Analytical Performance Evaluation and Optimization of Resonant Inductive Decoupling (RID)

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Target Audience: Researchers interested in MR coil array design

Purpose: In this work we aim to establish a basis for analytically investigating the performance of resonant inductive decoupling (RID) elements [1] in transceive coil arrays, in order to predict their optimal application regimes.

Theory: Inter-coil coupling complicates coil array construction and leads to a loss of available power for transmission by depositing a fraction of the input power in other element's source impedances. RID elements are capable of compensating both reactive and resistive coupling, thus theoretically allowing complete coil isolation. However, conservation of energy dictates that this can only be achieved through the introduction of additional losses in case that resistive coupling is present [2], which mandates a close view on decoupling performance vs. power deposited in the load. Based on the impedance matrices of the coil array and RID, the respective losses can be calculated in a straightforward manner, which is shown in Fig. 1. Instead of devising a matching circuit, we change the source impedance of the feeds to achieve matching, which results in identical currents compared to a realistically matched coil.

1. Define general N-port **Z** matrix of the array with an RID, i.e. $\mathbf{Z}=\mathbf{Z}_L+\mathbf{Z}_R$, where $\mathbf{Z}_L$ is the coil's matrix and $\mathbf{Z}_R$ is the RID's matrix.
2. Transform **Z** to **S**-Matrix with an unknown source impedance vector $\mathbf{R}_S$ and solve for $\mathbf{R}_S$ by setting the diagonal of **S** equal to 0.
3. Solve for the loop current vector $\mathbf{J} = (\mathbf{Z} + \mathbf{I}\mathbf{R}_S)^{-1}\mathbf{U}$ in the matched system with **I** being an identity matrix and an arbitrary excitation voltage vector **U**.
4. Calculate forward power via $P_F = {}^{1}/_{4}\, \mathbf{U}^H(\mathbf{I}\mathbf{R}_S)^{-1}\mathbf{U}$
5. Calculate power absorbed in the load via $P_L = \mathbf{J}^H\mathbf{Z}_L\mathbf{J}$, where $\mathbf{Z}_L$ is the impedance matrix of the system without any decoupling components.
6. The power efficiency of the RID decoupled array is now $\eta = P_L/P_F$.

Fig. 1: Algorithm for calculating forward and load power deposition in an N-channel coil array with RID circuits present.

Methods: We apply the shown algorithm to a symmetric 2-channel coil array. To simplify matters, we assume that all reactive (imaginary) components of the impedance matrices have been compensated. Starting from the definitions in Fig. 1, the elements of $\mathbf{Z}_L$ are $\mathbf{Z}_{L,11} = \mathbf{Z}_{L,22} = \mathrm{R}$ and $\mathbf{Z}_{L,12} = k\mathrm{R}$, with the resistive coupling constant k and the coil resistance R. Matrix $\mathbf{Z}_R$, is defined by $\mathbf{Z}_{R,11} = \mathbf{Z}_{R,22} = ck\mathrm{R}$ and $\mathbf{Z}_{R,12} = -ck\mathrm{R}$. Here, c describes the degree of coupling compensation, with c=1 corresponding to perfect decoupling and c=0 depicting a system without an RID element. We are interested in the efficiency of feeding both coils with the same voltage amplitude v and a phase offset ϕ between both channels, i.e. $\mathbf{U} = \mathrm{v}[1, \exp(\mathrm{i}\phi)]$. After solving for $\mathrm{R_S}$, we obtain $\mathrm{R}_S = \beta\mathrm{R}$, where $\beta = \sqrt{1 + 2ck + (2c-1)k^2}$. The expression for the power efficiency η can be shown to be of the form $\eta = a/d + (b/d)\cdot\cos(\phi)$, with $a = \beta^2 - k^2 + 1$, $b = 2ck(1+k)$ and $d = \beta(1 + ck + \beta)$. The coil coupling can be expressed as $S_{12} = (1 + ck - \beta)/(k - ck)$. The performance of the decoupling as expressed by a potential in- or decrease of load power by using RID with varying compensation constants c was consecutively explored, assuming a coil with no intrinsic losses. For validation, we compared the analytical results to numerical circuit simulations using ADS (Agilent, Santa Clara, CA) of two resonating, inductively and resistively coupling coils with RID.

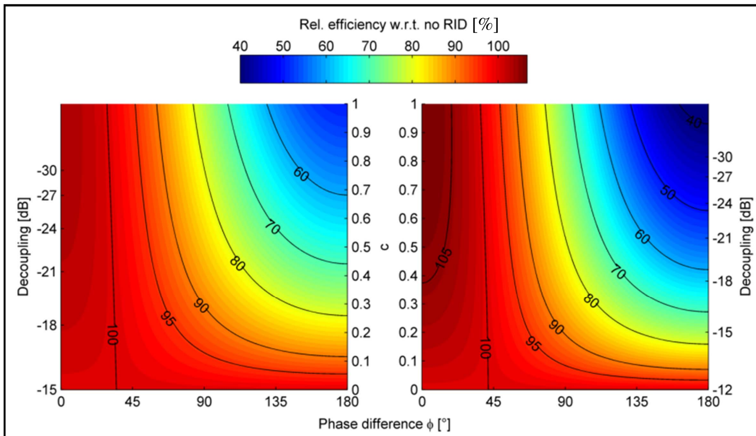

Fig. 2: RID performance behavior as measured by power deposited in the load for two different resistive coupling constants k, resulting in coupling of -15 dB (left, $k \approx 0.345$) and -12 dB (right, $k \approx 0.473$) when not using an RID. The graph shows relative performance as $\eta(c,k,\phi)/\eta(c=0,k,\phi)$. The compensation constant c is increased along the y axis, and the resulting decoupling is shown on the second y axis.

Results: We can gain valuable insight by looking at some boundaries of the (c,k,ϕ) parameter space. Achievable decoupling without RID can be predicted by setting c=0, which yields $S_{12} = (1 - \sqrt{1-k^2})/k$. In this case, the phase dependence in the absorbed load power vanishes, as b=0. For c=1 and $\phi = 0$, the power efficiency η equals 1, meaning that the RID element can compensate coupling for the equal phase mode without any losses. Contour plots of the performance impact of RID are shown in Fig. 2. It becomes obvious, that below a certain phase offset, the RID array will always result in better performance. In this region, the decrease in coupling losses outweighs the power dissipation in the RID circuit, leading to a net performance gain. This threshold increases with increasing k. However, once the phase offset increases towards 180°, potentially significant losses appear that also increase with c. The comparison of analytical predictions and numerical results are given in Fig. 3, showing perfect agreement.

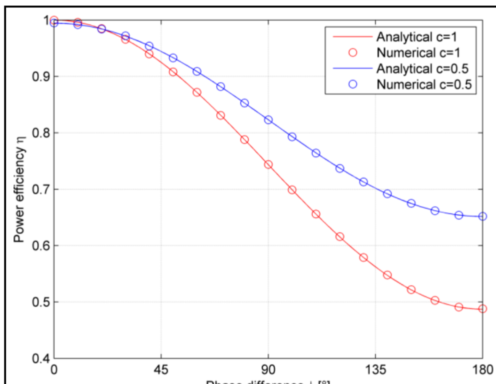

Fig. 3: Comparison of the analytical solution to numerical circuit simulations with $k \approx 0.345$, for two different values of c (0.5 and 1). The numerical results perfectly follow the analytical predictions (mean rel. error < 0.05%). The reactive coupling component was completely compensated for both cases. Analytically predicted decoupling (S_{12}) was also exactly reproduced.

Discussion: The results for the 2 channel array show, that great care needs to be taken when employing RID. Losses increase with better coil decoupling, which requires a careful analysis of the gains a better isolated coil array yields in terms of parallel transmit- and receive performance versus losses incurred by the additional decoupling. An individual optimum will always need to be found based on the application, with the mantra "better decoupling = better array" not being generally true. One main advantage of the RID, the simple tuneability of the decoupling, may outweigh minor loss increases if complex multi-channel coils are otherwise hard to properly adjust. In addition the phase difference between adjacent elements in multi-channel circumferential transceiver arrays with 8 or more channels is often equal or smaller than 45° (i.e. in CP mode), which corresponds to an operation regime that is loss free. The comparison of analytical results to numerical circuit simulations showed perfect agreement, which confirms that neglecting all reactive components of the impedance matrix is a valid approach when expected losses are the only concern to analyze.

Conclusion: We have derived an analytical solution for the power efficiency of a coil array with resistive coupling and RID elements. The presented approach can straightforwardly be extended to more than two channels, and could help predict decoupling and coil performance simply based on the real part of a coil's impedance matrix, e.g. as gained from 3D simulations. While the presented approach directly yields the noise correlation matrix of an array decoupled using RID elements, it has to be used in conjunction with realistic 3D EM simulations in order to accurately quantify the impact on SNR and parallel techniques. Practical application of RID elements requires great care in order to preserve coil performance while enhancing channel isolation.

References:

[1] Avdievich NI et al., *NMR Biomed*, 2013;26:1547–54 [2] Kuehne et al., *MRM*, 2014, doi:10.1002/mrm.25493

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