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MIMO Reference Antennas with Controllable Correlations and Total Efficiencies

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Abstract—MIMO reference antennas are proposed for over the air (OTA) measurement applications. The reference antennas could get rid of feeding cable interference and control envelope correlation coefficients (ECC) continuously by only changing the length of an etched slot on a dual-feed PIFA. If only the ECC is investigated, the MIMO reference antenna is optimized to have a small variation of total efficiency from 70% to 50% when the ECC increases from 0.1 to 0.88. The prototypes are fabricated and measured in a scattered field chamber (SFC). Measurements agree well with the simulations. If the MIMO performance is studied, the MIMO reference antenna is proposed to own a large variation of total efficiencies from 90% to 47% while the ECC increases from 0 to 0.98. The bandwidth of the proposed reference antennas depend on the size of the antennas. This method is valid for all the frequencies.

1. INTRODUCTION

Multiple-input and multiple-output (MIMO) technology has been well known for its effectiveness in channel capacity and coverage enhancement [1, 2]. MIMO over the air (OTA) performance highly depends on the antenna multiplexing efficiency [3, 4], which is determined by the MIMO antenna performance such as mutual coupling, antenna total efficiency and correlation. A good MIMO reference antenna design requires controllable levels of the envelope correlation coefficients (ECC) and total efficiencies in a mobile terminal device for the test. However, the conventional dual-element MIMO antenna systems are difficult to satisfy these requirements.

A kind of MIMO reference antenna has been proposed in [5–7]. It consists of two inverted-F antennas (IFA) on two corners of a ground plane. By controlling the length of another metal plane between two IFAs, the antenna isolation could be enhanced and the ECCs could be reduced. However, due to the diagonal antenna-chassis modes [8, 9], this reference antenna is hard to design for the high ECC cases. Furthermore, the total efficiencies of this design are not controllable. For each band, the MIMO reference antenna systems have been defined as "good" (with low correlation and high efficiency), "nominal" (with moderate correlation and moderate efficiency), and "bad" (with poor correlation and low efficiency). If the reference antennas require different ECCs with small variation of total efficiencies, the design in [5–7] is difficult to achieve it.

In [10], another MIMO reference antenna has been proposed for different ECCs with small variation of total efficiencies (less than 20%). The ECC is simply controlled by changing the cutting slot lengths on a dual-feed PIFA without modifying the other configurations. In this paper, the MIMO reference antenna in [10] is further investigated and extended. The mechanism of the reference antenna in [10] is provided here. The effects of 20% total efficiency differences in different ECC levels are analyzed on the throughput multiplexing efficiency [3]. The cable interference is studied. Moreover, the proposed antenna is also re-designed for the similar properties as that in [7] for the "good" and "normal"

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situations. In the "bad" case, with a total efficiency of 47%, the ECC of the designed antenna is around 0.98, which is much higher than the 0.84 in [7]. Finally, some key parameters for antenna designs are also provided.

Compared with the previous work in [7] the proposed MIMO reference antenna has the following advantage:

1. More compact structure.
2. Reach much higher ECC.
3. Capable to be designed for the investigation of only ECC or MIMO performance.
4. Simply controlled ECC by different lengths of etched slot without changing the other configurations. In [7], the lengths of two IFAs still need to be adjusted from the case "good" to "bad".
5. Less feeding cable interference.

All the simulations in this paper are carried out with the commercial software of CST Microwave Studio 2013 [15].

2. MIMO REFERENCE ANTENNA FOR THE INVESTIGATION OF ENVELOPE CORRELATION COEFFICIENT

In field trials, we need to study the impact of different ECC levels on the throughputs. In this application, the variation of total efficiencies in all the ECCs should be as small as possible.

2.1. Configurations and Performance of the Proposed MIMO Reference Antenna

The configurations of the proposed MIMO reference antenna are shown in Fig. 1. Three specific designs are presented to demonstrate our method: high correlation, mid correlation, and low correlation. All the ECCs in this paper are obtained from the 3D E-field radiation patterns as defined in [11]. Technically, the proposed method is valid for all the frequencies. The operating band of 2.6–2.7 GHz is selected here. In Fig. 1, a dual-feed PIFA is mounted on a copper ground plane with the size of 40 mm $\times$ 100 mm.

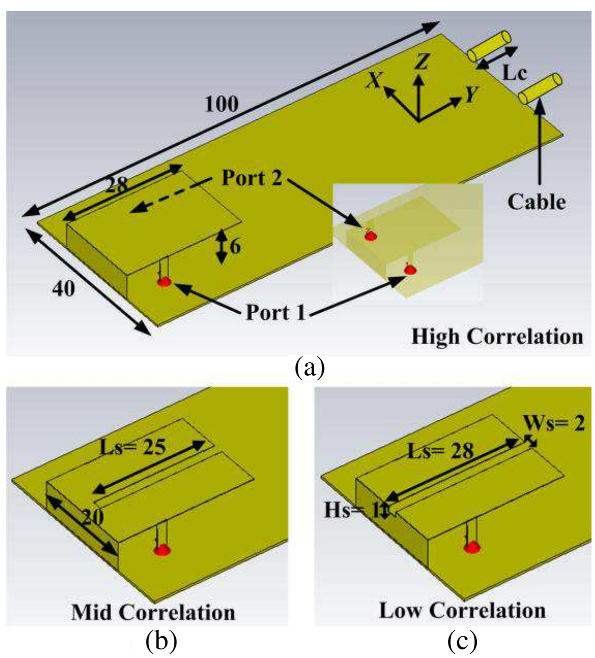

Figure 1. MIMO reference antennas with (a) high correlation, (b) mid correlation, and (c) low correlation. (Unit: mm).

The width of the feeding strip is 2 mm. In fact, the antenna performance is almost the same when the width changes from 1 mm–3 mm. A slot is etched on the dual-feed PIFA to control the ECC.

The ECC and total efficiencies of the three MIMO antennas (see Fig. 1) are shown in Figs. 2(a) and (b), respectively. It is observed that in the high correlation case the total efficiency of the reference antenna is better than 50%, while in the low correlation case the total efficiency is lower than 70%. In our designs, as the ECC changes from 0.1 to 0.88, the variation of the total efficiency is less than 20%. In fact, even the 20% difference is very challenging to realize. If the ECC reaches 0.9, the radiation patterns of two MIMO elements are very similar. This will result in a high mutual coupling to reduce the total efficiency. From our studies, when the ECC is close to 1, the highest achievable total efficiency is around 50%, where the radiation efficiency is nearly 100%. In order to achieve a small total efficiency variation, we have to decrease the total efficiency in the low correlation case. Due to the high radiation efficiency, a bad impedance matching or strong coupling could be applied for a low total efficiency in low correlation case. However, both of them will lead to the increase of ECC.

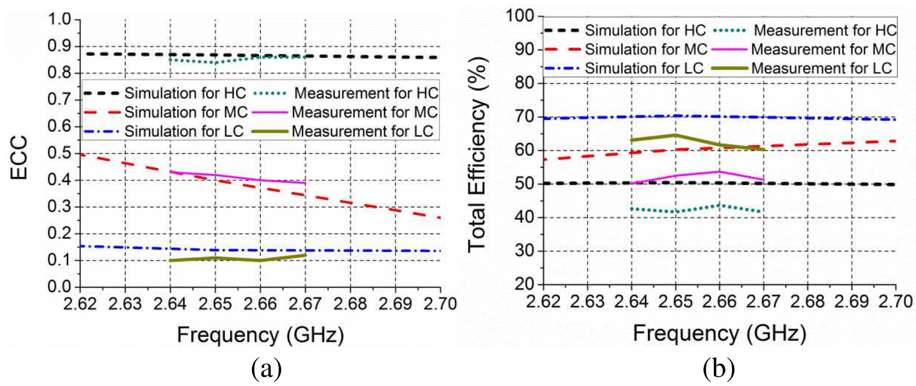

Figure 2. (a) Envelope correlation coefficient and (b) total efficiency of the MIMO reference antennas.

The radiation patterns of the MIMO reference antennas with high ECC and low ECC have been shown in Fig. 3. With the proper length of the etched slot, the mutual coupling between two MIMO elements can be reduced and consequently the radiation patterns are separated efficiently.

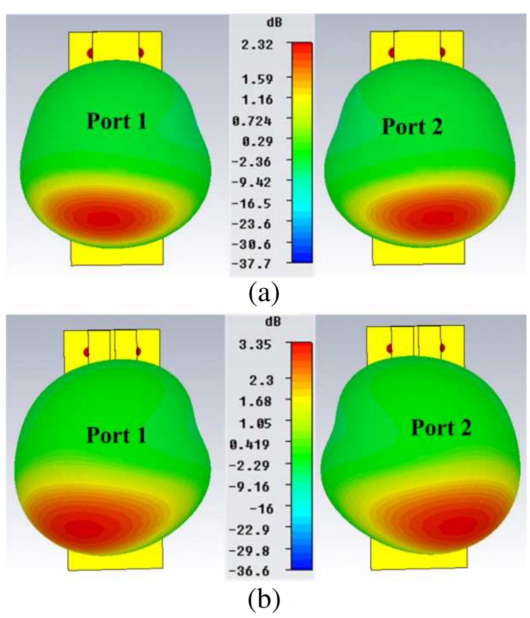

Figure 3. 3D Radiation patterns of the MIMO reference antennas with (a) high correlation and (b) low correlation.

2.2. Parasitic Studies

In order to further investigate the decorrelation mechanism of the etched slot on the dual-feed PIFA, the total slot lengths have been swept from 0 mm to 35 mm. The S parameters, ECCs and total efficiencies of different total slot lengths are presented in Fig. 4. In Fig. 4(b), we observe that when the total length of the slot increases from 0 mm to 35 mm, a decoupling null moves from the high frequency to the low frequency. In fact, this decoupling mode is introduced by the slot. This decoupling slot mode has been studied in [12, 13]. In this paper, by adjusting the length of the slot, a proper amount of the decoupling mode will be introduced to control the ECC levels. With the length of 30 mm (see Fig. 1(c)), the decoupling null is placed at the desired frequency point of 2.65 GHz and the ECC reaches the lowest value in all, as shown in Fig. 4(c). With the length longer than 30 mm, the ECC begins to increases due to the shift of the decoupling mode to a lower frequency. Please note that the impedance matching is kept the same or even a little worse with the slot increasing from 0 to 30 mm, which can help reduce the variation of total efficiency. The total efficiencies for different slot lengths are presented in Fig. 4(d). A variation of less than 20% is observed for all the slot lengths. The upper and lower boundary of the total efficiency is 70% and 50% (when ECC is around 0.1 and 0.88), respectively. In practical applications, we can assume the MIMO reference antenna has a fixed total efficiency of 60% in different ECCs. The throughput multiplexing efficiency [3] is calculated with the actual and assumed total efficiency. When ECC is 0.88, they are 5% and 6%, respectively. When ECC is 0.1, they are 62% and 53%, respectively.

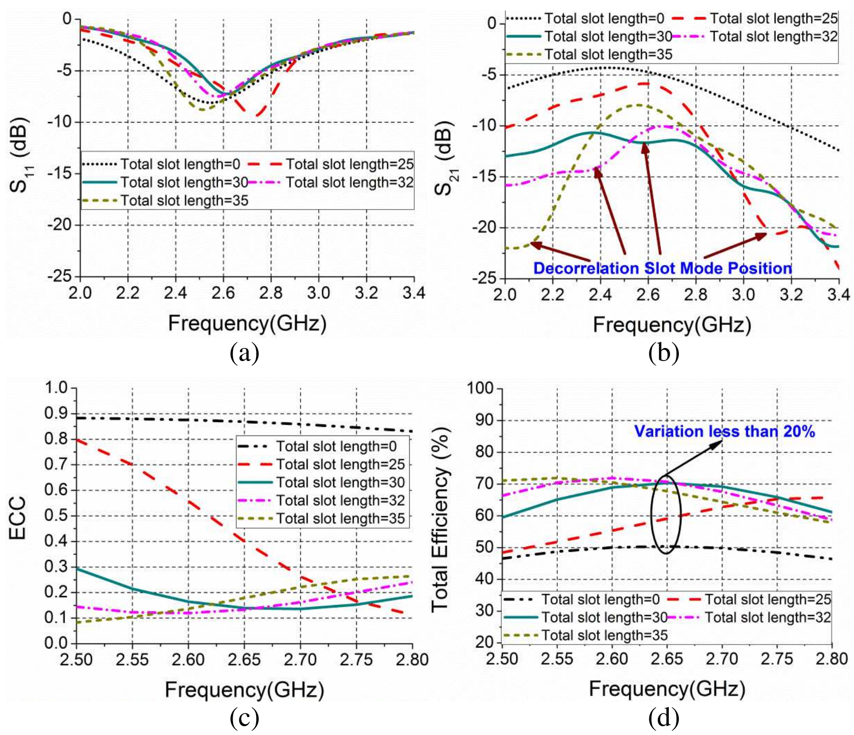

Figure 4. (a) S_{11}, (b) S_{21}, (c) ECC and (d) total efficiency of the MIMO reference antennas with different lengths of the etched slot.

In Fig. 5, it is observed that the ECCs are controlled continuously with the slot length from 0 to 30 mm. Please note that in Fig. 5, the ECC of 21 mm slot is 0.89, which is similar to the ECC of 0 mm slot (0.88) in Fig. 4(a). In fact, the ECC will not change significantly until the slot length is longer than 21 mm. This is because for this kind of MIMO reference antennas the ECC reduction is mainly due to the decoupling slot mode. The slot starts to work when the length is comparable with the resonant frequency of the PIFAs.

In order to study the interference of the feeding cables on the MIMO reference antenna, two cables with the length L_c are added at the end of the chassis, as shown in Fig. 1. This cable arrangement is

Figure 5. ECC of the MIMO reference antennas with the length of the slot from 21 mm to 30 mm.

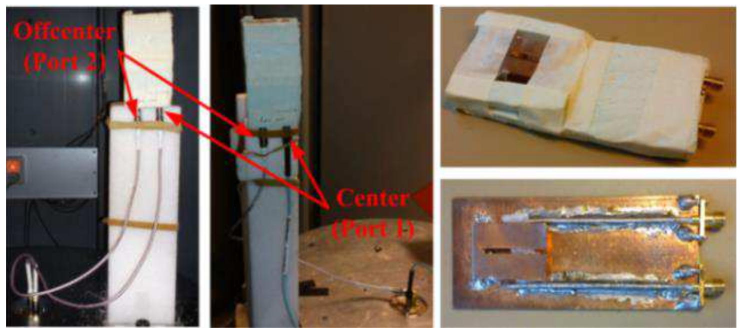

Figure 6. The fabricated prototypes and measurement setups.

also utilized in the measurement in Fig. 6. When the L_c increases from 0 mm to 100 mm, the variations of total efficiencies and ECCs are less than 4% and 0.03, respectively. It indicates that the proposed MIMO reference antenna has little interference from the feeding cables.

2.3. Experiments

The prototypes of the MIMO reference antennas with high, mid and low correlations are fabricated and measured in a scattered field chamber (SFC) [14] at Sony Mobile, as shown in Fig. 6. The SFC is a kind of reverberation chamber, where the isotropic angle of arrivals is applied. The two ports of the fabricated MIMO antenna are connected with the cables from the center and off-center of the positioner. According to the signal strengths received by the two ports of the MIMO antenna, the total efficiency and ECC can be evaluated directly. During the measurement, more samples will lead to a higher accuracy, but also cost longer time. From the experience, at least 3000 samples and 4000 samples should be selected to guarantee the accuracy for the operating frequency higher than 1500 MHz and lower than 960 MHz. In this paper, 3000 samples have been selected. The measured results are shown in Fig. 2 and compared with the simulations. The ECC agrees very well with the simulations. The measured total efficiencies are around 8% lower than the simulated, which is still reasonable and acceptable.

3. MIMO REFERENCE ANTENNA FOR THE INVESTIGATION OF MIMO PERFORMANCE

The proposed MIMO reference antenna can also be designed for the reference antennas with “good”, “normal” or “bad” MIMO performance, as defined in [7]. The detailed configurations of the designed antenna are shown in Fig. 7, where only the parameters different from those in Fig. 1 are presented. In this design, the decoupling slot mode has not been utilized. Since increasing the slot length will help separate the radiation patterns of MIMO elements, the mutual coupling can also be reduced but not as efficiently as the decoupling slot mode. Different from the antenna in Section 2, with a longer slot, the impedance matching is much more improved, which will significantly improve the total efficiency and decrease ECC [16]. In the “good” MIMO case, the slot will be totally etched, as shown in Fig. 7. In the “bad” MIMO case, no slot will be applied between two PIFAs. There is slot length variation to implement “good” and “bad” cases. In Table 1, the ECCs and total efficiencies in the “good” and “bad” cases are compared between the proposed antenna and the antenna in [7]. It is observed that the designed antenna could reach a much higher ECC in the “bad” case than that in [7]. It should be mentioned that Table 1 is only used for the comparison between the MIMO reference antenna proposed in Section 3 and the antenna in [7]. In Section 2, the proposed MIMO reference antenna is optimized to have a small variation of total efficiency from 70% to 50% when the ECC increases from 0.1 to 0.88. This property is difficult to realize by the antenna in [7]. Please note that similar to the antenna in

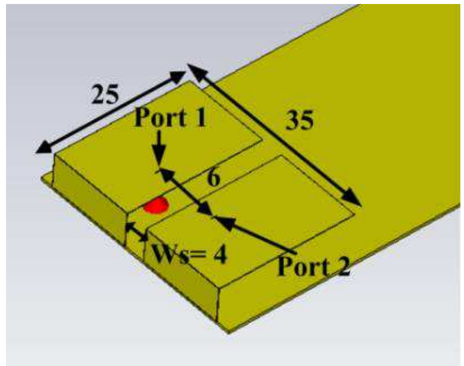

Figure 7. MIMO reference antennas for the investigation of MIMO performance. (Unit: mm).

Table 1. Performance comparison.

	Good		Bad	
	ECC	TE	ECC	TE
Proposed Antenna	0	90%	0.98	47%
Antenna in [7]	0.0005	90.1%	0.84	50%

TE represents the total efficiency.

Section 2 only the slot length of the proposed antenna is changed from "good" to "bad". All the other structure parameters are still kept the same.

4. KEY PARAMETERS FOR ANTENNA DESIGNS

In this section, some important parameters for antenna designs are given in the following:

a. The distance between two feeding strips: a smaller feeding strip distance could help increase the ECC in the high correlation case.
b. The width of each PIFA: a wider PIFA will lead to a higher total efficiency in all the cases.
c. The width of slot between two PIFAs: a wider slot will reduce the ECC and improve the total efficiency in the low correlation case.

5. CONCLUSION

A novel MIMO OTA reference antenna has been proposed in this paper. By changing the length of the etched slot on a dual-feed PIFA, the ECCs have been controlled continuously. It could be designed to realize small or large variation of total efficiencies in different ECC levels. A high ECC of around 0.98 has been achieved in high correlation case. The prototypes have been fabricated and measured to verify the simulations.

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