

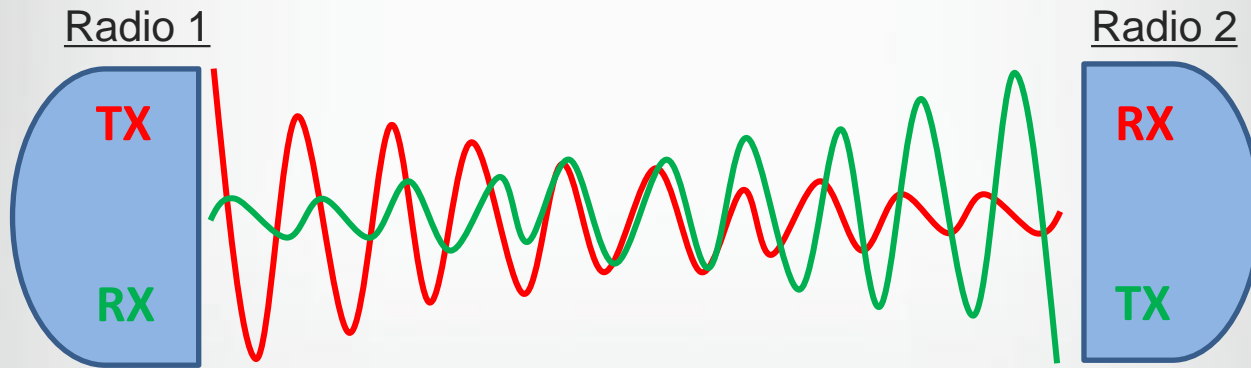
# Full Duplex Radios

Sachin Katti  
Kumu Networks & Stanford University

“It is generally not possible for radios to receive and transmit on the same frequency band because of the interference that results.”

- Andrea Goldsmith, “Wireless Communications,” Cambridge Press, 2005.

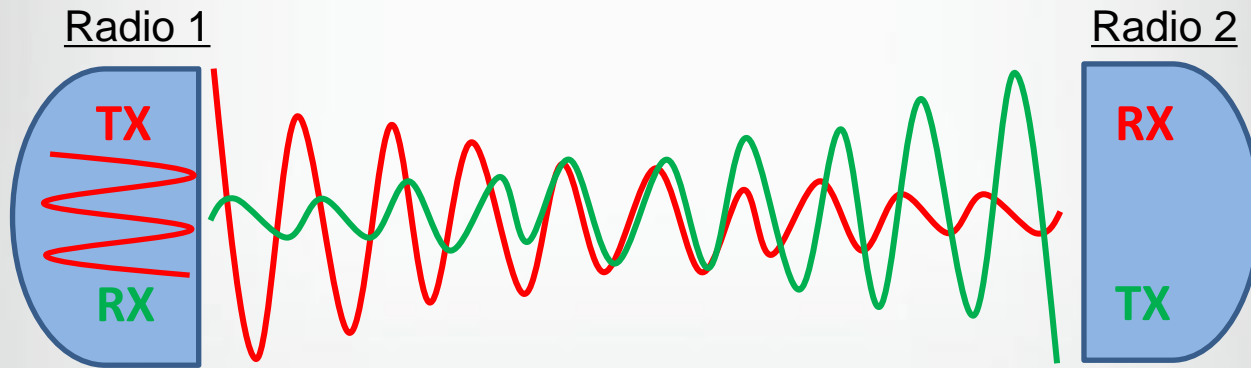
Why are radios half duplex?



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Why are radios half duplex?

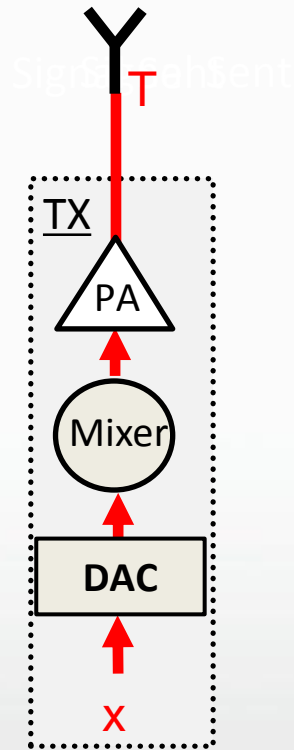


Self-Interference is a hundred billion times (110dB+) stronger than the received signal

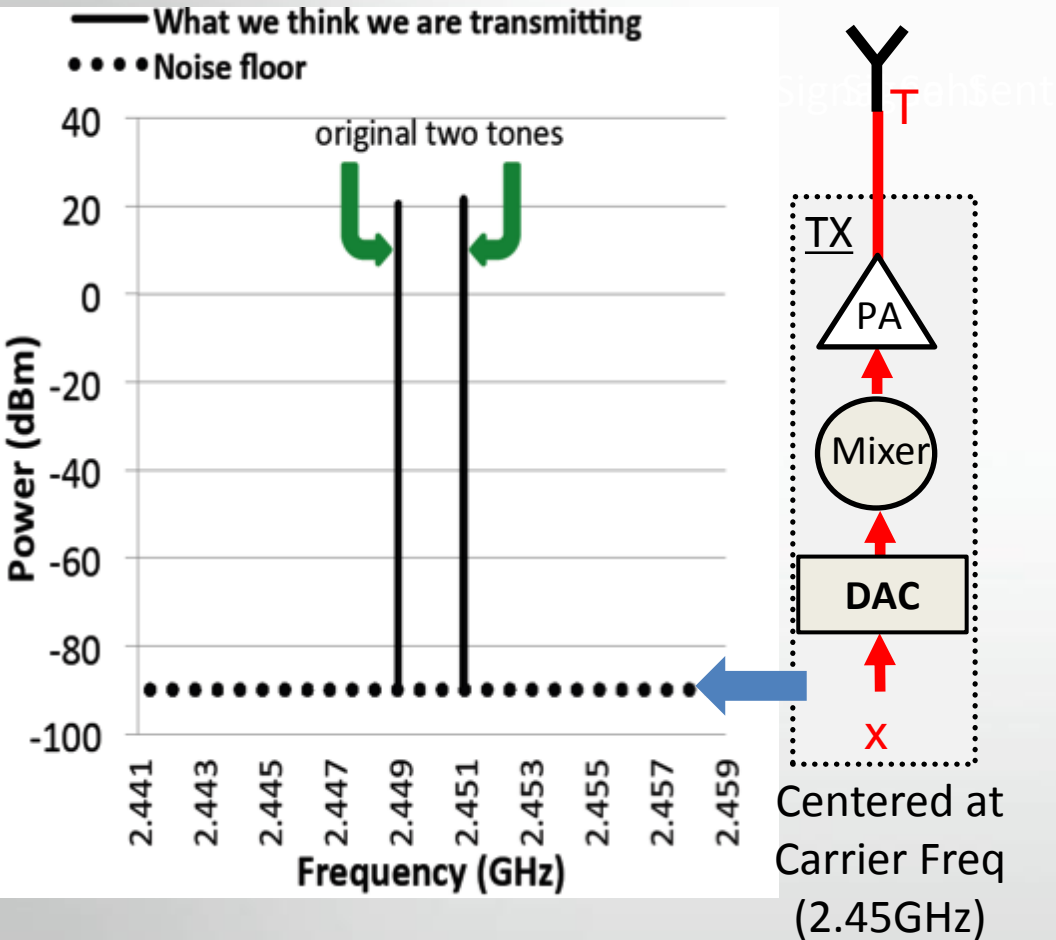
Isn't this easy to solve?

*After all we know the interfering signal, why can't we just "subtract" it?*

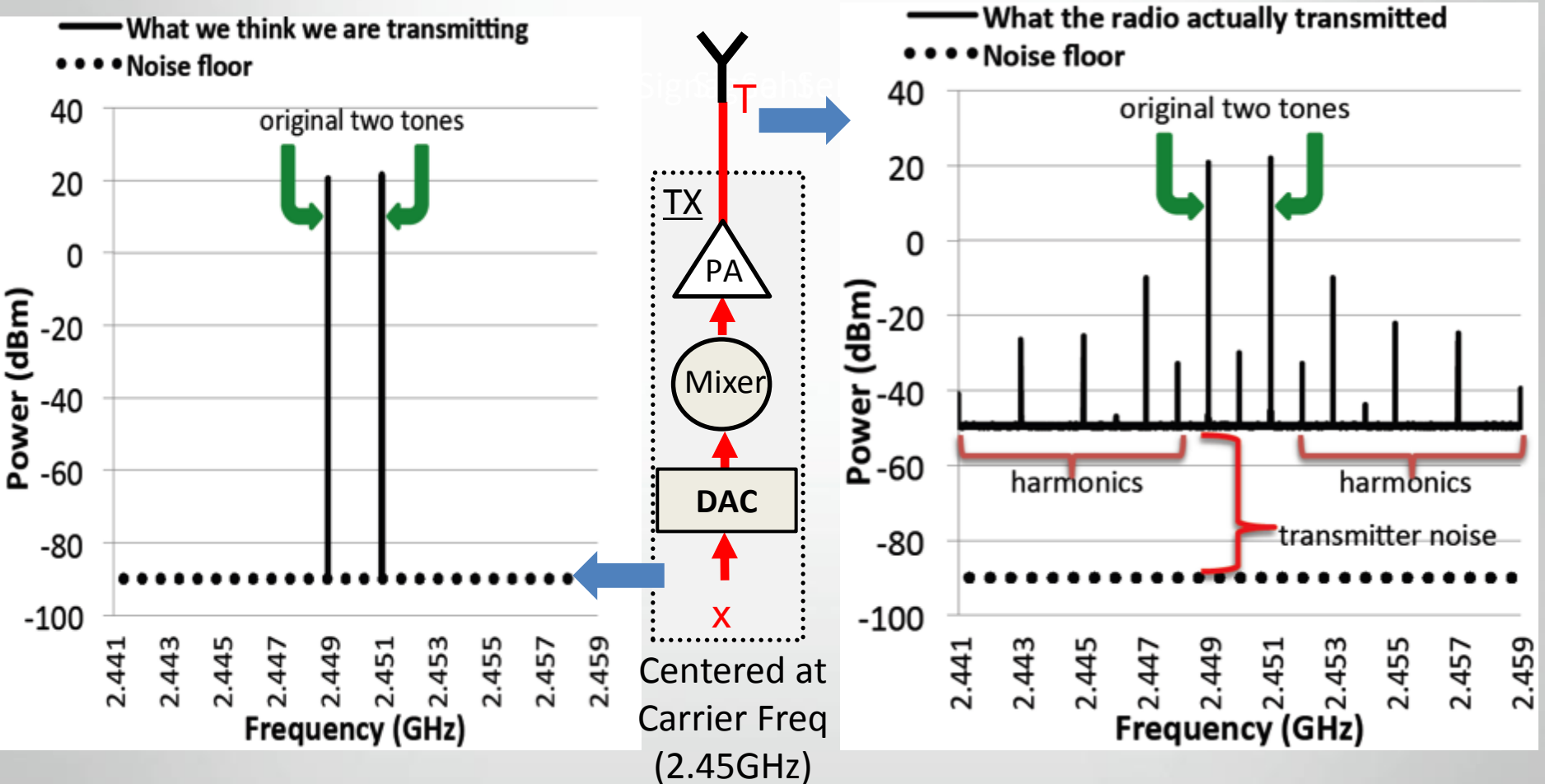
# Do we know what we are transmitting?



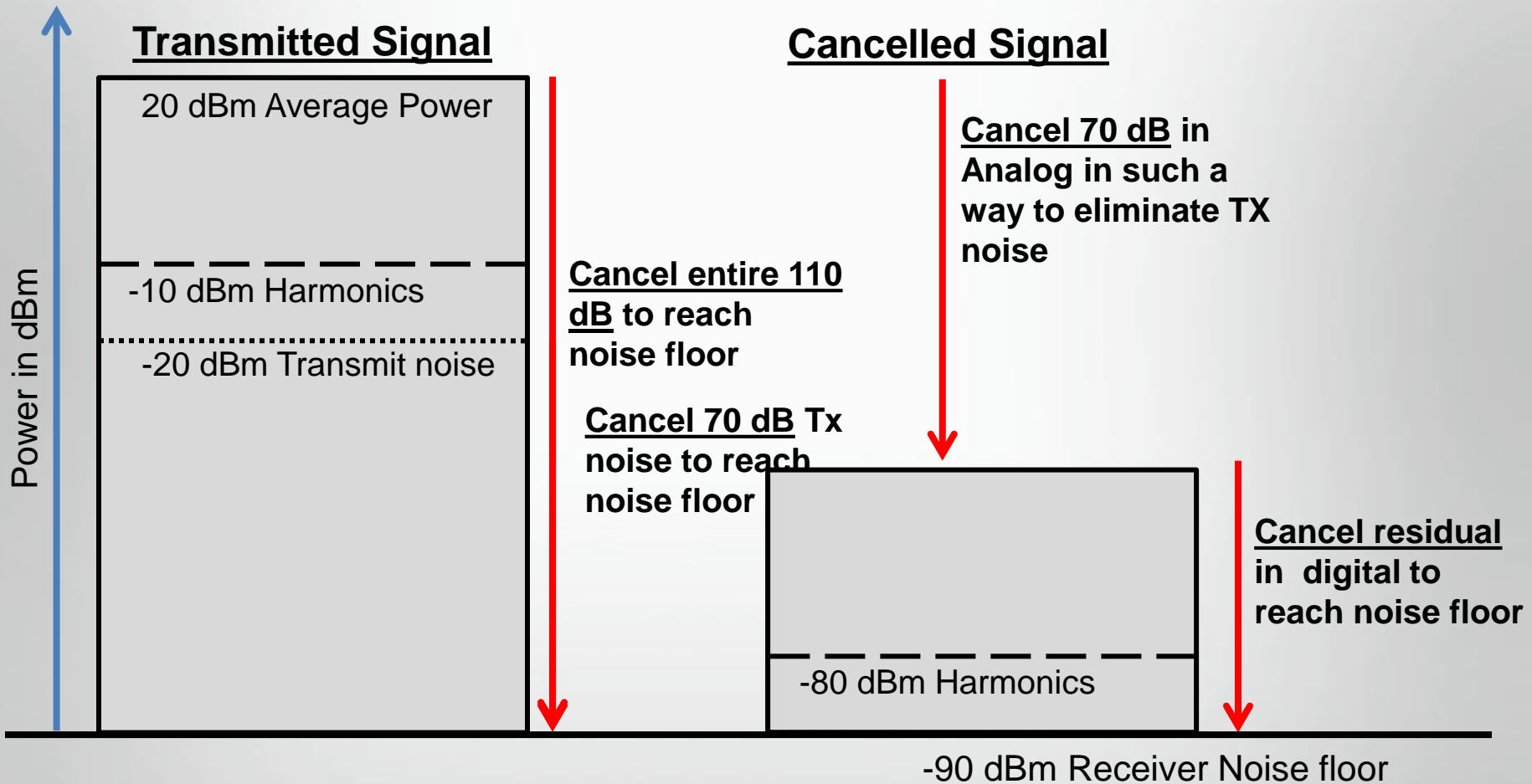
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# If you were to cancel, how much do we need?



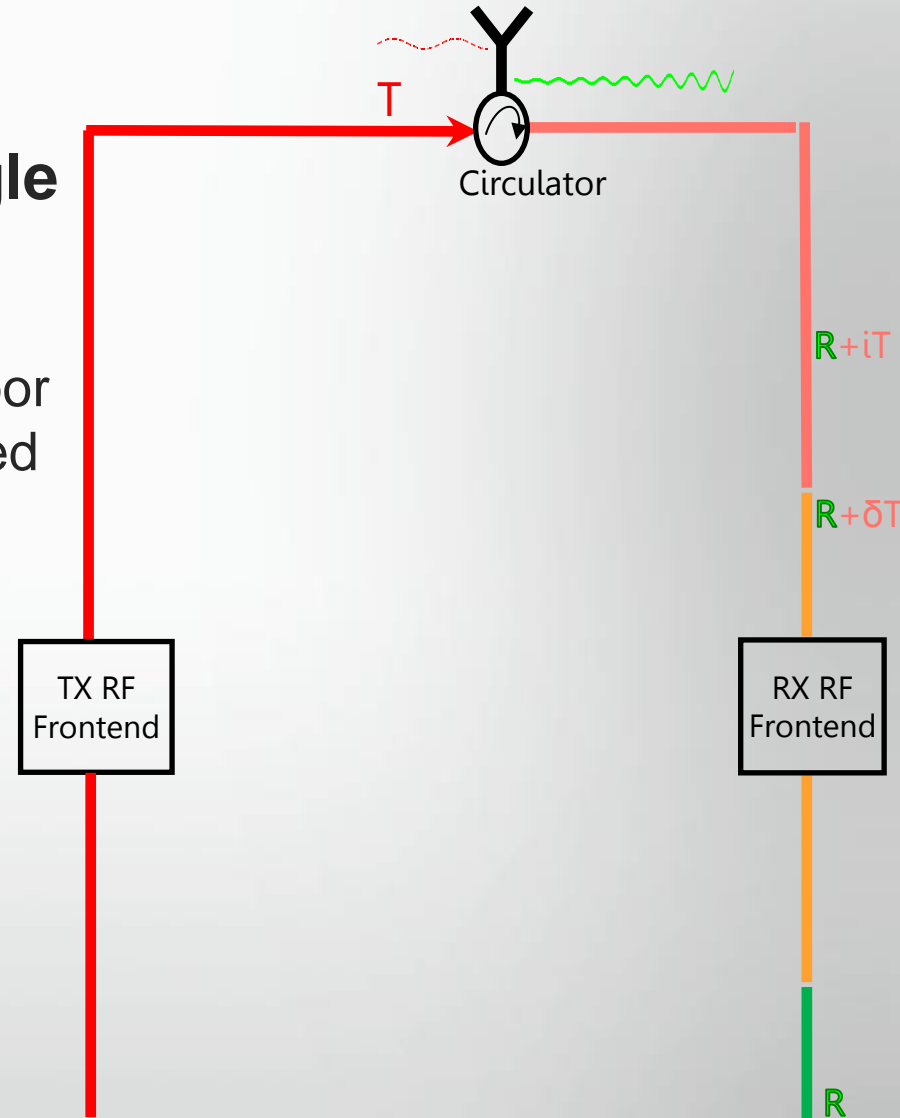
**Takeaways: Require 110dB of total cancellation, of which at least 70dB has to eliminate transmitter noise in analog.**



# Contributions

## We have invented in-band single antenna full duplex radios

- Self-Interference cancellation that eliminates everything to the noise floor
- Practically achieves close to expected theoretical 2x throughput increase



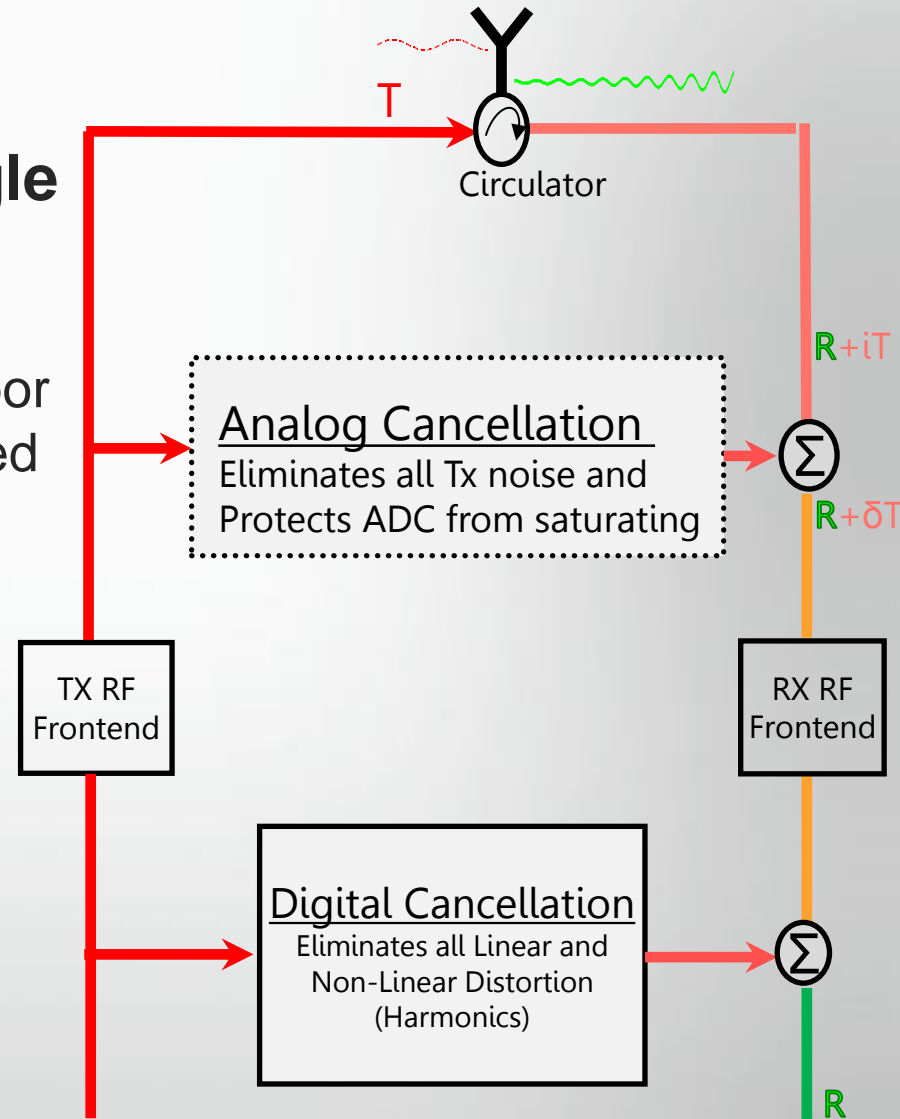
# Contributions

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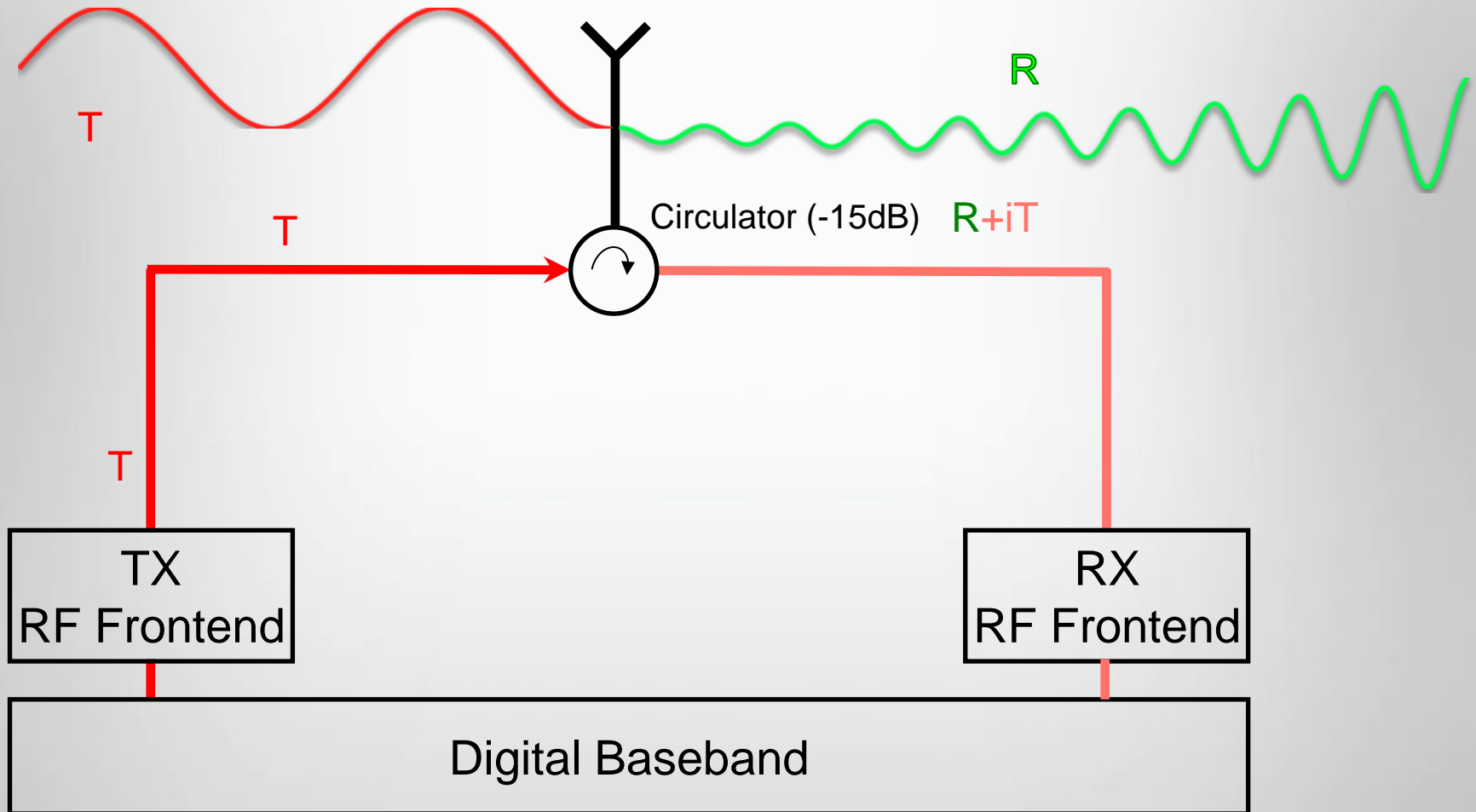
- Self-Interference cancellation that eliminates everything to the noise floor
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## Algorithms & circuits to estimate transceiver distortion and cancel self interference

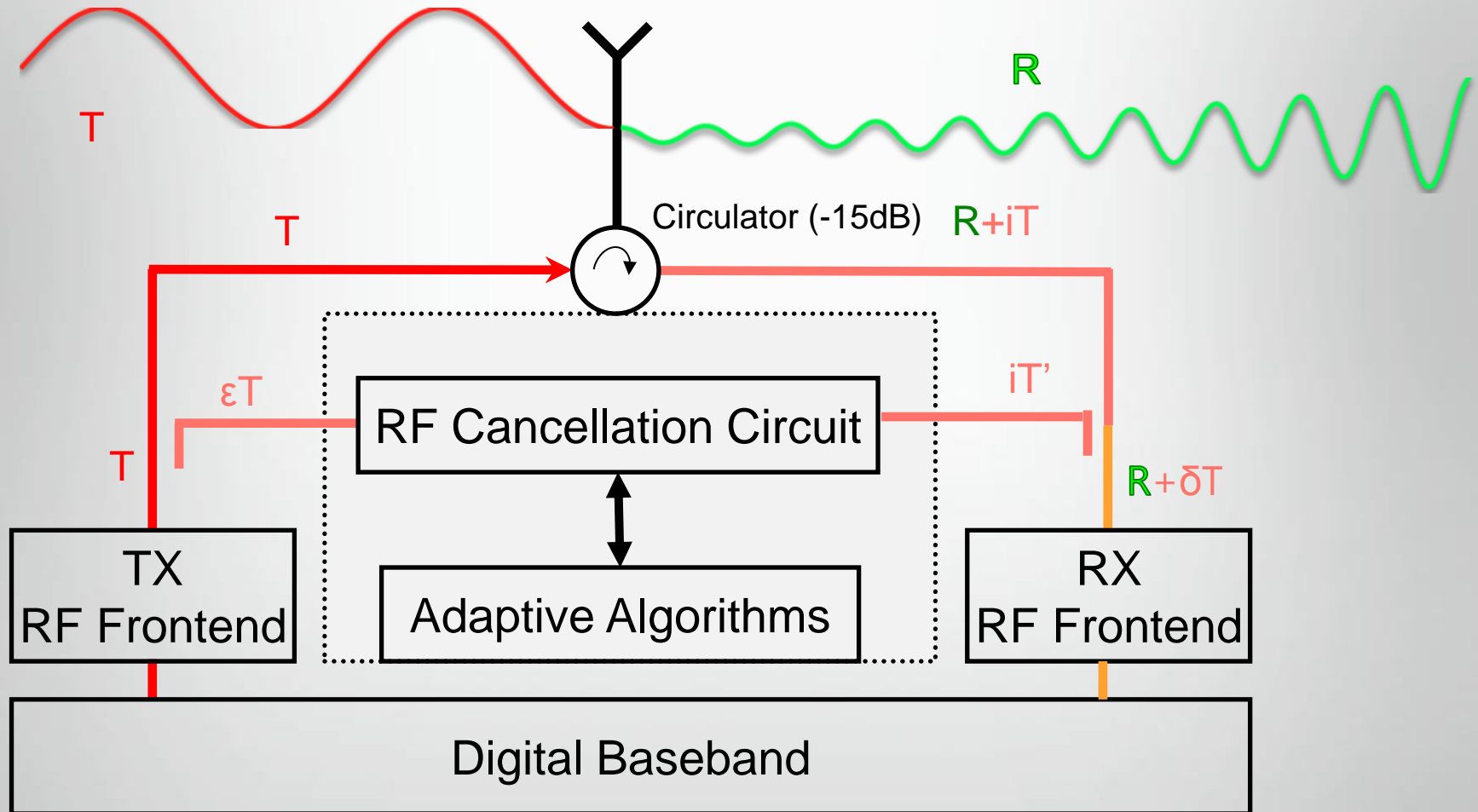
- Hybrid (analog & digital) design with RF cancellation circuit and DSP algorithms



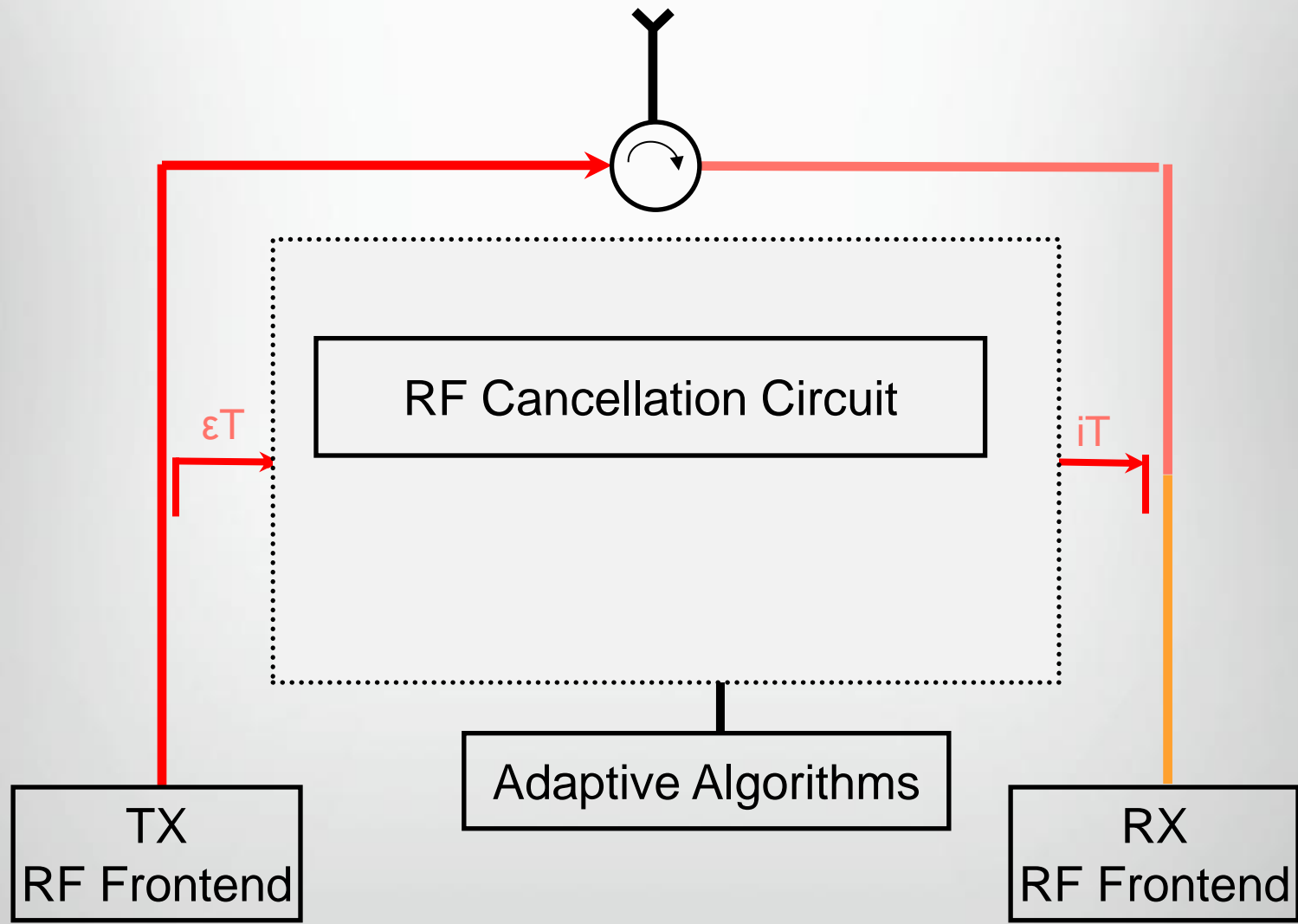
# Mixed RF/Digital Design: Analog + Digital Cancellation



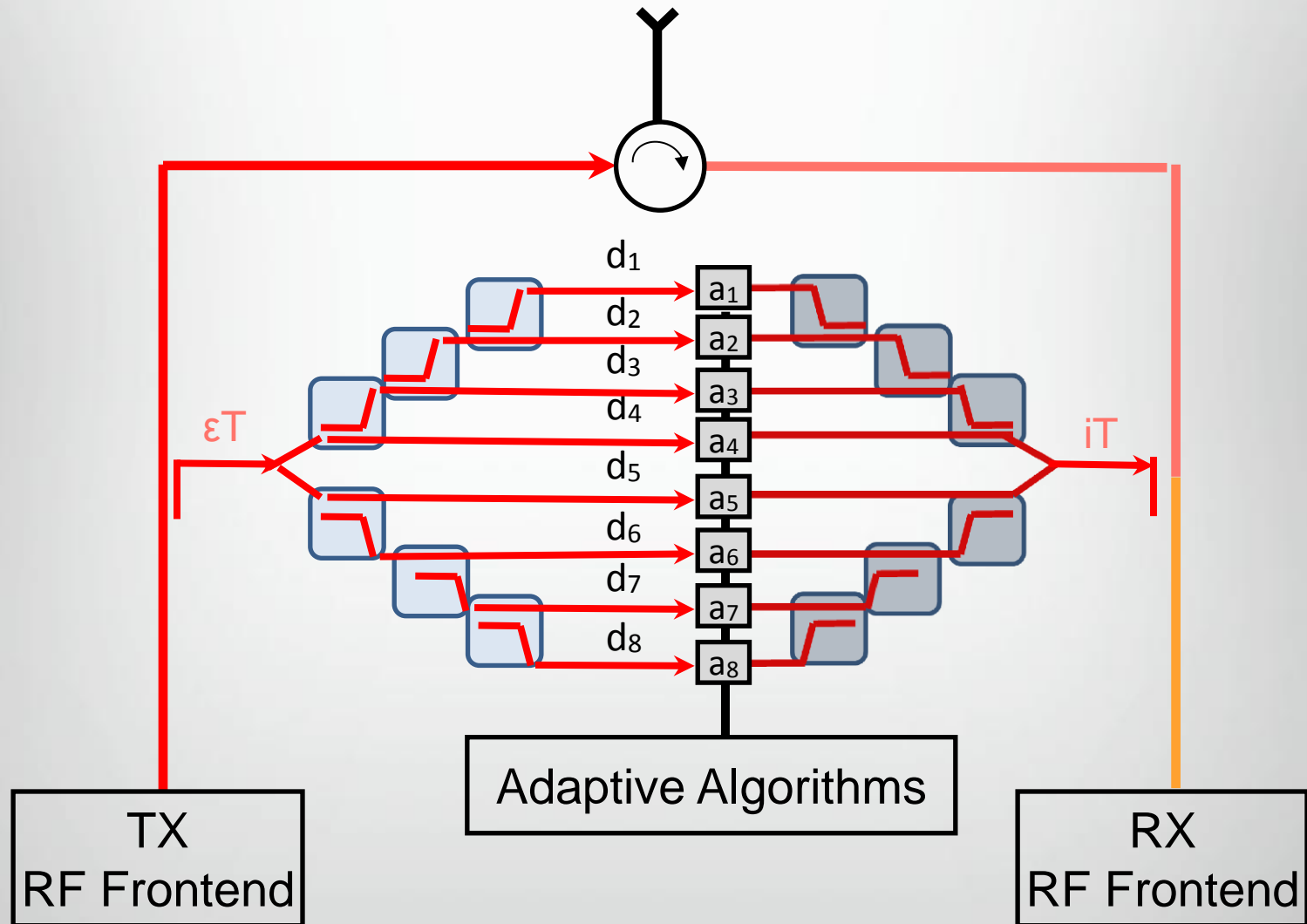
# Analog RF Cancellation



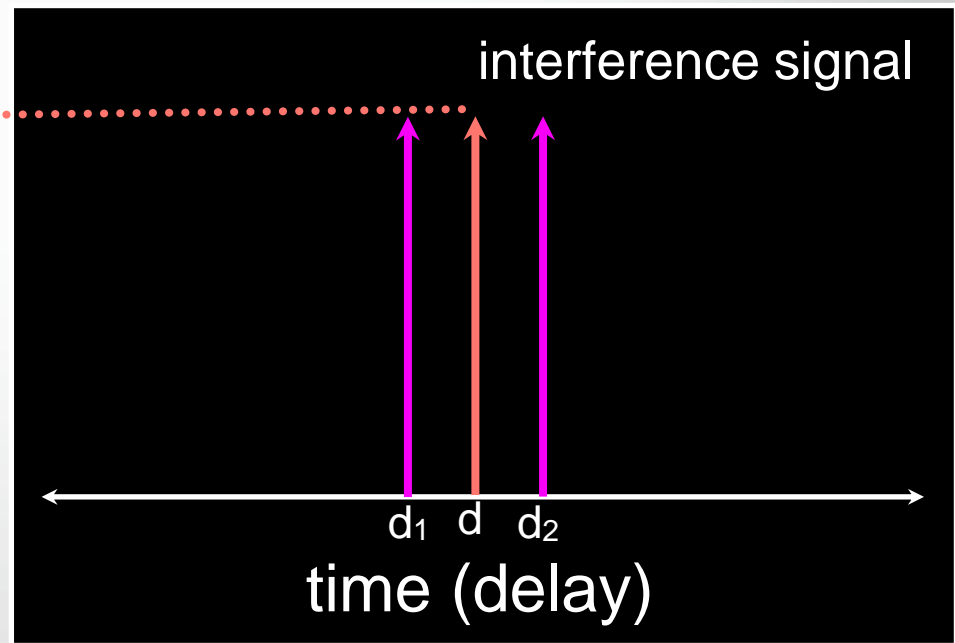
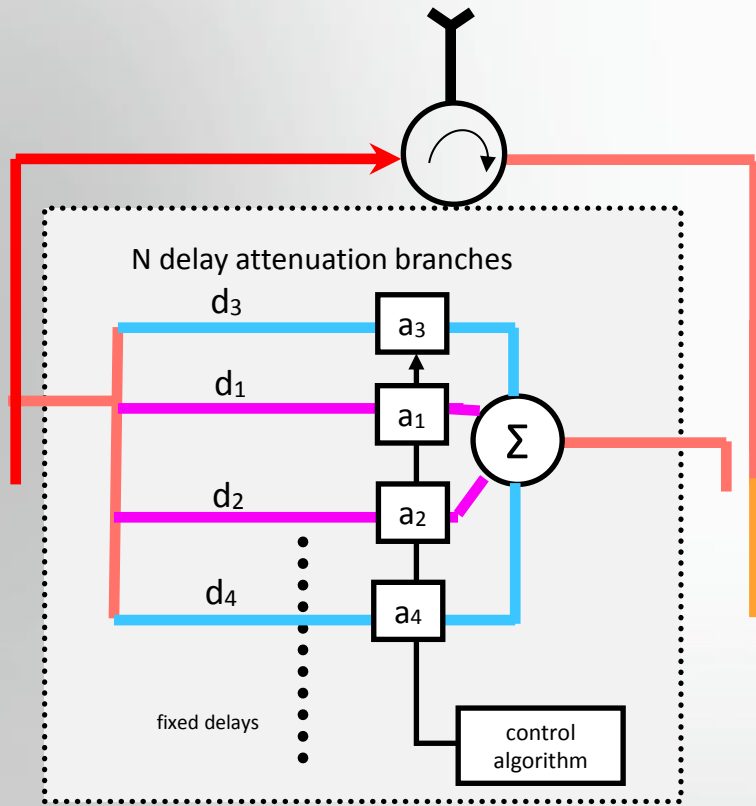
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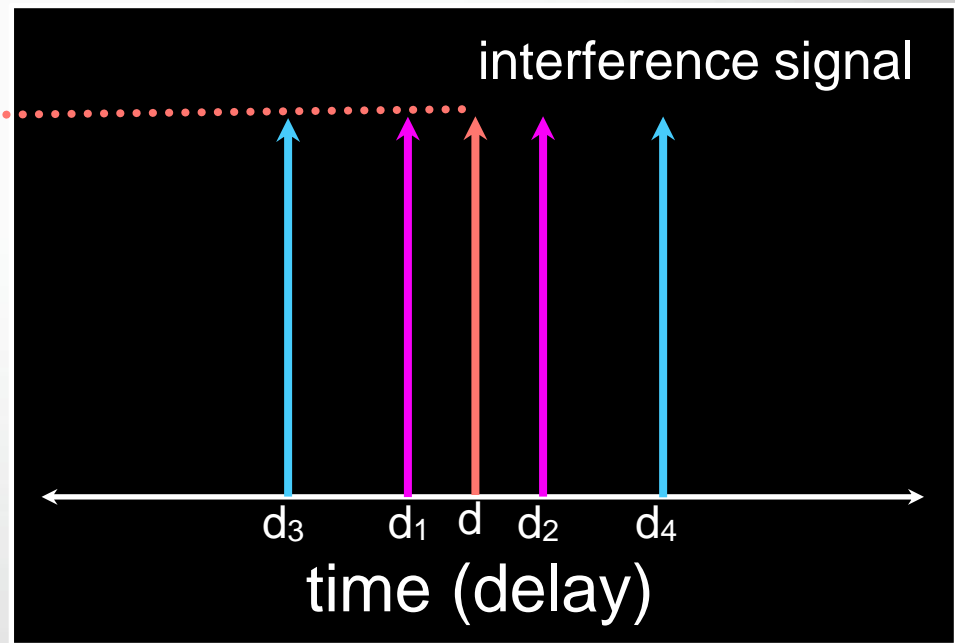
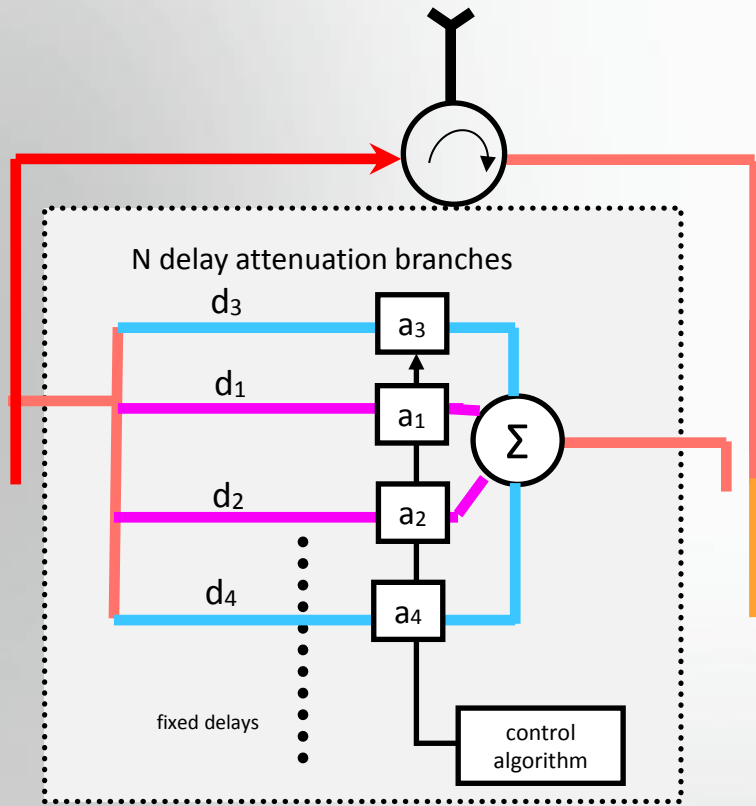


# Analog Theory Intuition: Branch Delays



Delays are fundamentally related to sampling theory

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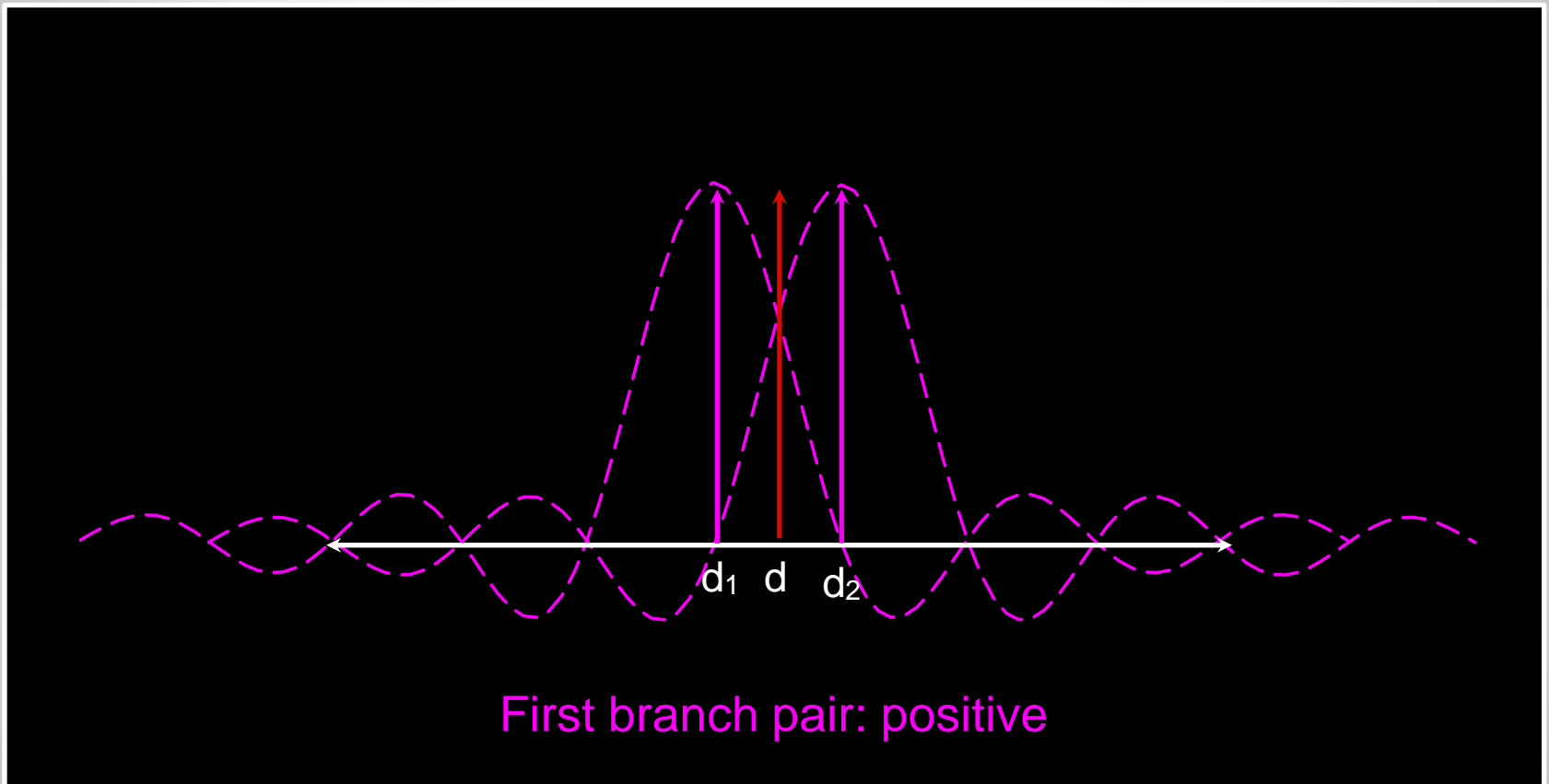


Delays are fundamentally related to sampling theory



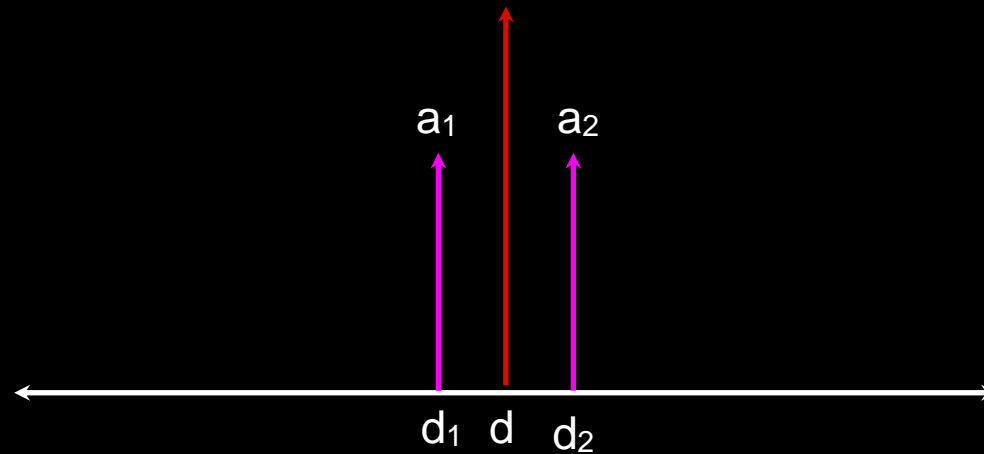
# Estimating Branch Attenuation

How do we fix attenuation ranges?



# Estimating Branch Attenuation

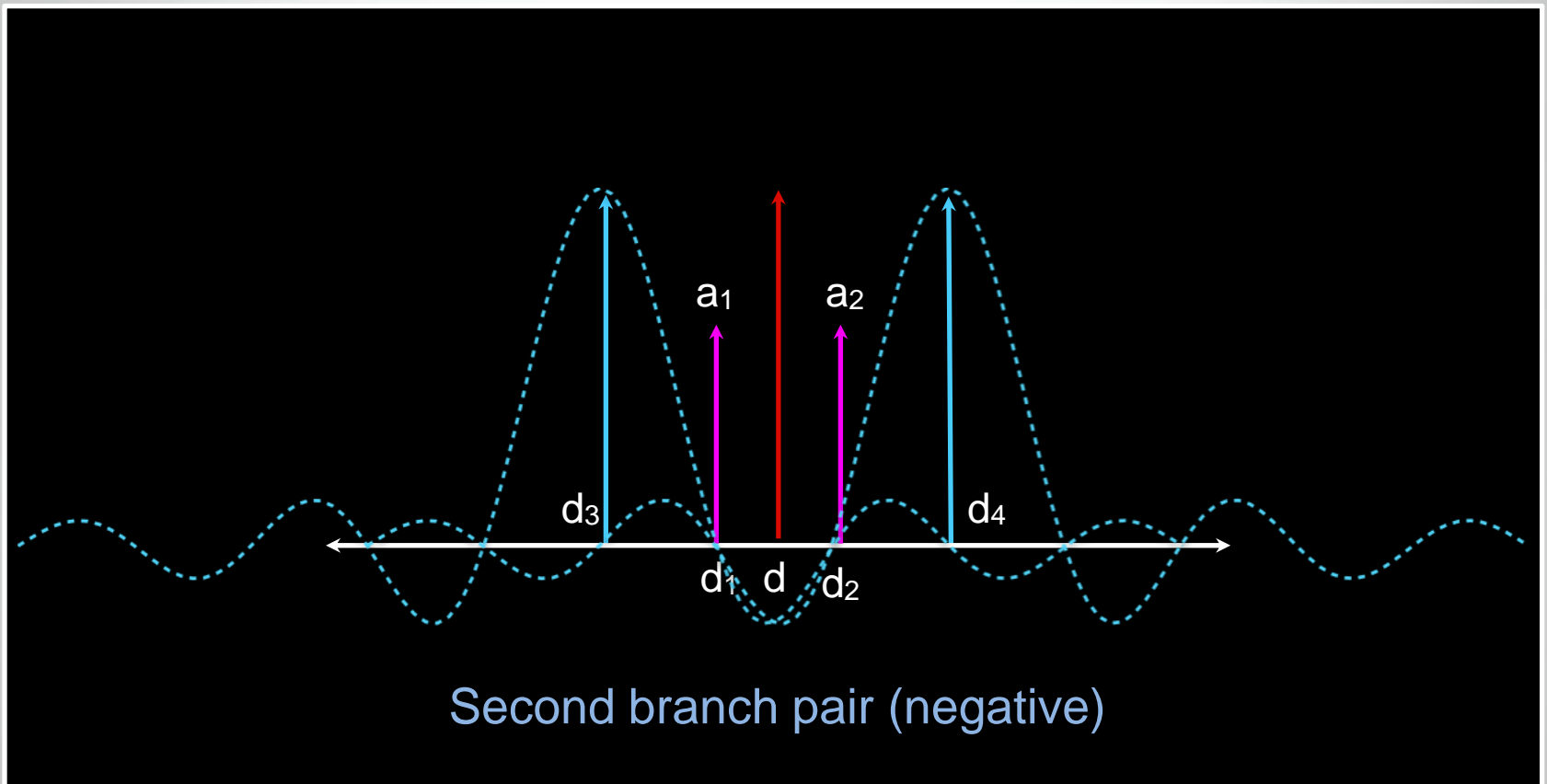
How do we fix attenuation ranges?



First branch pair: positive

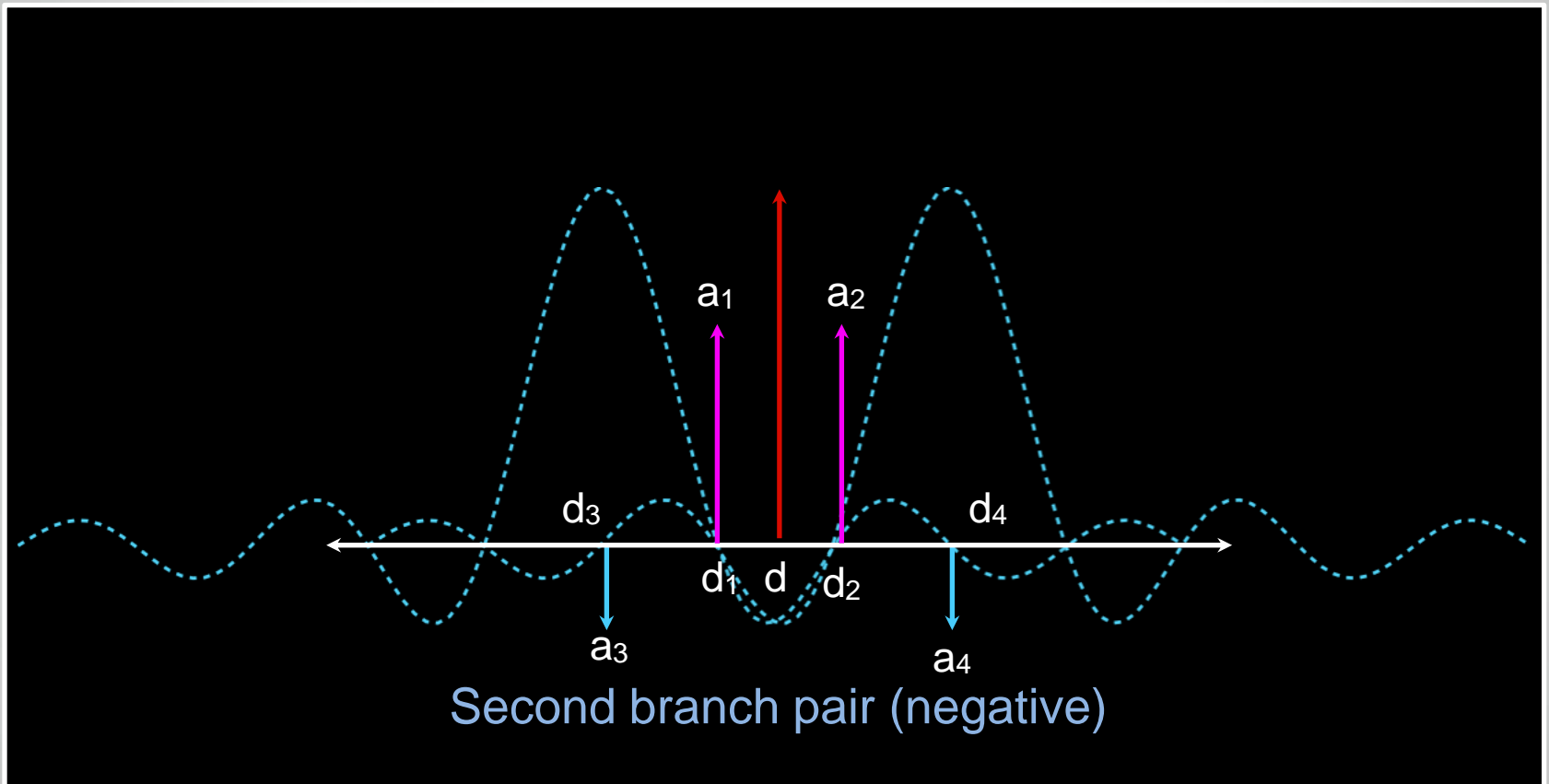
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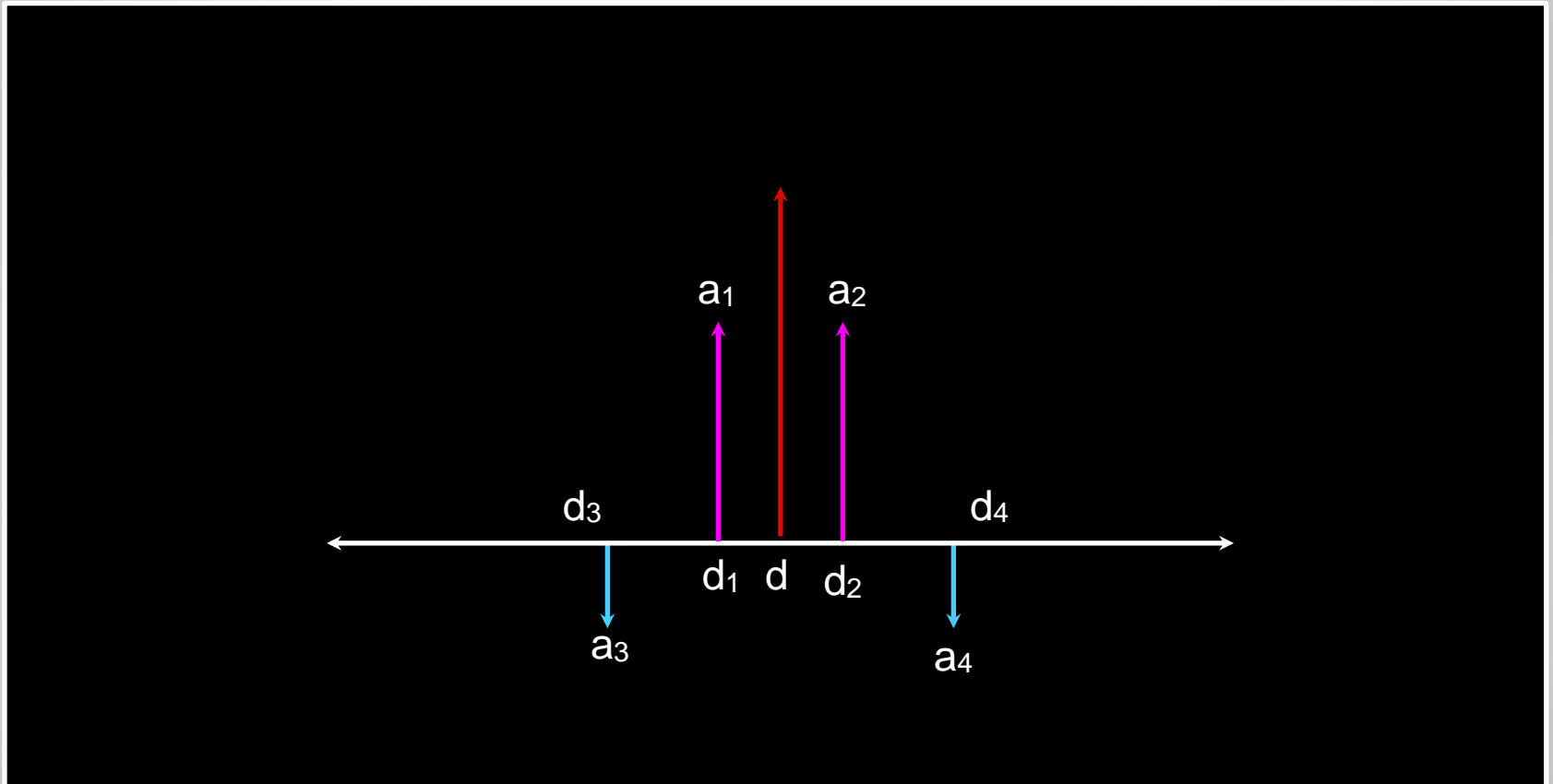
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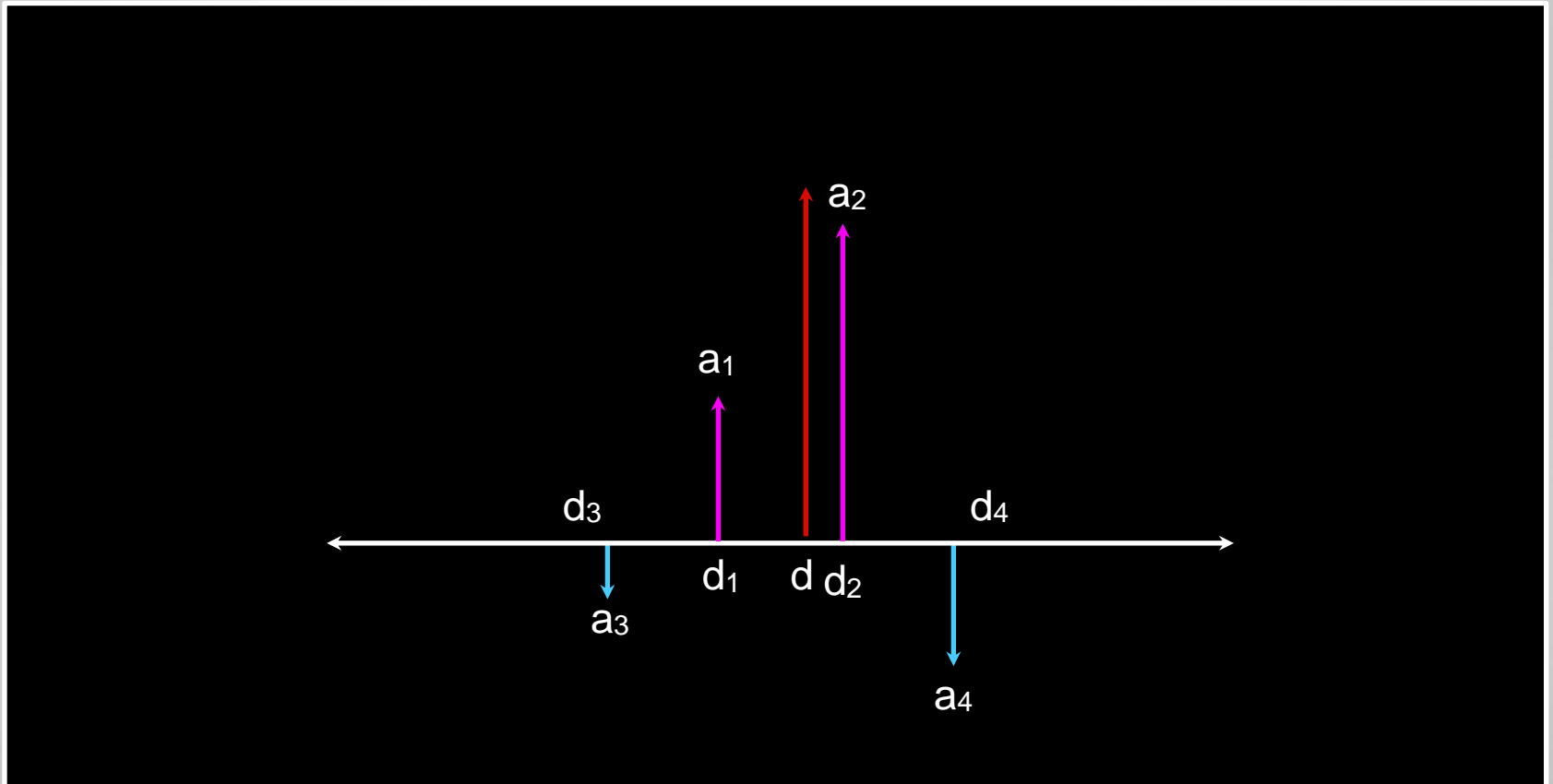
# Estimating Branch Attenuation

Adaptation to environmental changes: Assumption  $d$  known



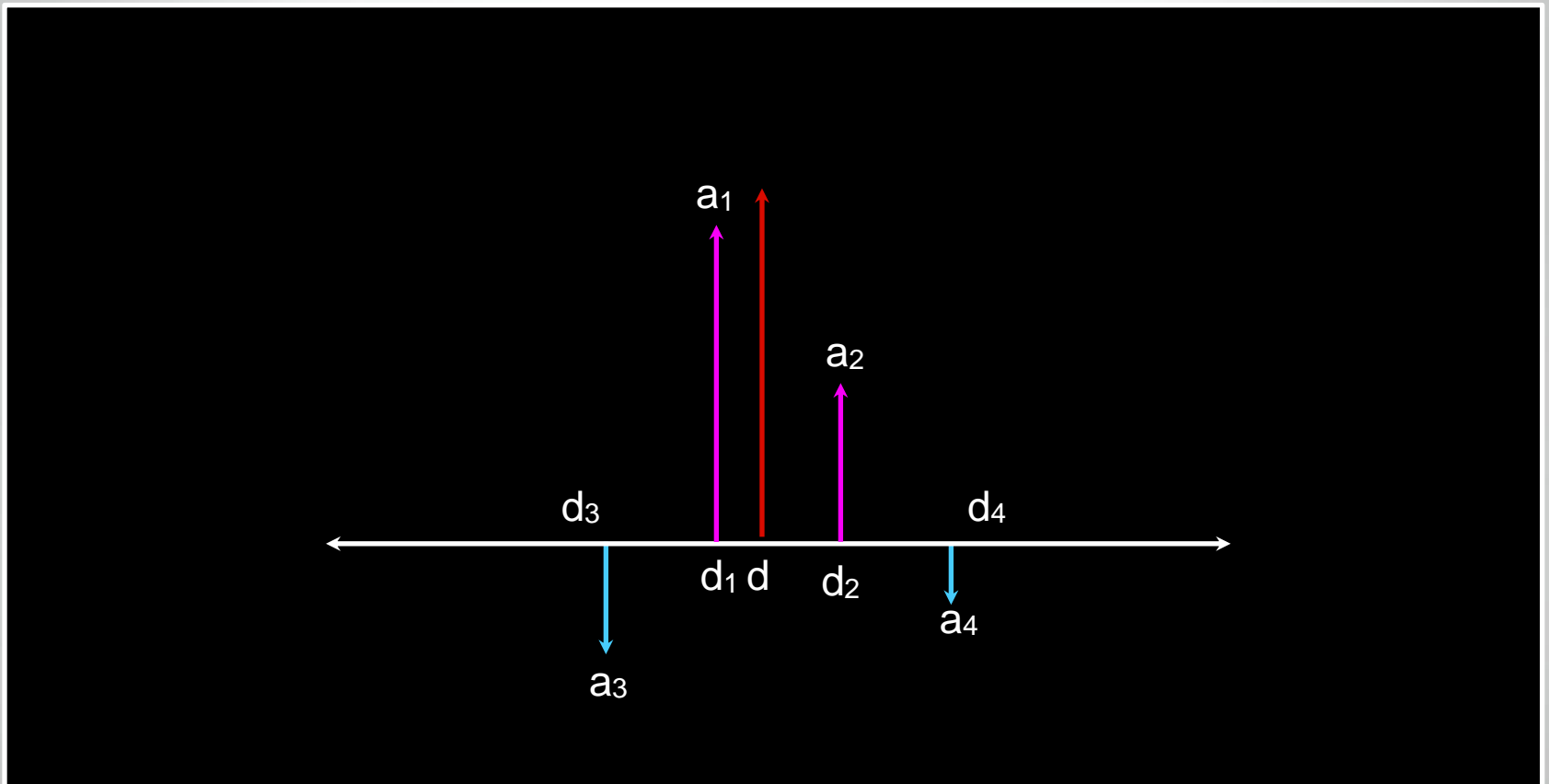
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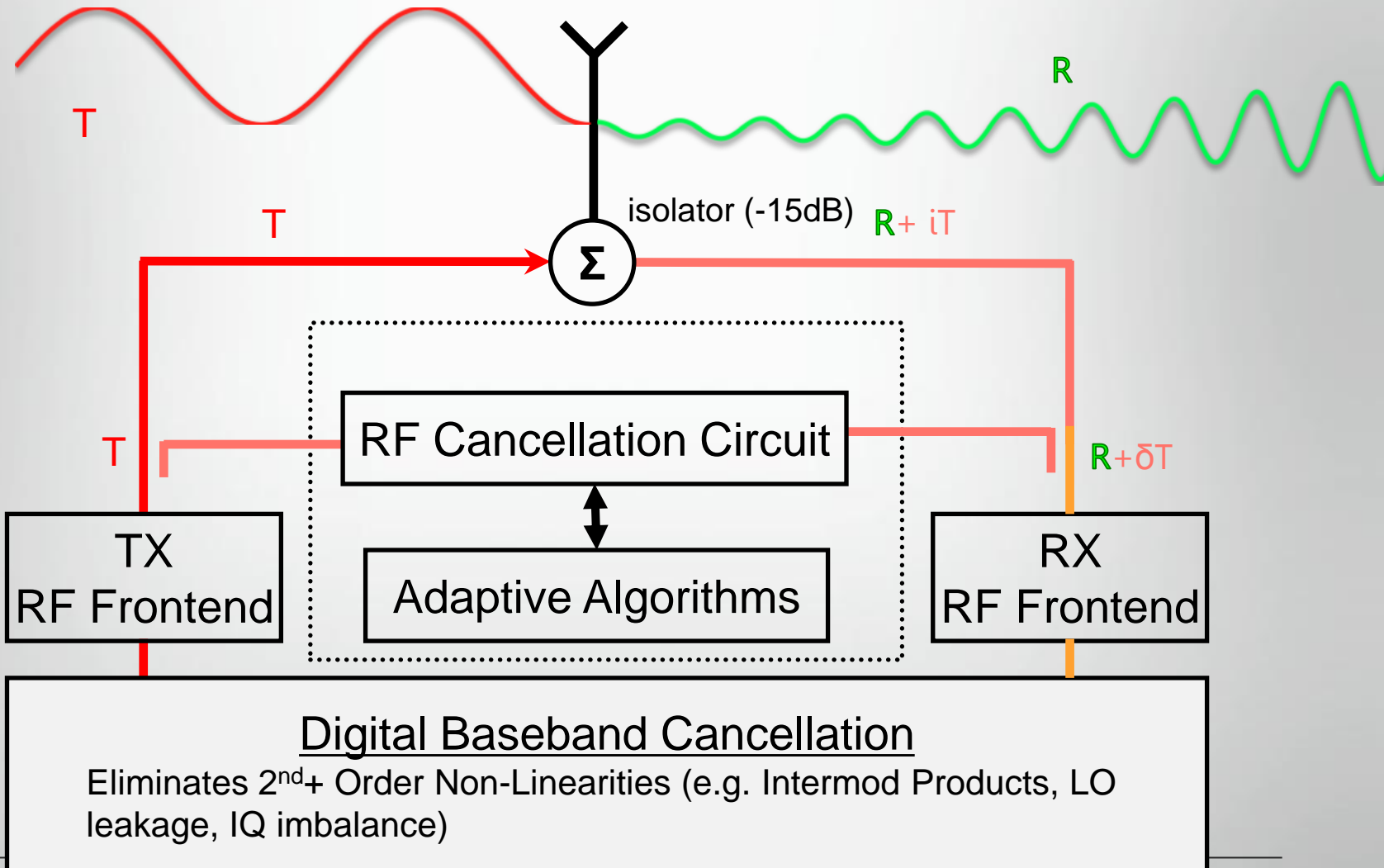


# Estimating Branch Attenuation

Adaptation to environmental changes

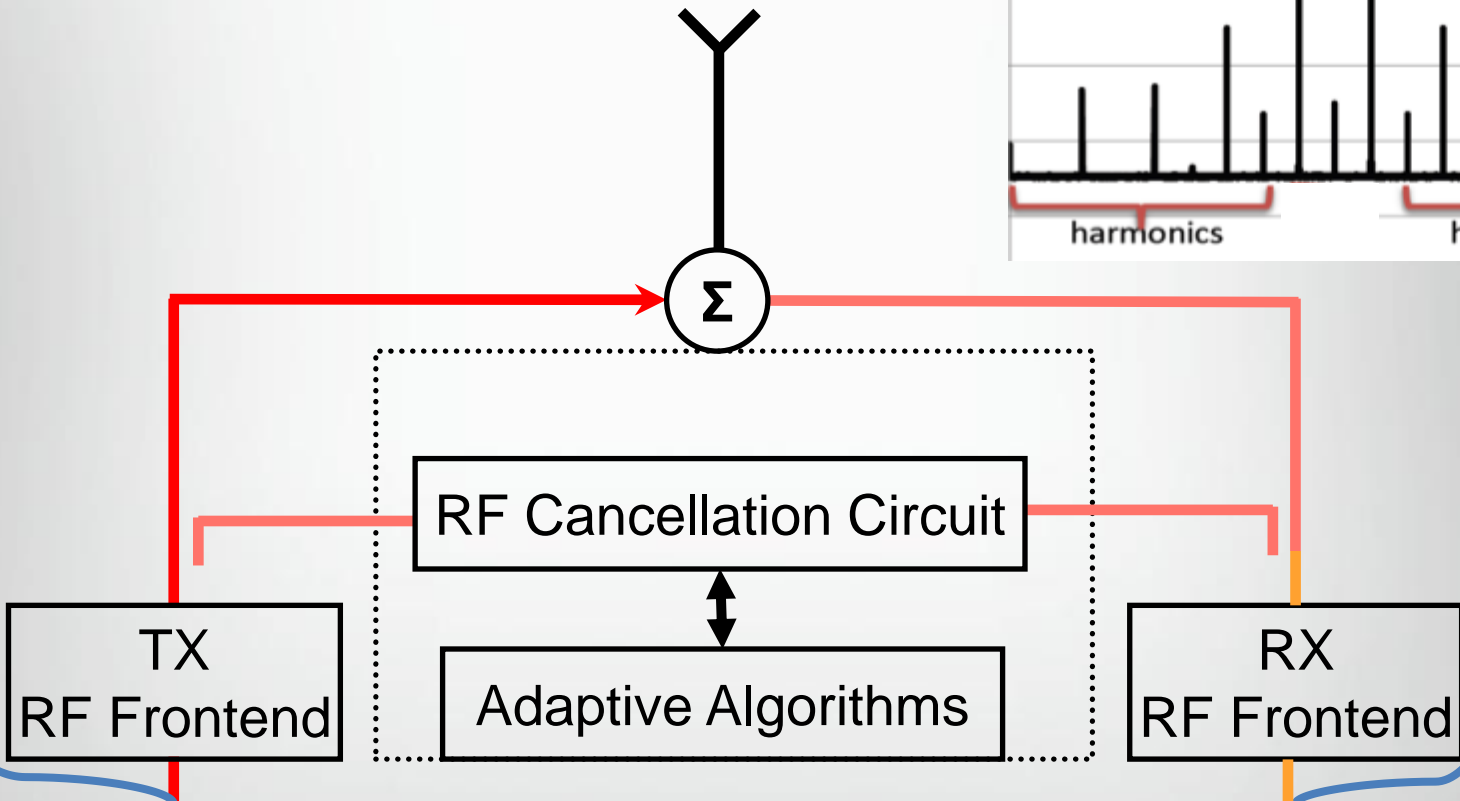
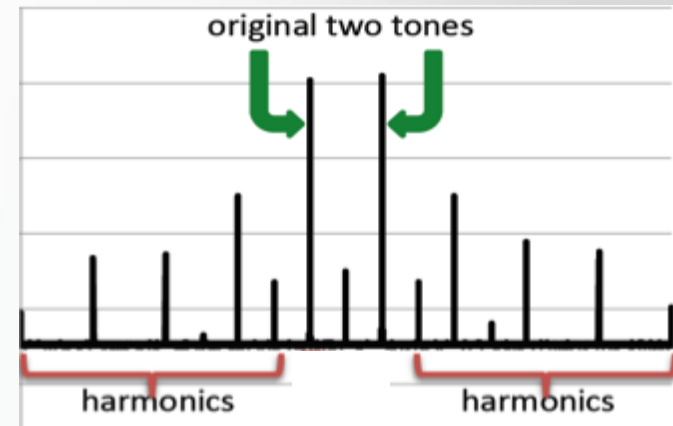
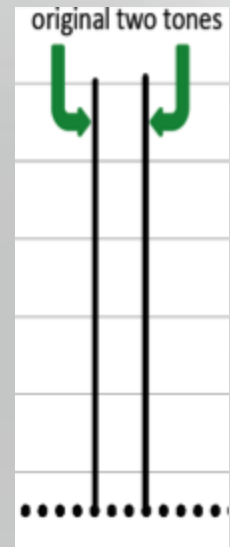


# Digital Baseband Cancellation





# Digital Baseband Cancellation



Digital Baseband Cancellation  
Eliminates 2<sup>nd</sup>+ Order Non-Linearities (e.g. Intermod Products, LO leakage, IQ imbalance)

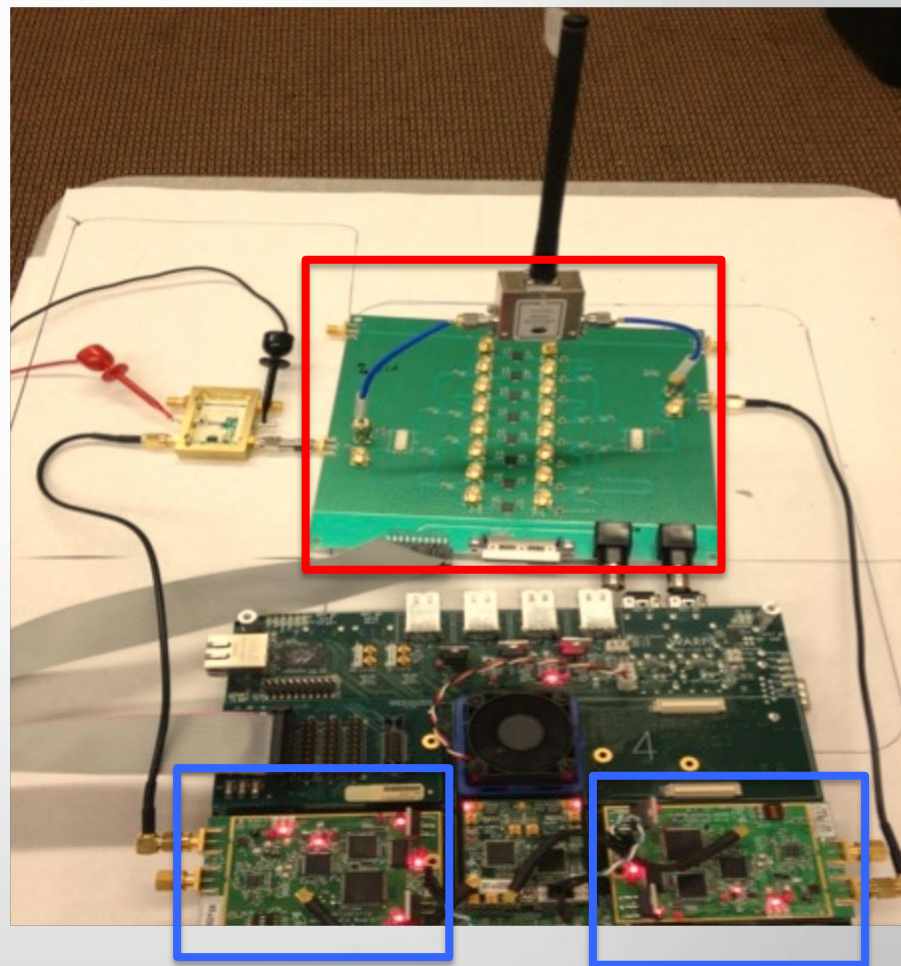
# Digital Self-Interference Cancellation

- Challenge: Need to cancel main signal as well as higher order harmonics upto the 11<sup>th</sup> order
- Prior approaches only cancel main signal, ignore hamonics
- Naïve approach to non-linearities: Needs to estimate ~1200 coefficients, would require a large number of training symbols & hardware resources, infeasible in practice
- Our approach: Compact and fast digital self-interference cancellation algorithm (needs to only estimate ~200 coefficients, works with existing WiFi packet format)

# Evaluation Q1: Does it work with commodity radios?

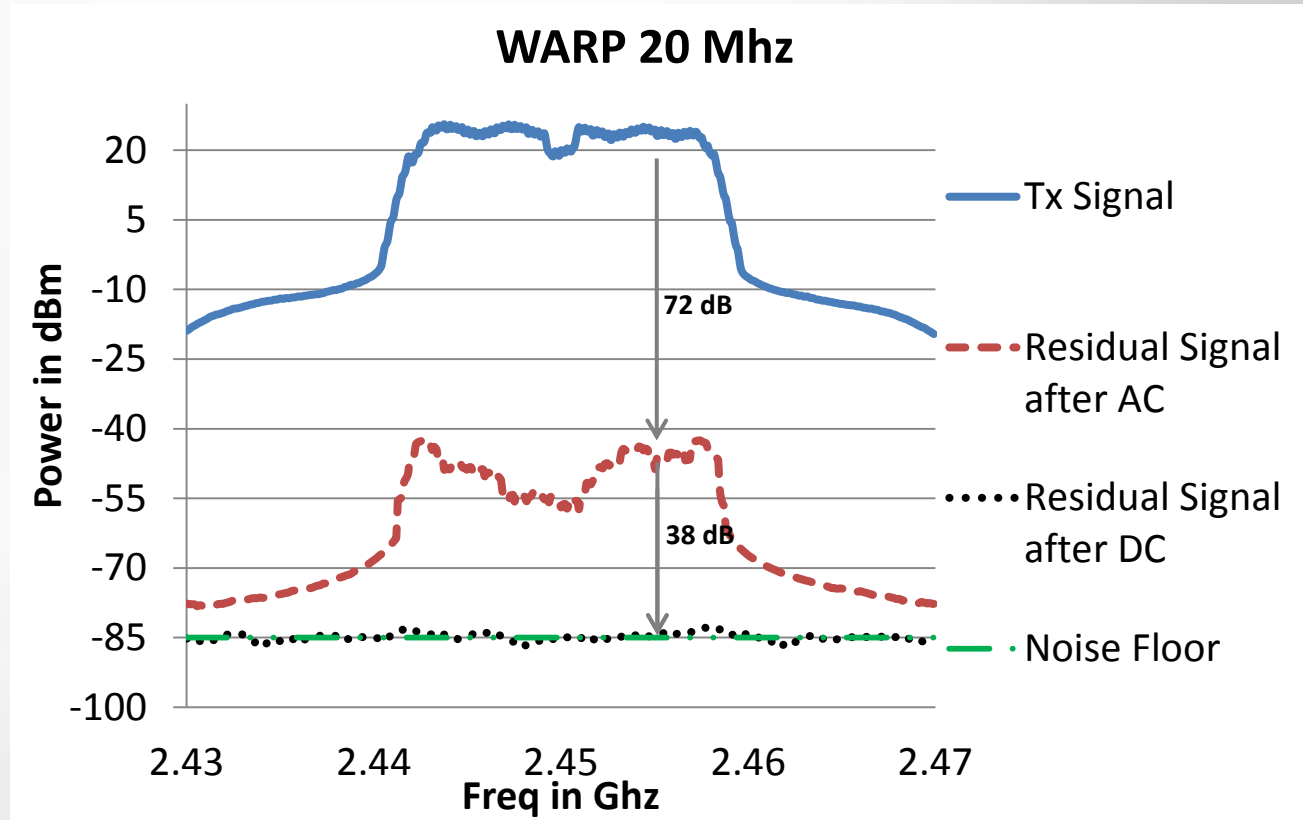
Goal: Build a full duplex radio using a cheap \$2 COTS Maxim transceiver

- Challenge: **Extremely high transmitter noise and non-linearities**
- 20MHz BW (transceiver limitation)
- 25dBm max TX power
- WiFi 802.11n PHY



# Evaluation Q1: Does it work with commodity radios?

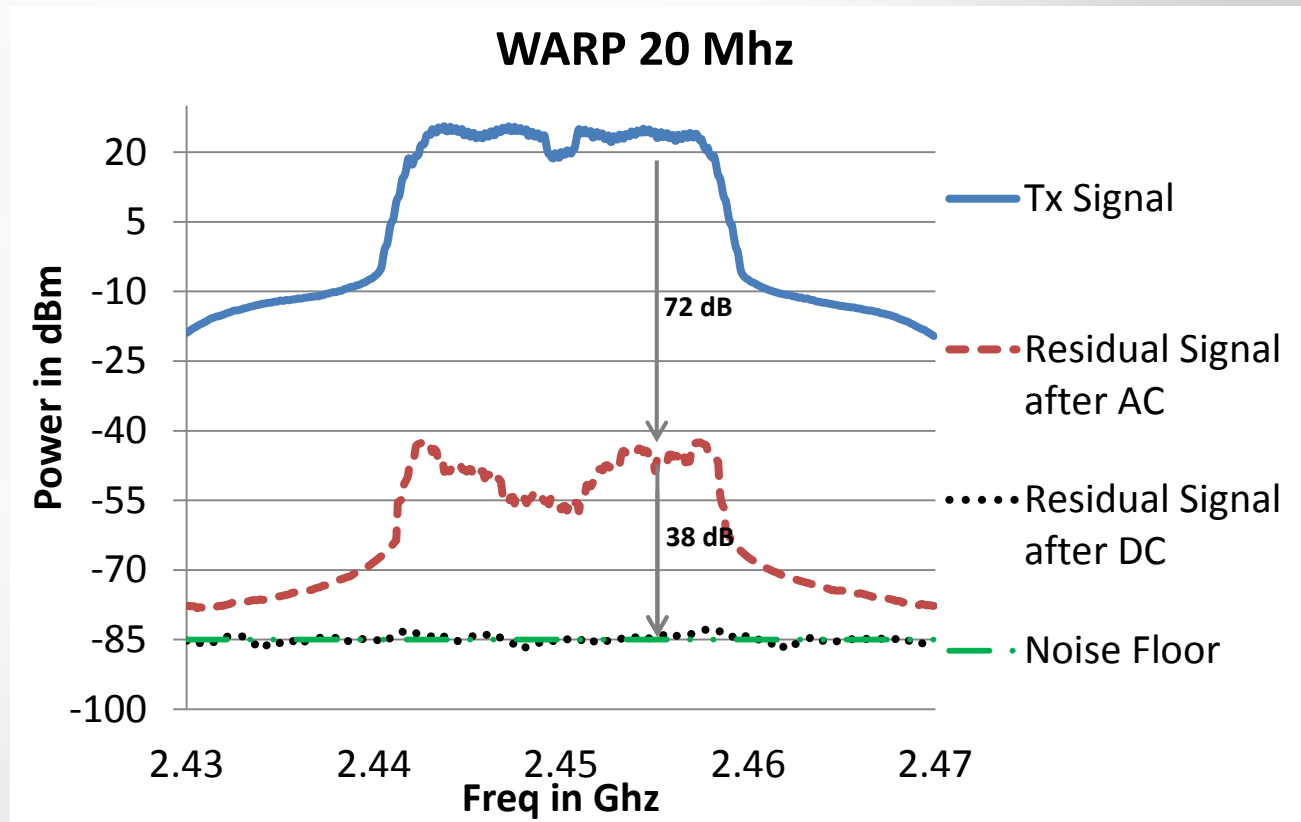
- Commodity transceiver



$$\begin{array}{|c|} \hline \text{Analog} \\ \hline > 70\text{dB} \\ \hline \end{array} + \begin{array}{|c|} \hline \text{Digital} \\ \hline \sim 40\text{dB} \\ \hline \end{array} = \begin{array}{|c|} \hline \text{Total} \\ \hline > 110\text{dB} \\ \hline \end{array}$$

# Evaluation Q1: Does it work with commodity radios?

- Commodity transceiver
- Tunes to environmental changes within 8us, needs to be re-tuned every 100ms



$$\begin{array}{|c|} \hline \text{Analog} \\ \hline > 70\text{dB} \\ \hline \end{array} + \begin{array}{|c|} \hline \text{Digital} \\ \hline \sim 40\text{dB} \\ \hline \end{array} = \begin{array}{|c|} \hline \text{Total} \\ \hline > 110\text{dB} \\ \hline \end{array}$$

# How do we compare against prior designs?

20 MHz Bandwidth. WiFi OFDM waveform, 25 dBm TX power

## Compared Approaches

Our Design

Balun Cancellation  
(Mobicom'11)

Extra-Tx Chain Design  
(Sigcomm'11, Asilomar'11)

# How do we compare against prior designs?

20 MHz Bandwidth. WiFi OFDM waveform, 25 dBm TX power

Compared Approaches	Cancellation in (dB)
Our Design	110
Balun Cancellation (Mobicom'11)	85
Extra-Tx Chain Design (Sigcomm'11, Asilomar'10)	80

# How do we compare against prior designs?

20 MHz Bandwidth. WiFi OFDM waveform, 25 dBm TX power

Compared Approaches	Cancellation in (dB)	Self-interference residue over noise floor (dB)
Our Design	110	~1
Balun Cancellation (Mobicom'11)	85	25
Extra-Tx Chain Design (Sigcomm'11, Asilomar'10)	80	30

Minimum SNR required for receiving a packet > Self-interference residue over noise floor

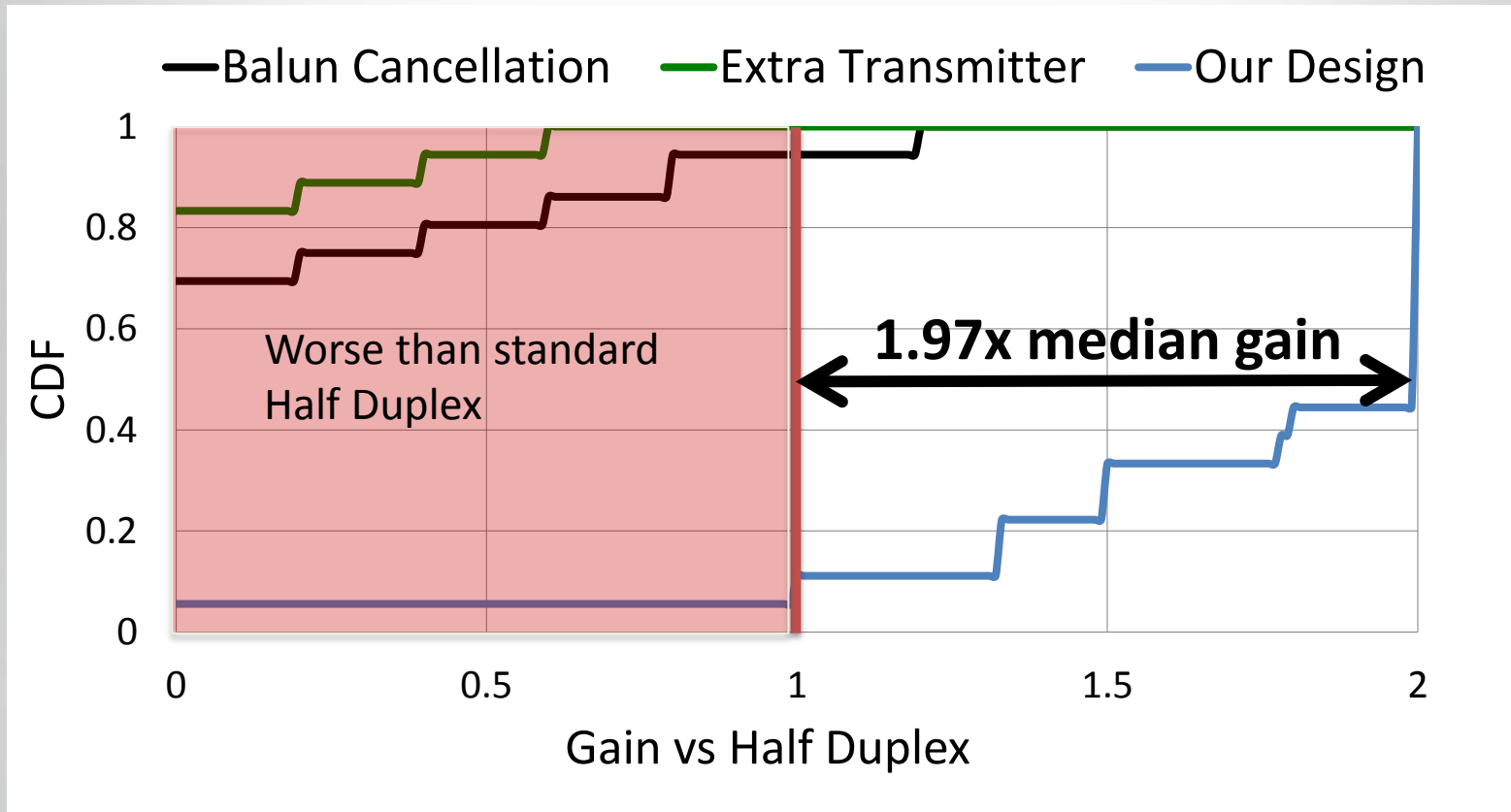


# Evaluation Q2: Does that translate to doubling of throughput in practice?

- Testbed: Indoor office noisy environment, various locations for the two full duplex radios.
- Compare throughput achieved in full duplex with that achieved in half duplex
- Full duplex implemented using our approach, and prior balun and extra TX chain based approaches

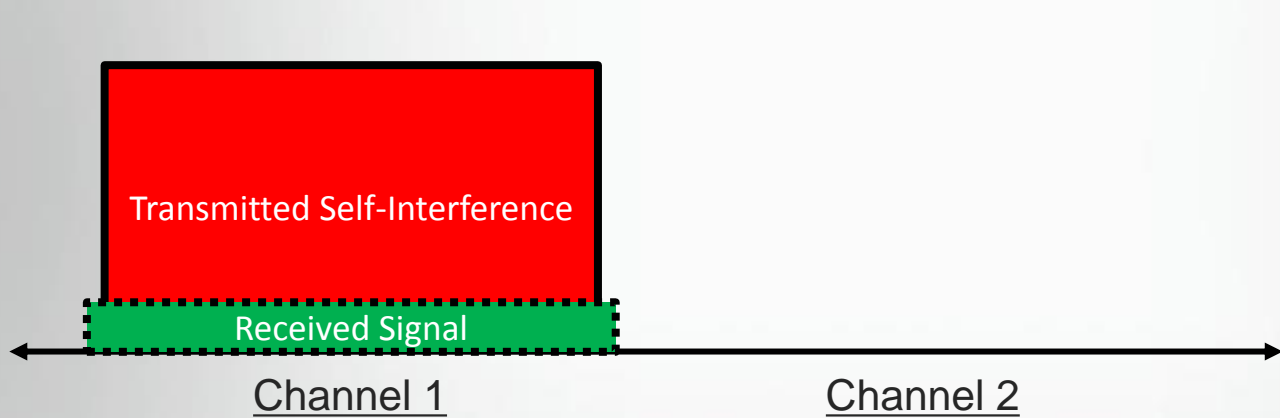
$$\text{Gain} = \frac{\text{Throughput of FD}}{\text{Throughput of HD}}$$

# Evaluation Q2: Does that translate to doubling of throughput in practice?



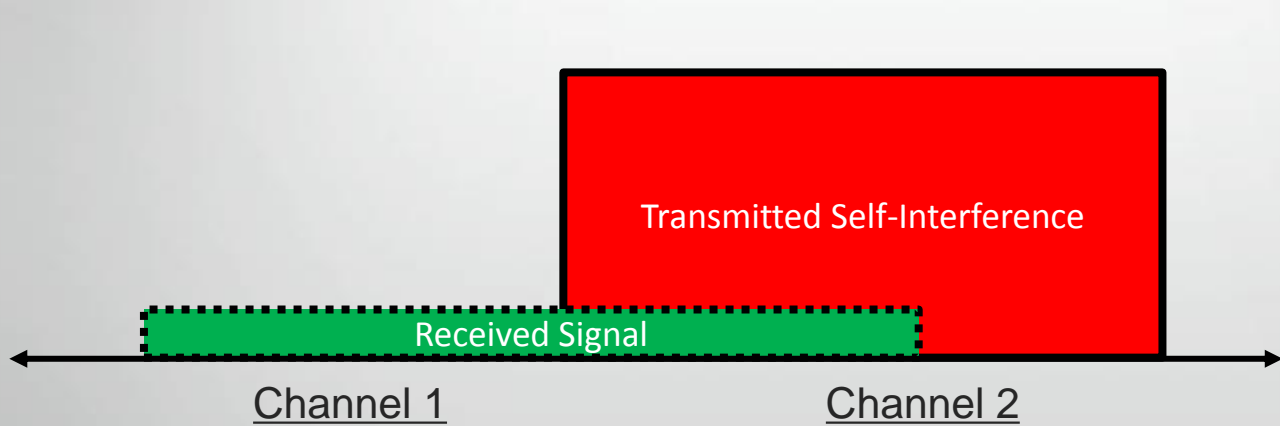
Our design achieves the theoretical throughput doubling

# Self-interference cancellation is broadly applicable



## In-Band Full Duplex

Double capacity



## Adaptive Frequency Division Full Duplex (FDD)

Flexibly decide which channels to transmit & receive on

# Full Duplex Everywhere

## Applicable To a Host of Problems



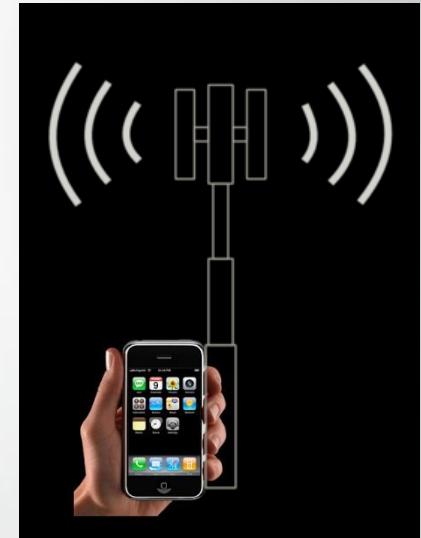
**PtP and PtMP Backhaul**  
Doubles spectral efficiency, and mitigate interference in unlicensed bands



**WiFi Access**  
Dense coverage by avoiding interference between adjacent bands



**Mobile Devices**  
World phones supporting any FDD channel pairs with adaptive duplexers



**LTE Access**  
High performance Relay Node. Doubles spectral efficiency for TD-LTE.

# To Conclude

Key contribution: Cancellation design that eliminates all self-interference to the noise floor

- Full duplex radio is one application of this interference cancellation technique.
- Widely applicable (Picasso, IMDShield, WiVi, Dhvani, ...)

Emphasizes the need for an interdisciplinary approach that combines RF circuit design, signal processing and communication algorithm design