# On parallel transmission - Transmit SENSE


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**INTORDUCTION**

The concept of parallel transmission based on multiple individual RF transmit coils has been introduced to overcome $B_1$ homogeneity limitations caused by dielectric resonance effects at very high frequencies (1-3). Triggered by these hardware developments and based on the analogy between RF pulse design and MR imaging (4,5), the principles of parallel imaging have been applied to RF transmission recently (6,7). This allows improving spatially selective multi-dimensional RF pulses by shortening their duration, enhancing their spatial definition, or reducing the required RF power. Using parallel transmission $T_2^*$- and all kinds of off-resonance limitations (chemical shift, $B_o$ inhomogeneities) can be overcome making 3D pulses really feasible in the future. This may be useful for volume selective excitation (8-11), for curved slice imaging (12) or for navigators employed for motion sensing (13).

In the present paper a brief overview is given over some selected aspects of parallel transmission with special focus on shortening spatially selective RF pulses (2D, 3D). The basic principles of parallel transmission (in particular Transmit SENSE) will be outlined, initial experimental proofs will be described and the impact of error propagation and the role of coil design will be discussed.

**THEORY**

In parallel MR imaging, the undersampling artifact is avoided by taking the coil sensitivity information into account during image reconstruction (14,15). In analogy, in parallel transmission each individual transmit coil excites a specific magnetization pattern that could show artifacts, caused by subsampling of the excitation *k*-space. However, their parallel superposition should result in the desired artifact-free magnetization pattern. Thus, the question is: what undersampled spatial patterns $P_i(\mathbf{x})$ have to be excited by each of the $N$ transmit coils, each exhibiting a characteristic sensitivity profile $S_i(\mathbf{x})$, to obtain the desired excitation pattern $P_{des}(\mathbf{x})$? This constraint leads to Eq. [1], which is the central equation of parallel transmission

$$P_{des}(\mathbf{x}) = \sum_{i=1}^{N} S_i(\mathbf{x}) P_i(\mathbf{x}) \quad . \qquad [1]$$

This linear equation states, that the superposition of all the individual pulse profiles $P_i(\mathbf{x})$, weighted by the corresponding (complex) coil sensitivity profiles, should yield the desired excitation pattern. It is assumed, that the $S_i(\mathbf{x})$ are known, which can be determined by direct $B_1$ mapping techniques (16,17) or in case of coils usable in the transmit/receive mode by approaches based on the reciprocal principle (18,15). To derive the unknown, wanted waveforms $B_{1i}(t)$ for the $N$ transmit coils Eq. [1] has to be transformed into the Fourier domain, according to Pauly's RF pulse design concept (4). Given in simple terms: the $B_1$ waveform to excite a desired magnetization pattern is just its Fourier transform sampled along the chosen k-space trajectory multiplied by some trajectory dependent weighting coefficients (4). The Fourier transform of Eq.[1] results in a convolution making inversion for the $p_i(\mathbf{k})$ difficult.

$$p_{des}(\mathbf{k}) = \sum_{i=1}^{N} s_i(\mathbf{k}) \otimes p_i(\mathbf{k}) = s_{full}(\mathbf{k}) \; p_{full}(\mathbf{k}) \qquad [2]$$

To separate the unknown $p_i(\mathbf{k})$, Eq.[2] has to be "inverted", which is nontrivial for an arbitrary *k*-space trajectory. To facilitate this, the sensitivities $s_i(\mathbf{k})$, transformed into *k*-space, can be grouped to a single, "invertible" sensitivity matrix $s_{full}$ and, correspondingly, the individual $p_i(\mathbf{k})$ to form to a single vector $p_{full}$, which can be solved using regularization (19).

$$p_{full} = s_{full}^H \left( s_{full} s_{full}^H + \lambda^2 \right)^{-1} p_{des} \qquad [3]$$

In Eq.[3] $\lambda$ denotes a suitable regularization parameter. The two different approaches of parallel transmission (6,7) proposed so far differ on the central matrix inversion. Either it is performed in the Fourier space (6) or in the spatial domain (7). While the first approach is capable for arbitrary trajectories in the excitation k-space, the latter one is restricted to Cartesian ones. Once Eq. [3] has been solved the individual excitation patterns $p_i(\mathbf{k})$ can be extracted from $p_{full}$. This represents the general solution without any constraints and has to be mapped into the time domain using the sampling density compensation W(t).

$$B_{1i}(t) = W(t)\, p_i(\mathbf{k}(t)) \qquad [4]$$

The problem to derive the actual $B_1$ waveforms as given in Eq. [4] will be over-determined in most cases. The resulting degree of freedom thus introduced by the use of multiple transmit coils can be exploited in several directions. A major application is given by the reduction of the pulse duration, corresponding to the reduction of acquisition time in parallel imaging. Instead of reducing the pulse duration, the spatial definition of the excitation pattern can be increased without changing the pulse duration. A further possibility to utilize multiple transmit coils is to reduce the required RF power, and thus, the resulting SAR (7).

**ERROR PROPAGATION**

Noise in parallel transmission may mainly originate from the D/A converting process and RF amplifier imperfections. This system noise affects the individual pulse profiles $P_i(\mathbf{x})$, and thus, influences the final result in a linear way as a superposition in the spatial domain (cf. Eq. [1]). Errors in the coil sensitivity profiles caused by noise present during their measurement or other imperfections also influence the final result linearly according to Eq. [1]. However, theoretically they can be determined with a high accuracy. It is important to note, that the system noise does not interact with the central matrix inversion. This is a crucial difference with respect to parallel imaging, where the system noise generated in the receive chain is enhanced, if the matrix inversion is ill-conditioned (15). In parallel imaging, the inverted matrix is multiplied with the measured data bearing noise. In parallel transmission, the inverted matrix is multiplied with the desired excitation pattern, which is free of noise [Fig. 1]. In that respect, the concept of the geometry factor as deduced for standard SENSE in the receive case (15) cannot be adapted directly to Transmit SENSE.

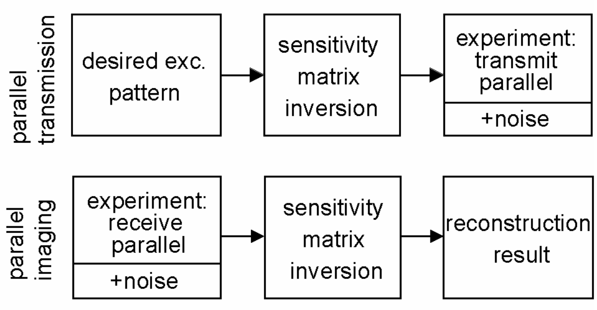


Fig. 1. Schematic comparison of parallel transmission and parallel imaging. Experimental noise comes into play after / before the inversion of the sensitivity matrix, which leads to a larger robustness of parallel transmission than parallel imaging.

If the inverse problem of parallel transmission is ill-posed, the superposition of Eq. [1] does not lead to a complete cancellation of the subsampling artifacts, and noise-like aliasing structures appear in the final result. The problem becomes ill-posed, if the spatial frequency components of the actual coil sensitivity profiles are not able to compensate for the missing parts of a reduced *k*-space trajectory. Thus, a proper interplay between the coil sensitivity profiles and the involved trajectories has to be found.

## ASPECTS OF COIL DESIGN AND SAR

It is important to know how sensitive the RF pulse performance depends on the transmit coil array geometry. Due to the different error propagation behavior compared to parallel imaging, parallel transmission should be less sensitive. This was confirmed recently by corresponding simulations, which showed, that RF pulse performance is in general rather robust (20) against variations of the transmit coil array configuration and becomes critical only for very artificial cases.

On the other hand, if the sensitivity matrix $s_{full}$ to be inverted becomes ill-posed, the norm of the resulting vector $p_{full}$, containing the RF waveforms, may increase (c.f. Eq.[3]). The norm of the waveform corresponds to the required RF power, which might become relevant for the specific energy absorption rate (SAR). However, further simulations have shown that the SAR problem in Transmit SENSE seems to be good-natured and thus ill-posed inverse problems only play a minor role in parallel transmission (21). These findings give rise to a much larger freedom in designing coil arrays for parallel transmission than for parallel imaging.

## SUMMARY

Parallel transmission follows the development of parallel imaging. Parallel transmission can be used to shorten the duration of spatially selective RF pulses or to increase their spatial resolution definition maintaining the pulse duration. Other applications envisaged might be the reduction of the required RF power, i.e. the SAR, or RF shimming. In parallel imaging and transmission it is necessary to determine and invert a matrix derived from the spatial sensitivities of the coils involved. However, parallel transmission is not just the reciprocal version of parallel imaging. As a consequence of this asymmetry, it seems that the error propagation in parallel transmission does not lead to pronounced non-linear effects as in parallel imaging, described by the geometry factor.

MR systems fully capable for parallel transmission will probably be available in the near future. These MR systems are expected to improve RF pulse performance in many respects, and thus, opening a wide range of new and exciting applications.

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