RF Transmit and Receive Chains

Greig C. Scott,
Electrical Engineering, Stanford, CA, United States

Introduction In MRI, pulse sequences begin as digital waveform specifications, and images are constructed from digitized data. The RF transmit and receive chains provide the link from the digital representation of RF waveforms to the physical RF signal power transported to and from MRI coils. The goal of this tutorial is to review the system issues and core components required to deliver RF power to a coil with high fidelity (the transmit chain), and the components that in turn convey the low level NMR signals for analog to digital conversion (the receive chain). Emphasis will be placed on the functional limitations that may be unfamiliar to MRI users and programmers.

Transmit Chain The RF transmit chain must synthesize complex RF waveforms, amplify to high power RF with high fidelity, monitor power levels, and maximize delivered power to the coil. The key system components include:
1) Waveform Synthesis, 2) RF Power Amplifier, 3) Power monitors, and 4) RF switches.

1) Waveform Synthesis: All MRI systems employ direct digital synthesis to generate the RF excitation signals. To support multiple field strengths, and maintain optimal performance of the DDS block, an additional mixer and phase locked loop local oscillator often provides the final conversion to the target 1.5T, 3T or even 7T operating frequency. In a transmit array, gangs of DDS blocks are common. On single channel DDS systems, multiple signal channels can be generated with multiple vector modulators.
2) RF Power Amplifiers: 1.5T and 3T scanners typically employ 15-35 kW power amplifiers. Internally, these amplifiers use power-combined arrays of transistors. Since patient size is quite variable, these amplifiers often include circulators to protect the amplifier from severe load conditions. Power amplifiers also suffer from several sources of nonlinearity, of which the least understood are memory effects. When the RF waveform envelope has a complex structure, the amplifier power supply fails to track the demand current, causing distortions that are difficult to pre-calibrate.
3) Power Monitors: Directional couplers are placed between the amplifier and coil to determine forward and reverse power flow. This component can flag extreme levels of reverse power due to coil failure, or adverse patient loading. In transmit arrays, one can also place a form of loop sensor at each coil to monitor local circulating current.
4) RF Power Switches: Some means must exist to disconnect the transmit circuitry from the coil to avoid noise injection and loading, while connecting in the receive circuitry. Today, the switch is almost always a PIN diode circuit. PIN diodes have under 0.5 ohm on resistance at RF when biased by 100mA or more, while they exhibit very high off impedance when reverse biased.

Receive Chain The receive chain must amplify the NMR signals with minimal added noise, protect preamps from the high power transmitter, and digitize the data subject to dynamic range and clock jitter constraints of analog-digital conversion. To construct a fully operational receive chain, the critical components include 1) Preamplifier, 2) Protection Circuits, 3) Analog to Digital Converters.

1) Preamplifiers: Today, all MRI preamps use a form of HEMT (high electron mobility) Field Effect Transistor (FET), which are capable of noise figures below 0.5dB. The role of the preamplifier is to amplify the signal from the coil to drive a coax cable and ensure the fundamental noise floor is above that of the digitizing circuits. The preamplifier must also have sufficiently fast recovery following the inevitable transmit pulse and feed-through.
2) Protection Circuits: During transmit, voltages at coil receive ports can exceed 100 V which would destroy a transistor. Protection circuits include active PIN diode switches, and passive Schottky diodes, and limiter diodes, both of which attempt to clamp the input signal level below about 1 V. Since diode turn-on time is finite, some level of voltage spike can often leak through.
3) Analog-Digital Converters (ADC): MRI signals can exhibit very high dynamic range for 3D acquisitions, with signal peaks at the center of k-space, and noise-like signal levels at the outer edges of k-space. The ADC bit resolution ultimately determines the dynamic range that can be supported. Many ADC architectures exist, (SAR, $\Sigma-\Delta$, pipeline, flash) but pipeline ADCs offer the best combination of bit depth, bandwidth and low sampling jitter for MRI. Oversampling, decimation, and sampling at alternate Nyquist bands are now used to improve ADC dynamic range in MRI.

Future Trends MRI transmit/receive chains benefit directly as device technology evolves. Gallium Nitride (GaN) will become prominent in RF power amplifiers and perhaps replace PIN diode switches. Silicon Germanium (SiGe) bipolar preamps bipolar have potential for very low power. Wireless power delivery, and wireless receivers are on the horizon.
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References:

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