ACCELERATED MR IMAGING WITH SPREAD SPECTRUM ENCODING

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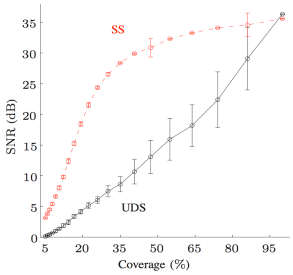
Objectives: Accelerating MR acquisitions is of major interest for applications ranging from structural MRI to dynamic imaging. Recent approaches seek to reconstruct the image from incomplete **k**-space coverage by under-sampling in the phase encoding directions, using the well-known compressed sensing theory [1]. A straightforward, but naïve, uniform density (random) sampling (UDS) in **k**-space leads to poor reconstruction qualities. The variable density (random) sampling (VDS) method proposed in [2] greatly enhances the results by concentrating most of the measurements at the center of the **k**-space. VDS may not be optimal in several aspects though. Firstly, it is empirical and the reconstruction quality might appear to be sensitive to the precise shape of the sampling profile and to the signal itself. Secondly, in the perspective of combining compressed sensing and parallel imaging, the convolutions in **k**-space space induced by the multiple coils at each spatial frequency probed should be less efficient if VDS is used, due to redundancy in more densely sampled regions. Finally, in many dynamic MR applications, optimal smooth variable density profiles may appear complex to implement.

In the present work, we advocate a spread spectrum technique (SS) for accelerating single-coil MRI with uniform sampling profiles. The SS technique is fully justified by the theory of compressed sensing, and tested on numerical simulations and real acquisitions.

Theory: Our strategy resides in pre-modulating the image $\boldsymbol{\rho}$ by a linear chirp $C(x) = exp[i\pi(w_x\, x^2 + w_y\, y^2)]$ before uniformly and randomly under-sampling the **k**-space. The quantities (w_x, w_y) are called chirp rates. This modulation convolves and spreads the spectrum of $\boldsymbol{\rho}$ or, equivalently, acts on each vector of the sparsity basis $\boldsymbol{\Psi}$, where the signal $\boldsymbol{\rho} = \boldsymbol{\Psi\alpha}$ is compressible, so that information of these vectors is accessible at every **k**-space position. In the context of compressed sensing, this effect is theoretically explained by a decrease of coherence between $\boldsymbol{\Psi}$ and the Fourier basis **F**, and provides an enhancement of the reconstruction quality [3, 4]. The technique was proved to be universal relative to the sparsity basis [3].

This measurement procedure defines an ill-posed inverse problem: $\mathbf{v} = \boldsymbol{\Theta\alpha}+\mathbf{n}$, where $\mathbf{v}$ are the measurements and $\mathbf{n}$ is the noise. In the standard VDS or UDS approaches, $\boldsymbol{\Theta}$ reads as $\mathbf{MF\Psi}$ where **M** is a mask indicating the **k**-space positions probed. In our setting, $\boldsymbol{\Theta}$ reads as $\mathbf{MFCU\Psi}$ where **C** implements the chirp modulation and **U** is an up-sampling operator needed to simulate an analog modulation. In this case, the extent of the uniform sampling region implemented by **M** is optimized by the constraint that the average sampling density must not exceed $(1+|w_x|)^{-1}(1+|w_y|)^{-1}$, given the spread of information in **k**-space due to the modulation.



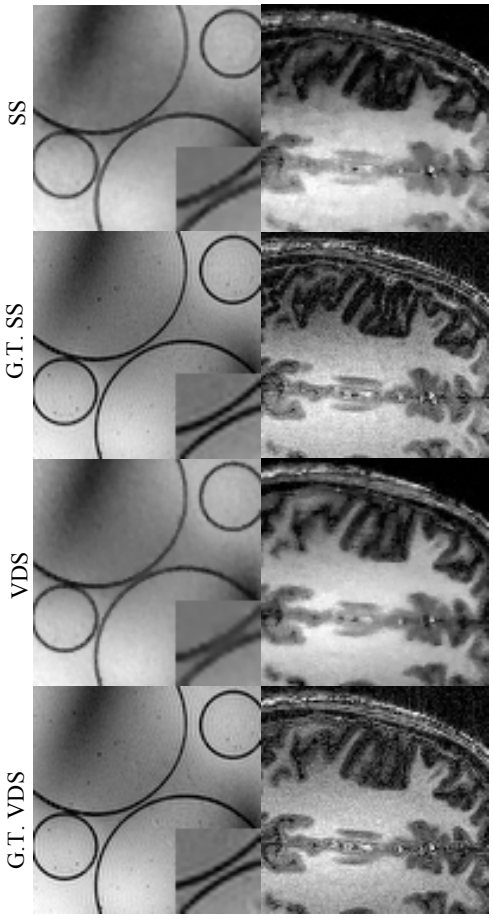


Figure 1: Top left panel: reconstruction SNR (mean and standard deviation over 30 simulations) of the Shepp-Logan phantom as a function of the percentage of coverage in **k**-space, with the SS (dot-dashed red curve) and the UDS (continuous black curve) techniques. Right panels: reconstruction of one sagittal slice of the phantom (first column) and the human brain (second column) from 20 and 40 percent of phase-encodings respectively, with the SS (first row) and the VDS (third row) techniques, as well as ground truths (G.T.) for the acquisitions with chirp (second row) and without chirp (fourth row).

Method: The performance of the SS technique is evaluated by simulations and by real acquisitions. The chirp modulation was implemented on a 7T MR scanner (Siemens, Erlangen, Germany) with the use of a 2nd order shim coil x^2-y^2. At an arbitrary time after the excitation, it imprints a quadratic phase modulation along the two phase-encoding directions (x, y). The mean chirp rate is controlled by the intensity κ of the quadratic field and the echo time TE. In this implementation, the induced modulation varies linearly along the readout direction k_z but this effect can easily be accounted for in the operator **C**. 3D acquisitions of a phantom using a gradient echo sequence acquired in sagittal direction were performed (192x192x192, res=1/1/1mm, TE/TR = 6/10ms, BW = 300Hz, κ = 4500 μT/mm^2). For the human scans, the conventional clinical MPRAGE sequence was used (192x160x192, res=1.1/1.1/1.1mm, TE/TI/TR = 5.41/950/3000ms, BW = 300Hz, κ = 4500 μT/mm^2). Subjects provided written informed consent prior to the imaging session. The signals are reconstructed by solving the Basis Pursuit (synthetic data) or TV minimization (real data) problems [1, 2].

Results: Comparison of the reconstruction quality of the Shepp-Logan phantom with the SS and the UDS techniques are presented Fig. 1. The reconstruction quality is drastically enhanced by the chirp modulation. The ratio between the number of measurements needed to reach 25dB with and without chirp is around by 0.3. This is in line with the compressed sensing prediction of 0.1 based on the coherence ratio [3, 4].

On the real acquisitions of the phantom and human brain, acceleration factors of 5 and 2.5 relative to standard full acquisitions defining the ground truths (G.T.) images can be respectively reached. The overall visual quality with the SS and VDS approaches are similar, however our method exhibits better high frequency details on the phantom: the separation between the two biggest circles is more visible in the SS reconstruction.

Conclusion: Our SS technique, defined in the context of the compressed sensing theory, was implemented using a 2nd order shim coil x^2-y^2 for the required signal modulation. First results, from single coil acquisition, already exhibit reconstruction qualities similar to the VDS method, with better preserved high spatial frequency content.

References: [1] Lustig et al., Magn. Reson. Med., 58:1182-1195, (2007) [2] Candès, Proc. Int. Congress Math., 3:1433-1452, (2006) [3] Wiaux et al., Mon. Not. R. Astron. Soc., 400:1029-1038 (2009) [4] Wiaux et al., Proc. IEEE Int. Sym. On Biomed. Imaging, Vol. CFP10BIS-CDR: 756-759, (2010). This work is supported by the CIBM of the Geneva and Lausanne Universities, EPFL, the Leenaards and Louis-Jeantet foundations, by the SNSF under grant PP00P2-123438, and by the EPFL-Merck Serono Alliance award.