Automatic matching of transmit arrays with optically controlled capacitors

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Introduction: The desire for improved spatial control of spin handling in high-field MR urges the use of multi-channel transmission RF arrays. The transmission efficiency of such an array depends critically on accurate matching. However, accurate array matching is tiresome to achieve due to the coupling among the transmitting elements which is load-dependent. In this work, we investigate methods for automated matching solutions. The use of remotely actuated variable capacitors to achieve better matching conditions has been previously demonstrated by the use of piezoelectric motors [1,2,3]. The goal of the present work is to extend this concept to fully automatic array matching using real-time feedback, relying on pre-characterized adjustable matching networks.

Methods: It has been previously shown [2], that two sets of two capacitors in L-network topology, able to withstand 54 dBm of power, can match a 2-element coil array in a 7T Philips system. A single capacitor consists of two distinct areas where the electric field is build up and those areas are connected in series. The decision for this design was driven by the requirement of galvanic connections which are fixated on an FR4 epoxy substrate (ε~4.4, tanδ<0.02). The floating top of the capacitors varies the capacitance from 3-126 pF through the mechanically coupled piezoelectric actuators (SQUIGGLE motor, New Scale Technologies). The capacitors have increased range due to a ceramic dielectric (K0140, Kyocera) with dielectric constant of ε~142, breakdown voltage 8.2KV/mm and dissipation factor of ~1 at 1MHz. For every capacitor, a differential optical linear encoder (HEDS9720, AVAGO) with a resolution of 90 um has been added with the objective to track the position of the moving plate. The encoder strip is an alternating sequence of equidistantly transparent windows and non-transparent bars. The strip was produced in-house with a standard photolithographic method and was attached on the moving part of the capacitor.

The electrical characterization of each 2-port matching network is done by collecting a lookup table of 2x2 S-matrices for all combinations of discrete positions of the capacitors. The accuracy required due to the high dielectric constant, is achieved by the exact position provided by the encoders. For a grid of positions we collect the corresponding S-matrices provided by a network analyzer (Agilent N5230C). The whole procedure is controlled by a computer responsible to communicate with standard serial connections both with the network analyzer and the motors. This procedure is performed only once when the system is built.

Given the lookup tables, the feedback from the network analyzer and the exact position of the motors, the matching algorithm calculates an optimum matching condition. The algorithm consists of the following three conceptual steps: Initially, a measurement on the input of the combined network $\tilde{S}$ is taken which is used to calculate the 2x2 S-matrix of an in-house coil array. This calculation is done when capacitors are in an arbitrary position i, j. The S-matrix of the coil array is calculated by $S = (AS^M_{22,i,j} + I)^{-1}A$, where $A = \left(S^M_{11,i,j}\right)^{-1}\left(\tilde{S} - S^M_{11,i,j}\right)\left(S^M_{21,i,j}\right)^{-1}$ and $S^M_{ij,i,j}$ are block sub-matrices of the 4-port matching network S^M. The derived S is used as an input to an exhaustive search routine which minimizes the objective function $\tilde{S}_{11}{}^2 + \tilde{S}_{22}{}^2 + \tilde{S}_{12}{}^2 + \tilde{S}_{21}{}^2$, taking into account the lookup table of S^M. When the optimization algorithm returns the corresponding target position of each capacitor the motors travel to the targeted position in a one-jump fashion. The dialing of the motors towards this position is achieved by the use of the encoders and lasts 2 seconds at the most which is the longest distance the capacitors are allowed to travel in our design.

Results: We conducted two experiments; one with a phantom filled with an aqueous solution of 2000mg/L NaCl and 770 mg/L $CuSO_{4\cdot5}(H_20)$ and one in-vivo in the lower leg of a volunteer after informed consent. Figure 1 shows the image acquired after the algorithm achieved an one-jump match, the matching when we manually matched the coils unloaded and the AFI B1 maps in the unmatched and matched case, along with the corresponding readings from the network analyzer. The average B_1^+ increase withing the object was 83.9% which is analogous to the decrease of the reflected power on both input ports. Figure 2, shows the in-vivo results, unmatched and matched condition along with the network analyzer readings. Here, the average signal increase within the object was 38.9%. These results conclude the successful operability of the system in a 7T magnet.

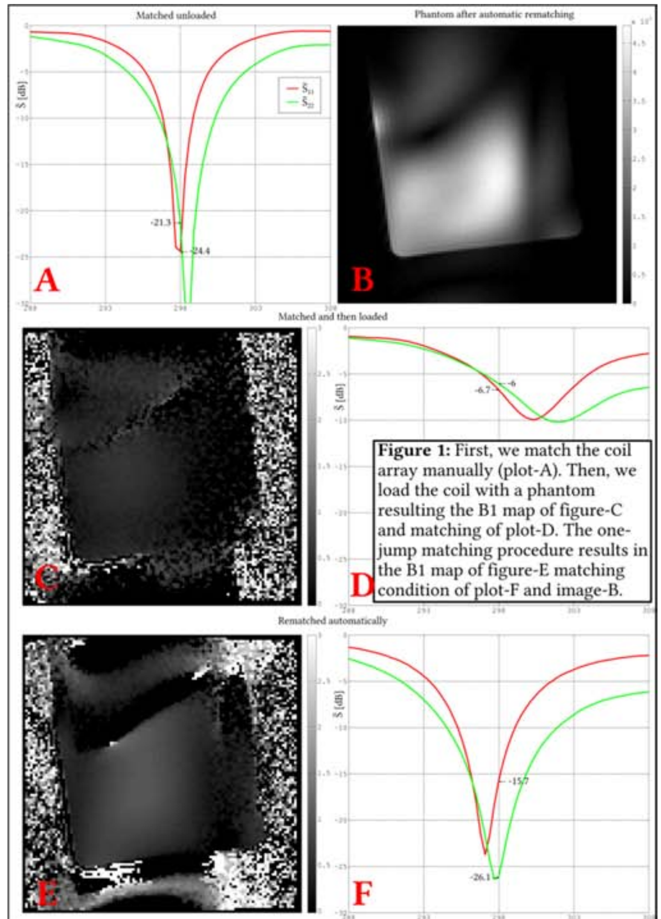

Figure 1: First, we match the coil array manually (plot-A). Then, we load the coil with a phantom resulting the B1 map of figure-C and matching of plot-D. The one-jump matching procedure results in the B1 map of figure-E matching condition of plot-F and image-B.

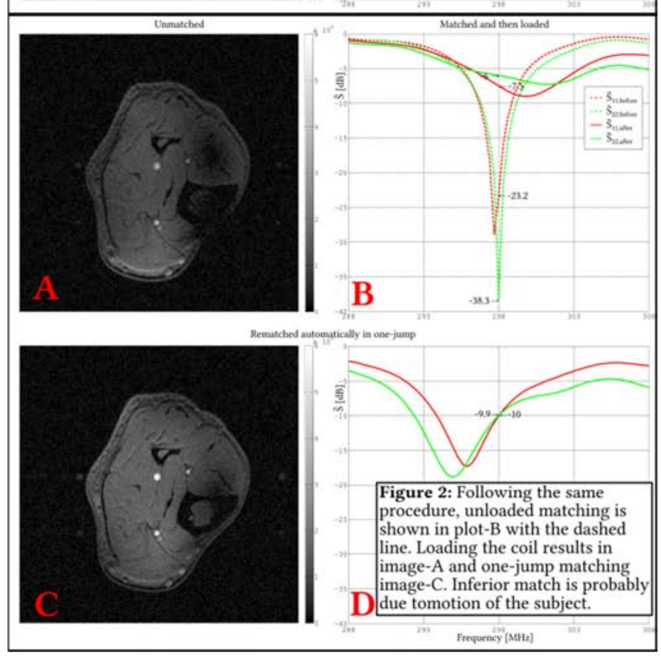

Figure 2: Following the same procedure, unloaded matching is shown in plot-B with the dashed line. Loading the coil results in image-A and one-jump matching image-C. Inferior match is probably due tomotion of the subject.

Discussion: A feedback controlled matching system for Tx-arrays autonomously reacts to load changes in various stages of an MR experiment. The fully automated procedure led to reproducible array matching experiments from various initial conditions. Further investigation into different optimization criteria and propagation of errors in calculated S-matrices remains to be performed.

References: [1] Carl J. Snyder, et al. ISMRM 2010:1523, [2] G. Katsikatsos, et al. ISMRM 2013:5601, [3] G. A. Keith, et al. ISMRM 2013:2743