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Publication date:
2006

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Lau, B. K., Andersen, J. B., Molisch, A., & Kristensson, G. (2006). *Antenna Matching for Capacity Maximization in Compact MIMO systems*. Paper presented at 3rd International Symposium on Wireless Communications Systems, invited, Valencia, Spain.

Antenna Matching for Capacity Maximization in Compact MIMO systems

Invited Paper

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***Abstract*—As MIMO technology slowly matures, it is finding its way into more wireless applications. However, some important applications, including mobile communications, require compact implementations. One important challenge in miniaturizing MIMO systems for compact terminals is to overcome capacity performance degradation resulting from mutual coupling among closely separated antennas. In this contribution, we begin with a review of the state-of-the-art, with particular emphasis on impedance matching and its impact on capacity. Whereas it has been shown that a multiport extension of the conjugate match is optimum in a reference environment with uniform 3D angular power spectrum, its bandwidth is severely reduced by decreasing antenna separation. On the other hand, noncoupled, individual port matching is inherently simpler to implement and broader in bandwidth, but offers a smaller capacity. Here, we demonstrate that mean capacity can be easily maximized with respect to individual port matching in a given random field. The extent of capacity gains provided by the optimized matching network over existing individual port matching networks strongly depends on the propagation environment.**

Keywords-MIMO systems; compact; mutual coupling; capacity; correlation; impedance matching; optimization

I. INTRODUCTION

Although multiple antenna technology has been around for over half a century, its usage has been limited to physically large systems such as ground based radar systems and cellular base stations [1], [2]. One critical barrier to its implementation in compact systems is the problem of high signal correlation among antennas that are packed into a small (in wavelength units) spatial volume. The advent of multiple-input multiple-output (MIMO) technology [3]-[8] only serves to highlight the shortcomings of compact implementations, as low signal correlation at *both* ends of the communication system is necessary to realize the full potential of MIMO system, i.e., linear channel capacity increase with the number of transmit and receive antennas.

Small spatial separation of the antennas not only leads to correlation of the associated signals, but also gives rise to electromagnetic interactions among the antennas (or mutual coupling), which in turn distorts antenna characteristics such as radiation pattern and input impedance [9], [10]. This distortion can impact the capacity of MIMO systems in two ways: (i) it can introduce (or add to) dissimilarity between the antenna patterns and thus reduce signal correlation to a degree; (ii) it can induce a loss of radiation efficiency due to an increase in impedance mismatch between the typically 50Ω feed line and the antenna input. While the former effect tends to improve capacity, the latter decreases it. Mutual coupling can thus have an either positive or negative effect on MIMO system performance.

The remainder of this paper is organized as follows. Section II gives a review of the state-of-the-art on antenna matching for performance improvements. The MIMO system model in the commonly used Z-parameter representation is the subject of Section III. The performance metrics of output correlation, received power and mean capacity are provided in Section IV. Section V summarizes existing individual port matching networks, and proposes two novel matching networks which maximize received power and mean capacity, respectively. A numerical study on the mean capacity of different matching networks individual port impedance matching is presented in Section VI. Section VII concludes the paper.

II. REVIEW OF ARRAY IMPEDANCE MATCHING

There is no disagreement in the impact of mutual coupling on correlation or diversity gain [9]-[15] and radiation efficiency [11], [16]. On the other hand, conflicting views arise on the impact of mutual coupling on capacity performance [13]-[20], with some papers claiming mutual coupling effects to be beneficial for capacity [13], while others either completely disagree [14], [18], [19], or indicate that its benefits apply only to selected cases (e.g. a range of antenna separations) [15], [16]. The discrepancy is largely due to different assumptions on the system setup, e.g. (i) the normalization used for channel matrix, (ii) whether the transmit power or the source voltage is kept constant, and (iii) whether antenna matching has been considered. In fact, with the exceptions of [12] and [16], these studies only employ simple matching circuits (such as 50Ω and open-circuit terminations).

This work was supported by VINNOVA (grant no. P24843-3).

Recently, it has been shown that the use of the so-called *multiport conjugate match* can simultaneously offer both zero return loss and zero correlation in a uniform 3D angular power spectrum (APS) for *any* antenna separation [12], [16]. At first glance, this seems to imply that at least in theory i.i.d. Rayleigh fading can be obtained in a fixed spatial volume for infinitely many infinitely thin antennas, and thus infinite capacity can be achieved.

However, the effectiveness of a matching network is limited by physics: (i) it can only facilitate perfect match (or zero return loss) for one frequency point; (ii) the bandwidth of a multiple antenna system reduces with antenna separation [21]-[25]. In the limit, as the antenna separation tends to zero, the bandwidth reduces to zero. Indeed, in the case of two half-wavelength ($\lambda/2$) electric dipole antennas, the correlation and efficiency (fractional) bandwidths for the multiport conjugate match are as small as 0.4% and 0.2%, respectively, for an antenna separation of 0.01λ [24]. This is in stark contrast with the > 10% bandwidth of a single dipole antenna [24]. In other words, information capacity which requires a non-zero bandwidth cannot grow infinitely with the number of antennas in a given volume. Moreover, the contrast between the narrowband and wideband mean capacities for multiport vs. individual port matching in [25] reveals that in practice the latter offers a broader bandwidth matching solution.

It is partly in this context that the individual port match (with no interconnection between the different ports of the matching circuits) has been more carefully investigated in [26]. In particular, it is shown that for a given environment, which is represented by an open-circuit correlation, it is possible to optimize the matching network, so that it yields low correlation or high received power. However, these two criteria appear to be in conflict with each other. It is worth pointing out that an earlier work [27] also presents related results on this topic, although it assumes real-valued antenna and load impedances.

Some further studies in [28] reveal that while optimum correlation and received power are sensitive to variations in the impedance matching load, the optimum capacity is more robust to such variations. A further result is that different complex open-circuit correlations of the same absolute value have been found to give different results for the MIMO performance metrics of received power, output correlation, and mean capacity, indicating that significant discrepancies can arise from neglecting the phase of complex correlations. A study of the interdependence of the aforesaid metrics was also performed. Whereas no obvious relationship could be found between received power and output correlation, as well as between output correlation and capacity, a strong relationship was observed between received power and capacity. As a result, good capacity performance can be expected from optimizing the load impedance for maximum received power.

Experimental studies in [29] largely confirm the analytical and simulation results in [26] and [28]. However, not unexpectedly, the super-directivity characteristics [30] observed in [26]-[28] could not be replicated in the experiments. This is due to both the difficulties in the precise localization of the narrow super-directivity peak and the significant ohmic power loss resulting from high current flow.

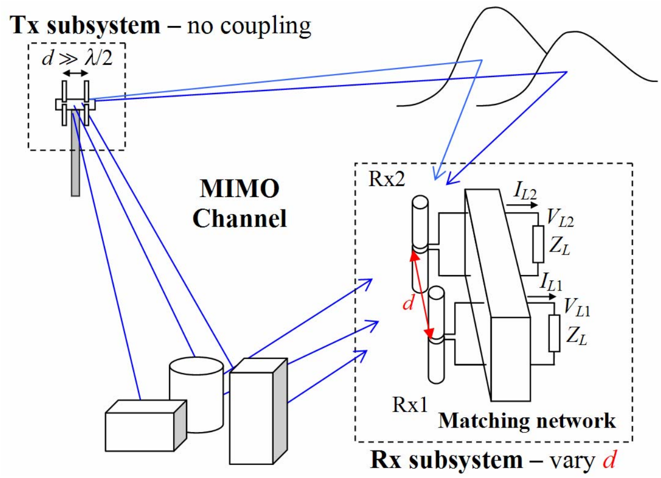

Figure 1. MIMO System Setup.

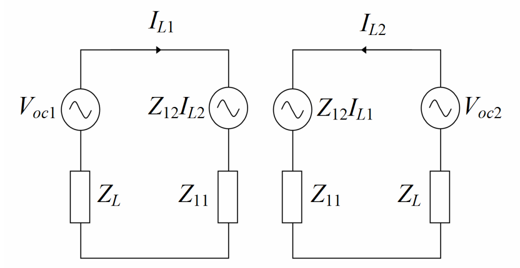

Figure 2. Equivalent circuit for receive subsystem.

III. MIMO SYSTEM MODEL

A. MIMO System Model

We consider the 2 × 2 MIMO system setup in Fig. 1 and identical vertically polarized half-wavelength ($\lambda/2$) electric dipole antennas of diameter $\lambda/400$. For simplicity, we assume that each of the two transmit antennas are conjugate matched and are sufficiently far apart such that there is no coupling/correlation between them. In other words, the requirement of small antenna separation d is on the receive end, as would occur, e.g., in cellular downlink transmission. Each receive circuit consists of a dipole terminated with a load impedance Z_L.

Two different mathematical representations are commonly used for the MIMO system of Fig. 1: the S-parameter (e.g. [12], [16], [20], [23]-[24]) and the more conventional Z-parameter (e.g. [10], [11], [15], [18], [27]). While the S-parameter representation is more suited for representing microwave systems, the Z-parameter representation is simple and more intuitive. The equivalent circuit of the receive subsystem is given in Fig. 2, where V_{oc1}, V_{oc2} denote open-circuit voltages of antennas 1 and 2, respectively, Z_{11} the self impedance of antenna 1 (or antenna 2) and Z_{12} the mutual impedance between antennas 1 and 2. For the transmit subsystem, the circuit diagram is equivalent to Fig. 1, with V_{oc1}, V_{oc2} replaced by V_{S1}, V_{S2} and Z_S by Z_L. In addition, using our earlier assumptions, it follows that $Z_{12} = 0$ and $Z_S = Z_{11}^*$.

On the transmit side, the excitation current is given by

$$\begin{bmatrix} I_{S1} \\ I_{S2} \end{bmatrix} = \frac{1}{2\,\mathrm{Re}(Z_{11})} \begin{bmatrix} V_{S1} \\ V_{S2} \end{bmatrix}. \tag{1}$$

The excitation currents are sources of radiation from the antennas and since they are sufficiently separated, the transmit antenna correlation is zero. On the receive end, however, the open-circuit voltages are highly correlated (with correlation α) due to the small antenna separation. Using the Kronecker model [31], the propagation channel is represented as

$$\mathbf{H}_{Ch} = \mathbf{\Psi}_R^{1/2}\mathbf{H}_{iid}(\mathbf{\Psi}_T^{1/2})^T, \tag{2}$$

where $$\mathbf{\Psi}_R = \begin{bmatrix} 1 & \alpha \\ \alpha^* & 1 \end{bmatrix},$$

and $\mathbf{\Psi}_T = \mathbf{I}$ (identity matrix) are the receive and transmit correlation matrices, respectively, each entry of the 2 × 2 matrix $\mathbf{H}_{iid}$ is a complex Gaussian random variable of zero mean and average power of 1.

At the receive subsystem (see Fig. 2), the excitation sources are the open-circuit voltages. The currents are given by

$$\begin{bmatrix} I_{L1} \\ I_{L2} \end{bmatrix} = \Bigg(\underbrace{Z_L\mathbf{I} + \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{12} & Z_{11} \end{bmatrix}}_{\mathbf{Z}}\Bigg)^{-1} \begin{bmatrix} V_{oc1} \\ V_{oc2} \end{bmatrix}. \tag{3}$$

The output (or load) voltage is then

$$\begin{bmatrix} V_{L1} \\ V_{L2} \end{bmatrix} = Z_L\mathbf{I}\begin{bmatrix} I_{L1} \\ I_{L2} \end{bmatrix}. \tag{4}$$

IV. PERFORMANCE METRICS

Antenna correlation has been used extensively to measure diversity gain [27]. The expressions for output correlation ρ and *total* mean received power P_T (relative to that of a reference conjugate matched single antenna) are given in (5) and (6), respectively, at the bottom of the page (see also [26]). The expression for MIMO capacity (assuming no CSI at the transmitter) is given by [28]

$$\begin{aligned} C &= \log_2 \det\left(\mathbf{I} + \frac{\gamma_{ref}}{2P_s}\mathbf{HQH}^H\right) \\ &= \log_2 \det\left(\mathbf{I} + 2\gamma_{ref}R_{11}R_L\mathbf{Z}^{-1}\mathbf{H}_{Ch}\left(\mathbf{Z}^{-1}\mathbf{H}_{Ch}\right)^H\right), \end{aligned} \tag{7}$$

where $Z_{11} = R_{11} + jX_{11}, Z_{12} = R_{12} + jX_{12}$, γ_{ref} the reference SNR, $\mathbf{Q} = P_{in}\mathbf{I}$, $P_{in} = 2\,\mathrm{Re}(Z_{11})|I_{S1}|^2$, $\mathbf{H}$ the overall channel or transfer function matrix between the transmit sources and the receive loads, P_s the average received power for a single antenna system with conjugate impedance match at both the source and load impedances (used to normalize $\mathbf{H}$).

V. IMPEDANCE MATCHING CONDITIONS

For the two-element receive array, we evaluate the capacity performance with respect to the characteristic impedance (or Z_0) match $Z_L = Z_0$, the self impedance match $Z_L = Z_{11}^*$ and the input impedance match [32]

$$Z_L = \sqrt{R_{11}^2 - R_{12}^2 + X_{12}^2 - \frac{R_{12}^2X_{12}^2}{R_{11}^2}} + j\left(\frac{R_{12}X_{12}}{R_{11}} - X_{11}\right). \tag{8}$$

The input impedance match takes into account both self and mutual impedances (8) and offers zero output correlation in uniform 3D APS for any antenna separation. A recent paper demonstrates that the input impedance match maximizes the effective diversity gain for two closely coupled dipoles in uniform 3D APS [33]. Whereas the input impedance match facilitates maximum power transfer from the single excited voltage source into the corresponding antenna port, it does not consider power coupled into the adjacent antenna. The latter dominates over radiated power at small antenna separations [24]. Therefore, the input impedance match does not maximize received power for the receive array [26].

It was demonstrated in [26] and [28] that there exist a global maximum for the received power, and likewise the mean capacity, over the domain of individual port matches. Here, we propose two optimum matching networks (maximum power match and maximum capacity match) based on the load impedances chosen corresponding to these two maxima. In order to find the maximum power match, a simple two-dimensional grid search can be performed using the closed form expression (6). The mean capacity is evaluated using the closed-form expressions of [34].

VI. NUMERICAL STUDY

For the numerical study, we investigate the relative merits of the five different matching networks described in Section V. In particular, the mean capacity over antenna separation is examined in two different propagation environments: uniform 2D APS and Laplacian 2D APS [8]. The open-circuit antenna patterns together with the self and mutual impedances of the two-dipole receive array are obtained from the method-of-moments (MoM) implementation of [35]. The open-circuit correlation α is then calculated using the open-circuit antenna patterns [28]. A reference SNR of 20 dB is assumed.

$$\rho = \frac{\alpha|Z_{11}+Z_L|^2 + \alpha^*|Z_{12}|^2 - 2\,\mathrm{Re}\left((Z_{11}+Z_L)Z_{12}^*\right)}{\sqrt{|Z_{11}+Z_L|^2 + |Z_{12}|^2 - 2\,\mathrm{Re}\left(\alpha(Z_{11}+Z_L)Z_{12}^*\right)}\sqrt{|Z_{11}+Z_L|^2 + |Z_{12}|^2 - 2\,\mathrm{Re}\left(\alpha^*(Z_{11}+Z_L)Z_{12}^*\right)}} \tag{5}$$

$$P_T = \frac{8\,\mathrm{Re}(Z_L)\mathrm{Re}(Z_{11})\left[|Z_{11}+Z_L|^2 + |Z_{12}|^2 - \mathrm{Re}\left(\alpha(Z_{11}+Z_L)Z_{12}^*\right) - \mathrm{Re}\left(\alpha^*(Z_{11}+Z_L)Z_{12}^*\right)\right]}{\left|(Z_{11}+Z_L)^2 - Z_{12}^2\right|^2} \tag{6}$$

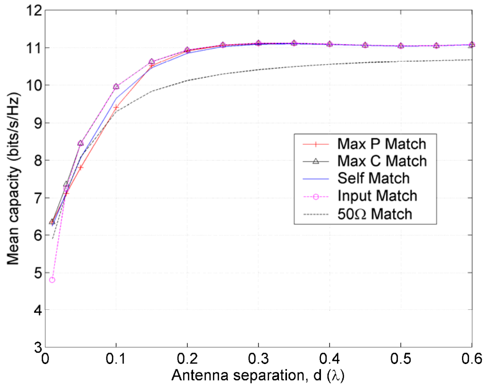

Figure 3. Mean capacity over antenna separations for different matching networks in uniform 2D APS.

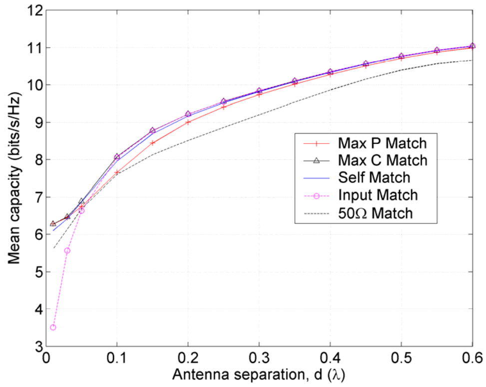

Figure 5. Mean capacity over antenna separations for different matching networks in Laplacian 2D APS.

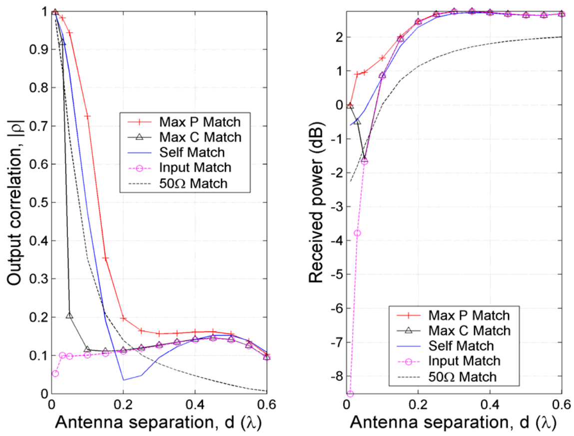

Figure 4. (a) Output correlation and (b) received power – over antenna separations for different matching networks in uniform 2D APS.

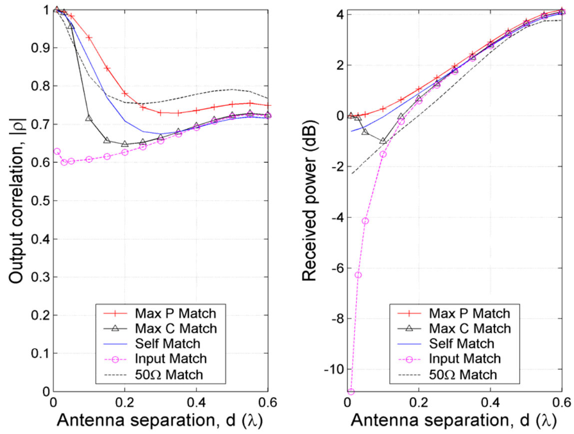

Figure 6. (a) Output correlation and (b) received power – over antenna separations for different matching networks in Laplacian 2D APS.

A. Uniform 2D APS

In Fig. 3, it can be seen that the 50Ω match has the worst overall capacity performance. This is due to a large impedance mismatch loss as can be seen in its received power curve in Fig. 4(b), even when the mutual coupling effect is small, i.e., for antenna separation $d > 0.5\lambda$. On the other hand, all other matching networks converge to the same capacity performance of around 11 bits/s/Hz for $d > 0.2\lambda$, which is close to the mean capacity of the corresponding Rayleigh i.i.d. case. The input match, which offers the lowest correlation values (see Fig. 4(a)), is able to retain the maximum capacity performance down to $d = 0.03\lambda$. Its demise for even smaller d is due to increasing proportion of received power being coupled into the adjacent antenna and re-scattered (Fig. 4(b)). The self impedance match has moderate correlation and received power, resulting in a capacity performance which lies between those of the 50Ω match and the maximum capacity match. As expected, the received power of the maximum power match is better than all other cases. However, since the correlation is highest among all cases, its capacity performance is even poorer than the self impedance match (cf. Figs 4(a) and 4(b)). Interestingly, the maximum capacity match gives neither the lowest correlation nor the maximum power, indicating that a suitable compromise between the two criteria is necessary for maximizing capacity.

B. Laplacian 2D APS

For the Laplacian 2D distribution, we choose the mean angle-of-arrival to be the array broadside and standard deviation to be 41.2°. In comparison to Fig 3, the mean capacities of all cases in Fig. 5 suffer from significant degradation, especially for moderate antenna separations. This is due to the smaller angular spread of the Laplacian 2D APS than that of the uniform 2D APS. For the input match, the larger difference between the Laplacian 2D APS and the uniform 3D APS (which gives zero correlation) also results in the capacity performance deteriorating with respect to the maximum capacity curve at $d < 0.1\lambda$ (as compared to $< 0.03\lambda$ in Fig. 3). As opposed to the previous case, the self match gives mean capacities that are close to that of the maximum capacities over the given range of d. This indicates that optimizing mean capacity gives only marginal gain over the simple self impedance match in this propagation environment.

Overall, some gains in mean capacity can be expected from implementing the proposed adaptive (or propagation-dependent) maximum capacity match. Moreover, the same technique for maximizing capacity can be extended to study cases involving user interactions, where the more complicated propagation mechanisms can give different conclusions.

VII. CONCLUSIONS

The focus of this contribution is on the role of impedance matching in determining MIMO capacity. While the use of multiport matching network can improve capacity, it is at the price of narrower system bandwidth, especially at small antenna separation. The more convenient individual port matching network, on the other hand, is inherently wider in bandwidth and is thus an attractive alternative for wideband capacity improvement. In this paper, we demonstrate that the mean capacity can be maximized with respect to load matching in a given random environment. The capacity gain of the optimized network over the existing matching network strongly depends on the propagation environment.

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