# Closed-loop control for transmit array matching

Giorgos Katsikatsos[1] and Klaas Paul Pruessmann[1]
[1] *Institute for Biomedical Engineering, Zurich, ZH, Switzerland*

**Introduction:** Multiple-channel transmission with RF arrays is increasingly used to improve the spatial control of spin manipulation in high-field MR. Similar to the single-channel case, the efficiency of array transmission depends critically on accurate matching. For arrays, however, accurate matching is tedious to achieve due to load-dependent coupling among the transmitter elements, calling for automated matching solutions. The use of electronically actuated variable capacitors for this purpose has previously been demonstrated using piezoelectric motors [1,2]. The goal of the present work is to extend this concept to fully automatic array matching using closed-loop control relying on pre-characterized adjustable matching networks and iterative refinement.

**Methods:** Under the assumption that any load can be transformed from capacitive to inductive by introducing a delay line, we use custom flat variable capacitors able to withstand 54 dBm of power to match an inductive 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. This decision was driven by the requirement of galvanic connections which are fixated at the bottom FR4 epoxy substrate ($\varepsilon$~4.4, tan$\delta$<0.02). The shape of the copper plates is optimized to minimize electric field in acute edges. Two of the aforementioned capacitors constitute an L-network and their inter-connection along with the connection to the SMA cable connectors is made by impedance matched striplines. The variability of the capacitors is accomplished by the floating top part which is mechanically coupled to the piezoelectric motors (SQUIGGLE motor, New Scale Technologies) by PMMA parts (Fig. 1). The capacitors have increased range due to the ceramic dielectric (K0140, Kyocera) with dielectric constant of $\varepsilon$~142, breakdown voltage 8.2KV/mm and dissipation factor of ~1 at 1MHz. The whole structure is fixated by hard Teflon walls (PTFE) in dimensions that allow the moving part to relocate smoothly, while keeping the rest in position.

We electrically characterize each 2-port matching network by collecting a lookup table of 2x2 $S$-matrices for all combinations of discrete positions of the capacitors. This automated procedure requires great accuracy, due to the high dielectric constant and is maintained by keeping a log of reference positions along with their corresponding $S$-matrices (Fig. 2) provided by a network analyzer (Agilent N5230C). These logs play key role to the stability of the closed-loop control. The characterization of each matching network is done independently to eliminate errors introduced by mechanical imperfections. The whole procedure is controlled by a personal 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.

The matching algorithm uses as input the lookup tables and feedback from the network analyzer in order to find 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 the stripline array [3,4]. This calculation is done when all capacitors have returned to a reference position $S^M_{ref}$. The $S$-matrix of the array is calculated by $S = (AS^M_{22,ref} + I)^{-1}A$, where $A = \left(S^M_{11,ref}\right)^{-1}\left(\tilde{S} - S^M_{11,ref}\right)\left(S^M_{21,ref}\right)^{-1}$ and $S^M_{ij,ref}$ are block sub-matrices of $S^M$. Then, the calculated $S$ is used as an input to an exhaustive search routine which minimizes the objective function $\tilde{S}_{11}{}^2 + \tilde{S}_{22}{}^2$, taking into account the lookup table of $S^M$. The optimization algorithm returns the corresponding target position and the motors are adjusted in a single step operation. Lastly, an iterative alternating step-wise heuristic algorithm attempts to further minimize the aforementioned objective function. Moreover, it keeps a limited memory for the last 3 steps, to refine the final position by low speed motor movements. Its termination is done by an arbitrarily set threshold (-30 dB in our experiments).

**Results:** Figure 3, is the figure of merit for the 2-port L-network power which is in the range of ~0.8 dB. The maximum power loss is encountered at full capacitance, where losses due to the dielectric, are more pronounced. Figure 4, shows $|\tilde{S}_{11}|$ of one L-network as a function of the position of the capacitors. Figure 5, shows how the matching evolves by starting from a fully reflective situation to a 1-jump near-match condition and finally refining the matching condition by the iterative heuristic fine-tuning algorithm. Finally, figure 6 presents the number of steps for re-matching after the subject has moved. The capacitor operates successfully in a 7T Philips system.

**Discussion:** A closed-loop controlled matching for Tx-arrays has been implemented as an autonomous system to react 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 remains to be performed.

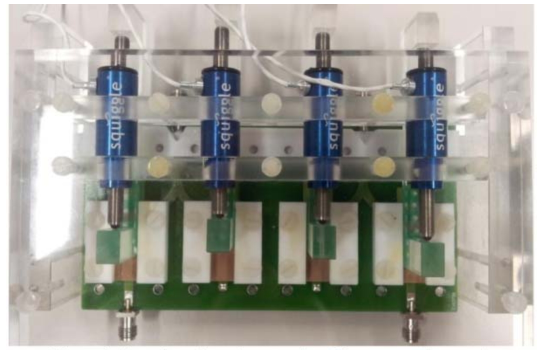


**Figure 1**. Top view of two L-networks with two capacitors each.

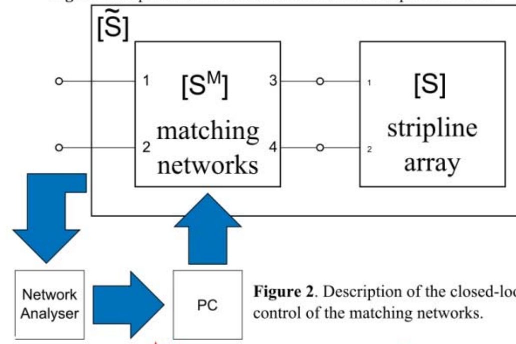


**Figure 2**. Description of the closed-loop control of the matching networks.

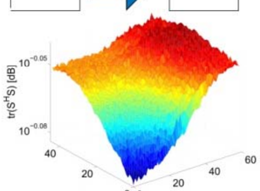


**Figure 3**. Power dissipation through one L-network.

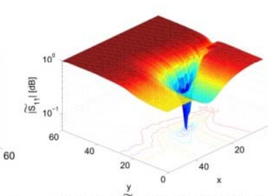

**Figure 4**. $\tilde{S}_{11}$ as calculated from a reference position.

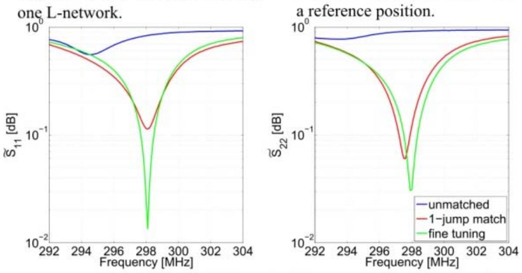


**Figure 5**. $|\tilde{S}_{11}|$ and $|\tilde{S}_{22}|$ initially, after 1-jump matching and after fine tuning with the iterative algorithm.

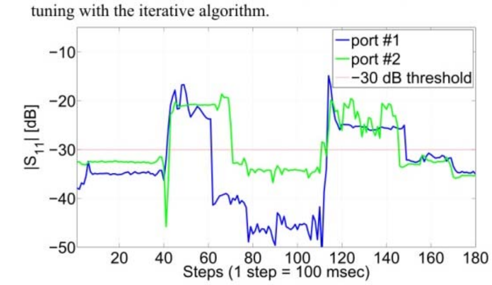


**Figure 6**. Re-matching with the fine-tuning routine while moving the subject.

**References:** [1] Carl J. Snyder, et al. ISMRM 2010:1523, [2] G. Katsikatsos, et al. ISMRM 2012, [3] D. O. Brunner DO, et al. ISMRM 2007, p. 448 [4] Froehlich J, et al. 10.1109/MWSYM.2007.380401