibeam elements. IEEE Transactions on Antennas and Propagation. 2019;**67**(3):1898-1903. DOI: 10.1109/TAP.2018.2889034

[76] Jehangir SS, Sharawi MS. A miniaturized UWB biplanar Yagi-like MIMO antenna system. IEEE Antennas and Wireless Propagation Letters. 2017;**16**:2320-2323. DOI: 10.1109/LAWP.2017.2716963

[77] Jehangir SS, Sharawi MS. A compact single-layer four-port orthogonally polarized Yagi-Like MIMO antenna system. IEEE Transactions on Antennas and Propagation. 2020;**68**(8):6372-6377. DOI: 10.1109/TAP.2020.2969810

[78] Sung Y. Closely spaced MIMO antenna based on substrate-integrated waveguide technology. Microwave and Optical Technology Letters. 2018;**60**(7): 1794-1798. DOI: 10.1002/mop.31249

[79] Niu B, Tan J. Compact four-element MIMO antenna using T-shaped and anti-symmetric U-shaped slotted SIW cavities. Electronics Letters. 2019;**55**(19): 1031-1032. DOI: 10.1049/el.2019.2142

[80] Chang L, Zhang G, Wang H. Triple-band microstrip patch antenna and its four-antenna module based on half-mode patch for 5G 4 × 4 MIMO operation. IEEE Transactions on Antennas and Propagation. 2022;**70**(1): 67-74. DOI: 10.1109/TAP.2021.3090572

[81] Niu B, Tan J. Compact self-isolated MIMO antenna system based on quarter-mode SIW cavity. Electronics Letters. 2019;**55**(10):574-576. DOI: 10.1049/el.2019.0606

[82] Nandi S, Mohan A. A compact eighth-mode circular SIW cavity-based MIMO antenna. IEEE Antennas and Wireless Propagation Letters. 2021; **20**(9):1834-1838. DOI: 10.1109/LAWP.2021.3098711

[83] Tripathi S, Mohan A, Yadav S. A compact octagonal fractal UWBMIMO antenna with WLAN band-rejection. Microwave and Optical Technology Letters. 2015;**57**(8):1919-1925. DOI: 10.1002/mop.29220

[84] Singhal S. Four element ultra-wideband fractal multiple-input multiple-output antenna. Microwave and Optical Technology Letters. 2019;**61**(12): 2811-2818. DOI: 10.1002/mop.31980

[85] Sampath R, Selvan KT. Compact hybrid Sierpinski Koch fractal UWB MIMO antenna with pattern diversity. International Journal of RF and Microwave Computer-Aided Engineering. 2019;**e22017**:1-13. DOI: 10.1002/mmce.22017

[86] Rajkumar S, Anto Amala A, Selvan KT. Isolation improvement of UWB MIMO antenna utilising molecule fractal structure. Electronics Letters. 2019;**55**(10):576-579. DOI: 10.1049/el.2019.0592

[87] Choukiker YK, Sharma SK, Behera SK. Hybrid fractal shape planar monopole antenna covering multiband wireless communications with MIMO implementation for handheld mobile devices. IEEE Transactions on Antennas and Propagation. 2014;**62**(3):1483-1488. DOI: 10.1109/TAP.2013.2295213

[88] Rajkumar S, Srinivasan N, Natesan A, Selvan KT. A penta-band hybrid fractal MIMO antenna for ISM applications. International Journal of RF and Microwave Computer-Aided Engineering. 2018;**28**(2):e21185. DOI: 10.1002/mmce.21185

[89] Rajkumar S, Vivek Sivaraman N, Murali S, Selvan KT. Heptaband swastik arm antenna for MIMO applications. IET Microwaves, Antennas & Propagation. 2017;**11**(9):1255-1261. DOI: 10.1049/iet-map.2016.1098

[90] Peristerianos A, Theopoulos A, AnastasiosG K, Kaifas T, Siakavara K. Dual-band fractal semi-printed element antenna arrays for MIMO applications. IEEE Antennas and Wireless Propagation Letters. 2016;**15**:730-733. DOI: 10.1109/LAWP.2015.2470681

[91] Chattha HT, Nasir M, Abbasi QH, Huang Y, AlJa'afreh SS. Compact low-profile dual-port single wideband planar inverted-F MIMO antenna. IEEE Antennas and Wireless Propagation Letters. 2013;**12**:1673-1675. DOI: 10.1109/LAWP.2013.2293765

[92] See CH, Hraga HI, Noras JM, Abd-Alhameed RA, McEwan NJ. Compact multiple input and multiple output/diversity antenna for portable and mobile ultra-wideband applications. IET Microwaves, Antennas & Propagation. 2013;**7**(6):444-451. DOI: 10.1049/iet-map.2012.0574

[93] Lim J-H, Jin Z-J, Song C-W, Yun T-Y. Simultaneous frequency and isolation reconfigurable MIMO PIFA using PIN diodes. IEEE Transactions on Antennas and Propagation. 2012;**60**(12):5939-5946. DOI: 10.1109/TAP.2012.2211552

[94] Lee B, Harackiewicz FJ, Wi H. Closely mounted mobile handset MIMO antenna for LTE 13 band application. IEEE Antennas and Wireless Propagation Letters. 2014;**13**:411-414. DOI: 10.1109/LAWP.2014.2307310

[95] Bhatti RA, Choi J-H, Park S-O. Quad-band MIMO antenna array for portable wireless communications terminals. IEEE Antennas and Wireless Propagation Letters. 2009;**8**:129-132. DOI: 10.1109/LAWP.2008.2012274

[96] Radhi AH, Nilavalan R, Wang Y, Al-Raweshidy H, Eltokhy AA, Aziz NA. Mutual coupling reduction with a novel fractal electromagnetic bandgap structure. IET Microwaves, Antennas & Propagation. 2019;**13**(2):134-141. DOI: 10.1049/iet-map.2018.5273

[97] Chiu C-Y, Murch RD. Compact four-port antenna suitable for portable MIMO devices. IEEE Antennas and Wireless Propagation Letters. 2008;**7**:142-144. DOI: 10.1109/LAWP.2008.919341

[98] Yao Y, Wang X, Chen X, Yu J, Liu S. Novel diversity/MIMO PIFA antenna with broadband circular polarization for multimode satellite navigation. IEEE Antennas and Wireless Propagation Letters. 2012;**11**:65-68. DOI: 10.1109/LAWP.2012.2183335

[99] Mun B, Jung C, Park M-J, Lee B. A Compact frequency-reconfigurable multiband LTE MIMO antenna for laptop applications. IEEE Antennas and Wireless Propagation Letters. 2014;**13**:1389-1392. DOI: 10.1109/LAWP.2014.2339802

[100] Abbosh AI, Al-Rizzo H, Abushamleh S, Bihnam A, Khaleel HR. Flexible CPW-IFA antenna array with reduced mutual coupling. In: Dans: 2014 IEEE Antennas and Propagation Society International Symposium (APSURSI). Memphis, TN, USA: IEEE; 2014. pp. 1716-1717

[101] Chang L, Wang H. Miniaturized wideband four-antenna module based on dual-mode PIFA for 5G 4 × 4 MIMO applications. IEEE Transactions on Antennas and Propagation. 2021;**69**(9):5297-5304. DOI: 10.1109/TAP.2021.3069490

[102] Yuan X-T, Chen Z, Gu T, Yuan T. A wideband PIFA-pair-based MIMO antenna for 5G smartphones. IEEE Antennas and Wireless Propagation Letters. 2021;**20**(3):371-375. DOI: 10.1109/LAWP.2021.3050337

[103] Liu DQ, Zhang M, Luo HJ, Wen HL, Wang J. Dual-band platform-free PIFA for 5G MIMO application of mobile devices. IEEE Transactions on Antennas and Propagation. 2018;**66**(11):6328-6333. DOI: 10.1109/TAP.2018.2863109

[104] Barani IRR, Wong K-L. Integrated inverted-F and open-slot antennas in the metal-framed smartphone for 2×2 LTE LB and 4×4 LTE M/HB MIMO operations. IEEE Transactions on Antennas and Propagation. 2018;**66**(10):

5004-5012. DOI: 10.1109/TAP.2018.2854191

[105] MoradiKordalivand A, Rahman TA, Khalily M. Common elements wideband MIMO antenna system for WiFi/LTE access-point applications. IEEE Antennas and Wireless Propagation Letters. 2014;**13**:1601-1604. DOI: 10.1109/LAWP.2014.2347897

[106] Mao C-X, Chu Q-X. Compact coradiator UWB-MIMO antenna with dual polarization. IEEE Transactions on Antennas and Propagation. 2014;**62**(9): 4474-4480. DOI: 10.1109/TAP.2014.2333066

[107] Piao D, Wang Y. Tripolarized MIMO antenna using a compact single-layer microstrip patch. IEEE Transactions on Antennas and Propagation. 2019;**67**(3):1937-1940. DOI: 10.1109/TAP.2018.2889147

[108] Huang H, Jiang W, Zhang T, Zhu Y, Pang B, Hu W. Shared radiator based high-isolated tri-port mobile terminal antenna group design. International Journal of RF and Microwave Computer-Aided Engineering. 2022; **32**(7):e23177. DOI: 10.1002/mmce.23177

[109] Liu X-L, Wang Z-D, Yin Y-Z, Ren J, Wu J-J. A compact ultrawideband MIMO antenna using QSCA for high isolation. IEEE Antennas and Wireless Propagation Letters. 2014;**13**: 1497-1500. DOI: 10.1109/LAWP.2014.2340395

[110] Potti D, Tusharika Y, Alsath MGN, Kirubaveni S, Kanagasabai M, Sankararajan R, et al. A novel optically transparent UWB antenna for automotive MIMO communications. IEEE Transactions on Antennas and Propagation. 2021;**69**(7):3821-3828. DOI: 10.1109/TAP.2020.3044383

[111] Kumar K, Dwari S. Compact four-element MIMO SIW cavity backed slot antenna with high front-to-back ratio. International Journal of RF and Microwave Computer-Aided Engineering. 2019;**29**(1):e21512. DOI: 10.1002/mmce.21512

[112] Jehangir SS, Sharawi MS. A single layer semi-ring slot Yagi-like MIMO antenna system with high front-to-back ratio. IEEE Transactions on Antennas and Propagation. 2017;**65**(2):937-942. DOI: 10.1109/TAP.2016.2633938

[113] Molins-Benlliure J, Cabedo-Fabres M, Antonino-Daviu E, Ferrando-Bataller M. sector unit-cell methodology for the design of Sub-6 GHz 5G MIMO antennas. IEEE Access. 2022;**10**: 100824-100836. DOI: 10.1109/ACCESS.2022.3207163

[114] Anguera A, Jayasinghe C, Chowdary P, et al. Fractal antennas: an historical perspective. Fractal and Fractional. 2020;**4**(1):3. DOI: 10.3390/fractalfract4010003

[115] Dwivedy B, Das TK. Introduction to fractal antennas and their role in MIMO applications. In: Kumar Y, Tripathi S, Raj B, editors. Multifunctional MIMO Antennas: Fundamentals and Application. 1re éd ed. Boca Raton: CRC Press; 2022. pp. 1-25. DOI: 10.1201/9781003290230

[116] Chen Y, Wang CF. Characteristic mode theory for PEC bodies. In: Characteristic Modes: Theory and Applications in Antenna Engineering. 1st ed. Hoboken, NJ: Wiley; 2015. pp. 37-97. DOI: 10.1002/9781119038900.ch2

[117] Kumar Kishor K, Hum SV. A pattern reconfigurable chassis-mode MIMO antenna. IEEE Transactions on Antennas and Propagation. 2014;**62**(6):

3290-3298. DOI: 10.1109/TAP.2014.2313634

[118] Deng C, Lv X. Wideband MIMO antenna with small ground clearance for mobile terminals. IET Microwaves, Antennas & Propagation. 2019;**13**(9): 1419-1426. DOI: 10.1049/iet-map.2018.5972

[119] Lu D, Wang L, Yang E, Wang G. Design of high-isolation wideband dual-polarized compact MIMO antennas with multiobjective optimization. IEEE Transactions on Antennas and Propagation. 2018;**66**(3):1522-1527. DOI: 10.1109/TAP.2017.2784446

[120] Li Q-Q, Chu Q-X, Chang Y-L. Design of compact high-isolation MIMO antenna with multiobjective mixed optimization algorithm. IEEE Antennas and Wireless Propagation Letters. 2020; **19**(8):1306-1310. DOI: 10.1109/LAWP.2020.2997874

[121] Koziel S, Bekasiewicz A, Cheng QS. Conceptual design and automated optimisation of a novel compact UWB MIMO slot antenna. IET Microwaves, Antennas & Propagation. 2017;**11**(8): 1162-1168. DOI: 10.1049/iet-map.2016.0703