

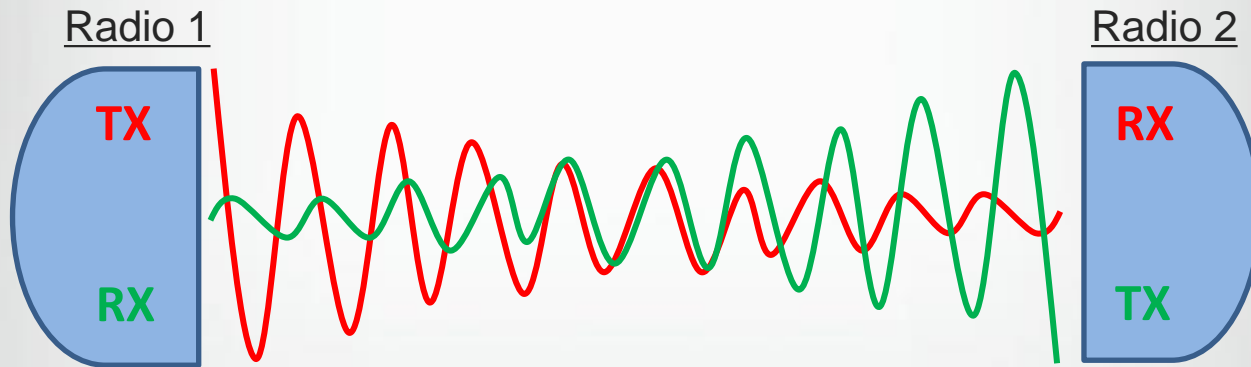
Full Duplex Radios

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.

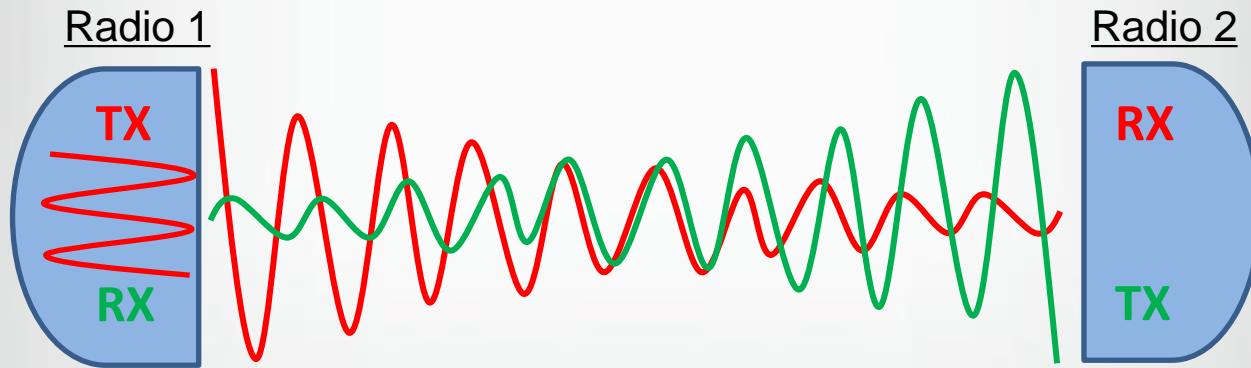
Why are radios half duplex?



“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?

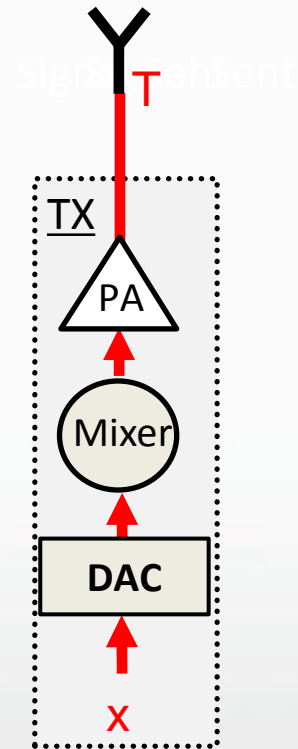


Self-Interference is a hundred billion times (110dB+) stronger than the received signal

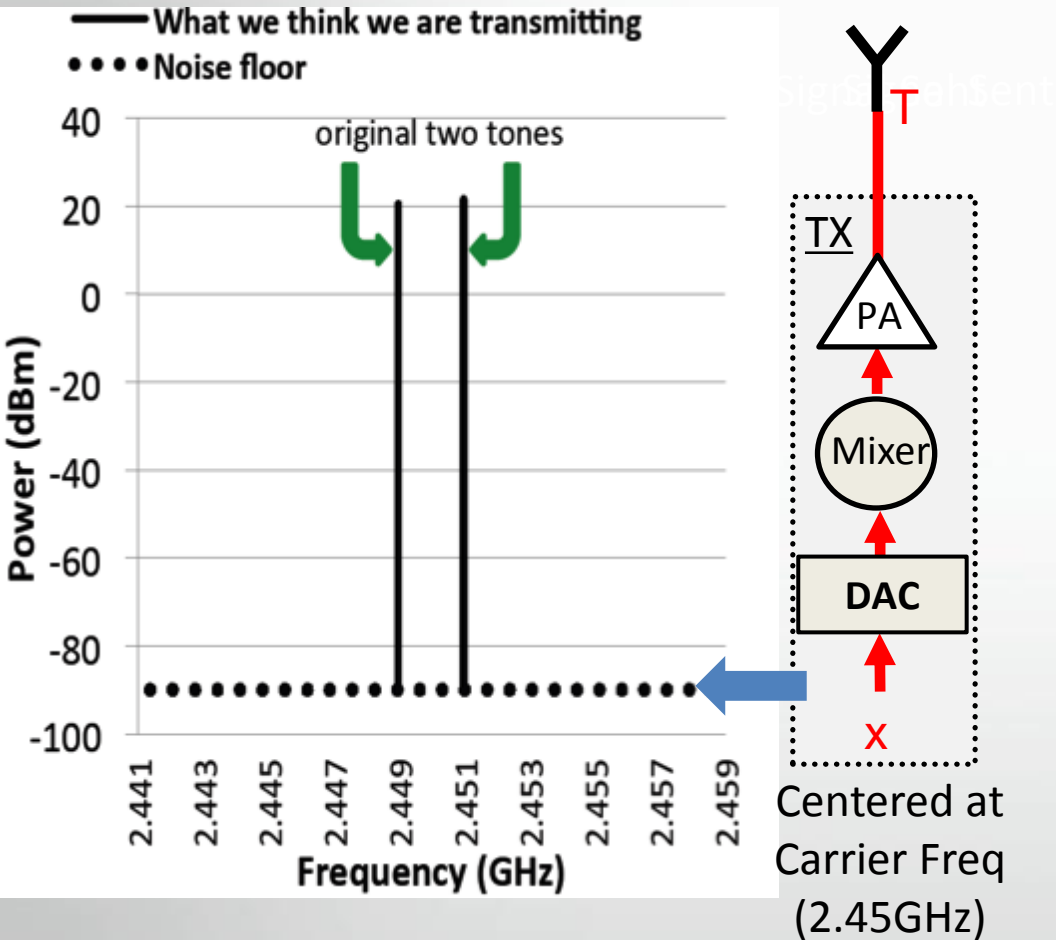
Isn't this easy to solve?

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

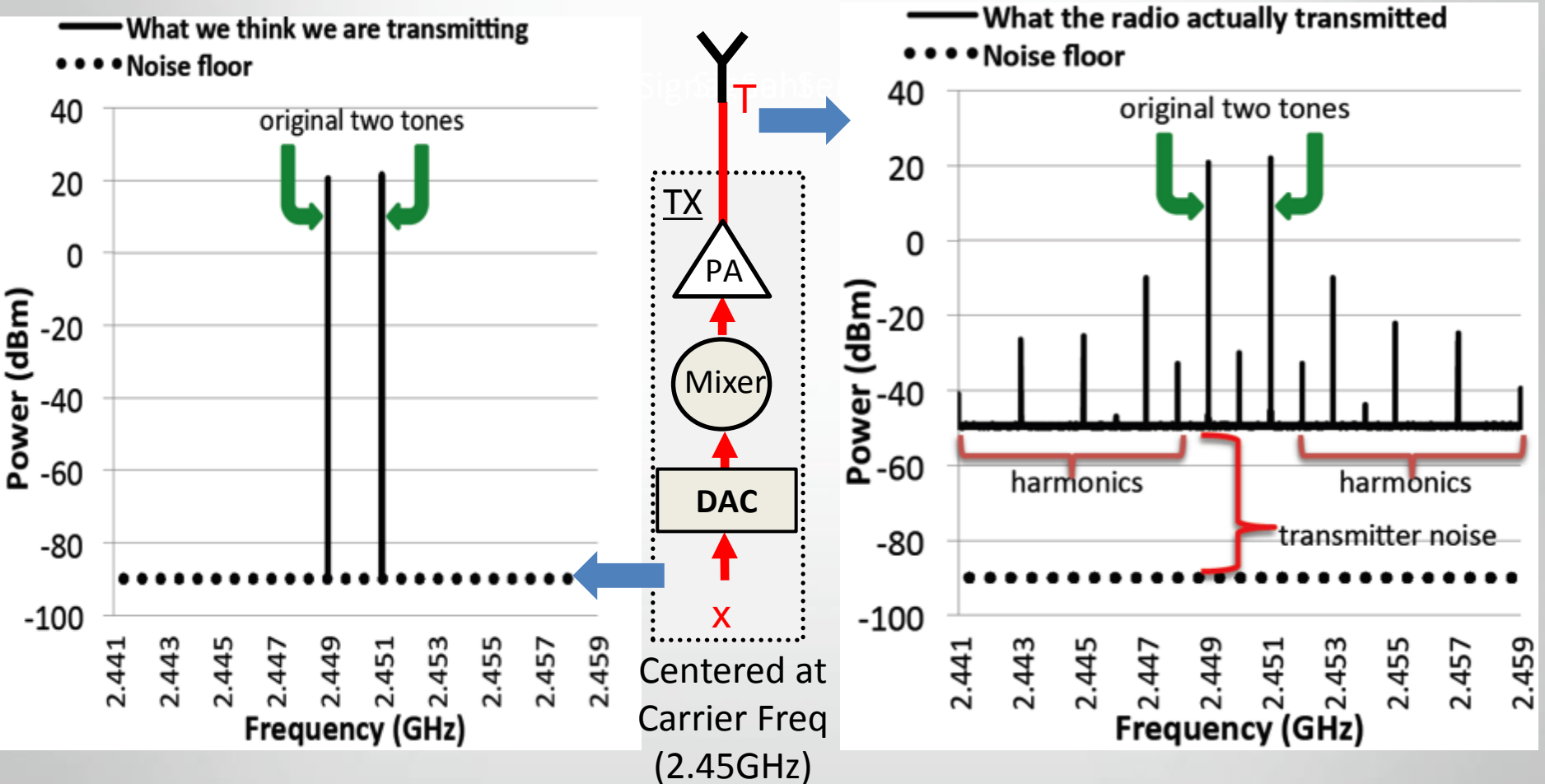
Do we know what we are transmitting?



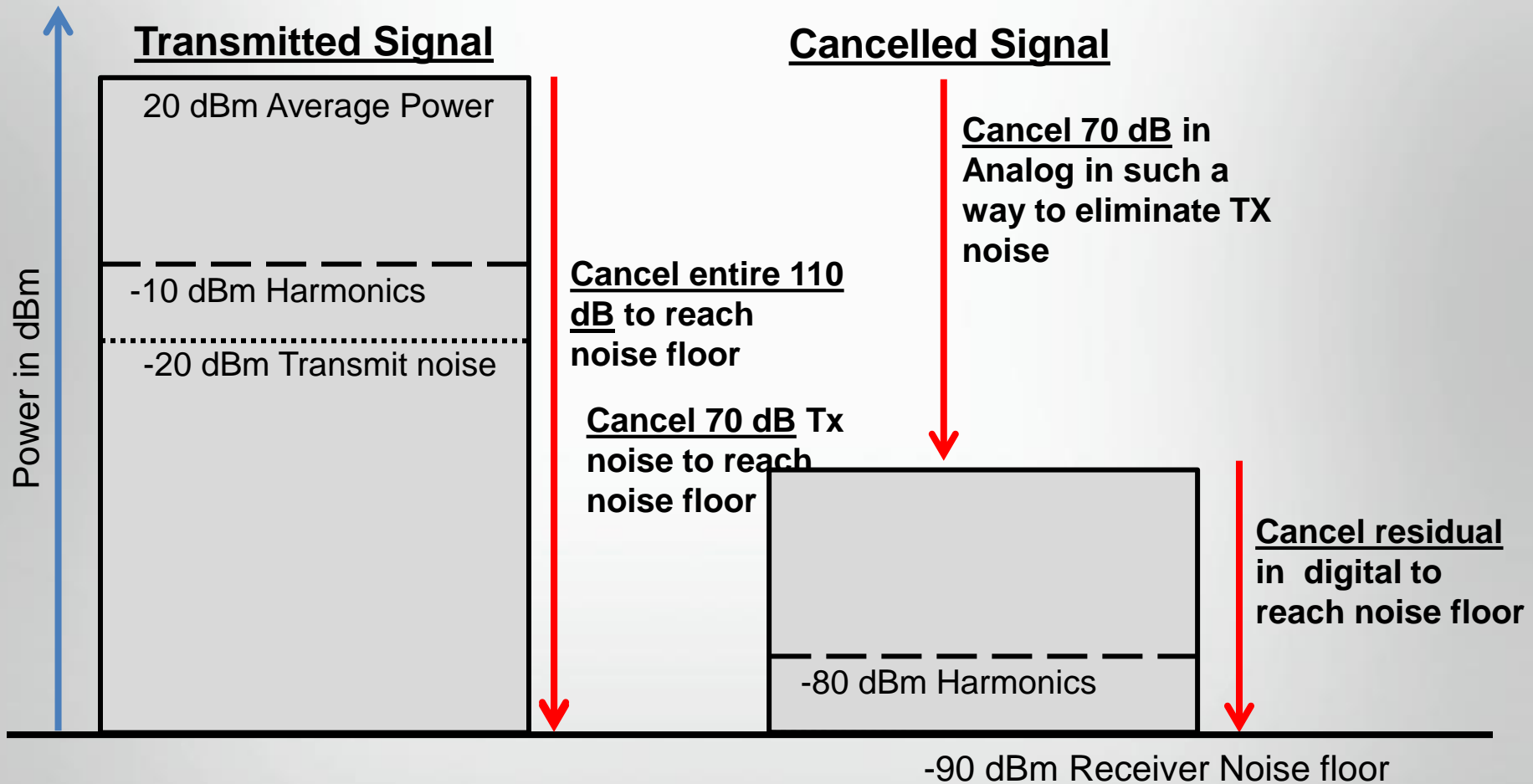
Do we know what we are transmitting?



Do we know what we are transmitting?



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

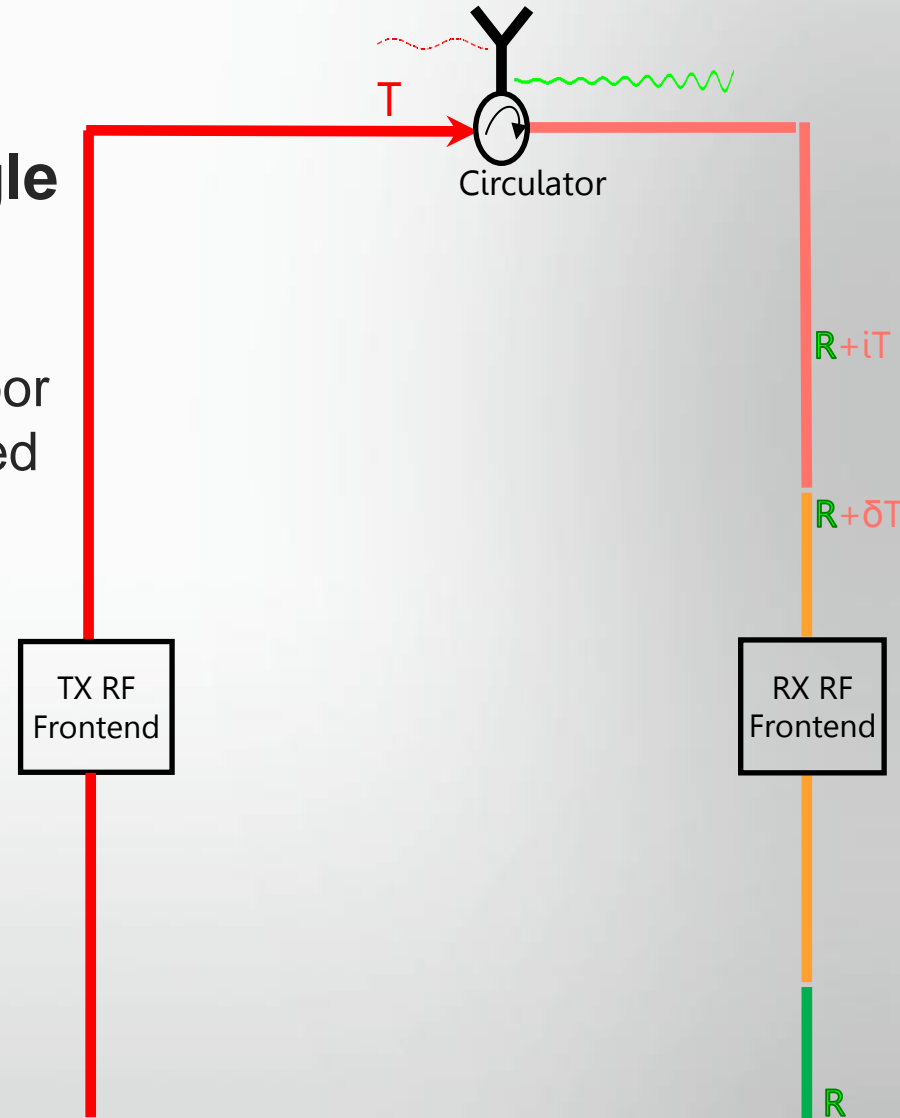


Takeaways: Require 110dB of total cancellation, of which at least 70dB has to eliminate transmitter noise in analog.

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



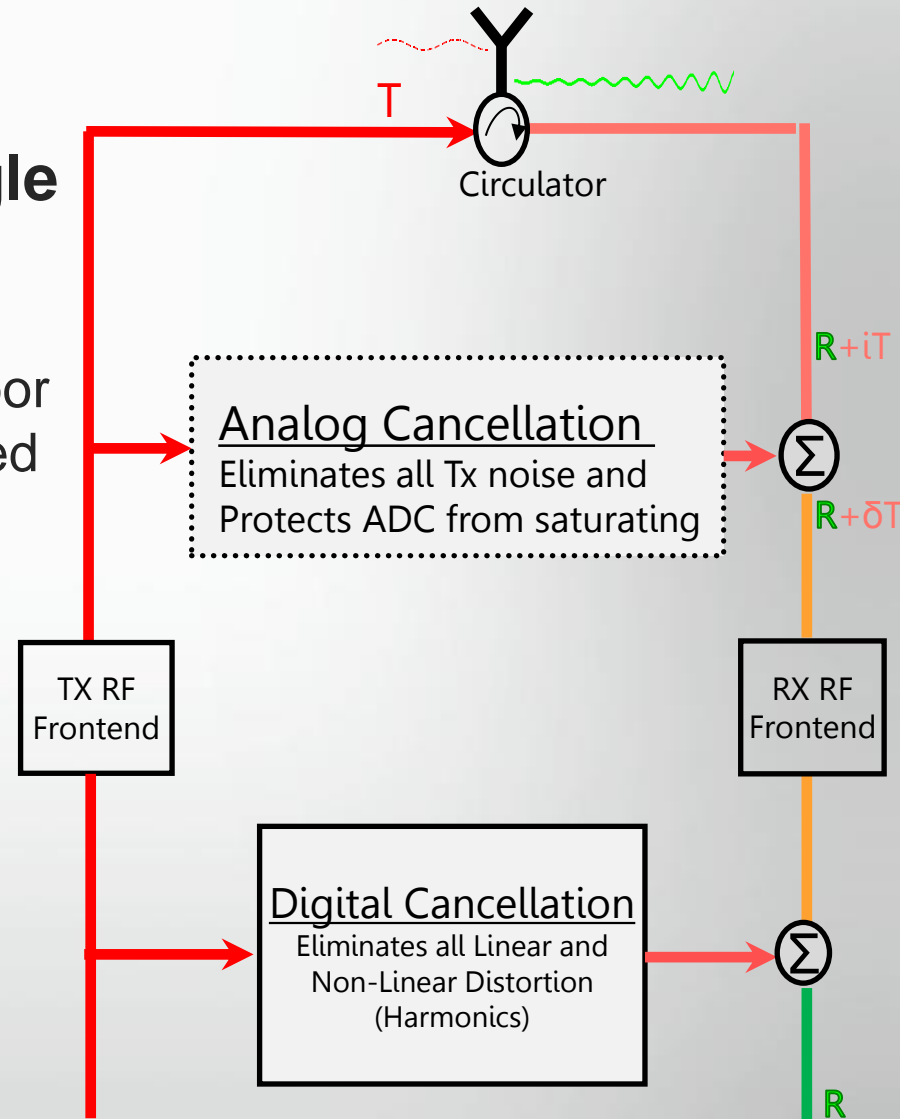
Contributions

We have invented in-band single antenna full duplex radios

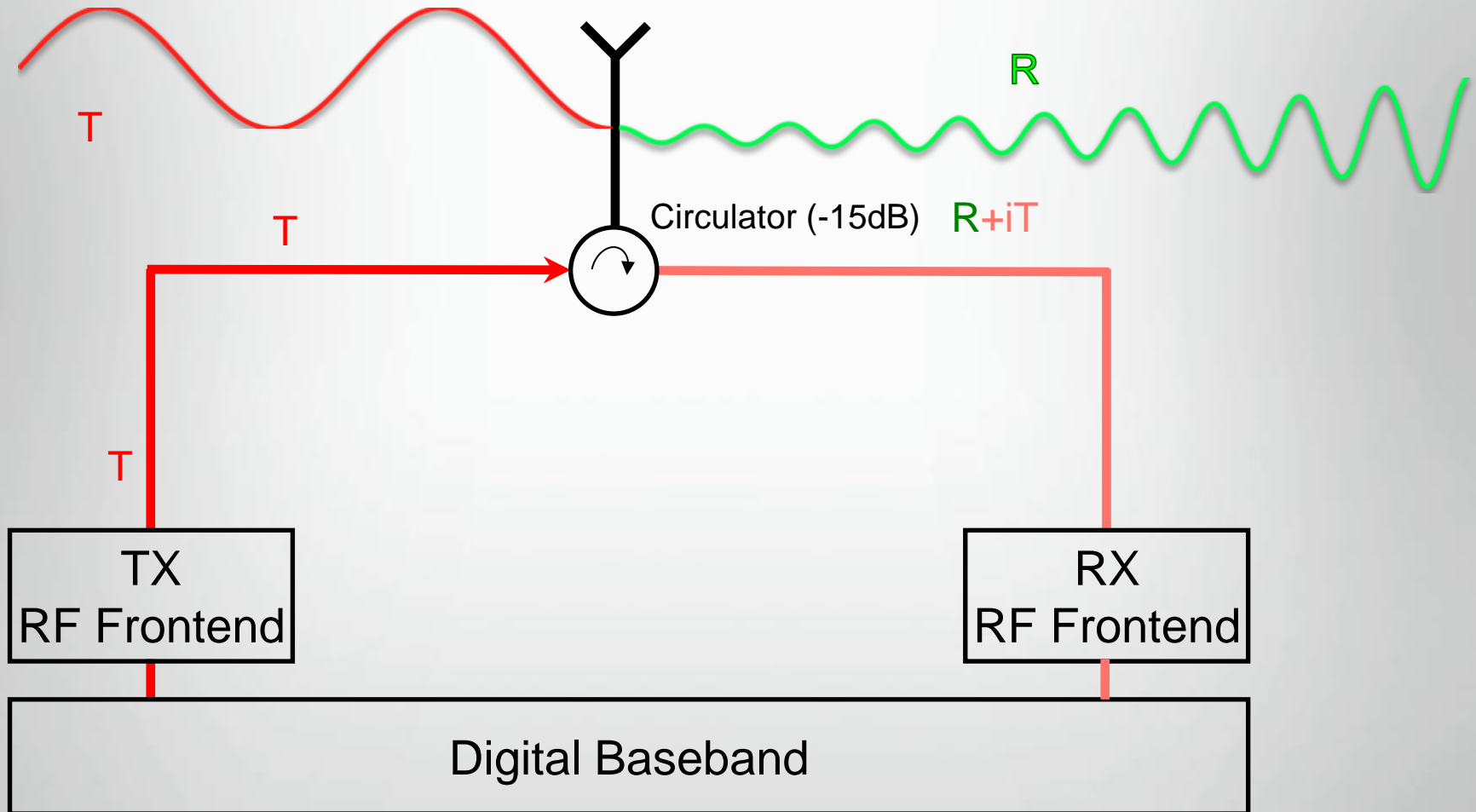
- Self-Interference cancellation that eliminates everything to the noise floor
- Practically achieves close to expected theoretical 2x throughput increase

Algorithms & circuits to estimate transceiver distortion and cancel self interference

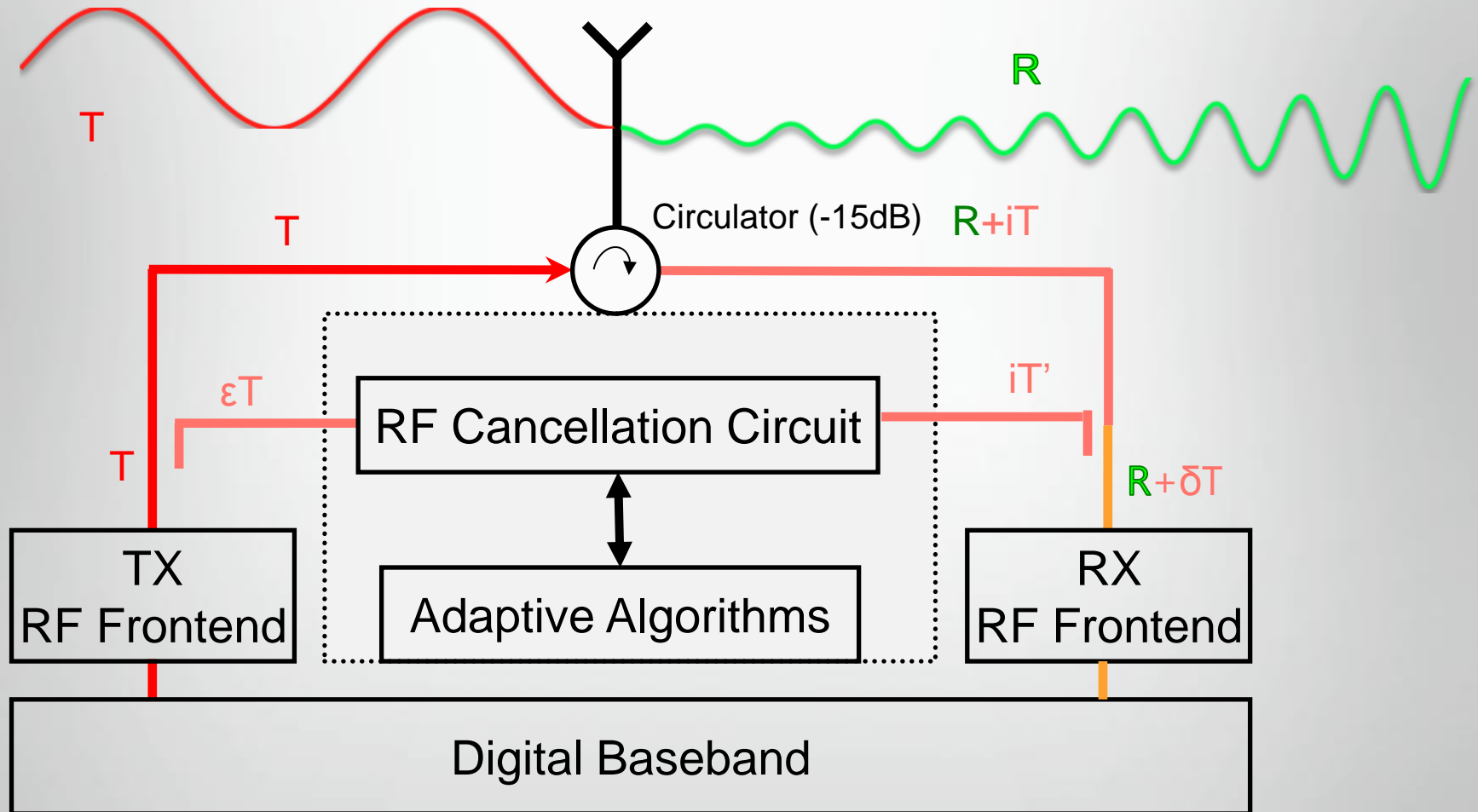
- Hybrid (analog & digital) design with RF cancellation circuit and DSP algorithms



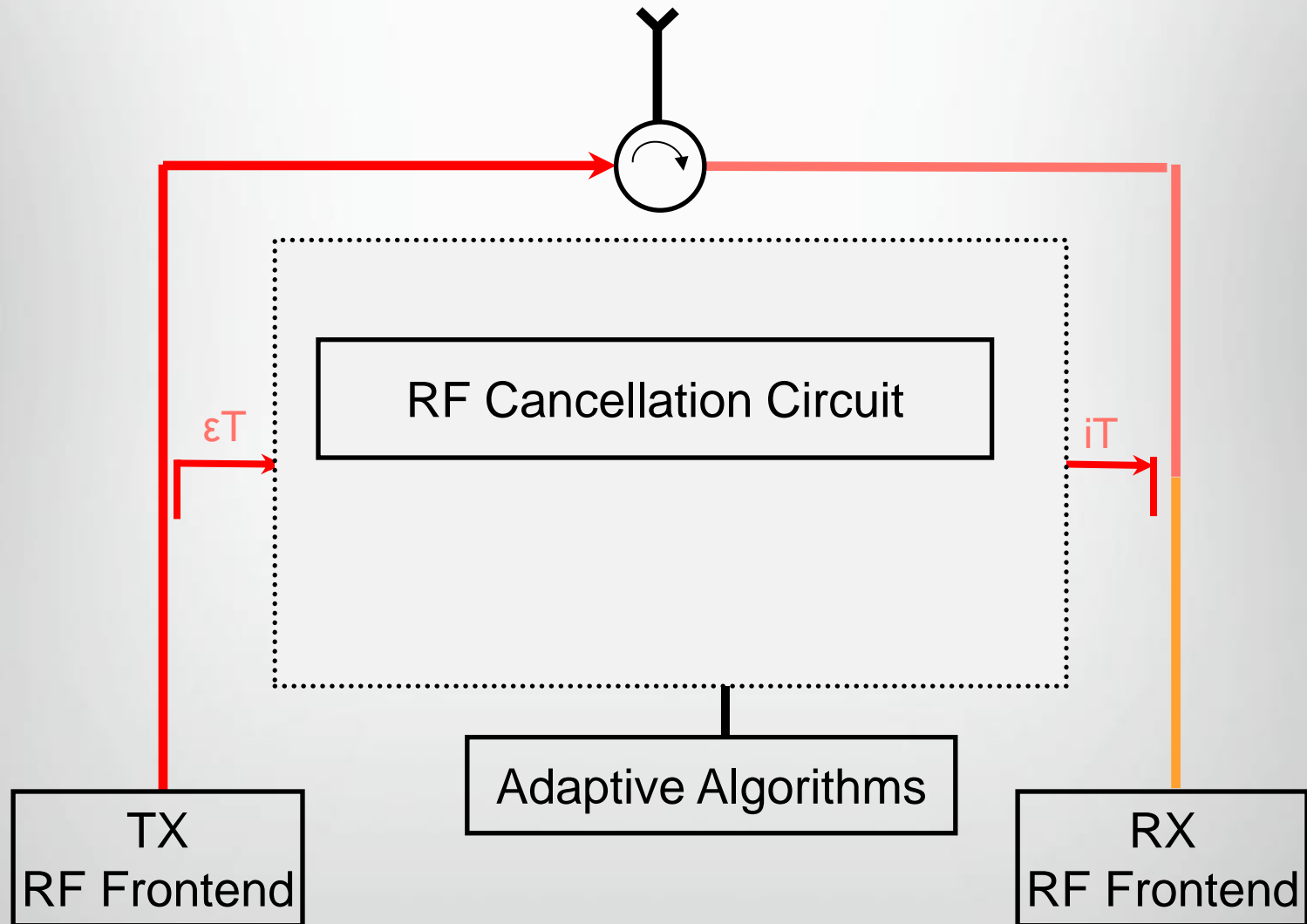
Mixed RF/Digital Design: Analog + Digital Cancellation



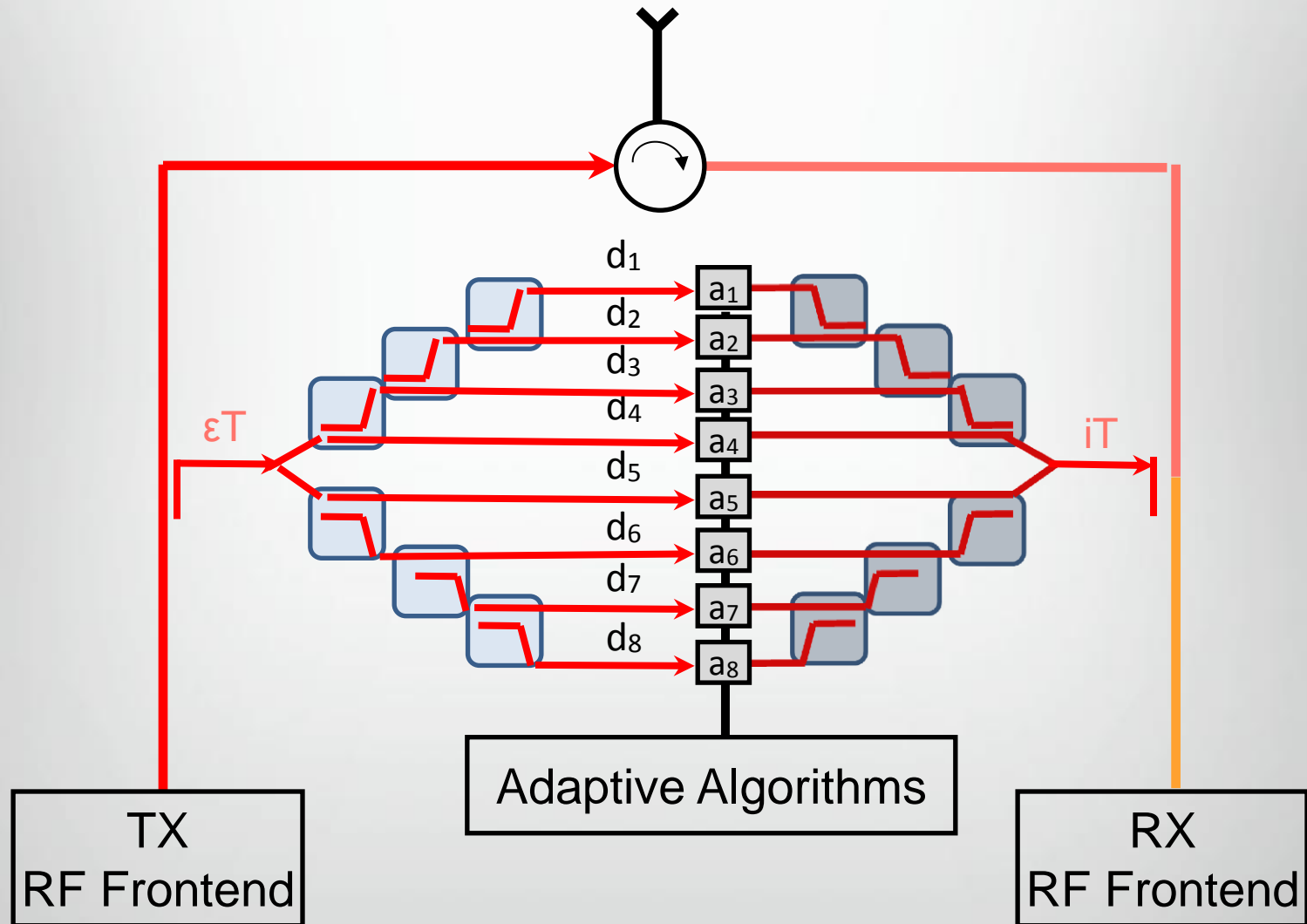
Analog RF Cancellation



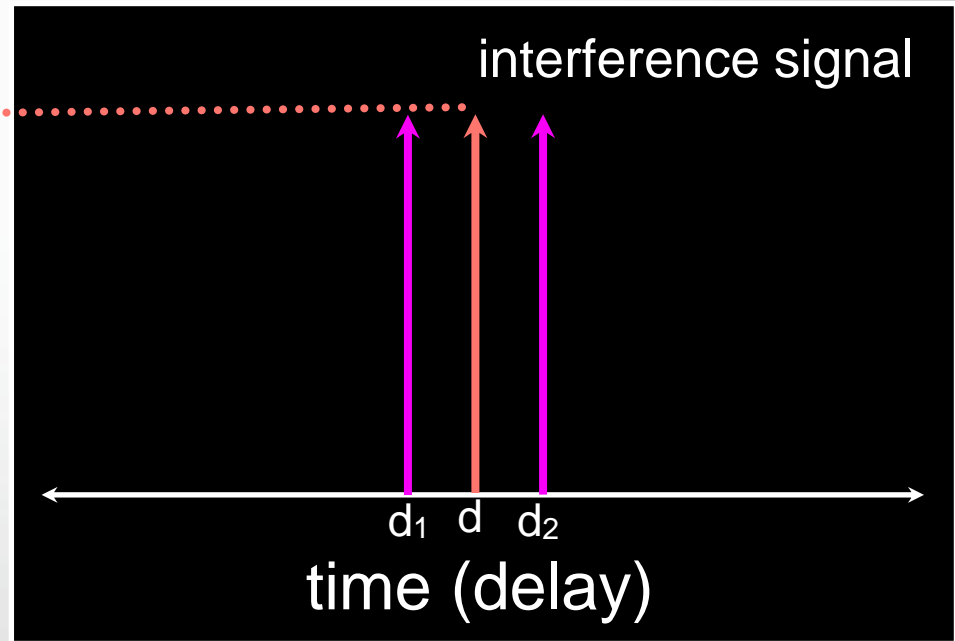
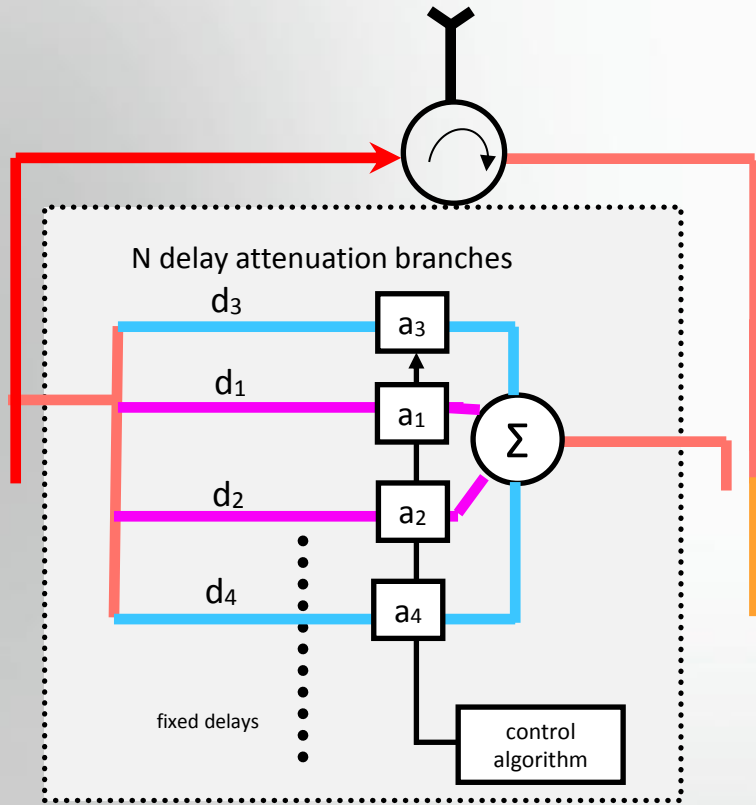
Analog RF Cancellation



Analog RF Cancellation

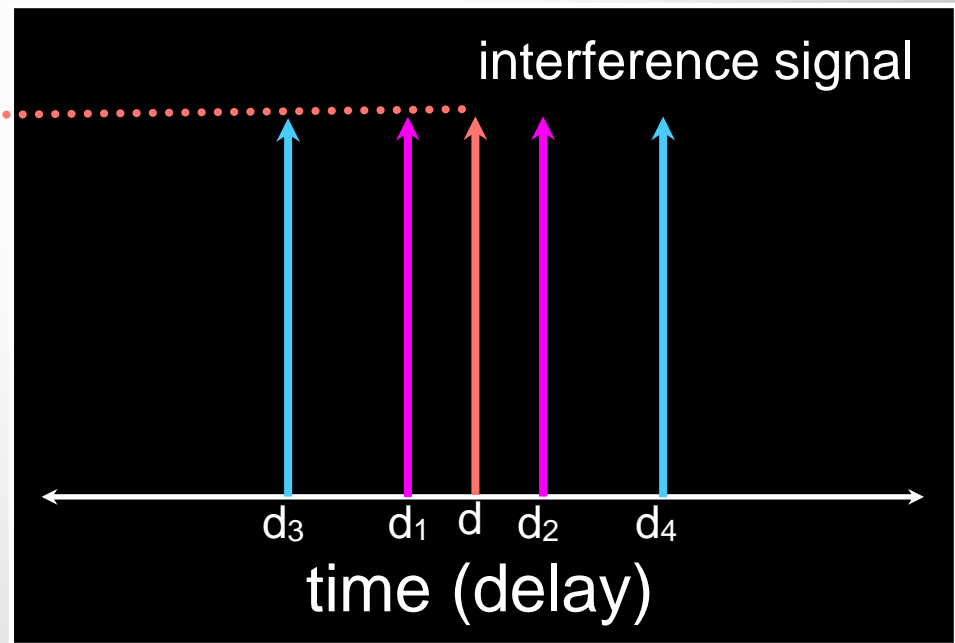
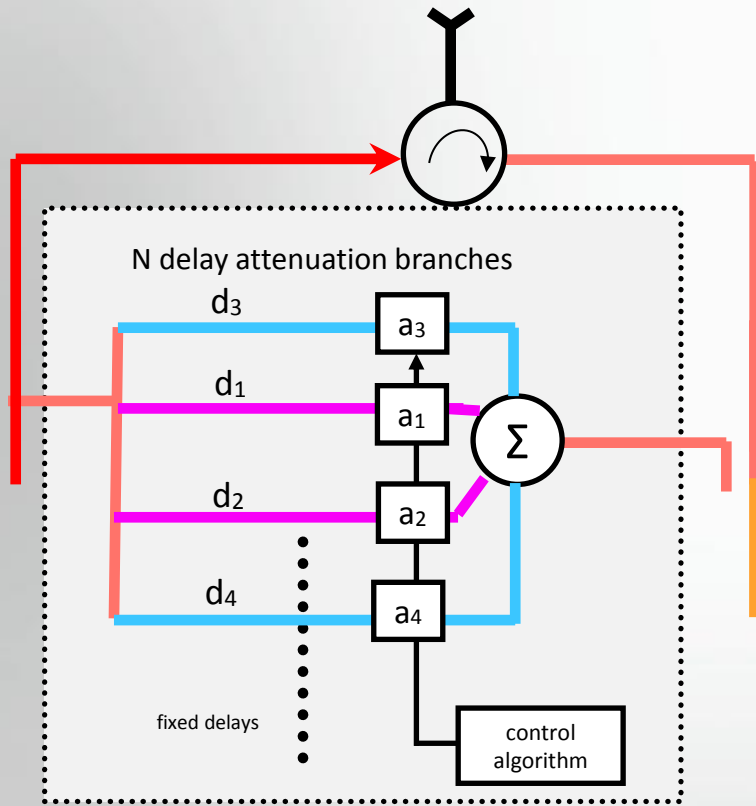


Analog Theory Intuition: Branch Delays



Delays are fundamentally related to sampling theory

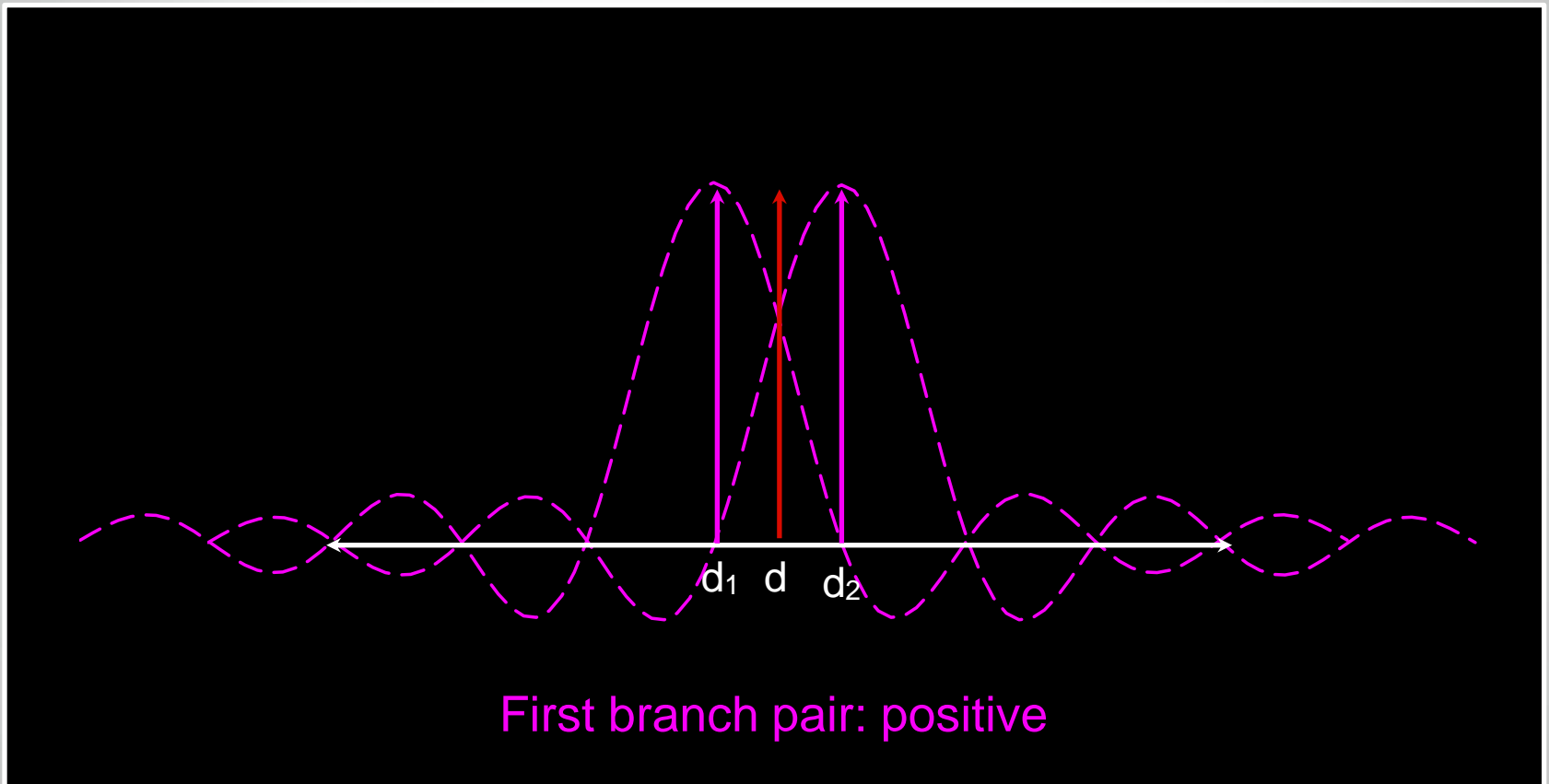
Analog Theory Intuition: Branch Delays



Delays are fundamentally related to sampling theory

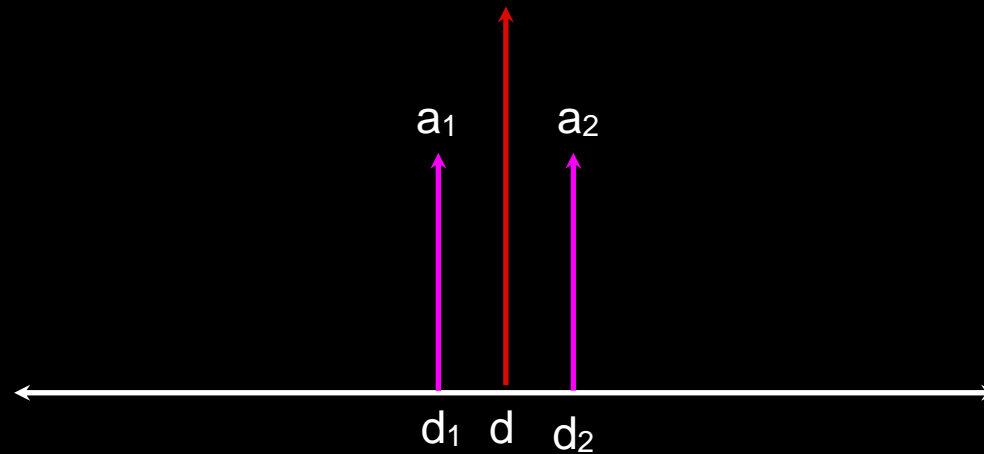
Estimating Branch Attenuation

How do we fix attenuation ranges?



Estimating Branch Attenuation

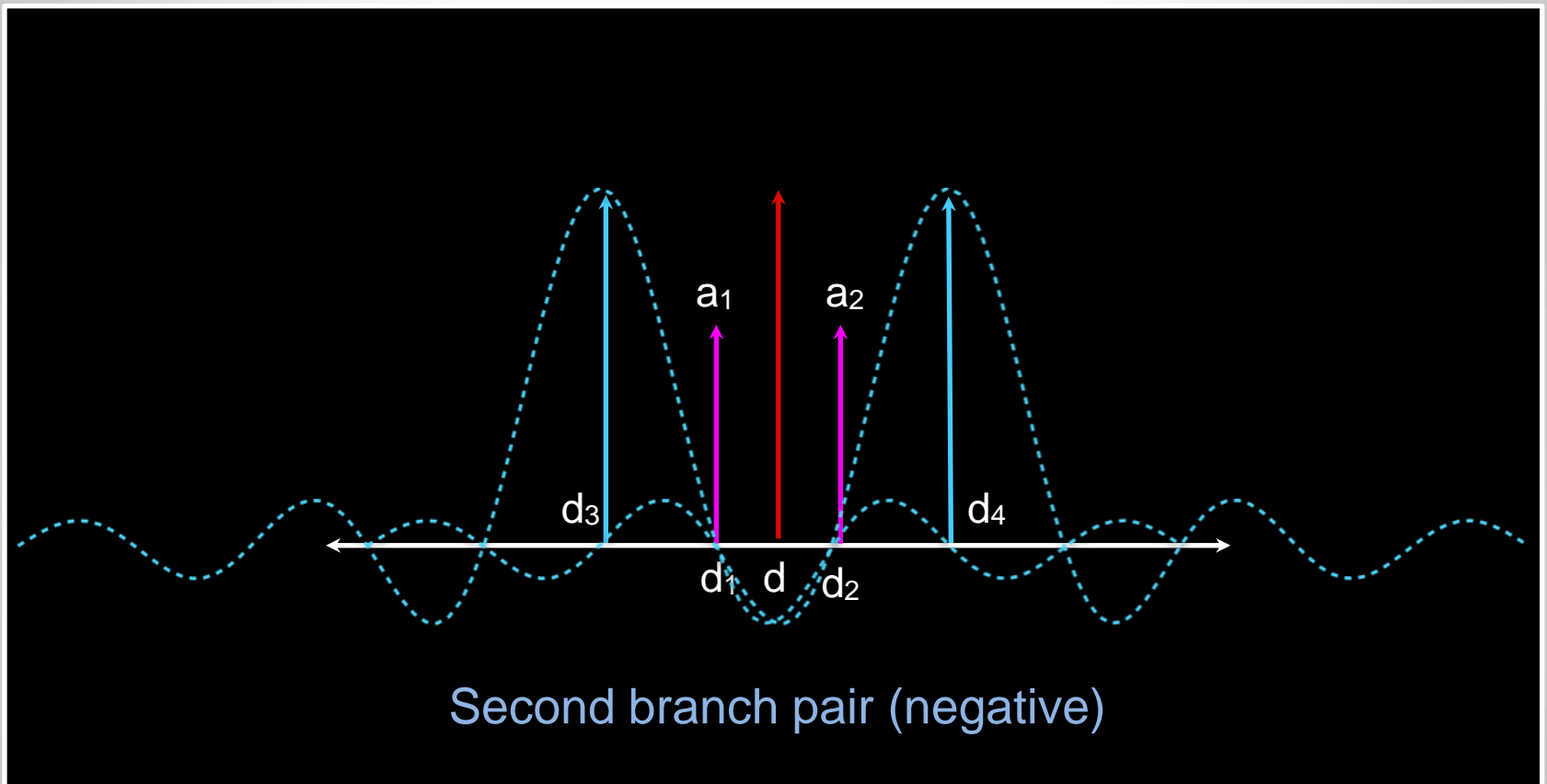
How do we fix attenuation ranges?



First branch pair: positive

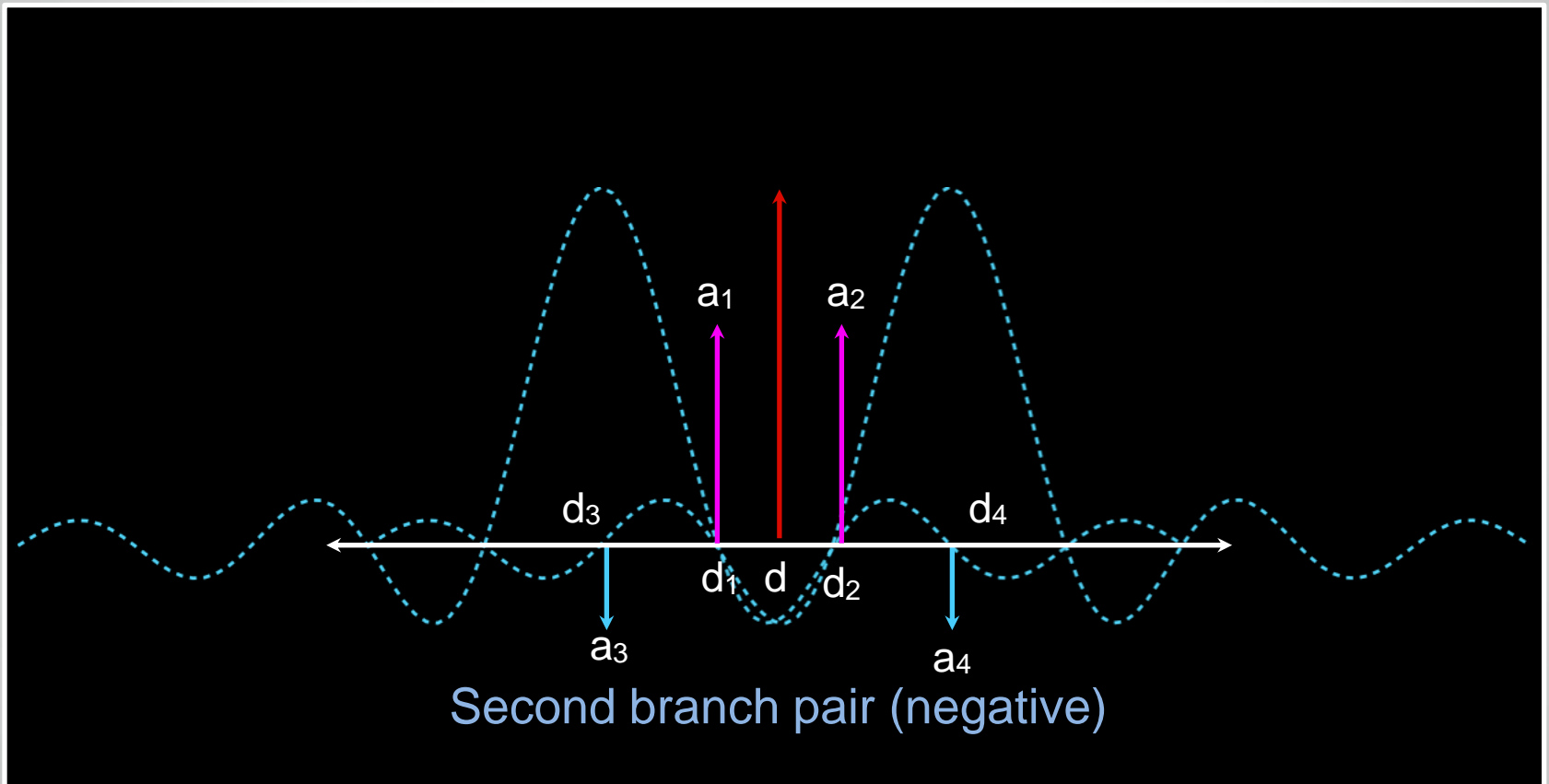
Estimating Branch Attenuation

How do we fix attenuation ranges?



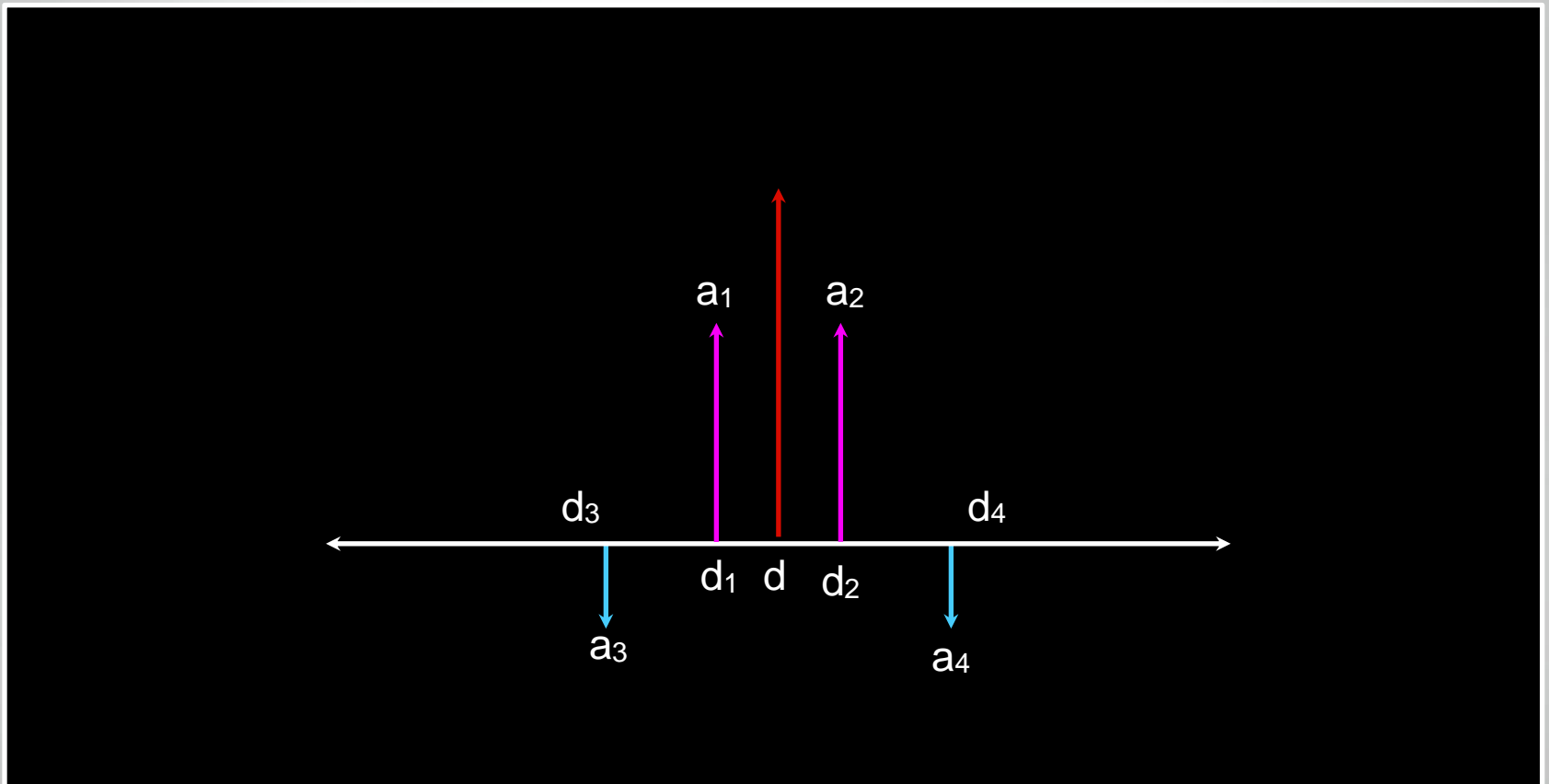
Estimating Branch Attenuation

How do we fix attenuation ranges?



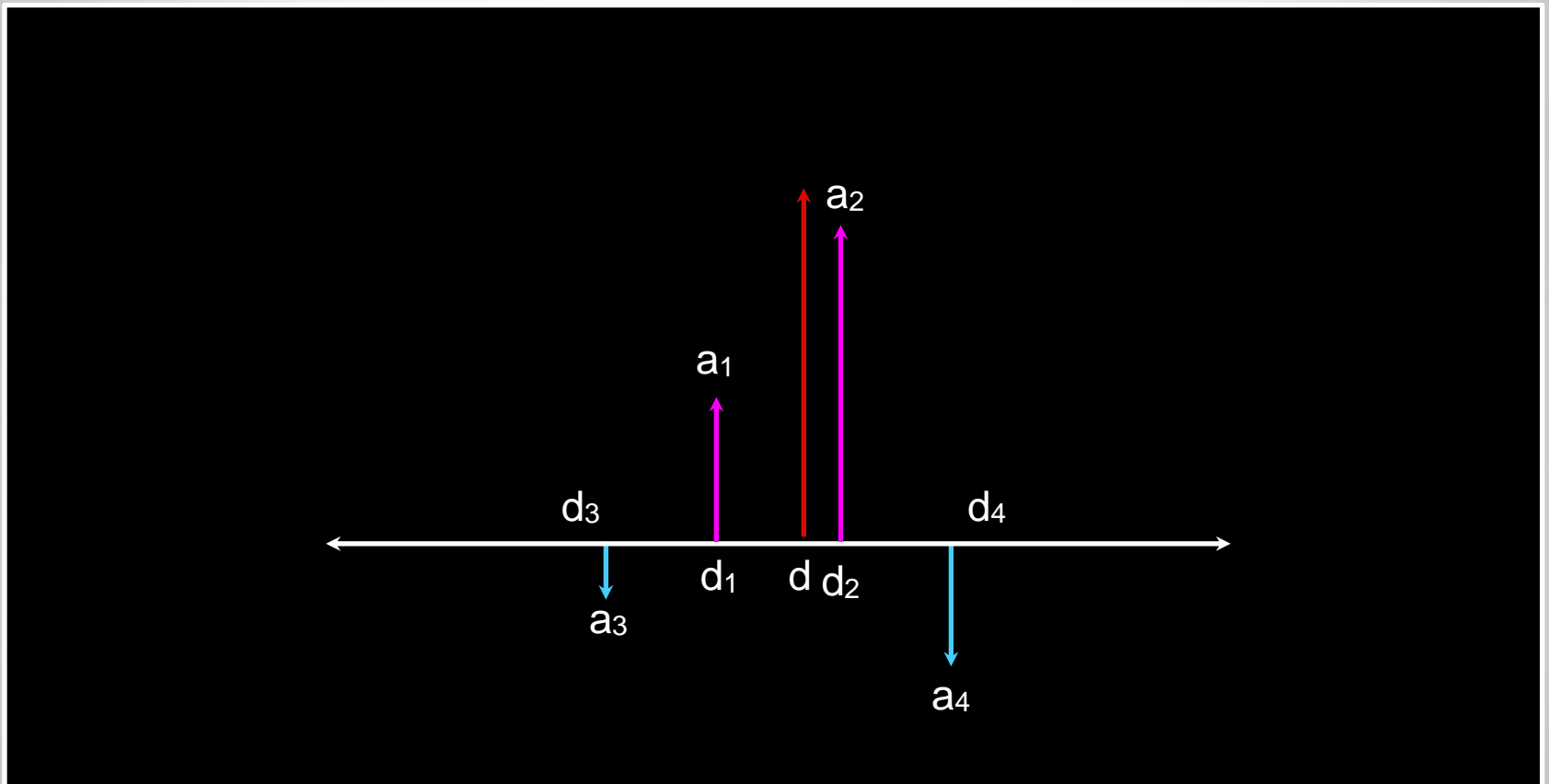
Estimating Branch Attenuation

Adaptation to environmental changes: Assumption d known



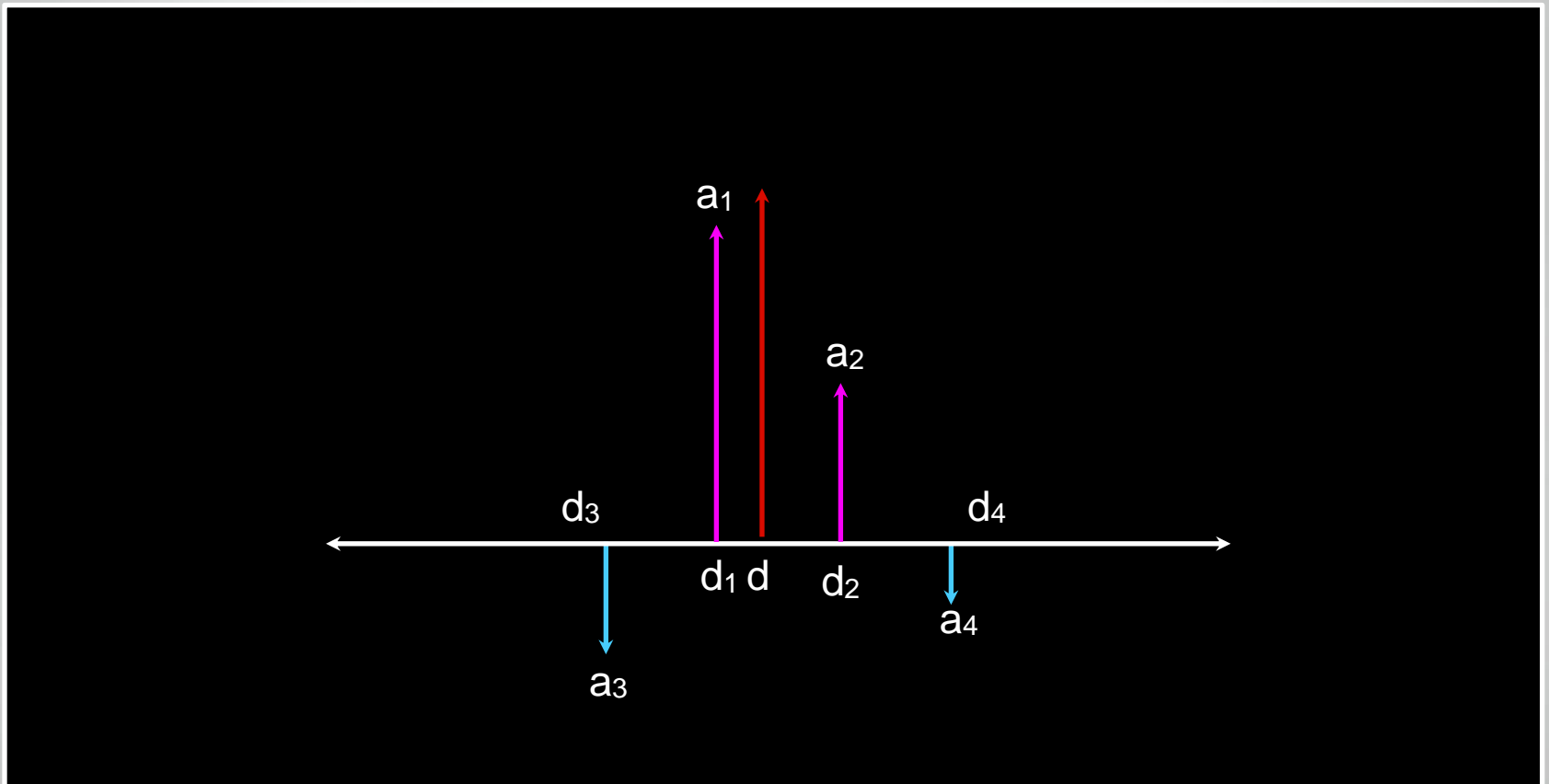
Estimating Branch Attenuation

Adaptation to environmental changes

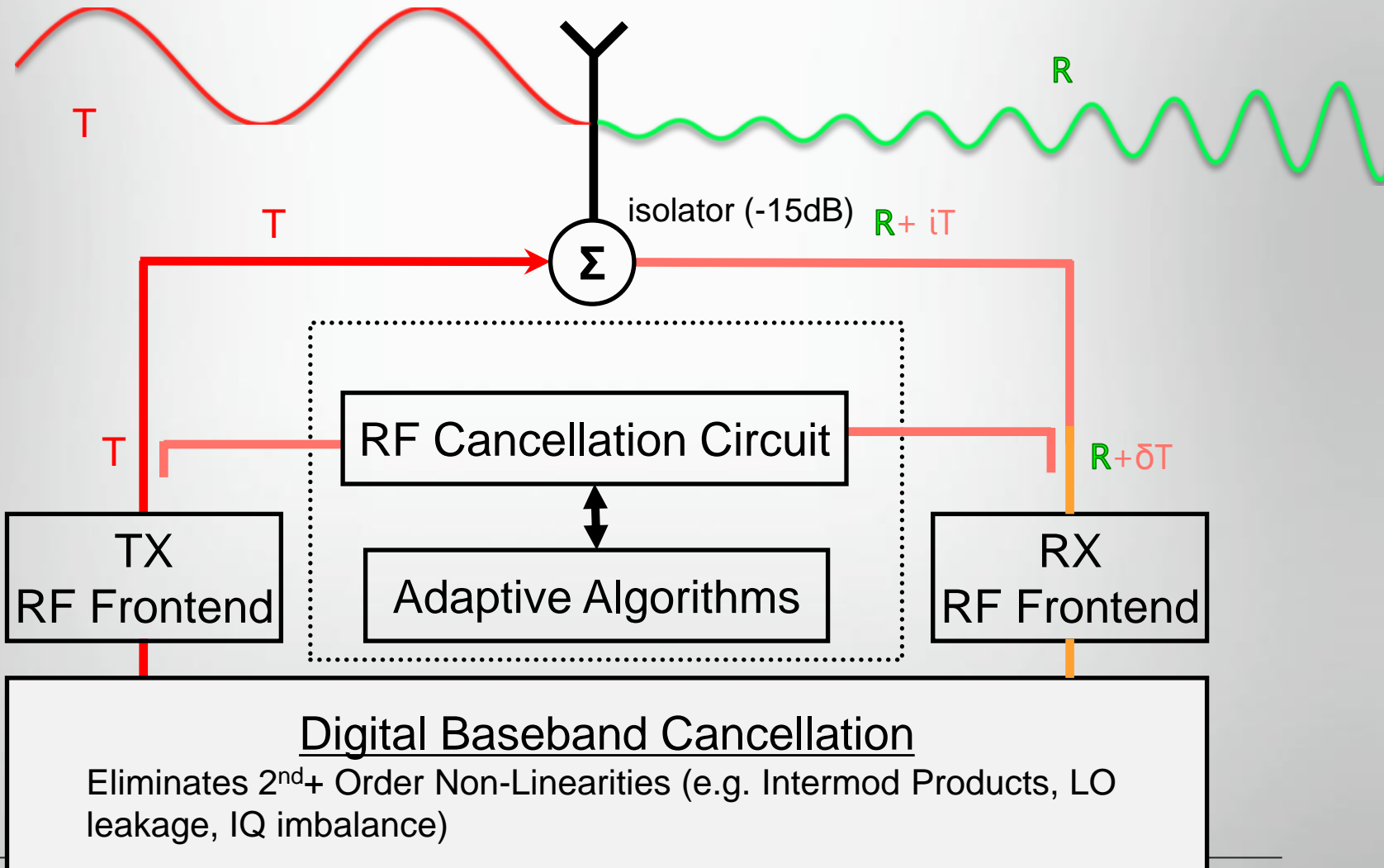


Estimating Branch Attenuation

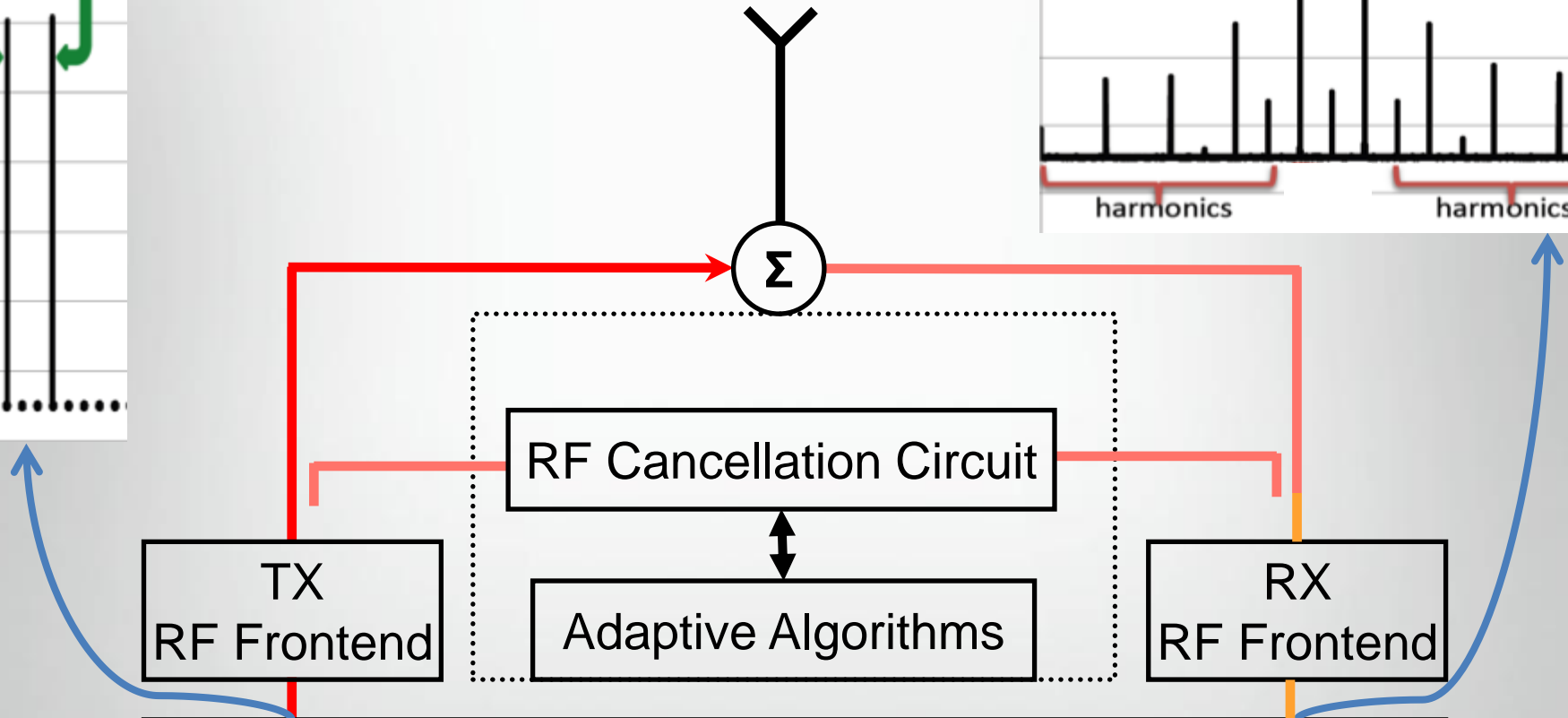
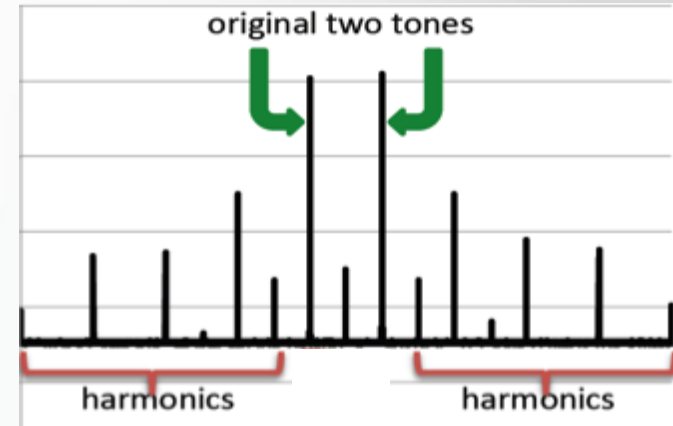
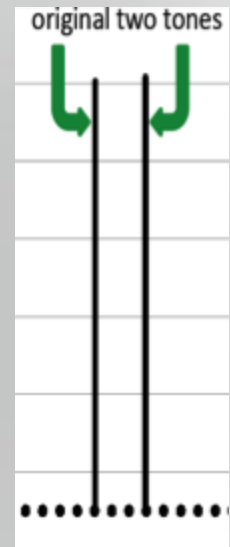
Adaptation to environmental changes



Digital Baseband Cancellation



Digital Baseband Cancellation



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

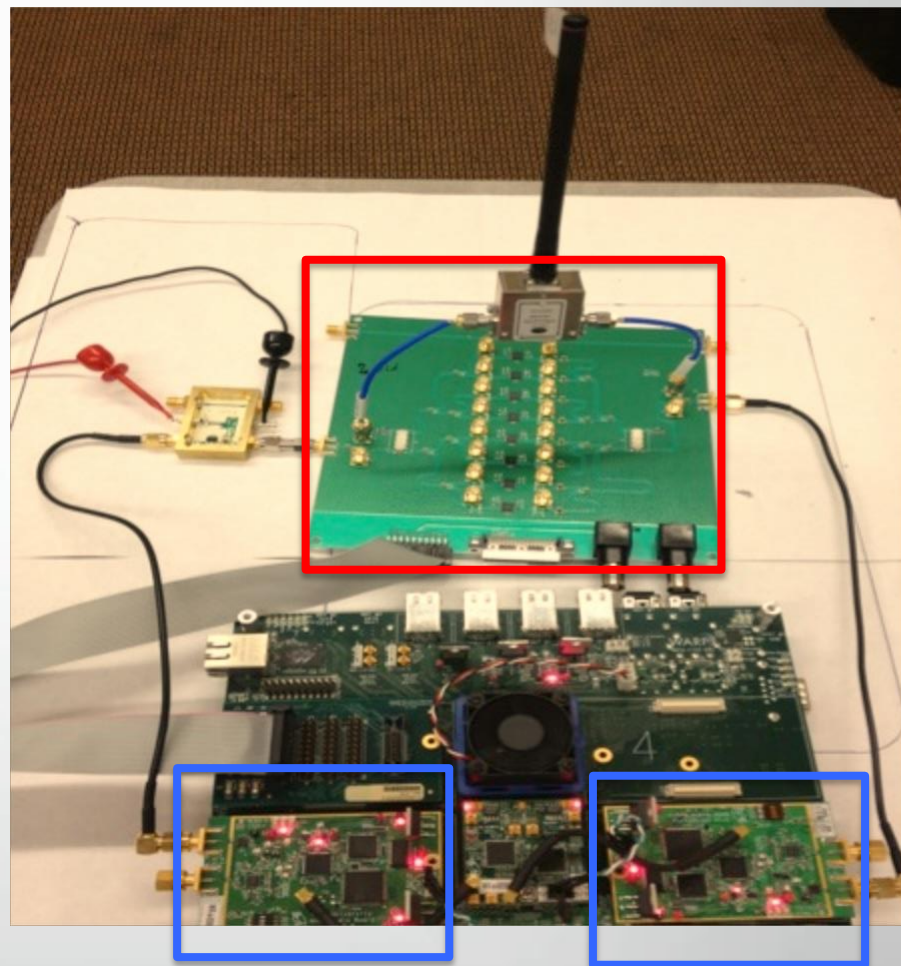
Digital Self-Interference Cancellation

- Challenge: Need to cancel main signal as well as higher order harmonics upto the 11th 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?

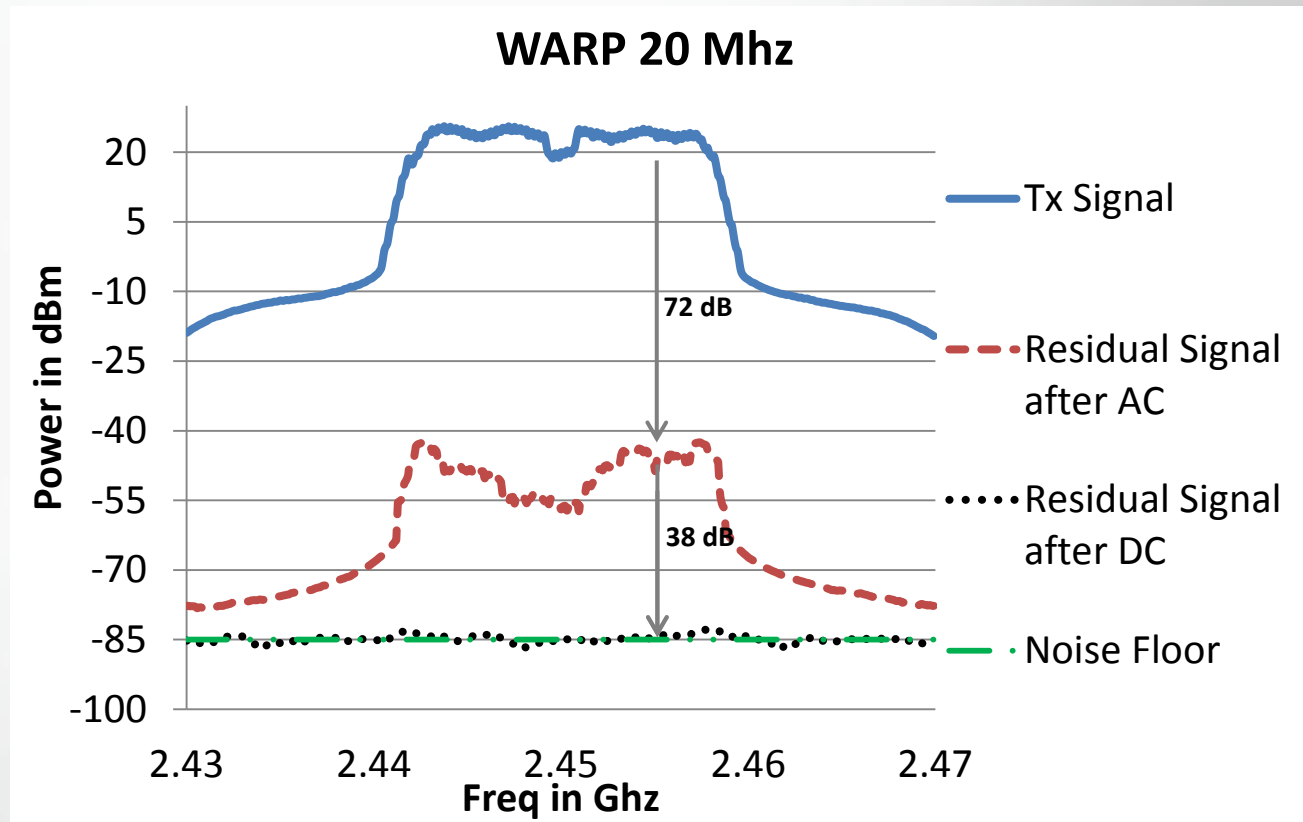
Goal: Build a full duplex radio using a cheap \$2 COTS Maxim transceiver

- 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?

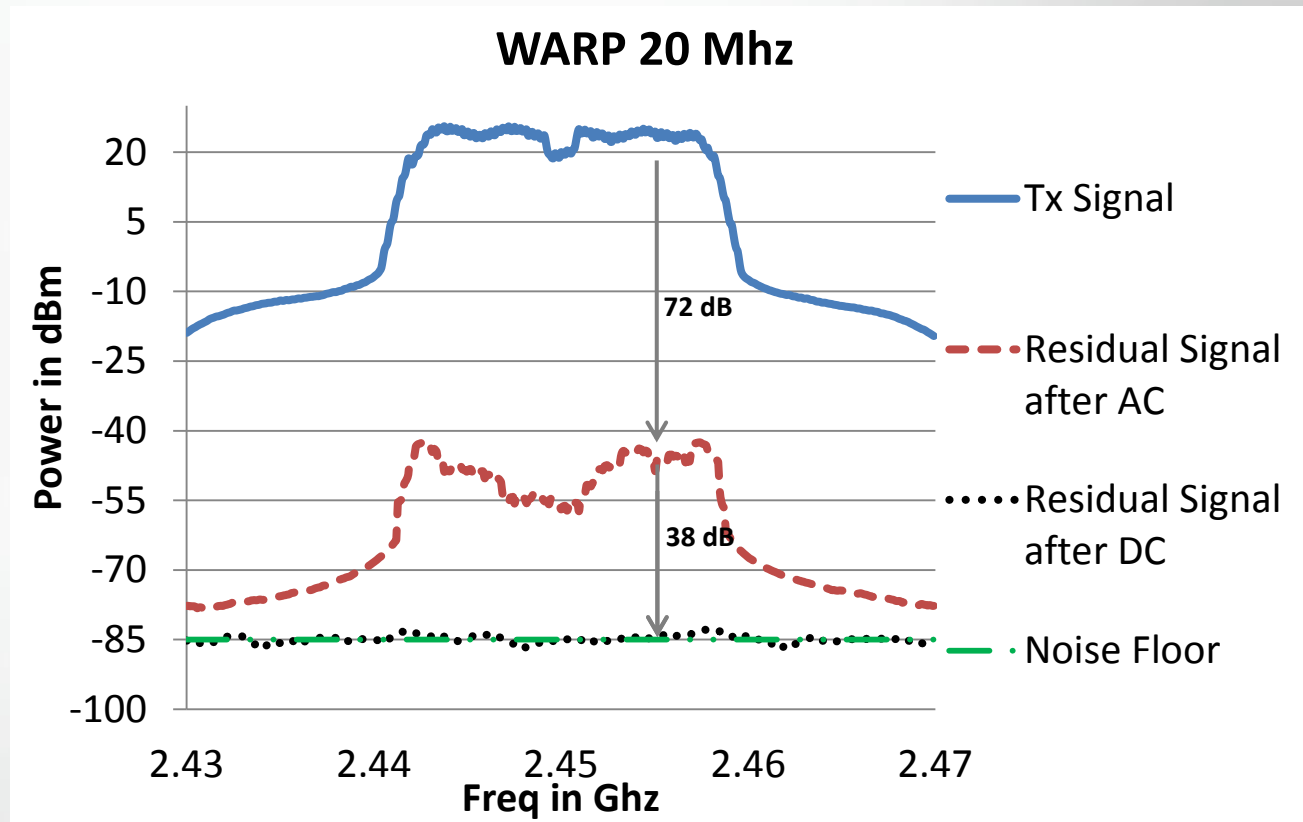
- Commodity transceiver



<u>Analog</u> > 70dB	+	<u>Digital</u> ~40dB	=	<u>Total</u> > 110dB
-------------------------	---	-------------------------	---	-------------------------

Evaluation Q1: Does it work with commodity radios?

- Commodity transceiver
- Tunes to environmental changes within 8 μ s, 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

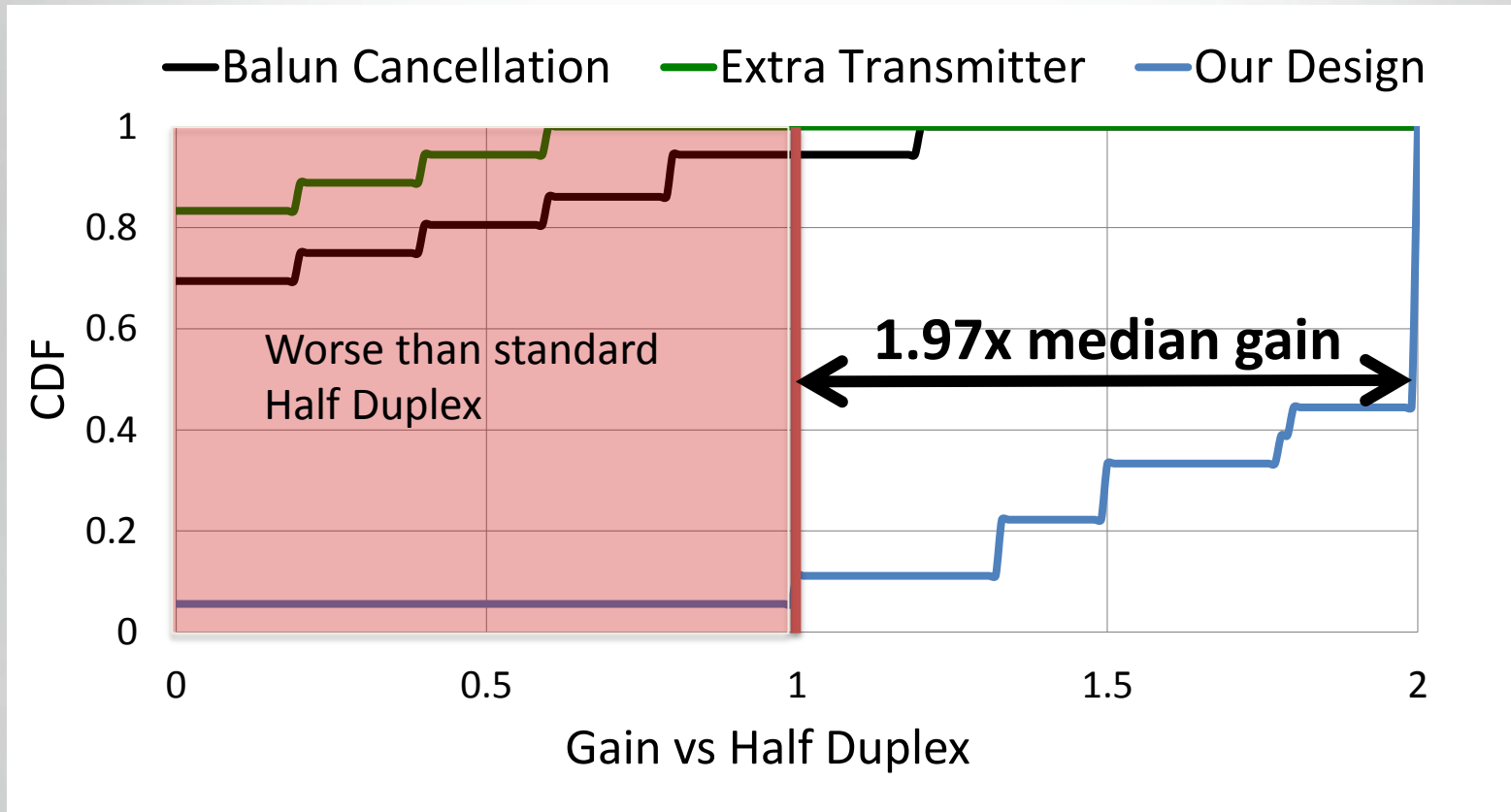
Minimum SNR required for receiving a packet > Self-interference residue over noise floor

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

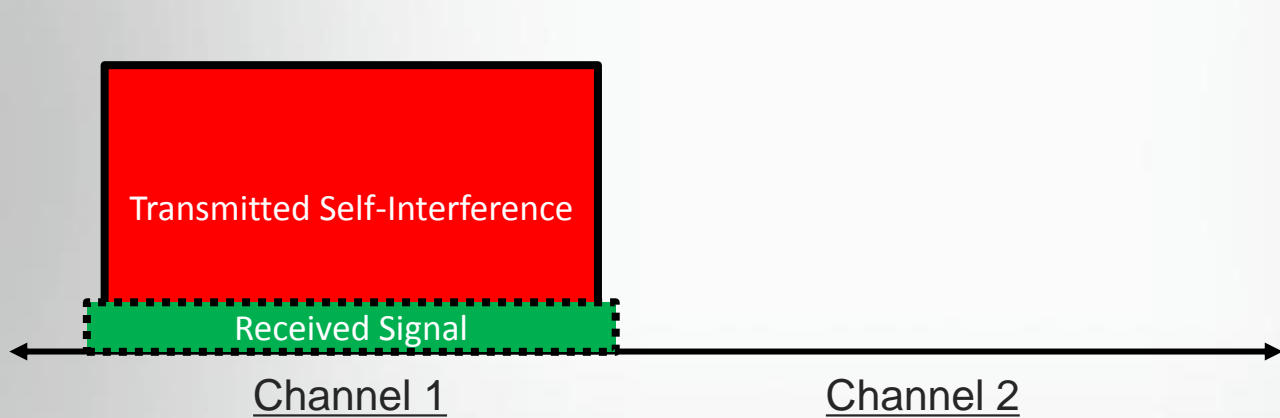
$$\text{Gain} = \frac{\text{Throughput of FD}}{\text{Throughput of HD}}$$

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



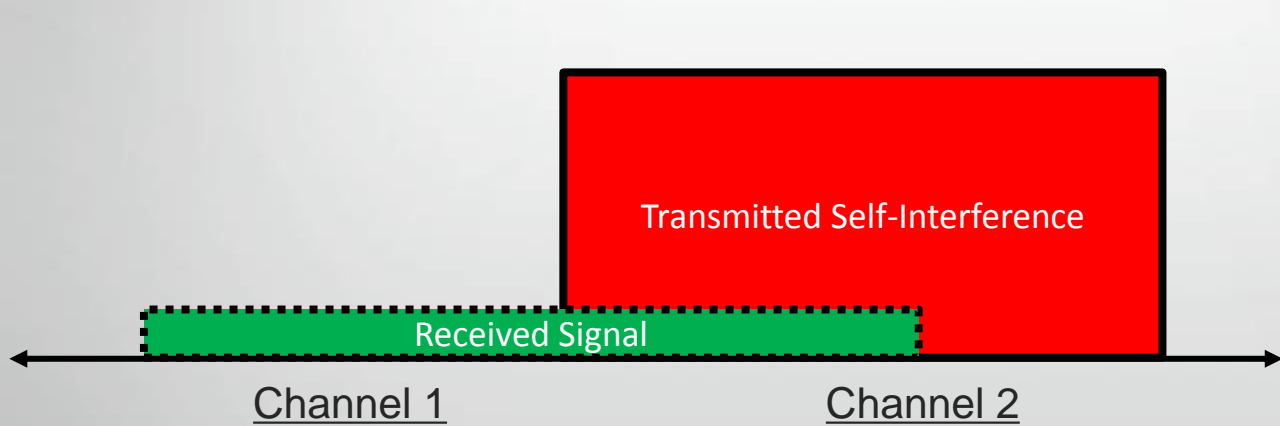
Our design achieves the theoretical throughput doubling

Self-interference cancellation is broadly applicable



In-Band Full Duplex

Double capacity



Adaptive Frequency Division Full Duplex (AFDD)

Flexibly decide which channels to transmit & receive on

Full Duplex Everywhere

Applicable To a Host of Problems



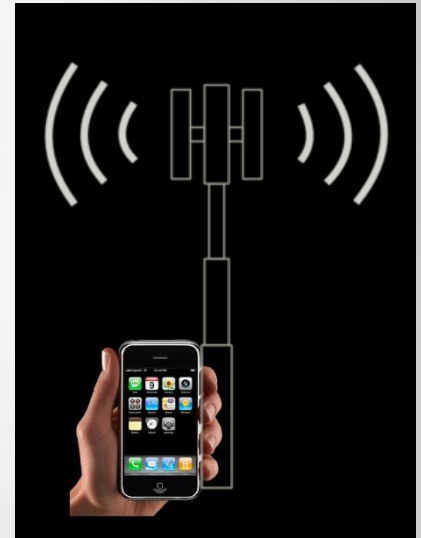
PtP and PtMP Backhaul
Doubles spectral efficiency, and mitigate interference in unlicensed bands



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, Dhwani, ...)

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