Understanding Parallel Transmit Array Efficiency

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Introduction: A common approach for evaluating the efficiency of a conventional transmit coil is to measure the amplitude of the created B1 field or spin flip angle given a certain input power. However it is not yet clear how the efficiency of a transmit array in B1 shimming / parallel Tx applications could be evaluated. This may be attributed to the shear number of possible weighting configurations (induced statically by B1 shimming coefficients or dynamically by parallel excitation RF pulses) in driving individual Tx channels or ports. A conventional quadrature drive coil in comparison employs a fixed weighting configuration (typically 1 and $e^{j\pi/2}$ for the coil's two ports). We hereby present a unifying efficiency metric that is a clear extension of the conventional efficiency metric, and is as practical to quantify as is the conventional metric.

Methods and Results: We define the new transmit efficiency metric as $B1^+$ strength squared per unit dissipated power. The rational of the definition lies with a linear system's superposition principle and its ramifications. Let the weighting configuration at time t be denoted by $\mathbf{w}$, a complex-valued vector whose nth entry, $w^{(n)}$, defines the amplitude and phase of the sinusoid RF pulse driving the nth channel of an N-channel Tx array at time t. The net $B1^+$ and E fields can be expressed as:

$$\mathbf{B1}^+(\mathbf{x})=\Sigma_n w^{(n)}\, \mathbf{b}^{(n)}(\mathbf{x}) \quad \text{and} \quad \mathbf{E}(\mathbf{x})=\Sigma_n w^{(n)}\, \mathbf{e}^{(n)}(\mathbf{x}), \quad \text{or, in matrix notation, vector of } \mathbf{B1}^+ \text{ samples} = \mathbf{C}\,\mathbf{w} \quad \text{and} \quad \text{vector of } \mathbf{E} \text{ samples} = \mathbf{D}\,\mathbf{w} \qquad [1]$$

$\mathbf{b}^{(n)}(\mathbf{x})$ and $\mathbf{e}^{(n)}(\mathbf{x})$ represent respectively, the $B1^+$ and E fields due to a weighting configuration with 1 on the nth channel and zeros on the others. For checking $B1^+$ at a single location $\mathbf{x}_1$, matrix $\mathbf{C}$ is 1 by N with $\mathbf{C}(1,n) = \mathbf{e}^{(n)}(\mathbf{x}_1)$. For checking $B1^+$ at multiple locations $\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_M$, matrix $\mathbf{C}$ is M by N, with $\mathbf{C}(m,n) = \mathbf{e}^{(n)}(\mathbf{x}_m)$. In either case (average) $B1^+$ strength squared can be expressed with $\mathbf{w}^H\, \mathbf{\Gamma}\, \mathbf{w}$ where $\mathbf{\Gamma} = M^{-1}\, \mathbf{C}^H\, \mathbf{C}$.

Recent studies further suggest that parallel Tx power dissipation may not be as evasive as it appears. In fact a structure exists, and a complete determination of RF power dissipation as a function of $\mathbf{w}$ is feasible by using calibration data from a set of quick experiments (1,2). The underlying principle for tracking parallel Tx power is E field superposition's impact on RF power dissipation:

$$\text{Local RF power dissipation} = \frac{\sigma}{2}\left|\mathbf{E}(\mathbf{x})\right|^2 = \frac{\sigma(\mathbf{x})}{2}\mathbf{E}(\mathbf{x})^* \bullet \mathbf{E}(\mathbf{x}) = \frac{\sigma(\mathbf{x})}{2}\left(\sum_{m=1}^{N} w^{(m)}\mathbf{e}^{(m)}(\mathbf{x})\right)^* \bullet \left(\sum_{n=1}^{N} w^{(n)}\mathbf{e}^{(n)}(\mathbf{x})\right) = \mathbf{w}^H \mathbf{\Lambda}(\mathbf{x})\,\mathbf{w}$$

Taking volume integral yields a quadratic function relating $\mathbf{w}$ to total RF power dissipation: Total RF power dissipation = $\mathbf{w}^H\, \mathbf{\Phi}\, \mathbf{w}$

The results above make it practical to evaluate the new efficiency metric *in vivo* as well as on the bench. For the former the power correlation calibration scheme (1,2) gives $\mathbf{\Phi}$, allowing tracking of power requirement/consequence of any possible weighting configuration. B1 mapping gives $\mathbf{C}$, allowing evaluation of $\mathbf{\Gamma}$ and (average) $B1^+$ strength squared. The transmit efficiency metric takes the explicit form of:

$$\eta = \mathbf{w}^H\, \mathbf{\Gamma}\, \mathbf{w} \,/\, \mathbf{w}^H\, \mathbf{\Phi}\, \mathbf{w} \qquad [2]$$

A suitable unit is uT squared per Watt. In the conventional single channel case $\mathbf{\Gamma}$ and $\mathbf{\Phi}$ reduce to scalars, and the metric captures B1 strength squared per unit power, compatible with existing practice. In the parallel Tx case, different $\mathbf{w}$'s correspond to different efficiency in general, as expected. Yet the metric sufficiently captures the increased complexity of multi-channel Tx by adopting a structure tracking parallel Tx power.

Depending on the B1 shimming coefficients or parallel RF pulses applied, one operates a transmit array at a range of efficiency levels, as quantified by the metric. Maximum and minimum exist that bound the efficiency spectrum. It can be shown that calculating maximum and minimum of η is a generalized eigenvalue problem. From the solution obtained with numerical calculations (e.g., with Matlab function call eig($\mathbf{\Gamma}$,$\mathbf{\Phi}$)), the largest eigenvalue and its corresponding eigenvector represent respectively, the maximum Tx efficiency and the corresponding $\mathbf{w}$. And the smallest eigenvalue and its corresponding eigenvector represent respectively, the minimum Tx efficiency and the corresponding $\mathbf{w}$.

To assess the efficiency of a Tx array in imaging a specific subject, it is possible to take several angles, including: 1) What are the best and worst case use scenario? This can be answered using the generalized eigenvalue solution described above. 2) What does an efficiency spectrum probably look like? One way to approach this is to consider $\mathbf{w}$ as a random vector with a suitable distribution and to accordingly conduct Monte Carlo simulations to estimate the probability profile of η. 3) What is the Tx efficiency associated with a particular set of B1 shimming coefficients or parallel Tx pulses? This involves directly plugging in the coefficients / pulse samples. It gives a most specific answer which comes with qualifiers that include the target excitation profile, the specific k-space trajectory, and etc., all belonging to the set of parameters that define an RF excitation.

A simulation was conducted where Tx efficiency of imaging a block phantom at 7T using three different Tx arrays was evaluated. The three arrays assume different array geometry but otherwise use same size loop coils as array elements (Fig.1a-c). $B1^+$ and E fields were calculated using xFDTD (Remcom, State College, PA). Following the evaluation framework introduced above we quantified the maximum and minimum efficiency with each array in imaging a coronal slice inside the phantom (red dotted line). Monte Carlo simulations further predicted efficiency spectra (solid line) associated with driving the arrays with uniformly distributed random weights. For each array one linear class large tip parallel excitation pulse was designed and its corresponding average efficiency was determined (green dotted line).

Efficiency of a prototype 7T Tx and Rx array in imaging a phantom was further evaluated on an 8-channel parallel Tx and Rx 7T scanner (Siemens, Erlangen, Germany). Following B1 and $\mathbf{\Phi}$ calibration, η was quantified for various choices of $\mathbf{w}$. In imaging a center axial slice it was observed that driving the array coil with the eigenvector corresponding to the largest eigenvalue of eig($\mathbf{\Gamma}$,$\mathbf{\Phi}$) led to a 4-fold increase in Tx efficiency compared to driving the coil in an approximate CP mode. This increase was also reflected in a significantly larger average $B1^+$ with the most efficient driving given comparable total output power from the 8 RF power amplifiers.

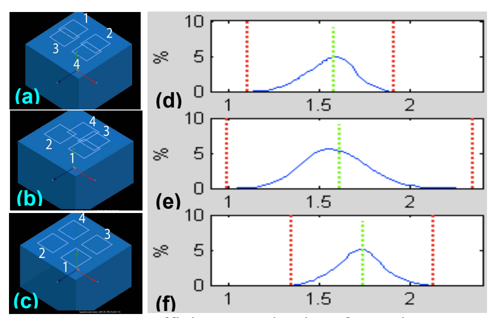

Fig. 1 Tx array efficiency evaluation: for each case illustrated on the left, the corresponding plot on the right shows (in a.u.) η_{max}, η_{min}, η's distribution from Monte Carlo simulations, and average η corresponding to a linear class large tip parallel excitation.

Discussions: Note that there are useful adaptations to the present efficiency metric. One version arises from limiting the power dissipation volume integral to a local region inside the subject – the resulting metric assesses a coil array's efficiency in avoiding RF power dissipation in the region while inducing B1 for spin excitation. However it is not yet clear how a local power calibration can be noninvasively and robustly conducted in practice. For parallel receive array an interesting hypothesis is that an analogous framework that assesses sensitivity squared per unit noise power may be useful. Especially for any linear operator-based image reconstruction, a reconstructed image can be equivalently expressed as weighted summation of multi-channel MR signals. The principle of reciprocity in this case supports efficiency evaluation using a metric in the same form as that of Eqn 2, except for the use of $B1^-$ values in constructing $\mathbf{\Gamma}$ and the use of noise correlation calibration in obtaining $\mathbf{\Phi}$. Assessing receive array efficiency following angles analogous to that described above are potentially useful.

References: 1. Y. Zhu, In Vivo RF Power and SAR Calibration for Multi-Port RF Transmission, *Proc. ISMRM 17th Meeting*, 2009. 2. L. Alon et al., Automated In Vivo Global SAR Prediction for Parallel Transmission, *Proc. ISMRM Third International Workshop on Parallel MRI*, 2009.