Self-Interference Canceller for Full-Duplex Hybrid Beamforming Massive-MIMO Systems

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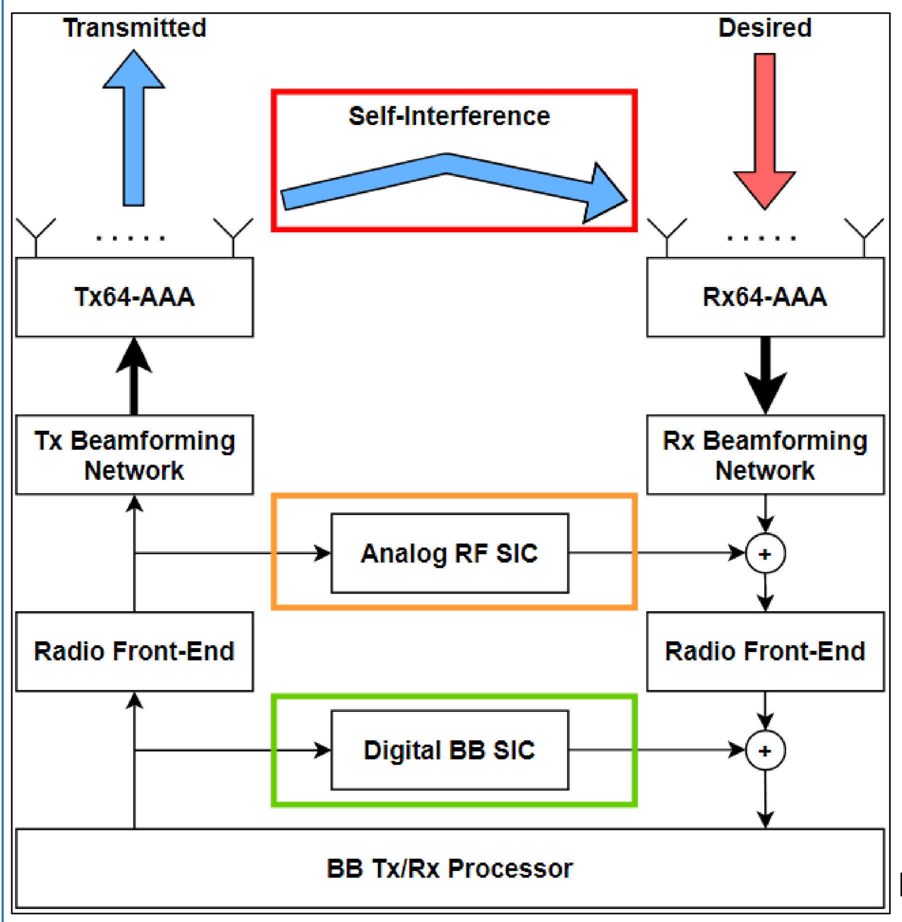
Introduction

- Full-duplex radios enable transmit and receive operations simultaneously, using the same frequency band. Compared with existing TDD and FDD systems, full-duplex increases the throughput and reduces the latency in communication.
- Full-duplex massive-MIMO with phased array antenna and spatial multiplexing can create very narrow signal beams with very low latency, enabling the massive connectivity of various autonomous machines and sensors, which will help reduce the number of automobile, industrial, and environmental accidents.
- The full-duplex radio inevitably receives its own transmitted signal (self-interference), which overwhelms the received weak intended signal. The self-interference canceller (SIC), present at both analog and digital stages, aims to remove the SI transmitted signal at the receiver.
- The SIC tuning is a non-trivial problem with many local minima. A strong optimization algorithm can maximize the cancellation and tuning efficiency.



Stages of SI cancellation

Antenna level: special polarized high-isolation Tx/Rx structure design and large number of antenna elements for beamforming.

RF data stream level: tapped delay-line filter with RF electronics. There are 4 RF streams and 64 antenna elements on both the Tx and Rx side.

BB data stream level: SI cancellation through advanced DSP techniques in baseband.

Figure 1. Full-duplex base station system architecture.

- Restrictions in antenna design and hardware complexity limit the amount of SI cancellation we can achieve.
- Multiple stages of SIC are necessary to maximize the cancellation amount.

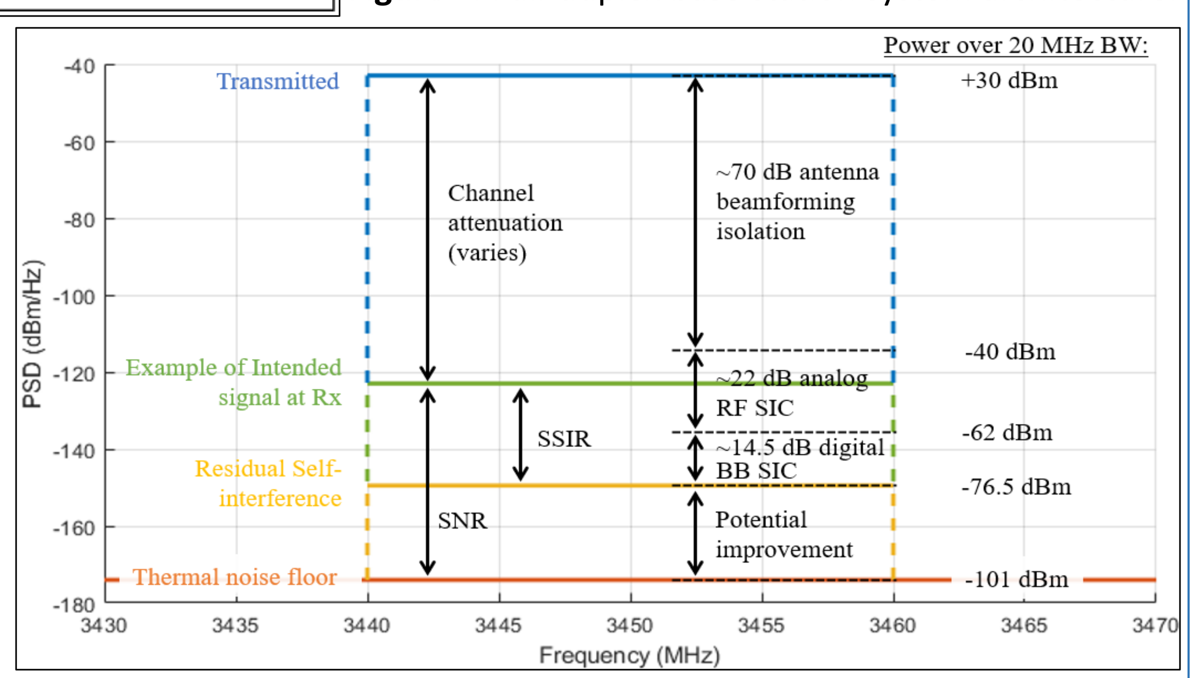


Figure 2. Signal levels of example scenario of full-duplex system.

Objective

The objective of this research is to develop and evaluate the combined performance of various cascaded practical SIC techniques for hybrid-beamforming massive-MIMO systems. My roles are constructing the 4x4 analog RF SIC at the RF data stream level, tuning the hardware parameters for optimal configuration, and running data flow simulations to evaluate the performance of the canceller.

Methodology

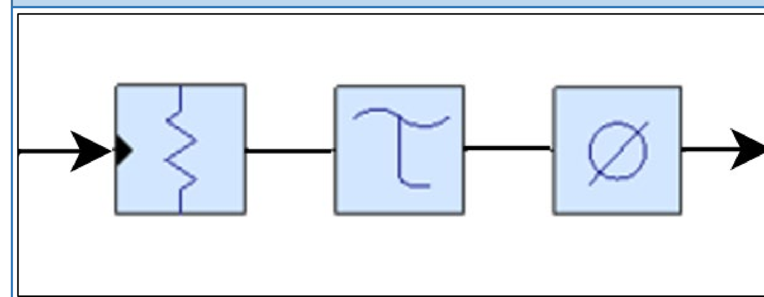


Figure 3. Simplified model of an SIC tap.

- Each tap contains a digitally-controlled variable attenuator, time delay, and phase shifter.

- Fully connected analog RF SIC with 4 inputs on Tx side and 4 outputs on Rx side.
- A total of 16 channels and 32 taps, with 2 taps to model each SI channel.
- The cancellation signal is ideally 180 degrees out-of-phase with the SI signal, and combined with the received signal at the receiver.

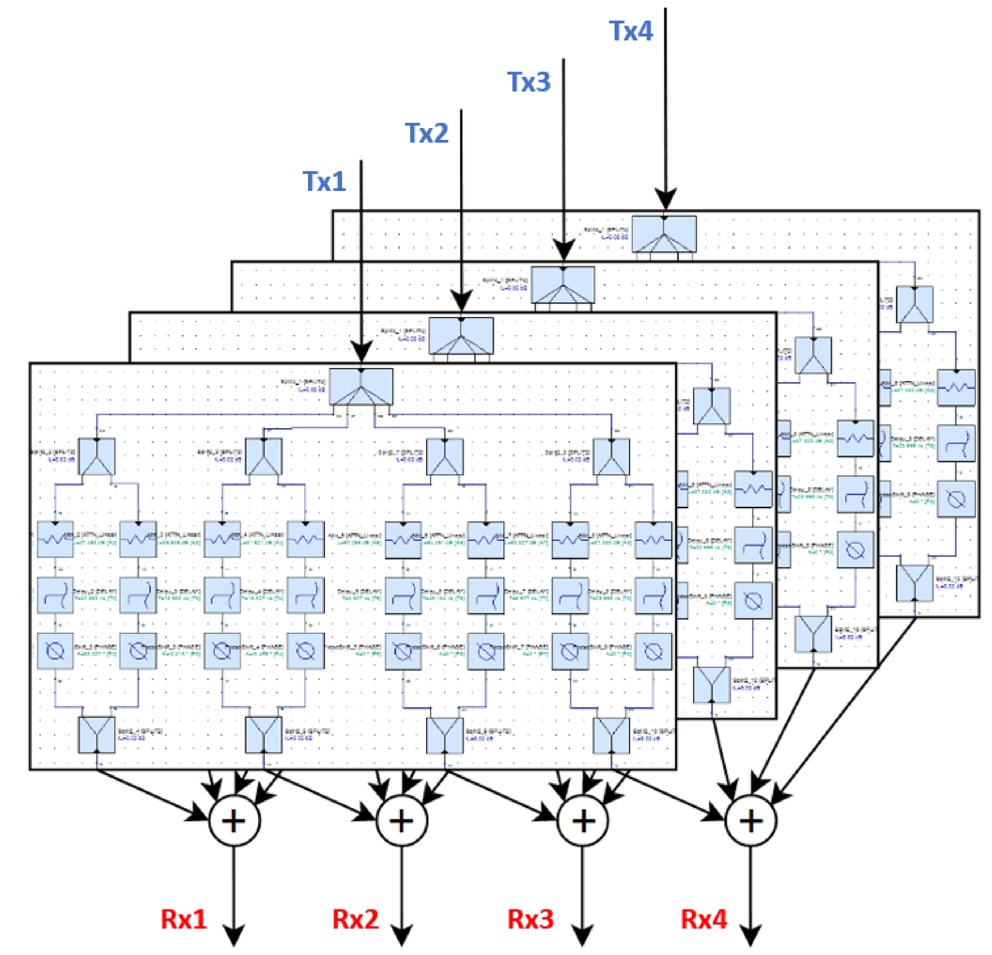


Figure 4. Simplified model of the analog RF SIC.

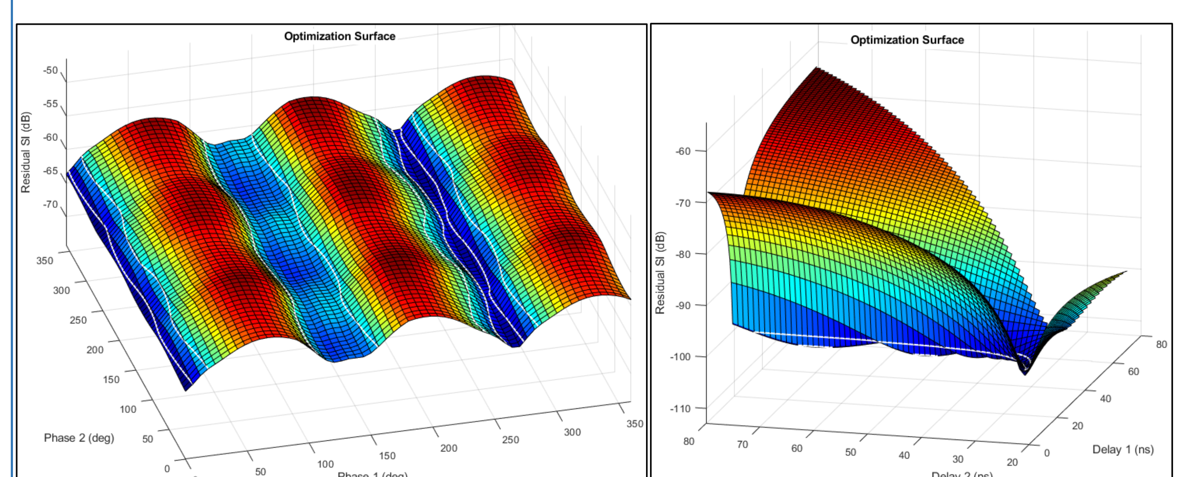


Figure 5. 3D optimization surfaces with respect to phase shift (left) and time delay (right).

- The optimization surfaces with respect to phase shift (left) and time delay (right) both contain multiple local minima.
- Requires tuning of analog RF SIC parameters (attenuators, time delays, and phase shifters).

- The minimum mean-squared error (MMSE) estimator computes the attenuation and phase shift, given the time delay, that minimizes the residual SI power.
- The optimization solver (such as Particle Swarm Optimization) finds the best time delays to feed to the MMSE estimator that minimizes the residual SI power.
- Both MMSE and optimization solver are currently implemented in Matlab.

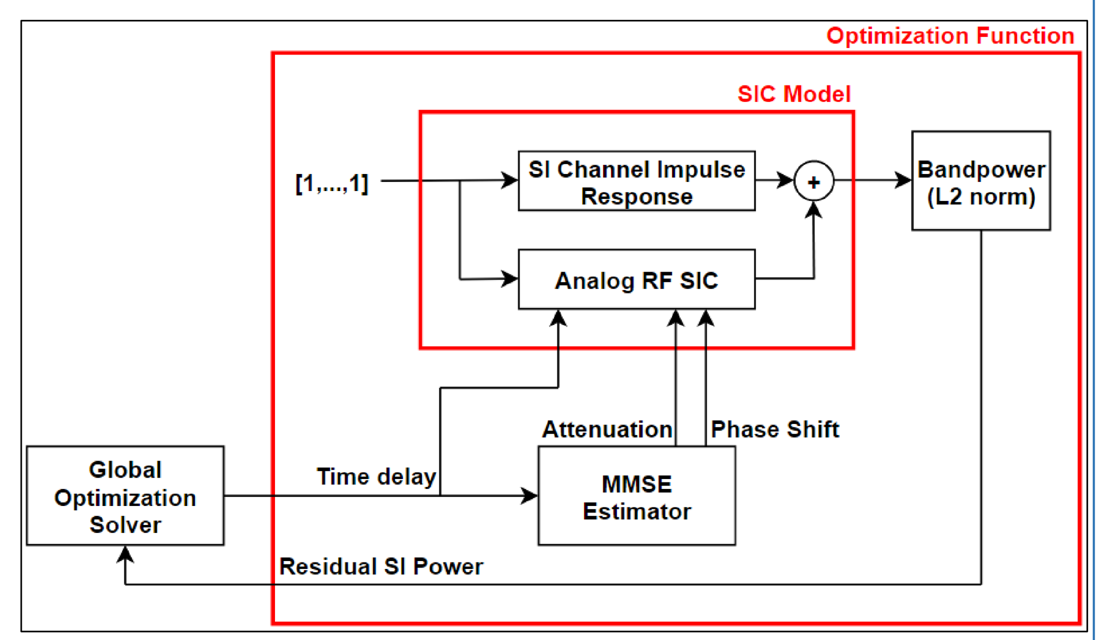


Figure 6. The analog RF SIC parameter tuning process logic.

- Performed system-level simulation in SystemVue software to evaluate cascaded SIC performance and model practical aspects of the RF components in the system.
- Channel estimation and least-squares algorithm used in the digital baseband SIC.

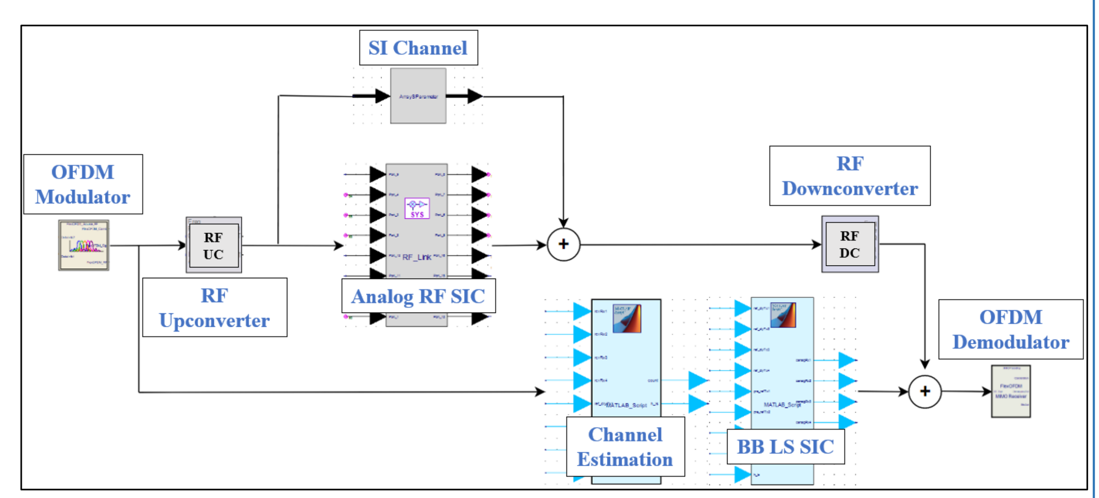


Figure 7. Simplified diagram of system-level simulation.

Results

SIC with antenna and analog RF stages:

The system will be operating in the FR1 range of the 5G NR protocol; the possible channel bandwidths are 20, 40, 60, and 100 MHz. The cancellation for S51 20MHz uplink scenario with only 1 active data stream is shown below:

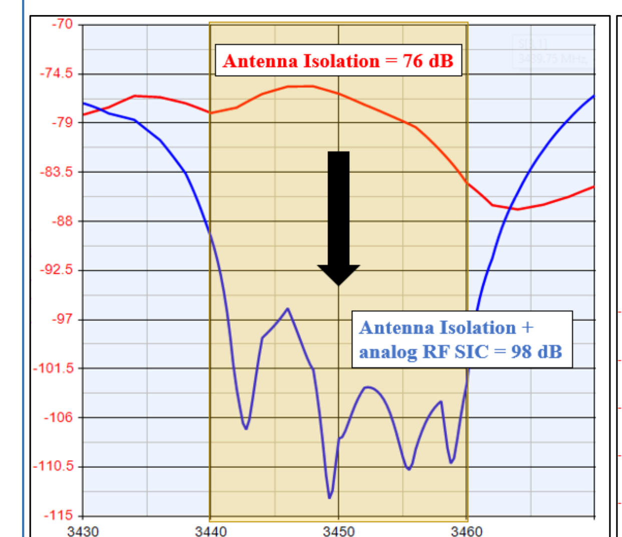


Figure 8. S51 frequency response.

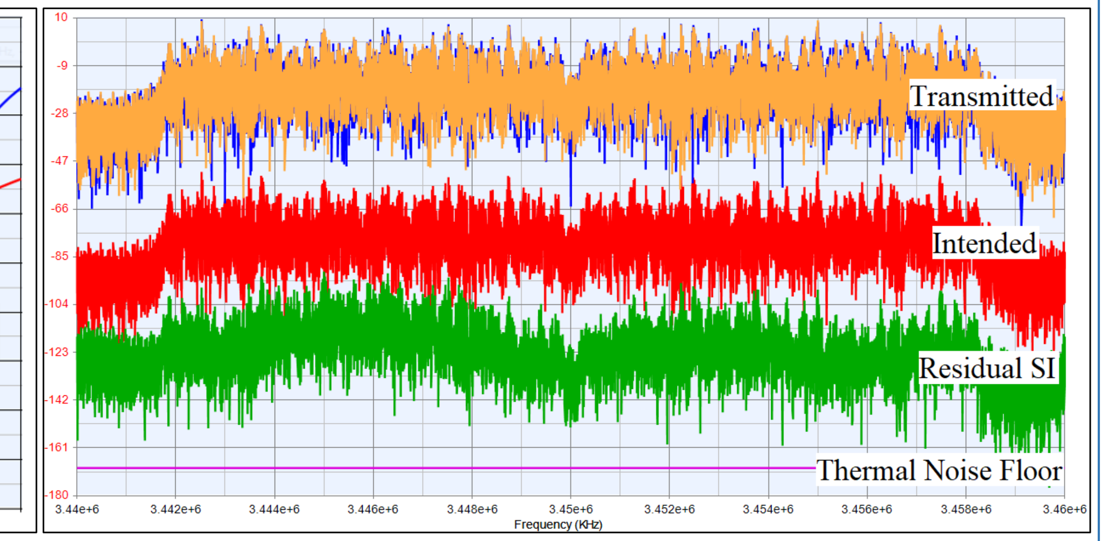


Figure 9. Comparison of PSD for various signals of interest.

MMSE-predicted and final tuned parameter values and SIC performance:

Results for the SI channel S51 (Tx1 to Rx1) over 20, 40, 60, and 100 MHz:

	Matlab MMSE Predicted							Final Tuned						
Bandwidth	Attenuator (dB)		Time Delay (ns)		Phase Shift (deg)		Canc. (dB)	Attenuator (dB)		Time Delay (ns)		Phase Shift (deg)		Canc. (dB)
20 MHz	82.3	81.7	10.14	40.82	79.8	140.2	22.4	54.3	53.5	10.17	40.87	5.0	68.3	22.4
40 MHz	84.3	81.3	11.18	27.46	135.9	105.9	14.0	56.4	53.0	11.22	27.51	121.6	108.1	14.0
60 MHz	84.9	80.3	10.37	23.35	28.7	162.5	12.9	56.6	52.4	11.58	24.29	26.8	159.0	12.6
100 MHz	84.9	79.9	11.59	23.34	-23.2	-70.2	12.8	56.9	51.9	11.01	22.96	0.0	0.0	12.4

The attenuator values differ largely since the Matlab model does not consider the power splitters used to split the signal. However, the cancellation between predicted and the final tuned are highly alike.

System-level simulation with antenna, RF, and BB SIC stages:

The simulation is performed with all 4 data streams active. Results measured at Tx1 and Rx1 over 20 MHz bandwidth:

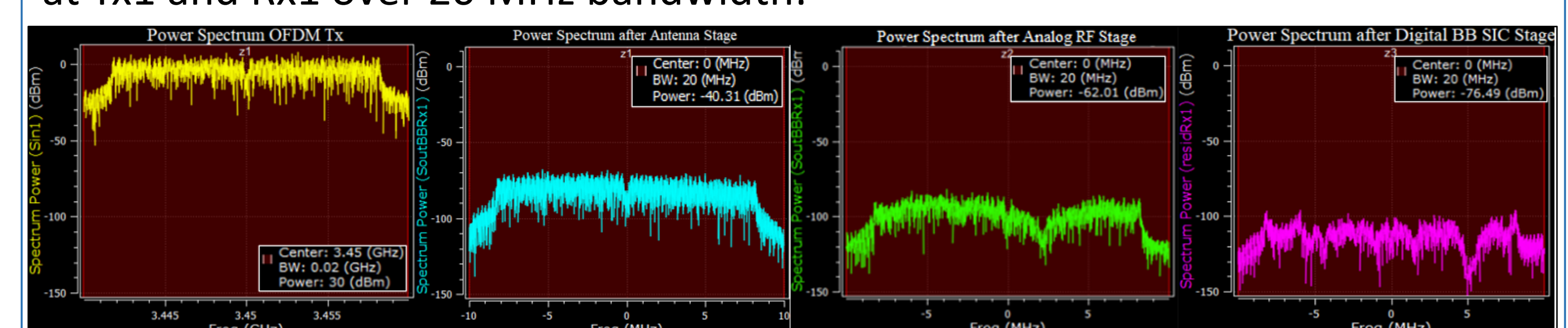


Figure 10. Power spectrum for the SI signal at different stages.

Antenna provides **~70 dB**, analog RF stage provides **~22 dB**, and digital baseband stage provides **~15 dB** of cancellation for 20 MHz bandwidth case.

Conclusion & Future Work

- The cascaded SIC stages can provide a total of **~107 dB** of cancellation for SI channel S51 and **~110 dB** on average for the other channels in 20 MHz bandwidth case. Our goal would be to achieve a total cancellation of 115 dB or more.
- In the future, we would like to investigate the Particle Swarm Optimization technique and other optimization algorithms for rapid real-time tuning of the analog RF SIC parameters, and potentially implementing the system on the embedded CPU of an FPGA.
- We would like to explore methods and techniques for joint optimization of the RF beamforming, analog RF SIC, and digital BB SIC.