SAMPLLAB Signal Acquisition Modeling Processing and Learning
מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE

Analog Combiner for RF Chain Reduction Demo

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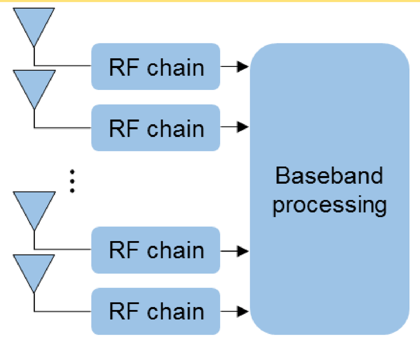
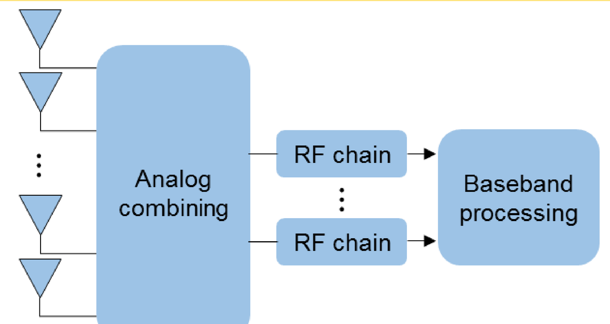
Motivation and Contributions

- Radio frequency (RF) chains play a major role in digital receivers
- Allocating a dedicated RF chain per antenna in massive MIMO systems is infeasible due to high cost and power consumption
- We propose an analog combining hardware for reducing the number of RF chains
- The prototype employs 16 antennas and 4 RF chains, and the analog combiner consists of a controllable network of gains and phase shifters
- Channel state information of a massive MIMO system is accurately and cost-effectively estimated with the developed analog combining board

MIMO Receivers



(a) Fully-digital MIMO receiver



(b) Hybrid MIMO receiver

- Each antenna is followed with a dictated RF chain.
- All analog inputs from the antennas are accessible at the baseband
- All signal processing operations are performed in baseband (fully-digital)

- An analog combiner projects the high number of analog inputs from antennas onto the low number of RF chains
- The analog combiner consists of a controllable network of gains and phase shifters
- Only a low number of measurements are accessible in baseband

Problem Formulation

- The received baseband signal at base station:

$$\mathbf{Y} = \mathbf{W}\mathbf{H}\mathbf{S}^T + \mathbf{W}\mathbf{N}$$

Received digital signal matrix ($\mathbf{Y}$); Analog combiner matrix ($\mathbf{W}$); Channel matrix ($\mathbf{H}$); Pilot sequences matrix ($\mathbf{S}$); AWGN matrix with entries $\sim \mathcal{N}(0, p_n)$ ($\mathbf{N}$)

- Kronecker channel model:

$$\mathbf{H} = \mathbf{Q}^{\frac{1}{2}}\bar{\mathbf{H}}\mathbf{P}^{\frac{1}{2}}$$

Receive side correlation matrix ($\mathbf{Q}$); Rayleigh Channel matrix with entries $\sim \mathcal{CN}(0,1)$ ($\bar{\mathbf{H}}$); Transmit side correlation matrix ($\mathbf{P}$)

- The MSE in estimating $\mathbf{H}$ is given by:

$$\epsilon = tr\left(\mathbf{P}\otimes\mathbf{Q}\right) - tr\Big(\left(\mathbf{P}\mathbf{S}^*\otimes\mathbf{Q}\mathbf{W}^*\right)\left[\left(\mathbf{S}\mathbf{P}\mathbf{S}^*\otimes\mathbf{W}\mathbf{Q}\mathbf{W}^*\right) + p_n\left(\mathbf{I}\otimes\mathbf{W}\mathbf{W}^*\right)\right]^{-1}\left(\mathbf{S}\mathbf{P}^*\otimes\mathbf{W}\mathbf{Q}^*\right)\Big).$$

Analog Combiner Design

- Consider some power constrained analog combiner on its rows, minimize the MSE is equivalent to maximize the following problem without considering the noise[1]

$$\arg\max_{\mathbf{W}} \; tr\Big(\mathbf{Q}\mathbf{W}^*\left(\mathbf{W}\mathbf{Q}\mathbf{W}^*\right)\mathbf{W}\mathbf{Q}^*\Big) \quad \text{s.t.} \; diag\{\mathbf{W}\mathbf{W}^*\} \le p_w diag\{\mathbf{I}\}$$

- Due to the separable structure of the Kronecker model, an optimal analog combiner is derived as

$$\mathbf{W}_{cg} = \sqrt{p_w}\mathbf{U}^*$$

$\longleftarrow$ First N_{rf} eigenvectors of $\mathbf{Q}$

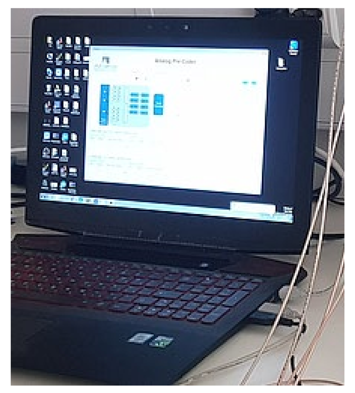
- The phase-shifter-only combiner is a projection of the optimal analog combiner on the feasible set determined by the controllable network

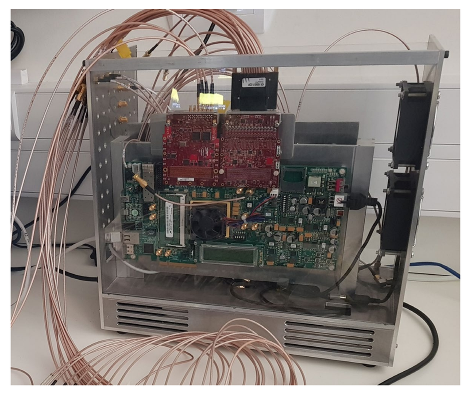
$$\mathbf{W}_{pso} = \mathcal{P}\left(\sqrt{p_w}\mathbf{U}^*\right)$$

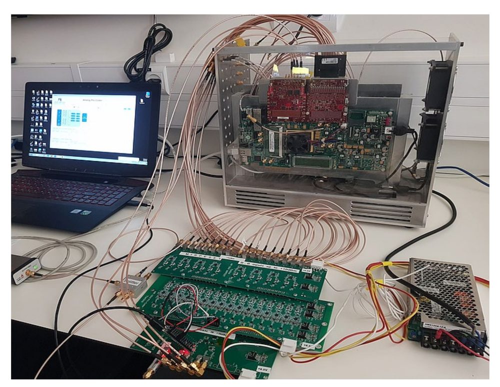
$\longleftarrow$ Projection operator $e^{j2\pi\angle\mathbf{U}}$

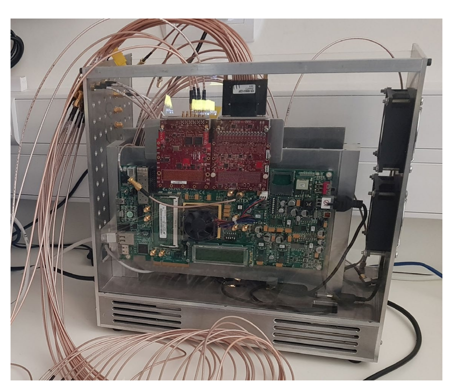
[1] T. Gong, N. Shlezinger, S. S. Ioushua, M. Namer, Z. Yang, and Y. C. Eldar. “RF chain reduction for MIMO systems: A hardware prototype”. IEEE System Journal, vol. 14, no. 4, Dec. 2020, pp. 5296-5307

Hardware

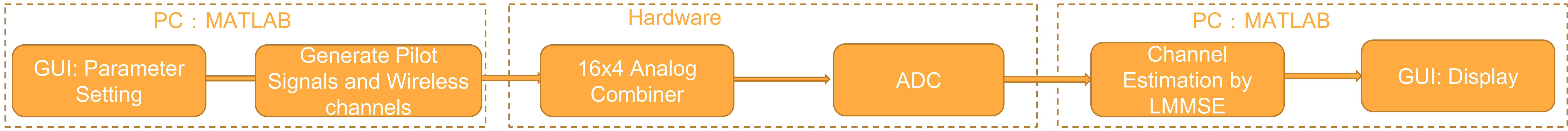




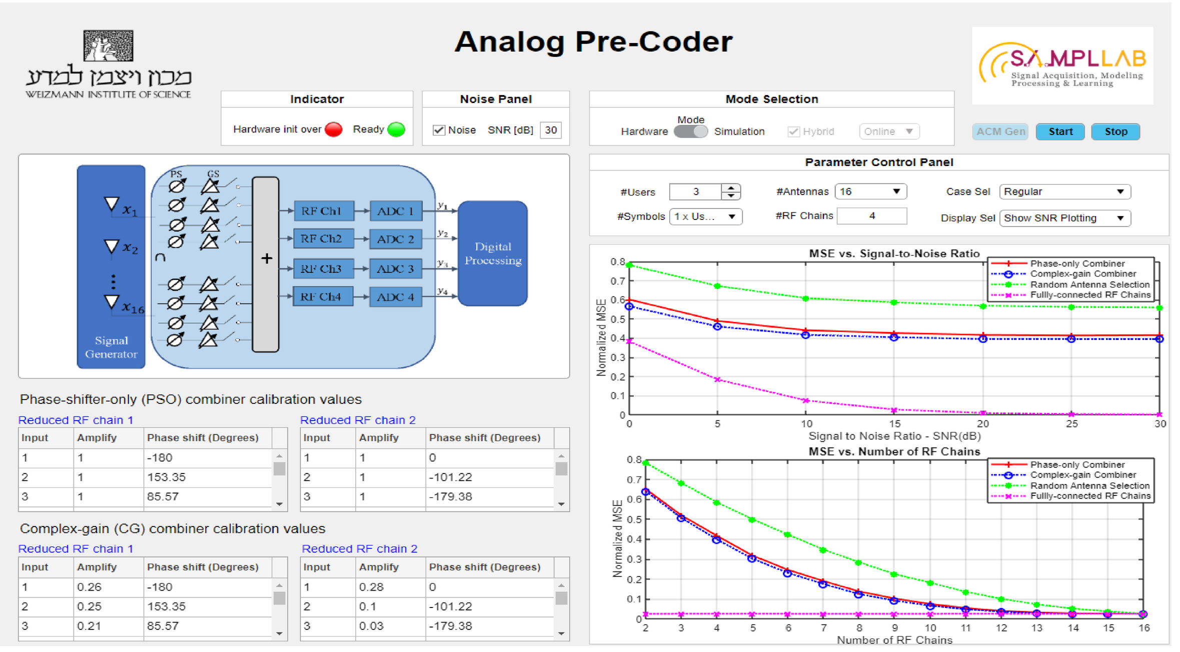




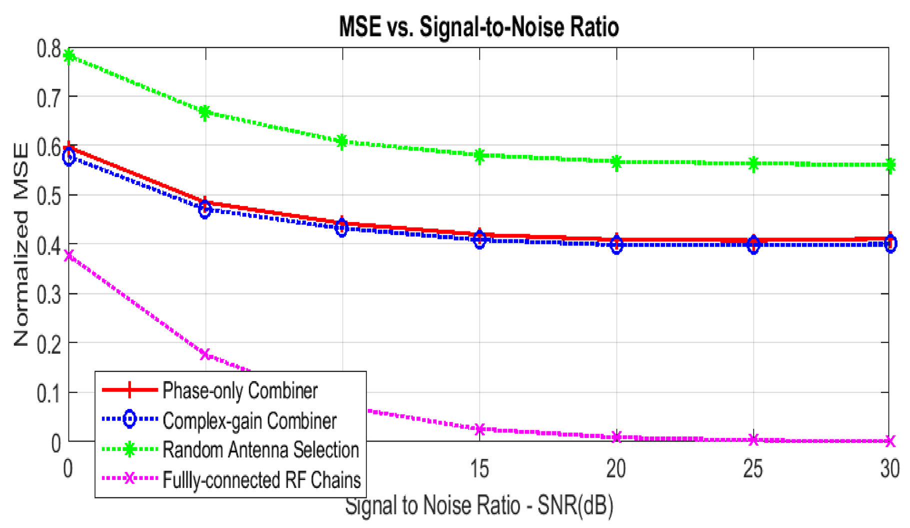
Parameters	Value
Carrier frequency	$f_c = 1$ GHz
Baseband bandwidth	$BW = 125$ MHz
DAC	4 channels, each $f_s = 125$MHz
ADC	4 channels, each 250 MSPS



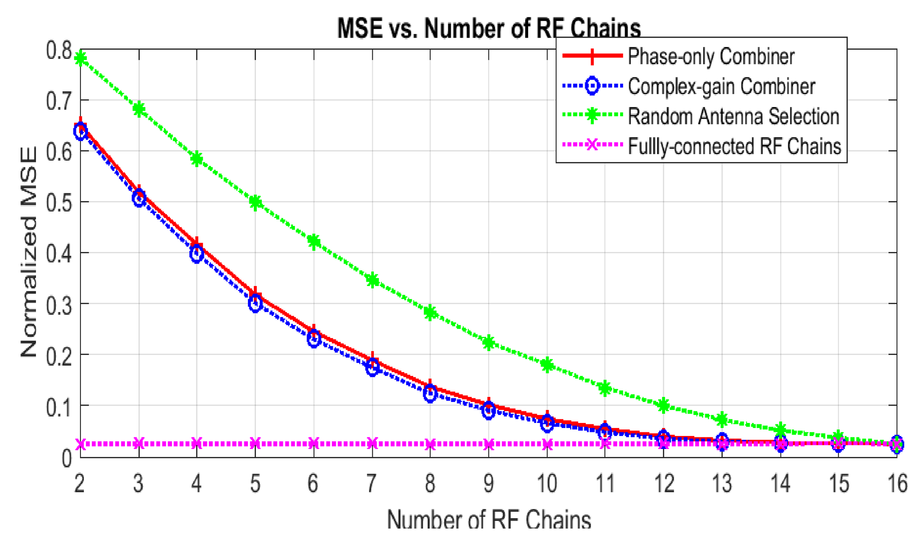
User Interface



Results



(a)



(b)

- We compare the channel estimation performance of our hardware prototype (implementing Phase-only and Complex-gain Combiner) with other theoretical analog combiners. Figs. (a) and (b) show the normalized MSE with varying SNRs and number of RF chains, respectively
- From Figs. (a) and (b), it can be observed that our Phase-only Combiner achieves channel estimation accuracy within a very small gap compared to the Complex-gain Combiner architecture, and notably outperforms the random antenna selection approach