Array-compressed parallel transmit pulse design

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Target Audience: High field parallel transmit pulse designers and hardware developers.

Introduction: Parallel RF transmission (pTx) with a multichannel transmit array is an important technique for high field MRI. pTx has been applied to B_1 shimming [1], B_1 inhomogeneity mitigation with spokes and k_T points tailored RF pulses [2,3], and reduced field-of-view (rFOV) imaging [4]. While transmit coil arrays with large numbers of coil elements are desired in pTx for tailoring the spatial B_1 distribution while minimizing SAR [5], the high cost, large footprint and cabling requirements of corresponding RF power amplifier arrays have limited the number of transmit channels used in practice, and most ≥ 7 T scanners today are equipped with either 2 or 8 transmit channels. To address this problem, we present an array-compressed pTx pulse design concept that relates an N_{coil}-element pTx coil array to N_{amp} ($< N_{coil}$) amplifiers. It is based on integrating RF pulse matrix rank constraints into pTx pulse design and RF shimming algorithms. In hardware the concept may be implemented using power combiners, and variable attenuators and phase shifters. The concept is demonstrated in the design of spiral and k_T points pulses and in dynamic multislice RF shimming, and compared to coil combination using geometrically-dependent phase shifts and singular value decomposition (SVD) approaches.

Theory: The idea of array-compressed pTx pulse design is to jointly design a set of compressed set of N_{amp} RF pulses and a corresponding set of $N_{coil} \times N_{amp}$ coil combination weights that compress the array down to N_{amp} channels. The pulses are played through the amplifiers, and the weights are applied using power combiners, variable attenuators and variable phase shifters placed between the coil array and the amplifiers. For example, the small-tip-angle pulse design embodiment of this concept can be stated as:

$$\begin{aligned} &\text{minimize} \quad \|\boldsymbol{d} - \boldsymbol{A}\boldsymbol{b}\|^2 \\ &\text{subject to} \quad \text{rank}(\boldsymbol{B}) = N_{amp} \end{aligned}$$

where $\boldsymbol{d}$ is a target excitation pattern, $\boldsymbol{A}$ is an excitation system matrix comprising Fourier kernels and B_1 maps [6], $\boldsymbol{b}$ is a vector of N_{coil} RF pulses stacked end-to-end, and $\boldsymbol{B}$ is an $N_t \times N_{coil}$ RF pulse matrix, formed by reshaping $\boldsymbol{b}$ so that each column contains one coil's length-N_t pulse. In practice this problem can be solved by alternating between updating $\boldsymbol{b}$ to minimize the squared error objective, and applying singular value thresholding to limit the rank of $\boldsymbol{B}$ [7]. The final pulses and coil combination weights are obtained by SVD of $\boldsymbol{B}$.

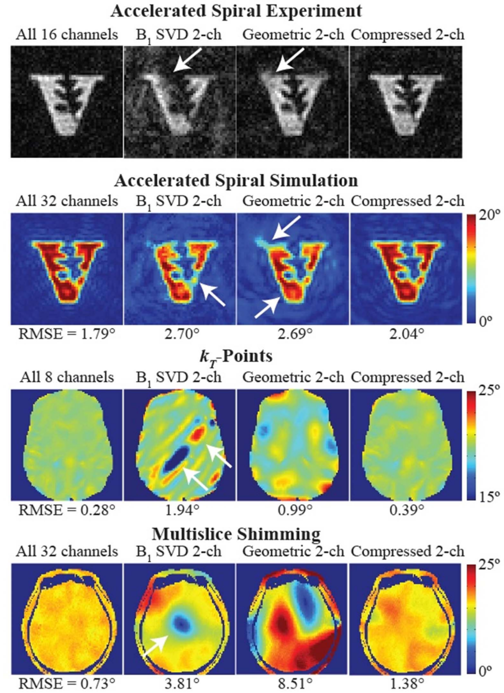

Figure 1. *Representative excitation patterns for the three pulse design applications and the accelerated spiral experiment. One of 10 slices is shown for the multislice shimming case.*

Methods: The array-compressed pulse design concept was integrated into three pTx pulse design algorithms: i) an accelerated spiral pulse design [6]; ii) a magnitude least-squares spokes/k_T points pulse design with joint gradient optimization [2]; and iii) a multislice magnitude least-squares shimming optimization. Since hardware to apply the coil combination weights is not yet available, a pseudo-pTx experiment [8] was performed with accelerated spiral excitations on a 7T Philips Achieva scanner (Philips Healthcare, Cleveland, OH, USA) using 16 channels of a 32-channel receive coil and 3 mm-thick slice-selective refocusing (TE/TR = 2.8/500 ms). The experiment exploited the commutative property of small-tip-angle excitation by designing pulses using the receive B_1 maps, then imaging their patterns individually and summing them offline to obtain the total pattern [8]. Additionally, simulations were performed using 32-channel B_1 maps measured from the same coil and 8-channel B_1 maps simulated for a 7T head transceive array using FDTD. All spiral pulse designs used a 4×-accelerated trajectory. The k_T points pulse designs used 5 k_T points. The RF shim optimizations were performed over 10 contiguous slices, with independent shim weights for each slice and a common set of compression weights for the entire volume. The compressed pulse designs were compared to pulses designed after compressing the coil arrays using a) direct SVD of the B_1 maps, and b) every-other-coil geometric combination, wherein the B_1 maps were adjusted to be in-phase in the center of the volume prior to summation.

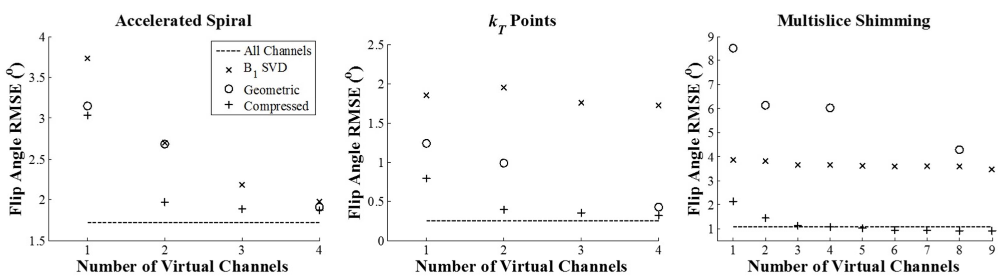

Figure 2. *Flip angle RMSE versus number of virtual channels N_{amp} for the three design scenarios.*

Results: The measured spiral excitations, simulated flip angle maps (Fig. 1) and flip angle RMSE versus N_{amp} plots (Fig. 2) demonstrate that the proposed array-compressed pulse design approach produces more accurate pulses than designs using fixed coil combinations determined prior to pulse design. Averaged across N_{amp}, the array-compressed pulses had 17%/75%/68% lower RMSE's compared to B_1 SVD, and 11%/43%/78% lower RMSE's compared to geometric combination for the spiral/k_T points/multislice shimming cases, respectively.

Conclusion: We have presented an array-compressed pTx pulse design concept that will enable many-coil transmit arrays to be optimally driven by a small number of RF amplifiers/channels. By integrating coil compression into pTx pulse design, more accurate pulses can be designed than with approaches that do not consider the spatial encoding demands of the pulse design problem when computing coil array combination weights.

References: [1] Ibrahim et al., MRI 2001, 19:1339-1347; [2] Grissom et al., MRM 2012, 68:1553-1562; [3] Cloos et al., MRM 2012, 67:72-80; [4] Zhu et al., MRM 2004, 51:775-784; [5] Lattanzi et al., MRM 2009, 61:315–334. [6] Grissom et al., MRM 2006, 56: 620–629. [7] Cai et al., J Optim 2010, 20:1956-1982. [8] Zhang & Stenger, ISMRM 2005, p 2434. **Acknowledgment:** This work was supported by NIH R01 EB016695.