Theoretical Background

Main Contributions

- This prototype demonstrates a MIMO receiver with reduced number of RF chains
- Employs 4 antennas and only 2 RF chains
- Demonstrates an analog combiner that consists of controllable analog network of phase shifters, gains and switches
- Performs MMSE channel estimation for Kronecker channel model in a multi-user MIMO scenario
- When the channel matrix is low rank the RF reduction does not increase the channel's MSE

Conventional MIMO Receiver
- Each antennas is followed by a dedicated RF chain
- All the analog inputs from the antennas are accessible at the baseband
- All the signal processing operations are performed in baseband (fully-digital)

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

Optimal Analog Combiner
- Due to the separable structure of the Kronecker model, an optimal analog combiner can be derived.
- \[ W_{opt} = TU_1^* \]
  - \( U_1 \) - First 2 eigenvectors of \( R_r \)
  - \( T \) - Any \( 2 \times 2 \) invertible matrix

Problem Formulation
- Multi-user MIMO scenario with 2 user terminals and a base station with 4 antennas and 2 RF chains
- The users transmit known, orthogonal pilot sequences of length \( \tau \) to the base station, over a TDD uplink channel
- Received signal at the baseband
- \[ \mathbf{h} = \left( \mathbf{S} \otimes \mathbf{W} \right) \mathbf{h} \]
- MMSE channel estimator

Overview of Hardware Architecture

GUI

ADC estimation

Digital Processing

Analog Combiner & Sampling

Signal Generator
Channel Estimation with Reduced RF Chains

Technical Specification

- Carrier Frequency - $f_c = 1$GHz
- Baseband BW = 125MHz – can be extended up to 2GHz
- DAC - 4 output channels at 250MSPS
- ADC – 4 input channels
  - Sampling Rate – 250MHz for each channel

Theoretical MSE

- For the suggested combiner $W_{opt}$ the theoretic MSE in a noise free scenario is the sum of 2 smallest eigenvalues of the receive-side correlation:
  $$\mathbb{E} \left[ \| \hat{H} - H \|^2 \right] = \lambda_3 (R_r) + \lambda_4 (R_r)$$
- Best case scenario:
  - rank($R_r$) ≤ 2. In this case the MSE is:
  $$\mathbb{E} \left[ \| \hat{H} - H \|^2 \right] = 0$$
- Worst case scenario:
  - $\lambda_3 (R_r) = \lambda_2 (R_r) = \lambda_3 (R_r) = \lambda_4 (R_r) = a$.
  - In this case the optimal combining scheme is a simple “antenna-selection” scheme, and the MSE is:
  $$\mathbb{E} \left[ \| \hat{H} - H \|^2 \right] = 2a$$

Measurement Result

<table>
<thead>
<tr>
<th>Scenario</th>
<th>H-H estimator based on 4 RF chains</th>
<th>MSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.06</td>
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<td>0.16</td>
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<table>
<thead>
<tr>
<th>Scenario</th>
<th>H-H estimator based on 4 RF chains + simple antenna selection</th>
<th>MSE</th>
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<tr>
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<td>0.12</td>
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</tbody>
</table>

Analog Pre-Processor (APP) Board

- APP filters the receiver data coming from four channels into two channels
- APP in a single chassis
- Phase shifters and Amplitude shifters easily configured by FPGA controller

Digital Receiver and Waveform Generator

- 16-bit 8-channel digitizer
- 16-bit 4-channel DAC for Waveform Generation
- Analog signal phase shift resolution - 0.5°
- Amplitude modulation

User Interface

- Channel Estimation with Reduced RF Chains
- Input mode state
- Noise enable/disable
- Scenarios selection
- Full chains receiver performance
- Suggested optimal combiner performance
- Analog 4-channel & 8-channel DSP
- Optimal combiner weights
- Antennas selection combiner performance