Vector Iterative Pre-Distortion: An Auto-calibration Method for Transmit Arrays

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INTRODUCTION:
Transmit arrays hold growing promise for MRI by enabling improved safety, RF homogeneity, selectivity, and pulse acceleration. Yet achieving good performance with complex Transmit-SENSE pulses [1] requires Tx array channels to be characterized, closely calibrated, and decoupled. To address these needs, we propose Vector Iterative Pre-distortion (VIP), a multi-channel iterative correction method which pre-distorts RF amplifier input to achieve desired output at the coil. VIP uses current-sensor feedback from the coil array to detect and correct errors in transmit behavior.

METHODS:
We test VIP on a four-channel parallel transmit system at 1.5T (Figure 1). Our system is built around a Medusa MRI Console which synthesizes multi-channel RF from a single input using vector modulation at 250kHz [2]. RF channels are passed to a bank of low-cost 300W RF amplifiers to drive a 5-inch diameter 4-channel coil. Current loop sensors on each coil provide feedback. The Medusa Console drives the RF excite and receive path used for system characterization, while a GE Signa scanner performs the underlying imaging.

In previous work, we calibrated the transmit array using a four-part process: (1) offset calibration to eliminate leakage, (2) lookup-table correction for amplitude and phase non-linearity, (3) Y-matrix measurement for coil decoupling [3], and (4) VIP to correct for loading and temporal response errors. This suite of corrections constrains RF Tx error below 0.1dB and +/-1 deg phase for a wide variety of pulses, while decoupling yields over 40dB of isolation between coils.

Here, we investigate using VIP alone to correct offset, non-linearity, coupling, and temporal errors simultaneously. For each coil, VIP begins by exciting an undistorted version of the desired transmit pulse, while concurrently monitoring the actual result using the coil's current transducer. To accurately calculate error, we must eliminate loop delay using correlation between the feedback data and the transmitted pulse. Error vectors are then calculated for each point in the RF pulse, either in Cartesian or polar space. The error is multiplied by a gain factor and applied as a distortion to the transmit pulse. To aid convergence, a bulk phase correction is determined via least-squares and applied in the first iteration.

For multi-coil arrays, VIP must be applied with all coils transmitting. Ideally, the method is executed on all coils simultaneously, but a round-robin approach may be used at the expense of calibration time with just one receiver channel. Coil coupling is treated like an ordinary disturbance and is counteracted by iterative correction.

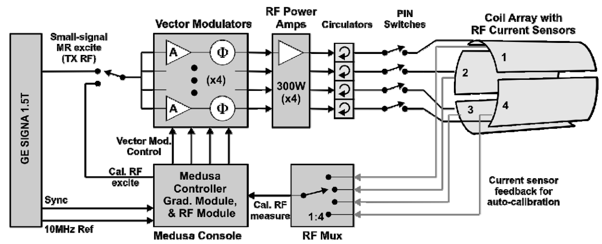

Figure 1: The Medusa Console performs vector modulator control as well as RF coil excite and measurement when executing VIP.

RESULTS:
VIP achieves high RF fidelity, equivalent to our four-part calibration process. In Figure 2, considerable error is seen at iteration 0, dropping rapidly to 1% as VIP applies successive corrections. Despite a corrective gain of 1.0, system non-linearity and temporal effects prevent driving directly to a solution. We see little difference in convergence between Cartesian and polar direct feedback methods. To assess the effect of VIP on imaging, we use a 3.8ms 2x accelerated Transmit-SENSE pulse designed using a spatial-domain method [1]. Figure 3 compares pulse performance with and without VIP. Without correction, we observe distortion in the main excitation profile and poor background suppression peaking at 22% of full-scale, while with VIP, background ripple is visibly reduced to 7% and the excitation profile is more clearly defined. The pulse design itself contributes 1.1% ripple.

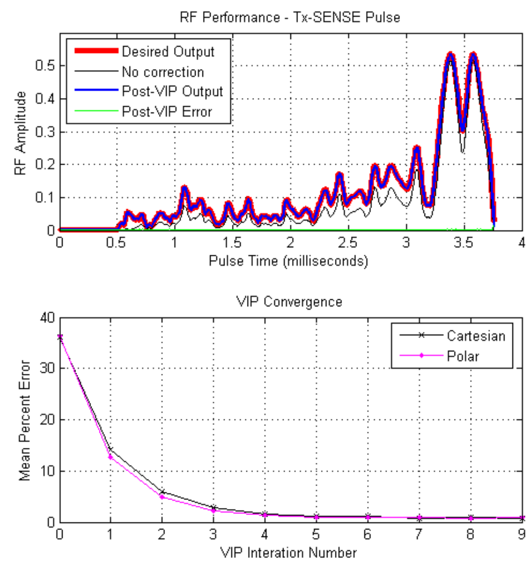

Figure 2: VIP converges quickly to the desired RF output in ~5 iterations, reaching a mean error of 1% and 0.25 deg.

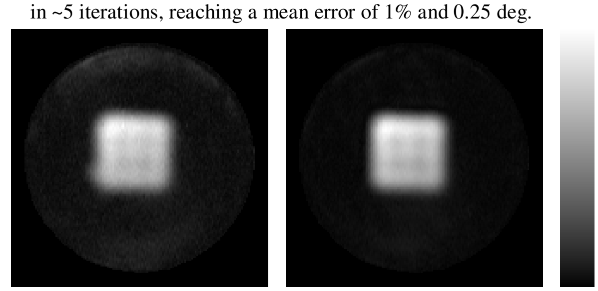

Figure 3: left: Tx-SENSE pulse without corrections produces distortion. **right:** Applying VIP sharpens profile and reduces ripple.

DISCUSSION & CONCLUSIONS:
We have successfully demonstrated VIP as general method for correcting non-ideal transmit behavior, and have shown that pulse performance improves when using the method. VIP corrects a broad set of system distortions in relatively short time, and intrinsically provides confirmation of pulse fidelity prior to scan, an important factor for safety. VIP's insensitivity to system loop delays is a distinct advantage over memory-less real-time feedback methods, as we can correct using the full RF modulation bandwidth. Real-time methods must accommodate delay by limiting closed-loop bandwidth, resulting in poorer correction for wideband pulses. Moreover, we are not limited to direct feedback, and model-based feedback approaches hold certain advantages [4]. Finally, VIP's ability to correct broad errors may permit the use of lower-spec amplifiers, potentially reducing a major multiplicative cost in transmit array systems. We are currently upgrading our equipment to four receivers to further investigate simultaneous multi-coil VIP.

REFERENCES:
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