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Unleashing Multiple Antenna Systems in Compact Terminal Devices

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ABSTRACT: The effective use of multiple antenna systems in compact terminal devices is plagued by the problems of mutual coupling and spatial correlation. Consequently, increasing the number of antennas per unit volume results in rapidly diminishing returns after an upper limit is reached. We review recent advances on this topic of closely coupled antennas, including several existing techniques that may be used to push the boundary further, such that closely spaced antennas can still give good performance. A new approach of decoupling closely spaced antennas is also introduced.

INTRODUCTION

Today, it is well known that multiple antenna systems are able to bring about significant improvements in wireless communications. For mobile communications, the first step to apply this technology was taken at the introduction of diversity reception at base stations. This was later followed by the so-called smart antennas or adaptive antennas, which relies on array beamforming techniques to achieve system performance improvements [1]. Both these techniques are only implemented at the base station side, since the complexity was considered to be too high for mobile terminals, and the improved performance was already "good enough" at the time.

Nevertheless, the search was on for even better ways of improving the performance of wireless systems. In the late 1990s, the idea of using multiple antennas at both the transmit and receive ends to pave the way for simultaneous transmission of multiple data streams [2] finally started to gain momentum as one such breakthrough [3], [4]. Due to the limited availability of radio frequency spectrum, a technique which enables the data rate to increase linearly with the number of antennas for a given frequency bandwidth has a particularly strong appeal. The technique is commonly known as multiple-input-multiple-output (MIMO), although strictly speaking, the term may also encompass diversity and beamforming techniques, since these techniques can also be utilized in multiple antennas at both link ends.

Notwithstanding, applying multiple antenna techniques at both ends of the mobile communication system implies that the mobile terminal must be equipped with multiple antennas. Since mobile devices typical have compact form factors, the finite footprint of the antenna elements impose an upper limit on the number of antennas that may be present. More importantly, even though electromagnetic coupling between transmit and receive antennas is the enabling mechanism for wireless communications, the co-existence of co-polar multiple transmit or receive antennas that are closely spaced result in a loss of antenna efficiency and a high signal correlation. Depending on the level of coupling and spatial separation, these effects can drastically reduce the performance gains of multiple antenna systems. Thus, this degradation is analogous to the limited availability of frequency spectrum in that the performance of multiple antenna systems is limited by the spatial volume it occupies.

In this paper, we continue the story in [5] and review some recent results on the topic. We begin by quantifying the impact of coupling and correlation on MIMO diversity and capacity performance for closely spaced antennas on terminal antennas [6]-[10]. This is followed by a summary of recent advances in the use of adaptive impedance matching to unleash the potential of compact MIMO systems [11]-[15]. Then, the prediction of MIMO performance based on only the magnitude of the antenna pattern [16],[17] and the direction-of-arrival estimation of compact arrays with impedance matching [18] are briefly reviewed. Finally, a new and simple complete decoupling approach for compact arrays is briefly introduced.

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PERFORMANCE OF CLOSELY SPACED MOBILE TERMINAL ANTENNAS

Although a significant number of studies have been made on the subject of diversity and MIMO techniques in small devices, most are based on simple single-band antennas that are either distinct in polarization or separated by more than half-a-wavelength. This means that these antennas are almost unaffected by the problem of coupling and correlation. Moreover, such antennas may not lend themselves to practical implementations according to today's requirements and trends. Thus, several recent studies focus on diversity [6]-[8] and capacity [9], [10] performance of common mobile phone antennas – compact, internal-to-chassis, multiband, low cost and robust. The effect of user is also investigated in [7]-[10]. For diversity performance, it was found that when antennas are separated by 1/4 of a wavelength, coupling and correlation contribute to a 4 dB loss in diversity gain, at the 1% probability level [6]. The metric of *actual diversity gain* was used to quantify the diversity gain that may be achieved for the diversity antenna setup, when referred to a single antenna solution in the same user setup [7]. The actual diversity gain was found to be 5-10 dB (5 dB for no user case) for the 850 MHz band, and 8-12 dB (10 dB for the no user case) for the higher bands of 1800 MHz and 2100 MHz, which suggests that user interaction can in fact be beneficial, when the single antenna reference has the same user interaction. The ergodic capacity gain for the same prototype is 40-90% (40% for no user case) at 850 MHz and 60-80% (70% for no user case) at 2100 MHz, comparing with a single antenna prototype under the same user interaction [10]. Again, the actual gains strongly depend on the user scenario, and can approach the ideal gain of twice the capacity.

ADAPTIVE MATCHING FOR MULTIPLE ANTENNAS

Adaptive matching is an effective tool to mitigate the problem of coupling and correlation, as it allows one to optimize closely coupled arrays against MIMO performance, e.g. capacity [5]. One added benefit is that it also adapts to the random environment as seen by the array, which for mobile communications include both user interaction and propagation effects [11]. Although the focus has been on adaptive matching networks which are uncoupled across the antennas, the concept applies to multiport matching networks as well [11]. A more comprehensive parametric study in [12] clearly illustrates that the optimum matching condition for capacity gain strikes a compromise between the correlation and received power performance. Not surprisingly, the relative performance gains of adaptive matching over conventional fixed matching strongly depends on the propagation environment [12]. A further investigation in [13] indicates that if the uncoupled matching networks are separate parameters in the capacity optimization, such that there are $2N$ parameters for N antennas, instead of only 2 parameters in the simple case of identical matching for N antennas as in earlier studies, the optimum capacity can be higher than the simple case. This approach is more effective with increased asymmetry between the propagation environment and the array geometry, as can be understood by drawing an analogy between impedance matching "weights" with array weights in beamforming applications. Some experiments were also performed to verify the key principles of the adaptive matching idea [14]. Another recent contribution is the derivation of a closed form solution for capacity optimization with uncoupled matching for closely spaced arrays [15].

ESTIMATING CAPACITY WITH MAGNITUDE ONLY ANTENNA PATTERNS

With the expected large scale introduction of multiple antenna terminals in the near future, mobile phone manufacturers and network operators are keen to find simple but effective ways of characterizing the performance of such terminals. Conventional test methods based on total radiation power (TRP) and total isotopic sensitivity (TIS) are designed for single (multiband) antenna terminals, and are inadequate for the multiple antenna case. One simple approach is to only use the magnitude of the antenna patterns, which can be measured for the device under test (DUT) by simply disabling the transmission from all except one antenna, in succession. The phase of the antenna patterns are not as easily obtained due to the strict timing requirement [16]. However, one can synthesize phase information in the measured magnitude only antenna patterns. For antennas that are well separated in polarization and/or spatial distance, adding randomly generated phase from a uniform distribution between 0 and 2π appears to give similar capacity performance to the case when the correct phase information is available [16]. However, a refined phase synthesis approach based on the antenna spacing and the correlation of the magnitude patterns is needed when the coupling and correlation is significant [17].

IMPEDANCE MATCHING AND DIRECTION FINDING

The direction-of-arrival (DOA) estimation of closely spaced antennas may provide useful location-related information and give insights into different multiple antenna algorithms [18]. Although coupling can reduce the antenna efficiency and thus the received SNR, the antenna patterns can become more directional, which is favourable for DOA estimation. However, if multiport conjugate matching is used, then both high efficiency and pattern directionality can be maintained. This leads to the interesting conclusion that closely spaced arrays can still give good DOA estimation [18].

COMPLETE DECOUPLING WITH A PARASITIC ANTENNA

Although multiport conjugate matching is able to provide complete decoupling between closely spaced antennas, its implementation involves interconnecting the antenna ports to a lossy multiport matching network that has a finite footprint. On the other hand, one can place a load terminated parasitic antenna ("antenna 2") in the midpoint of the closely coupled active antennas ("antennas 1 and 3") to achieve the same result of complete decoupling. The self and mutual impedances of the antennas are Z_{ii} and $Z_{ij,}\ i \neq j$, respectively, where $i, j \in \{1,2,3\}$, and Z_L is the impedance load of the parasitic antenna. For convenience and without loss of generality for single mode antennas (or multimode antennas with a dominant mode), we describe the decoupling procedure for the case of simple dipoles and assume the same length L and thickness for three antennas. We begin by showing the equivalent impedance matrix for the active antennas, which is obtained by substituting for the current in the parasitic element

$$\mathbf{Z}' = \begin{bmatrix} Z_{11}' & Z_{13}' \\ Z_{31}' & Z_{33}' \end{bmatrix}, \tag{1}$$

where $Z_{11}' = Z_{11} - Z_{12}^2 / (Z_{22} + Z_{L2})$, $Z_{13}' = Z_{13} - Z_{12}Z_{23} / (Z_{22} + Z_{L2})$, $Z_{33}' = Z_{11}'$, $Z_{31}' = Z_{13}'$, with the unprimed quantities are for the original 3 by 3 case, and the primed are for the reduced 2 by 2 equivalent representation. In order to perfectly decouple the two antennas we require $Z_{13}' = 0$, which translates into

$$Z_L = Z_{12}Z_{23} / Z_{13} - Z_{22}\,, \tag{2}$$

and since the real part of (2) must be zero for a lossless decoupling, we arrive at a condition that must be satisfied,

$$\mathrm{Re}\{Z_{12}Z_{23}/Z_{13}\} = \mathrm{Re}\{Z_{22}\}\,. \tag{3}$$

This is achieved by adjusting the length of the dipoles L slightly. After (3) is satisfied the reactive loading $X_L = \mathrm{Re}\{Z_L\}$ may be found from $X_L = \mathrm{Im}\{Z_{12}Z_{23}/Z_{13}\} - \mathrm{Im}\{Z_{22}\}$. To complete the design procedure, the new input impedance of the dipole Z_{11}' should be matched to that of the feed cable, as is also needed even for isolated dipole antennas.

To give a numerical example, the impedance matrix of two closely coupled (active) dipoles and a parasitic dipole are obtained from a method of moments software. The two active dipoles are separated by 0.1λ, where λ is the wavelength of the signal, and the parasitic antenna is at their midpoint. Following the above design procedure, two solutions are found for condition (3), corresponding to $L = \{0.377\lambda, 0.482\lambda\}$ and the reactance loads $X_L = \{137.2\Omega, 21.2\Omega\}$, respectively. Any one of the two solutions ensures that $Z_{13}' = 0$. Finally, a simple matching network consisting of distributed elements of transmission line and open-circuited stub is used to match the input impedance of the antenna to the characteristic impedance of 50 Ω. The S-parameters of the matched active antennas are plotted in Fig. 1.

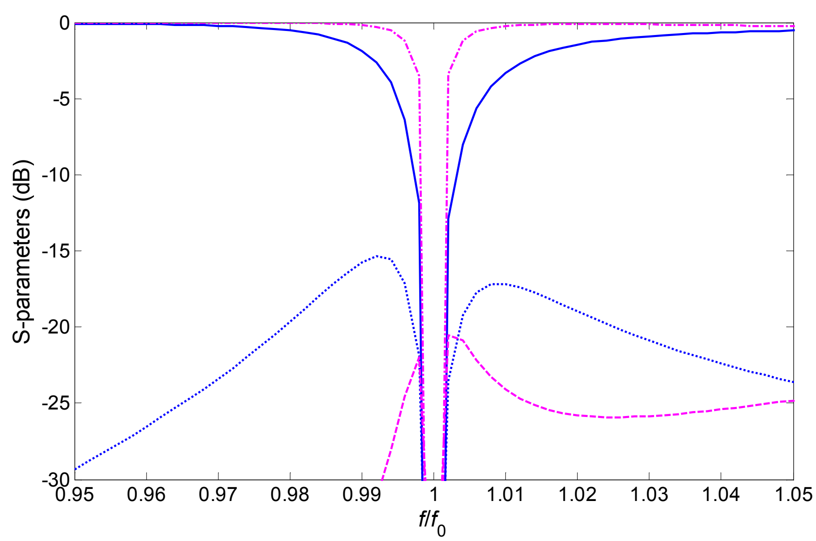

Fig. 1. S-parameters of decoupled active antennas for (i) $L = 0.377\lambda$, S_{11}' (- · - · -), S_{13}' (— — —) and (ii) $L = 0.482\lambda$, S_{11}' (——), S_{13}' (··········).

As may be observed from Fig. 1, both solutions achieve complete decoupling between the active dipoles at the center frequency $f = f_0$. However, they offer different impedance bandwidths. Not unexpectedly, the longer dipole solution (i.e., the physically larger array system) of $L = 0.482\lambda$ gives the larger bandwidth.

CONCLUSIONS

The paper surveys some recent work on multiple antennas in compact devices, starting with a study of the coupling and correlation problem for mobile phones in typical user scenarios. Some countermeasures to allow more antennas to be included while maintaining the required performance are then introduced. Practical issues of benchmarking compact mobile devices and direction-finding for compact devices are briefly discussed.

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