In-Bore Broadband Array Receivers with Optical Transmission

Jonas Reber[1], Josip Marjanovic[1], David Otto Brunner[1], Thomas Schmid[1], Urs Moser[1], Benjamin Emanuel Dietrich[1], Christoph Barmet[1,2], and Klaas Paul Pruessmann[1]
[1]*Institute for Biomedical Engineering, University and ETH Zurich, Zurich, Switzerland,* [2]*Skope Magnetic Resonance Technologies, Zurich, Switzerland*

Introduction: The need for large receive channel counts in MRI spectrometers has been constantly increasing over the past decades for providing optimal SNR yield and imaging acceleration by large coil arrays and most recently also for monitoring of the MRI system function e.g. of the gradient fields [1] or of parallel RF transmit systems [2]. However, the routing of the cabling and the inflicted couplings as well as implications on safety, patient comfort and handling become a substantial challenge for the design and integration of systems with very high channel counts. Further, modern ultra-high field systems are increasingly used for acquisition of other nuclei's spectra with similarly high channel counts ([1,3]) which necessitates the receivers being broadband and flexibly tunable but nevertheless offering large dynamic range at all signal levels offered by the different applications. In this work we present initial measurements from a novel in-bore RF acquisition platform in which the mentioned challenges are tackled by high sampling rate but low power analogue-to-digital converters (ADC), flexibly programmable high-speed computing units in the bore and high bandwidth digital optical transmission capabilities. It is demonstrated that signal quality and performance can be achieved at tolerable power levels without the need for highly integrated circuitry which would only come to cost effective realms for very large volume productions.

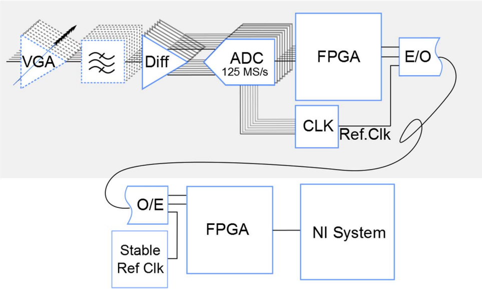

Figure 1: Schematic of the parts exposed to the magnetic field on top and the host system on the bottom.

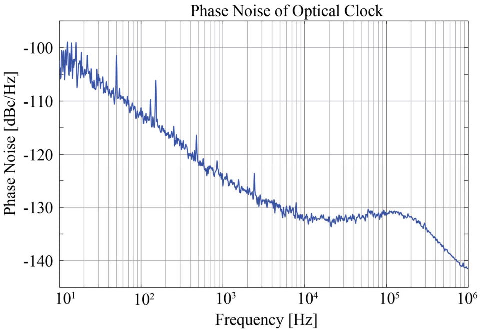

Figure 2: Phase noise spectrum of the clock.

Methods: The basic topology of the converter (Fig. 1) was a direct undersampling scheme in which the ADC offers the analog bandwidth (800 MHz) to digitize signals with sampling rates up to 125 MSps offering in principle 60 MHz analogue instantaneous bandwidth with high dynamic range (14 bit). The appropriate band is anti-alias filtered by custom, drop-in LC filter networks whose selectivity requirements are greatly reduced by the large instantaneous bandwidth delivered by the fast sampling. A 32 dB variable gain block is deployed for signal pre-scaling and a highly linear differential amplifier is used as a single-ended-to-differential converter. The digitized samples are transmitted via partially serialized lines to a low power field programmable gate array (FPGA) unit which allows to reconfigurably demodulate, bandpass and downconvert the incoming data stream of 16 channels (3.5 GBps). Further the unit allows to process and output additional sequence triggers and can control peripheral devices through high speed digital lines with very close timing constraints for future feedback applications as e.g. for RF safety [2] or field stabilization [4]. The downsampled data is routed via a high speed (12 Gbps) optical link to a second FPGA unit outside the scanner linking via a PCI express bus to a PC hard disk. For the first experiments this step was implemented as an actual optical loop-back line between two clock domains of a FPGA development board. In order to allow for synchronization of several 16 channel units and improved clocking wander performance, the long-term time and phase reference clocking was transmitted in opposite direction to the data via the same optical link, based on wavelength multiplexing. The quality of the RF signal acquisition was tested by bench measurements using a high quality reference signal source (SMA 100 A, Rhode&Schwarz,Munich, Germany) evaluating the SNR and linearity of the acquired signals. The SNR was evaluated by single tone measurements while the linearity was assessed by a two tone approach with 100 kHz spacing using a second signal source (which provided lower quality HP8648A). Clocking performance was evaluated using a high-end spectrum analyzer (PXIe-5665, National Instruments, Austin, Texas).

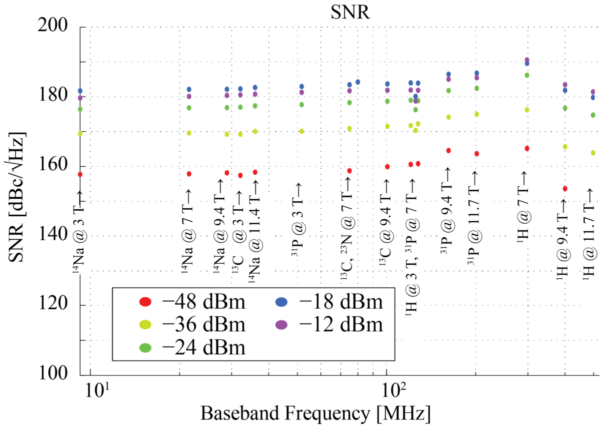

Figure 3: SNR measured dependent on signal input level

Results: The test system consisted of two ADC boards hooked to a FPGA motherboard (13x15 cm). The determinant factor for the SNR resolution capabilities was found to be the clocking accuracy. As shown in Fig. 2 a total jitter of 300 fs (from 10 Hz to 1 MHz) was achieved which coincides very closely with the noise floor of the available reference instrument. Once accurately sampled the broadband architecture allows for large dynamic range as seen Fig. 4 because the excess bandwidth of the acquisition can be used for spur rejection as well as for vertical up interpolation which increases the instantaneous dynamic range as much as 194 $dB/\sqrt{Hz}$. Largest 3rd order intermodulation products were -88 dBc at -6 dB full range. Total power dissipation in the bore was about 1 W per channel when acquiring 16 channels with 2 MHz bandwidth, full dynamic range and 100% duty cycle.

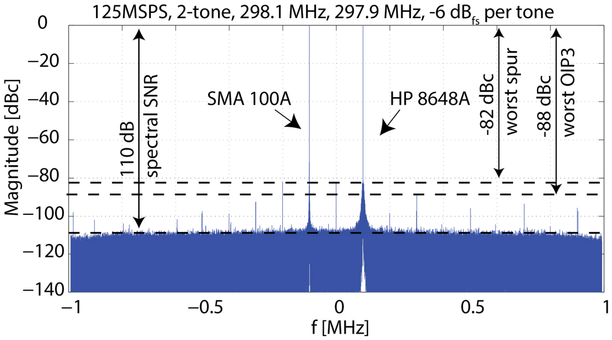

Figure 4: Spectrum of 2-tone measurement, AQ duration: 250 ms

Discussion & Conclusion: Although spectrometers outside the magnetic field benefit from very clean electromagnetic environment and comparably unlimited power dissipation capabilities it was found that comparable signal quality could be achieved with equal flexibility and modularity for in-bore systems. Broadband topologies allow modular acquisition of all routinely used frequency bands across field strength and applied nuclei by exchangeable filters. The reduced primary bit-depth of the high-speed sampling ADCs compared to slower siblings results nevertheless in comparably high dynamic ranges after downconversion to equal bandwidths. The SNR and the dynamic range were found to be mostly limited by the clocking accuracy of the system. The flexibly programmable units allow acquisition of different frequency bands per channel on a common timing basis as it is needed for certain multi-nuclear experiments and system monitoring applications [4]. Several modules can be synchronized and phase locked for achieving larger channel counts in principle without impact on acquisition duty cycle and bandwidth.

References:[1] Barmet, MRM (2008), [2] Graesslin, Proc ISMRM (2010), [3] Brunner, Proc ISMRM (2013) , [4] Wilm, MRM (2013),