An RF Small Signal Unit Optimized for a 7T Multinuclear MR System

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Introduction:

The move to higher magnetic field strengths has come about because of the desire for increased signal to noise ratio (SNR), spatial resolution and specificity for functional imaging as well as for improved spectral dispersion and quality for MR spectroscopy and chemical shift imaging [1]. On the one hand this improvement in system performance opens up a wide range of applications across the biological and medical-based sciences. On the other hand the increasing MR frequency and signal dynamic range (DR) requires a critical review of the RF small signal unit (RFSU) specifications.

Impact of 7T specific parameters on the RFSU specifications:

Since the MR frequency is directly proportional to the magnetic field strength, the highest 7T frequency of interest (1H nucleus, 300MHz) is more than doubled compared to the 3T system frequency (123MHz). The receiver input frequency range scales up by the same relationship. As the SNR is approximately linearly increasing with B_o [2] the DR of the receiver system has to be adapted. FMRI experiments require extremely stable and clean sampling clocks (SC) and local oscillator signals (LO). SAR follows a B_o^2 rule. Therefore keeping the necessary SAR headroom low becomes more important with increasing field strengths. Thus measurement uncertainties and emissions of undesirable spectral components have to be considered carefully.

7T RFSU design considerations:

In order to keep the number of receiver gain steps low, it is desirable to design the coherent receiver DR as large as possible. The analog to digital converter must be able to fully capture the DR of the signal in k-space from the central peak to the thermal noise floor. Each frequency converter stage (e.g. Transverter Unit) reduces the system DR since the noise budget has to count for the intrinsic noise of the converter itself. Also, care has to be taken that noise which is picked up in the image bands of the involved mixer stages does not sacrifice the receiver sensitivity and the DR. A high fidelity oven controlled crystal oscillator (OCXO) should be used as a system reference. The reference signal has to show excellent long-time stability and very low phase noise simultaneously. Compared to the noise floor coherent spurious signals on the RF- or IF-signal will be enhanced by a factor of N by performing a N x N FFT and show up as bright dots in the final image. Coherent spurious signals on the SC or LO can cause additional artefacts. For this reason the spurious free dynamic range (SFDR) of the LO signals should be as large as practicable. Transmitter spurious signal levels (e.g. unwanted carriers or sidebands of the modulator signal) have to be kept as small as possible so as not to affect the cumulative SAR. Furthermore the designer has to deal with challenging effects related to the increase of the radio frequencies: Device parameter tolerances, device parasitic effects and phase errors due to PCB line length tolerances.

Practical realization of a high performance 7T RFSU:

Figure 1 shows a basic block diagram of the RFSU used in the Siemens 7T MR system. The whole RFSU is frequency agile, multi-channelled and applicable to multinuclear operation. High speed optical fibre links are used for the communication between the RFSU boards and the image processing and measurement control units to minimize EMI. The synthesizer unit contains two independent direct digital synthesizers (DDS). Their supplying high quality 640MHz reference clock is generated by multiplying a stable 10MHz OCXO signal. The multiplier is built with cascaded frequency doublers. A crystal filter and high quality lumped element interface filters between the different stages ensure extremely low phase noise and sufficient high SFDR. The whole multiplier block is integrated into a phased locked loop to achieve phase stability adequate for the most demanding MR experiments (Fig. 2). Careful frequency planning avoids problems with DDS related spurious signals. The architecture of the multi-channelled receivers is based on a purpose designed signal amplitude compressor/expander (compander) technique. This achieves an outstanding high DR while eliminating the need for automatic gain control within the receiver which would constrain performance and system flexibility [3]. The independent receiver channels are continuously processed simultaneously. An option to switch the receiver input selectors to external paths enables the system to close different signal loops. This ensures proper operation of all components within the loop and reduces down time for servicing in the failure case. The receivers and modulators contain only one analog frequency mixing stage per channel. Analog to digital and digital to analog conversion is performed in the IF domain. The mixers are of a quadrature type which suppresses the unwanted image band. The necessary LO quadrature splitting is controlled via phase and amplitude locked loops to provide the required accuracy over the entire LO frequency range.

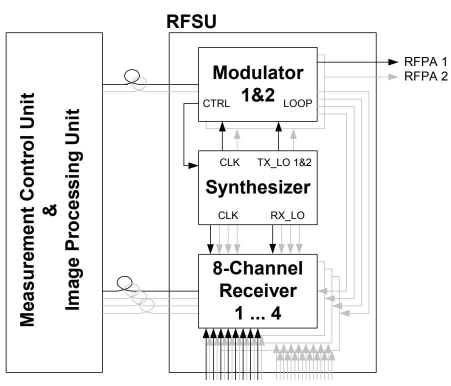

Fig. 1. Basic RFSU block diagram

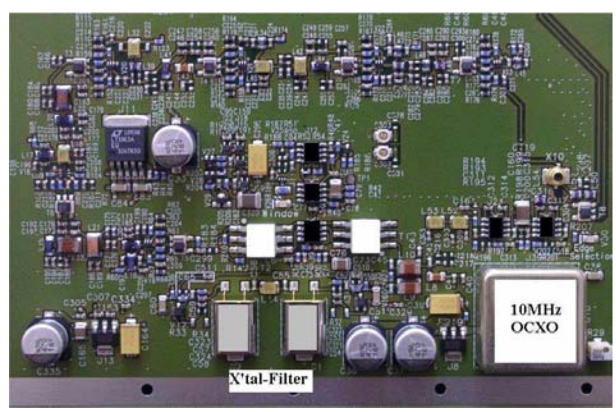

Fig. 2. 7T Synthesizer Reference Clock Unit

Conclusion:

7T specific RFSU design challenges have been highlighted. It has been shown that the step to higher magnetic field strength requires in particular increasing the DR of the system. The higher maximum frequency dramatically complicates the design of a high quality frequency agile system. Some basic design strategies are proposed and illustrated on a state-of-the-art commercial RFSU designed to perform to the limit of currently available technology. The described unit is scalable in numbers of receiver and modulator channels. Several Siemens 7Tesla 32 channel human scanners have been successfully installed already.

References:

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