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 B1 shimming [1], B0 inhomogeneity mitigation with spokes and k1 points tailored RF pulses [2,3], and reduced field-of-view (FOV) imaging [4]. While transmit coil arrays with large numbers of coil elements are desired in pTx for tailoring the spatial B0 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 Ncoil-element pTx coil array to Namp (< Ncoil) 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 k1 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 Namp RF pulses and a corresponding set of Ncoil × Namp coil combination weights that compress the array down to Namp 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:

\[
\text{minimize } \| d - Ab \|_2
\]

subject to \( \text{rank}(B) = N_{\text{amp}} \)

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

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/k1 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 maps [6], then imaging their offline to obtain the total pattern [8]. Additionally, simulations were performed using 32-channel B1 maps measured from the same coil and 8-channel B1 maps simulated for a 7T head transceive array using FDTD. All spiral pulse designs used a 4×-accelerated trajectory. The k1 points pulse designs used 5 k1 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.

Results: The measured spiral excitations, simulated flip angle plots (Fig. 1) and flip angle RMSE versus \( N_{\text{amp}} \) 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 \( N_{\text{amp}} \), 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/k1 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.