# Full-Duplex Wireless Nodes

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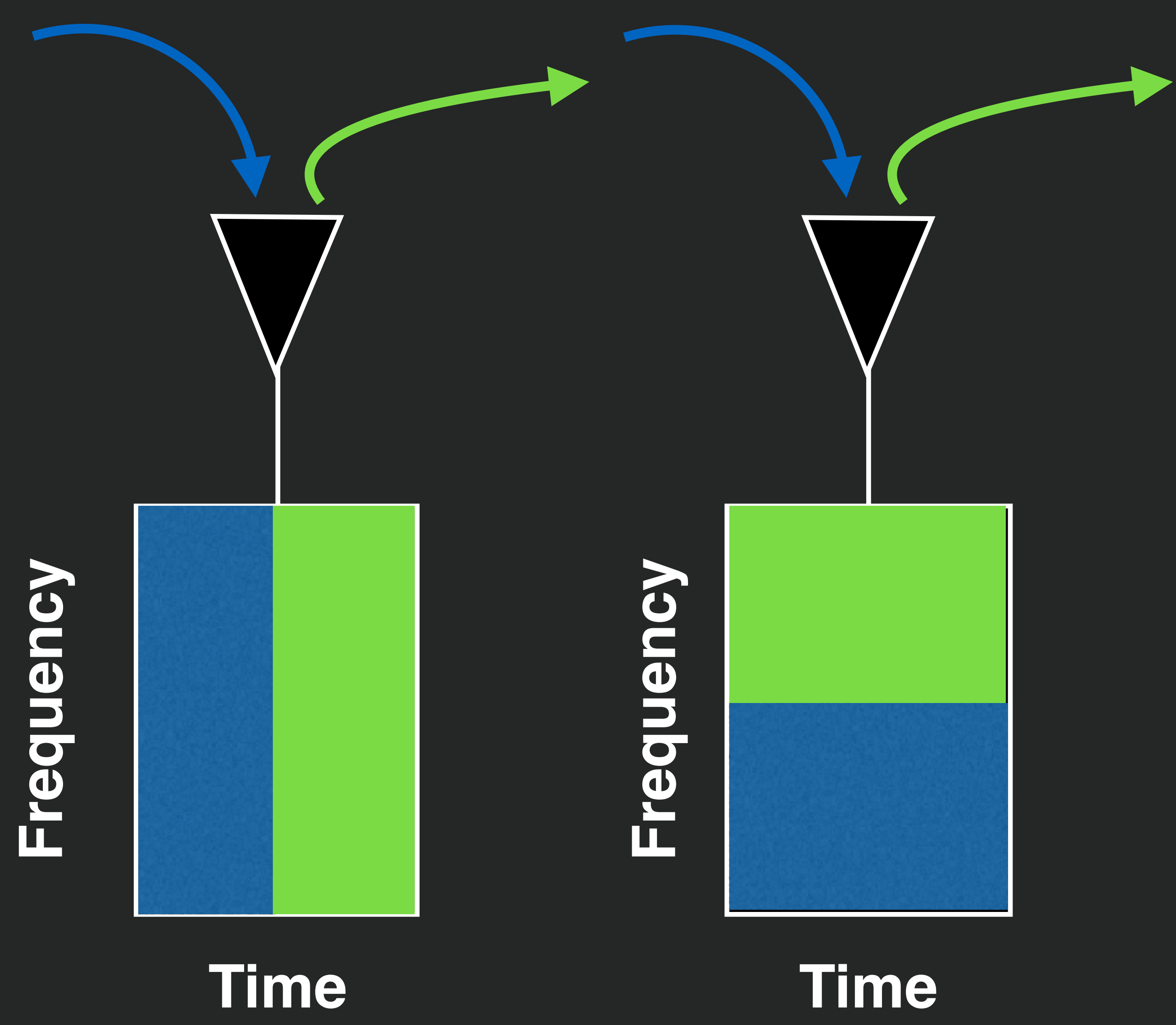
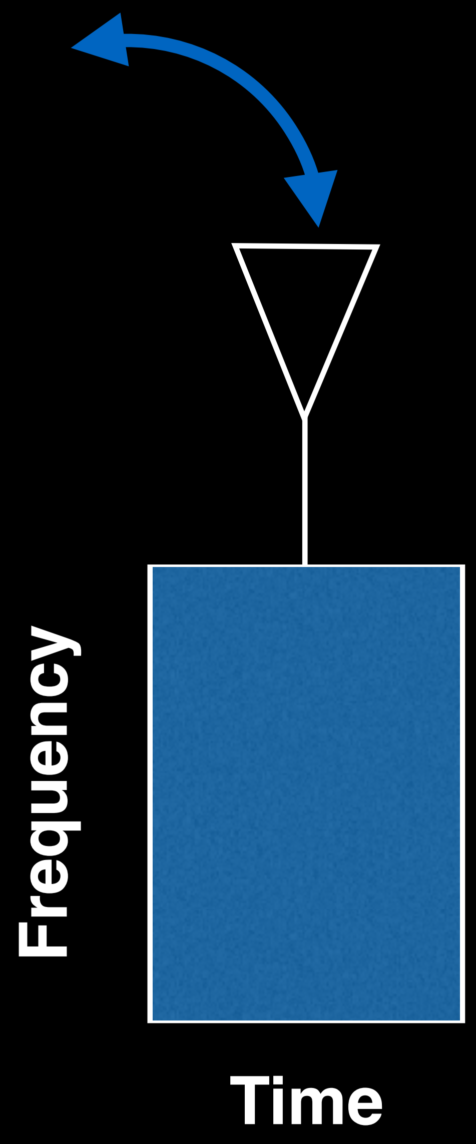
# Current wireless devices are half-duplex




Half-duplex

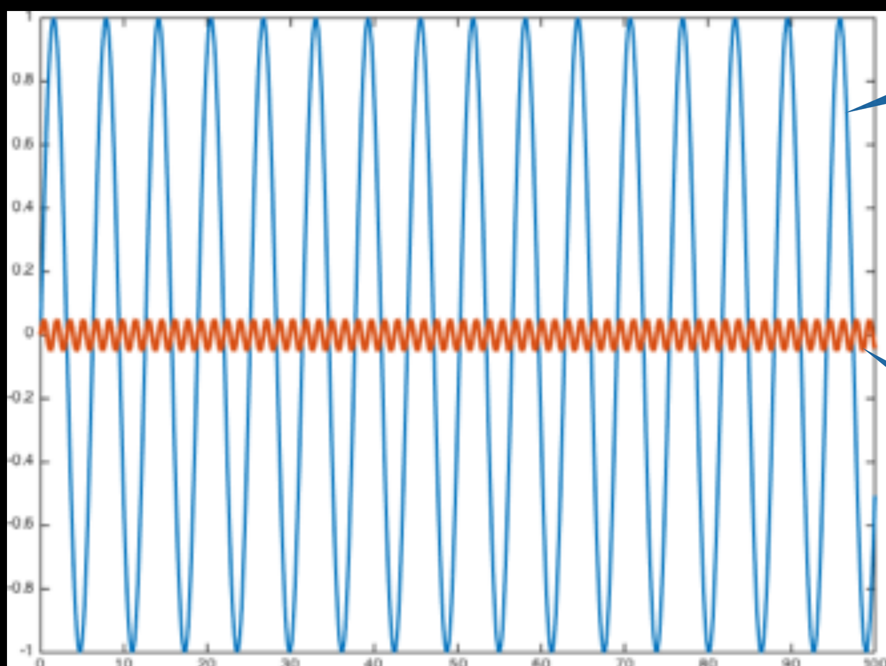



Full-duplex

**Ideal full-duplex doubles the available resources**

# Why is it difficult?

# Self interference



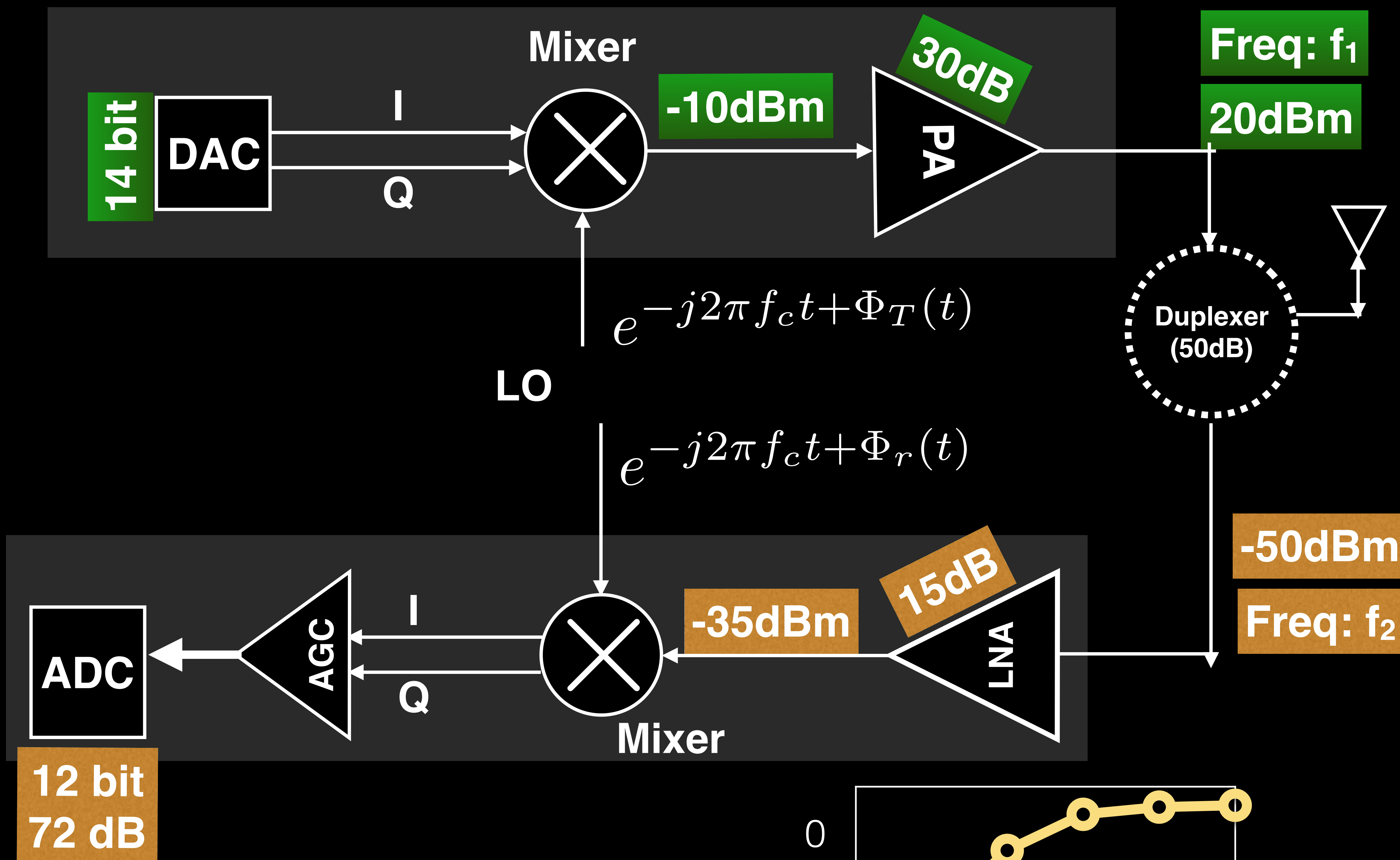
Transmit signal: 20dBm

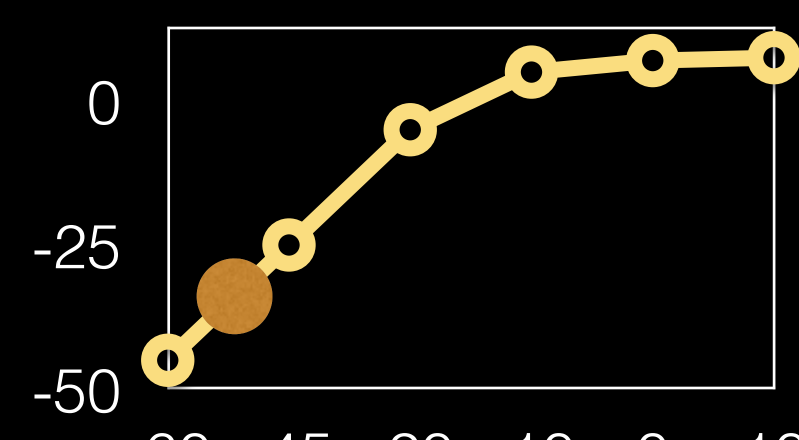
Receive signal: -70dB,

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

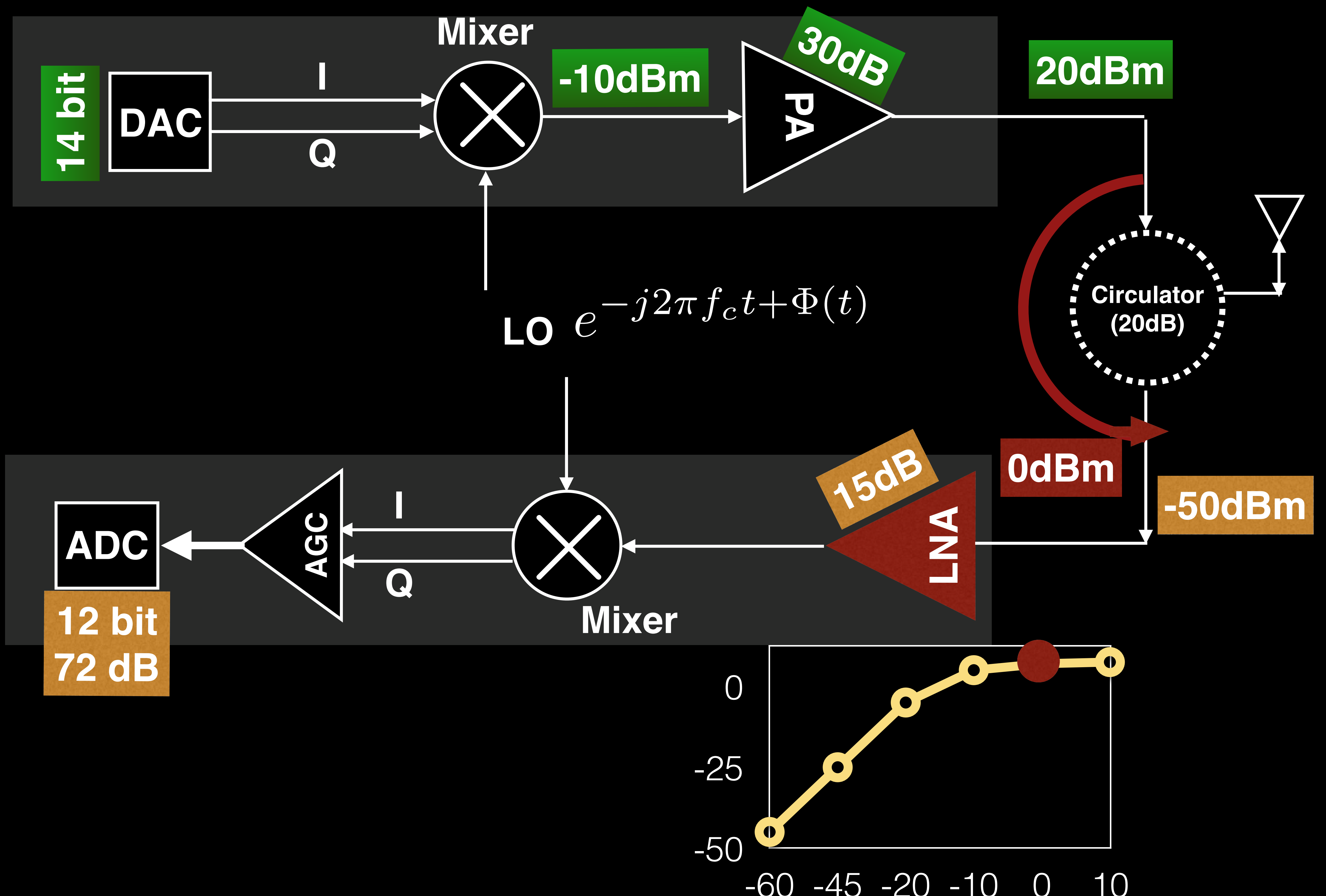
**Large dynamic range**

# Typical TX-RX numbers

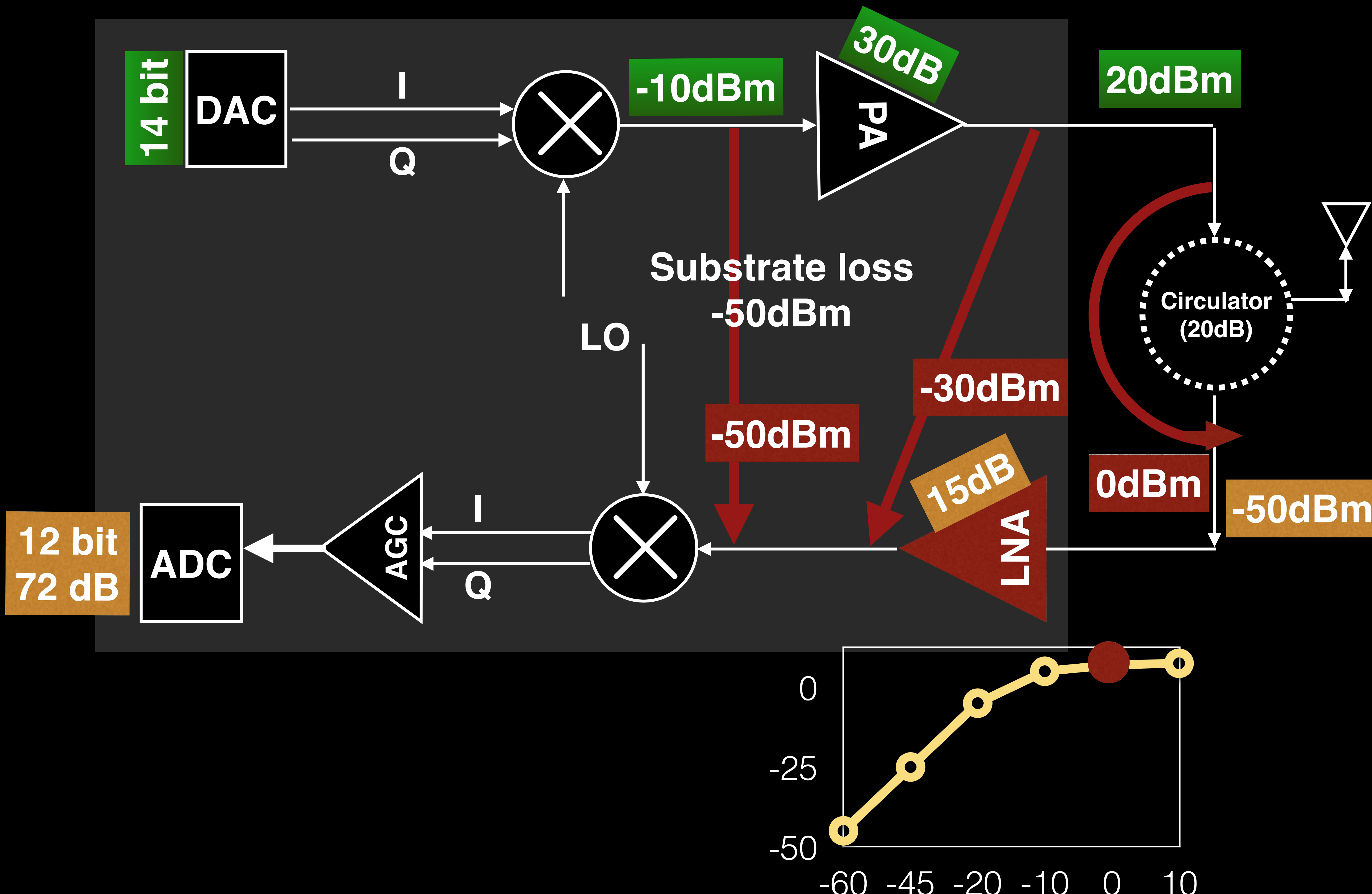


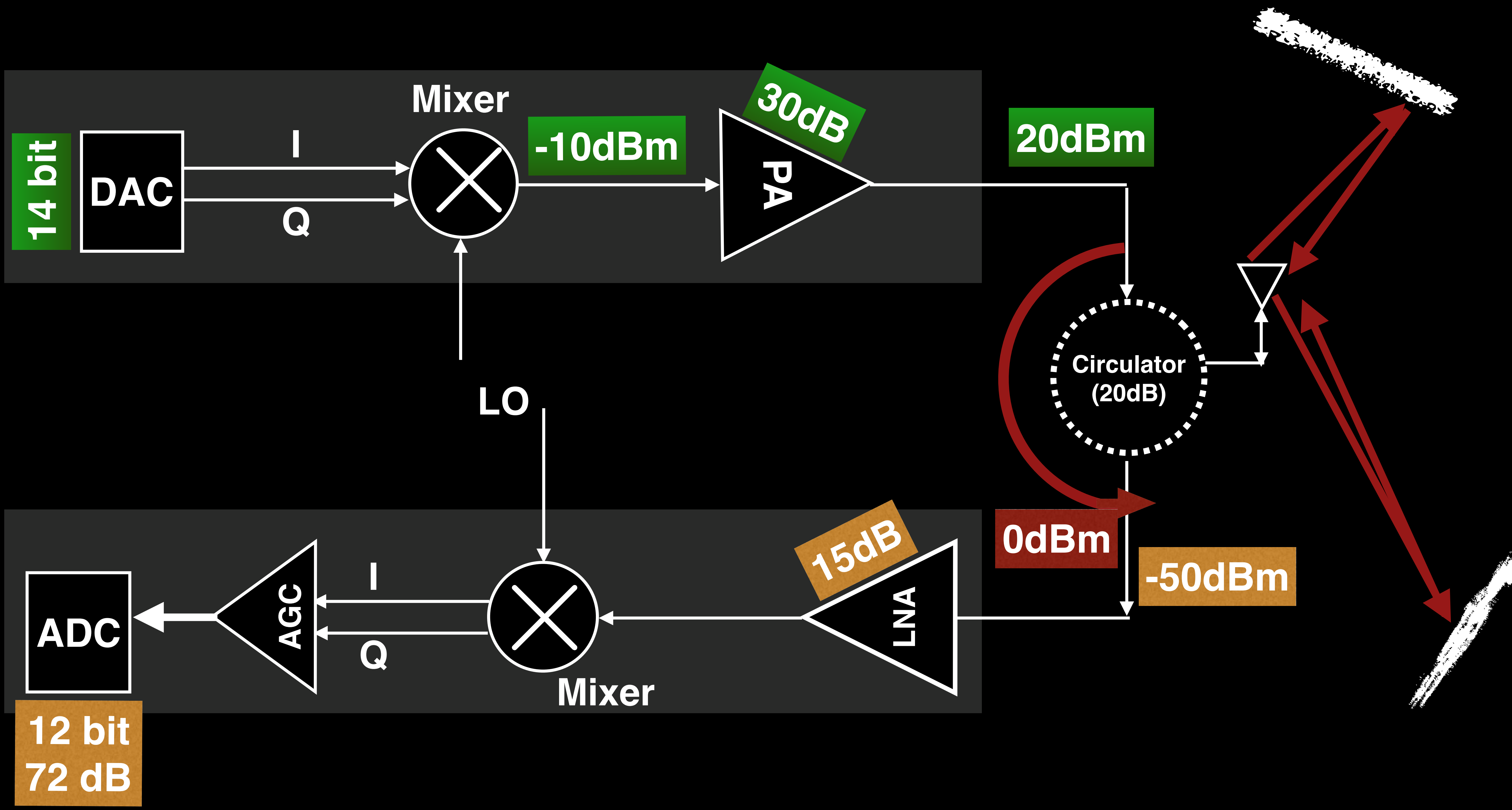
# Full-duplex: Antenna sharing



# Same board/chip

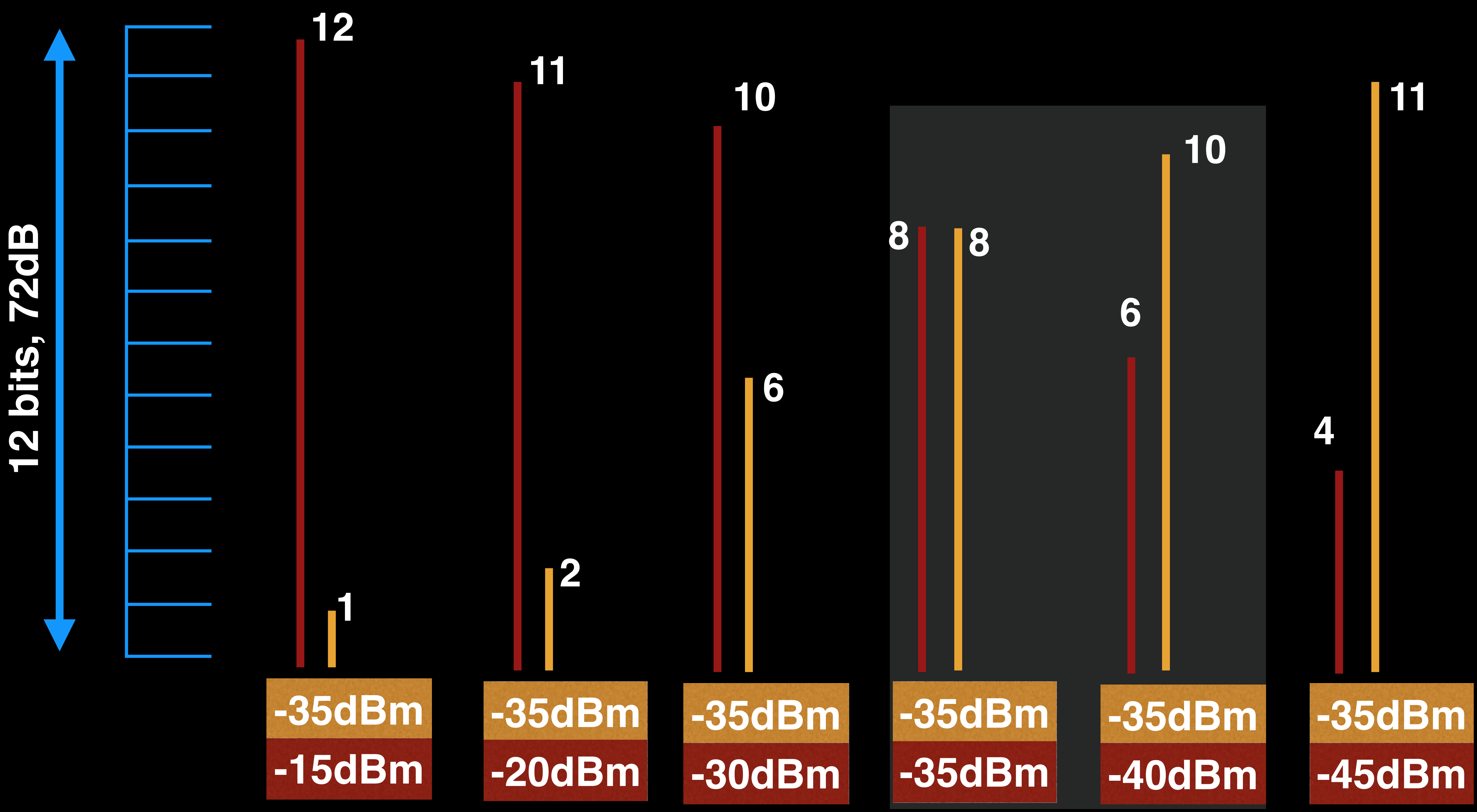


# Self-Interference multi-path



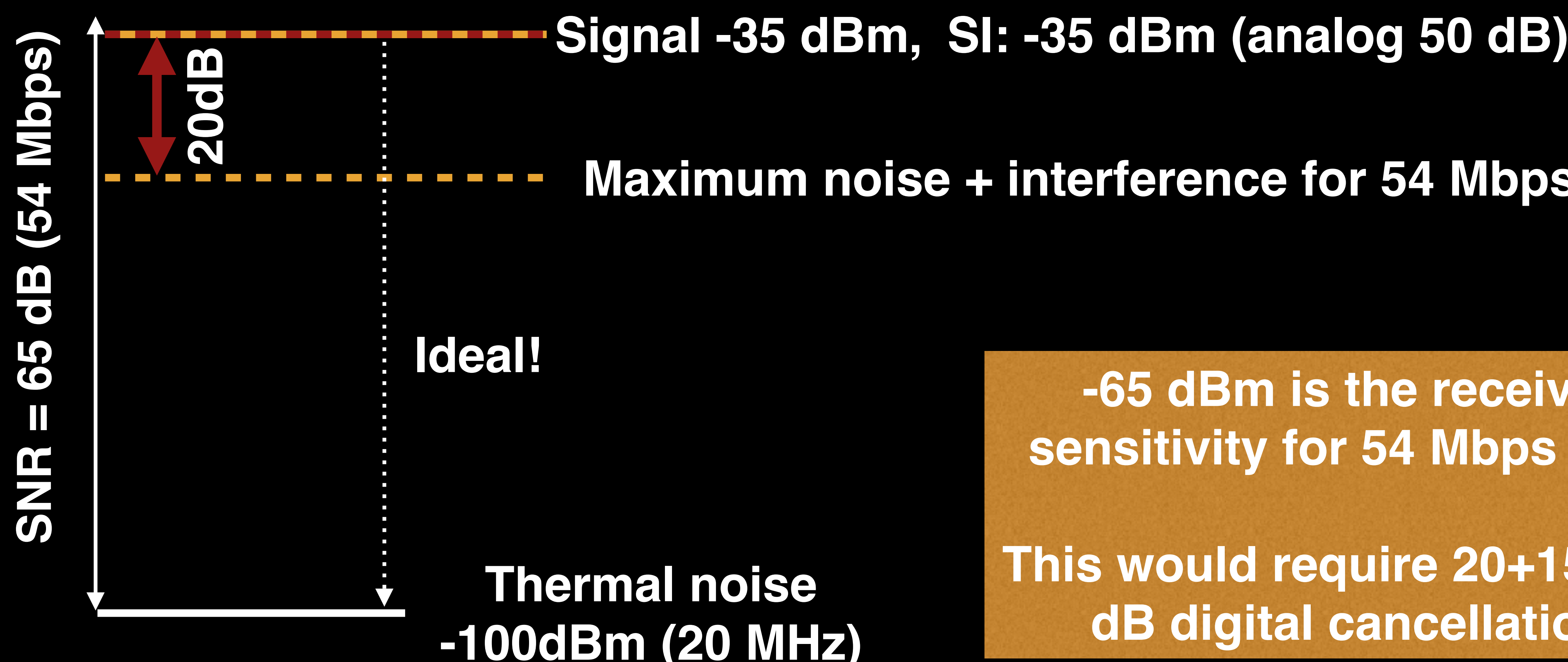

Different paths have different delays and attenuations

# ADC resolution




- 55 - 60 dB cancellation required before ADC
- Quantization noise limits digital cancellation

# After ADC
# (assume infinite resolution)




**-65 dBm is the receiver sensitivity for 54 Mbps WiFi**

**This would require 20+15 = 35 dB digital cancellation**

# 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
- Should be robust to self-interference multi-path

# Self-interference model

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

**Number of dominant paths** ($N$)

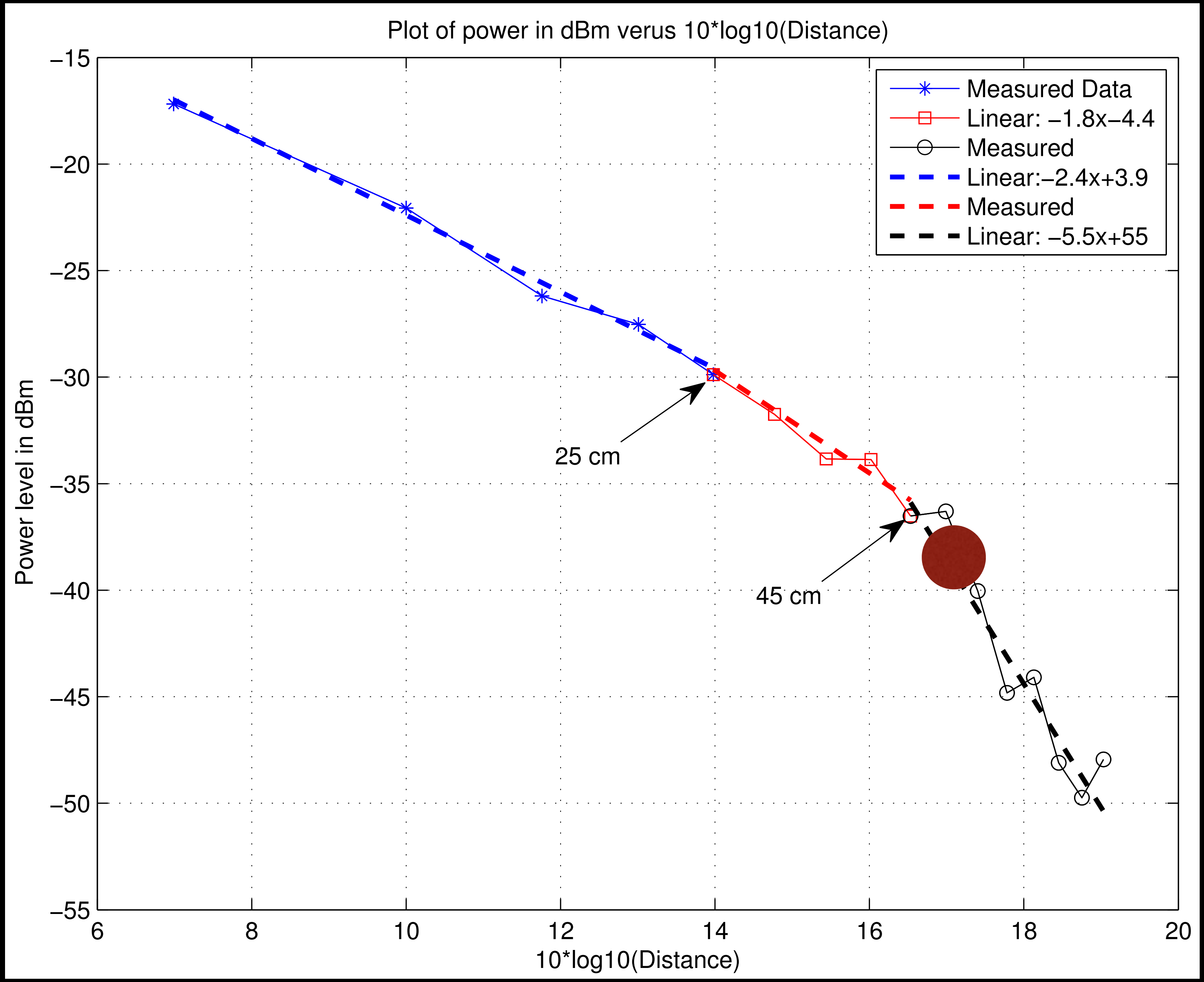
**Gain of path k** ($a_k$)

**Delay of path k** ($\tau_k$)

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

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

# What paths matter?

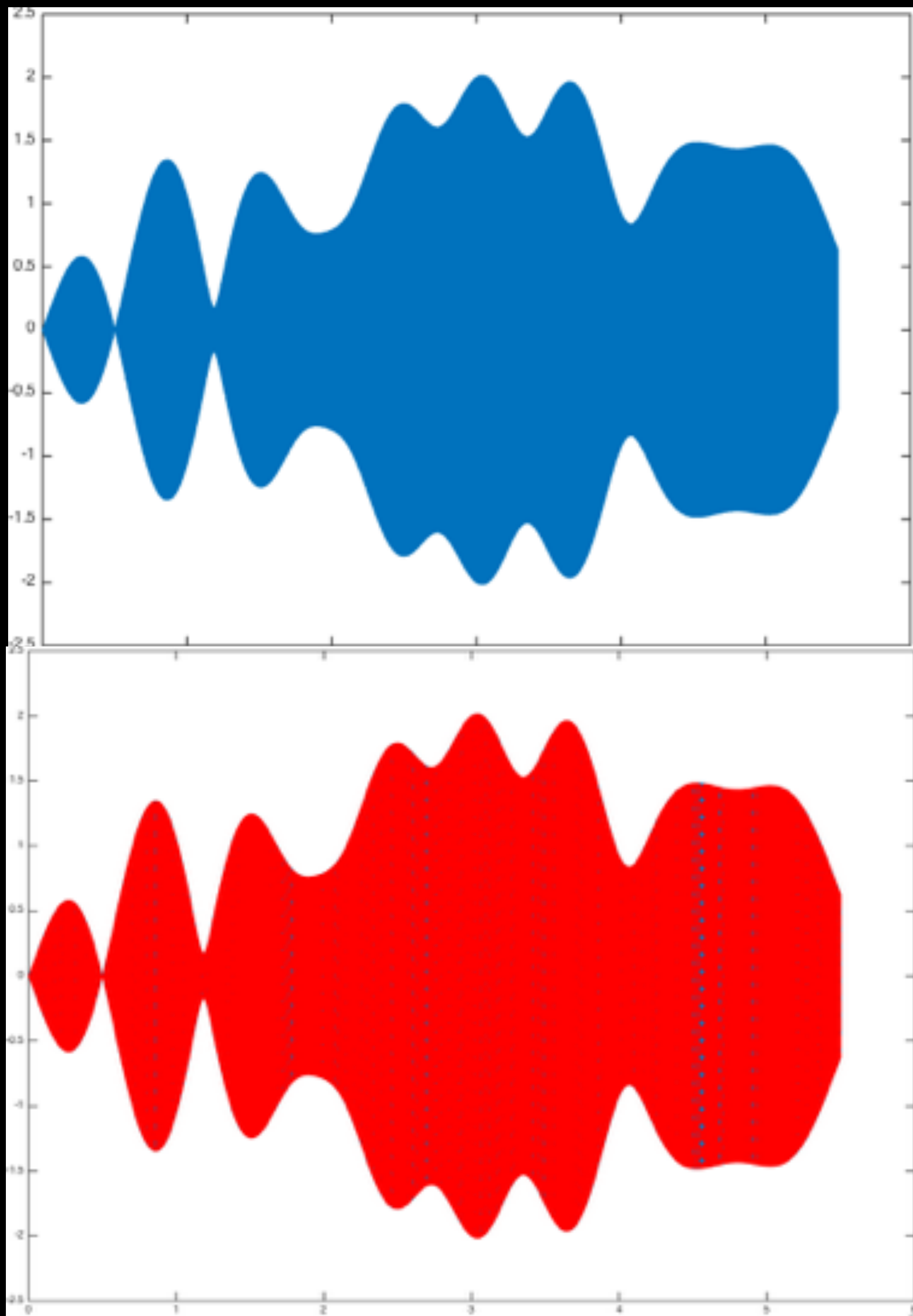



- On board paths
  - D = 5cm
  - T =160 ps

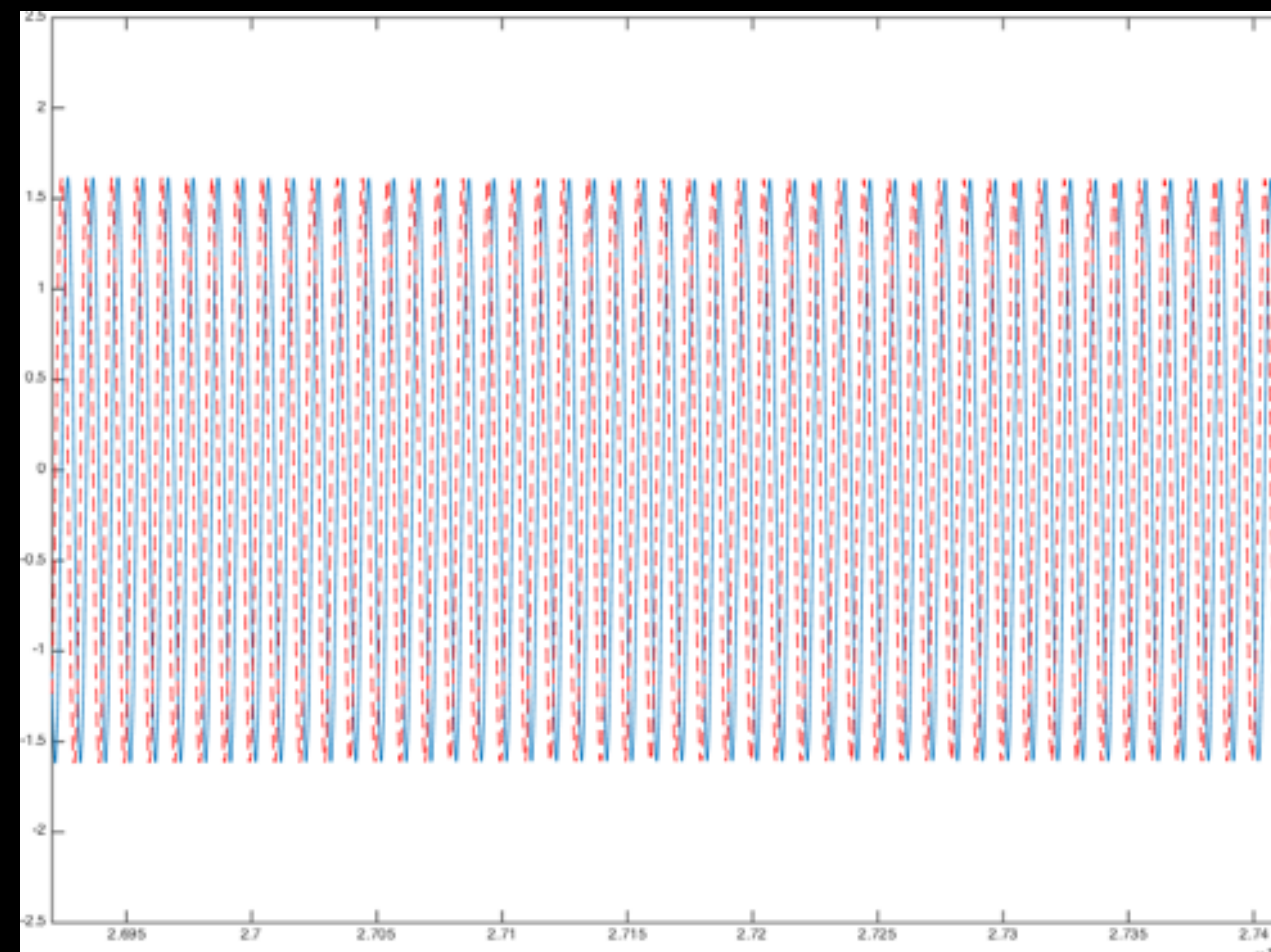
- 25 cm reflector
  - T =1600 ps
  - 40 dB

**Only few paths matter; delays in 100s of pico seconds**

# How close are x(t) and x(t-a)?



**x(t) and x(t-100ps)**



**Carrier changes at 400 ps**
**Signal changes at 1/W (50 ns)**

**Residual error is in the carrier**

# Part 2

**Goal: A full-duplex capable transceiver ASIC for cellular/wlan systems**

# Basic (only) idea

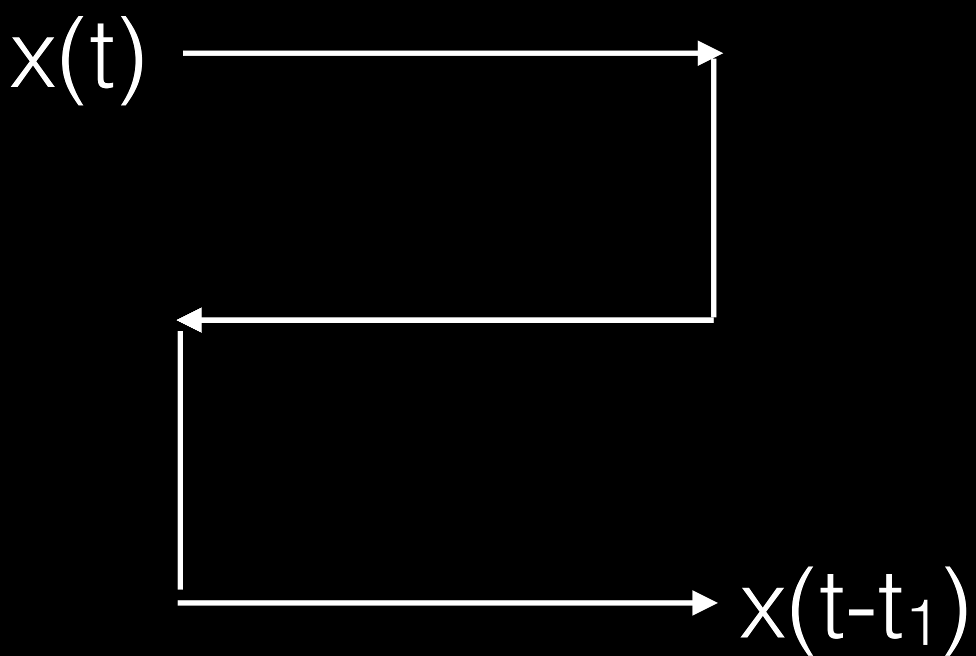
**Transmitted signal is know at the node**

- 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

# RF time (true/phase) delay

How to obtain 800 ps delay?

**True time delay**




**Phase delay**

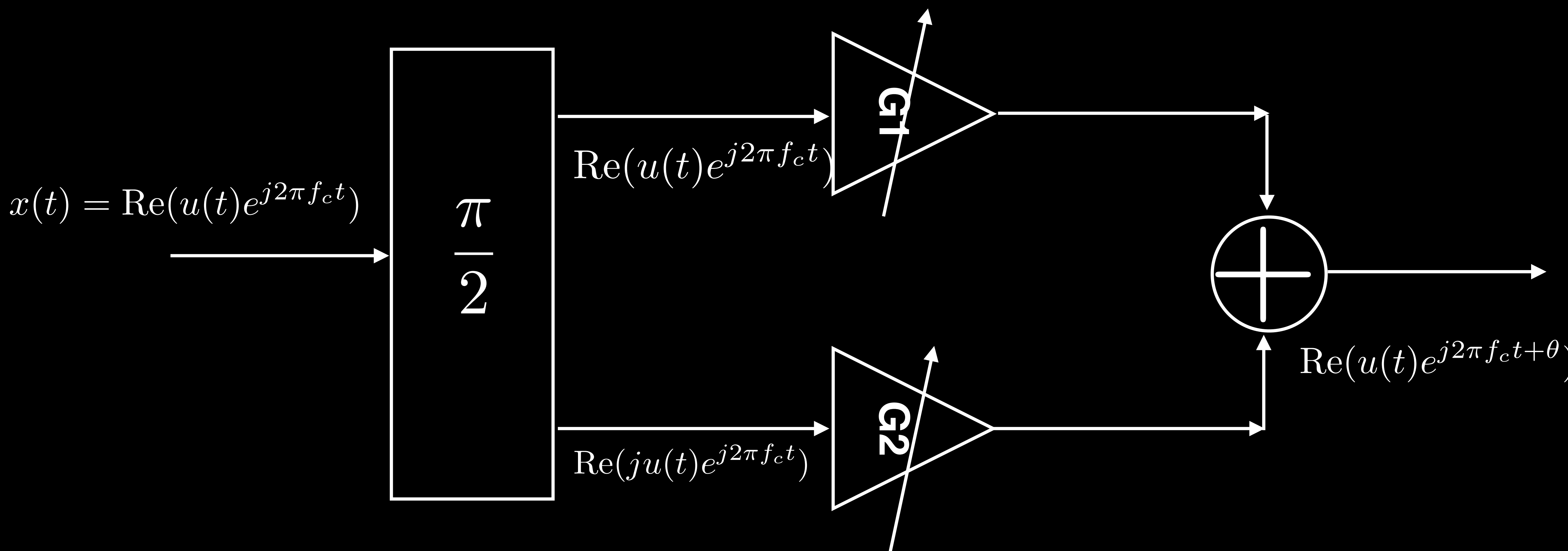
$$x(t - t_1) = \text{Re}\left(u(t - t_1)e^{j2\pi f_c(t - t_1)}\right)$$

$$\approx \text{Re}\left(u(t)e^{j2\pi f_c(t - t_1)}\right)$$

**Long transmission line (25cm)**

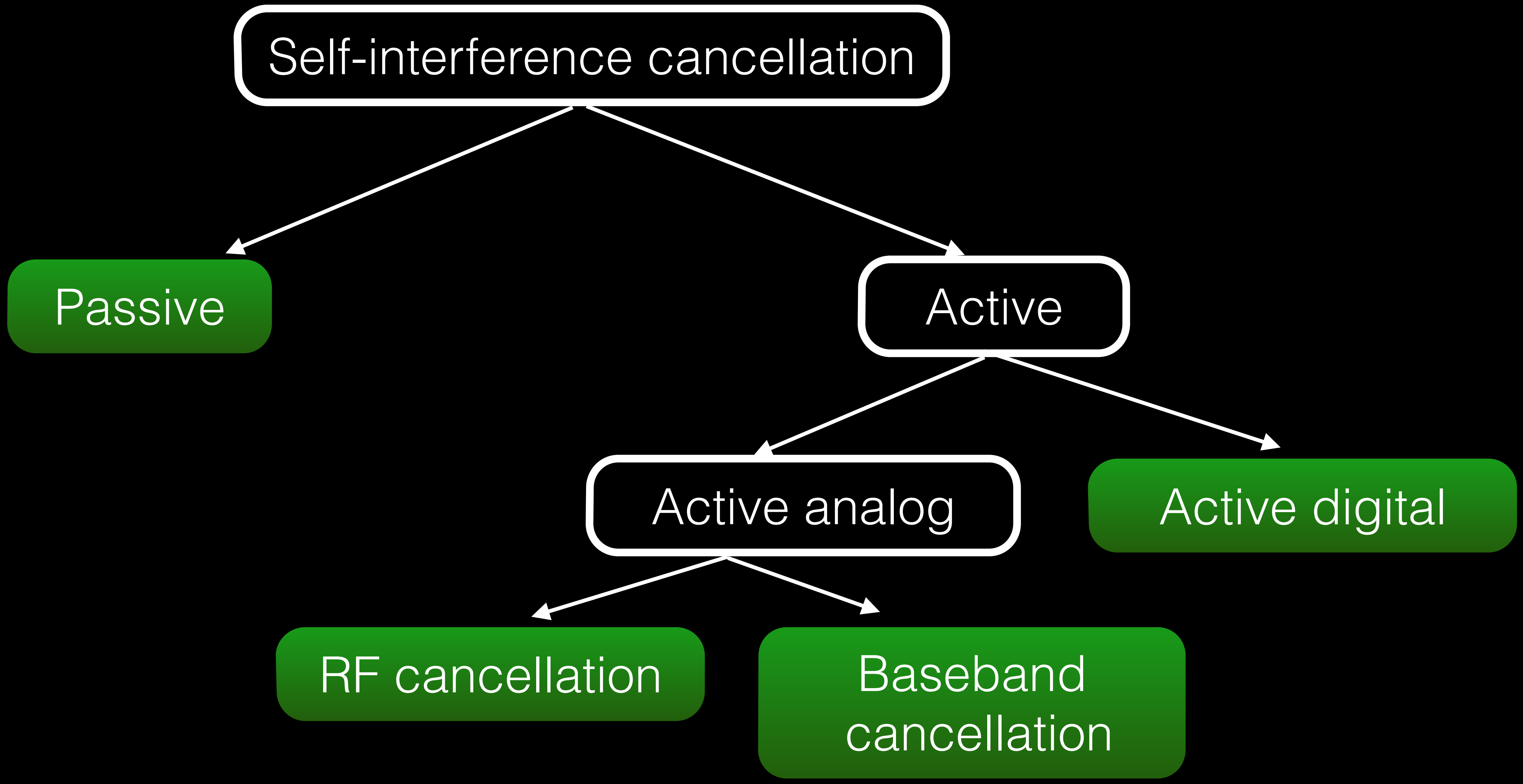
**Implemented using vector modulator**

# Vector modulator (RF phase shifter)

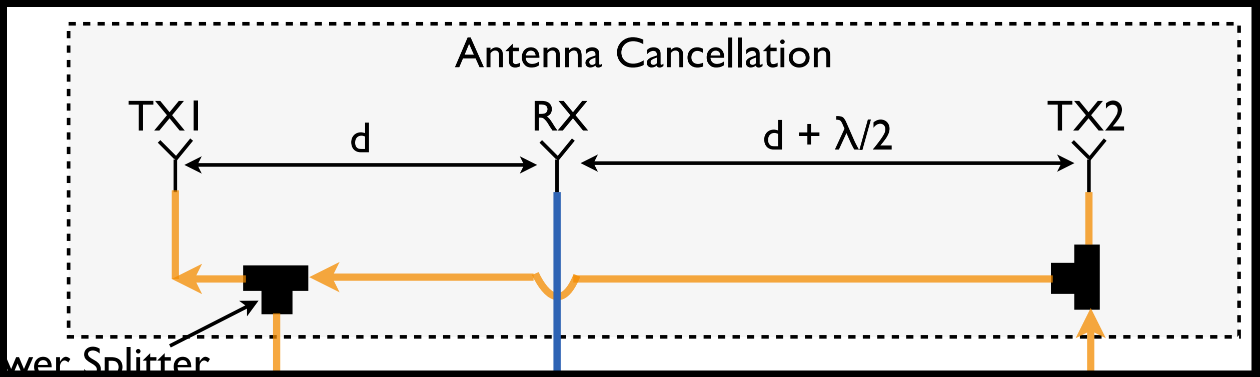



$$u(t - \lambda/4) \approx u(t)$$

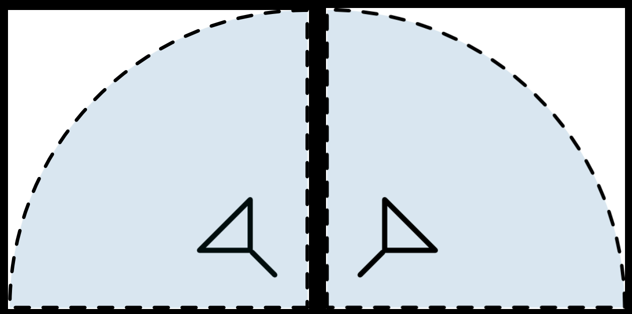
# Implementation



# Passive cancellation




Choi, Jung Il, et al. "Achieving single channel, full duplex wireless communication."



Everett, Evan, Achaleshwar Sahai, and Ashutosh Sabharwal. "Passive self-interference suppression for full-duplex infrastructure nodes."

- Antenna placement
- Separate antenna
- Polarization
- Transmit beamforming

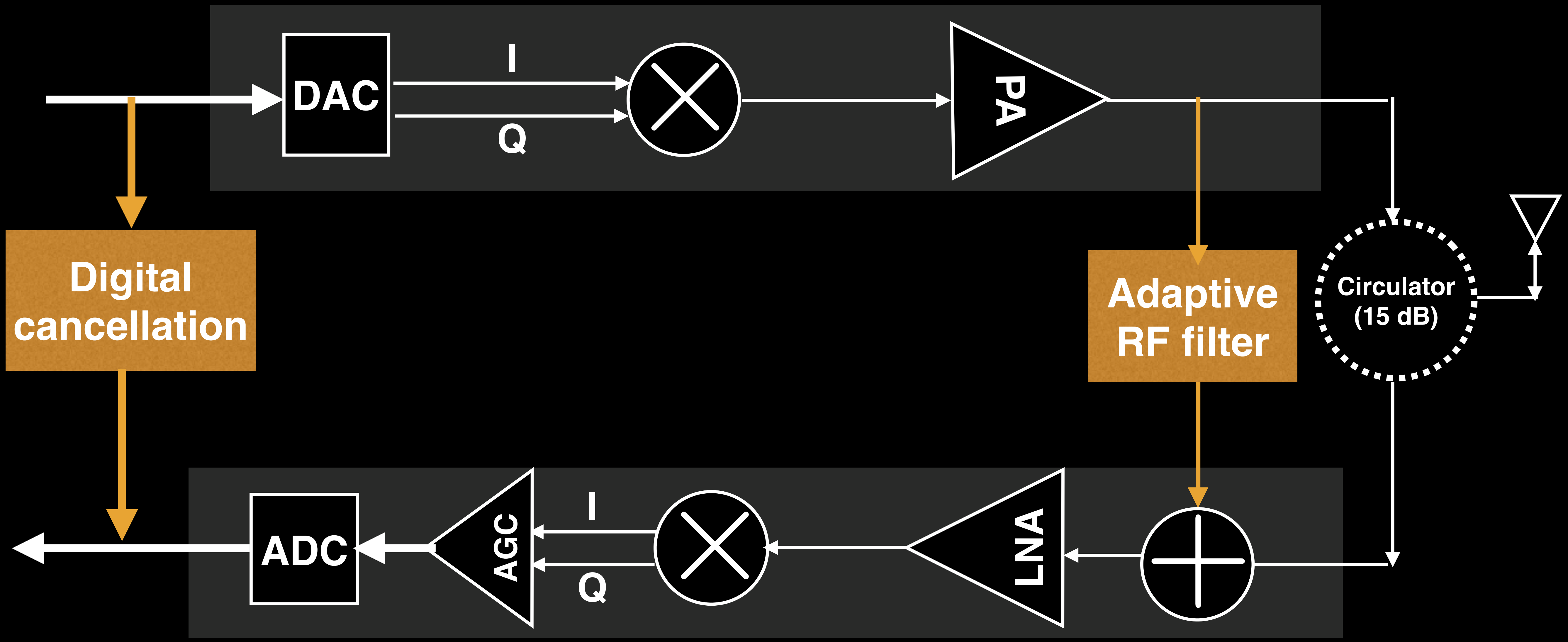
**Pros**

- Simple implementation

**Cons**

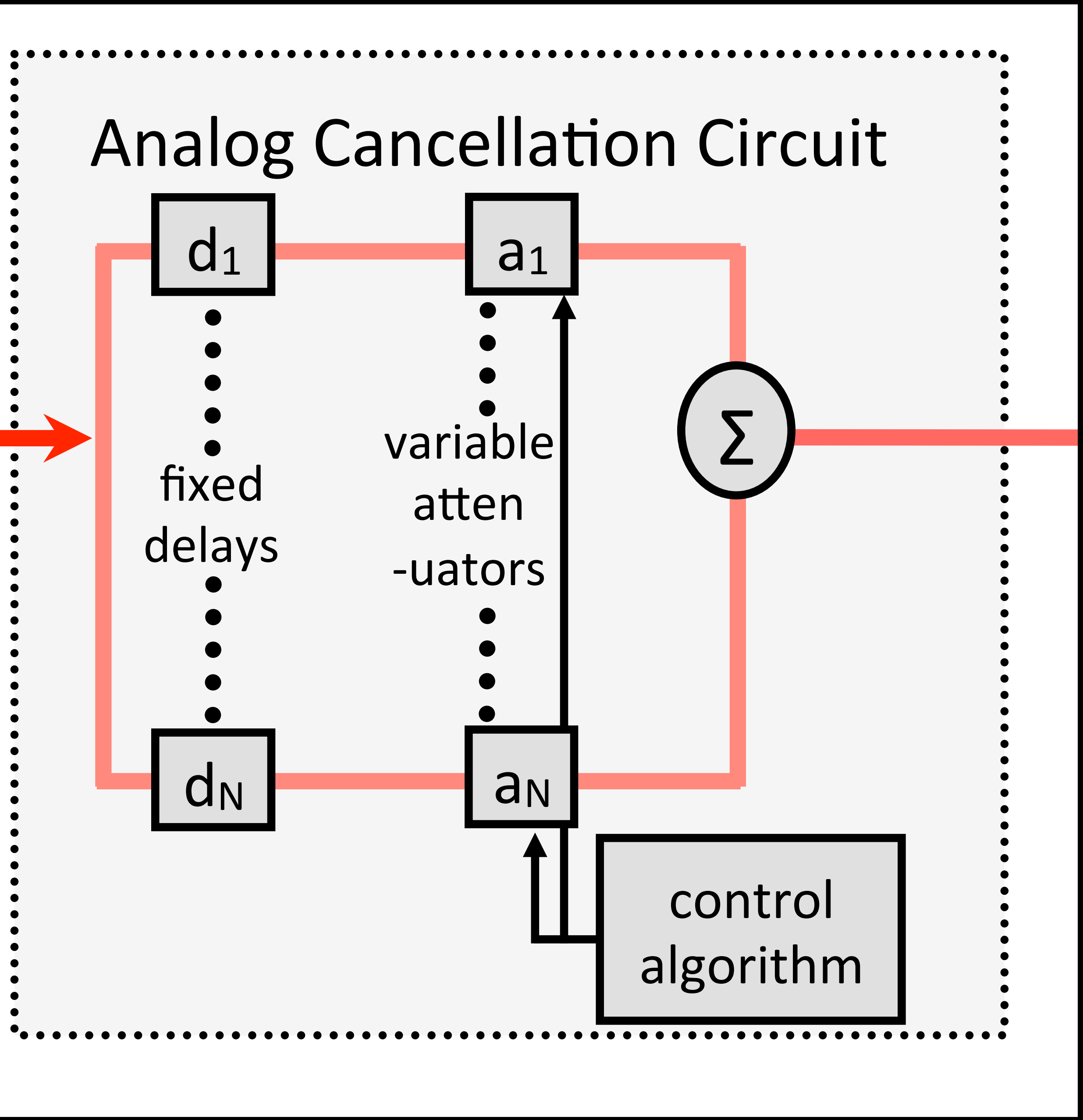
- Narrow band
- Cannot handle multipath

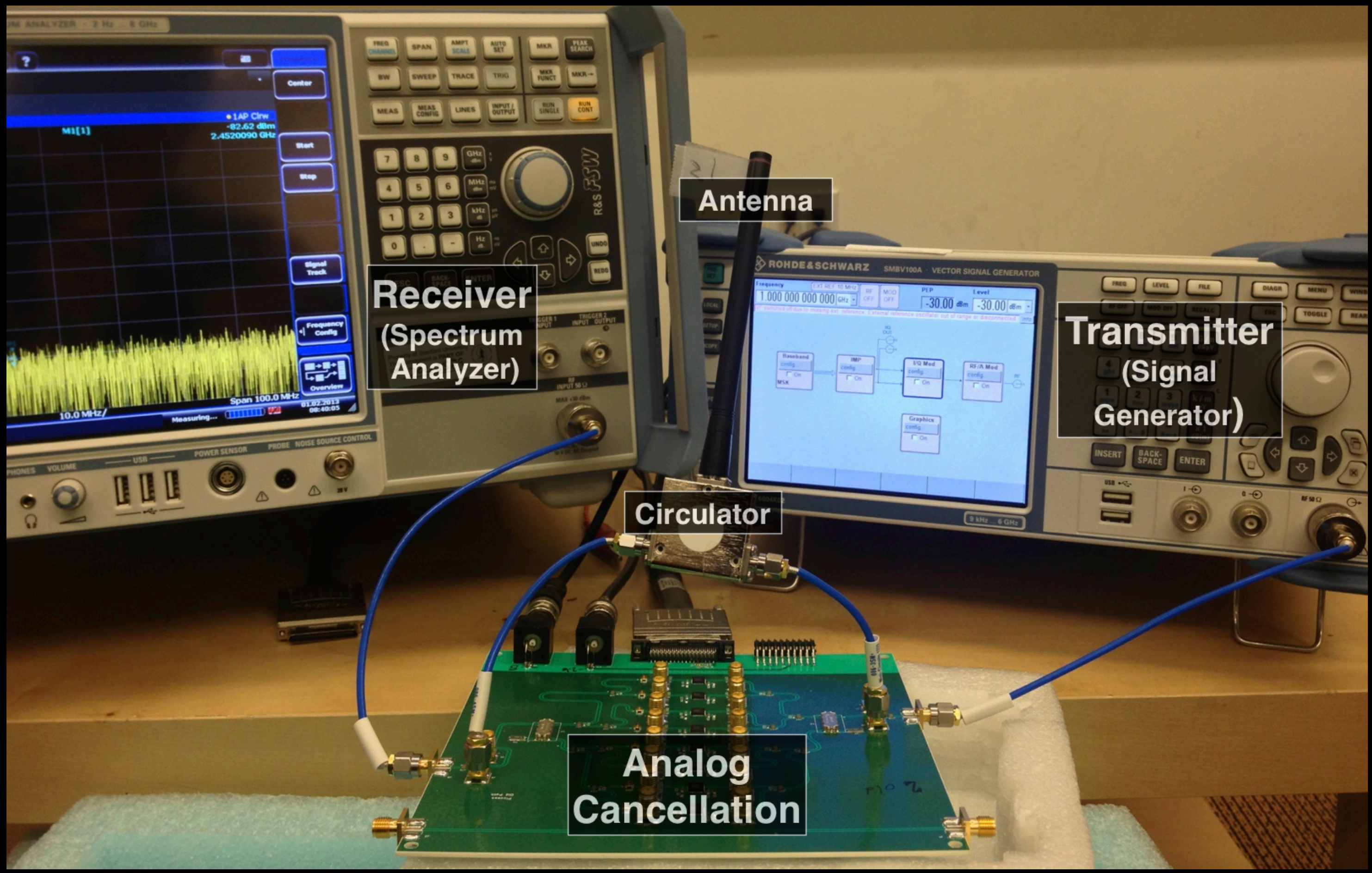
# Stanford design




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

# RF filter

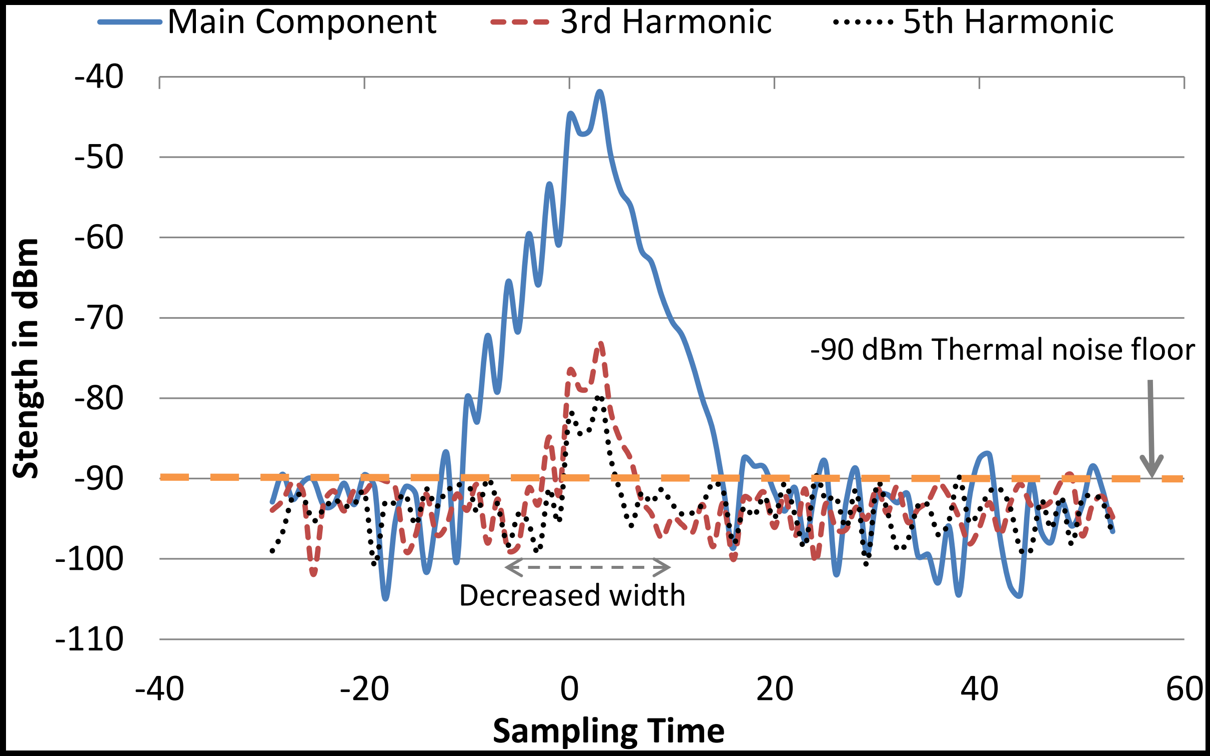


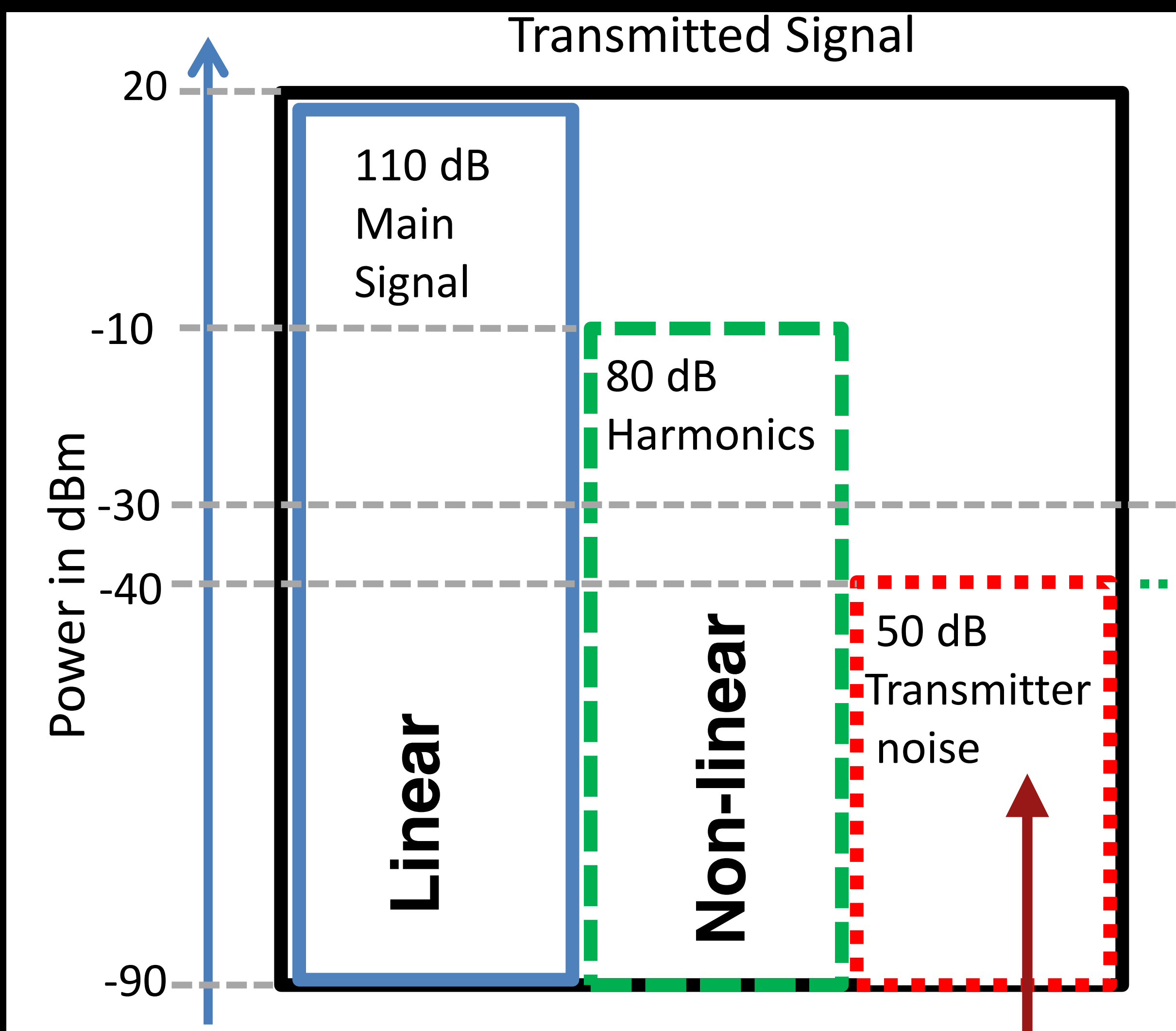

**Cancel a few dominant paths**

# Digital cancellation

- Linear component $$y[k] = \sum_{m=1}^{N} x[m-k]h[m]$$
    - Channel filter: Solve least squares
    - Use preamble or known pilots
- Non-linearities
    - Odd harmonics
        - 3 and 5th harmonics
    - Least squares



# Components to cancel

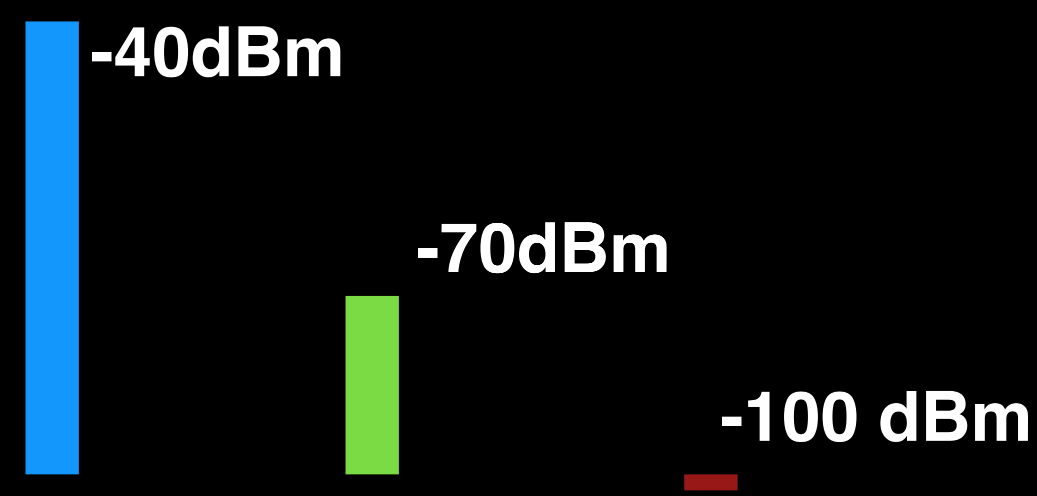



**80 MHz signal**
**12 bit ADC**

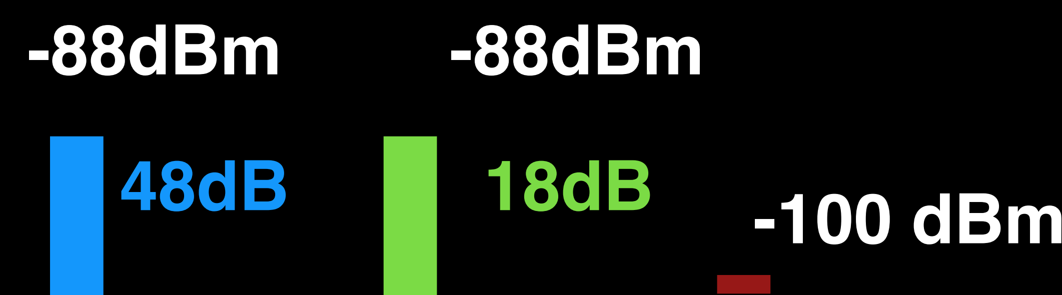
**Non-linear**
**+**
**Random**

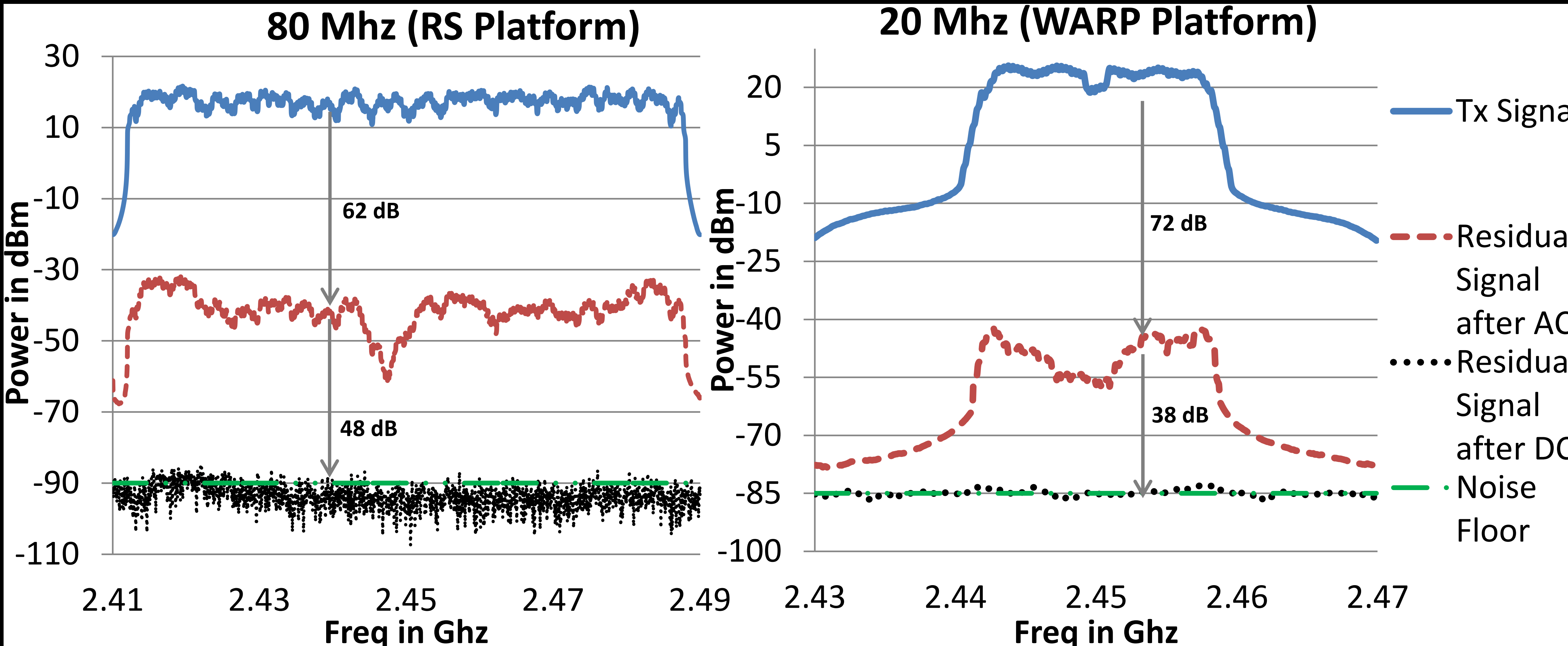
## Analog cancellation: 60 dB

(circulator 15dB)



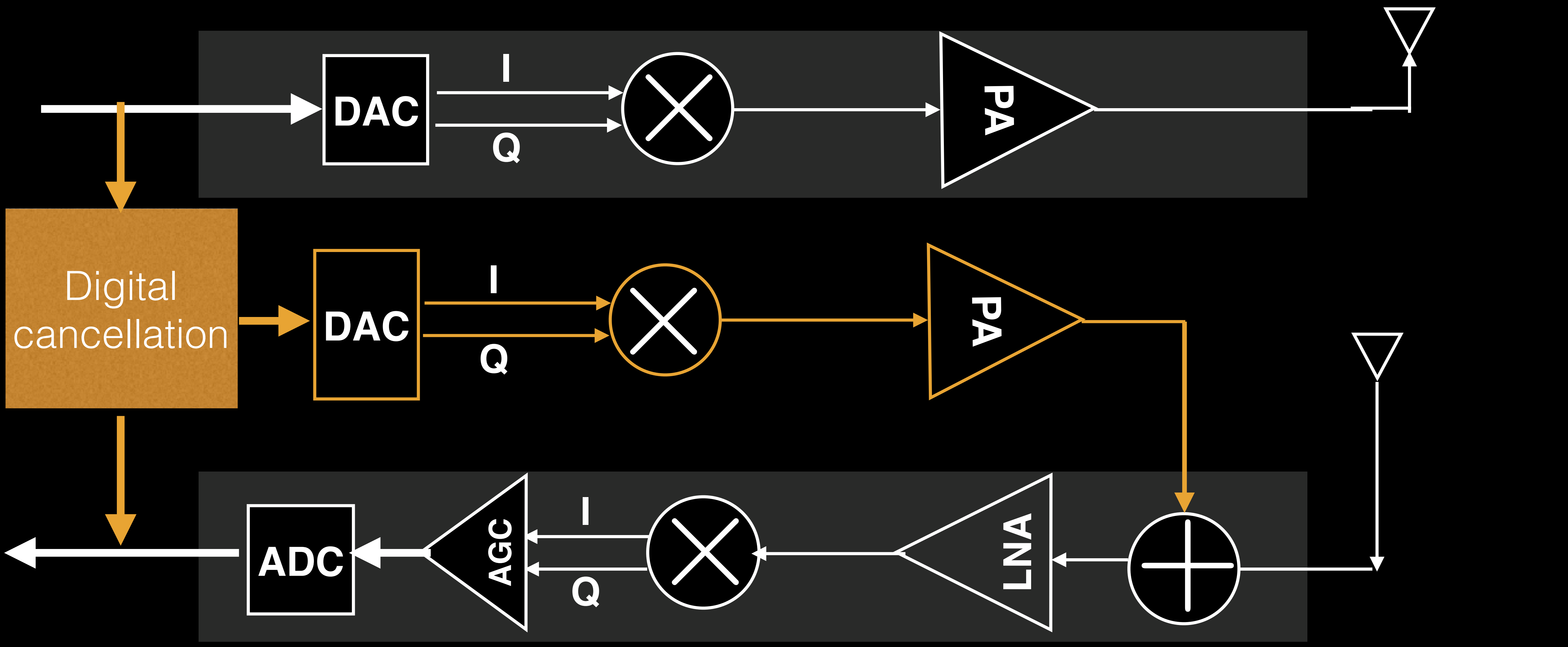

## Digital cancellation





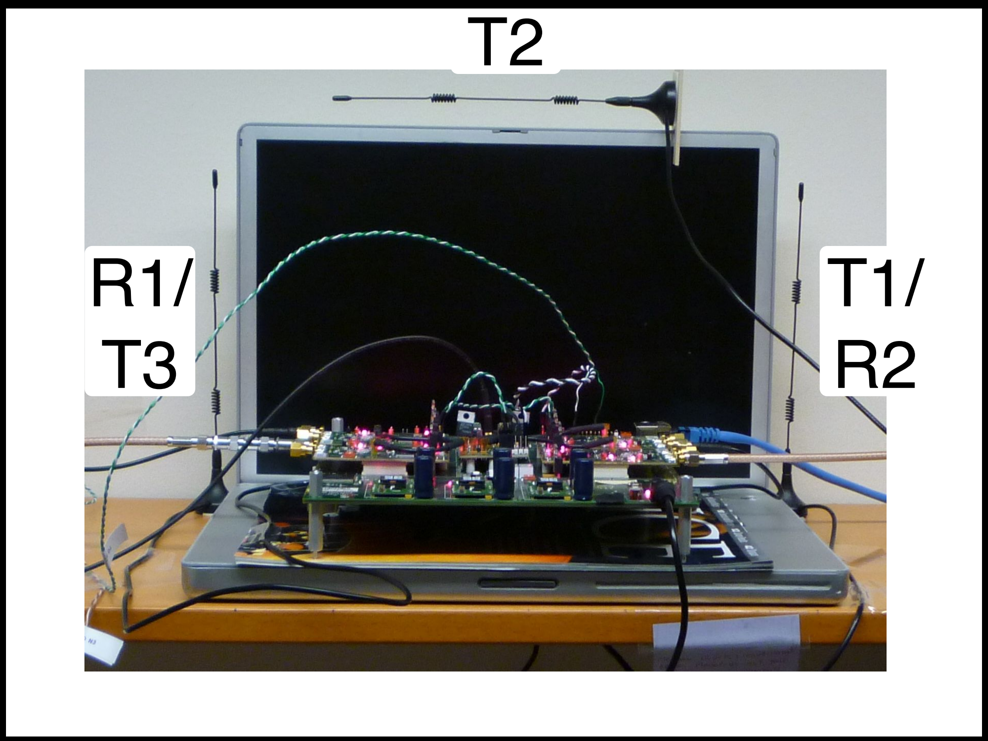

| Pros | Cons |
| --- | --- |
| • Wide band cancellation<br>• Scales with input power<br>• Best cancellation till date | • Bulky board<br>• Analog cancellation tuned to few paths |

# Rice design



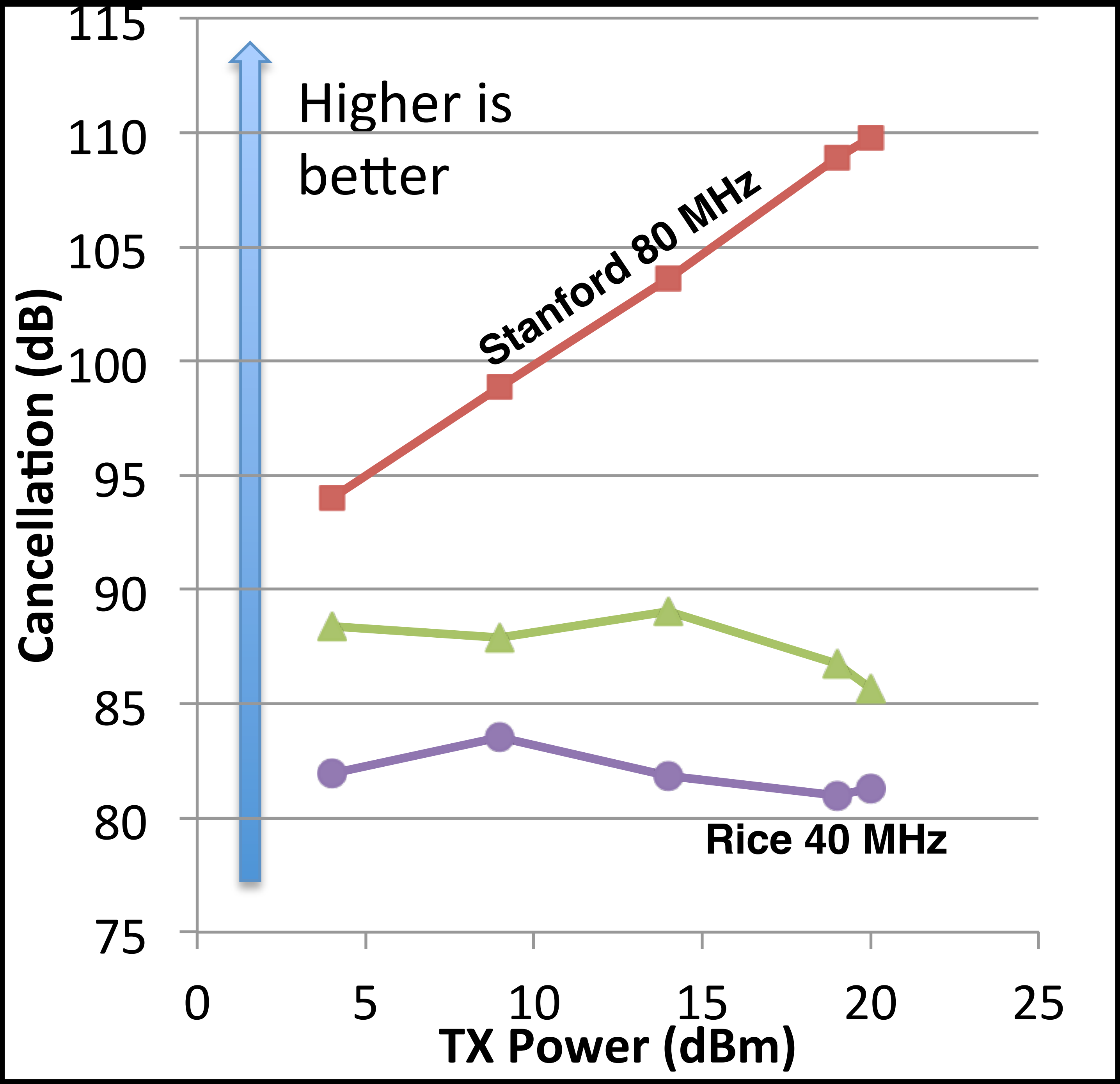

Duarte, Melissa, Chris Dick, and Ashutosh Sabharwal. "Experiment-driven characterization of full-duplex wireless systems."

# Performance




**625 KHz**

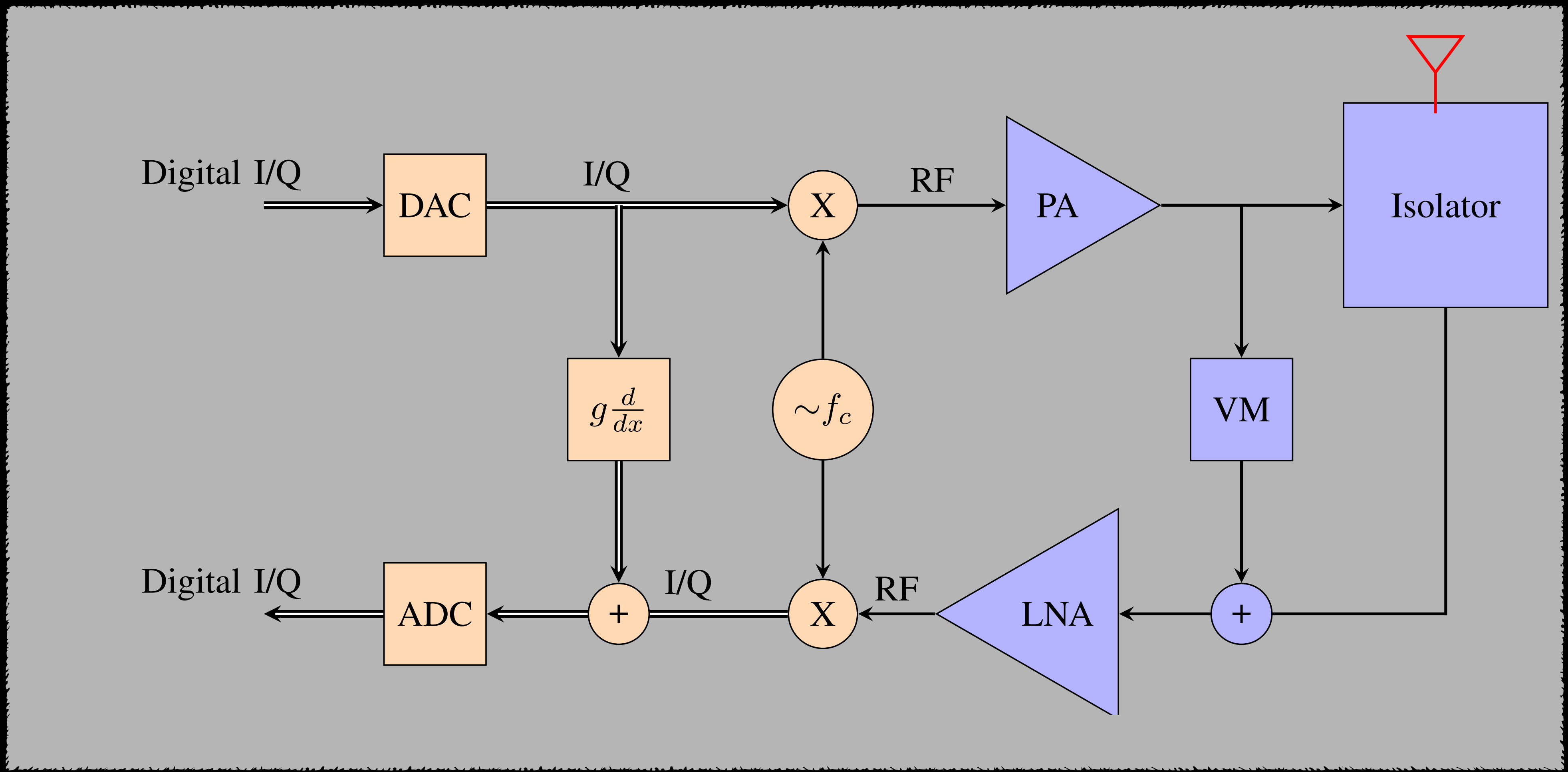
| | AS | ASDC | ASAC | ASAD |
|---|---|---|---|---|
| 20cm | 39 dB | 70 dB | 72 dB | 78 dB |
| 40cm | 45 dB | 76 dB | 76 dB | 80 dB |




**Non-linear components not removed**

| Pros | Cons |
| --- | --- |
| • Simple implementation<br>  • Base band processing | • Narrow band<br>• Low cancellation<br>• Three RF chains<br>• Does not scale with TX power<br>• Phase noise limited |

# IIT Madras




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

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

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

# Cancellation

| Pros | Cons |
| --- | --- |
| • Robust to multipath<br>• Small form factor | • Additional analog circuits |

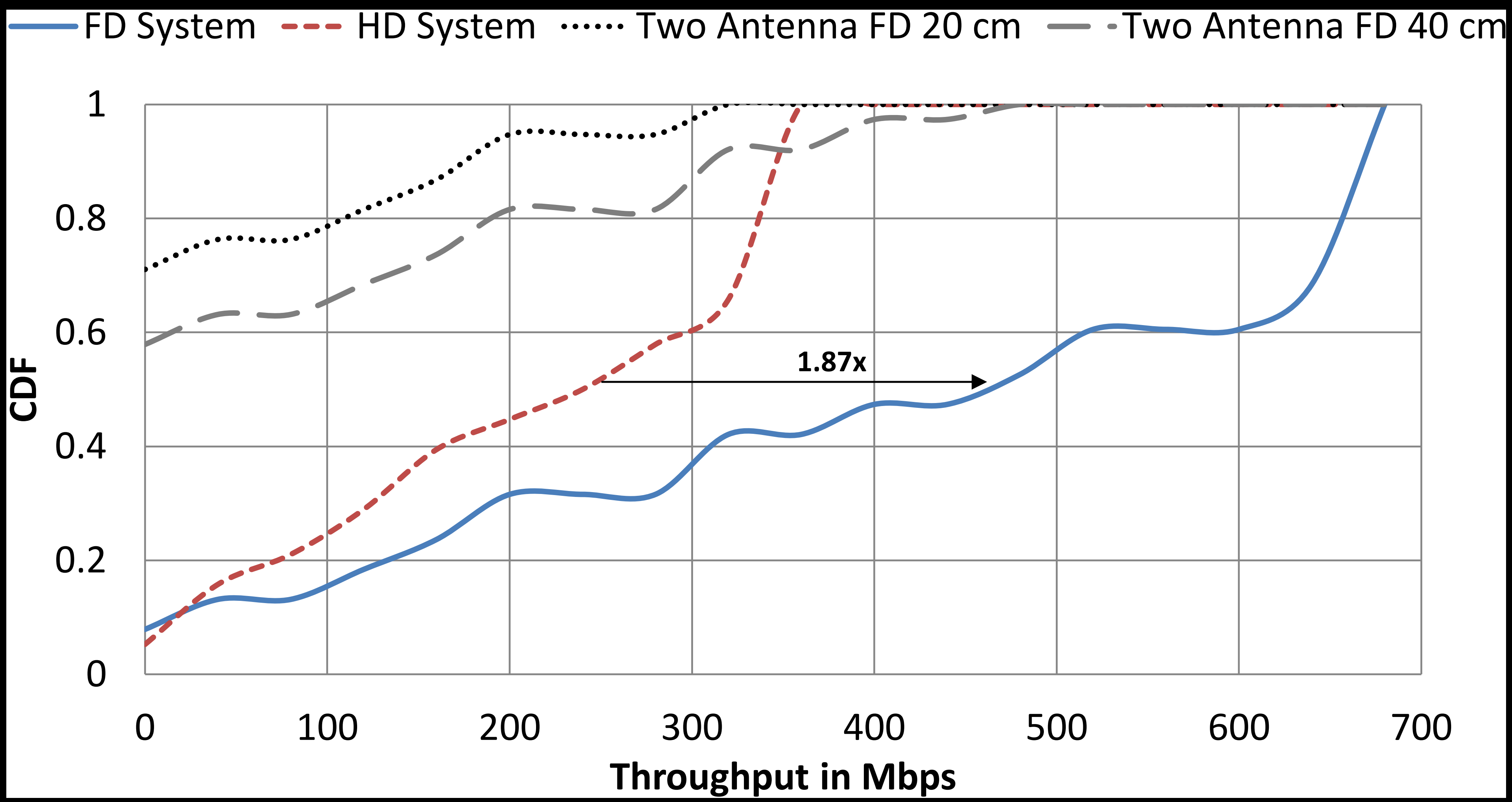
> 60 dB analog cancellation (simulation and preliminary experiments)

More details: Talk at NCC on Sunday

# Challenges

- High power in the RX chain
  - Non-linearities
- Phase-noise
- Transmitter noise
- Multi-path
- Finite quantization

# Throughput




**WiFi physical layer**

**Full-duplex communication is possible!**