Simultaneous tuning of multiple modes for an RF transmit array

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Purpose: Combination of multiple circular polarization (CP) modes of an RF transmit array has recently been proposed for some MRI investigations. For example, with 7T head imaging the second polarization mode (CP2) excites the brain periphery efficiently, and for interleaved body excitation a combination of CP1 and CP2 modes provides good excitation homogeneity.

For RF transmit array fabrication and in most simulations, the transmit array performance criteria that are commonly used in the frequency domain are optimization of element impedance matching and minimization of inter-element coupling, at the Larmor frequency ($\boldsymbol{F}_{\mathbf{MRI}}$). This strategy can be seriously hampered by a lack of reliable information regarding array performance for given excitation modes. Brunner noticed [1] that the best achievable decoupling of adjacent array elements can results in array transmit performance degradation in CP1 due to a significantly increased coupling between the second-neighbour elements. He proposed to use the highest eigenvalues of the reflection matrix as a figure of merit for transmit array optimization. This clever approach is seldom used in practice, however, because calculation of the eigenvalues is not a common feature of available RF tools. In addition, the highest eigenvalue can correspond to an excitation mode that is useless for MRI and thus cannot guide array optimization.

After frequency domain optimization, most 7 and 9.4T head arrays that we have investigated provide sub-optimal performance for higher mode excitation. For array performance optimization in a specific excitation mode (defined by the transmit amplitude and phase for each array element) we have earlier proposed an improved strategy: minimization of the power reflected by the entire array ($\boldsymbol{P}_{\mathbf{array\_refl}}$), calculated in the time domain [2]. The lower the reflected power for a given excitation mode, the better the transmit array performance in this mode. However, optimization using this strategy for any specific excitation mode results in an array element matching and adjacent element coupling configuration that does not allow static RF shimming or multi-mode excitation. Our goal was to implement an approach for array tuning that improves transmit performance in all selected excitation modes, and thus enables the optimal use of these valuable techniques.

Method: In this investigation, we used our large data base of numerical electromagnetic simulations obtained within several previous studies [3, 4]. To overcome the limitations in each optimization domain, time and frequency, we implemented a dual-domain optimization strategy. For all excitation modes to be optimized, we first defined the transmit amplitude and phase for each array element. A new set of optimization criteria, defined at $\boldsymbol{F}_{\mathbf{MRI}}$, consisted of individually weighted criteria: a) for matching all array elements; b) for minimization of adjacent element coupling; and c) for minimization of $\boldsymbol{P}_{\mathbf{array\_refl}}$ in each excitation mode. For 12-element arrays this results in 12 criteria for matching, 12 criteria for decoupling, and 1 criterion for $\boldsymbol{P}_{\mathbf{array\_refl}}$. Optimizations were performed using the Agilent ADS 2011.05 RF circuit simulator. It takes less than 1 minute to compute the values of all components (variable capacitors, inductors, coupled inductors, etc.) required for array tuning, matching, and decoupling.

To test our approach the arrays investigated were excited in the CP1 and CP2 modes, applying 1W power to each port (array transmit power, $\boldsymbol{P}_{\mathbf{transmit}}$=8W), with a sequential phase increment for each mode. We analyzed element matching, coupling between adjacent elements, and the power balance.

Results and discussion: Our new array performance data were compared with data obtained from previous studies in which optimizations were separately performed in time and frequency domains. For 7T arrays frequency domain optimization resulted in excellent single resonance matching (always below -40 dB at $\boldsymbol{F}_{\mathbf{MRI}}$), for all array elements in all array geometries. The worst case coupling between adjacent elements was in the range of 12 dB to 16.9 dB. Coupling between the second-neighbour elements was much stronger, however, and approached -6 dB for some array geometries. Larger array diameters, larger numbers of elements in the array, and closer element spacing resulted in higher second-neighbour couplings. Despite this coupling, in CP1 mode $\boldsymbol{P}_{\mathbf{array\_refl}}$ was relatively small (less than 10% of $\boldsymbol{P}_{\mathbf{transmit}}$) for all arrays. However, in CP2 mode, $\boldsymbol{P}_{\mathbf{array\_refl}}$ was significantly large (mostly more than 25% of $\boldsymbol{P}_{\mathbf{transmit}}$). All arrays (especially closely spaced 12-element arrays) consequently provided much poorer transmit performance in CP2 mode than in CP1 mode. Time domain optimization resulted in nearly optimal transmit performance ($\boldsymbol{P}_{\mathbf{array\_refl}}$=0) for a given array geometry and excitation mode, but if the array was optimized for CP2 performance, its CP1 transmit performance could be very low ($\boldsymbol{P}_{\mathbf{array\_refl}}$ about 30% of $\boldsymbol{P}_{\mathbf{transmit}}$), and vice-versa. B1+ homogeneity was similar after both optimizations.

For 9.4T capacitively decoupled arrays, the frequency domain optimization resulted in relatively large reflected power, up to 20% of $\boldsymbol{P}_{\mathbf{transmit}}$, in both CP1 and CP2 modes.

For both 7 and 9.4T arrays, dual-domain optimization resulted in negligible $\boldsymbol{P}_{\mathbf{array\_refl}}$ (less than 3% of $\boldsymbol{P}_{\mathbf{transmit}}$) for both CP1 and CP2 modes, provided that coupling to the second-neighbour elements was less than -9 dB after frequency domain optimization. This procedure resulted in poorer single resonance element matching (in the range -10 dB to -15 dB), greater adjacent element coupling (by 3 to 5 dB), and decreased coupling between the second-neighbour elements (by 4 to 8 dB).

We tested a frequency domain optimization that included minimization criteria both for matching and for adjacent-element and second-neighbour couplings (24 and 32 optimization criteria for 8 or 12 channel arrays respectively). However such an optimization (compared with the original frequency domain optimization) did not essentially improve CP2 mode transmit performance.

It should be noted that after dual-domain optimization, despite giving the best transmit performance in the desired excitation modes, both the frequency dependence of element matching and the coupling between adjacent elements resemble the corresponding frequency dependence of a sub-optimal, badly tuned array. For test purposes, to mimic a sub-optimally tuned array, the criteria in the frequency domain optimization were modified to obtain imperfect element matching (at a level about -10 dB to -14 dB) and to reduce the coupling between adjacent elements to not more than -12 dB. Starting the optimization from several different initial conditions, a set of tuning parameters (values of variable capacitors, inductors, coupled inductors, etc.) was obtained for several array geometries. Despite the very similar visual appearance of the frequency dependence of element matching and coupling between adjacent elements for all tuning parameters inside the set of tuning parameters, the transmit performance showed highly significant variation, from very sub-optimal ($\boldsymbol{P}_{\mathbf{array\_refl}}$ about 30% of $\boldsymbol{P}_{\mathbf{transmit}}$) to nearly the best ($\boldsymbol{P}_{\mathbf{array\_refl}}$ ~0). This finding has a rational explanation: the reflected power depends on all the interactions within the array (not only the subset of interactions described by element matching and coupling between adjacent elements), and also on the phases of coupling between adjacent elements, which are rarely analyzed.

Conclusion: Applying a dual-domain optimization approach results in improved performance for 7 and 9.4 T head arrays in multi-mode operation, without limiting the use of static RF shimming and even pTX. The existence of sub-optimally tuned arrays (in term of imperfect element matching and relatively large coupling between adjacent elements) with different transmit performances underlines the importance of measuring and reporting the total reflected power, for the reliable and adequate comparison of different arrays.

[1] D. Brunner. Diss. ETH No. 19052, [2] M. Kozlov, R. Turner, JMR 200 (2009) 147–152. [3] M. Kozlov, R. Turner, Proceedings of the 40th EuMC, 2010, pp. 328- 331. [4] M. Kozlov, R. Turner, Proceedings of IEEE AP-S/URSI 2011, pp. 1715-1718.