Evaluation of the Effect of Phase Errors on the Performance of a Butler Matrix

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Introduction.

The Butler matrix transforms the N channels of a phased array into a new set of so-called eigenmodes with useful properties for both reception [1] and transmission [2]. In the current work, we performed simulations of an eight-channel phased array based on microstrip transmission line (MTL) elements [3-4] and driven in an eigenmode configuration to investigate the effects of errors of individual components of the Butler matrix on the obtained electromagnetic fields. Results of the calculations were compared to experimental data recorded at 3 T.

Methods.

The electromagnetic field distribution of a single MTL element was simulated using HFSS 11 (Ansoft, Pittsburgh, PA) (Fig. 1A) and then imported into MATLAB (Mathworks, Natick, MA) to generate the fields for the whole array by symmetry operation (rotation) [5]. Transformation into the eigenmode configuration was performed as outlined in Ref. [6]. Figs. 1B,C show the resulting magnitude- and phase patterns obtained with an ideal Butler matrix for the four quadrature modes used for transmission. To simulate the impact from finite manufacturing tolerances, a random phase error was added at each phase shifter of the hardware combiner, and the output phase of the obtained imperfect Butler matrix was calculated. In particular, normally distributed random errors were assumed with standard deviations (SDs) varying between 1/3° and 5/3°. Polarization ratios (Figs. 2-4) were computed according to Ref 3 and coupling coefficients between modes n and m were obtained as

$$k_{nm} = \sum_V \mathbf{B}_{1n}^{+} \cdot \mathbf{B}_{1m}^{+} \Big/ \sqrt{\sum_V \mathbf{B}_{1n}^{+} \cdot \mathbf{B}_{1n}^{+} \times \sum_V \mathbf{B}_{1m}^{+} \cdot \mathbf{B}_{1m}^{+}} \; .$$

The calculations were repeated 40 times with variation of the random error for statistical analysis. For experimental validation, a Butler matrix was built containing 90°-Hybrids (1Z0280-3 & 1J0280-3, Anaren, East Syracuse NY) and coaxial cables as phase-shifters and was connected to an 8-channel MTL array [4]. The generated output phases had a mean and maximum errors of 1.6° and 5.2°, respectively. To simulate a systematic error in the setup, a single output cable of the Butler matrix was changed by a defined phase shift (10°, 20°, 30°, 40°). The same phase shifts were also applied in simulation studies. Magnetic resonance experiments were performed at 3 T using a MAGNETOM TIM Trio (Siemens, Erlangen, Germany) and a cylindrical water phantom with dielectric properties of brain tissue.

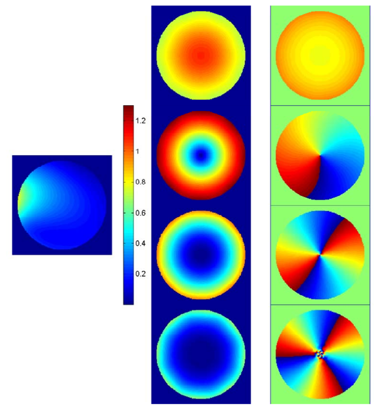

Fig. 1. *Simulated B_1^+ of one channel **(A)** and magnitude **(B)** and phase **(C)** of the quadrature eigenmodes −45°, −90°, −135°, −180°.*

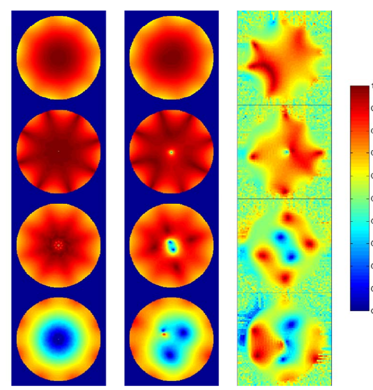

Fig. 2. *Simulated polarization patterns for the ideal case **(A)** and for a maximal random phase error of ±5° **(B)** and experimental results **(C)**.*

Results & Discussion.

The obtained polarization patterns of the simulated imperfect Butler matrix (random phase shifts) agreed reasonably well with the experimental results (Figs. 2B,C). Differences are mainly due to imperfections of the coil elements. Results obtained with single systematic phase shifts indicated robustness against phase errors for the homogeneous mode, whereas a greater impact was observed for the higher modes (Fig. 3). It is noted that a systematic phase shift applied to at a single output channel might be used to improve imperfections of the coil elements leading to a more homogeneous excitation pattern. The simulations of random phase errors yielded coupling coefficients of less than −20 dB in >90% of the repetitions if the maximum random phase error was ±2° (defined as 3 SD of the normal distribution). This condition produced a maximum error of ±5° for the output phases, which seems to yield acceptable performance. Similarly, maximum random errors of ±1° yielded a maximum error of ±2.6° for the output phases.

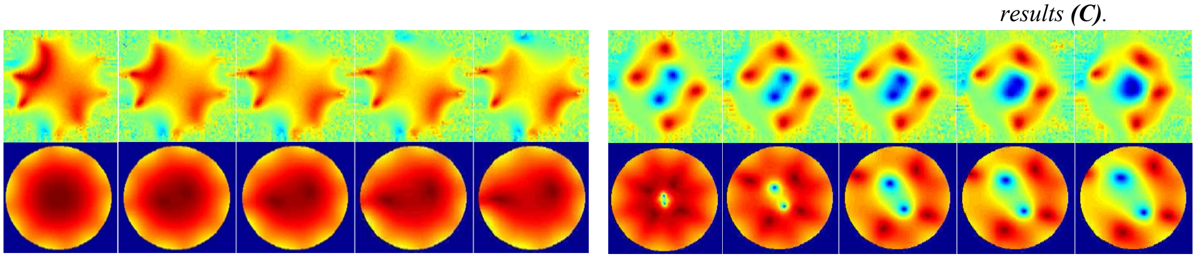

Fig. 3. *Polarization patterns obtained experimentally and by simulations for the −45° **(A)** and −135° mode **(B)** with a single systematic phase error of (from left to right 0°, 10°, 20°, 30°, 40°).*

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