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Lau, Buon Kiong; Ying, Zhinong

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Antenna Design Challenges and Solutions for Compact MIMO Terminals

Buon Kiong Lau*(1) and Zhinong Ying(2)

(1) Department of Electrical and Information Technology, Lund University, Box 118, SE-221 00 Lund. Sweden
Email:Buon_Kiong.Lau@eit.lth.se

(2) Corporate Technology Office, Sony Ericsson Mobile Communications AB, SE-221 88 Lund, Sweden
Email:Ying.Zhinong@sonyericsson.com

ABSTRACT: The design of antennas for compact multiple-input multiple-output (MIMO) terminals is a challenging feat, due to the space constraint and the physical structure of the terminal. The space constraint forces the antennas to be closely spaced, which degrades MIMO performance due to high signal correlation and low antenna efficiency. Moreover, the terminals are equipped with ground planes which further complicate the implementation of antennas for good MIMO performance. This paper elaborates on the two aforementioned challenges in MIMO antenna design and surveys recent techniques that are developed to address these challenges.

INTRODUCTION

The design of conventional single antennas for mobile terminals remains an interesting research topic today, partly due to the ever increasing number of frequency bands that should be covered by the antennas, without a corresponding increase in the volume provided for antenna implementation. However, the recent adoption of multiple-input multiple-output (MIMO) technology in all major wireless communication standards highlights that antenna researchers must now consider the co-existence of multiple antennas that cover the same frequency band(s) within a given terminal device.

Although the design of multiple antennas is not new from the perspective of antenna arrays, the focus in the past has been on the implementation of large phased arrays for radar applications. To a limited extent, antenna arrays have also been experimented and implemented in base stations for cellular communications (*e.g.*, by Arraycomm LLC, USA). In these applications, the physical size of the array structure is typically not an important design issue. For example, it is desirable for phased array applications to impose antenna spacing of around half-a-wavelength ($\lambda/2$), in order to both maximize array aperture and circumvent the problem of ambiguity in direction-of-arrival estimation. Conveniently, this spacing requirement also ensures that the array does not suffer from severe mutual coupling. In this context, the design of multiple antennas for compact MIMO terminals can be interpreted as an application-driven research topic, where the main interest is to achieve good MIMO performance in the case that the antenna spacing can be less than $\lambda/2$.

Extensive research efforts have been made in recent years to study the impact of closely spaced antennas on MIMO performance, some of which have been directly towards the special case of compact mobile terminals (see [1] and references therein). In this paper, we briefly present several recent advances in this research area. First, the focus is on the problem of coupling [1]-[3] and a new metric to characterize the system performance of MIMO antennas [4]. Then, we outline strategies to mitigate the problem of coupling, *i.e.*, decoupling the antennas [5]-[8] or matching the antenna to the environment [9],[10]. This is followed by the use of the theory of characteristic mode to analyze the negative impact of ground plane excitation on the performance of MIMO antennas [11],[12]. Finally, we present several practical techniques that may be used to mitigate performance degradation resulting from ground plane excitation [11]-[13].

COUPLING EFFECTS AND MIMO ANTENNA CHARACTERIZATION

The impact of coupling on MIMO performance has been analyzed for two multiband antennas in a representative terminal prototype, consisting of the two antenna elements on a compact ground plane [1]-[3]. In particular, it is found that severe degradation in diversity [2] and capacity [3] performance can be expected when the antenna spacing (in wavelength) is small, which is the case for frequency bands lower than 1 GHz and a typical ground plane (or chassis) with surface dimensions of 100 mm × 40 mm.

Although diversity gain and capacity are widely accepted metrics to characterize the performance of MIMO systems, they are not uniquely defined. For example, diversity gain (in dB) is evaluated at a certain outage probability level (*e.g.*, 1%, 10% and 50%), whereas capacity (in bits/s/Hz) is calculated based on a reference signal-to-noise ratio (SNR) value (*e.g.*, 10 dB and 20 dB). The lack of universal reference values for the outage probability level and SNR complicates the use of these metrics for comparison between different MIMO antennas. Moreover, depending on the reference antenna, diversity gain is described as apparent, effective, or actual diversity gain. Similarly, capacity can be given for equal or waterfilling power allocation, depending on the availability of channel knowledge at the transmitter. Therefore, it is beneficial for MIMO antenna designers to have a metric that is uniquely defined and simple enough for their purpose.

In this context, the *multiplexing efficiency* (η_{mux}) of a given M-element MIMO antenna is defined as the SNR required by the ideal $M \times M$ i.i.d. Rayleigh channel to achieve an ergodic capacity minus the required SNR to achieve the same ergodic capacity for the MIMO antenna under test [4]. For high SNRs, η_{mux} reduces to the closed form [4]

$$\eta_{\mathrm{mux}} = \left(\prod_{i=1}^{M} \eta_i \right)^{\frac{1}{M}} \det(\mathbf{R})^{\frac{1}{M}} = \overline{\eta}_g \det(\mathbf{R})^{\frac{1}{M}}, \quad 0 \le \eta_{\mathrm{mux}} \le 1, , \tag{1}$$

where $\overline{\eta}_g$ is the geometric mean of the antenna efficiencies, η_i is the total efficiency of the ith antenna element, $[\mathbf{R}]_{ii} = 1, i = 1, \ldots, M$ and $[\mathbf{R}]_{ij}$ is the complex correlation between the 3D radiation patterns of antennas i and j. It is observed in (1) that η_{mux} consists of the geometric mean of the antenna efficiency, as well as the loss of efficiency due to correlation. Thus, η_{mux} can be seen as a generalization of the concept of total efficiency to the multiple antenna case.

DECOUPLING TECHNIQUES FOR COMPACT MIMO ANTENNAS

To counteract the performance degradation in MIMO antennas due to mutual coupling, different strategies have been devised to achieve decoupling (or improve isolation) among the antennas. In broad terms, they can be classified into two categories [1]: (1) circuit-level decoupling, and (2) antenna-level decoupling.

Circuit-level decoupling is achieved by inserting a matching network which realizes conjugate match for the antenna impedances (so called “multiport conjugate match" in some literature). The circuit decoupling approach is convenient in that it only requires the knowledge of antenna impedances and does not need to modify the antenna structure. However, its usefulness can be limited by the size of the matching circuit, especially if it is realized with distributed elements, due to their dimensions being proportional to the signal wavelength. On the other hand, circuit miniaturization can be achieved by equivalent circuits of lumped elements. For the conjugate matching circuit that employs a hybrid 180° coupler [1], an equivalent lumped element circuit has been used to decouple two monopoles of 0.1λ spacing [5]. The corresponding scattering parameters are given in Fig. 1 [5]. The even mode (S_{11}) is observed to give significantly larger bandwidth than the odd mode (S_{22}), which implies that the approach may be suitable for systems (*e.g.*, LTE) which only require MIMO operation in the downlink. One drawback in using decoupling circuits is the relatively low measured total efficiency of one or more of the decoupled ports (*e.g.*, [6]), though no detailed analysis has yet been performed.

Antenna-level decoupling [1] requires modification of the multiple antenna structure in one way or another, and can be achieved using many different approaches, including ground plane modification, neutralization line, parasitic scatterers, and polarization diversity. In particular, the use of parasitic scatterer has been found to be an attractive alternative to circuit decoupling, since it replaces the decoupling circuit with a reactively loaded parasitic antenna and the parasitic-decoupled antennas have been measured to be relatively efficient. For a two-monopole setup with 0.1λ spacing, the total efficiency loss of each monopole is only about 0.5 dB when compared to an isolated single monopole [7].

Another promising antenna-level approach to achieve good isolation (or orthogonality) among antenna ports is to use dielectric resonator structures to realize polarization diversity among the antenna ports. As a proof of concept, a compact 6-port antenna structure that consists of two three-port dielectric resonator antennas (DRAs) is proposed in [8]. Though compact, the DRA array efficiently utilizes polarization, angle and space diversities to extract available degrees of freedom in the channel, as has been experimentally verified in both line-of-sight (LOS) and non-LOS indoor office scenarios (see Tab. 1). The 6-monopole array used for comparison is significantly larger in size and exploits only spatial diversity. Capacity with no channel knowledge at the transmitter is calculated at 10 dB SNR for the reference case (Case I). For fair comparison, the channels for Cases II and III are normalized to the reference case.

In general, perfect decoupling of closely spaced antennas with a coupled matching network or a parasitic scatterer is achieved with additional complexity and at the cost of narrow bandwidth [1]. Consequently, one may consider the use of uncoupled matching network to optimize MIMO performance [9],[10]. In fact, it is shown in [10] that the condition for multiport conjugate match can be realized with uncoupled matching, providing that the matching network can adapt to the instantaneous channel realization. Due to technological constraint, it is more practical to optimize MIMO performance according to the statistics of the channel. It has been shown that for some channel conditions, the performance of the optimal uncoupled matching network approaches that of the coupled matching network [10].

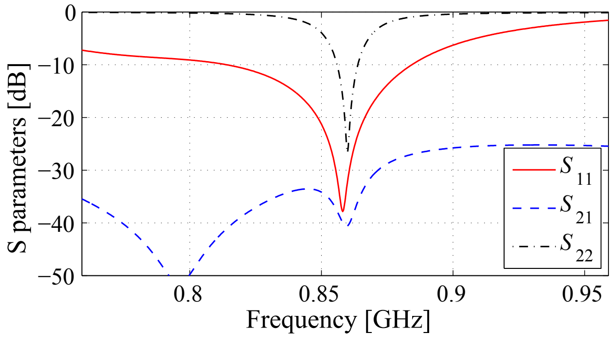

Fig. 1. Scattering parameters of two-monopole array with circuit of lumped elements.

Tab. 1 Capacity of 6 × 6 MIMO Antennas in Indoor Office Scenarios [8]

		Case I	Case II	Case III
6-port transmit array		Monopole	Patch	Patch
6-port receive array		Monopole	Monopole	DRA
Ergodic capacity [bits/s/Hz]	LOS	12.4	12.1	10.6
	NLOS	12.1	14.7	12

CHARACTERISTIC MODE ANALYSIS AND MITIGATION OF GROUND PLANE EFFECTS

It is commonly accepted that coupling increases as the spacing between the antennas decreases. However, in the case of compact MIMO antennas on a shared ground plane, a more dominant coupling mechanism occurs when more than one antenna element efficiently exploit the ground plane as a radiator [2],[11],[12]. This phenomenon of ground plane radiation has been studied primarily in the context of single antennas using different approaches, including the use of equivalent circuit and theory of characteristic mode. The focus in the single antenna case is to exploit the ground plane to improve the radiation characteristics of the antenna element, such that the antenna element can be seen as a "coupling element" which effectively excites the ground plane. In contrast, multiple antenna elements should avoid exciting the same characteristic radiation mode of the ground plane, since this will cause severe coupling as mentioned above. In [11],[12], the first characteristic resonance of a 100 mm × 40 mm ground plane is shown to occur near the GSM900 band. The characteristic electric field corresponding to this resonance has two maxima, one at each of the two shorter edges of the ground plane, whereas the minimum occurs at the center of the ground plane. This implies that in order to limit coupling due to common excitation of the ground plane, only one antenna should excite ground plane radiation.

A detailed parametric study has been performed based on the insight gained from characteristic mode analysis and the results indicate that isolation can be significantly improved by optimizing both the antenna type and the antenna location [11], although bandwidth performance may deteriorate. In reality, an improvement in isolation is only meaningful if it brings about an improvement in the system performance (*e.g.*, diversity gain and capacity). It is confirmed that both capacity and diversity performance for a given bandwidth can be improved using this simple approach of optimizing the antenna placement and type. One significant advantage of this approach is that no additional (and inherently lossy) lumped element or matching circuit is required to attain better MIMO performance.

One insight gained from the initial work in [11] is that the antenna type can influence the degree of isolation between the antennas. For example, the ground plane excitation current is less localized for monopoles than PIFAs. Thus, it is interesting to investigate the potential use of antennas with highly localized ground plane currents. This study is performed with two antennas on a 100 mm × 40 mm ground plane. A monopole is placed at one shorter edge of the ground plane, and a PIFA on the other shorter edge. The characteristics of the prototype is studied for dielectric loadings of different permittivity values (ε_r = 1, 6, 20) for the PIFA [13]. The simulation results for the case of lossless materials are summarized in Tab. 2. The ergodic capacity with no channel knowledge at the transmitter is obtained for the center frequency (f_c) and 6 dB impedance bandwidths of 10 MHz and 20 MHz, at a reference SNR of 20 dB. The MIMO channel is obtained using the Kronecker model with uniform 3D angular power spectrum at the receive end. The prototype's total antenna efficiency and correlation are taken into account in the receive correlation matrix. The transmit antennas are assumed to be uncorrelated. As the PIFA becomes more localized by the increase of ε_r (see Tab. 2), the efficiency of the PIFA and monopole antenna increases due to reduced mutual coupling. On the other hand, the bandwidth of the PIFA greatly decreases from 23 MHz to 8 MHz (the bandwidth of monopole is very much larger and does not change significantly). Nevertheless, the average capacity over 20 MHz still increases by 1.3 bits/s/Hz. This can be explained by the increase of the antenna efficiency. When the bandwidth becomes larger, the improvement is less obvious. The simulated case with lossy materials give slightly different results [13], but an improvement in capacity can still be observed. Therefore, localizing the excitation current is a promising technique for achieving good MIMO performance for closely coupled terminal antennas. Moreover, the PIFA with $\varepsilon_r = 20$ is significantly smaller than the PIFA with $\varepsilon_r = 1$, which indicates antenna miniaturization is an additional benefit of this technique.

Tab. 2 Antenna performance for lossless materials [13]

		$\varepsilon_r = 1$	$\varepsilon_r = 6$	$\varepsilon_r = 20$
Total efficiency of antennas at f_c	PIFA	40%	53%	55%
	monopole	34%	53%	55%
Bandwidth of PIFA (MHz)		23.2	14.2	8
Correlation at f_c		0.57	0.6	0.55
Ergodic capacity [bits/s/Hz]	at f_c	5.9	7.4	7.8
	10 MHz	5.9	7.2	7.3
	20 MHz	5.8	7.1	7.1

CONCLUSIONS

This paper briefly surveys several latest advances in the area of multiple antenna design for compact terminals. The design problem has been presented under the framework of understanding and overcoming the problem of coupling between closely spaced antennas. Moreover, it is explained that the ground plane can contribute to significantly higher coupling, when the antenna elements exploit the shared ground plane for radiation. Several strategies that have been devised to alleviate this problem are shown to improve not only isolation, but also the overall MIMO performance.

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REFERENCES

[1] B. K. Lau, “Multiple antenna terminals,” in *MIMO: From Theory to Implementation*, C. Oestges, A. Sibille, and A. Zanella, Eds., San Diego: Academic Press, 2011, pp. 267-298.

[2] V. Plicanic, B. K. Lau, A. Derneryd, and Z. Ying, “Actual diversity performance of a multiband antenna with hand and head effects,” *IEEE Trans. Antennas Propagat.*, vol. 57, no. 5, pp. 1547-1556, May 2009.

[3] V. Plicanic Samuelsson, B. K. Lau, A. Derneryd, and Z. Ying, “Channel capacity performance of multi-band dual antenna in proximity of a user,” in *Proc. Int. Workshop Antenna Technol. (IWAT)*, Santa Monica, LA, 2009.

[4] R. Tian, B. K. Lau and Z. Ying, “Multiplexing efficiency of MIMO antennas,” *IEEE Antennas Wireless Propagat. Lett.*, in minor revision.

[5] M. Håkansson, “Decoupling techniques for a multi-band MIMO antenna system,” *Master Thesis*, Department of Electrical and Information Technology, Lund University, Sweden, Nov. 2010.

[6] C. Volmer, M. Sengul, J. Weber, R. Stephan, and M. A. Hein, “Broadband decoupling and matching of a superdirective two-port antenna array,” *IEEE Antennas Wireless Propagat. Lett.*, vol. 7, pp. 613-616, 2009.

[7] B. K. Lau and J. B. Andersen, “Simple and efficient decoupling of compact arrays with parasitic scatterers,” *IEEE Trans. Antennas Propagat.*, in press.

[8] R. Tian, V. Plicanic, B. K. Lau, and Z. Ying, “A compact six-port dielectric resonator antenna array: MIMO channel measurements and performance analysis,” *IEEE Trans. Antennas Propagat.*, vol. 58, no. 4, pp. 1369-1379, Apr. 2010.

[9] J. B. Andersen and B. K. Lau, “On closely coupled dipoles in a random field,” *IEEE Antennas Wireless Propagat. Lett*., vol. 5, no. 1, pp. 73-75, 2006.

[10] M. Jensen and B. K. Lau, “Uncoupled matching for active and passive impedances of coupled arrays in MIMO systems,” *IEEE Trans. Antennas Propagat*., vol. 58, no. 10, pp. 3336-3343, Oct. 2010.

[11] H. Li, Y. Tan, B. K. Lau, Z. Ying, and S. He, “Characteristic mode based tradeoff analysis of antenna-chassis Interactions for multiple antenna terminals,” *IEEE Trans. Antennas Propagat*., under major revision.

[12] H. Li, B. K. Lau, Z. Ying, “Optimal multiple antenna design for compact MIMO terminals with ground plane excitation,” *Int. Workshop Antenna Technol. (iWAT)*, 2011, in press.

[13] H. Li, B. K. Lau, Y. Tan, and Z. Ying, “Impact of current localization on the performance of compact MIMO antennas,” *Europ. Conf. Antennas Propagat. (EuCAP)*, 2011, in press.