Isolation Improvement of an Overlapped Two-element MIMO Antenna

Wenchao Li and Kewei Qian
Research Institute of Electronic Science and Technology, University of Electronic Science and Technology of China, Chengdu, Sichuan, China
15682012296@163.com

Abstract. An overlapped two-element antenna structure with excellent compactness is proposed. Extraordinarily strong mutual coupling is effectively mitigated by a decoupling network with simple coupled microstrip lines connected to the antennas in shunt. Simulation example and results are demonstrated. The isolation improvement is better than 8 dB (from about 2 dB to over 10 dB) in most of the Wi-Fi 2.4 GHz band. Four lumped components networks are utilized to maintain the good impedance matching before and after decoupling, and the return loss is higher than 7 dB over the band of interest. Remarkable decrease in envelope correlation coefficient (ECC) in most of the working band is achieved. All these performances prove the presented antenna structure and decoupling scheme a promising option for those mobile terminals and wireless communication devices which have high data rate and compact volumes.

1. Introduction
As the demands on higher data rate, greater spectrum efficiency and better communication quality of wireless systems increase constantly, a great deal of advanced technologies for satisfying those requirements have been studied and utilized. Among them, the multiple-input multiple-output (MIMO) technology, featured with using multiple antennas at the transmitter and receiver, is deemed one of the most effective ways to increase channel capacity due to its spatial diversity gain [1]. Pioneering work by Winters [2] demonstrated that with the number of antennas at both transmitter and receiver increasing linearly, MIMO systems can obtain approximately linear enhancements in capacity, as long as the mutual coupling among antennas are sufficiently low and the sub-channels between transmitting and receiving antenna pairs are uncorrelated. However, with the increase of the number of antenna elements and the decrease of the spacing between them, the mutual coupling among antennas and the channel correlation become stronger, which will weaken the advantages of a MIMO system and then degrade its performance [3]. Therefore, achieving high isolation of antennas is an indispensable goal for any MIMO system, particularly for those mobile terminals enjoying multiband and high date rate advantages with compact size. Additionally, the envelope correlation coefficient (ECC), which is largely influenced by the isolation between the antenna elements, is one of the crucial factors for MIMO systems [4].

In [5], a printed ultra-wideband (UWB) MIMO antenna system working in 3.1-10.6 GHz is proposed. A tree-like structure on the ground plane is introduced in order to obstruct the current flowing from one radiator to the other. The isolation between the two antenna elements is higher than 16 dB over the whole operating band. In [6], a two-element directional slot antenna array which possesses a high front-to-back ratio of up to 19.2 dB is firstly introduced. Subsequently, a small-sized
four-element MIMO array utilizing the proposed slot antenna is presented. The array obtains a good isolation of over 22 dB over the bandwidth of 5.0-6.0 GHz. In [7], a reconfigurable four-port MIMO antenna array designed for WLAN applications is presented. The antenna has two working modes: one as a four-element antenna working at 5 GHz band; the other as a two-element antenna operating at 2.4 GHz band. The active mode is decided by the different states of a set of radio-frequency (RF) micro-electromechanical system (MEMS) switches. Good isolations between the antenna elements is achieved under both of the two configurations. In [8], an integrated scheme with only simple passive network is presented to realize decoupling and matching between two closely located antennas simultaneously. With its simple principle and coherent design procedure, this method proves to be an efficient way to enhance antenna isolation.

Although all the aforementioned solutions can provide satisfactory antenna isolation for MIMO systems, these structures are not compact enough to be implemented in a practical size-limited mobile terminal. With the technologies of carrier aggregation (CA) and massive MIMO having become the core technologies for 5G applications [9]-[14], the number of antenna elements co-existed in a single compact communication device will dramatically increase for the sake of realizing higher data rate and wider overall working bandwidth. In this situation, the problem of mutual coupling among the antenna elements will unavoidably become worse. Therefore, a more practical antenna array structure and decoupling scheme with adequately compact volume are recently in high demand.

In this work, unlike traditional MIMO antenna with coplanar elements reported in other literatures, a novel MIMO antenna structure with two elements printed respectively at the top and bottom side of the substrate is proposed to achieve remarkable compactness. Although the area of clearance region can be greatly reduced by overlapping, the mutual coupling between the elements will be violently stronger than its coplanar counterpart. In order to mitigate the severe mutual coupling, a simple decoupling network with only microstrip lines is designed based on the author’s previous research guided by Professor Wu Ke-li in The Chinese University of Hong Kong [15]-[17]. The basic principle and process of the decoupling approach can be explained as follows: design a coupling resonator network of 2nd or higher order which has a mutual admittance in versed to that of the original antennas, then insert this network between the two input ports of the antennas network and the resultant mutual admittance of the whole network will be eliminated, which means zero mutual coupling. The theory details and design process will be shown in the next section.

2. Design Theory

In [18], the correlation of multiple antenna elements as well as its impact on channel capacity of MIMO system has been studied. Furthermore, according to [19], the channel capacity of a general end-to-end MIMO system can be expressed as:

$$C = \log_2 \left[ \det \left( I_n^m + \frac{\rho}{m} HH^H \right) \right]$$

(1)

Where $m$ and $n$ are the number of transmitting and receiving antennas respectively, $I_n$ is an $n \times n$ identity matrix, $H$ is the channel matrix and $\rho$ is the average signal-to-noise ratio (SNR) at the receiver. Additionally, according to [20], we can see that antenna parameters such as isolation and ECC have huge impacts on the capacity and diversity performance of a MIMO system. Specifically, the more antenna isolation increase, the more ECC decrease, which contributes to higher diversity gain and channel capacity.

Figure 1 shows the schematic block diagram of our decoupling scheme. At the reference plane A, the 2×2 complex admittance matrix of the two well matched but strongly coupled antennas can be expressed as $[Y^a]$. We can infer from [21] that zero mutual admittance is equivalent to zero mutual coupling for a two-port network. Therefore, our goal is to eliminate the mutual admittance and maintain the good matching of the two antennas simultaneously. Since the shunt reactance element only provides a pure imaginary admittance ideally, two transmission lines with characteristic
impedance $Z_0 (= 50 \, \Omega)$ and electrical length $\theta$ are cascaded to the two antennas in order to transform its mutual admittance to be pure imaginary. Let the admittance matrix of the decoupling network be denoted as $[Y_N]$. As the decoupling network is directly inserted between the two input ports of antennas network, the admittance matrix at the reference plane C should be the sum of that of the two networks:

$$Y_C = \begin{pmatrix} Y_{11}^C (f) & Y_{12}^C (f) \\ Y_{21}^C (f) & Y_{22}^C (f) \end{pmatrix} = \begin{pmatrix} Y_{11}^B (f) + Y_{11}^N (f) & Y_{12}^B (f) + Y_{12}^N (f) \\ Y_{21}^B (f) + Y_{21}^N (f) & Y_{22}^B (f) + Y_{22}^N (f) \end{pmatrix}$$

(2)

Where the parameter $f$ represents the frequency variable. Thus, the conditions for realizing high isolation at reference plane C can be summarized as:

$$\text{Re} \left\{ Y_{21}^N (f) \right\} \approx 0, \quad f \in [f_1, f_2]$$

(3a)

$$\text{Im} \left\{ Y_{21}^N (f) \right\} + \text{Im} \left\{ Y_{21}^B (f) \right\} \approx 0, \quad f \in [f_1, f_2]$$

(3b)

And the impedance matching conditions at reference plane C can be expressed as:

$$\text{Re} \left\{ Y_{kk}^B (f) \right\} \approx Y_0, \quad f \in [f_1, f_2], \quad k = 1, 2$$

(4a)

$$\text{Im} \left\{ Y_{kk}^B (f) \right\} + \text{Im} \left\{ Y_{kk}^N (f) \right\} \approx 0, \quad f \in [f_1, f_2], \quad k = 1, 2$$

(4b)

Notice that when the two antennas are assumed to be well matched at the reference plane A over the operating band, equation (4b) can be simplified to:

$$\text{Im} \left\{ Y_{kk}^N (f) \right\} \approx 0, \quad f \in [f_1, f_2], \quad k = 1, 2$$

(4c)

Figure 1. The function blocks of the proposed decoupling scheme.

It is noteworthy that the self-admittance of an actual decoupling network is usually not zero. Consequently, the impedance matching is likely to be changed after the connection of the decoupling network. Thus, each input port is separately connected to a matching network to improve the impedance matching. Since the isolation is very high after the decoupling, the two input ports can be considered as independent of each other, and the insertion of the matching network will no longer degrade the isolation.

3. Design Example

A simulation work is presented in this section to verify the feasibility of the antenna structure and the decoupling scheme theoretically. Figure 2 shows the details of the simulation model. Two monopole antennas operating at WLAN 2.4 GHz (2.4 ~ 2.484 GHz) band are printed face-to-face at the upper and lower sides of a 46×40×1.6 mm$^3$ FR-4 substrate. The size of the ground plane is 40×35 mm$^2$. As shown in figure 2, Antenna 1, Decoupling Network and matching adjustment components are located on the upper side, and Antenna 2 is located on the lower side, which is connected to the transmission line on the top through a metal via. The values of the dimension parameters are: $d_1 = 4.4$ mm, $d_2 = 3.15$ mm, $d_3 = 4.2$ mm, $w_1 = 0.4$ mm, $w_2 = 0.6$ mm, $w_3 = 1$ mm, $w_4 = 0.8$ mm, $g_1 = 0.1$ mm, $g_2 = 8$ mm, $f_1 = 3.4$ mm, $f_2 = 2.2$ mm, $f_3 = 3.4$ mm, $f_4 = 1.6$ mm, $r_1 = 9.8$ mm, $r_2 = 3$ mm, $r_3 = 7$ mm, $r_4 = 6$ mm,
r5=3 mm, r6=3 mm, r7=5 mm, r8=11 mm, r9=3.5 mm, r10=3.5 mm, r11=7 mm and v=0.4 mm. The optimal values of the discrete components shown in figure 2 (a) are: C1=0.88 pF, C2=0.8 pF, L1=4.15 nH, L2=2.75 nH, C3=5.5 pF, C4=2.1 pF, L3=1.5 nH and L4=1.5 nH.

The S-parameters of the antennas with and without the decoupling network is shown in figure 3. It is evident that, without the decoupling network, a very poor isolation of lower than 3 dB within the operating band is obtained because of the overlapping structure. However, with the help of the proposed decoupling network, the isolation of the two elements has been increased by higher than 7 dB over the whole working band and 10 dB over 2.4-2.45 GHz, while the return loss is still acceptable. It can be also seen that the matching bandwidths of both antennas significantly reduce when the decoupling network is adopted. This can be explained that the antennas with poorer isolation have lower quality factor (Q) values than those with better isolation, and it is understandable that the decoupled antennas with higher isolation and Q values have narrower matching bandwidths.
Figure 3. (a) S-parameters before decoupling. (b) S-parameters after decoupling.

As mentioned before, ECC is a significant performance factor in MIMO systems. It can be directly derived from the S-parameters of MIMO antennas [4]:

$$\rho_e = \frac{\left| S_{11}^2 S_{22} + S_{12}^* S_{21}^* \right|^2}{\left(1 - |S_{11}|^2 - |S_{21}|^2 \right) \left(1 - |S_{22}|^2 - |S_{12}|^2 \right)}$$  (5)

The ECC of the two antennas with and without the decoupling network are illustrated in figure 4 based on equation (5). A notable decrease in ECC can be observed, which means better performance.

Figure 4. ECC between the two overlapped antennas

4. Conclusion

In this paper, an overlapped two-element antenna structure with remarkable compactness has been proposed. A simple decoupling network with only microstrip lines is adopted to increase the isolation between the two strongly coupled antennas. Lumped components are used to improve the impedance matching before and after decoupling. Simulation results show that no less than 5 dB improvement in isolation over the whole 2.4 GHz band and the best of 15 dB at 2.42 GHz are obtained. The return loss is better than 7 dB over the whole working band after decoupling. Further works of antenna fabrication and measurements need to be done in the future. Some other technologies for decoupling realization such as low temperature co-fired ceramics (LTCC), which can make the decoupling circuit more compact, will be of great research and practical value.

References
[1] Jensen M A and Wallace J W 2004 A review of antennas and propagation for MIMO wireless
communications IEEE Trans. Antennas Propag. 52 2810-21
[2] Winters J H 1987 On the capacity of radio communication systems with diversity in a Rayleigh fading environment IEEE J. Select. Areas Commun. 5 871-878
[3] Janaswamy R 2002 Effect of element mutual coupling on the capacity of fixed length linear arrays IEEE Antennas Wireless Propag. Lett. 1 157-160
[4] Blanch S, Romeu J and Corbella I 2003 Exact representation of antenna system diversity performance from input parameter description Electronics Letters 39 705-706
[5] Zhang S, Ying Z, Xiong J and He S 2009 Ultrawideband MIMO/diversity antennas with a tree-like structure to enhance wideband isolation IEEE Antennas Wireless Propag. Lett. 8 1279-82
[6] Hu H T, Chen F C and Chu Q X 2016 A compact directional slot antenna and its application in MIMO array IEEE Trans. Antennas Propag. 64 5513-17
[7] Soltani S, Lotfi P and Murch R D 2016 A port and frequency reconfigurable MIMO slot antenna for WLAN applications IEEE Trans. Antennas Propag. 64 1209-17
[8] Chen S C, Wang Y S and Chung S J 2008 A decoupling technique for increasing the port isolation between two strongly coupled antennas IEEE Trans. Antennas Propag. 56 3650-58
[9] Yuan G, Zhang X, Wang W and Yang Y 2010 Carrier aggregation for LTE-advanced mobile communication systems IEEE Commun. Mag. 48 88-93
[10] Pedersen K I, Frederiksen F, Rosa C, Nguyen H, Garcia L G U and Wang Y 2011 Carrier aggregation for LTE-advanced: functionality and performance aspects IEEE Commun. Mag. 49 89-95
[11] Liu J and Xiao W 2016 Advanced carrier aggregation techniques for multi-carrier ultra-dense networks IEEE Commun. Mag. 54 61-67
[12] Chavarria-Reyes E, Akyildiz I F and Fadel E 2016 Energy-efficient multi-stream carrier aggregation for heterogeneous networks in 5G wireless systems IEEE Trans. Wireless Commun. 15 7432-43
[13] Bhamri A, Hooli K and Lunttila T 2016 Massive carrier aggregation in LTE-advanced pro: impact on uplink control information and corresponding enhancements IEEE Commun. Mag. 54 92-97
[14] Zhang R, Zheng Z, Wang M, Shen X and Xie L L 2014 Equivalent capacity in carrier aggregation-based LTE-A systems: a probabilistic analysis IEEE Trans. Wireless Commun. 13 6444-60
[15] Zhao L Y, Yeung L K and Wu K L 2014 A coupled resonator decoupling network for two-element compact antenna arrays in mobile terminals IEEE Trans. Antennas Propag. 62 2767-76
[16] Qian K W, Zhao L Y and Wu K L 2015 An LTCC coupled resonator decoupling network for two antennas IEEE Trans. Microw. Theory Techn. 63 3199–3207
[17] Zhao L Y, Qian K W and Wu K L 2014 A cascaded coupled resonator decoupling network for mitigating interference between two radios in adjacent frequency bands IEEE Trans. Microw. Theory Techn. 62 2680–88
[18] Yanakiev B, Nielsen J O, Christensen M and Pedersen G F 2012 On small terminal antenna correlation and impact on MIMO channel capacity IEEE Trans. Antennas Propag. 60 689-99
[19] Foschini G J and Gans M J 1998 On limits of wireless communications in a fading environment when using multiple antennas Wireless Pers. Commun. 6 311-335
[20] Wang C W, Xiao S S, Wang W D, Wang C and Liu S J 2015 An analytical approach for antenna performance evaluation for MIMO systems IEEE Int. Symp. on Antennas and Propagation (Hobart) pp 1-4
[21] Pozar D M 2011 Microwave Engineering, 4th Edition (New York: Wiley) p 192