A comparison of matching strategies for RF transmission arrays based on network theory

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Introduction: Transmit array coils promise the possibility of tailored RF excitation fields, acceleration of spatially selective pulses, and SAR reduction. In order to provide optimal power transfer from the amplifiers the impedance matching to the coil array must account for back-scattering as well as coupling. In theory, a complete matching network interconnecting all ports could be designed to provide full power transfer ([1] conjugate match). Such a complete matching network is very difficult to put into practice for large port counts and sensitive to variations of coil parameters such as loading. Therefore transmit arrays are usually matched on a port by port basis and the question arises which single-port matching strategy will yield the best array performance. To address this problem we analyze three single-port methods, using general network theory in conjunction with signal statistics.

Theory: Figure 1 depicts a generic coil array considering only two coils for simplicity. The coils are viewed as composed of ideal decoupled impressed currents $\mathbf{b}_{coil,i}$ and a coupling network representing realistic coupling as represented by the impedance matrix Z seen by the matching circuitry at the coil ports. The matching circuits are uncoupled lossless two-port devices transforming the transmission line impedance (Z_{line}) to the output impedance Z_{out}. The value of Z_{out} was chosen by three different criteria to evaluate differences in amplifier power requirements:

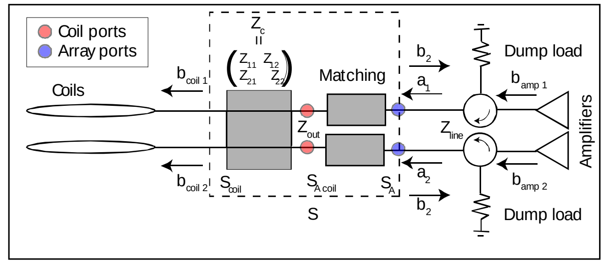

Figure 1: Setup

1. The target impedance for conjugate matching to was set to $\mathbf{Z}_{11}$ without accounting for Z_{12}. This approach was denoted as the *z match.*
2. The *input match* prevents any single port back-reflection ($\mathbf{S}_{ii}$=0) by conjugate-matching the port to the actual input impedance seen at the port: $Z_{in,i} = \sqrt{\mathbf{Z}_{ii}^2 - \frac{\mathbf{Z}_{ii}\mathbf{Z}_{12}^2}{\mathbf{Z}_{jj}}}$ where i, j = 1,2 and Z_{12} is the mutual impedance.
3. Controlling coupling by matching each port to the impedance of one of the eigenvalues of Z_c was denoted as the *mode match*.

Using the standard scattering (*S*) matrix formalism [3] the signal scattered by the array ports is dissipated in the dump loads, and hence by power conservation the signal going into the coils is given by $\mathbf{b}_{coil} = \Theta(1-\mathbf{S}_A^H\mathbf{S}_A)^{1/2}\mathbf{a} = \Theta(1-\mathbf{S}_A^H\mathbf{S}_A)^{1/2}\mathbf{b}_{amp}$. Here, $\mathbf{S}_A$ denotes the matrix that describes the scattering at the array ports (see Fig. 1) and $\mathbf{\Theta}$ is a diagonal matrix describing the phase delay of the signal from the port to the coil. The excess power rate R is defined as the relative additional power that the amplifiers must provide due the losses induced by back-scattering and coupling. It is calculated as the respective signal time correlation of the needed coil excitation waveforms:

$$R = Tr(\langle \mathbf{b}_{amp}(t), \mathbf{b}_{amp}(t) \rangle) / Tr(\langle \mathbf{b}_{coil}(t), \mathbf{b}_{coil}(t) \rangle)$$

$$= Tr(\mathbf{K}_c \underbrace{(1 - \mathbf{S}_A^H \mathbf{S}_A)^{-1}}_{\mathbf{A}}) / Tr(\mathbf{K}_c), \quad \text{with } (\mathbf{K}_c)_{ij} \equiv \langle \mathbf{b}_{coil,i}(t), \mathbf{b}_{coil,j}(t) \rangle$$

where **A** is the inverse of the power dissipation matrix.

Experiments and Results: Four representative cases of transmit operation were considered: a) uncorrelated signals sent to each coil; b) Transmit SENSE localized excitation on a Cartesian trajectory with undersampling factor UF = 2 c) the same without acceleration (UF = 1); and d) quadrature drive. These four situations cover the full range of possible signal correlation and give rise to different $\mathbf{K}_c$ for the three different matching approaches. Note that in this context the quadrature drive is highly similar to RF shimming, which also exhibits maximum signal correlation.

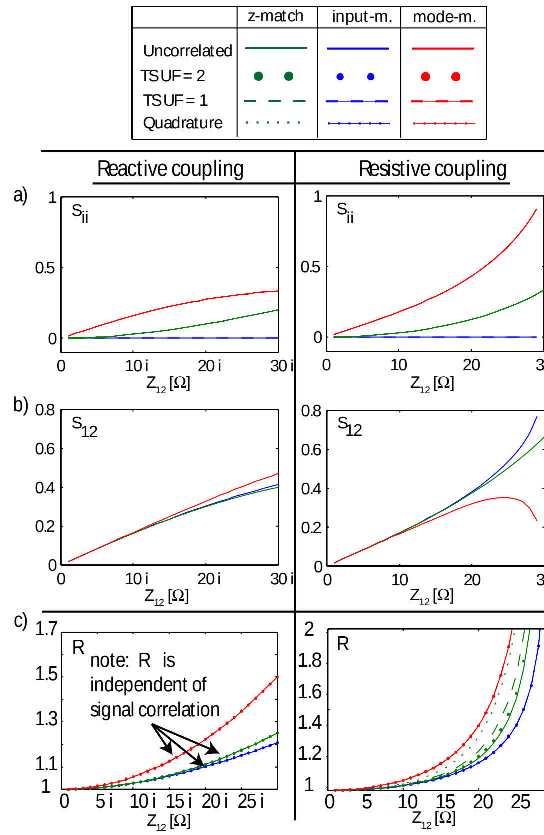

Figure 2

The diagonal elements of **Z** were assumed to be equal to 30 Ω (an arbitrary choice as long as it is different from the standard 50 Ω that would lead to trivial results in some cases) while $\mathbf{Z}_{12}$ was swept between 0-30 Ω of either purely resistive or reactive coupling. The input match and the mode match had the common feature of vanishing off-diagonals of **A** for all $\mathbf{Z}_{12}$ due to zero $\mathbf{S}_{11}$ and orthogonality of the corresponding modes. In general, **A** is diagonal if $\mathbf{Z}_{12}$ is imaginary, $\mathbf{S}_{ii}$ or $\mathbf{S}_{12}$ is zero and has the feature that the losses due to reflection and coupling become independent of the drive mode ($\mathbf{K}_c$). Figure 2 a) and b) show the resulting S-parameters obtained by using the three different matching strategies. As Fig.2 c) shows, for reactive coupling, the drive modes do not influence the performance significantly and the input impedance match performed best in terms of power efficiency. By comparison, resistive coupling proved more adverse, generally giving rise to larger power losses for a given impedance magnitude. It is important to note that the input match (blue) is the most power efficient in this regime although it exhibits the largest coupling between the two array ports. Note also that the power loss curves in Fig. 2 c) often coincide for the four modes of transmit operation.

Conclusion: The most important conclusion from this study is that input matching, i.e. nulling S_{11} reflection at each port, is the best single-port strategy, independent of the mode of operation. Better results can only be achieved with more complex matching topologies. Secondly, very different results were obtained for resistive and reactive coupling. The power loss due to purely reactive coupling was generally found to be less than that suffered through resistive coupling. This indicates that minimizing resistive coupling may be especially important in designing transmit arrays. Thirdly, using the input matching strategy the power loss due to coupling and reflection can be kept below a factor of 2 up to very high coupling. Consequently, it is not necessary to apply decoupling networks if the coupling still allows the individual elements to be tuned. Furthermore, using the input match or the mode match strategies the power loss is independent of the application (Transmit SENSE, RF-Shim, quadrature or even random signals).

References: [1] R.F.Lee et al. MRM 48:203–213 (2002) [2] J. L. Allen and B. L. Diamond, Lincoln Laboratory, M.I.T., Lexington, MA, Tech. Rep. 424 (ESD-TR-66-443), 1966., [3] D. M. Pozar, *Microwave Eng.*: John Wiley & Sons, 1998, [4] C. A. Balanis, *Antenna Theory: Analysis and Design*: Wiley, 1997.