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Channel Estimation with Reduced RF Chains Prototype

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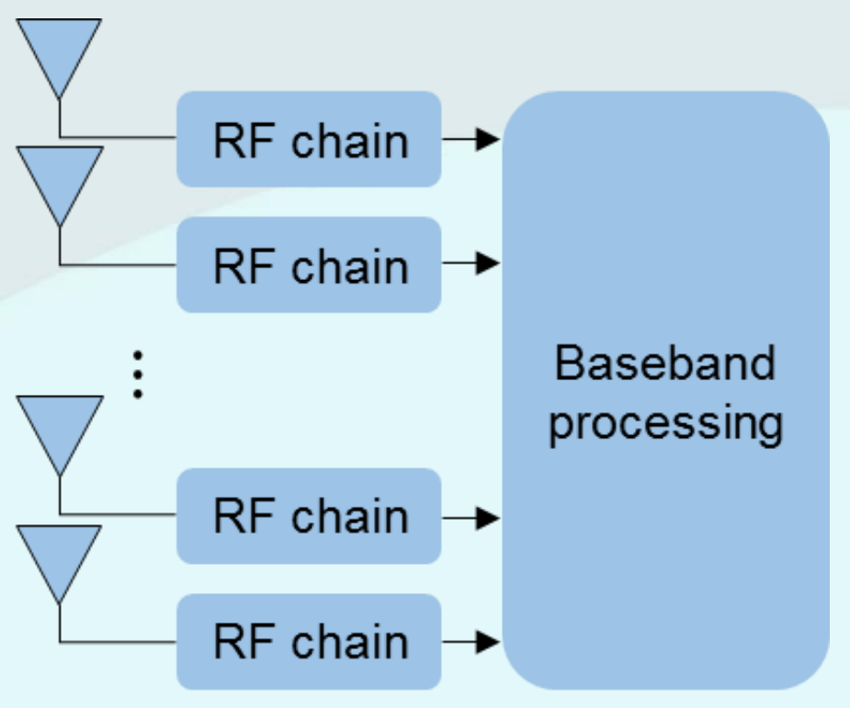
Main Contributions

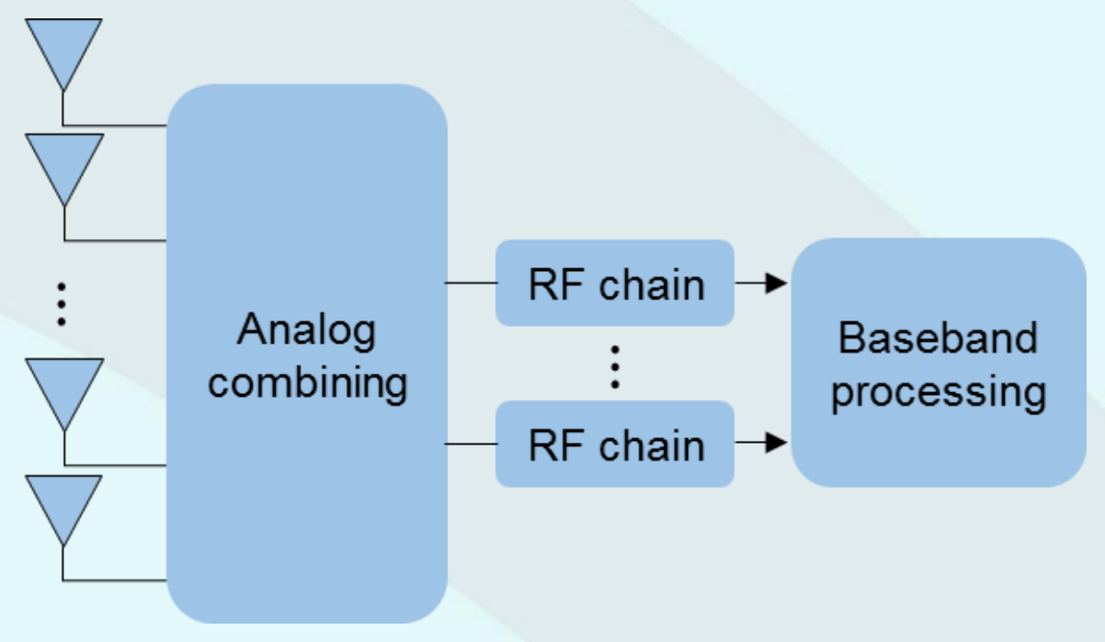
- This prototype demonstrates a MIMO receiver with reduced number of RF chains
- The prototype employs 4 antennas and 2 RF chains
- The analog combiner consists of a controllable network of gains and phase shifters
- The complex-gain combiner (CGC) and phase-shifter-only combiner (PSOC) are implemented.
- A LMMSE channel estimator is performed for the Kronecker channel model in a single-cell multi-user MIMO scenario.
- The RF chain reduction does not increase the MSE of channel estimation by exploiting the low rank fact of the channel.

Conventional 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)

Hybrid MIMO Receiver



- 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 single-cell multi-user MIMO scenario contains $K = 3{\sim}10$ user terminals (UTs) and a base station (BS) with $N_{bs} = 4, 8, 16$ antennas and $N_{rf} = 2, 4, 8$ RF chains
- The UTs transmit known, orthogonal pilot sequences of length τ to the BS, over a TDD uplink channel
- Received signals at the baseband

Received digital signal matrix

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

AWGN matrix with entries ~ $\mathcal{N}(0, p_n)$

Analog combiner matrix

Channel matrix

Pilot sequences matrix

- Kronecker channel model

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

Receive side correlation matrix

Rayleigh Channel matrix with entries ~ $\mathcal{CN}(0,1)$

Transmit side correlation matrix

- Vectorized received signal

$$\mathbf{y} = (\mathbf{S} \otimes \mathbf{W})\,\mathbf{h} + (\mathbf{I} \otimes \mathbf{W})\,\mathbf{n}$$

~ $\mathcal{CN}(\mathbf{0}, \mathbf{P}\otimes\mathbf{Q})$

- LMMSE channel estimator

$$\hat{\mathbf{h}} = (\mathbf{P}\mathbf{S}^* \otimes \mathbf{Q}\mathbf{W}^*)\,[(\mathbf{S}\mathbf{P}\mathbf{S}^* \otimes \mathbf{W}\mathbf{Q}\mathbf{W}^*) + p_n\,(\mathbf{I} \otimes \mathbf{W}\mathbf{W}^*)]^{-1}\,\mathbf{y}.$$

- Mean squared error

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

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 AWGN

$$\begin{aligned} \arg\max_{\mathbf{W}} \quad & tr\Big(\mathbf{Q}\mathbf{W}^*\,(\mathbf{W}\mathbf{Q}\mathbf{W}^*)\,\mathbf{W}\mathbf{Q}^*\Big) \\ \text{s.t.} \quad & diag\{\mathbf{W}\mathbf{W}^*\} \le p_w diag\{\mathbf{I}\} \end{aligned}$$

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

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

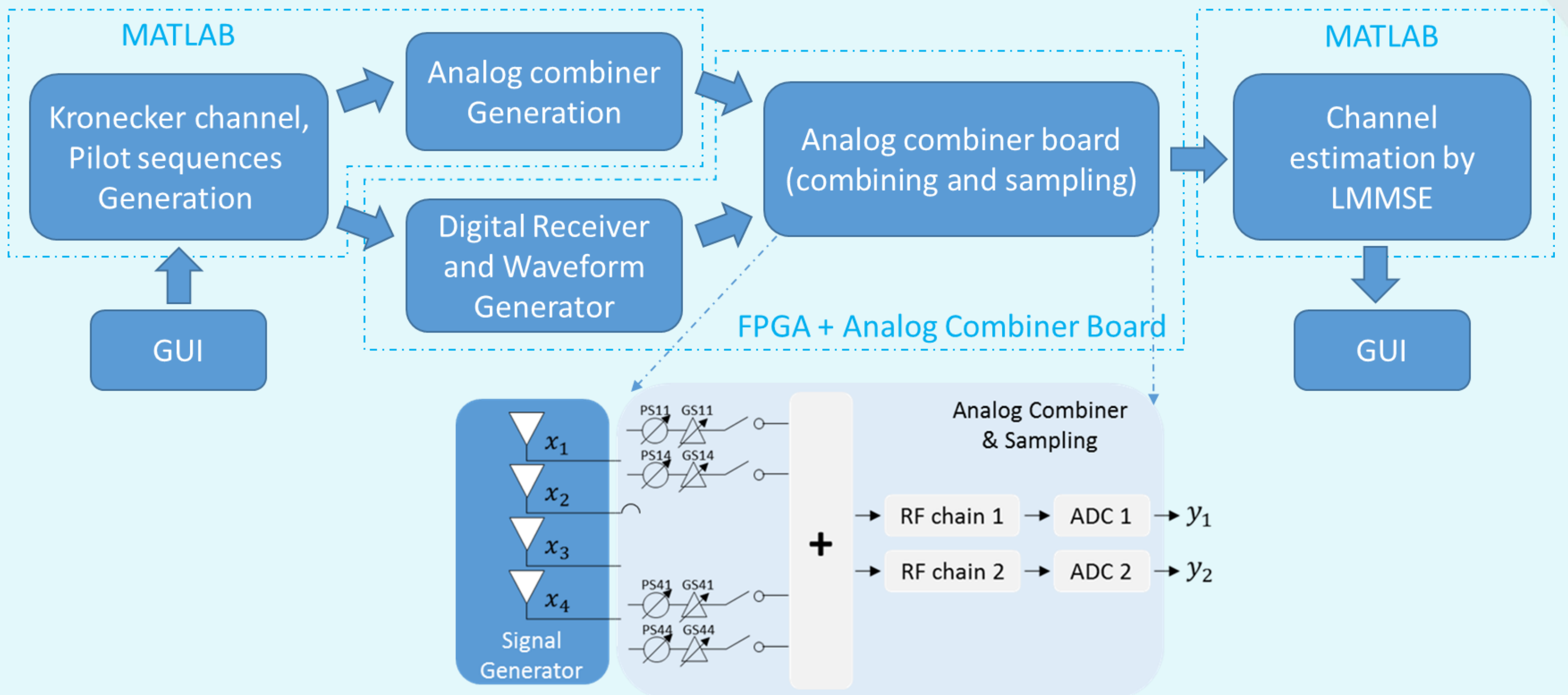
First N_{rf} eigenvectors of $\mathbf{Q}$

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

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

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

Overview of Prototype Architecture

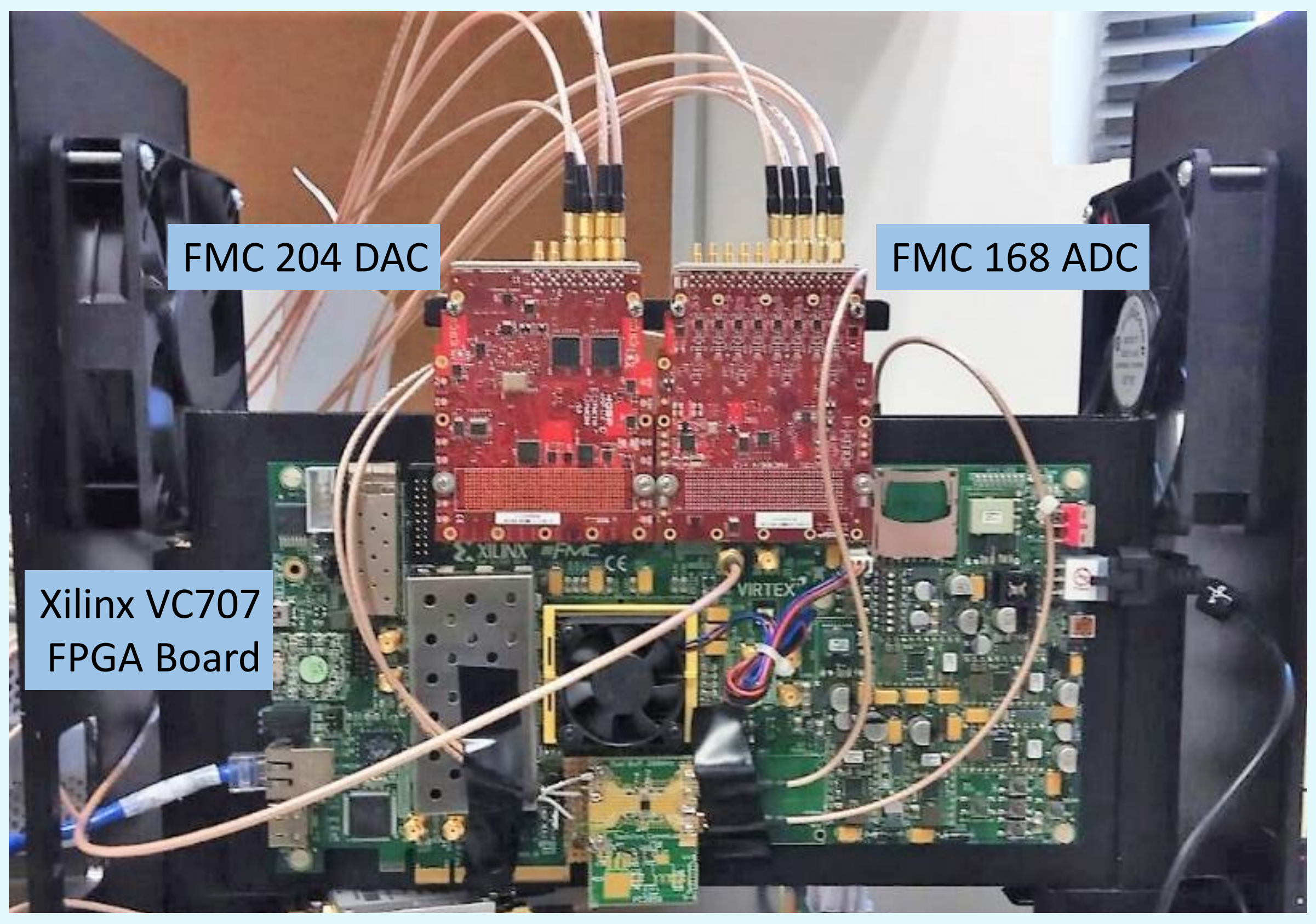


Technical Specification

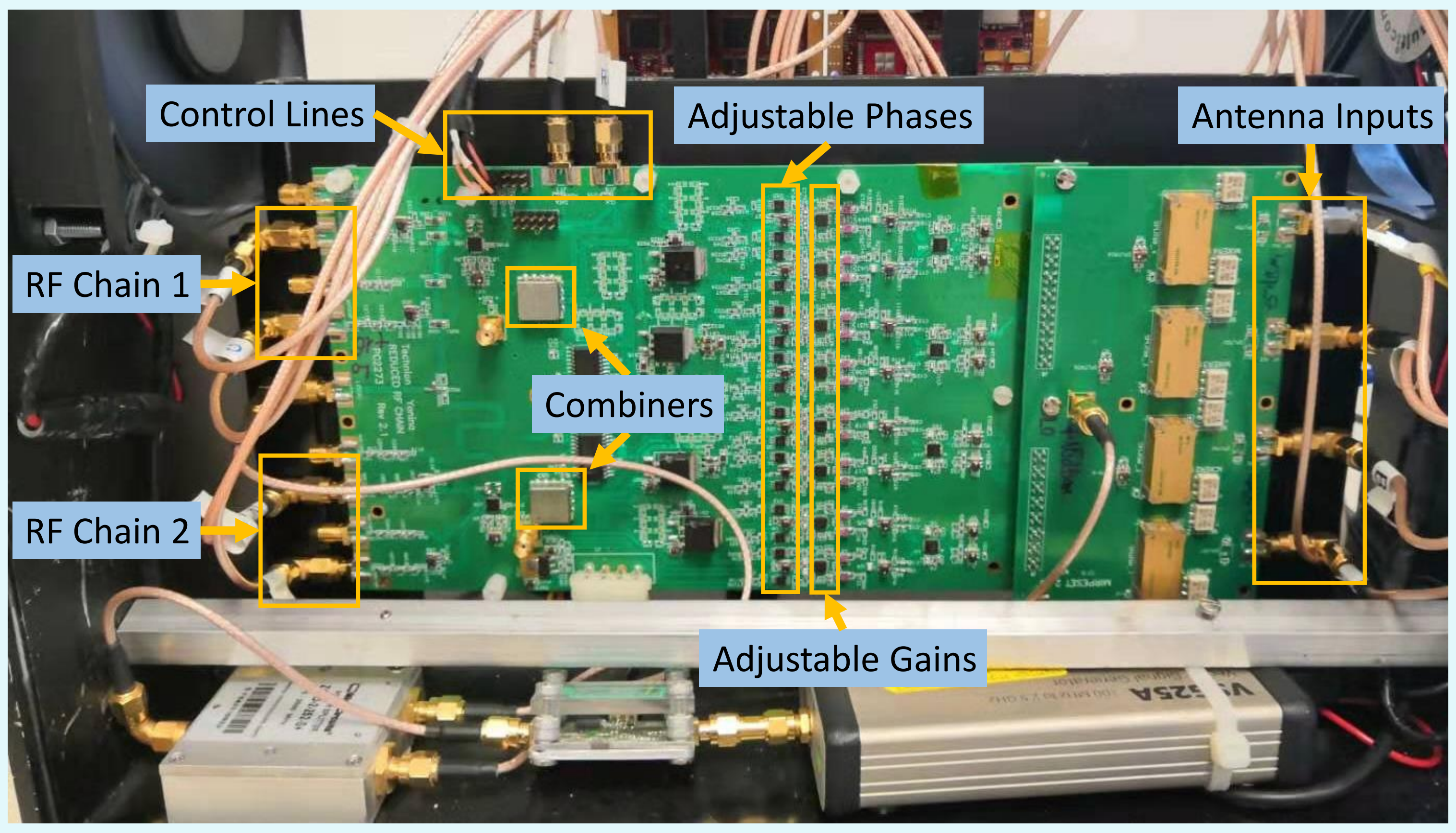
Parameters	Value
Carrier frequency	$f_c = 1$ GHz
Baseband bandwidth	$BW = 125$ MHz
DAC	4 channels, each 250 MSPS
ADC	4 channels, each $f_s = 250$MHz

Digital Receiver and Waveform Generator

- 16-bit 8-channel digitizer for I and Q streams
- 16-bit 4-channel DAC for waveform generation
- Analog signal phase shift resolution -0.5º
- Amplitude modulation

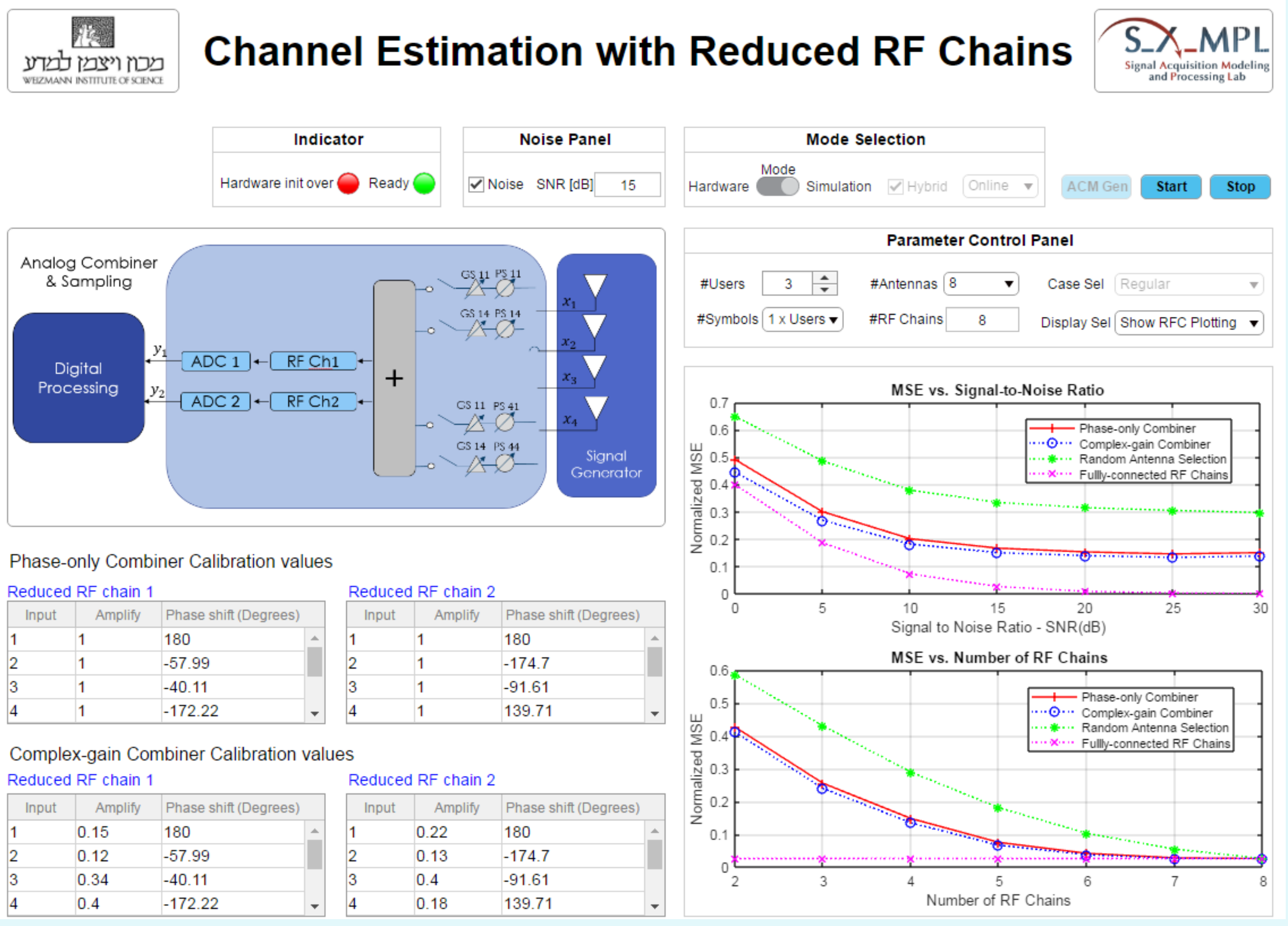


Analog Combiner Board



- The analog combiner board combines the received data coming from 4 input channels into 2 RF-Chains
- Gains and phase shifters are easily configured by FPGA controller
- Each RF-Chain has 2 outputs, I and Q
- The analog combiner board is mounted on a single chassis

Graphic User Interface



Channel Estimation with Reduced RF Chains

Indicator: Hardware init over ● Ready ●

Noise Panel: ☑ Noise SNR [dB] 15

Mode Selection: Mode Hardware / Simulation ☑ Hybrid Online

Parameter Control Panel

#Users 3
#Antennas 8
Case Sel Regular
#Symbols 1 x Users
#RF Chains 8
Display Sel Show RFC Plotting

Phase-only Combiner Calibration values

Reduced RF chain 1

Input	Amplify	Phase shift (Degrees)
1	1	180
2	1	-57.99
3	1	-40.11
4	1	-172.22

Reduced RF chain 2

Input	Amplify	Phase shift (Degrees)
1	1	180
2	1	-174.7
3	1	-91.61
4	1	139.71

Complex-gain Combiner Calibration values

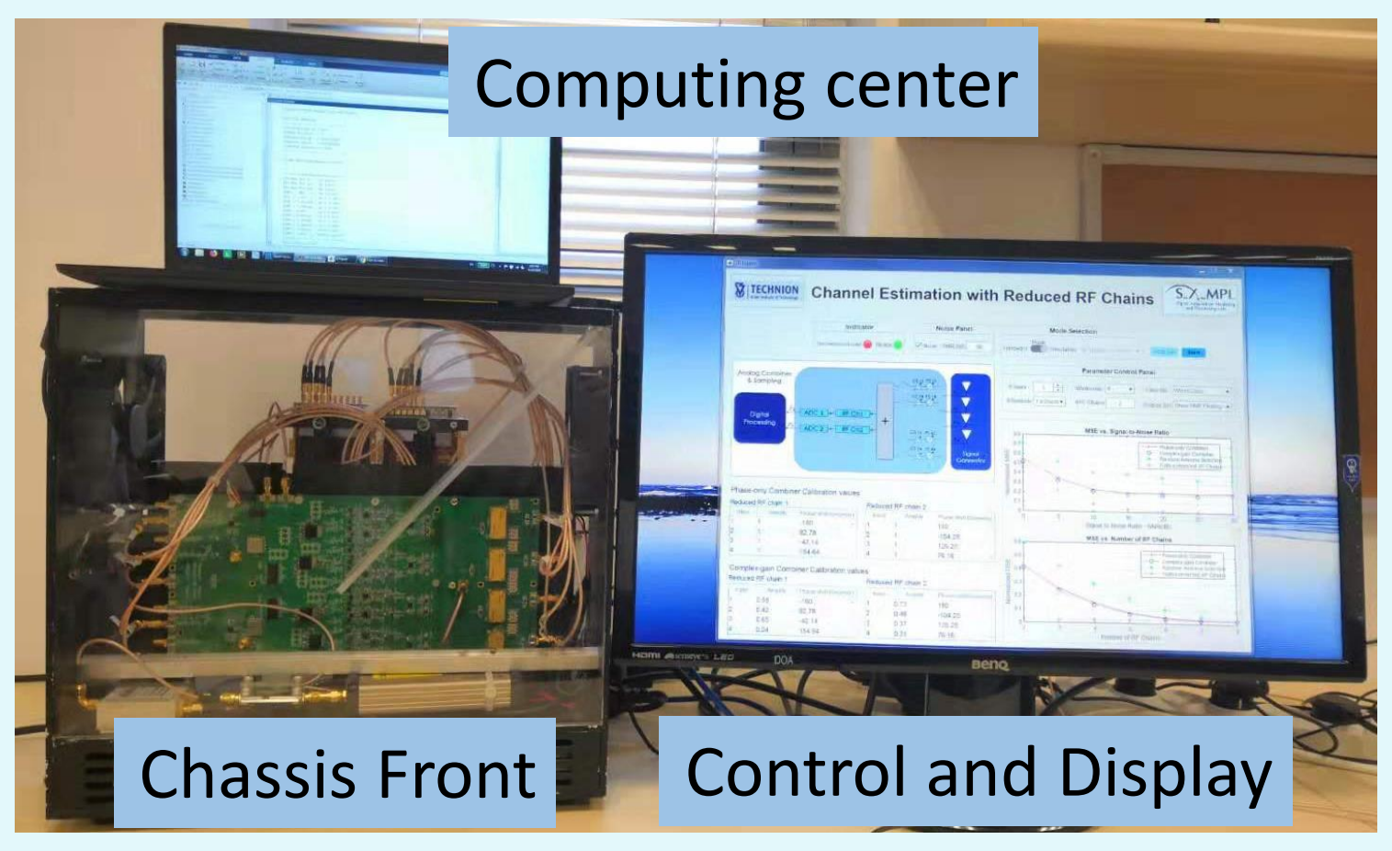
Reduced RF chain 1

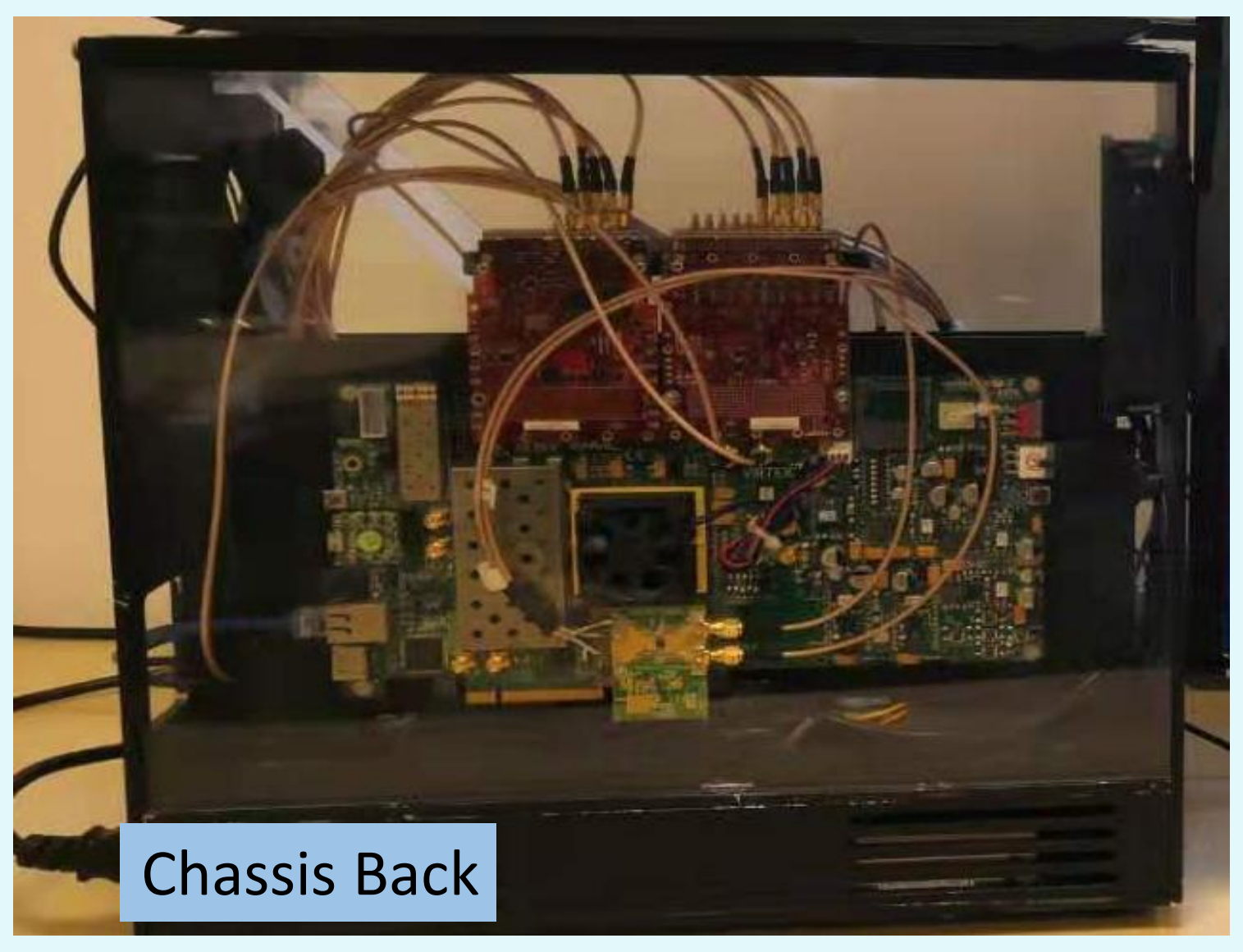
Input	Amplify	Phase shift (Degrees)
1	0.15	180
2	0.12	-57.99
3	0.34	-40.11
4	0.4	-172.22

Reduced RF chain 2

Input	Amplify	Phase shift (Degrees)
1	0.22	180
2	0.13	-174.7
3	0.4	-91.61
4	0.18	139.71

Prototype Overall





Measurement Results