DISTRIBUTION ERRORS IN 8×8 AND 16×16 BUTLER-MATRICES MULTI-COIL EXCITATION FOR 7T MRI

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Introduction
The use of a Butler Matrix [1] has several advantages over directly connecting the amplifiers to the coils [2, 3]. The Butler Matrix was also employed as a Variable Power Combiner improving the power utilization in a multi transmit-channel MRI system [4]. In [5, 6] the accuracy (amplitude- and phase-error) and insertion loss of low loss, reduced size, 8×8 and 16×16 Butler-Matrices in 7T MRI system have been evaluated. Although the magnitude of such errors (or loss) gives a good indication of the accuracy achieved in the implemented design, the meaning of the pure numbers is unclear in context with the application of a Butler matrix within an MR-system when driving a transmit coil array. In this article, a new evaluation method for the measured scattering transmission coefficients of the Butler matrix is derived, which allows for interpretation of errors in terms of CP-modes, which would be excited in the MRI coil system. This approach starts from the fact that each mode can be represented as a combination of equal amplitude signals at the output ports of a CP-Butler matrix with phase increments between consecutive ports fixed but different for each CP-mode. Therefore, in general, any given distribution of signals at the output ports can be represented as the superposition of an infinite number of CP-modes in the same way as a periodic signal can be represented as a combination of harmonic signals.

Methods
Fig. 1 shows an $n×n$ Butler matrix connected to n-coil array ($n=2^N$ and $N=2, 3,...$ is an integer) in an MRI system. The concept of distribution errors in a Butler Matrix has been introduced based on the calculation of corresponding Fourier-series of the CP-mode decomposition from the measured scattering transmission coefficients (when one particular input port is fed) by correlating the measured distribution with the distribution of each CP-mode. In this paper for low loss, reduced size 8×8 and 16×16 Butler Matrices for a 7T MRI system, designed and fabricated in [6] and shown in Fig. 2, the distribution errors in terms of the CP-modes will be determined and the applications will be discussed.

The corresponding CP-mode of the $n×n$ Butler matrix ($n =8$ or $n =16$), can be calculated from the equation: $C_k =1/n\sum(b_m exp[jk(m-1)\Delta])$ where $k = (- n/2 + 0)$, $(- n/2 + 1)$,…, $(- n/2 + n)$ and $n =8, 16$. $\sum$ is from $m =1$ to $m = n$ and $\Delta =2\Pi/n$. b_m ($m = 1,.., n$) are also the output signals from the Butler matrix, measured by the Automatic Vector Network Analyzer (ANA) as transmission coefficients, when one particular input port is fed. See Fig. 1. The resulting mode amplitudes indicate the purity of the field, which would be created in a perfect coil array excited by the Butler matrix.

Results and Discussion
Fig. 3 shows the measured transmission coefficients and gives the calculated spectrum of corresponding CP-modes of the 8×8 and 16×16 Butler matrices, shown in Fig.2, when we feed the input port for the CP+1 mode. We can recognize that the target mode is by far the most dominant mode and only slightly attenuated (amplitude smaller than $1/\sqrt{8}$ or $1/\sqrt{16}$); other "unwanted" CP-modes are kept below -40 dB relative to the target mode in the 8×8 Butler Matrix and below -35 dB in the 16×16 Butler Matrix. Since, the mode analysis also gives the relative phase of modes this result can be used for a compensation of the "unwanted" modes by feeding equivalent anti-phase signals into the affected mode input ports. However, this would only be feasible for relatively low levels of "unwanted" modes and has limitations if amplifiers are only connected to half of the input ports. On the other hand, without such compensation, we can conclude from the resulting magnitudes of "unwanted" modes, that the desired superposition of CP-modes in, e.g., an RF shimming scheme, would be degraded by spurious modes. Therefore, the requirement specification for Butler matrix phase- and amplitude-errors should be based on the application and, in the case of RF shimming, based on the required dynamic range of the CP-mode superposition. In our presently limited experience of RF mode shimming [3], optimization hardly requires more than 25dB of amplitude difference between excited modes. Realization of mode shim should rely on an accuracy margin such that we assume a mode purity of the Butler matrix of 35dB should be sufficient for most cases. Finally, a good comparison between two different excited CP-modes can be seen in Fig. 4. This Fig. shows T_1-weighted FLASH 2D images (FoV 300 × 300, TR 30 ms, TE 3,8 ms, 384 × 384, 2 av., breath hold) acquired in CP+1 and CP2+ mode of the 16 channel array when the Butler Matrix, shown in Fig 2(b), drives our 16 channel Tx body coil array [3] with volunteer. The images were acquired on a Siemens 7T whole- body system.
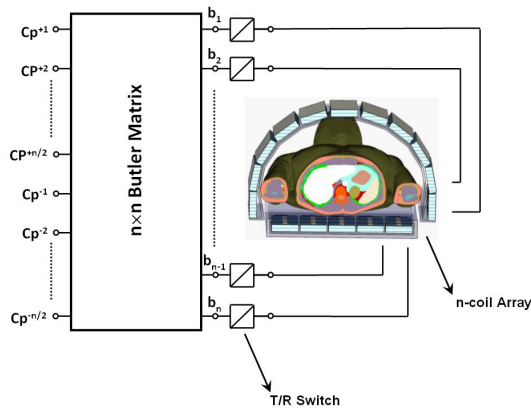

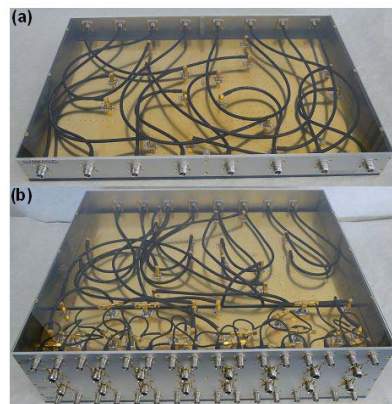Fig. 1 $n×n$ Butler Matrix driving n- Coil Array in an MRI system

Fig. 2 Realized 8×8 Butler matrix (a) and 16×16 Butler matrix (b), at 298 MHz to drive 8 and 16 coil arrays respectively in a 7T MRI system [4].
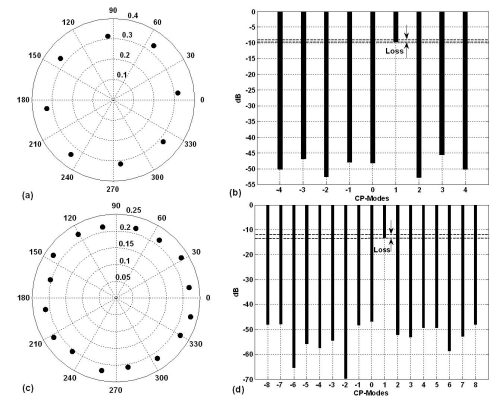

Fig. 3 Measured transmission coefficients of the 8×8 (a) and 16×16 (b) Butler Matrices, shown in Fig 2. Calculated spectrum of corresponding CP-modes of the 8×8 (c) and 16×16 (d) Butler Matrices, shown in Fig 2.

References
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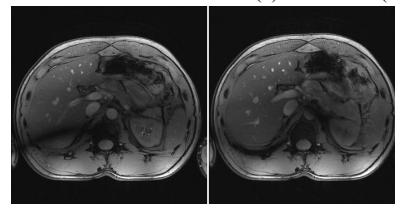[6] Yazdanbaksh et al, submitted to Magn Reson Med, July 2010, (MRM-10-11745)

Fig. 4 T_1-weighted FLASH 2D (FoV 300 × 300, TR 30 ms, TE 3.8 ms, 384 × 384, 2 av., breath hold) images acquired in CP+1 (left) and CP2+ (right) mode of the 16 channel array.