A generalized analog mode-mixing matrix for channel compression in receive arrays

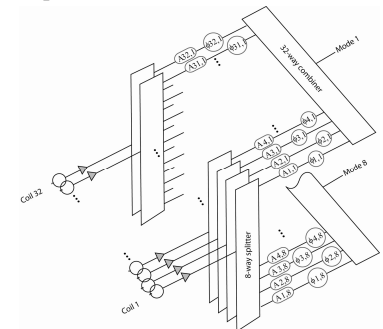**J. R. Polimeni[1], V. Alagappan[1], T. Witzel[2], A. Mareyam[1], and L. L. Wald[1,2]**

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Introduction: Highly parallel arrays of small receiver coils enable dramatic gains in both SNR and accelerated imaging performance, but at a considerable cost in system complexity. In addition to the cost of additional receiver channels and cabling, data throughput rates increase (and can exceed data-bus capabilities) and the computational and raw data storage burdens significantly increase. However, it is well known that the spatial patterns of a typical array, while roughly equal contributors to image SNR, are minimally orthogonal. For example, an array's maximum acceleration rate would be equal to the number of channels if the array possessed equal-energy orthogonal patterns. For the special case of cylindrical symmetry, it has been recognized that a linear transformation forming the orthogonal birdcage modes can concentrate the sensitivity and encoding ability in the lower-order eigenmodes [1-4]. The Butler matrix—a hardware implementation of this linear transform (which is an analog Fourier transform)—has recently been introduced for this purpose [3]. Also, the potential to perform software linear transformation to a reduced orthogonal basis has been demonstrated for reducing reconstruction time [1]. Here we present a general analog mode-mixing strategy to form arbitrary spatial modes in hardware and a theoretical framework for calculating the optimal coefficients which will retain a majority of the array capabilities in a reduced set of modes. We validate the method by developing a partially programmable analog matrix to reduce a 32-channel brain array to 8 receive channels.

Methods: While spatial orthogonality of the coil sensitivity matrix $\mathbf{S}$ determines acceleration capability, the whitened sensitivity matrix $\mathbf{S'}=\mathbf{WS}$ reflects the sensitivity of the array. Here $\mathbf{W}$ is the $N_{coil} \times N_{coil}$ whitening matrix formed from the noise covariance matrix ψ through $\mathbf{W^H W} = \psi^{-1}$. We then form the square "SNR matrix" $\mathbf{R'}=\mathbf{S'S'}^H$. $\mathbf{R'}$ can then be decomposed via the SVD to find the linear transformation into orthogonal modes [1], which can be ranked by their contribution to the sensitivity. Mode compression is achieved by retaining only those modes which contribute significantly to the sensitivity. The linear transformation defines complex-valued coefficients $A_{i,j}$ needed to combine the array elements to form mode M_i. The mode-mixer implements the amplitude weighting and phase shifts, then sums the weighted signals to produce the mode.

The mode-mixing method was tested on a 3T clinical scanner (MAGNETOM TIM Trio, Siemens Healthcare, Erlangen, Germany) using the manufacturer's 32-channel brain array. The modes were formed by intercepting the analog signal from the 32 receive elements after amplification and immediately before detection by the receivers. The analog mode-mixer (Fig.1) is comprised of 32 splitter boards feeding into 8 combiner boards (one for each mode produced) resulting in 256 total signal paths (see Fig.1). The signal from the 32 individual loop coils is amplified (ERA-3+, Mini-Circuits, NY) prior to being split by a 16-way splitter (JEPS-16-1W, Mini-Circuits) mounted on a printed circuit board routed with 50Ω traces. A copy of the split signal from each coil enters the eight combiner boards which implement a specific attenuation and phase shift on each signal path. A digital step attenuator (DAT-15R5-PP, Mini-Circuits) was programmed through a parallel port connection. The phase shifter was implemented as a lumped element circuit followed by a length of coaxial cable. The phase shift introduced by the varying PCB trace lengths was measured and subtracted from the target phase. The final vector summation is performed by a 32-way combiner formed by cascading two 16-way combiners with a 2-way combiner (JEPS-16-1W, ADP-2-1, Mini-Circuits). The resulting signal was then amplified (ERA-3+, Mini-Circuits) and connected to the system receiver. Ferrite cores were used to suppress cable currents.

Figure 1: 32-to-8 mode-mixing hardware, showing 32 splitter and 8 combiner boards.

The matrix coefficients of were calculated from sensitivity and noise measurements made in a body-shaped loading water phantom using a 3D gradient echo acquisition. Coefficients and SNR performance were calculated for an ROI containing the entire head. SNR was evaluated with the method of Kellman [5].
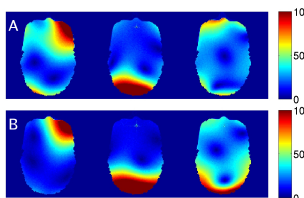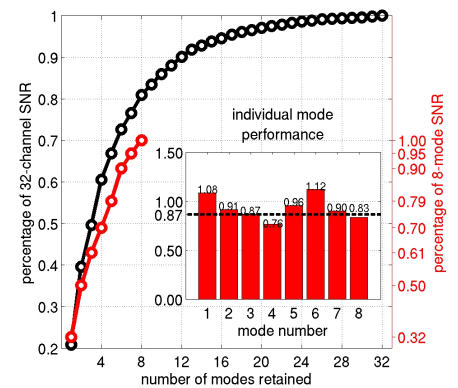

Figure 2: (A) Simulated and (B) measured mode SNR on a system with mode-mixing matrix installed.

Results: The implemented mode-mixing matrix produced eight modes (Fig. 2) that qualitatively resemble the calculated patterns with small discrepancies (likely due to errors in the attenuations and phase shifts.) Figure 3 shows the theoretical and measured SNR retain as a function of cumulative elements. The 8 modes are expected to retain 80% of the full arrays whole-head SNR while the constructed modes retained 70%. Thus the hardware realization realized 87% of its design SNR compression capability. Figure 3 (inset) also shows the performance relative to theory of the individual modes. To demonstrate the image quality obtained with the implemented 4× channel compression, we compared a standard 1-mm MPRAGE acquisitions in the human head with and without the mode mixing matrix present; image quality is comparable in the two acquisitions.

Conclusion: The current mode-mixing matrix was designed from sensitivity profiles calculated for a uniform water phantom and thus compression performance is likely to decrease for human subjects due to changes in coil sensitivities across individuals. A future implementation will adopt a programmable phase shifter such that the entire matrix can be adaptively calculated and applied to an individual, and allow for compensatory phase shifts and attenuation to offset errors in the matrix realization to boost SNR performance. The current analog mode-mixing design is immediately expandable to 16 modes, which could retain over 90% of the SNR of the 32-channel array.

Figure 3: Ideal versus measured SNR compression achieved by 32-to-8 mixing matrix. (Inset) Percentage SNR retained in each individual mode.

References: [1] Buehrer *et al.* (2007), *MRM* 57:1131–9. [2] King *et al.* (2003), *Proc ISMRM*, 712. [3] Alagappan *et al.* (2008) *Proc ISMRM*, 619. [4] Reykowski & Blasche (2004), *Proc ISMRM*, 1587. [5] Kellman & McVeigh (2005), *MRM*, 54:1439-47; 58:211-2.