Mitigation of inductive coupling in array coils by wideband port matching

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Introduction: We suggest a method for mitigating the effects of coil coupling. It is based on a wideband matching technique which can be implemented by a simple circuit modification. The reduced effective reflection will result in less degradation of preamp noise figure in a receive array, and in lower power loss in the transmitter isolators in a parallel transmit system.

Noise coupling: Inductive coil coupling can be viewed as a quarterwave line which is inserted between the grounds of the two source resistors. [Rey1] shows that despite preamplifier decoupling [Rey2], noise current i_{n1} from one preamp is transmitted into an additional noise voltage u_{n2}' at the other preamp, in effect increasing the noise temperature of the combined system. This is not visible as noise correlation, because the contributions from i_{n1} to u_{n2}' and from i_{n2} to u_{n1}' appear at the two outputs at +90° and -90° relative phase, and therefore cancel. The amount of degradation depends on kQ, ie. normalized magnetic coupling k times loaded Q of the antenna, which can be derived from s-parameter measurements. With kQ greater than unity, we have overcritical coupling and observe mode splitting with frequency spacing $\Delta f = k f_0$.

Modal noise analysis: Noise coupling between a pair of coils can be analyzed as mismatch of its two fundamental modes, a first (“even”) mode with parallel currents and fields, and a second (“odd”) one with antiparallel currents. The frequency allocation depends on the sign of k (Helmholtz vs adjacent surface coils). Separate equivalent circuits for the two modes (Fig.1) show that the even mode has a normalized source impedance (1+jkQ)/2, connected to two preamps in parallel. These preamps are equivalent to a single preamp, having the same noise figure and half the optimum impedance. Thus the mismatch is the same as for a single amp, driven by a source impedance of (1+jkQ) instead of 1. The odd mode presents an impedance of 2(1-jkQ) instead of 2. Thus both modes experience a noise mismatch of same magnitude $|r_{mode}| = kQ/\mathrm{sqrt}(4+kQ^2)$. We may note that $|r_{mode}|$ is the square root of the reflection which we would see into one coil with the other one terminated by 50 Ω ($|s_{11}| = kQ^2/(4+kQ^2) = |r_{mode}|^2 < |r_{mode}|$), so a noise mismatch estimation based on s_{11} alone would largely underestimate the effect of coupling. Assuming noise matching to the reference impedance, and uncorrelated noise voltage and noise current (which fixes the fourth noise parameter R_n), the noise temperature with source reflection is simply $T_n(r) = T_{nopt}\,(1+|r|^2)/(1-|r|^2)$.

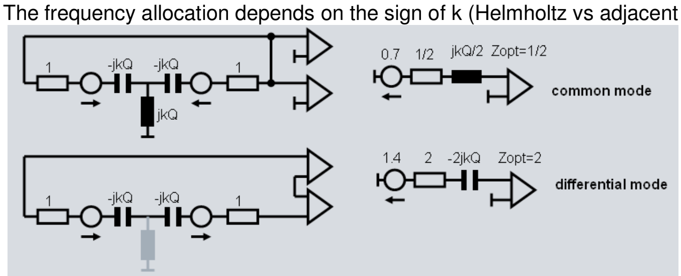

Fig. 1: Equivalent circuits for even and odd modes

[Fin1] and [Fin2] have shown that the port impedance matching can be optimized for a given signal ratio, which in many cases fully recovers the SNR for a predetermined target voxel. In terms of modes, this is equivalent to a tuning offset which brings the dominant mode back to resonance. But this “focusing” procedure necessarily increases the SNR penalty for other parts of the object space.

Overcoupling technique: This aims at reducing the reflections simultaneously for both modes. The two impedances 1+-jkQ for two spatial modes at the same MR frequency f_0 are equivalent to a single resonant circuit, observed at the two eigenmode frequencies. We propose to extend the well-known overcoupling approach to wideband matching to the problem of coupled coils.

Following Wheeler [Lop], we note that minimum reflection at the band edges can be achieved by matching to the magnitude of the source impedance rather than the real part, using a transformer with an impedance ratio $z_{opt}' = |1+jkQ|$. In practice, this can easily be achieved by tighter coupling of the preamp to the coil (eg. increasing the series capacitor C_s), creating an impedance circle which encircles the center of the Smith chart (Fig.2). Thus $|r_{mode}'|$ and noise figure at the band edges (ie. coupled modes) are significantly reduced, at the cost of some mismatch r_c' at the center frequency (ie. if the coils were decoupled):

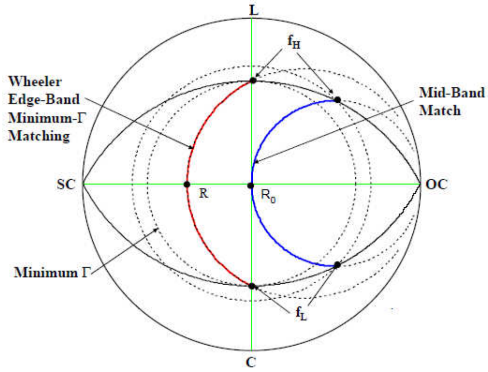

Fig. 2: Smith chart for wideband matching [Lop]

$$r_c' = \left(\frac{kQ}{1+\sqrt{1+kQ^2}}\right)^2 \qquad |r_{mode}'| = \frac{kQ}{1+\sqrt{1+kQ^2}}$$

Fig.3 is a plot of noise figure over a range of coil coupling levels for four match conditions. The standard match (blue line) results in a severe penalty when kQ >> 1, whereas the optimal match mitigates the penalty (dashed black line). In practice, the selected wide-band match must correspond to a specific coupling level to minimize the penalty (pink, red lines at kQ = 2, 8). Experimental verification of the benefit is shown in a separate abstract.

In the classic wideband matching problem, reflection can be further reduced across a limited frequency range by additional resonators (multiple tuned matching, within the Fano limit). But this cannot be applied to further mitigate coupling, because those correction circuits will vary their impedance only with temporal frequency (which is fixed at the Larmor frequency here), and not with the spatial mode structure.

Multiple coils: The overcoupling strategy is also applicable to a larger number of coupled elements or a near-degenerate birdcage. Then we need to obtain the mode spectrum (eg. by eigenmode simulation or double probe measurements) and select those modes which are producing a relevant signal. Optimizing the matching bandwidth to the outermost frequencies will result in a target r_c' to which each loaded coil can be matched individually.

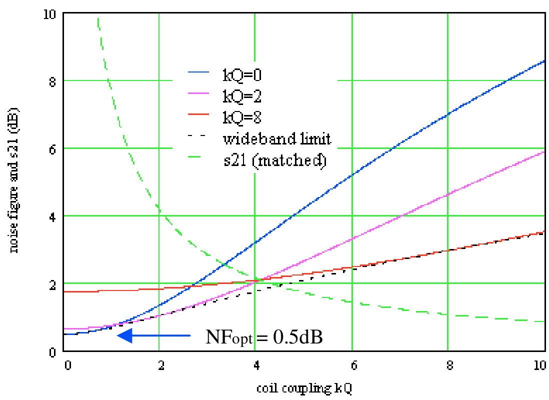

Fig. 3: Noise figure (match optimized for different kQ)

Resistive coupling: This analysis has focused on purely reactive (ie. inductive or capacitive) coupling, and neglected the effect of resistive coupling which is typically introduced by the load. In this case, the general overcoupling strategy still holds, but the optimization would need to be slightly adjusted to take into account different real parts of the modal impedances.

References: [Rey1] Reykowski, Wang: Rigid SNR analysis of coupled MRI coils…, ISMRM 2000 p1402; [Rey2] Reykowski, Saylor, Duensing: Do we need preamplifier decoupling? ISMRM 2011 p 3883; [Fin1] Findeklee, Duensing, Reykowski: Simulating array SNR and effective noise figure…, ISMRM 2011 p1883; [Fin2] Findeklee: Array noise matching…, IEEE Trans. Ant. and Prop., Vol 59 No 2 Feb 2011; [Lop] Lopez: Harold A. Wheeler’s Antenna Design Legacy, http://www.arlassociates.net/May2007WheelerAntennaDesignLegacy.pdf