SVD-based Hardware Concept to Drive N Transmit Elements of a Phased Array Coil with M≤N channels for High Field MRI

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INTRODUCTION The design of a parallel transmission system for high field MRI always requires the best compromise between excitation homogeneity, B_1 mapping time and hardware cost, which are proportional to the number of transmitting channels. More channels provide higher homogeneity and lower local SAR, since the total radiofrequency power can be optimally spread in the sample [1]. High-order circularly polarized modes and Butler matrix have been proposed [2] as a solution to reduce the number of channels. Nevertheless, this approach does not take into account the B_1^+ distribution inside the sample and cannot be easily implemented for a z-segmented phased array coil [3]. The singular value decomposition (SVD) offers a channel reduction concept that transcends these limitations. It is coil topology-independent. The B_1^+ maps generated by the transmit elements inside a typical sample are used to produce as many orthogonal modes as transmit elements. These modes are intrinsically ordered by SVD from the most to the least efficient. Therefore, the low-singular-value modes can be rejected with only little loss in parallel-transmit performance. Each mode, driven by one channel, corresponds to a linear combination of all the transmit elements. The complex weighting factors are given by SVD. A z-segmented transceiver coil for human head at 7 T is considered. It consists of 2x8 stripline–like transmit elements. The loss in flip angle (FA) shimming performance will be quantified by using only the first 8 modes instead of 16 independent channels. Finally, a hardware solution to construct 8 SVD modes is presented.

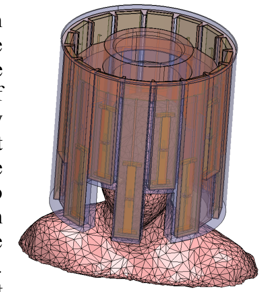
Fig. 1. Simulation model

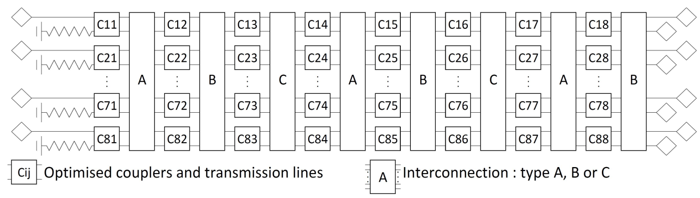

Fig. 2. Topology for SVD modes synthesis

METHOD A coil model including a 9-tissue head (reference phantom) was developed (Fig. 1) for full-wave FEM simulation (using HFSS from Ansoft Corp., Pittsburgh, USA). Once all 16 elements have been tuned and matched in simulation, the B_1^+ maps inside the head are extracted for each element with 5-mm resolution. Then, we can construct the matrix **B** to be decomposed in reduced singular values [4]: $\mathbf{B} = \mathbf{U}\,\boldsymbol{\Sigma}\,\mathbf{V}^H$, where the superscript H denotes the conjugate transpose. Each element $B_{i,j}$ of **B** contains the complex B_1^+-value produced by transmit element j in voxel i. The matrix **U** has the same dimension as **B**: 40,000x16 in this study. The 16x16 diagonal matrix $\boldsymbol{\Sigma}$ contains decreasing positive singular values. Meanwhile, each column of the 16x16 matrix **V** contains the complex weighting factors α_{ij} for transmit element j in mode i (with $|\alpha_{ij}|$ normalized to unit). In order to assess the parallel-transmit performance in the entire brain, whether using 16 independent channels or 8 modes, the k_T-points technique [5] was considered with 5 locations in transmission k-space. One critical issue of the concept lies in how to synthesize the SVD modes. The accuracy of the mode construction is limited by the complexity and insertion loss of the dedicated SVD network. The topology we propose for 8 modes consists in using 8 stages of hybrid couplers combined with phase shifters (transmission lines) as shown in Fig. 2. Each stage is connected to the next by alternating 3 topologies as shown in [6]: topologies A, B and C connect respectively 2 couplers to 2 couplers, 4 to 4 and 8 to 8. The coupling coefficients of the 90° hybrid couplers and transmission line lengths are optimized numerically with a Matlab routine to provide the most accurate mode construction. The synthesized coefficients α'_{ij} should best approximate α_{ij}. Parallel-transmit performances are compared between 8 ideal and 8 synthesized modes for the reference phantom. In addition, the 8 synthesized modes are used to shim a modified phantom, 20% larger in volume and rotated by 5° along the z-axis in order to assess the robustness of the concept. At the end, the feasibility of unequal coupling hybrids has also been checked with the Ansoft Designer software using circuit model simulation.

RESULTS & DISCUSSION The accuracy of SVD mode synthesis is given in Fig. 3 (each pixel corresponds to a mode weighting error $|\alpha_{ij}-\alpha'_{ij}|$). Higher accuracy could be obtained by increasing the number of stages at the expense of insertion loss. Amplitude pattern of each synthesized mode is shown in Fig. 4 while Fig. 5 collects the k_T-points results for different cases to assess performances and robustness of the concept. A flip angle of 5° was targeted with a peak power budget of 650 W per channel for the 16 independent channels configuration and 1300 W per mode for 8 modes. The FA homogeneity is given in the targeted brain and its distribution is displayed on axial, coronal and sagittal central slices. The colour bar indicates the flip angle distribution scale in degree. Obviously, some degrees of freedom are lost using only 8 modes instead of 16 independent channels (Fig. 5**a** & **b**). This limitation results in slightly longer excitation pulses and a FA homogeneity penalty (standard deviation increases from 3 to 6%). Nevertheless, thanks to the high accuracy of the mode synthesis we proposed (Fig. 3), simulations yield almost the same results for the 8 ideal and synthesized modes (Fig 5**b** & **c**). Since the SVD modes are derived from the field pattern inside a specific phantom, their shimming ability is slightly reduced for a bigger and rotated phantom (Fig. 5**d**). Better results are attainable for all cases with a more sophisticated k_T-points algorithm instead of the fast algorithm used in this study.

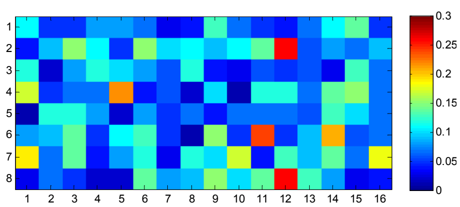

Fig. 3. Synthesis error for the first 8 SVD modes (mode and channel index respectively in vertical and horizontal axis)

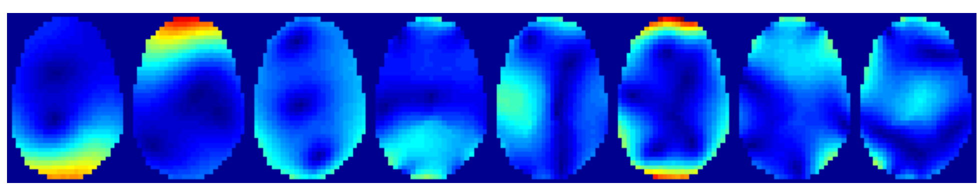
Fig. 4. Amplitude pattern of synthesized SVD modes in the brain central axial slice (mode 1 to mode 8 from left to right)

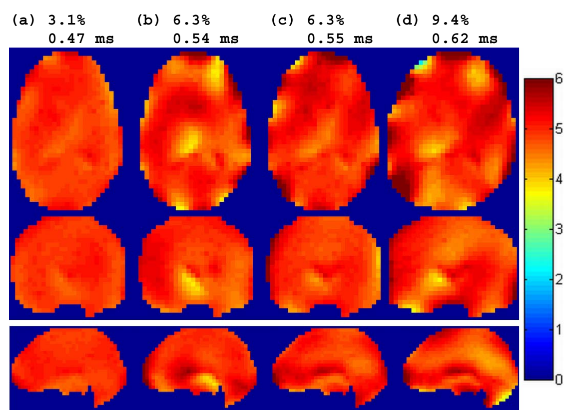

Fig. 5. Simulated FA homogeneity obtained using the k_T-points technique for performance and robustness analysis: (a) ref. phantom–16 independent channels, (b) ref. phantom–8 ideal modes, (c) ref. phantom–8 synthesized modes, (d) modified phantom–8 synthesized modes.

CONCLUSION As shown from parallel-transmit simulations, the SVD-based hardware concept is very promising to downsize transmit channels for large phased arrays required in UHF MRI.

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