RF Sensor Considerations for Input Predistortion Correction of Transmit Arrays

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Introduction Transmit array systems offer the promise of accelerated excitation, B1 shimming, and the potential for SAR and RF safety management [1,2], while also demanding high-fidelity RF playback in a challenging multi-channel environment. Tx coil arrays are subject to mutual coupling and loading variations, while RF power amplifiers exhibit non-linearity, ill-defined output impedances, and memory effects. We believe precision transmit array control is achievable by input predistortion with mutli-channel loopback sensing. As RF sensors are critical to this technology, we present our on-coil current sensor and in-line vector sensor, and consider the resulting capabilities and limitations in the context of loopback-enabled PTx array control.

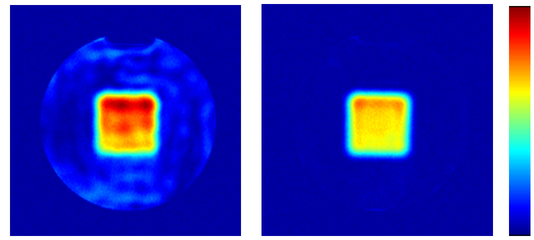

Figure 1: Vector Iterative Predistortion (VIP) uses coil sensors to detect virtually all amplifier non-ideality (left) and compensates to produce a high quality 4-ch 2x accelerated excitation with excellent profile and spurious excitation at the noise floor (right).

Parallel Transmit with Loopback
Vector Iterative Predistortion (VIP) [3] and Cartesian Feedback (CFB) [4,5] methods enable advanced calibration and linearization of transmit arrays through input predistortion and RF sensing loopback. VIP and CFB capabilities go beyond feed-forward or lookup-table linearization to also address coil decoupling and amplifier memory effects. An example 4-ch TxSENSE parallel excitation illustrates the need for high-fidelity RF and demonstrates VIP correction (Fig 1). While Cartesian feedback and VIP yield identical output coil V & I, they differ in their control architecture and stability constraints. Nonetheless, both methods depend on RF sensors to generate the required feedback signals. To enable these loopback calibration methods, we instrument our MEDUSA-based parallel transmit system with either vector RF power sensors at each power amplifier output, or RF current sensors on each coil (Fig 3).

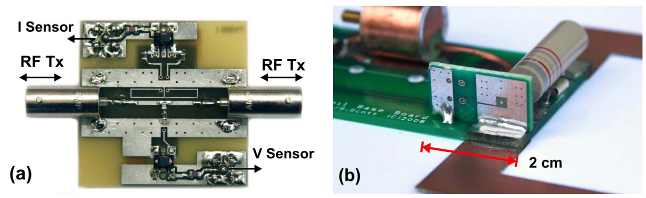

Figure 2: (a) Vector power sensor with V-I ports & (b) Slotted planar coil current sensor provide multiple feedback options for input predistortion

RF Current Sensor Our current sensors are 4-layer PCBs implementing a slotted planar 1:1 transformer, with the outer PCB layers carrying the coil current while squeezing flux to an internal coupled loop (Fig 2b). Although this 2-port sensor detects only coil current, producing 330mV/A, we use it to characterize and correct amplifier performance, determine B_1 strength, and null coil coupling currents. Still, on-coil current sensors are limited without a matching voltage measurement, as true impedances cannot be measured, and on-coil sensors may present practical challenges in routing additional cables from the coil array to receivers.

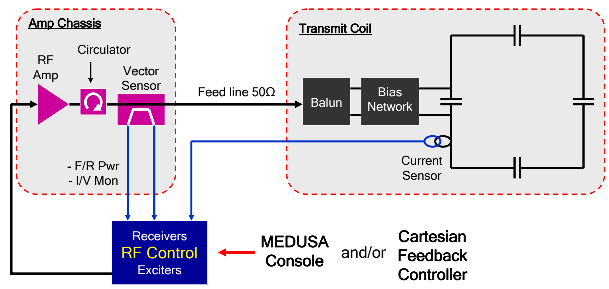

Figure 3: The vector power sensor may be placed anywhere in-line, eg. at the RF amp chassis to simplify cable routing, while the current sensor must be at the point of measurement, inserted into the electrical path on the coil.

RF Vector Power Sensor A 4-port vector sensor, eg directional coupler, is capable of full voltage, current, power flow, and impedance measurements similar to a one-port network analyzer. Our vector power sensors are slotted-line voltage and current transducers, employing transmission line construction designed for low 0.1dB insertion loss and -40dB sensor outputs [6] (Fig 2a). Although a 4-port sensor requires more extensive s-parameter calibration, we can use it to perform precision impedance and power flow measurements (Fig. 4).

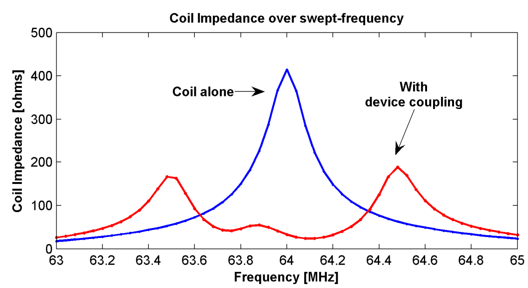

Figure 4: The vector power sensor provides precision measurement of instantaneous coil impedance over freq. and time, both at full RF power and micro-power. One observable effect, resonant peak splitting, may be used to detect unsafe coupling with embedded devices or wires.

Scan Impedance and Amplifier Limits Scan impedance, a concept from antenna array theory [7], describes the time-varying impedance modulation seen at each amplifier in an array due to mutually-coupled drive from other elements. Phased-array beam "scanning" is a close corollary to fully-parallel transmit excitation. Measuring scan impedance over the course of PTx playback can be done at low RF power to reveal any moments of significant amp-coil mismatch, allowing prediction of when and where an amp will exceed its voltage/current dynamic range causing the pulse to fail. Alternately, the same data can be used to make the pulse design realizable. This method is relevant even for high-Z amps.

Amplifier Impedance Control & Decoupling with Source Absorption
RF amplifiers are frequently used at their native uncontrolled output impedance, or with passive isolation methods, e.g. circulators, to induce a 50Ω Z_{out}. However, with the ability to sense load current and voltage, it is no longer necessary to rely on passive Z_{out} manipulation. Using the source absorption theorem [8], we can synthesize arbitrary passive impedances using our amplifier as an active dependent source. For example, a current-controlled voltage source with complex gain **Z** yields $\boldsymbol{V} = \boldsymbol{I}*\boldsymbol{Z}$, an active synthesis of Ohm's Law, the very definition of impedance behavior. Thus by using Cartesian Feedback or VIP, we can elicit high output impedance for coil decoupling even though the open-loop amplifier has 50Ω output impedance. The approach works as long as the amplifier is within its dynamic range.

Conclusions The use of RF sensor feedback is key to high-fidelity transmit array performance. Sensors enable iterative predistortion and Cartesian feedback techniques that provide adaptive amplifier linearization, transient corrections, and active output impedance control for array decoupling. Furthermore, vector RF sensors and in-system measurement of coil impedance makes possible significant new patient and equipment safety features.

References
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