SIMULATING ARRAY SNR AND EFFECTIVE NOISE FIGURE IN DEPENDANCE OF NOISE COUPLING

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Introduction:
The effect of element coupling in array coils on the image-SNR has been investigated for a long time [Ohl02]. Due to new insights into the theory of noise coupling of array coils attached to low noise amplifiers (LNAs) [Fin09, Fin11], we now can quantify these effects. In this experiment, we used a set of two circular coil elements and a cylindrical phantom (axis perpendicular to B_0) to simulate and measure (separate abstract) the SNR in dependence of element coupling.

Methods:
The array-SNR for point-wise optimal channel combination can be expressed by [Fin09,Fin11]

$$SNR = \boldsymbol{U}_{\mathrm{s}}^{\mathrm{H}} \Big(\boldsymbol{Z}_{\mathrm{a}}[cF_{\mathrm{opt}}] + [cF_{\mathrm{opt}}]\, \boldsymbol{Z}_{\mathrm{a}}^{\mathrm{H}} \ldots + (\boldsymbol{Z}_{\mathrm{a}} - [Z_{\mathrm{opt}}])\, [2P_{\mathrm{opt}}/R_{\mathrm{opt}}]\, (\boldsymbol{Z}_{\mathrm{a}} - [Z_{\mathrm{opt}}])^{\mathrm{H}} \Big)^{-1} \boldsymbol{U}_{\mathrm{s}}.$$

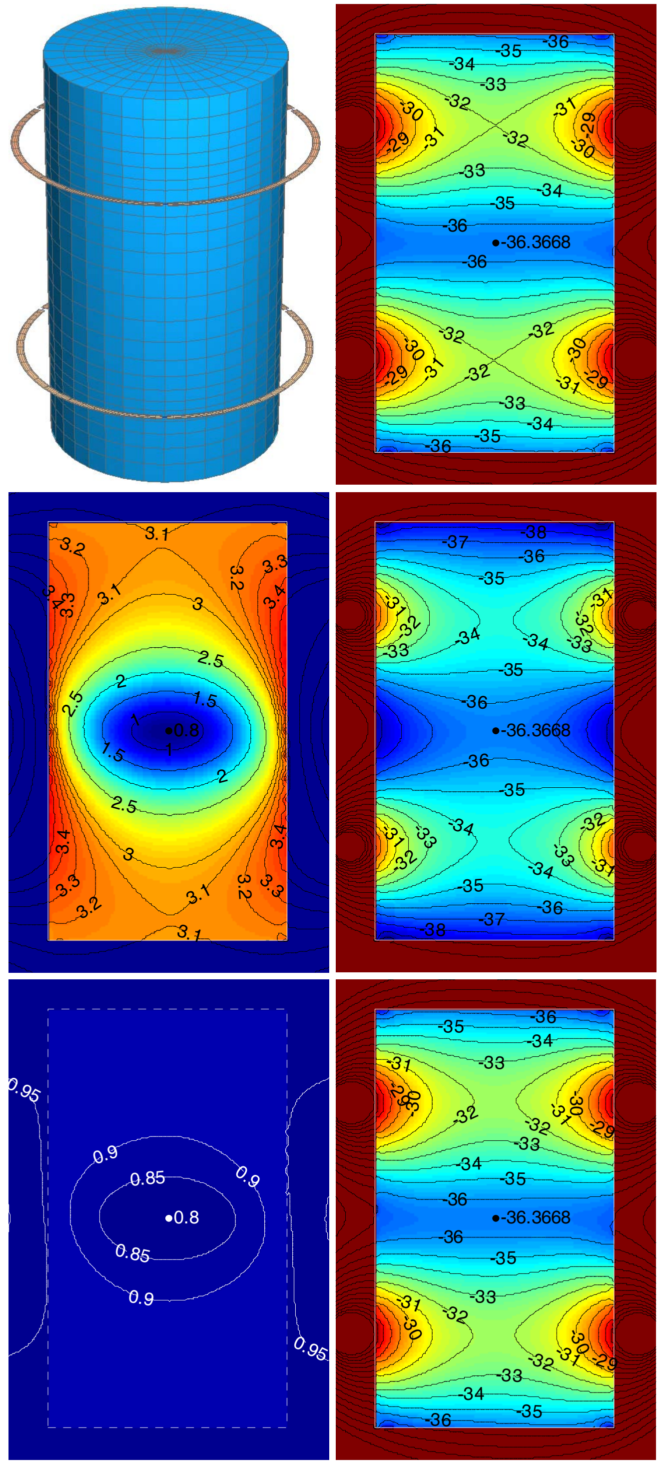
In this equation, $\boldsymbol{U}_{\mathrm{s}}$ is the vector of signal voltages in the individual coil elements. $\boldsymbol{Z}_{\mathrm{a}}$ is the impedance matrix of the MRI coil, $[cF_{\mathrm{opt}}]$ is a diagonal matrix containing the (scaled) optimal LNA noise figures, $[Z_{\mathrm{opt}}]$ is the corresponding diagonal matrix of the optimal LNA impedances (including matching circuits). The diagonal matrix $[2P_{\mathrm{opt}}/R_{\mathrm{opt}}]$ is related to the noise current, which is sent from the LNAs into the array ($R_{\mathrm{opt}}=\mathrm{real}(Z_{\mathrm{opt}})$).

Simulations of the electromagnetic fields were performed with the Method of Moments (CONCEPT). The received signal voltages were derived from the circular polarized magnetic field [Ibr05] assuming effective water proton density at 1.5T. The top left figure shows the phantom (diameter 12cm, height 21cm, 0.5S/m conductivity and relative dielectric constant of 50) and the two coil elements (diameter 15cm, distance 11.6cm). The LNA-parameters were chosen by typical values (0.8dB noise figure and P_{opt} as half of the thermal noise level).

The top right figure shows the absolute SNR ($1\mathrm{mm}^3$ Resolution, all plots in dB) without noise coupling ($P_{\mathrm{opt}}=0$). In this case, the SNR is globally reduced by just the 0.8dB noise figure of the LNAs. With noise coupling present, the SNR is further reduced in dependence of the signal voltage vector due to the second part in the above SNR equation. We call the resulting SNR-loss the effective noise figure (left figures below the geometry). This effect was simulated for the coupled coil elements (center) and also with an ideal inductive decoupling network attached, which removes the imaginary part in $\boldsymbol{Z}_{\mathrm{a}}$ (bottom figures). In both cases, ideal array noise matching was applied with respect to the isocenter signal, yielding the same receive voltage in both coil elements due to symmetry.

Results:
As can be seen bottom left, the inductively decoupled coil shows only a very small SNR reduction due to the resistive noise coupling. The effective noise figure is still below 0.95dB inside the phantom. For the coupled coil elements we obtain this high SNR just near the optimization point (isocenter). For other locations, the SNR is reduced by up to 3.5dB, which is significantly more than the LNA noise figure.

Conclusion:
The array SNR-equation can predict the SNR-loss due to noise coupling in the post-processing of electromagnetic field simulations. Array noise matching can compensate for noise coupling at a target location. Coil coupling causes significant SNR-loss in not optimized locations. However, this SNR-loss appears mainly near the subject surface, where the intrinsic SNR typically is high. Therefore, decoupling should be applied in trade off with additional losses which contribute further noise. It becomes more important for a larger field of view.



top left: geometry (numbers in dB)
top right: intrinsic coil SNR without noise coupling
center left: effective LNA noise figure with noise coupling
center right: SNR for coupled coil elements with noise coupling
bottom left: effective noise figure with inductive decoupling
bottom right: SNR in case of inductive decoupling

References:
[Ohl02] M. Ohliger: "The effect of Inductive Coupling on Parallel Image Reconstructions"; ISMRM 2002, p. 197
[Fin09] C. Findeklee: "Improving SNR by generalizing Noise Matching for Array Coils", ISMRM 2009, p. 507
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