Simulation of Full Duplex Communication Systems

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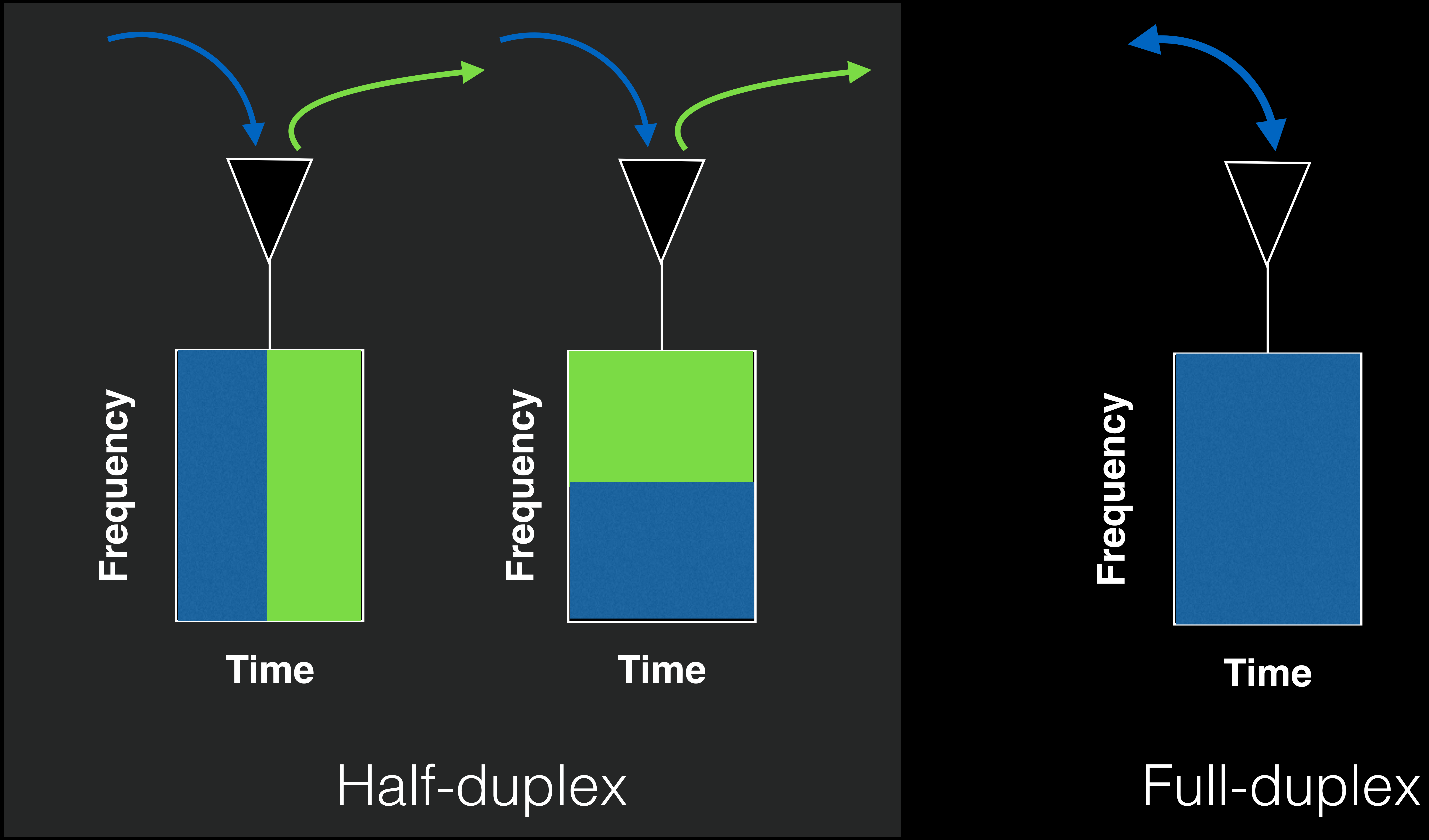
Joint work with Aniruddhan, Abhishek, Arjun Nadh

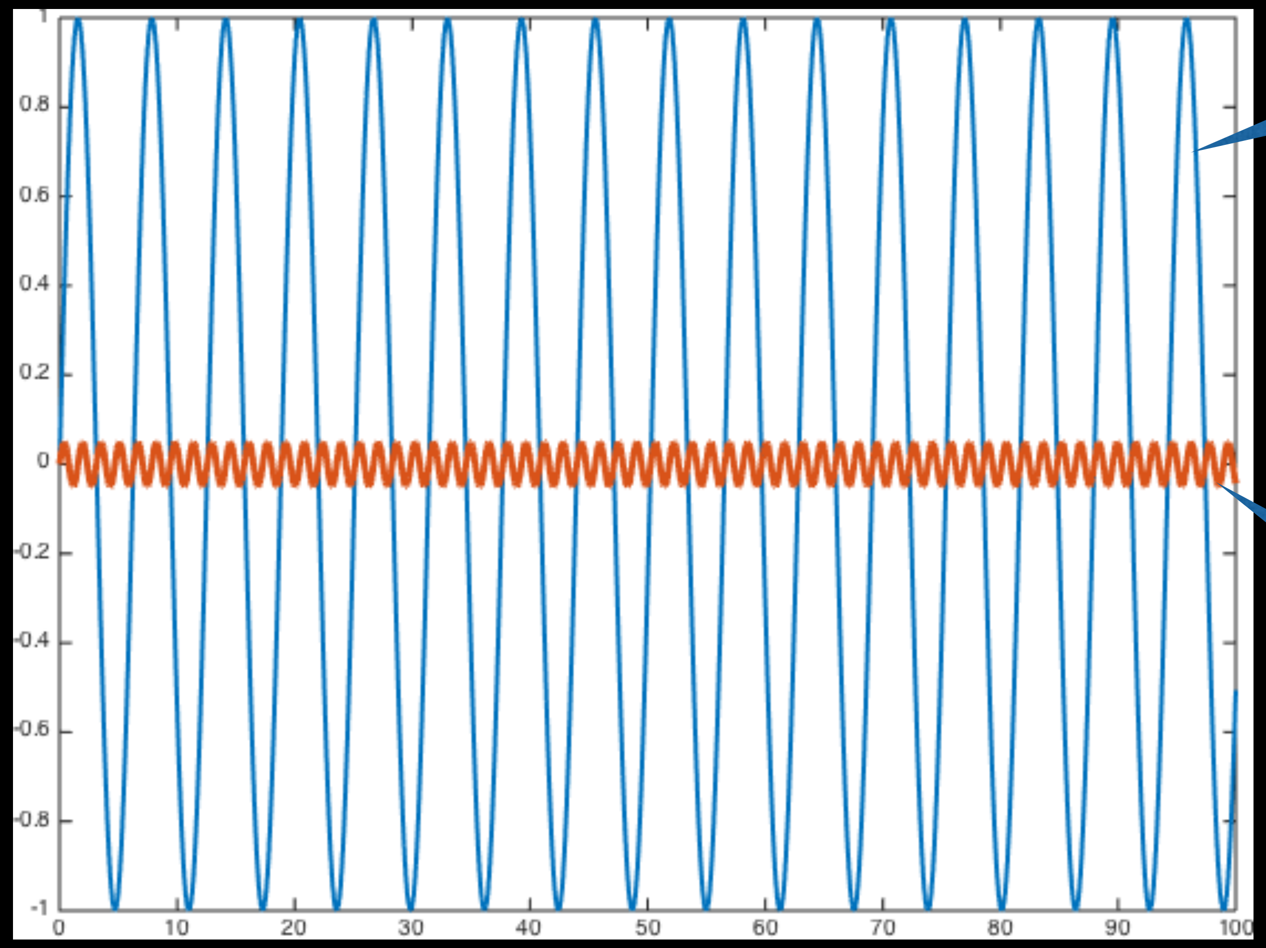
Current wireless devices are half-duplex



Ideal full-duplex doubles the available resources

Why is it difficult?

Self interference



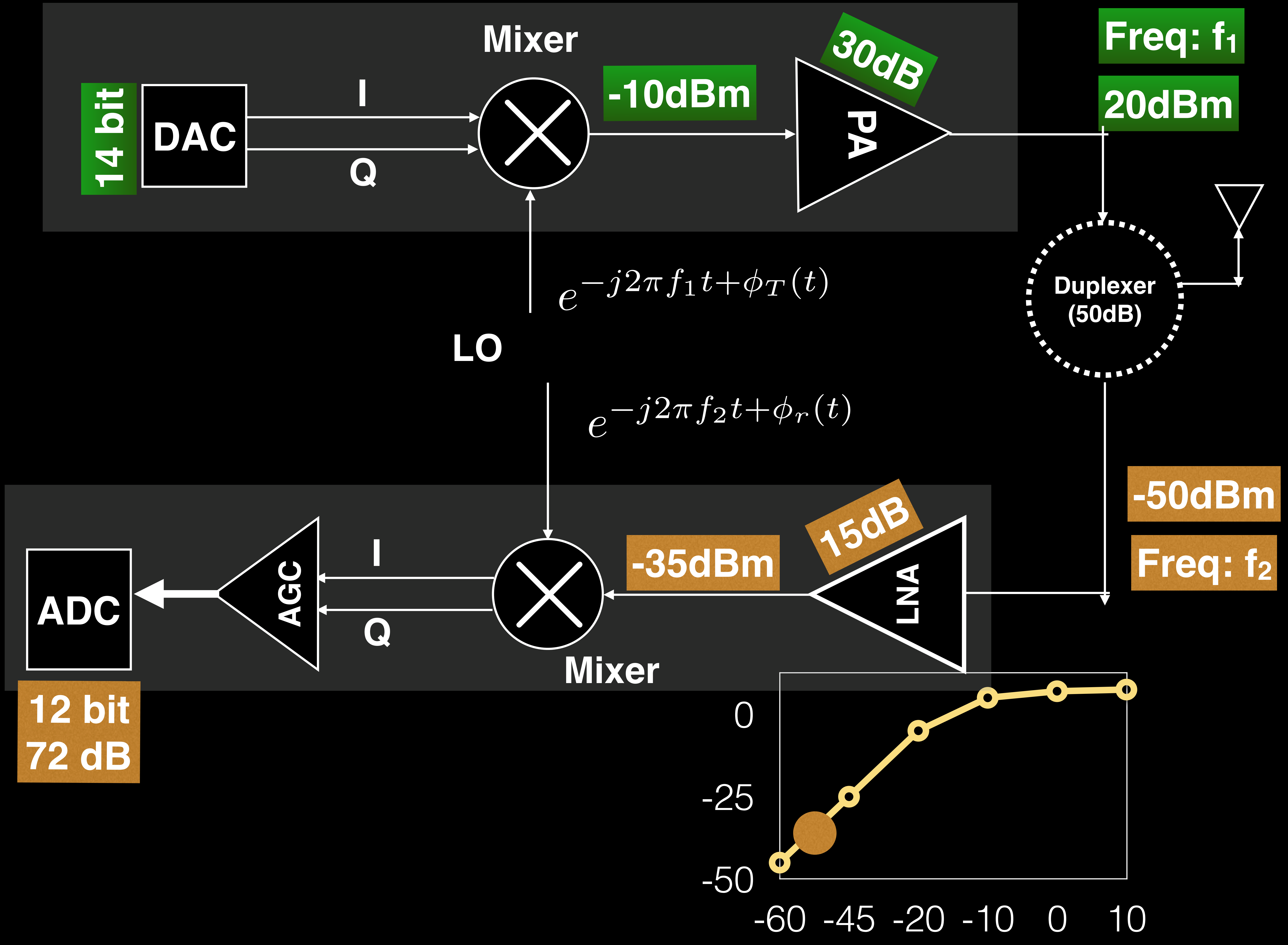
Transmit signal: 20dBm

Transmit signal is about a billion times stronger than the receive signal

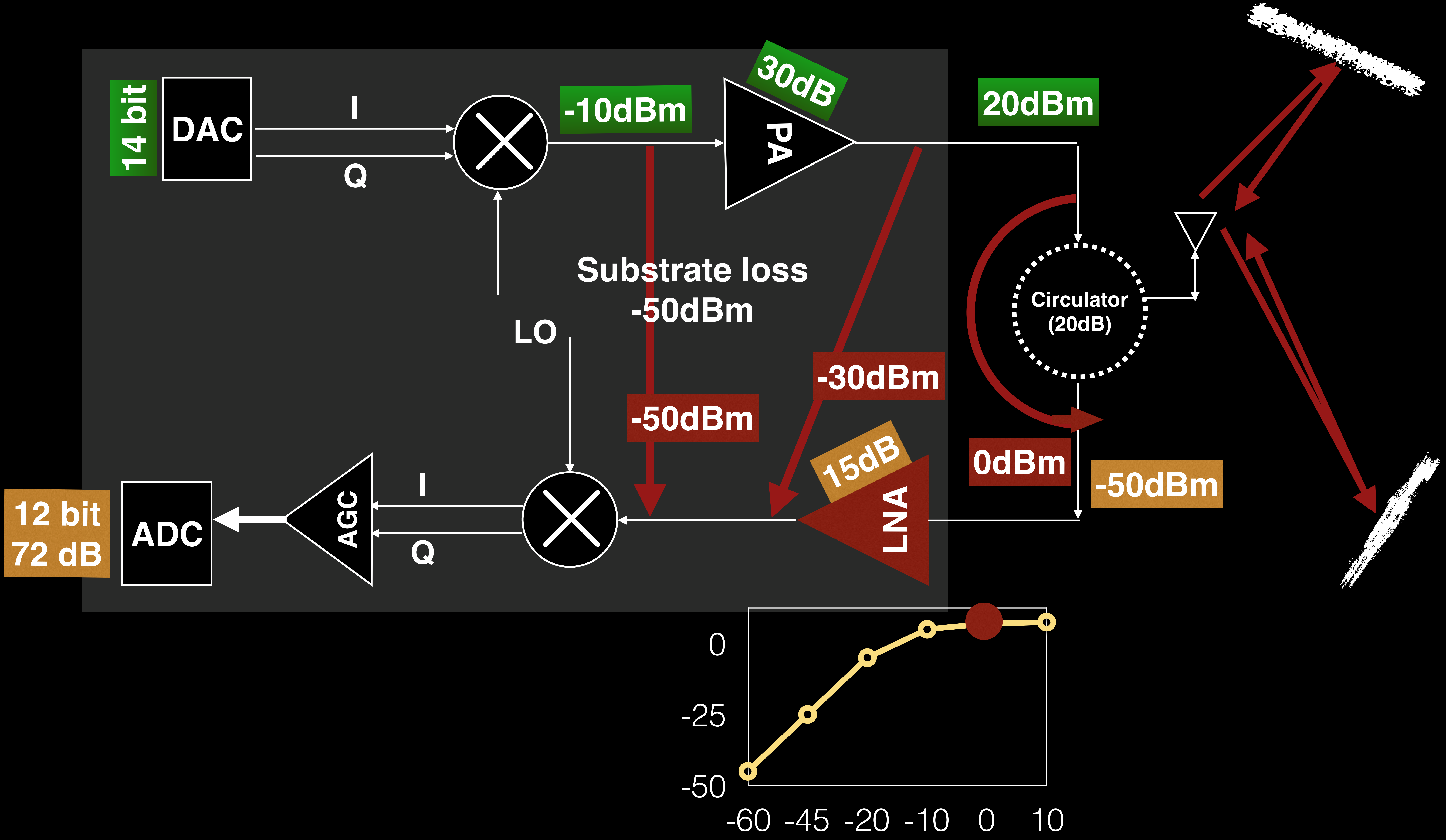
Receive signal: -70dB,

Large dynamic range

Typical TX-RX numbers



Self-Interference



Realising a full-duplex node

- Require about 90-**110**dB cancellation of self-interference
  - 55-**60** dB in analog domain (before ADC)
    - Some cancellation required before LNA
  - 35-**50** dB in digital domain

Self-interference model

$$I(t) = \sum_{k=1}^{N} a_k x(t - \tau_k)$$

Number of dominant paths

Delay of path k

Gain of path k

- x(t) is the RF signal
- Unknowns: Delays, gains, number of paths

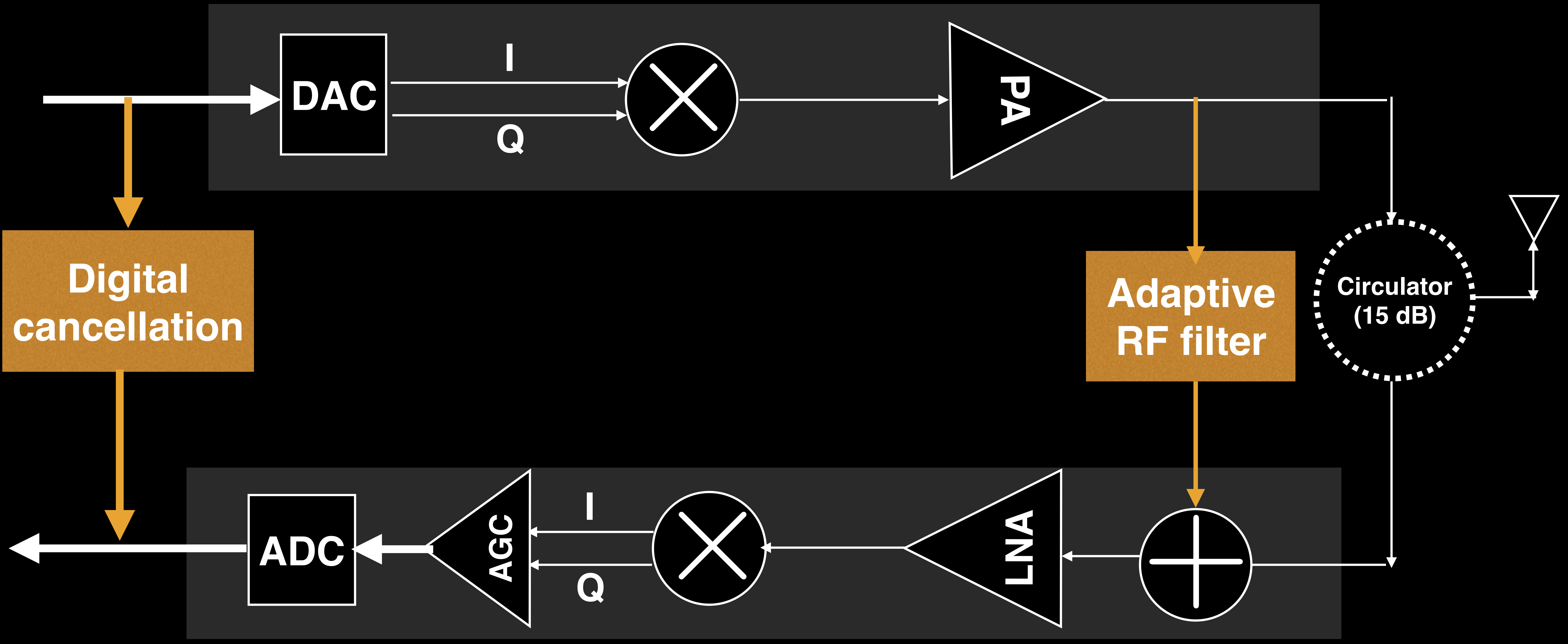
$$x(t) = \mathrm{Re}\left(u(t)e^{j2\pi f_c t}\right)$$

Basic idea

Transmitted signal is know at the node

- Subtract the known **self interference**
  - Digital domain: x - x = 0
  - Analog domain: x - x = 0.001x
- Filtered self-interference
  - Delayed and scaled versions of the transmit signal

Stanford design (Kumu Networks)



Bharadia, Dinesh, Emily McMilin, and Sachin Katti. "Full duplex radios." *ACM SIGCOMM Computer Communic*
Vol. 43. No. 4. ACM, 2013.

Our Technique: Linearization

$$I(t) = \sum_{k=1}^{N} a_k x(t - \tau_k)$$

[Self-Interferernce]

$$I(t) = \sum_{k=1}^{N} \mathrm{Re}\left(a_k u(t - \tau_k) e^{j2\pi f_c (t - \tau_k)}\right)$$

Taylor series

$$\approx \sum_{k=1}^{N} \mathrm{Re}\left(a_k \left(u(t) - \tau_k u'(t)\right) e^{j2\pi f_c (t - \tau_k)}\right)$$

$$\approx \mathrm{Re}\left(\left[\sum_{k=1}^{N} a_k e^{-j2\pi f_c \tau_k}\right] u(t) e^{j2\pi f_c t}\right) - \mathrm{Re}\left(\left[\sum_{k=1}^{N} a_k \tau_k e^{-j2\pi f_c \tau_k}\right] u'(t) e^{j2\pi f_c t}\right)$$

C_1 C_2

$$I(t) = \sum_{k=1}^{N} a_k \operatorname{Re}\left(u(t-\tau_k)e^{j2\pi f_c(t-\tau_k)}\right)$$

$$I(t) \approx \operatorname{Re}\left(C_1 u(t)e^{j2\pi f_c t}\right) - \operatorname{Re}\left(C_2 u'(t)e^{j2\pi f_c t}\right)$$

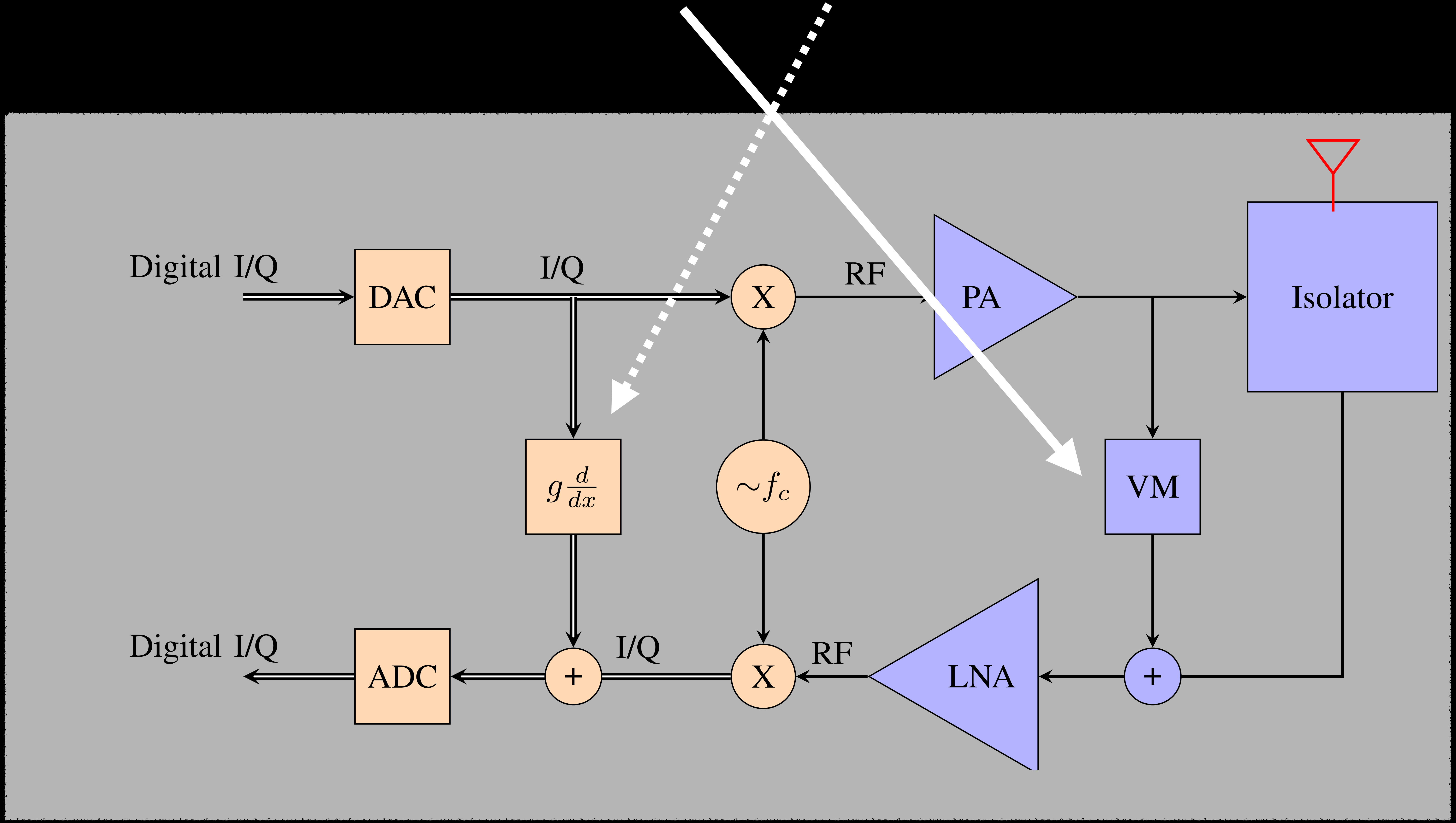
Original channel has 2N+1 unknowns
Only 2 unknowns in the approximated channel

$$I(t) = I_s(t) + I_d(t) + E(t)$$

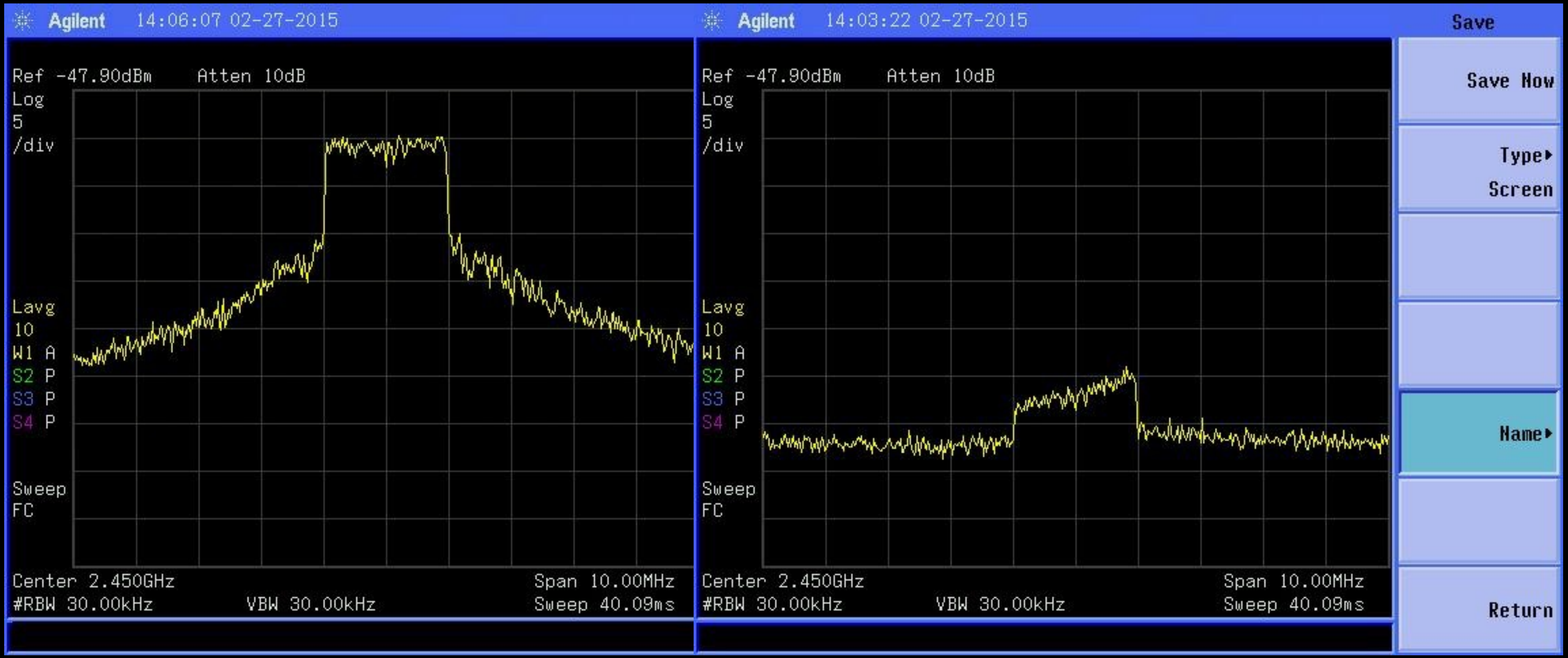
Circuit diagram

$$I(t) \approx \mathrm{Re}\left(C_1 u(t) e^{j2\pi f_c t}\right) - \mathrm{Re}\left(C_2 u'(t) e^{j2\pi f_c t}\right)$$

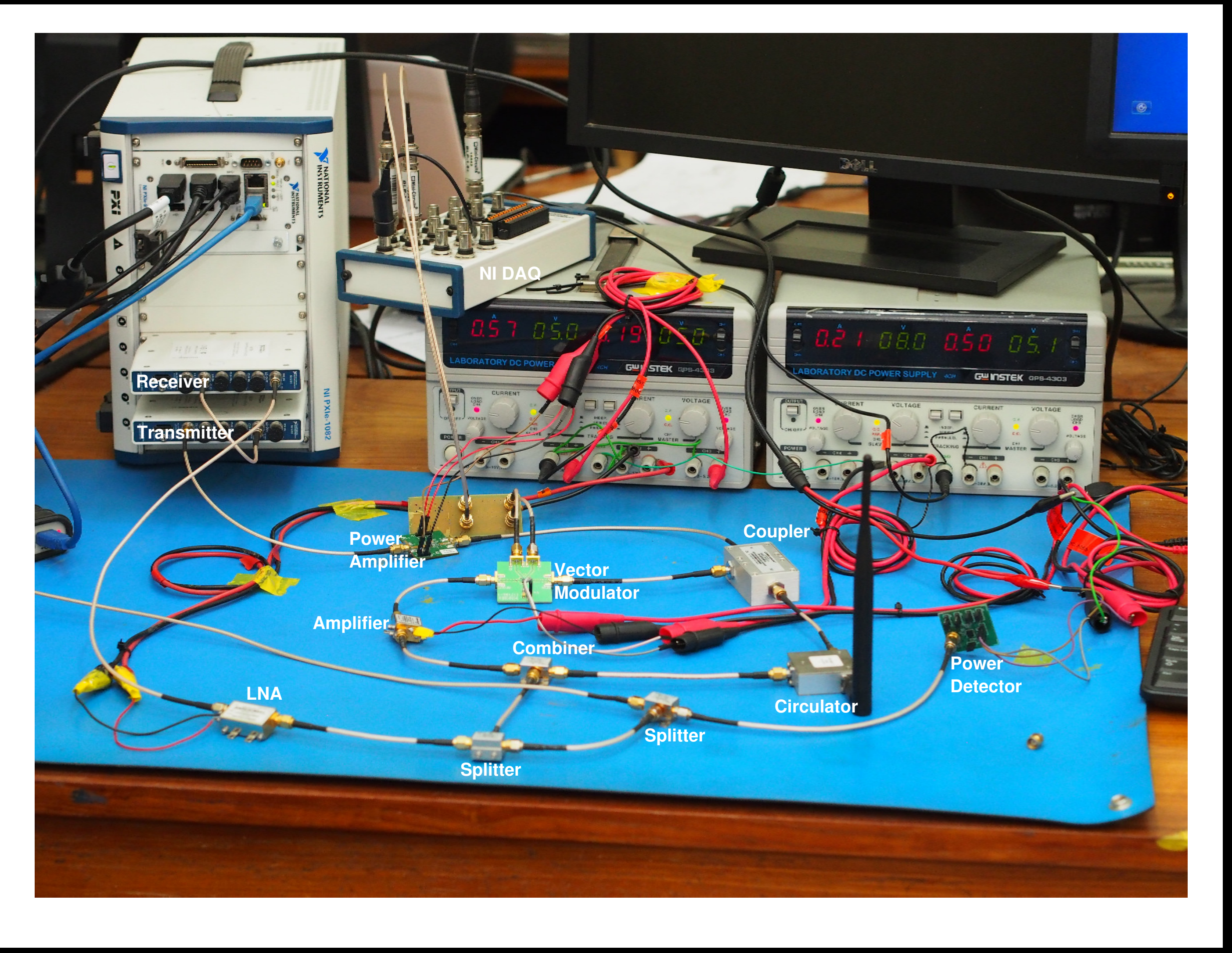
$$I(t) = I_s(t) + I_d(t) + E(t)$$

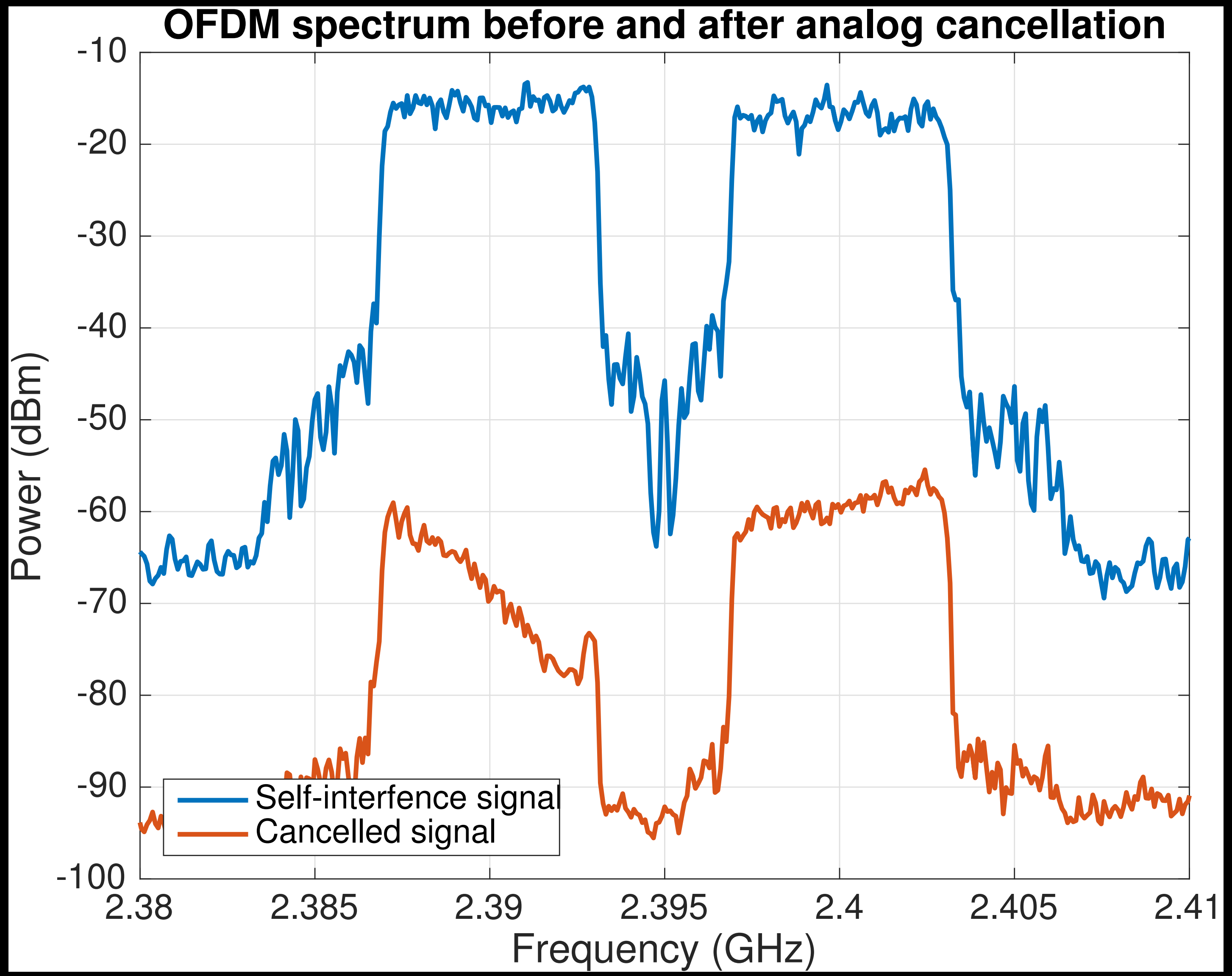


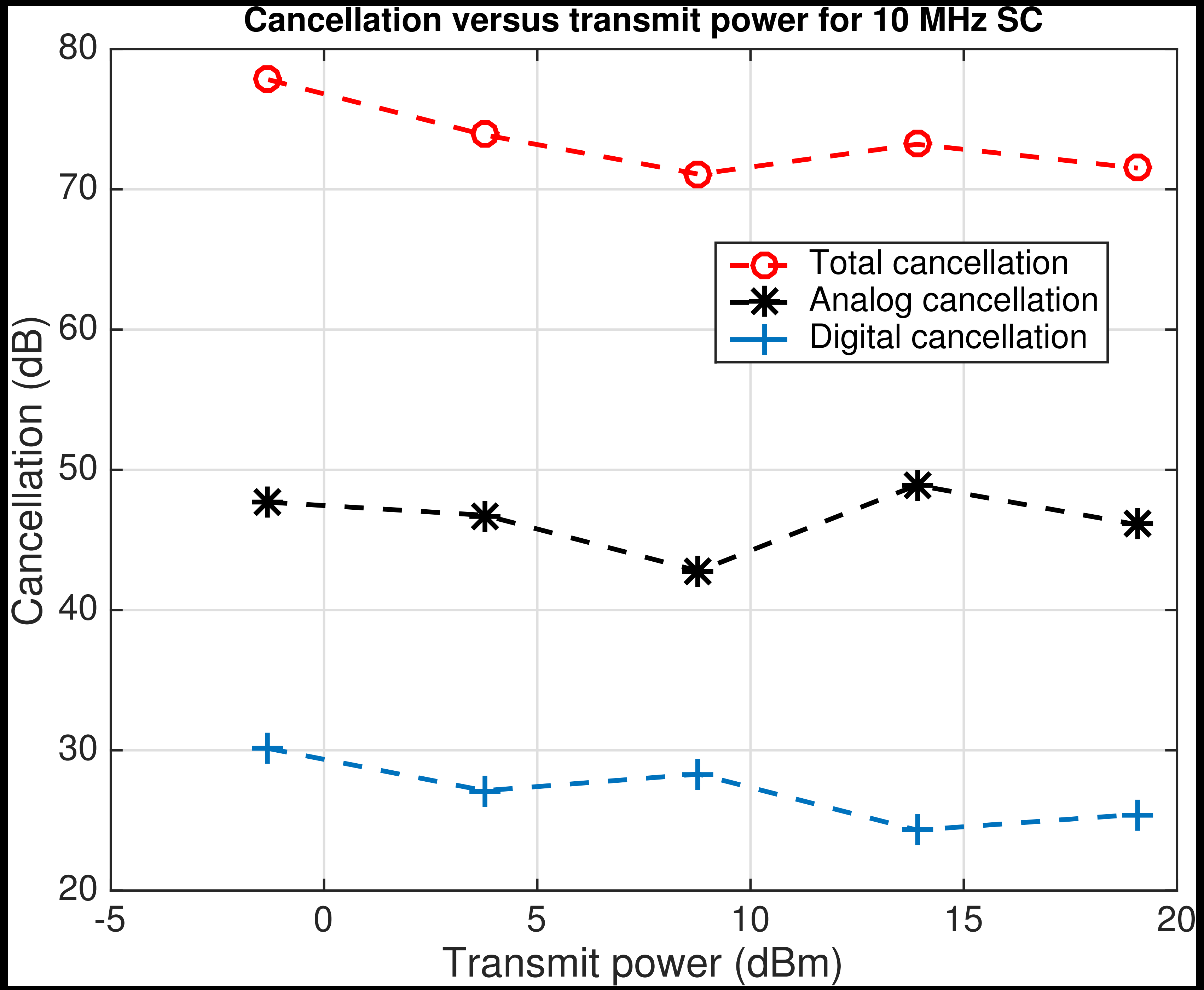
Derivative (experimental proof)



$$\mathcal{F}(u'(t)) = f\hat{U}(f)$$


Receiver
Transmitter
NI DAQ
Power Amplifier
Vector Modulator
Coupler
Amplifier
Combiner
LNA
Splitter
Splitter
Circulator
Power Detector


OFDM spectrum before and after analog cancellation
Power (dBm)
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
2.38
2.385
2.39
2.395
2.4
2.405
2.41
Frequency (GHz)
Self-interference signal
Cancelled signal


Cancellation versus transmit power for 10 MHz SC
Cancellation (dB)
80
70
60
50
40
30
20
-5
0
5
10
15
20
Transmit power (dBm)
Total cancellation
Analog cancellation
Digital cancellation

Hardware

New idea: 6 months (might not work)

Software ??

RF Blockset to the rescue

RF Blockset

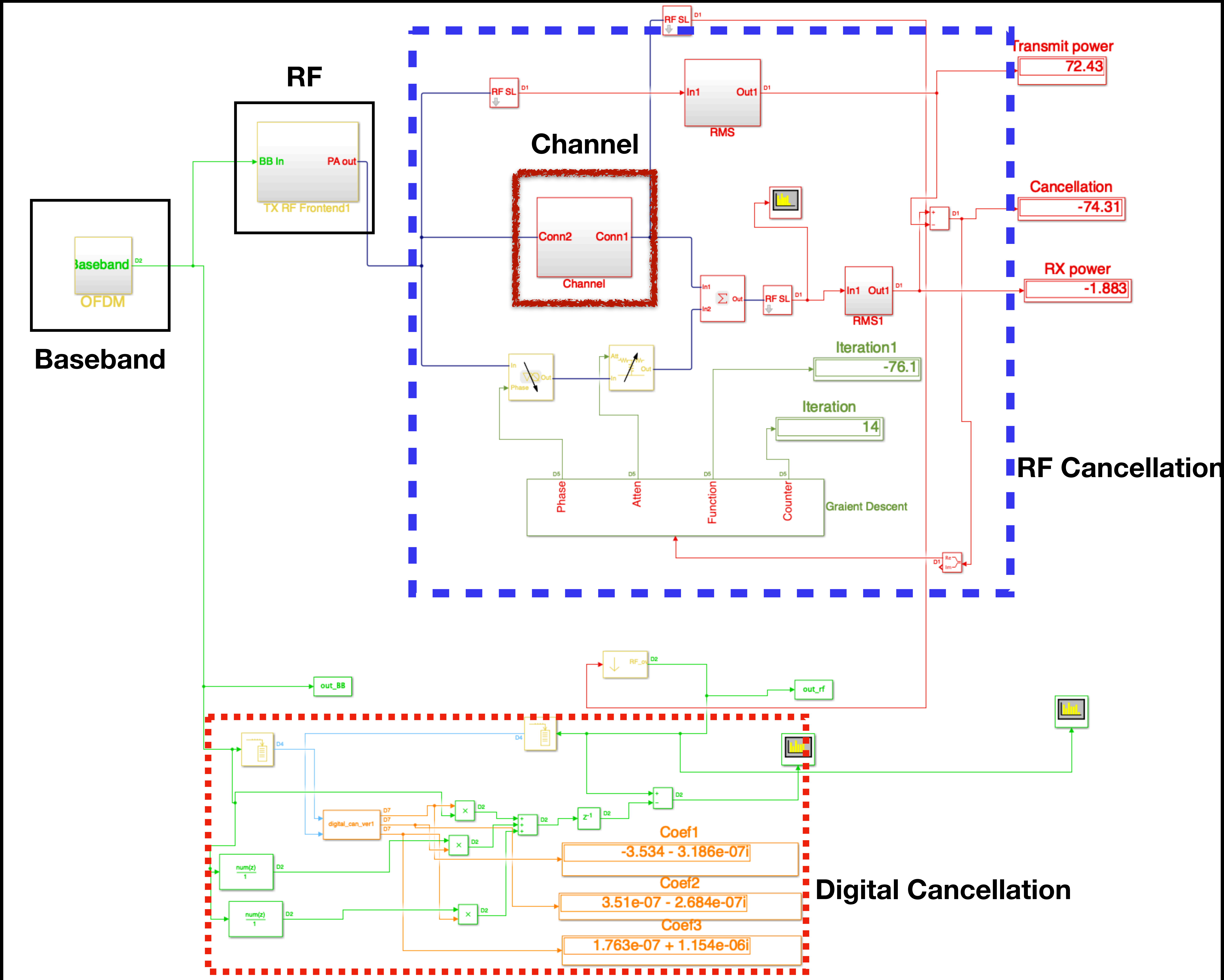
- OFDM modulation
- RF Blockset: Circuit-envelope blocks to model the RF
  - Analog cancellation
- Self-Interference channel model
- Digital cancellation
  - Signal and derivative cancellation

Blocks Used

- IQ Modulator/ IQ Demodulator
- Variable RF phase shifter
- Variable RF attenuator
- Custom analog cancellation algorithm (gradient descent)
  - Level-2 MATLAB S-Function

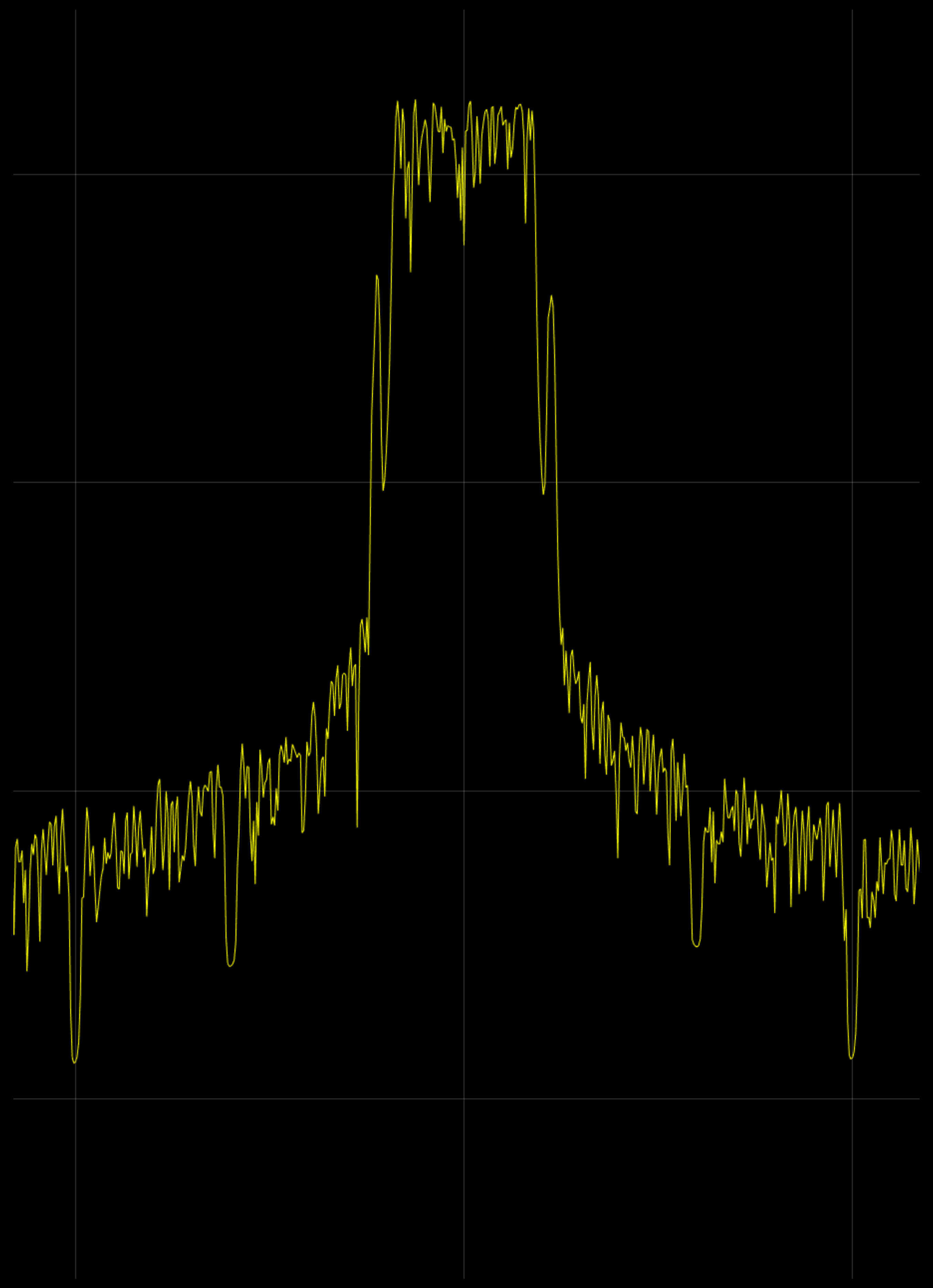
Novice user: 1 week

- Custom digital cancellation algorithm (derivative and LMS)
  - Level-2 MATLAB S-Function



RF
Channel
Baseband
RF Cancellation
Digital Cancellation
Transmit power
72.43
Cancellation
-74.31
RX power
-1.883
Iteration1
-76.1
Iteration
14
Graient Descent
Phase
Atten
Function
Counter
RMS
RMS1
TX RF Frontend1
BB In
PA out
OFDM
Conn2
Conn1
out_BB
out_rf
digital_can_ver1
Coef1
-3.534 - 3.186e-07i
Coef2
3.51e-07 - 2.684e-07i
Coef3
1.763e-07 + 1.154e-06i

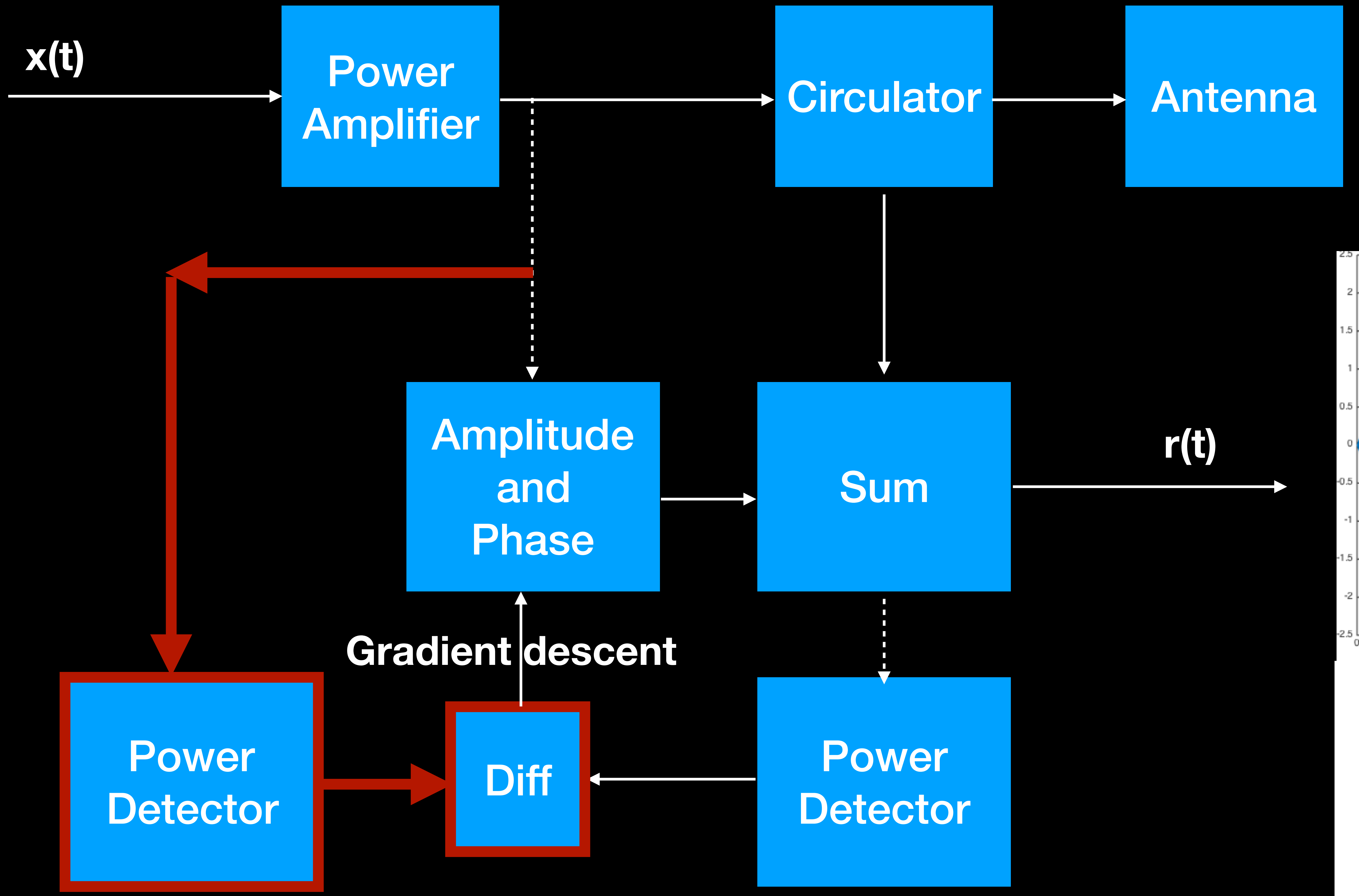
Self-Interference

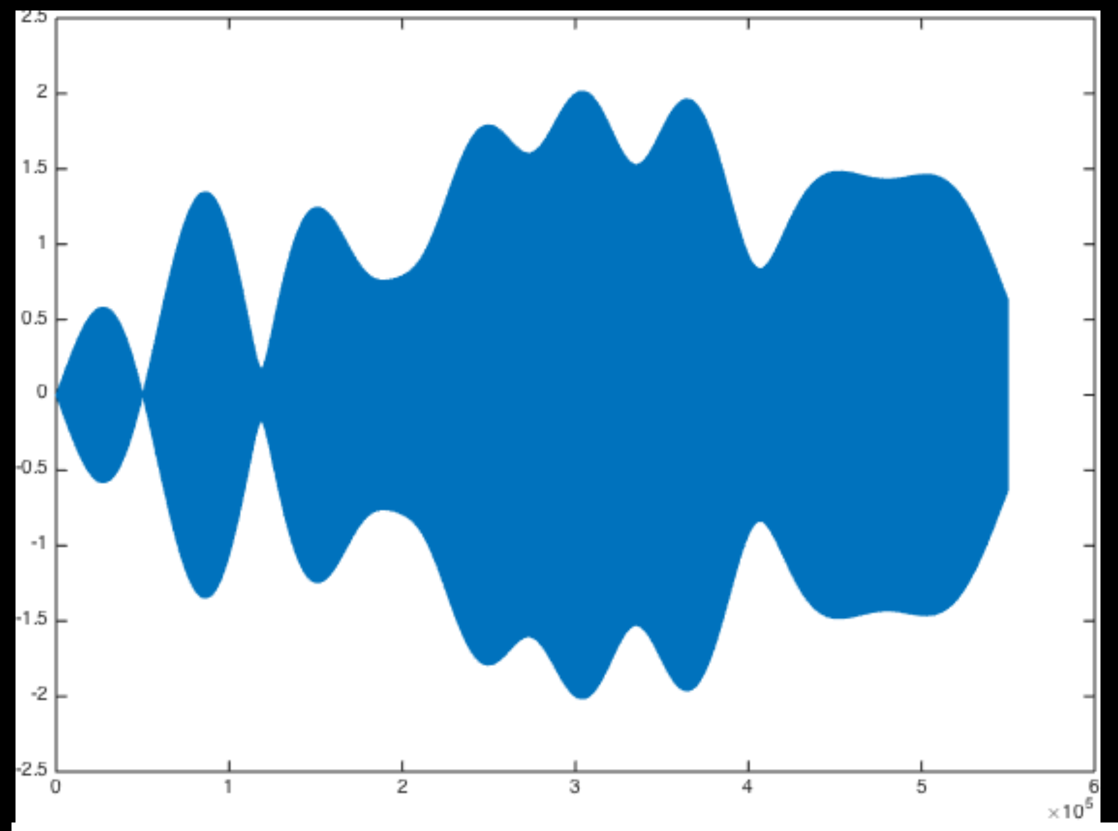


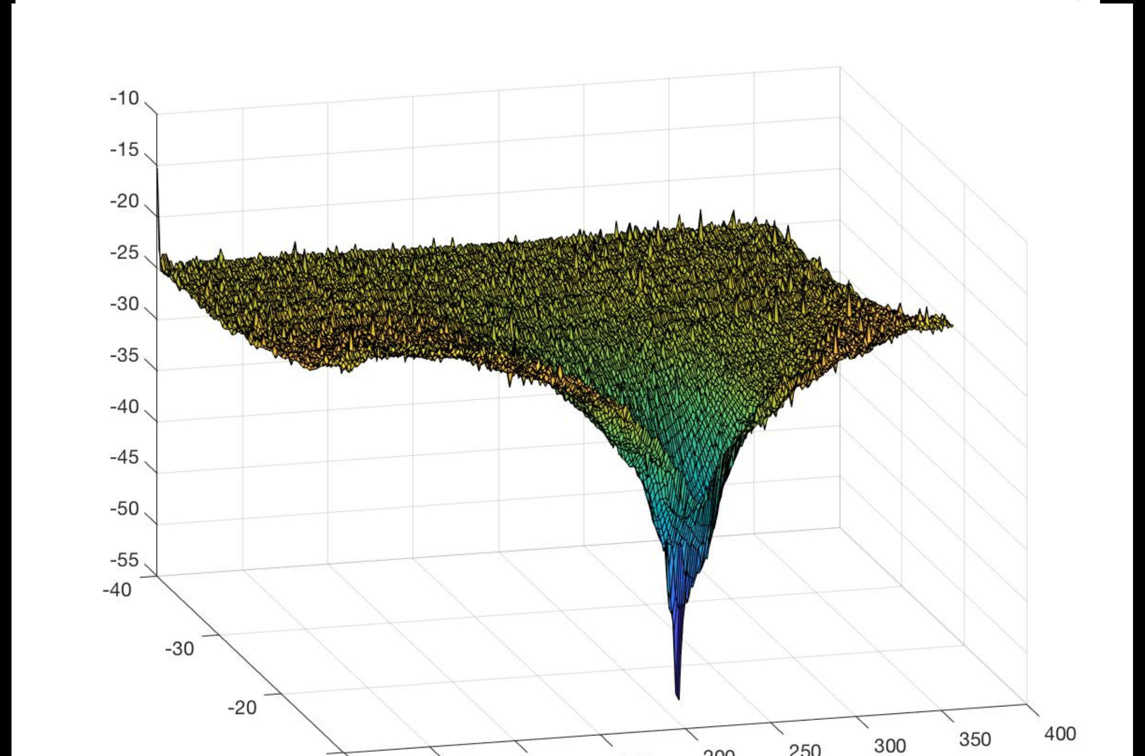
After Cancellation

Output from SIMRF

Learning



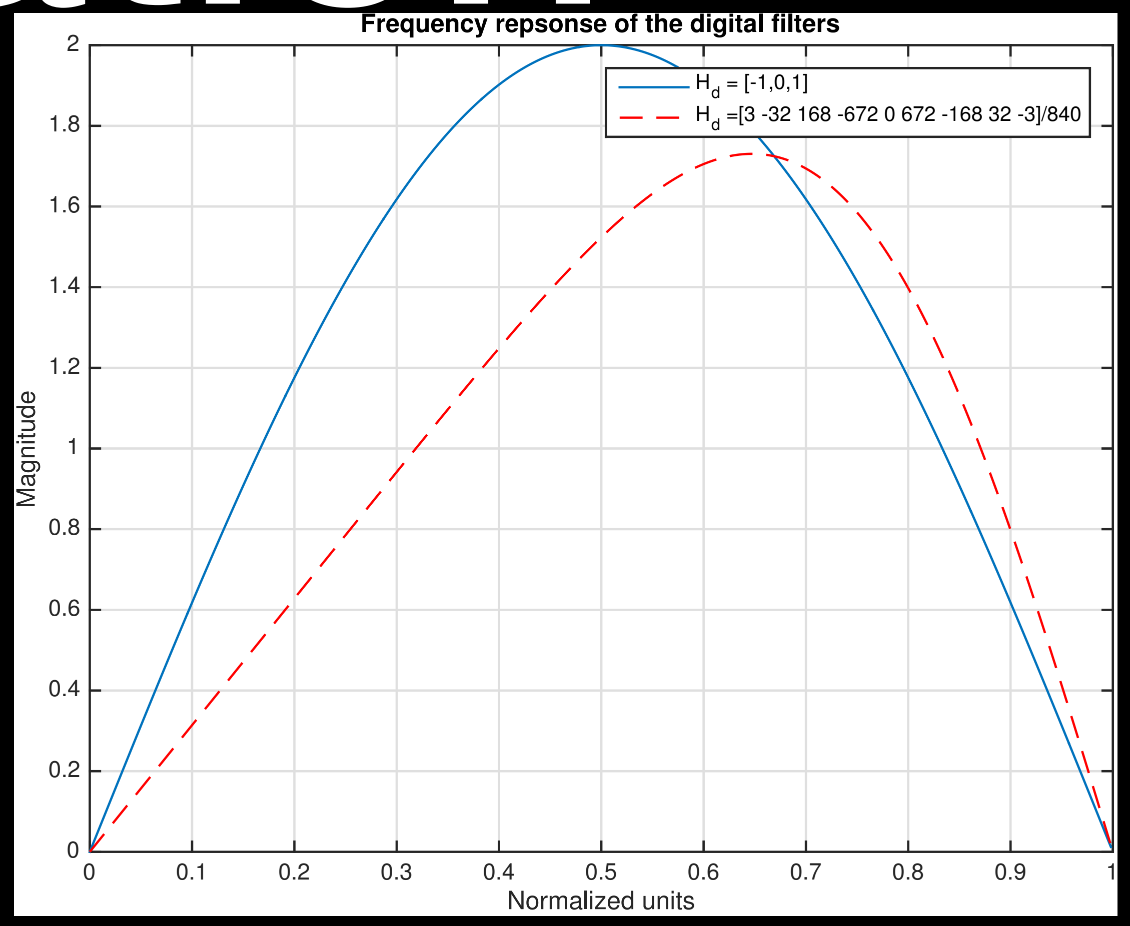


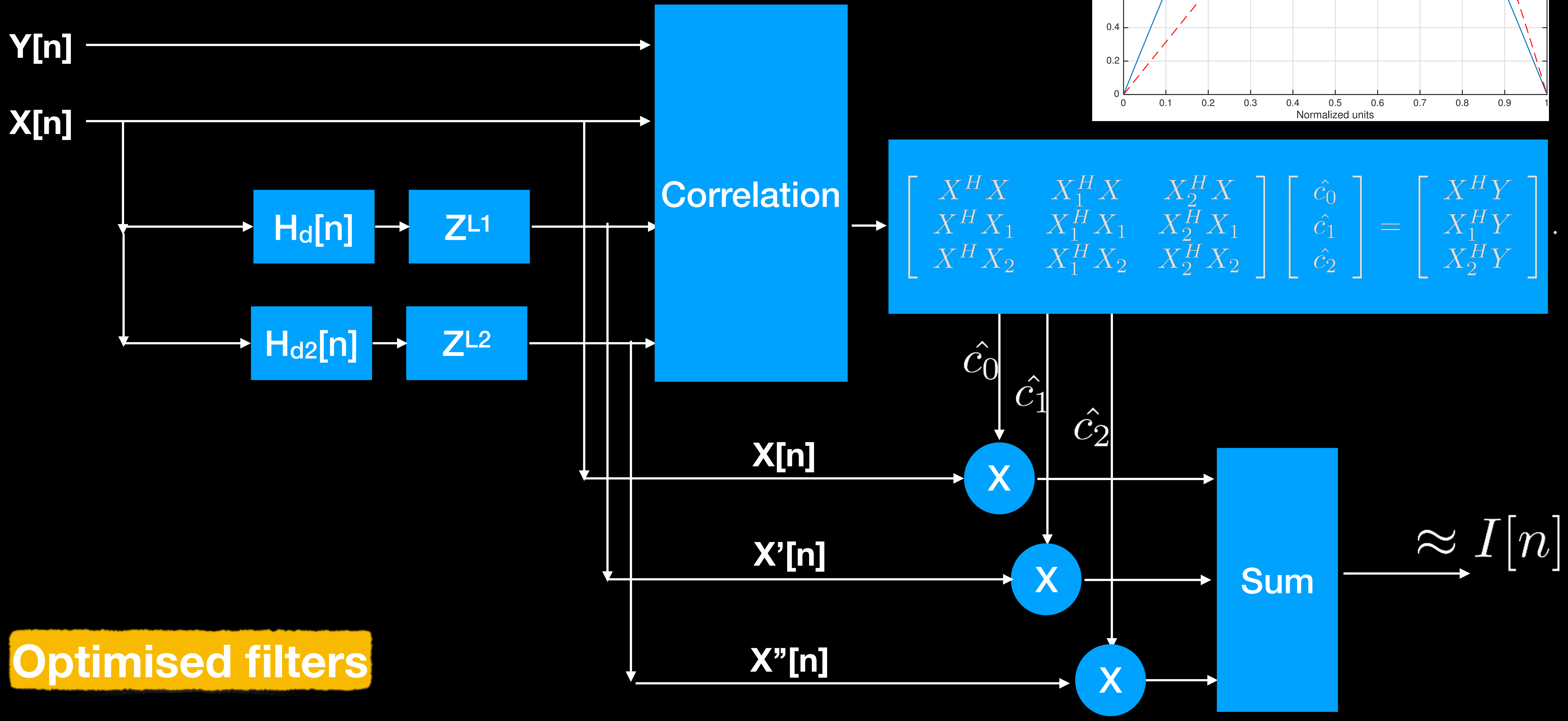


Faster GD convergence

Digital Cancellation

$$I(t) = c_0 x(t) + c_1 x'(t) + c_2 x''(t) + E_3(t)$$

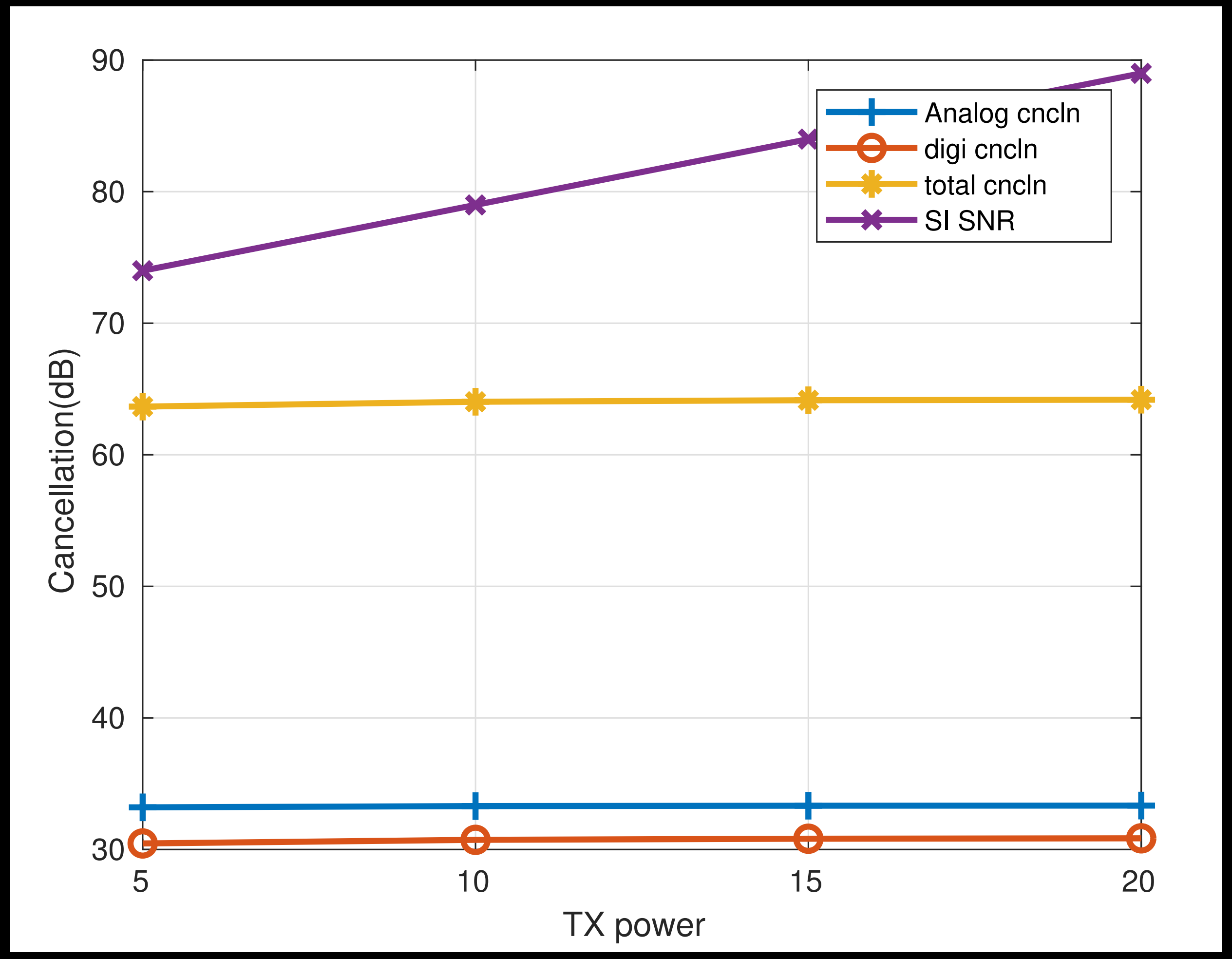




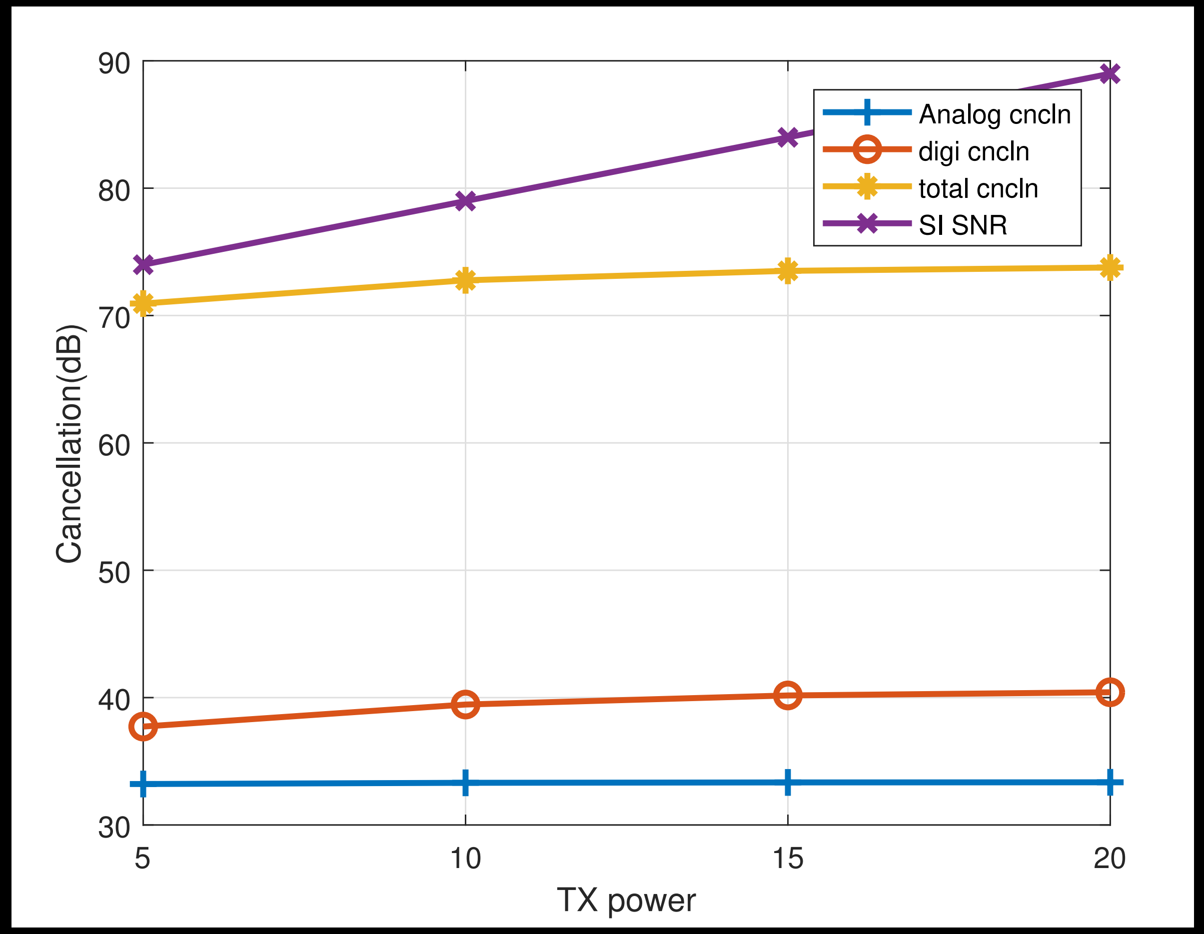
Optimised filters

RF Non-Idealities

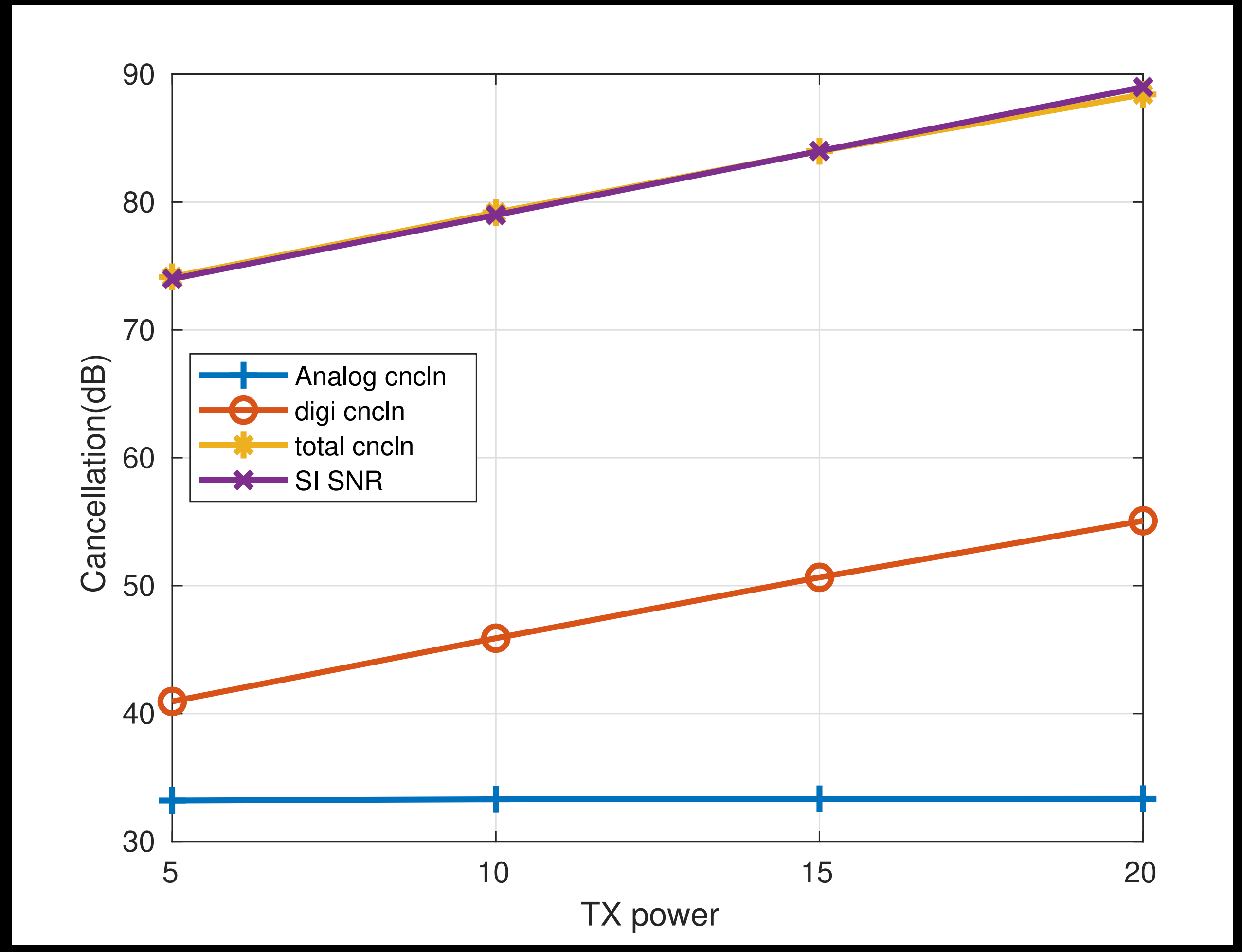
IQ Imbalance



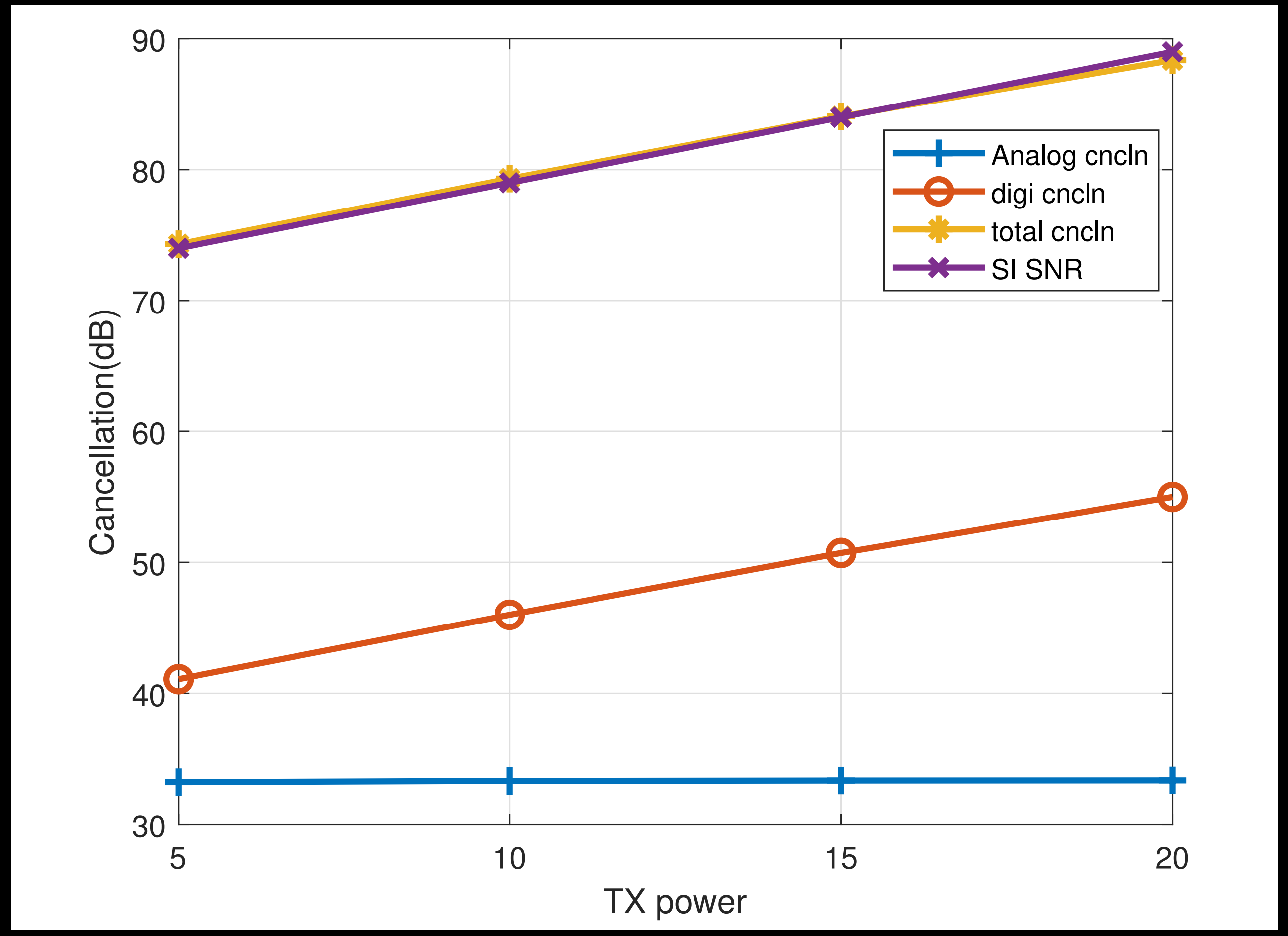
PA Non-Linearity



IRR: 25 dB



Memory Polynomial (3,5)



RF Blockset + Simulink

An Excellent Platform for Full-Duplex Work

Thank You
Any Questions/Comments?