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Review:

Decoupling methods of MIMO antenna arrays for 5G applications: a review*

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Abstract: Multiple-input multiple-output (MIMO) technique is a key technique for communication in the future. It can effectively enhance channel capacity. For future fifth-generation (5G) terminals, it is still a challenging task to realize desirable isolation within a compact size. To achieve an acceptable isolation level, many decoupling methods have been developed. We review the most recent research on decoupling methods, including the employment of external decoupling structures, orthogonal modes, and reduction of ground effect, and discuss the development trends of the MIMO array in 5G smartphones.

Key words: MIMO array; 5G smartphone; Decoupling methods
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1 Introduction

The increasing demands of wireless traffic have accelerated the development of mobile communication. Development trends of mobile communication systems are mobility, broadband, and intelligence. Compared with the fourth-generation (4G) mobile communication systems, the fifth-generation (5G) communication systems need to support more diverse scenarios and face extreme performance challenges (Hong, 2017). The main features of 5G mobile communication are ultra-high speed, low latency, and excellent reliability.

To meet the demands of diverse scenarios, different frequency bands need to be included in the 5G technology and specific properties of different frequency bands will be used. In the low-frequency bands, the spectrum of available resources is becoming small. However, rich spectrum resources are available in the millimeter-wave (mm-Wave) frequency bands. mm-Wave frequency bands can be used for high data transmission rates. Currently, the spectrum of 5G can be classified into sub-6 GHz and mm-Wave frequency bands.

Allocating the frequency spectrum of 3400–3600 MHz for upcoming 5G mobile communication at the 2015 World Radio Communication Conference accelerates the investigation of the multi-antenna multiple-input multiple-output (MIMO) array in a smartphone (Al-Dulaimi et al., 2015; ITU, 2015). It is well known that channel capacity will be linearly increased in MIMO technology with the increase of the number of antennas at both the transmitter and the receiver (Paulraj et al., 2003). With this technology, it is unnecessary to increase the frequency spectrum or transmit power. For a smartphone, many antennas need to be integrated to support multiple functions. As a result, the space for a 5G MIMO array is limited. Therefore, realizing the desirable isolation and

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envelope correlation coefficient (ECC) within a compact size is a problem full of challenge.

Currently, many decoupling methods, such as the neutralization line (NL) technique, defected ground structure (DGS) technique, and orthogonal mode technique, have been developed to enhance isolation. In this paper, these decoupling methods are summarized briefly. Finally, the future prospects of the MIMO array in 5G smartphones are discussed.

2 Decoupling methods of the MIMO array

2.1 Distance optimization and selection of different elements

Selecting a proper distance between elements is a traditional and easy method without employing any additional decoupling structure. By selecting an appropriate distance between adjacent elements, an acceptable isolation can be achieved (Lu et al., 2015; Huang et al., 2018; Wong et al., 2018a; Chen et al., 2019; Zhang et al., 2019).

A wideband antenna which can cover 4G and 5G communication (617–960, 1710–2690, and 3300–4200 MHz) was proposed to form a two-antenna MIMO (Wong et al., 2018a). To guarantee isolation, the two elements were placed along the two short edges of the main board of the system. A four-port MIMO array composed of four slot antennas was proposed, and the optimum distance between the slots was selected to ensure the isolation higher than 13 dB (Chen et al., 2019). An ultra-band (3.3–6.0 GHz) eight-antenna MIMO array formed by eight slot antennas was designed (Zhang et al., 2019). Without exploiting any decoupling structure, the isolation of the MIMO array was higher than 11 dB by choosing a proper space between elements (Zhang et al., 2019).

Since the space is limited, the improvement of isolation is limited by adjusting only the distance between elements. Therefore, different elements were selected to reduce mutual coupling (Al-Hadi et al., 2014; Deng et al., 2018; Li YX et al., 2018a; Jin et al., 2019). Four slots and six monopoles were implemented to constitute a ten-element MIMO array (Deng et al., 2018). The isolation of higher than 11 dB was obtained by alternately placing two elements along the four sides of the main board of the system. A 12-port MIMO array with three types of elements was proposed, in which eight elements can cover 3400–3800 MHz and six elements operate in the frequency range of 5150–5925 MHz (Li YX et al., 2018a). To enhance isolation, different elements were alternately arranged along the four edges of the main board of the system (Fig. 1).

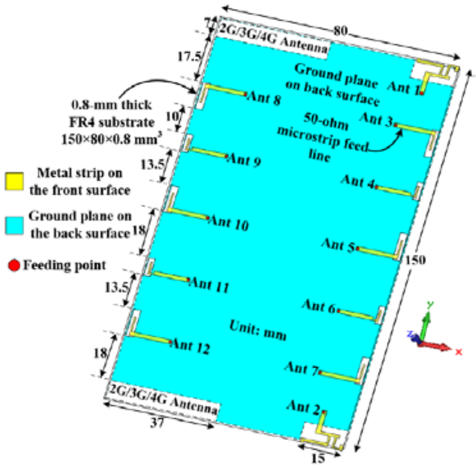

Fig. 1 Geometry of the 12-port MIMO array
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These MIMO arrays which ensure isolation by selecting proper distances and choosing different elements are compared in Table 1. According to Table 1, isolation of the MIMO array (eight elements or more than eight elements) is only around 12 dB at 3.5 GHz by only selecting proper distances or choosing different elements. Adjusting the distance between elements to obtain an acceptable isolation may result in a large size of the MIMO system.

2.2 External decoupling structures

Adding external decoupling structures is an efficient method to further improve the isolation. The NL technique, DGS technique, and grounding branches are included in the method of loading external decoupling structures. The NL technique can introduce opposite coupling to mitigate the existing coupling between two antennas at a certain frequency (Diallo et al., 2006). Since the NL technique can mitigate coupling, it is widely adopted to enhance the isolation of multi-antenna MIMO arrays. A quad-antenna linear (QAL) array composed of four open slot antennas was proposed (Wong et al., 2015, 2016).

Table 1 Comparison between the referenced antennas selecting proper distances and choosing different elements

Reference	Center frequency (GHz)	Isolation (dB)	ECC	MIMO order
Lu et al. (2015)	3.6	>10	<0.1	8
Wong et al. (2018a)	0.79/2.2/3.75	>8.5/>20/>10	<0.4/<0.1/<0.1	2
Huang et al. (2018)	1.6/3.45/4.9	>10	<0.23	8
Chen et al. (2019)	3.5	>10	<0.2	8
Zhang et al. (2019)	4.5	>11	<0.1	8
Deng et al. (2018)	3.45	>10	<0.15	10
Li YX et al. (2018b)	3.6/5.5	>12	<0.15/<0.1	12

ECC: envelope correlation coefficient

As there was a short distance between the four open slot antennas, three NLs were used to improve isolation. Eight- or sixteen-antenna MIMO arrays with acceptable isolation (>10 dB) can be implemented by exploiting the QAL array. In Lu et al. (2016), two NLs were applied to improve the isolation of a compact quad-antenna array. As presented in Ban et al. (2016), under consideration of the 4G and 5G antenna modules, a hybrid antenna was proposed (Fig. 2). As the two 4G antennas were placed at the same bottom edge of the ground plane, the coupling between the two antennas was inevitable. Accordingly, an NL was applied to enhance isolation (>10 dB). A QAL array composed of four dual-band antennas located on the side-edge frame was proposed (Guo et al., 2018). Since the distance between two adjacent antennas was only 10 mm, an NL was loaded to decoupling. Adopting two QAL arrays located at the two long edges of the ground plane, an eight-antenna MIMO array can be realized with mutual coupling of lower than −11.5 dB.

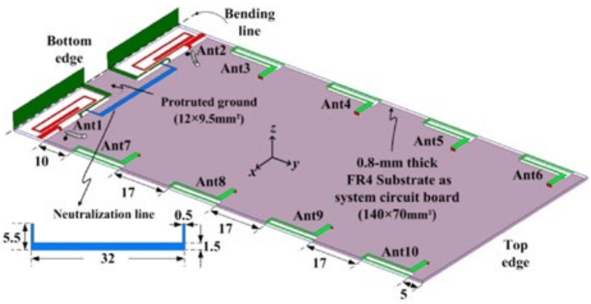

Fig. 2 Structure of the MIMO array

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The DGS technique reduces coupling by etching periodic or non-periodic structures on the ground plane. The DGS technique was employed to ensure the isolation, and the behavior of DGS was analyzed by the characteristic mode theory (CMT) for the first time. High isolation can be realized by loading the DGS to block coupling modes (Ghalib and Sharawi, 2017). Both NL and DGS were employed to guarantee high isolation (>15 dB) of the proposed eight-antenna MIMO array (Fig. 3) (Jiang et al., 2019a). The eight-antenna MIMO consisted of four U-shaped coupled-fed loop elements and four L-shaped coupled-fed loop elements. The NL was introduced to enhance the isolation of ants 2 and 3 (ants 6 and 7), and the DGS was employed to improve the isolation of ants 1 and 2.

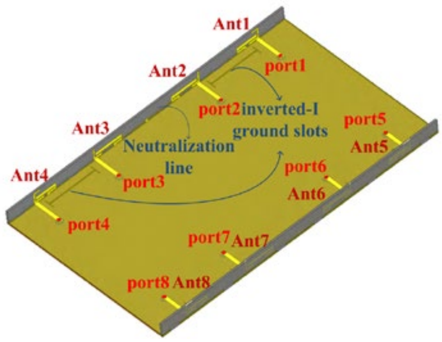

Fig. 3 Structure of the MIMO array with multi-decoupling elements

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In Xu et al. (2017) and Jiang et al. (2019b), grounding branches were employed to reduce decoupling. An eight-element MIMO array formed by eight folded monopole antennas was presented, which can cover 2400–2700 and 3300–3600 MHz (Jiang et al., 2019b). To acquire high isolation (>12.5 dB), grounding branches were inserted between the two elements located at the central region of the same long side (Fig. 4). In Xu et al. (2017), the multimode decoupling technique was investigated and the wideband/multiband decoupling was realized. An eight-antenna MIMO array exploiting the multi-decoupling elements was presented, which can acquire an isolation of higher than 20 dB.

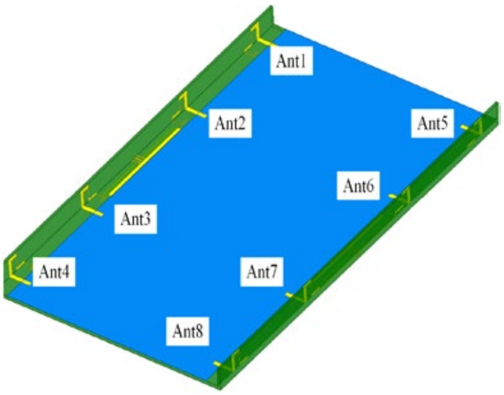

Fig. 4 Geometry of the eight-element MIMO system
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Comparison of these antennas employing additional decoupling structures is given in Table 2. According to Table 2, with the help of decoupling structures, the isolation of the 5G MIMO array can be improved to 20 dB. Although NL, DGS, and grounding branches can mitigate coupling, they have some deficiencies. Apparently, NL, DGS, and grounding branches will increase the complexity of the MIMO system and occupy additional space.

2.3 Orthogonal modes

The orthogonal mode technique is an efficient way to decouple without any external structure. Currently, this technique has been widely employed to improve the isolation of the 5G multi-antenna MIMO array (Qin et al., 2016; Li MY et al., 2016, 2017, 2018; Li YX et al., 2018b; Sun et al. 2018a, 2018b; Parchin et al., 2019; Ren et al., 2019).

Two types of elements, i.e., L-shaped monopole slot antenna and C-shaped coupled-fed antenna, were employed with orthogonal polarization to constitute an eight-port MIMO array (Li MY et al., 2016). Because of orthogonal polarization, isolation of higher than 12.5 dB was obtained. A ten-element MIMO array formed by T-shaped coupled-fed slot antennas was designed and an orthogonal polarization method was employed by arranging four elements along the short edges of the ground plane and six elements along the long edges of the ground plane (Li YX et al., 2018b), as shown in Fig. 5. Although low mutual coupling can be attained by applying the orthogonal polarization technique (Li MY et al., 2016; Qin et al., 2016; Li YX et al., 2018b), the space occupied by the multi-antenna MIMO system is large. In consequence, applying the orthogonal mode technique within a compact MIMO size has been investigated (Li MY et al., 2017, 2018; Parchin et al., 2019).

Feeding from the two vertical edges of a square loop can generate two orthogonally polarized waves. Because of the orthogonal polarization of the two ports, acceptable isolation can be achieved (>13 dB). By employing four square loops located at the four corners of the ground plane of the system, an eight-port MIMO system was realized (Li MY et al., 2017). A tri-polarized building block composed of two orthogonally placed open-end slots and a quarter mode substrate integrated waveguide antenna was shown in Fig. 6 (Li MY et al., 2018). The two open-end slots generated an x-polarized wave and a y-polarized wave. The quarter mode substrate integrated waveguide antenna generated a z-polarized wave. Three antennas

Table 2 Comparison between the referenced antennas employing additional decoupling structures

Reference	Center frequency (GHz)	Isolation (dB)	ECC	MIMO order
Wong et al. (2015)	3.5	>10	<0.3	16
Wong et al. (2016)*	3.5	>10	<0.25	8
Lu et al. (2016)	3.5	>12	<0.1	8
Ban et al. (2016)	3.5	>10	<0.2	8
Guo et al. (2018)	3.5/5	>11.5	<0.08/<0.05	8
Jiang et al. (2019a)	3.5	>15	<0.15	8
Jiang et al. (2019b)	2.55/3.45	>12.5	<0.25	8
Xu et al. (2017)	3.5	>20	–	8

*Only the performance of array A in Wong et al. (2016) is given due to the better performance. ECC: envelope correlation coefficient

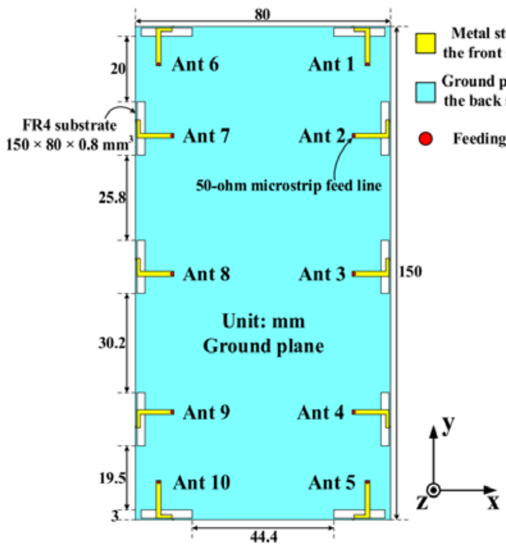

Fig. 5 Geometry of the ten-element MIMO array
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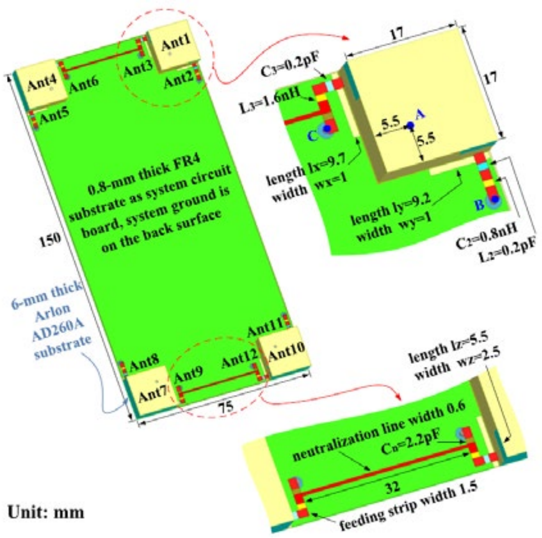

Fig. 6 Geometry of the 12-element MIMO array
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in the building block exhibited three orthogonally polarized waves. As a result, high isolation of the three-antenna building block was gained. Based on the tri-polarized building block, a 12-element MIMO array was proposed. To further improve isolation (>12.5 dB), NL was employed between two building blocks located at the same short edge of the ground plane. A square slot radiator with two ports was proposed, which can generate two linearly polarized waves (Fig. 7) (Parchin et al., 2019). To further reduce the mutual coupling between the two ports, a pair of open-ended parasitic structures was employed. An eight-antenna MIMO with isolation of higher than 15 dB was implemented by arranging four such square slots at the four corners of the main board of the system. In Li MY et al. (2017, 2018) and Parchin et al. (2019), the employment of the orthogonal mode technique was efficient in mitigating mutual coupling, and the size of the MIMO system was reduced. Nevertheless, these MIMO arrays are still not sufficiently compact.

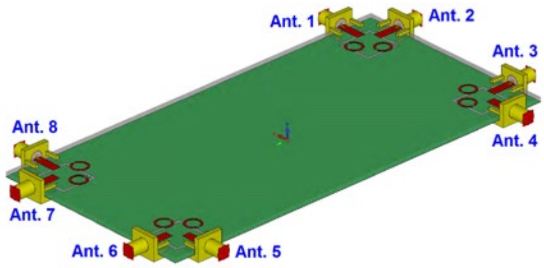

Fig. 7 Three-dimensional side view of the eight-element dual-polarized MIMO slot antenna system
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In Sun et al. (2018a, 2018b) and Ren et al. (2019), compact two-element building blocks with orthogonal polarization were proposed. In Sun et al. (2018a), a bent monopole and an edge-fed dipole were tightly arranged to constitute a compact building block with high isolation. Because of orthogonal polarization of the two antennas, the mutual coupling of the building block was lower than −20 dB. In Ren et al. (2019), a compact building block with desirable isolation was proposed by adopting the orthogonal mode technique. Although the physical distance between two antennas was zero, the isolation of the building block was higher than 19 dB. A compact eight-element MIMO with desirable isolation was brought by four such building blocks (Fig. 8).

CMT is an efficient way to provide guidelines for designing multi-antenna MIMO with high isolation. Low ECC can be obtained by exploiting the property if characteristic fields in the far field region are orthogonal.

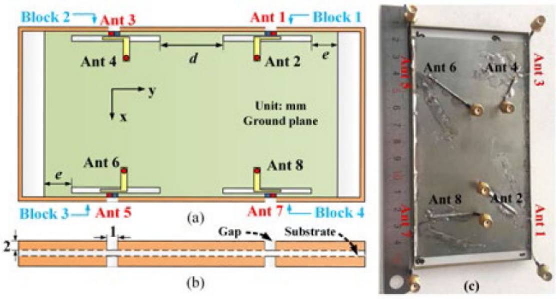

Fig. 8 Geometry of the eight-element MIMO array: (a) top view; (b) side view; (c) fabricated antenna
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A two-port MIMO with acceptable isolation and ECC was designed using CMT, in which the modes excited by the two antennas are orthogonal (Qu et al., 2017). It is difficult for the CMT to provide valid information for designing a multi-antenna system with multiple modes. By balancing the equiphase modes and antiphase modes, a desirable ECC can be attained (Liu Y et al., 2019). An eight-element MIMO system was designed by adopting this method, exhibiting high isolation (>15 dB) and low ECC (<0.16) (Fig. 9).

Fig. 9 Manufactured eight-port MIMO array
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Recently, the CMT has been widely employed to give guidelines for antenna design. To design a multi-antenna MIMO system for 5G applications, effective information can be supplied by the CMT. In conclusion, the CMT has great potential in the applications of the 5G MIMO arrays.

Comparison of these antennas exploiting orthogonal modes is given in Table 3. According to Table 3, the employment of orthogonal modes can improve isolation to 17 dB. Applying orthogonal modes to decouple under the consideration of the MIMO array size is a challenge and needs to be investigated.

2.4 Other decoupling methods

There are many other effective decoupling methods in addition to those already described.

In Wong et al. (2017) and Tsai et al. (2018), a very compact building block composed of two asymmetrically mirrored loop antennas was proposed to implement a multi-antenna MIMO array. Acceptable isolation was attained by asymmetrically arranging the two mirrored loop antennas. An ultra wide band (UWB) four-antenna MIMO array formed by four coupled-fed inverted-F antennas was proposed in 3.3–6.0 GHz (Wong et al., 2018b). To enhance isolation, the shorted strips of two antennas located at the same side of the ground plane were placed to face each other. An isolation of higher than 10 dB was attained.

To reduce coupling, self-isolated antennas have been investigated (Wong et al., 2019a, 2019b; Zhao and Ren, 2019a, 2019b). In addition to acting as a radiation element, the proposed compact self-isolated antenna can be used as a decoupling structure (Zhao and Ren, 2019b). An eight-antenna MIMO array using compact self-isolated elements was proposed which does not employ any additional decoupling

Table 3 Comparison between the referenced antennas exploiting orthogonal modes

Reference	Center frequency (GHz)	Isolation (dB)	ECC	MIMO order
Li MY et al. (2016)	2.6	>12	<0.15	8
Li YX et al. (2018b)	3.5/5.5	>11	<0.15/<0.05	10
Li MY et al. (2017)	2.6	>13	<0.2	8
Li MY et al. (2018)	3.5	>12.5	<0.2	12
Parchin et al. (2019)	3.6	>15	<0.01	8
Sun et al. (2018b)	3.5	>17	<0.07	8
Sun et al. (2018a)	3.5	>10	<0.11	4
Ren et al. (2019)	3.5	>16	<0.05	8
Liu Y et al. (2019)	3.5	>15	<0.16	8

ECC: envelope correlation coefficient

structure. To reduce the MIMO system size, two antennas with a conjoined section have been investigated (Wong et al., 2019a, 2019b). The conjoined section of the two antennas not only operated as a part of the resonant path but also worked like a band-pass resonant structure for decoupling.

If the induced current on the ground plane is localized around only the exit port, the corresponding ground current flowing to or affecting the adjacent ports will be weak. Therefore, the antennas with reduced ground effect have been studied to enhance isolation (Liu DQ et al., 2018; Li YX et al., 2019). To achieve the property of reduced ground effect, a vertical metallic patch was added to the planar inverted-F antenna (Liu DQ et al., 2018). Employing eight such antennas, a handset MIMO system was realized with the isolation of higher than 10 dB. A novel open slot antenna with balanced mode was studied and used to achieve an eight-element MIMO system with high isolation (>17.5 dB) (Li YX et al., 2019). In Liu DQ et al. (2018) and Li YX et al. (2019), although antennas with reduced ground effect were realized, the size of the eight-antenna MIMO system was still very large.

Stable null points of an electric field were investigated to enhance isolation (Zhao et al., 2018). The achieved isolation was higher than 25 dB through placing another antenna at the stable null point of the electric field.

Recently, Deng et al. (2019) proposed the method of loading an inductor at the position with the minimum current or a capacitor at the position with the maximum current of two antennas to reduce mutual coupling. A tightly arranged eight-antenna MIMO array with isolation of higher than 11.6 dB was proposed, in which the distance between two adjacent elements was only 1 mm.

The aforementioned methods are effective in isolating the mutual coupling between two elements. The performances of MIMO systems employing these methods are summarized in Table 4. It can be seen that the isolation of the multi-antenna MIMO array can be enhanced to around 20 dB by applying these methods. However, effectively enhancing isolation within a compact MIMO size needs further research.

3 Conclusions

The growing requirement for channel capacity accelerates research on the MIMO technique. It is well known that severe mutual coupling and poor ECC will result in deterioration of the channel capacity of a MIMO system. For future smartphone applications, acquiring high isolation and remaining compact are very difficult to realize. We briefly review recent works on the decoupling methods for sub-6 GHz MIMO arrays. The improvement of the isolation is limited by adjusting only the distance between elements. Although the application of additional decoupling structures can effectively mitigate mutual coupling, extra space will be taken up and the complexity of the MIMO system will increase. Furthermore, loading external decoupling structures will result in additional efficiency loss. The orthogonal mode technique results in great improvement in isolation without any external decoupling structure. Other decoupling methods, such as exploitation of CMT, the self-isolated antenna, and reducing the

Table 4 Comparison between the referenced antennas using other decoupling methods

Reference	Center frequency (GHz)	Isolation (dB)	ECC	MIMO order
Wong et al. (2017)	3.5	>10	<0.1	8
Tsai et al. (2018)	3.5	>10	<0.1	20
Wong et al. (2018b)	4.65	>10	<0.1	4
Zhang et al. (2019)	3.5	>20	<0.003	8
Zhao and Ren (2019b)	3.5	>19.1	<0.0125	8
Wong et al. (2019a)	3.75	>12	<0.1	2
Liu DQ et al. (2018)	2.6/5	>10/>20	<0.2/0.1	8
Li YX et al. (2019)	3.5	>17.5	<0.05	8
Zhao et al. (2018)	3.5	>25	<0.000 12	2
Deng et al. (2019)	3.5	>11.6	–	8

ECC: envelope correlation coefficient

ground effect of the elements, are presented. All these methods can achieve great enhancement of isolation. Several novel methods improving isolation within a compact size are also reviewed.

In the future, designing multi-antenna MIMO array systems for the unbroken metal-rimmed smartphone is worth investigating. Smartphones with a metal bezel have enhanced robustness and aesthetic appearance, which are attractive. Nevertheless, due to the presence of the metal bezel, it is difficult to arrange multiple antennas into a smartphone with acceptable isolation and ECC. Usually, to improve isolation or impedance matching of the multi-antenna MIMO system, some gaps need to be loaded into the metal bezel. However, the aesthetic appearance of the smartphone will be influence by the presence of gaps. In Liu DQ et al. (2019), an eight-antenna MIMO system with low profile was designed by adopting an artificial magnetic conductor (AMC) ground, which can be used as the back cover of a smartphone. This design can be effectively applied to the smartphone with an unbroken metal bezel. Further research is still necessary to design multi-antenna systems into a smartphone with an unbroken metal frame.

To meet the requirements of the future smartphone, continuous pursuit of the miniaturization of the MIMO size is necessary. At the same time, the desirable MIMO performance must be maintained. For practical applications, designing wideband MIMO arrays within compact sizes is meaningful and challenging. For miniaturized and broadband MIMO array designs, reducing mutual coupling will be difficult because of the small space and wide bandwidth. We are looking forward to observing novel methods of decoupling multi-antenna MIMO arrays in the near future.

Contributors

Xiao-xi ZHANG designed the research. Xiao-xi ZHANG wrote the first draft of the manuscript. Ying LIU and Ai-di REN helped organize the manuscript. Xiao-xi ZHANG and Ai-di REN revised and edited the final version.

Compliance with ethics guidelines

Xiao-xi ZHANG, Ai-di REN, and Ying LIU declare that they have no conflict of interest.

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