Full Duplex MIMO Radios

Dinesh Bharadia and Sachin Katti
Stanford University

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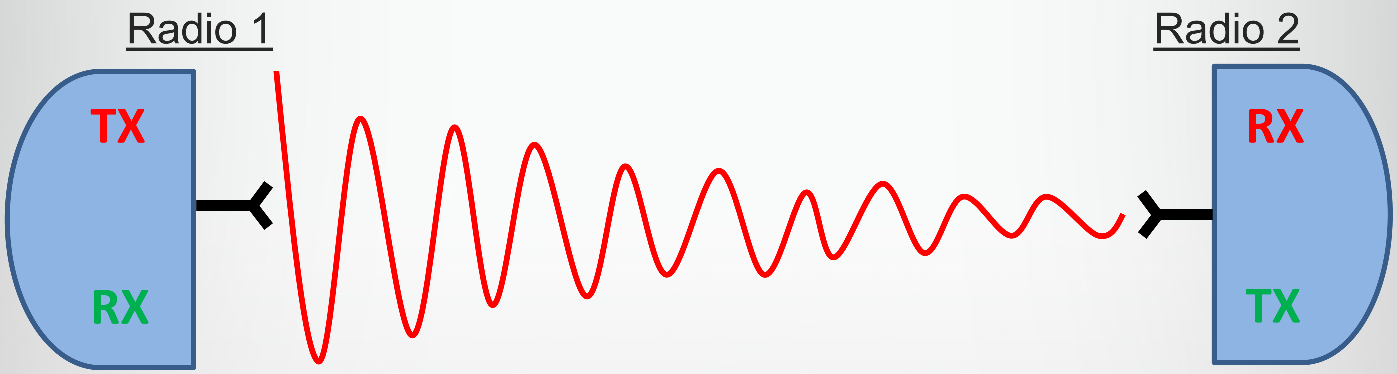

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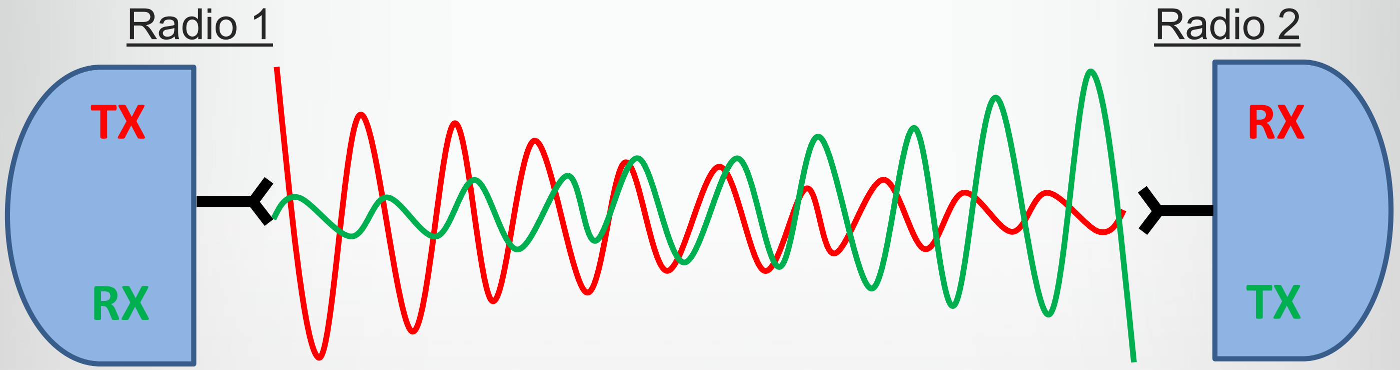

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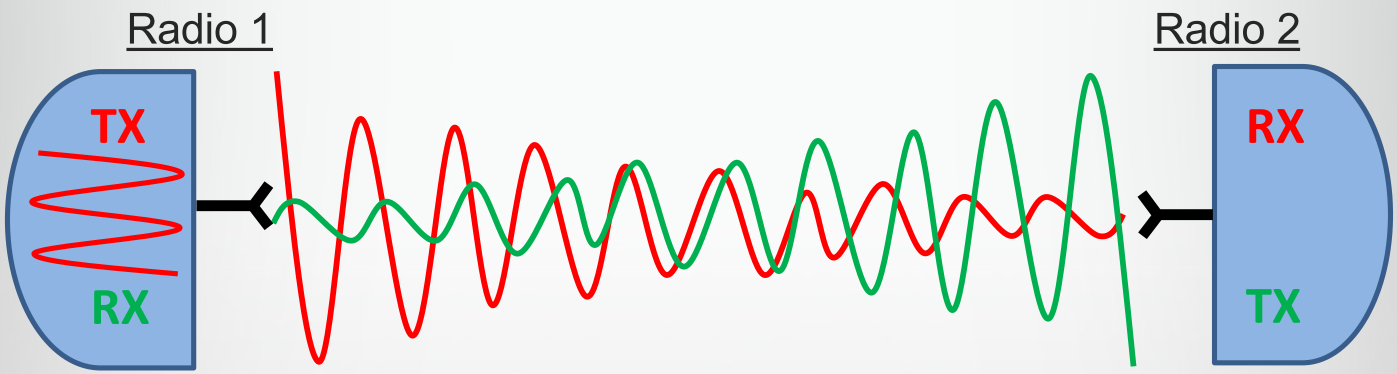
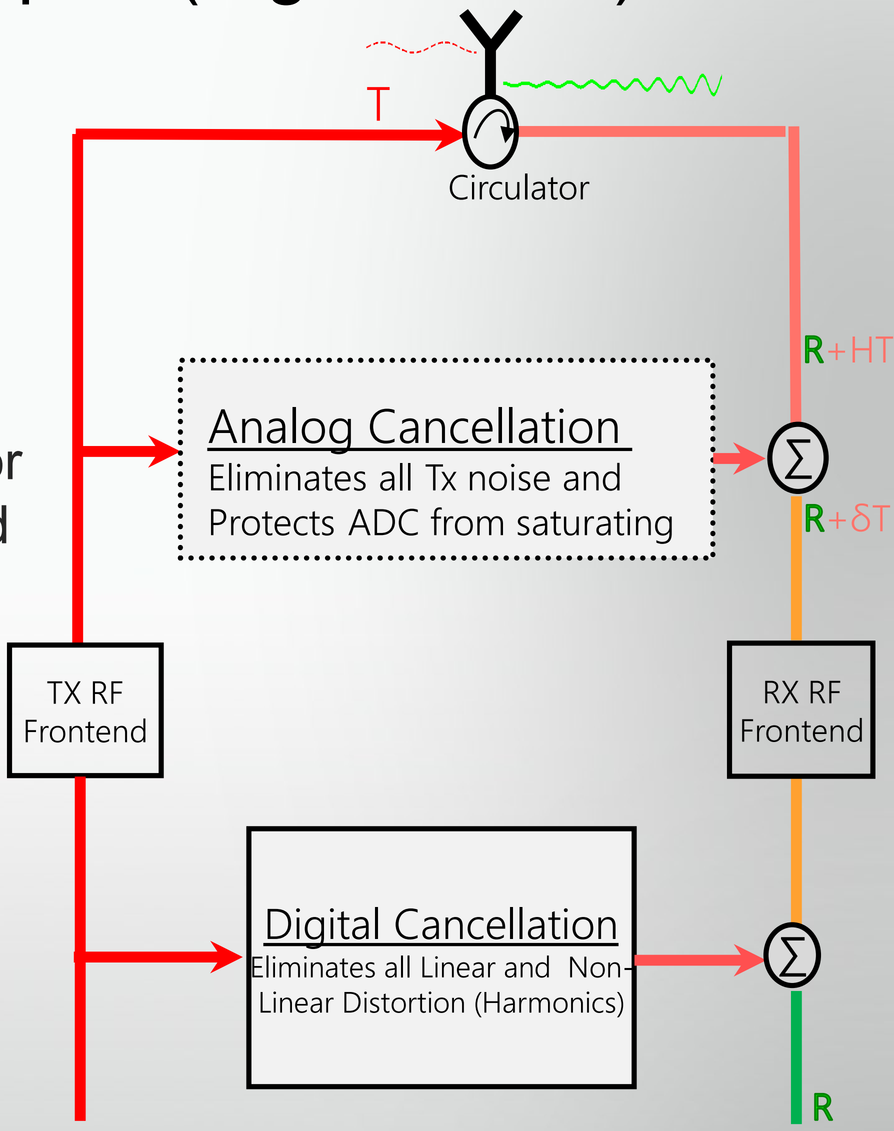


Self-Interference is a hundred billion times (110dB+) stronger than the received signal

State of the Art: SISO Full duplex (Sigcomm'13)

Demonstrated that practical in-band SISO (single antenna) full duplex radios are possible

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



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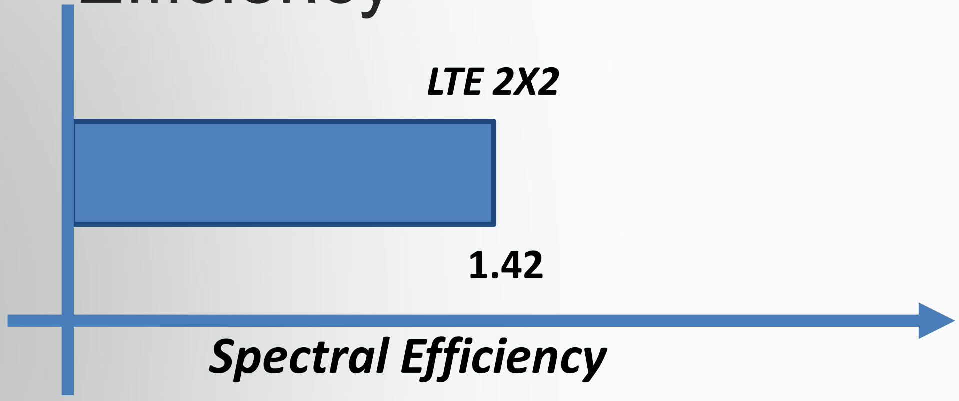

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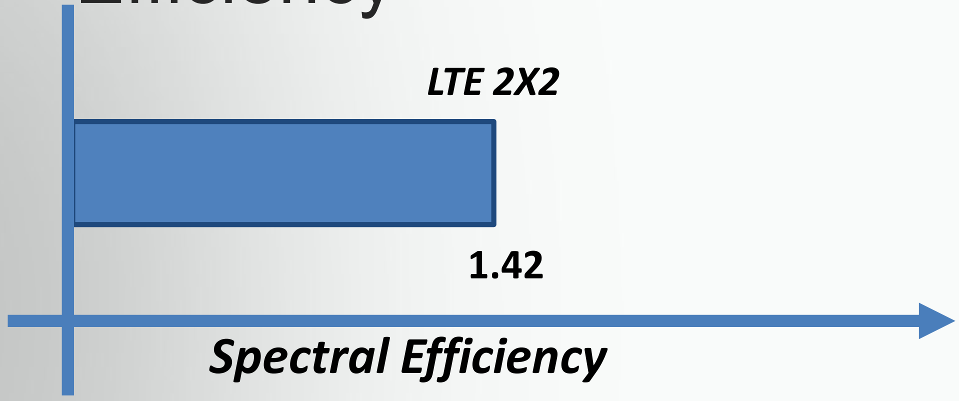

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- Spectra Efficiency Doubled over last decade

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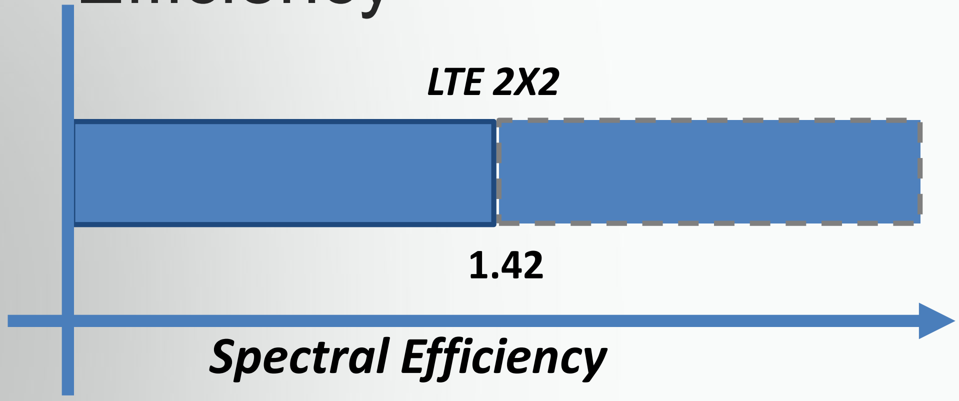

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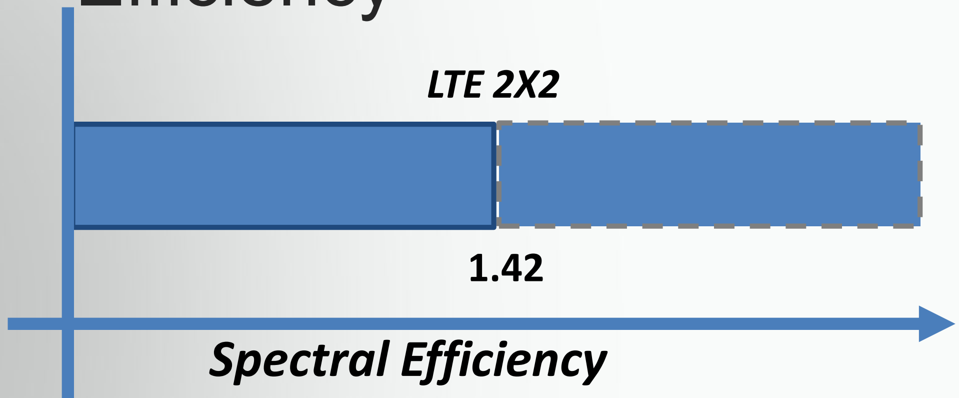

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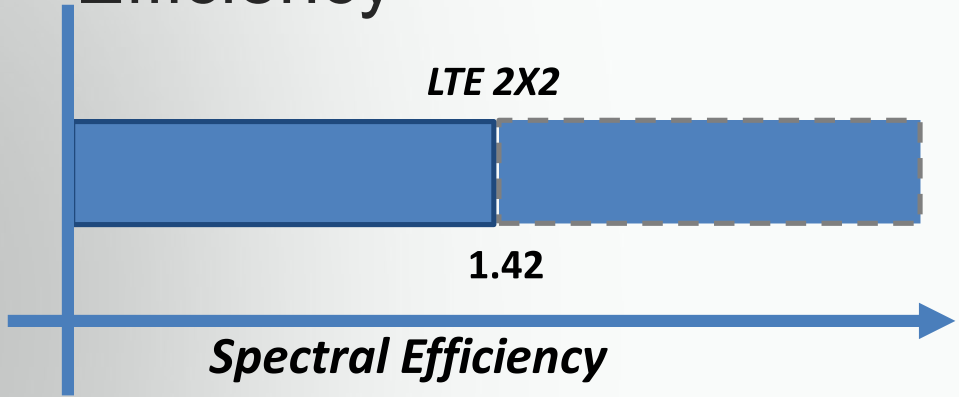

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Spectral efficiency gains over last decade mostly from MIMO
→ For full duplex to be viable, need to work with MIMO

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Prototype 3x3 MIMO full duplex radios using off-the-shelf WiFi radios

- Experimental indoor evaluation which demonstrates that our design practically achieves close to the 2x theoretically expected throughput gain

Why can not we use the SISO design to implement MIMO full duplex?

State of the Art for SISO full duplex

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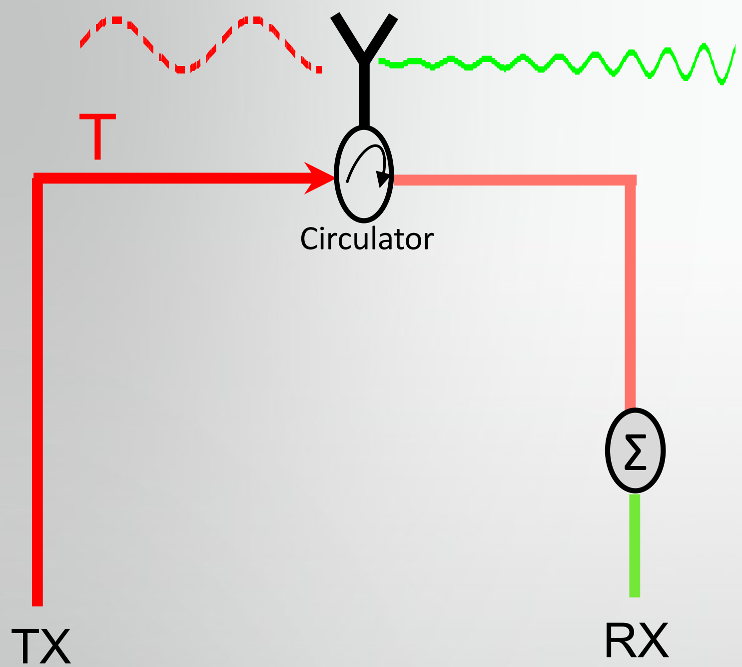
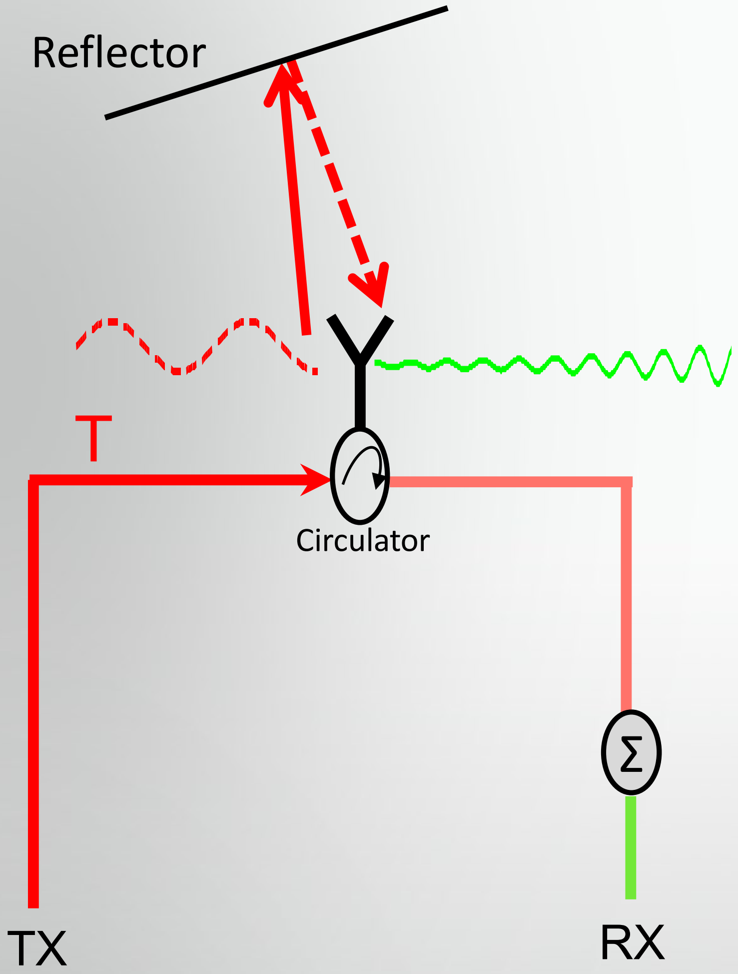


Conceptual model

State of the Art for SISO full duplex



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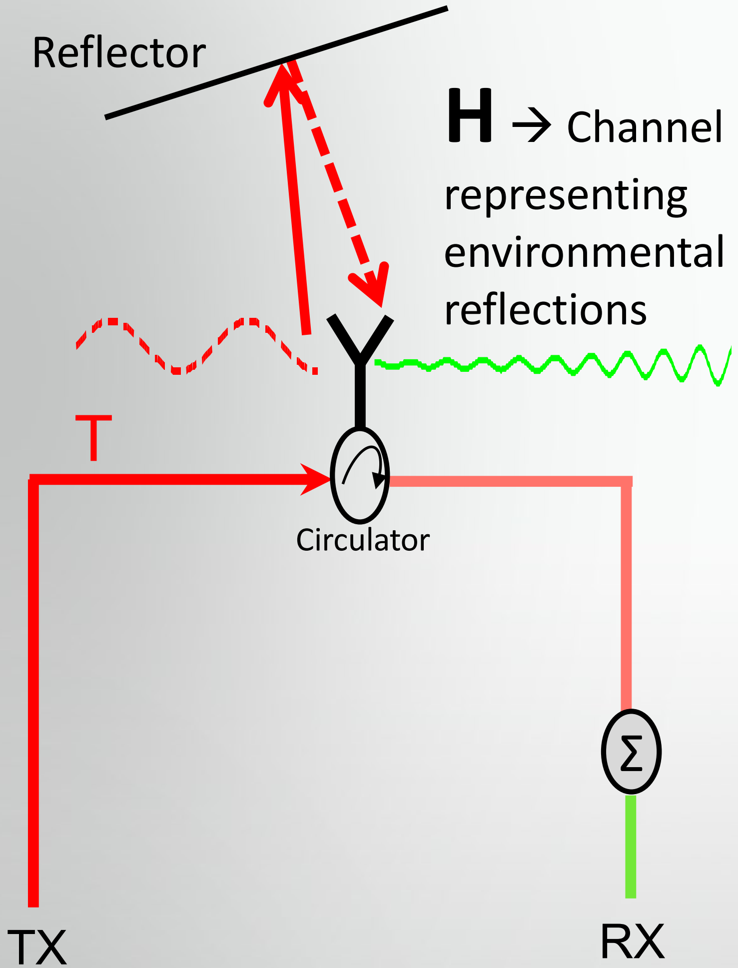

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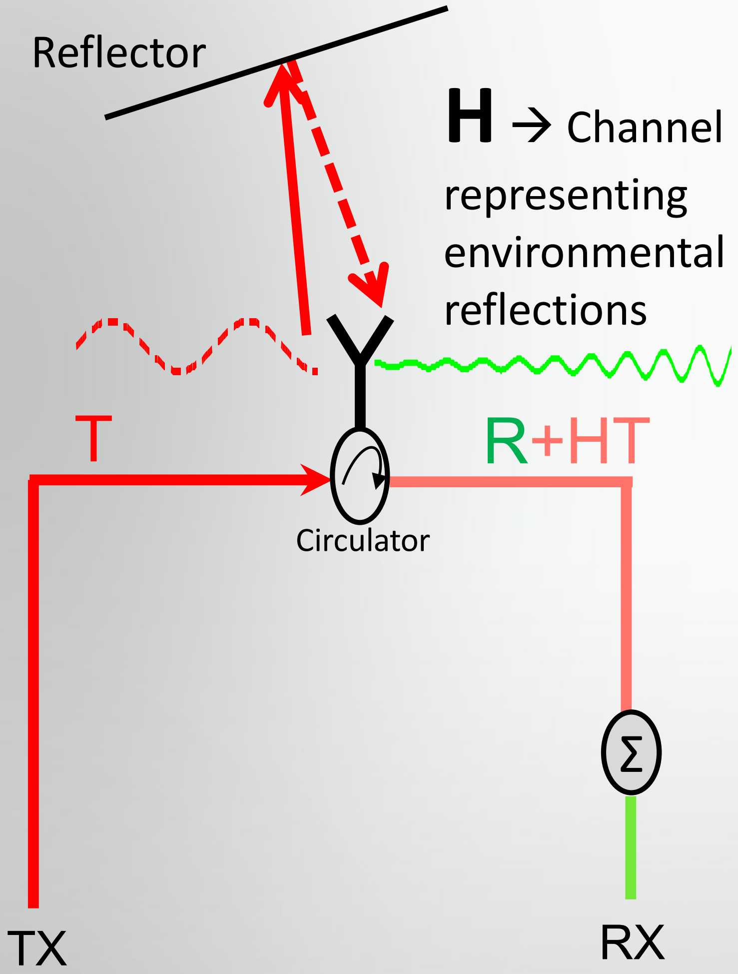

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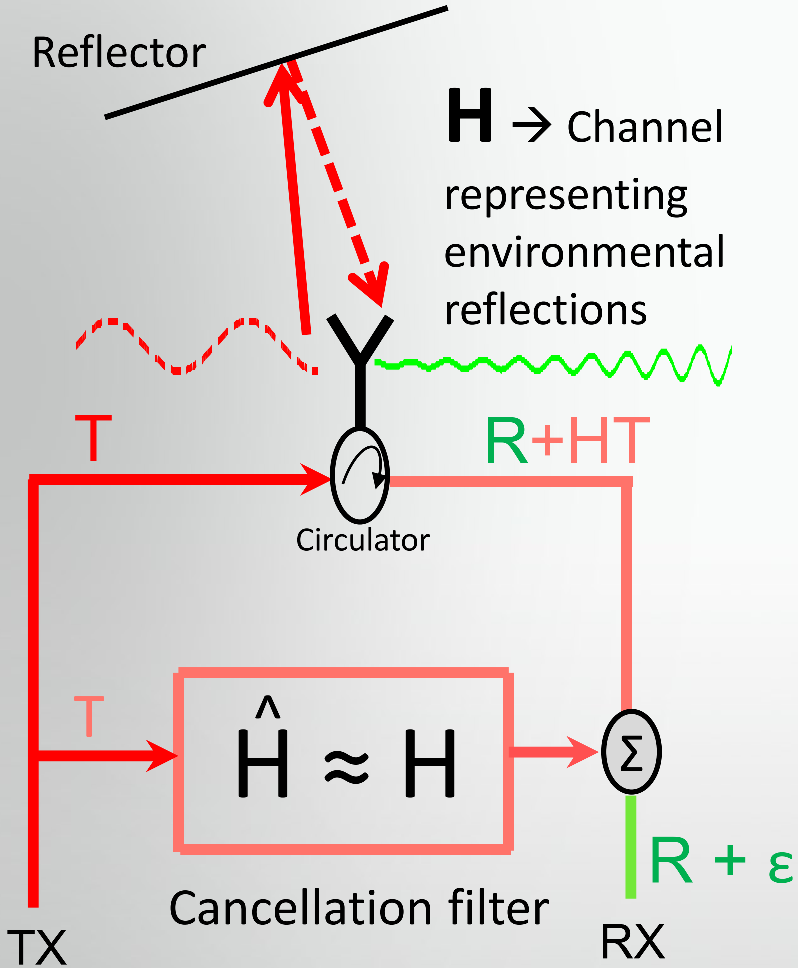

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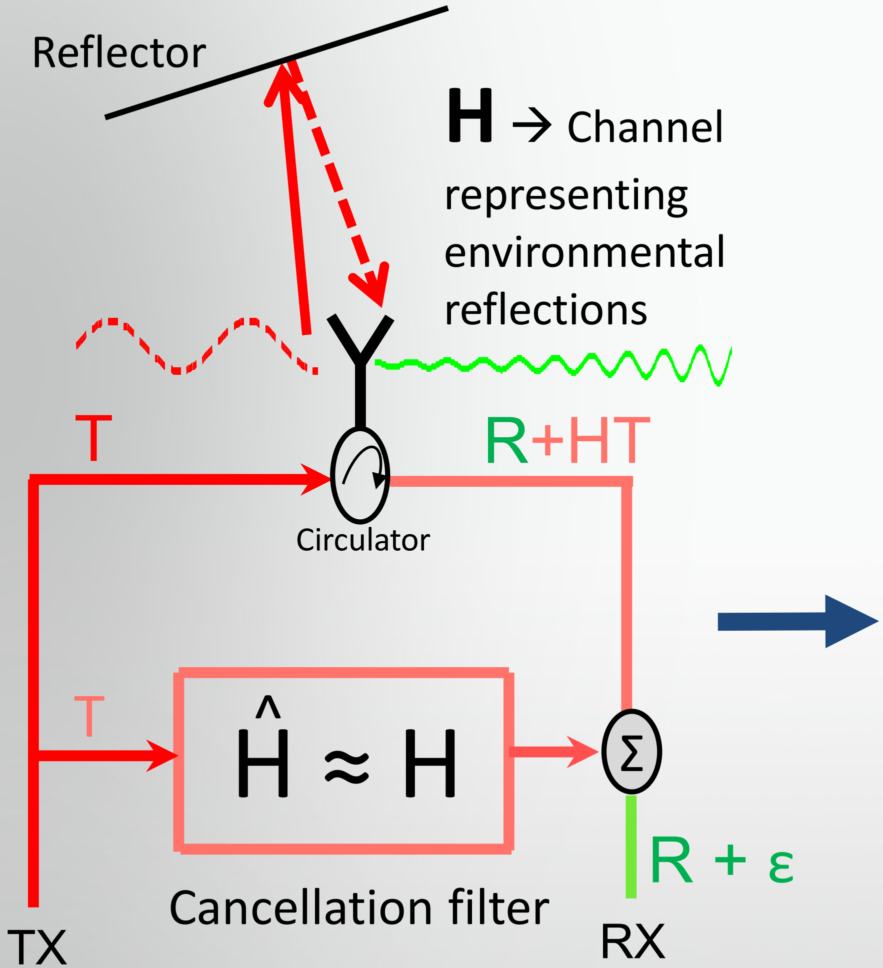

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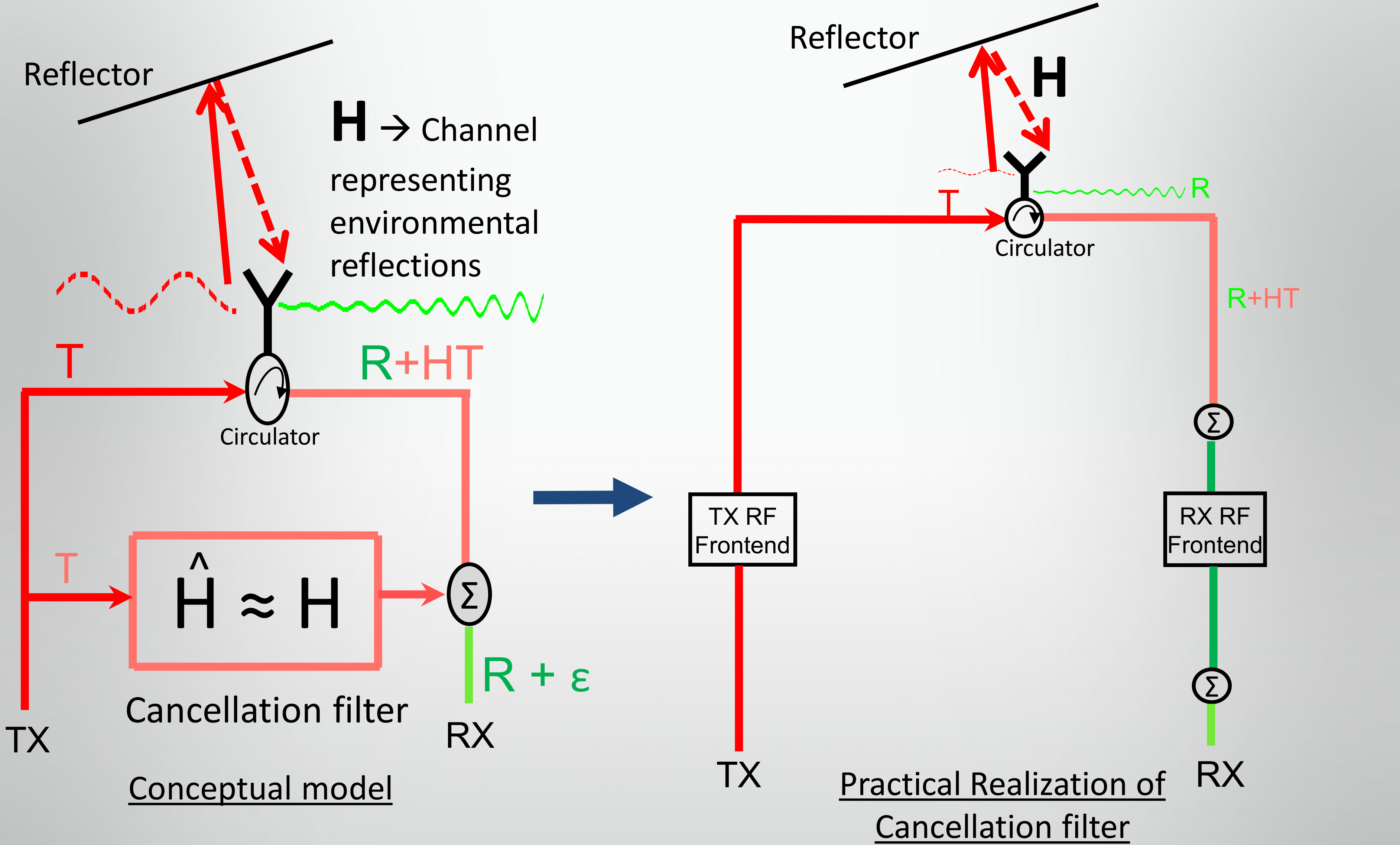

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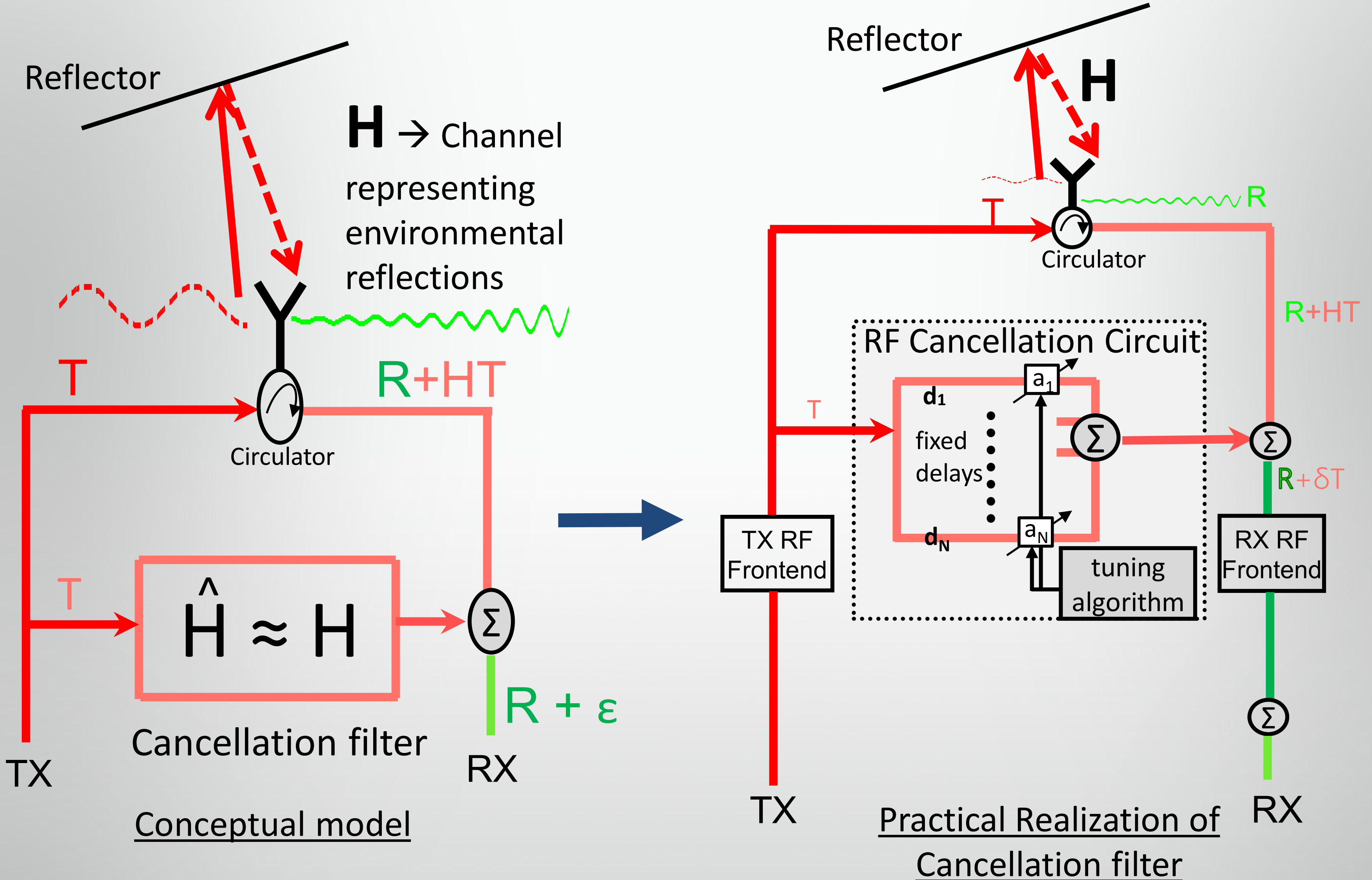

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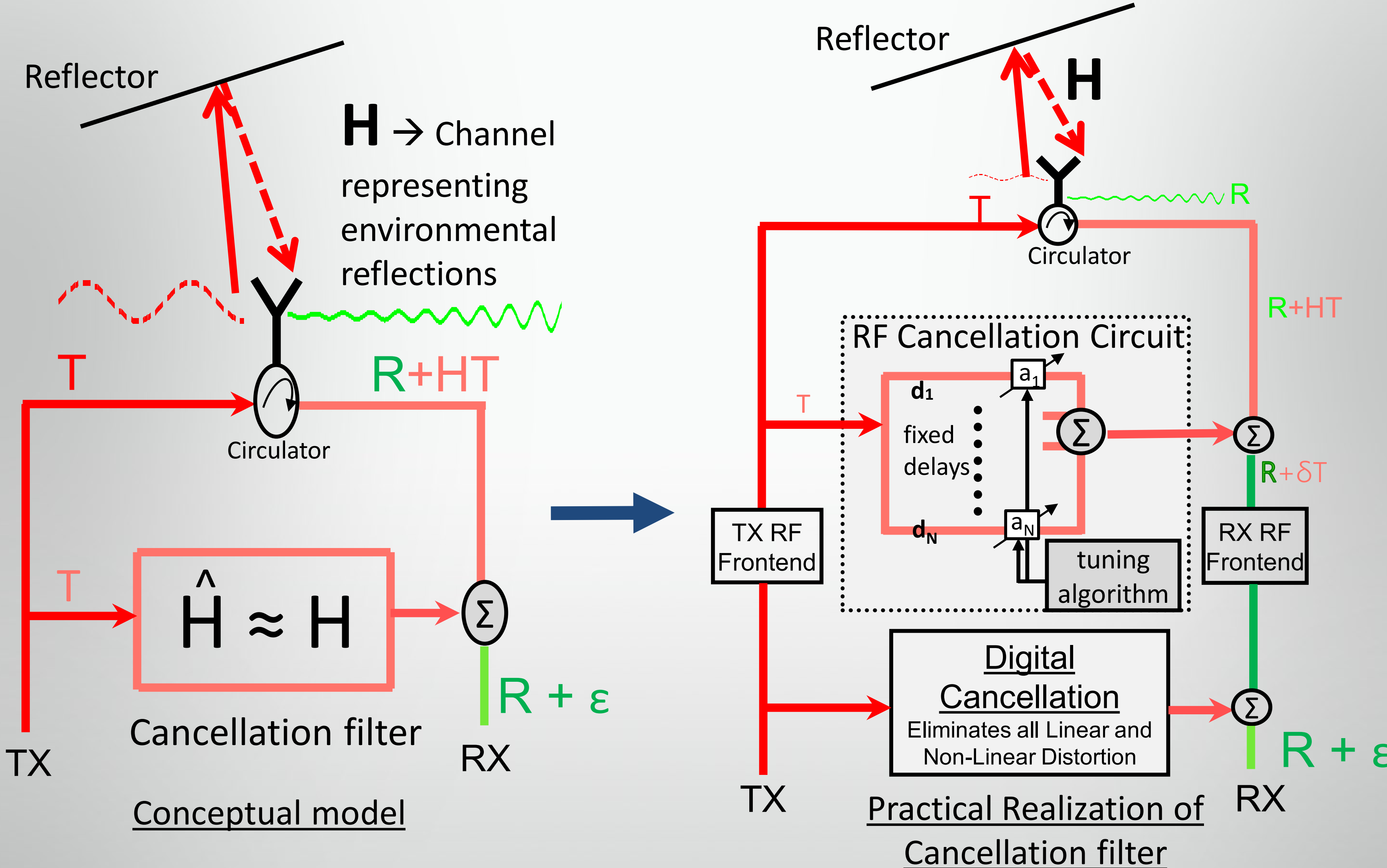

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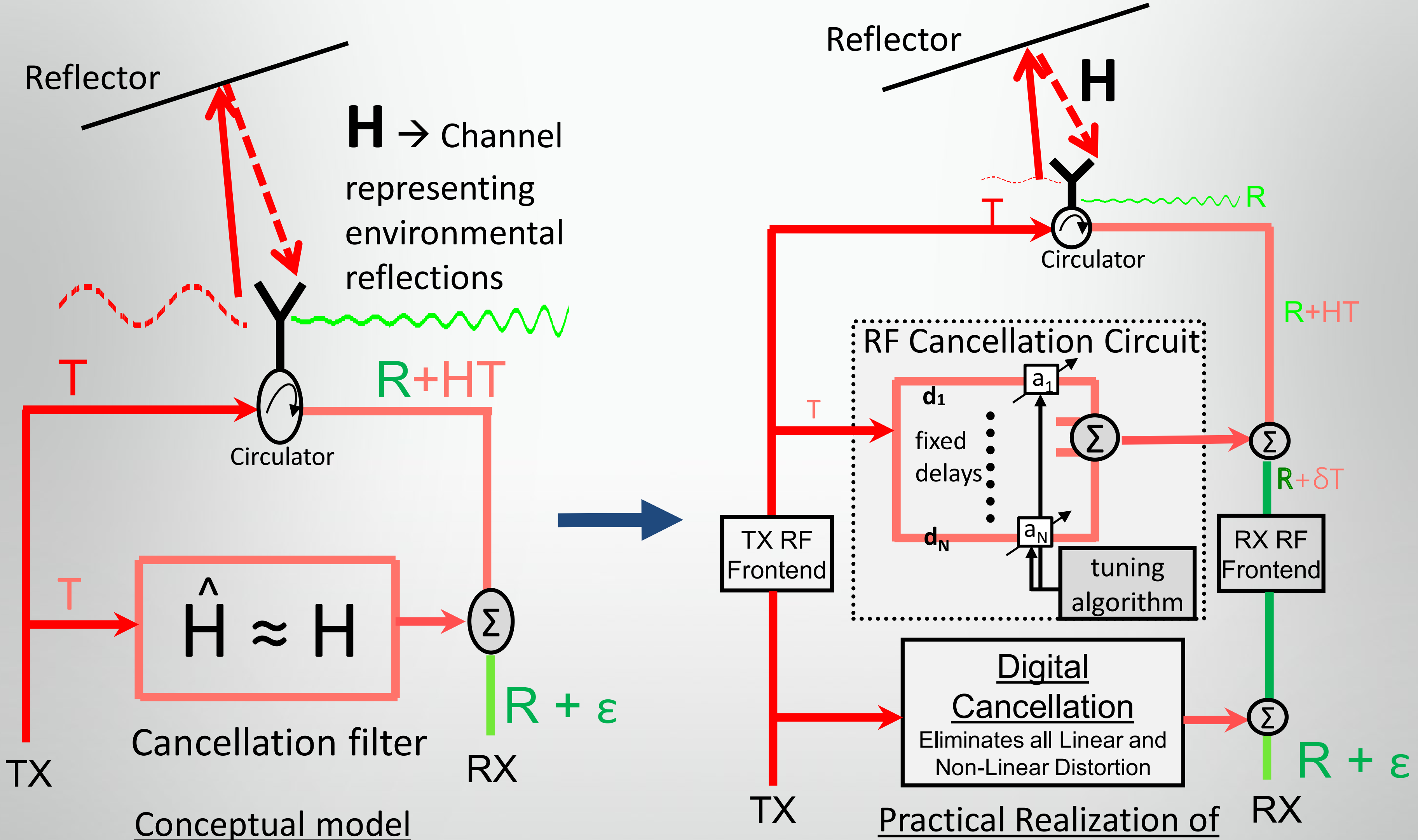

Full duplex designs are conceptually realizing an adaptive filter that closely matches the environmental

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Analog Cancellation taps	12	6x6 inches board
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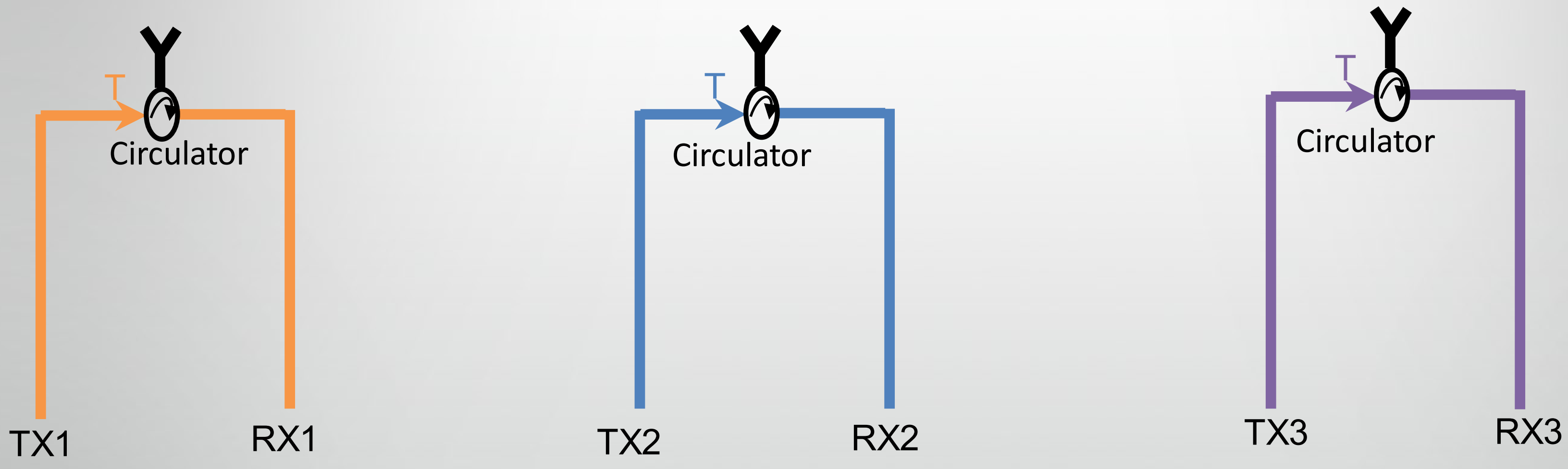
Goal for any full duplex design: Minimize interference residue to the noise floor with the lowest complexity cancellation filter

How is the MIMO full duplex problem different?



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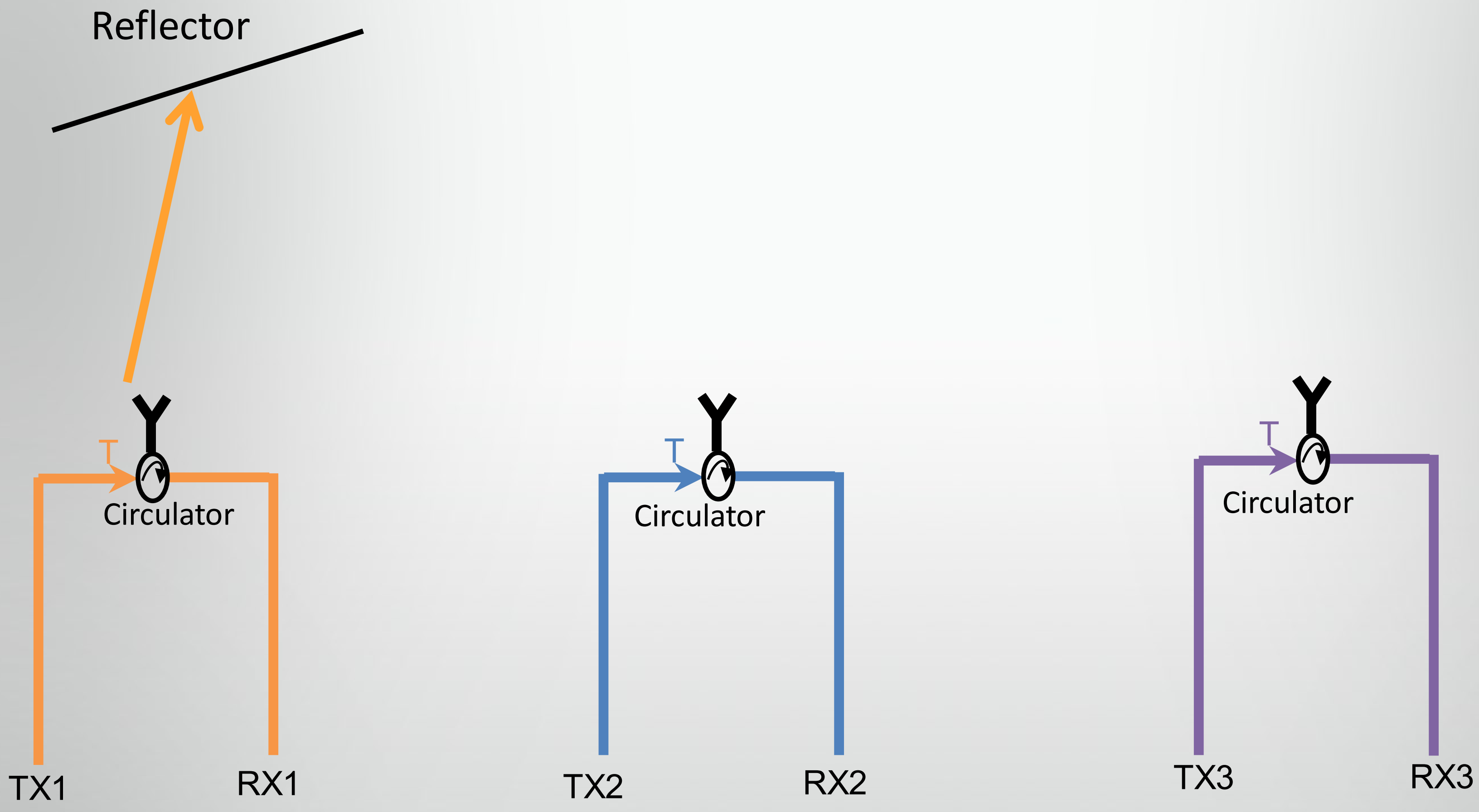

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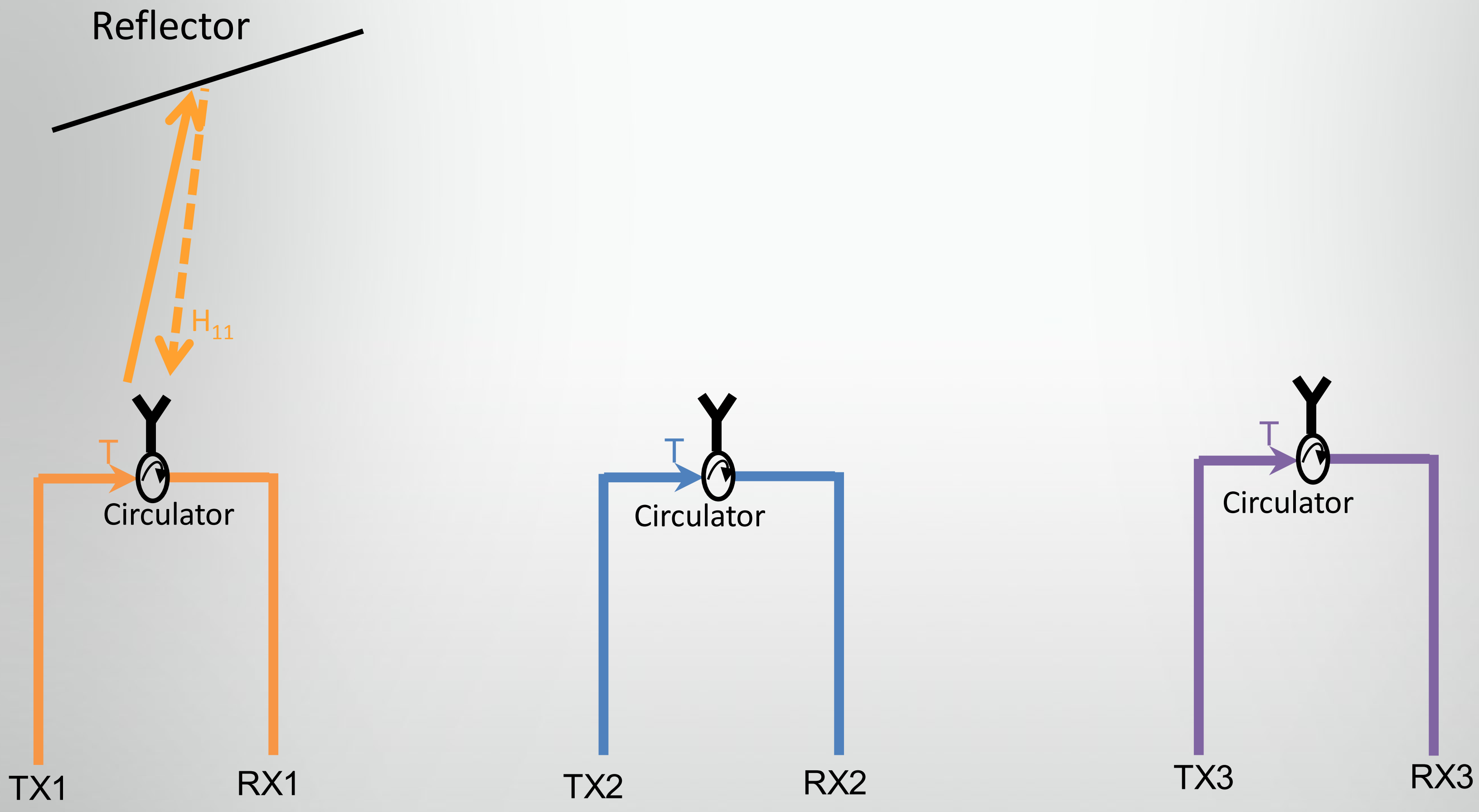

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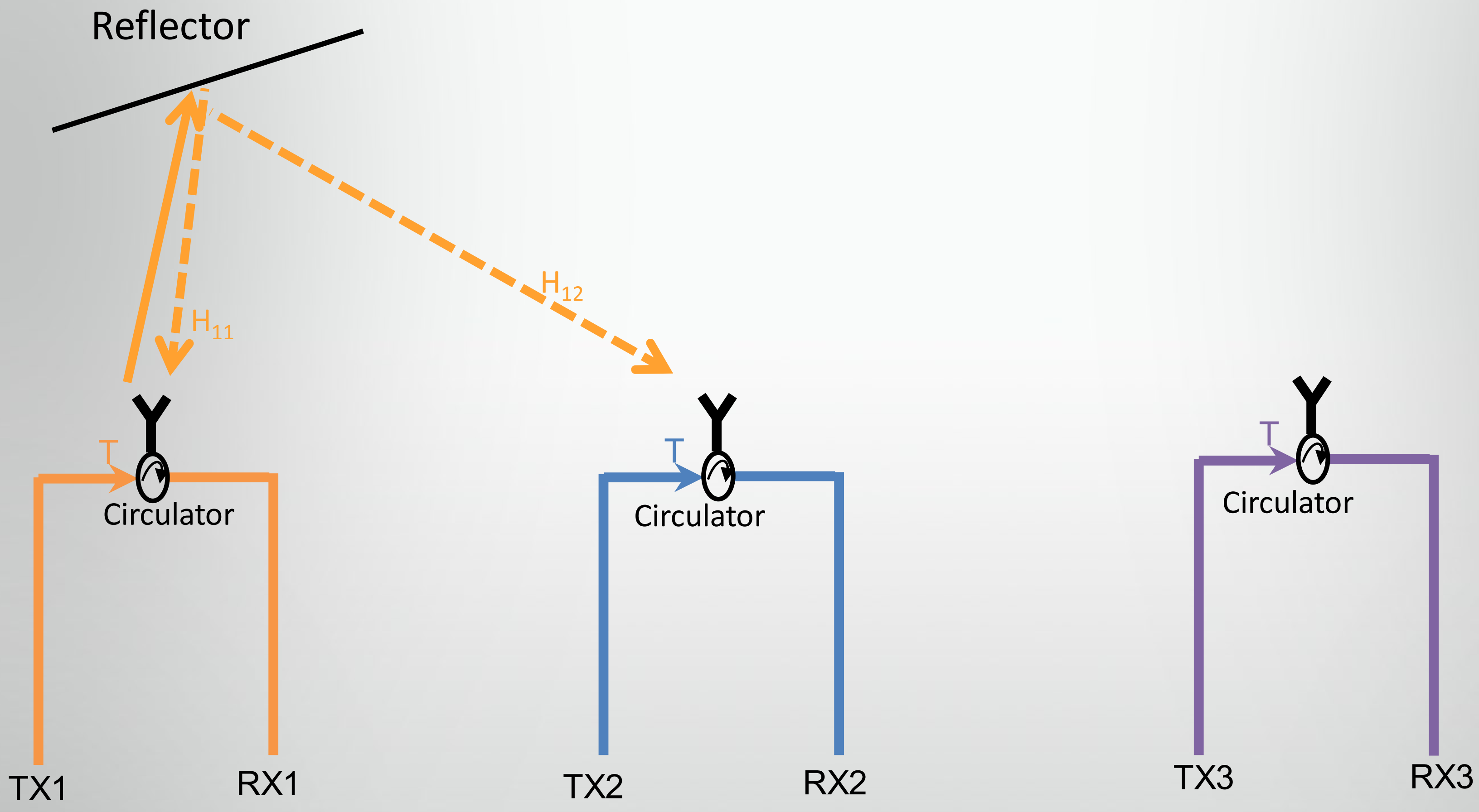

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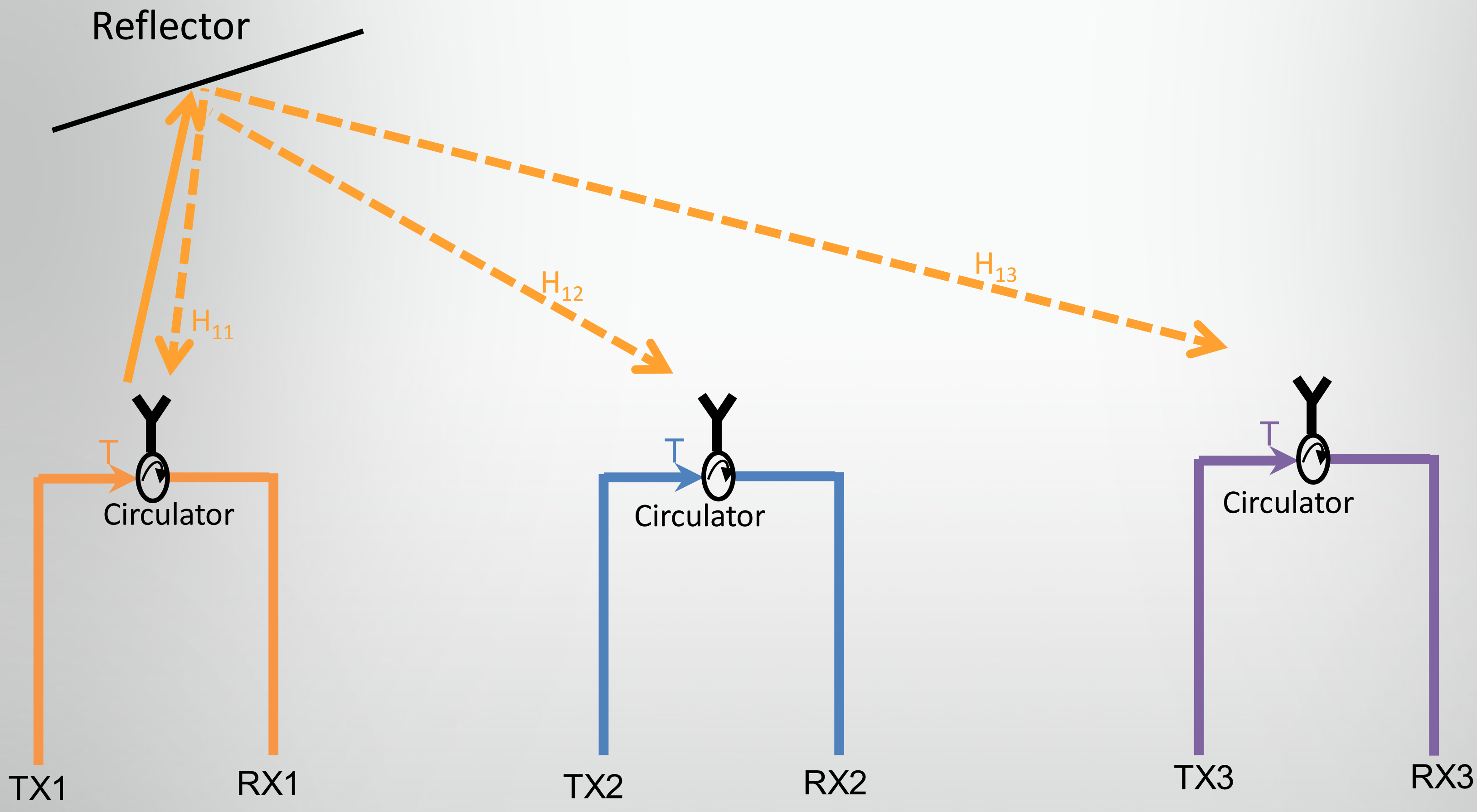

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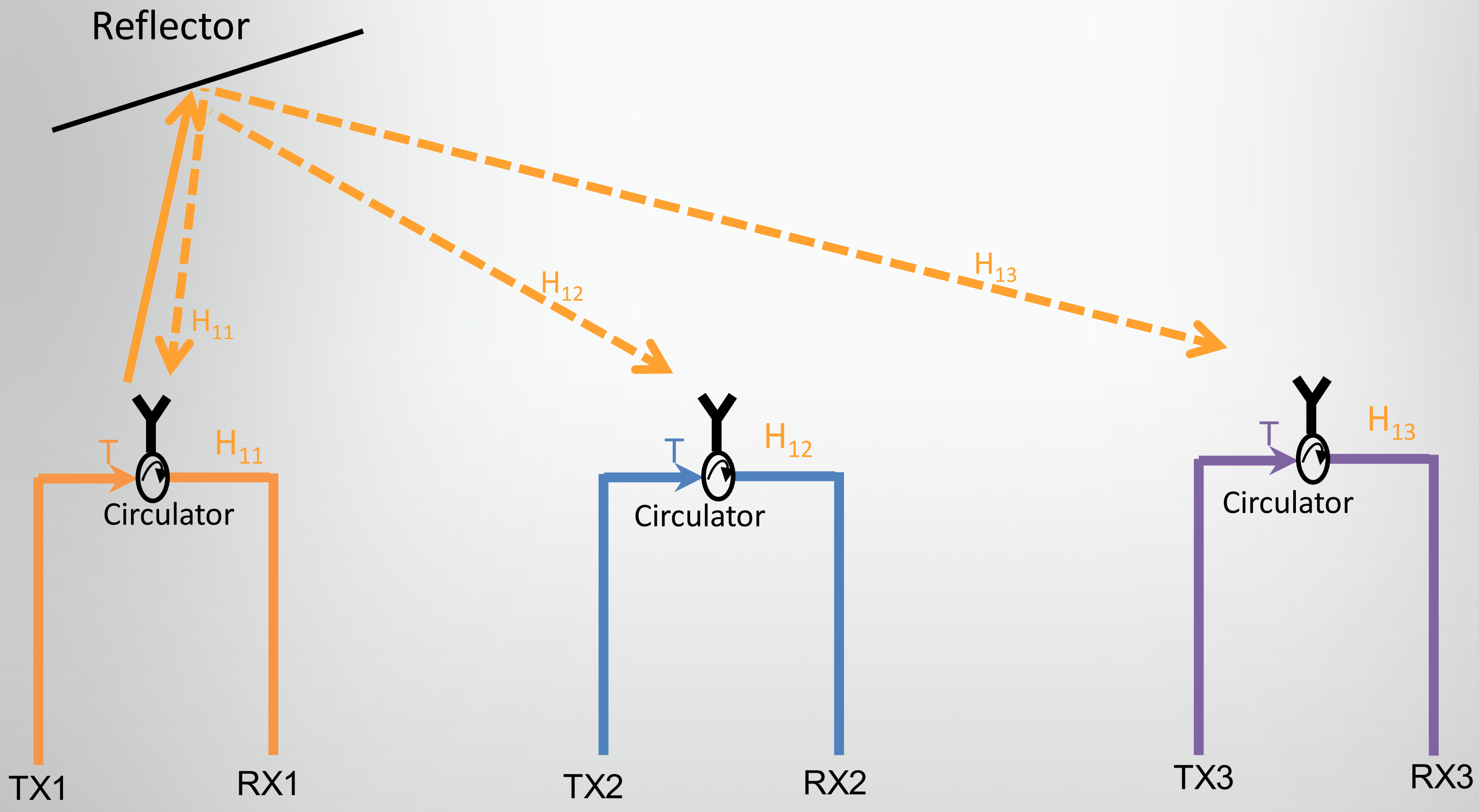

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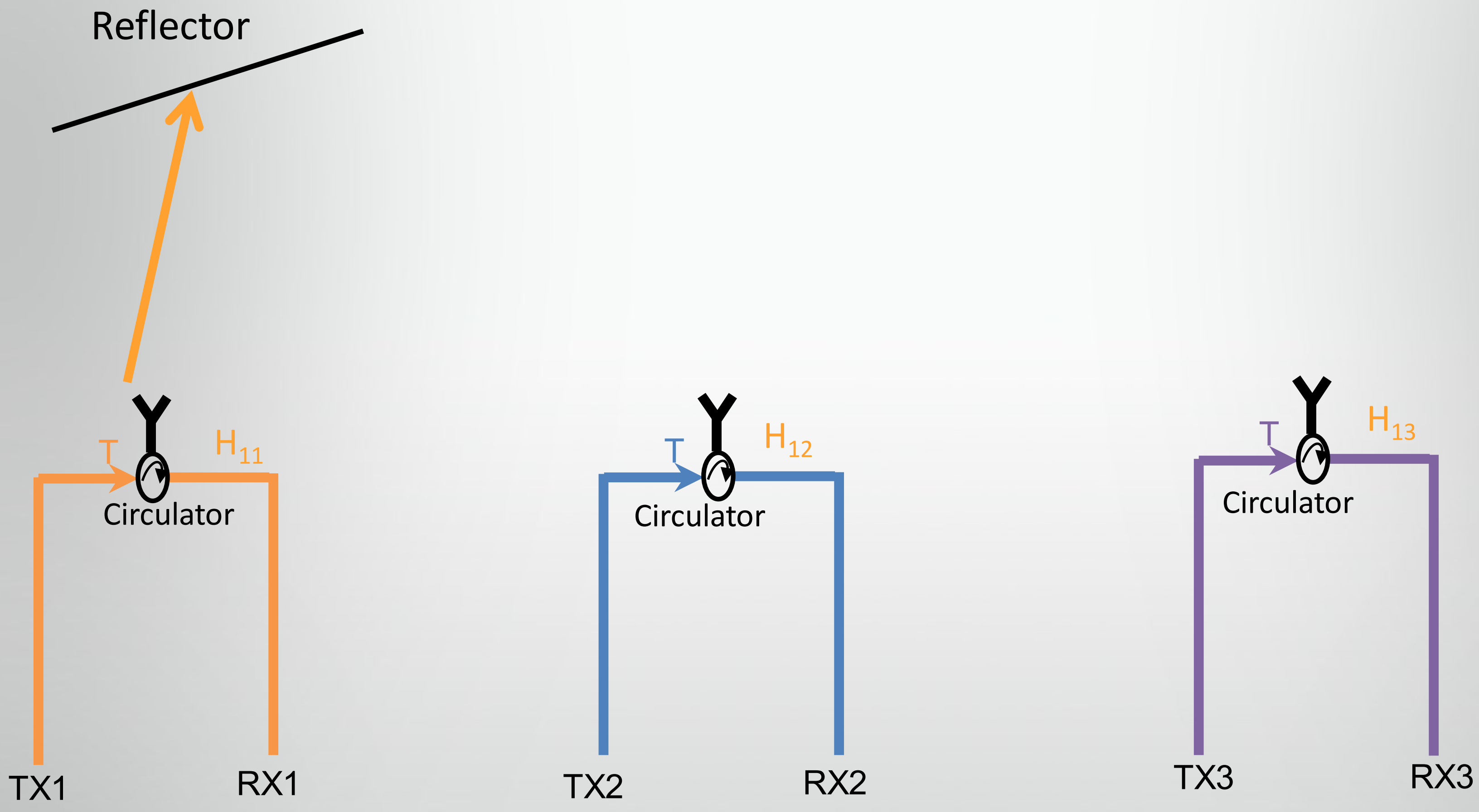

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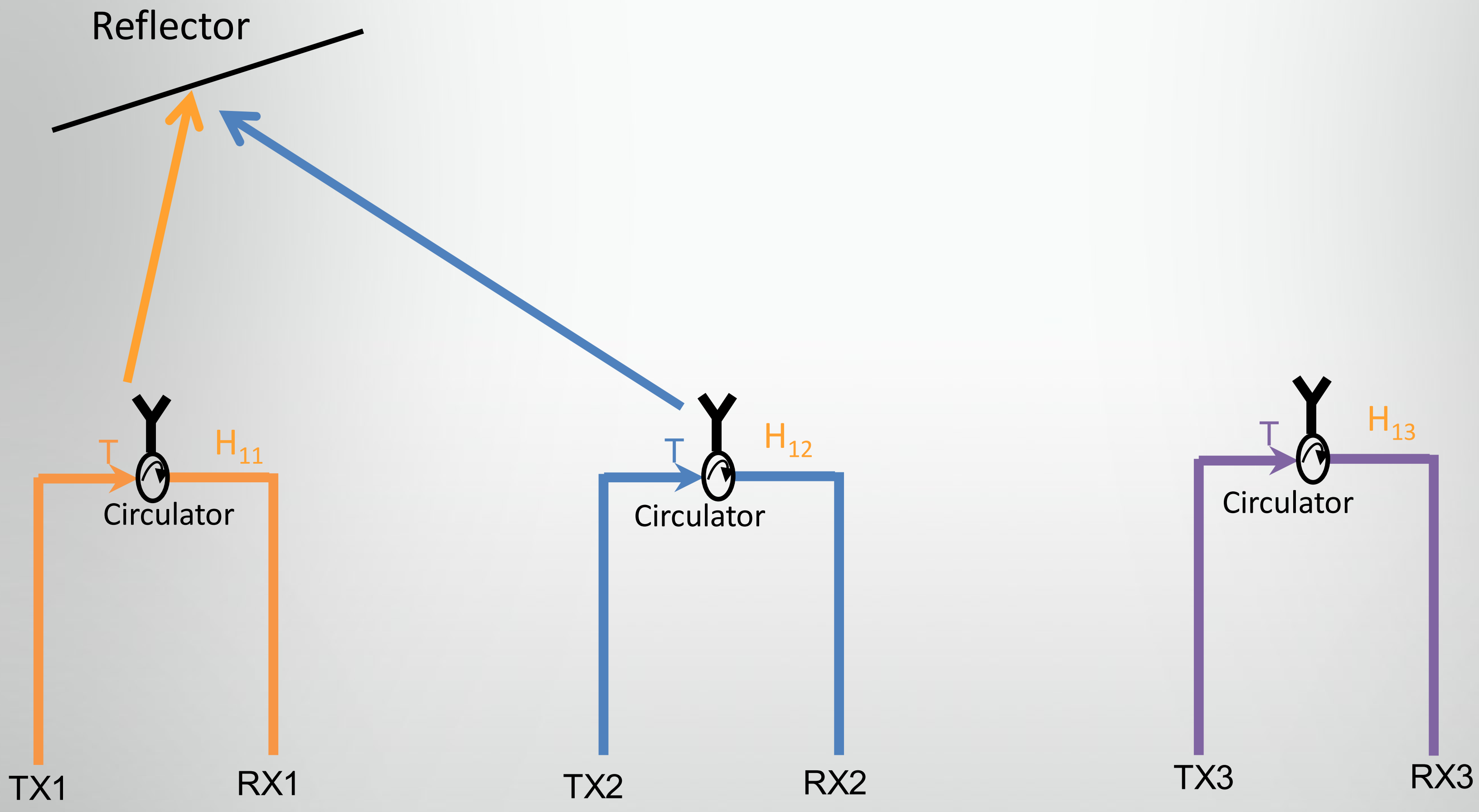

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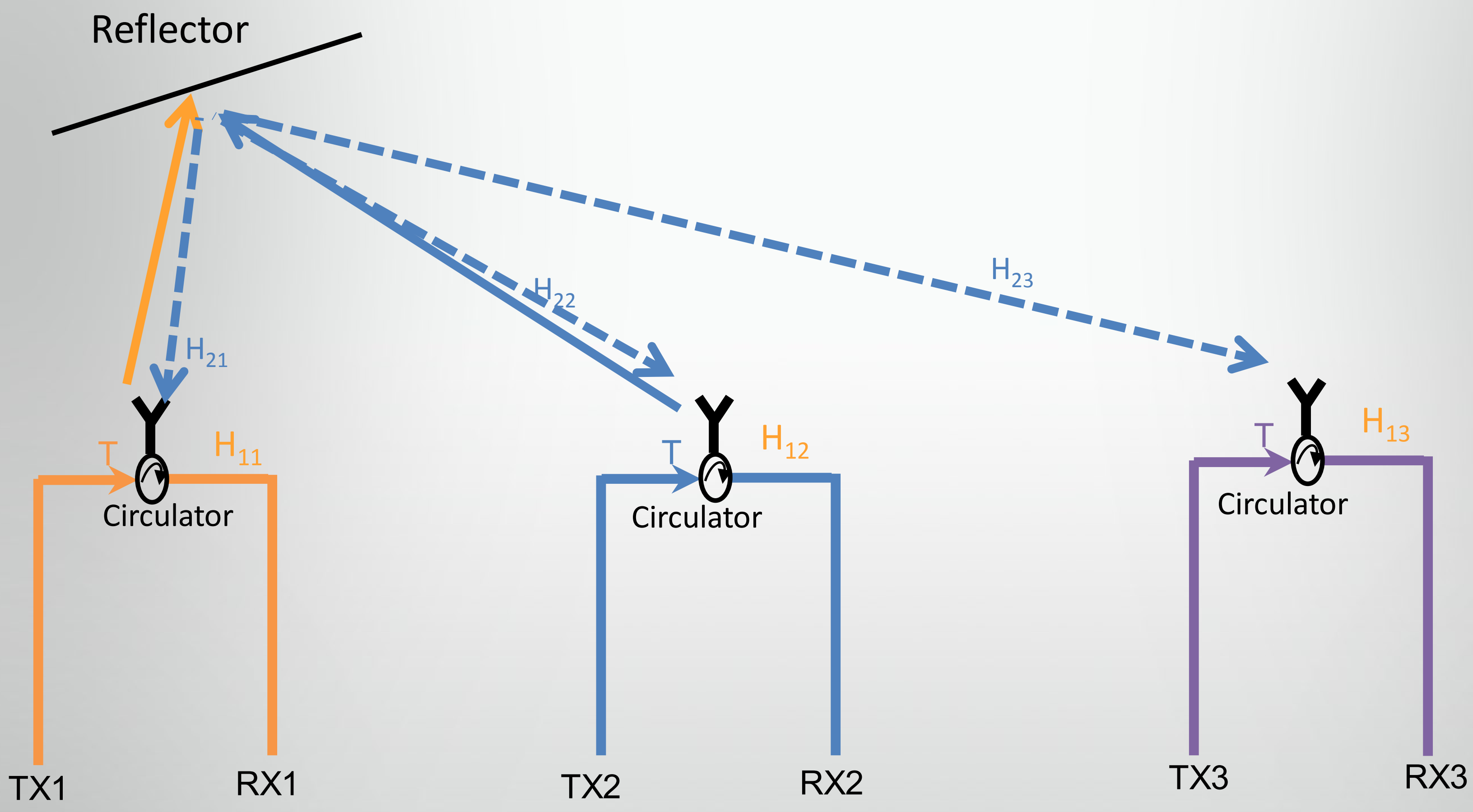

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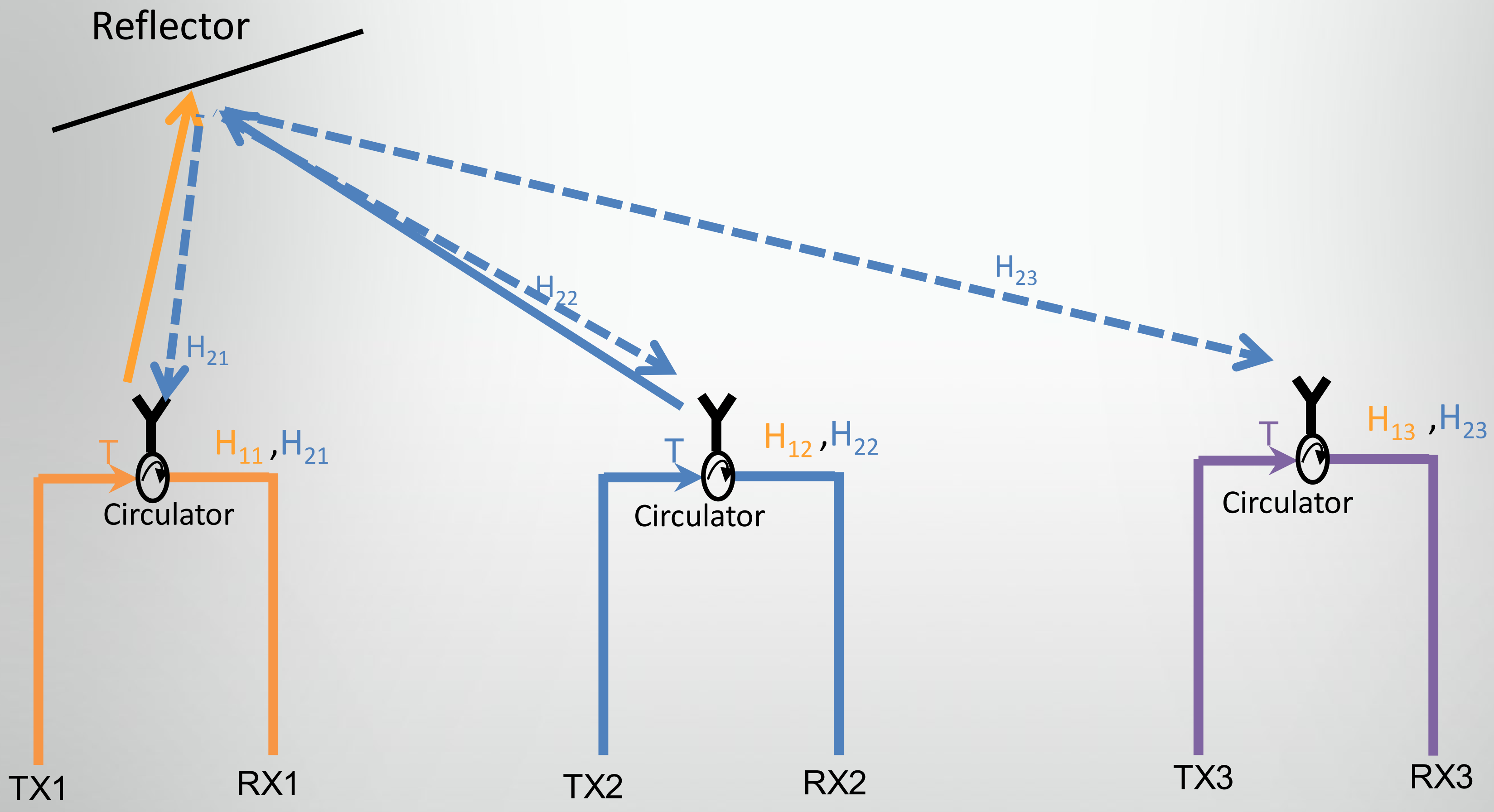

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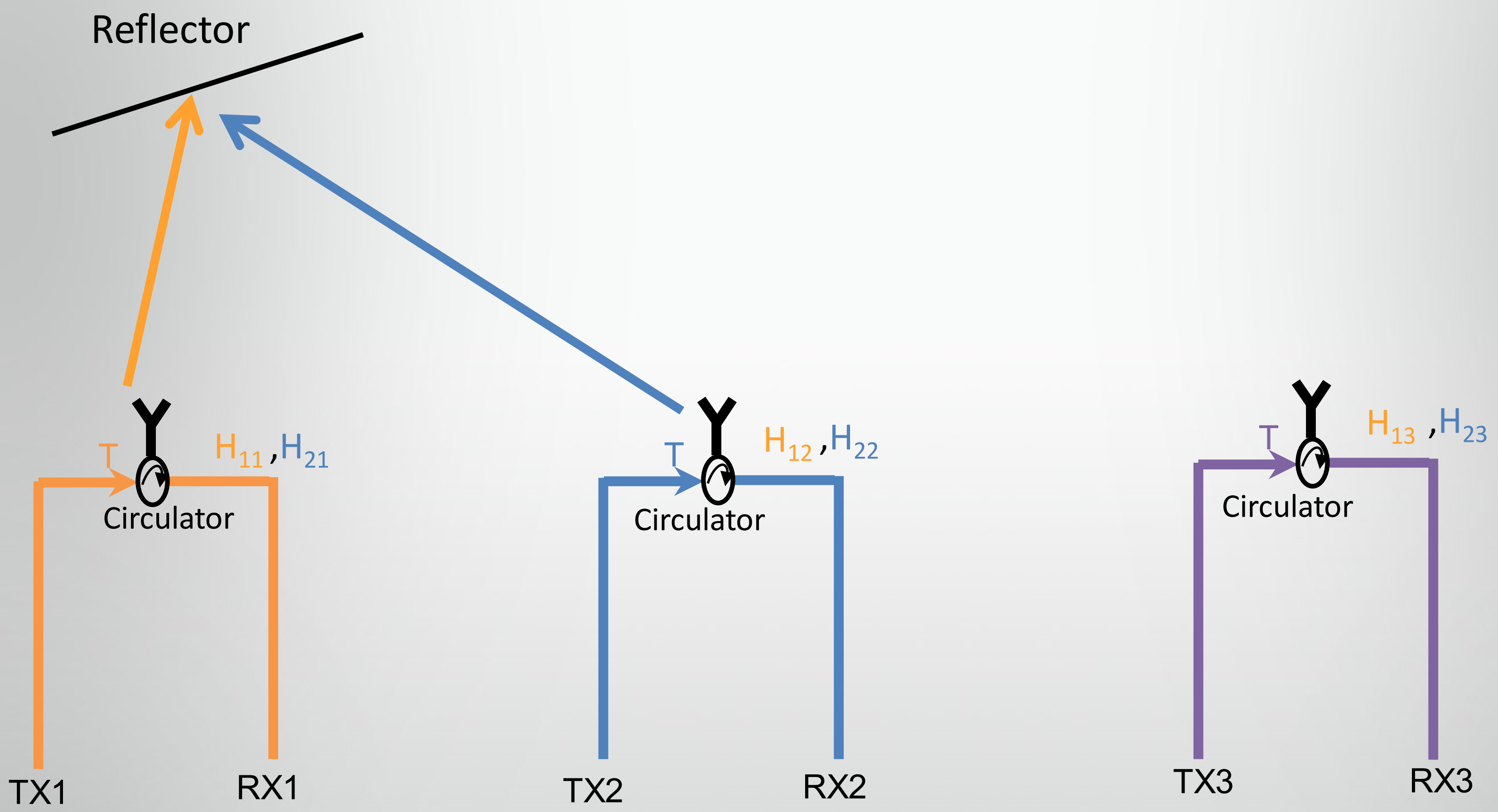

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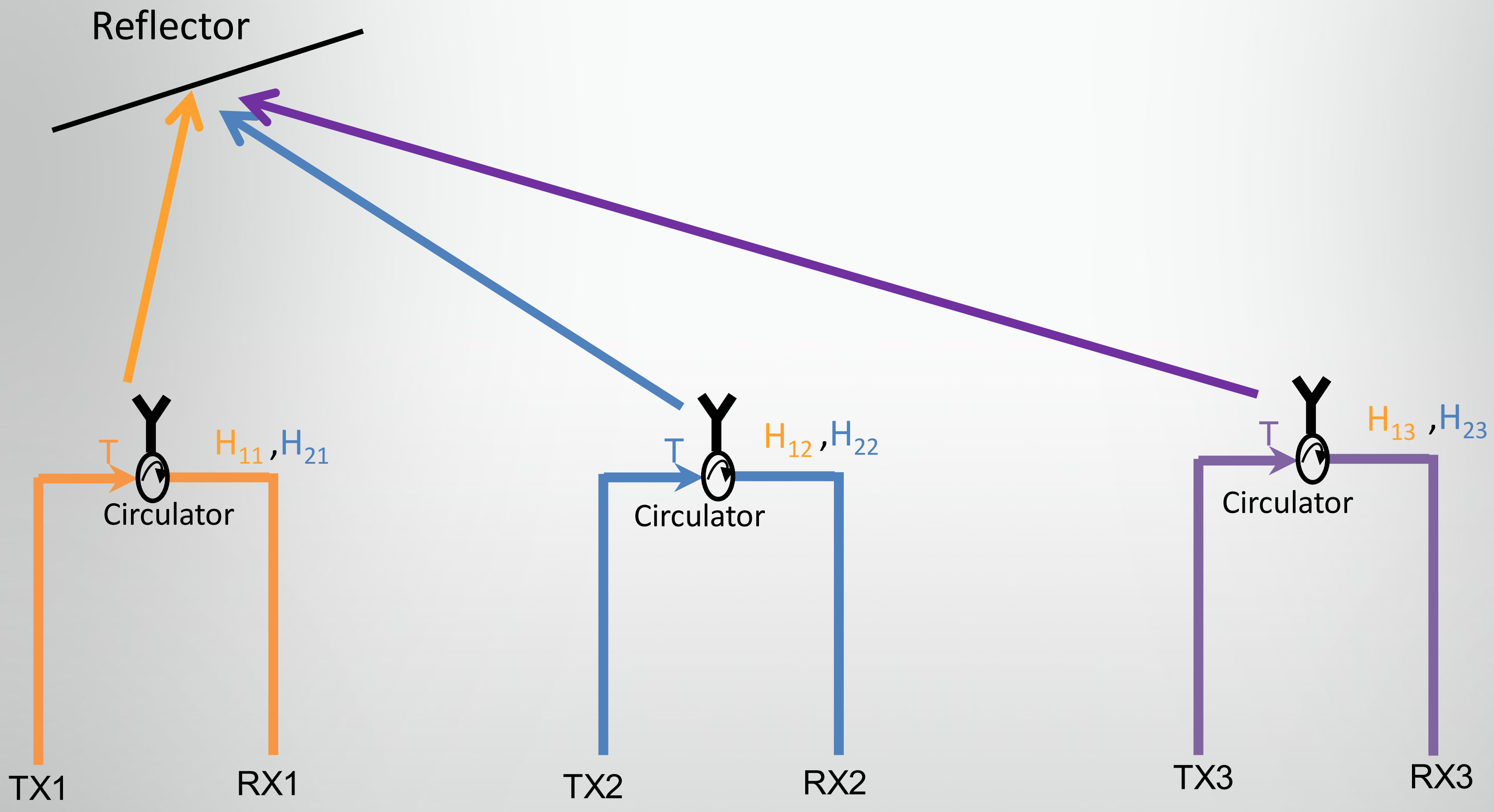

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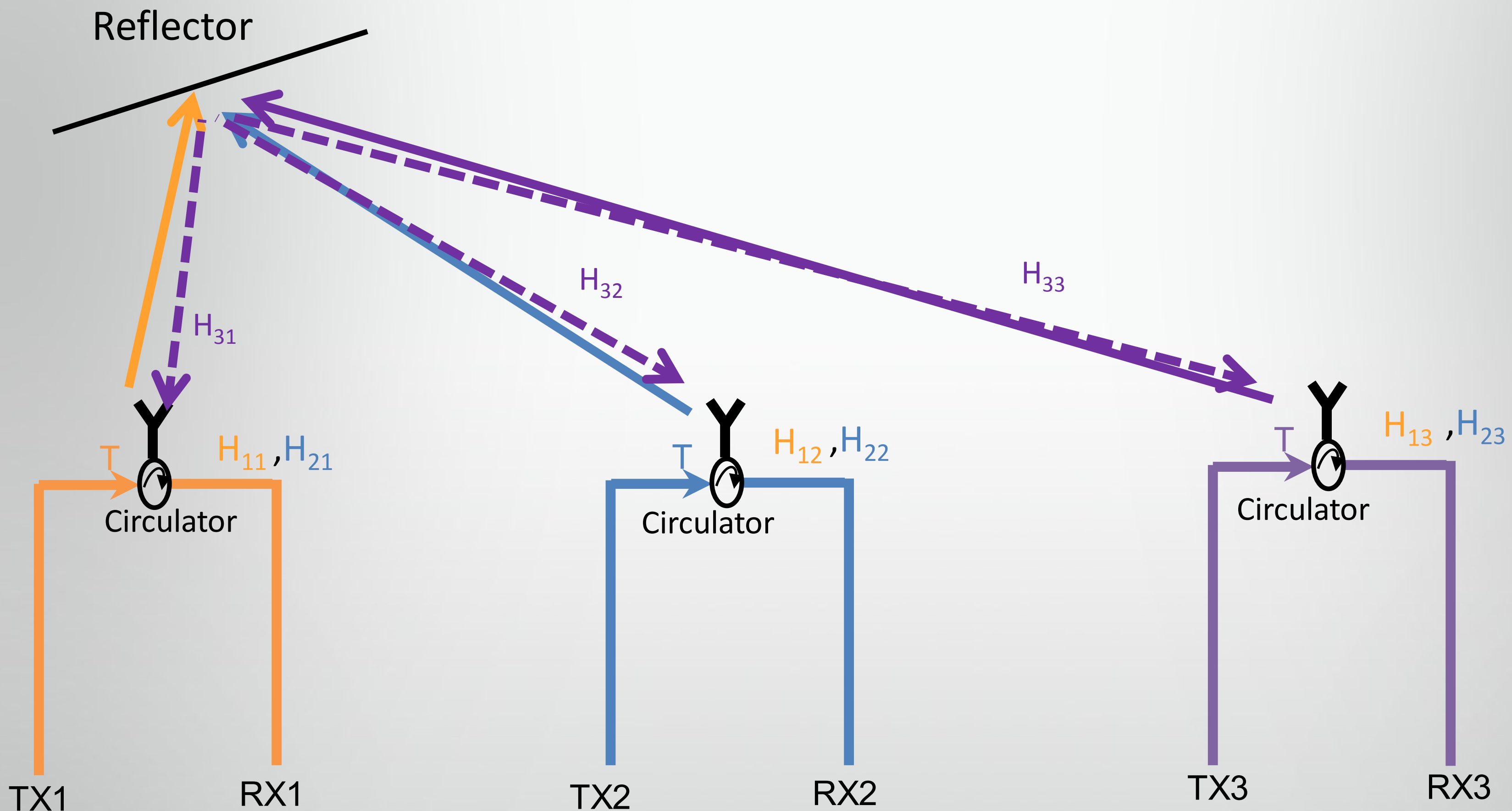

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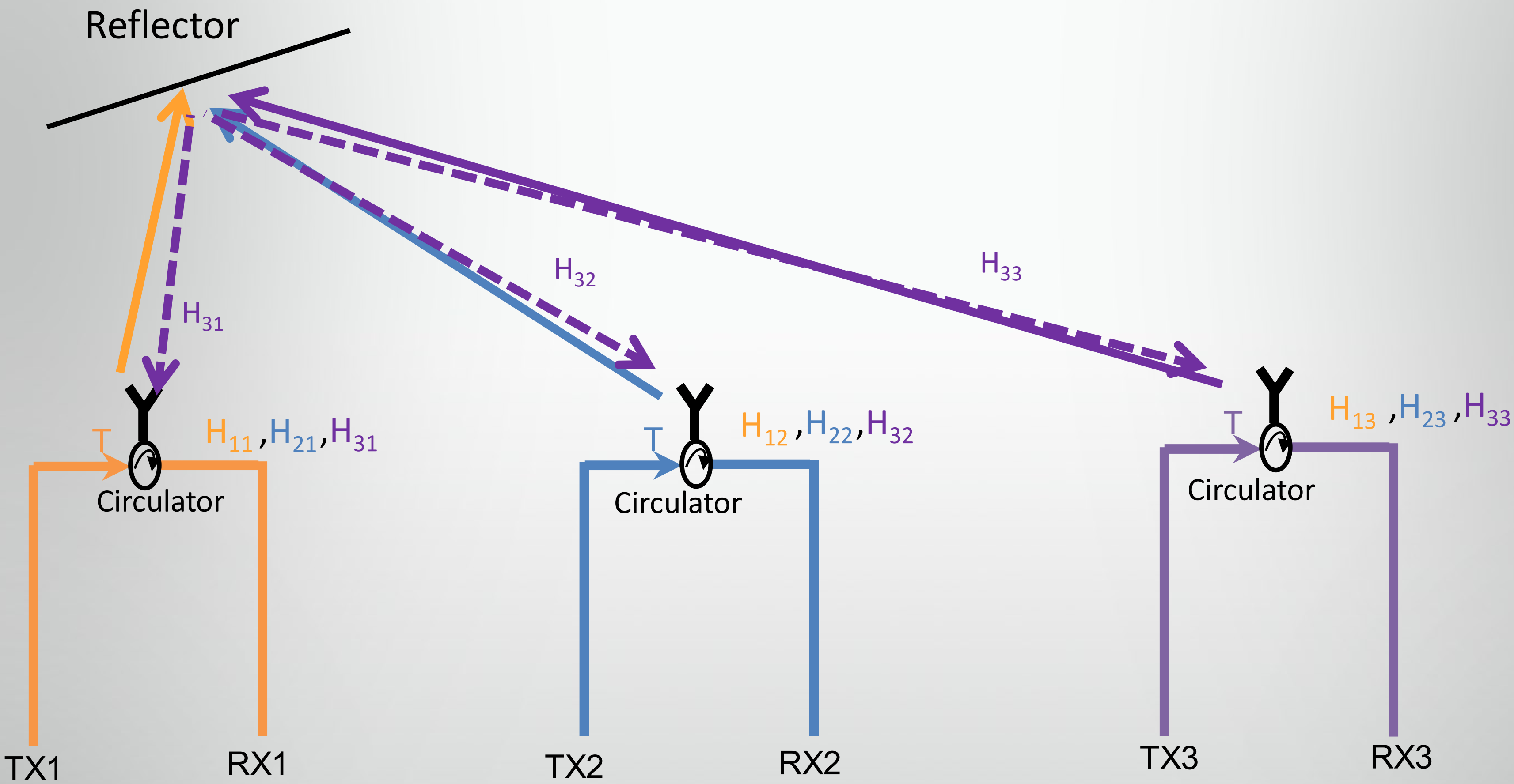

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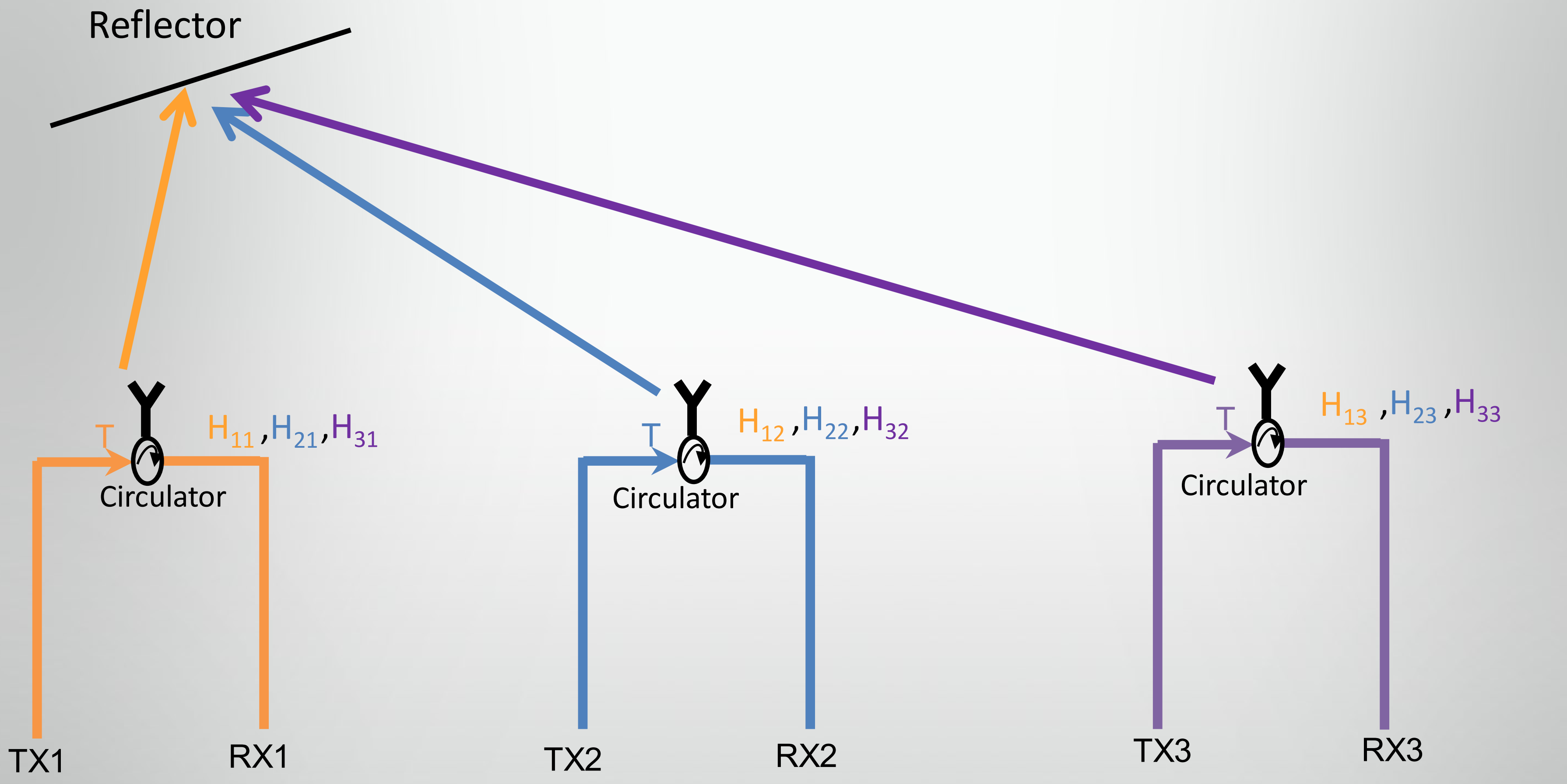

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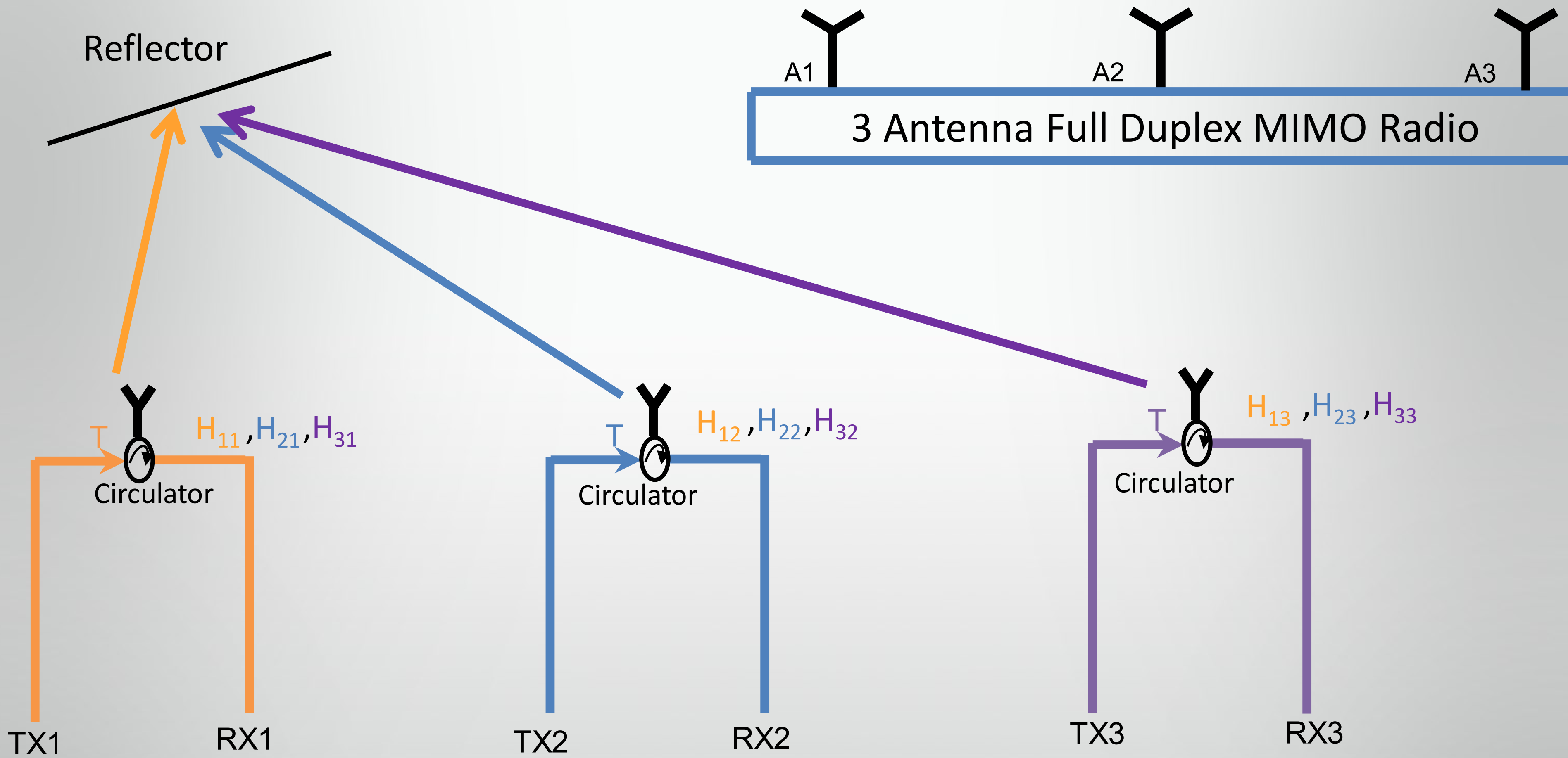

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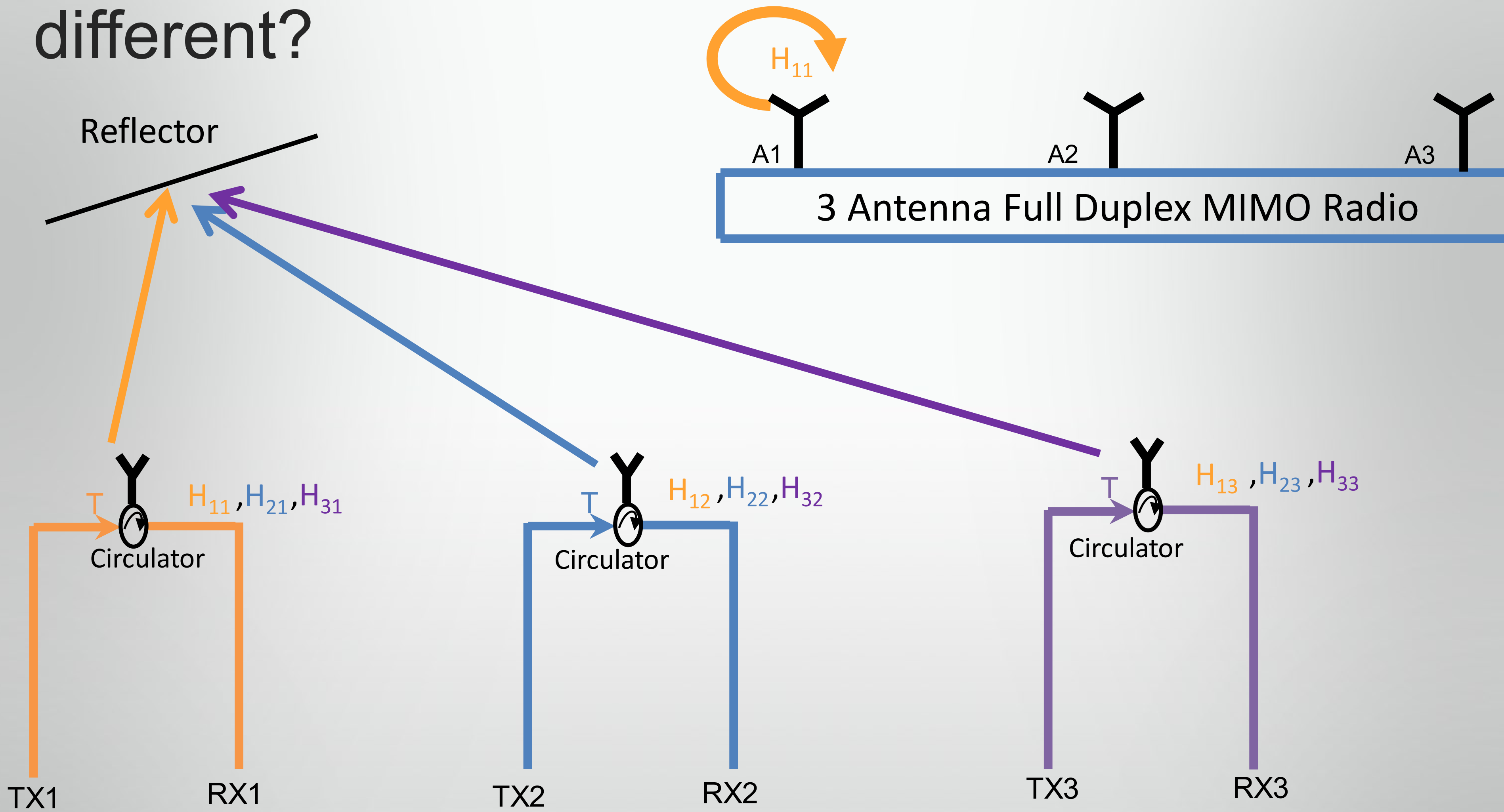

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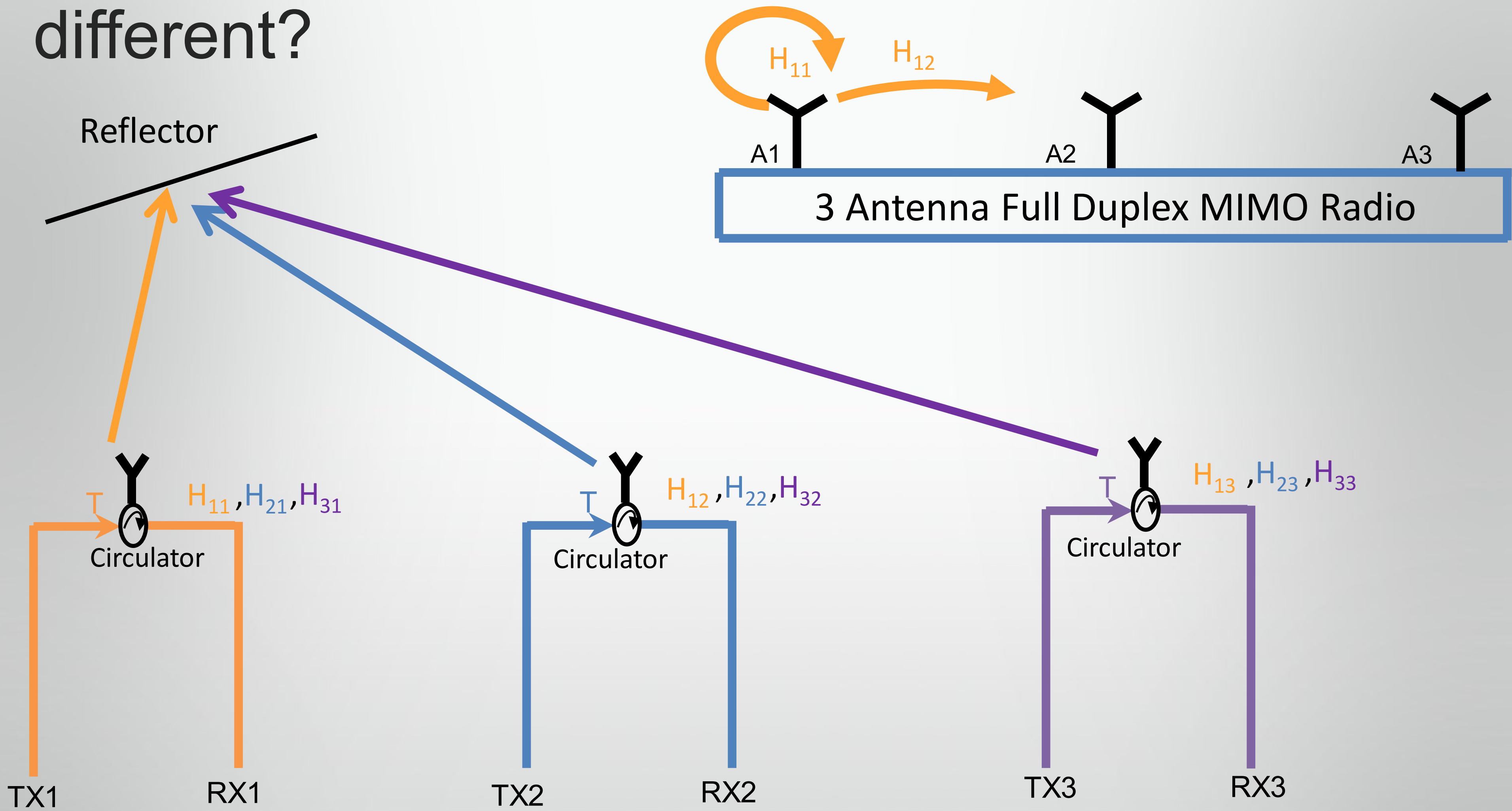

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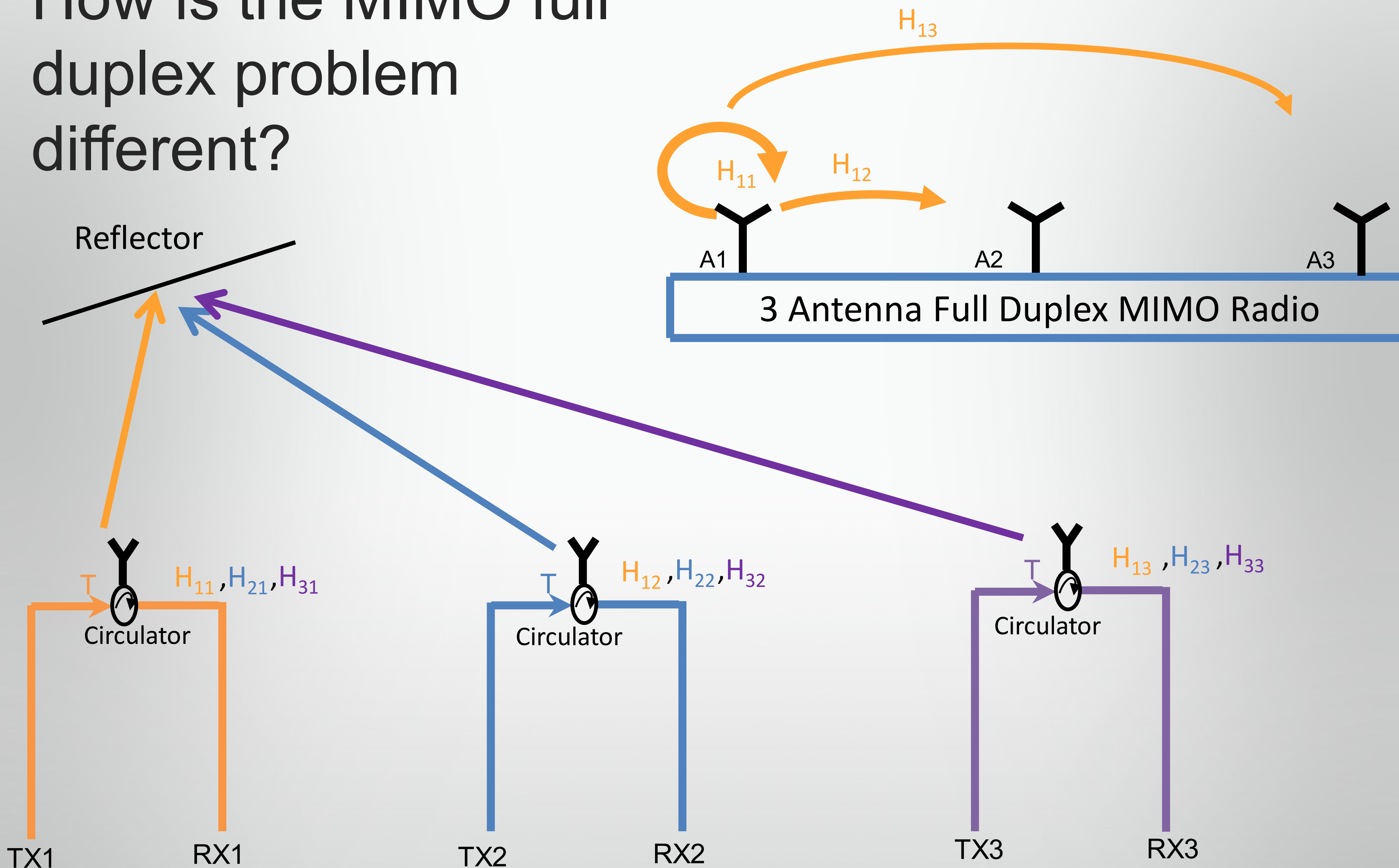

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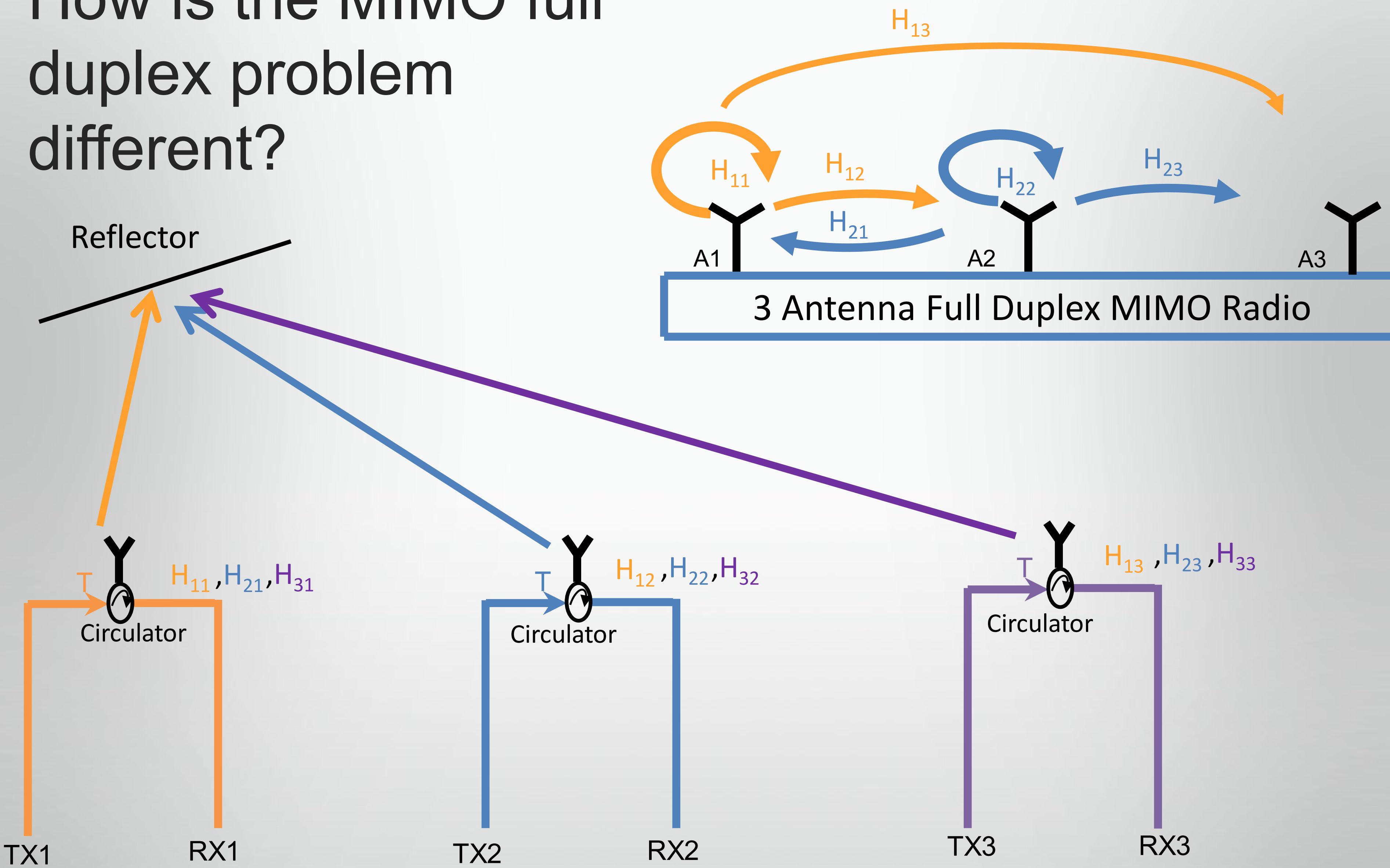

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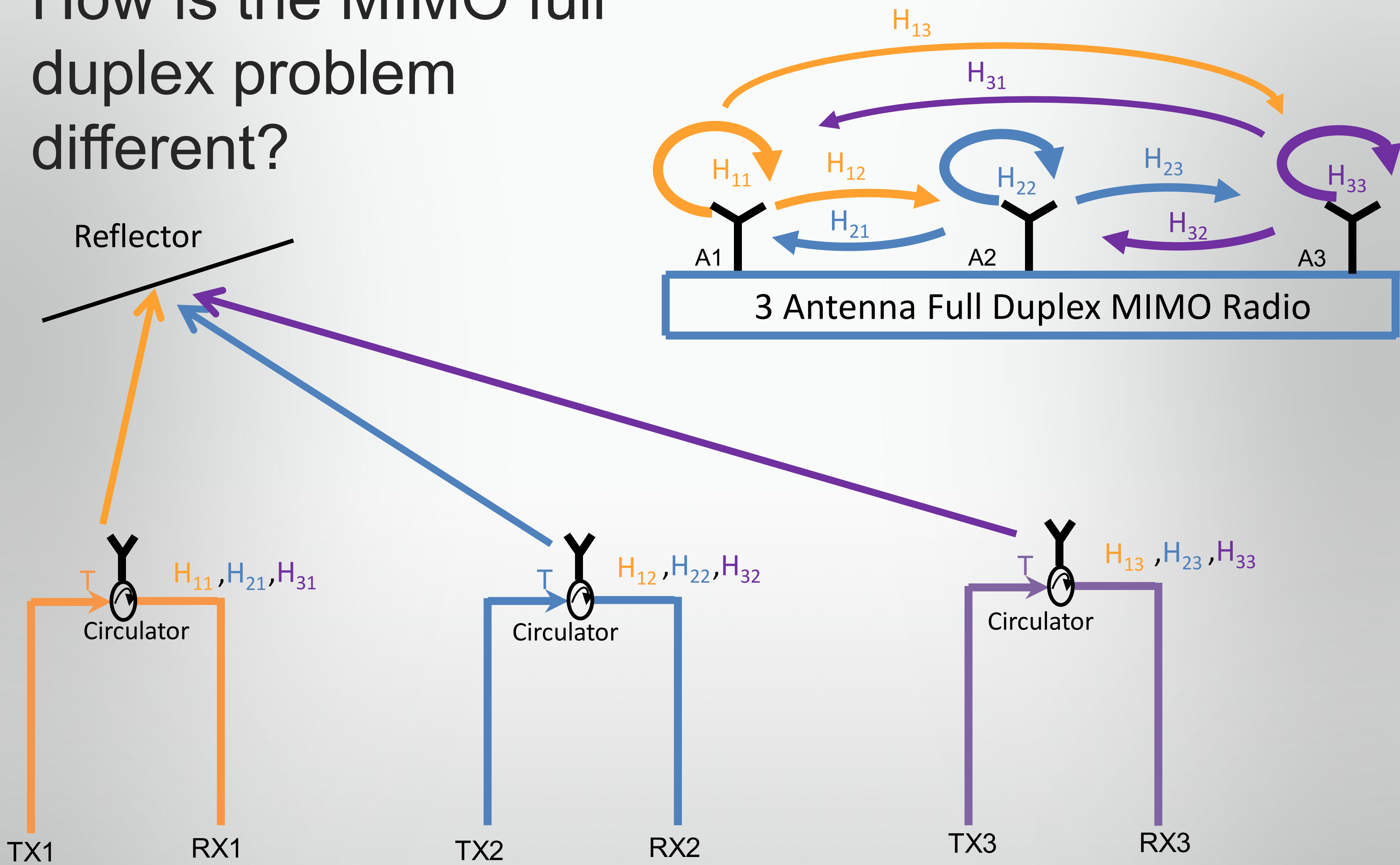

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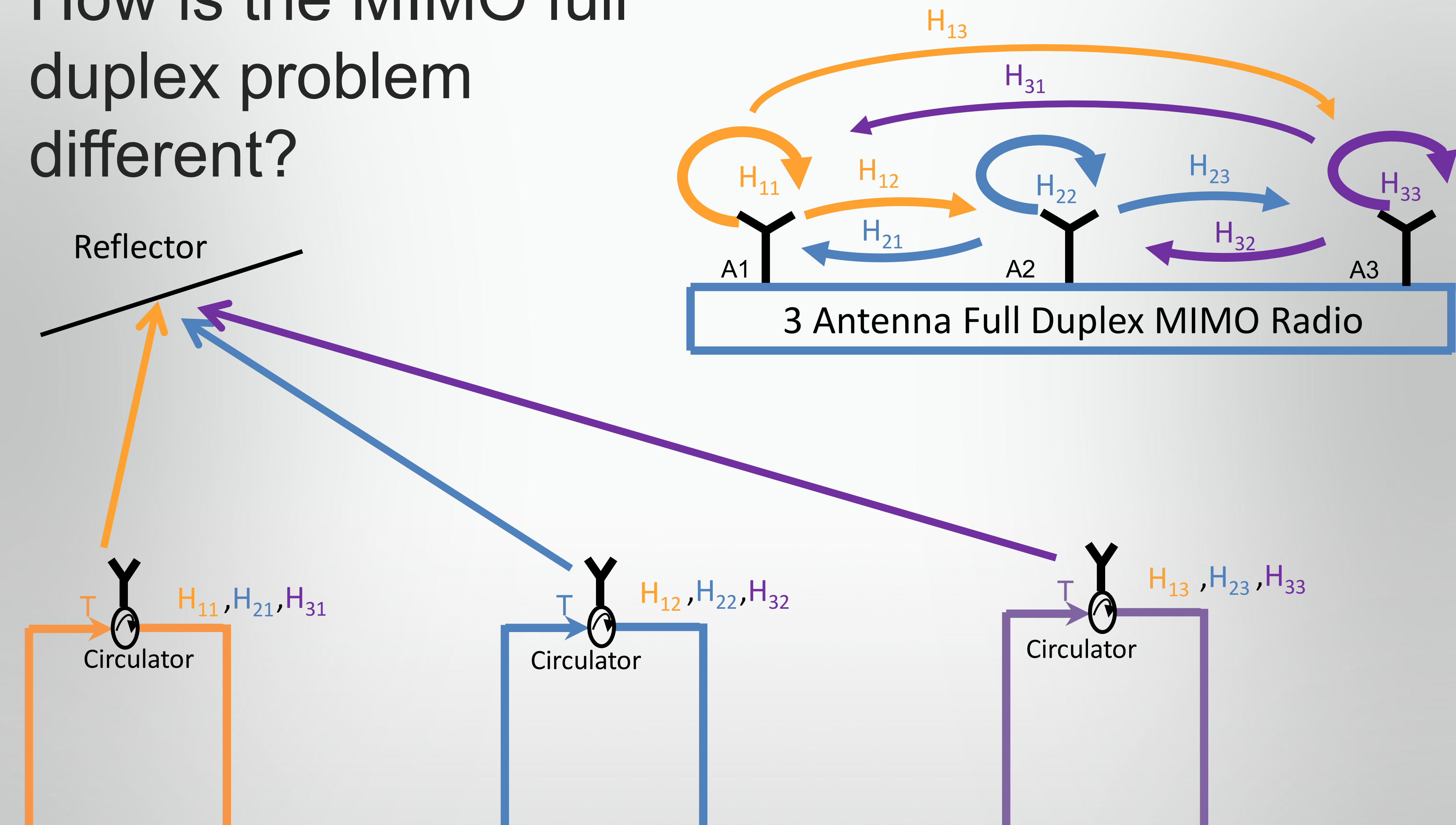
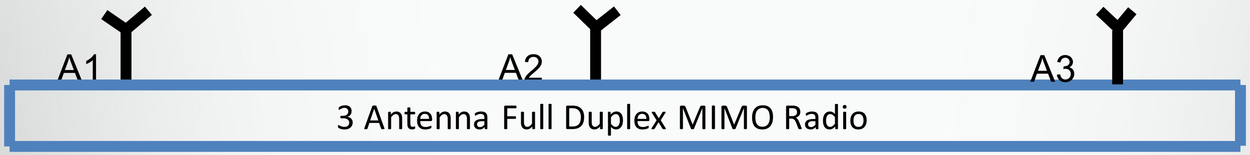


MIMO full duplex has quadratically more number of signals to cancel because of the presence of cross talk.

Why not replicate the SISO full duplex design to cancel all the self-talk and cross-talk components for MIMO?

Naïve Solution: Replicates SISO design



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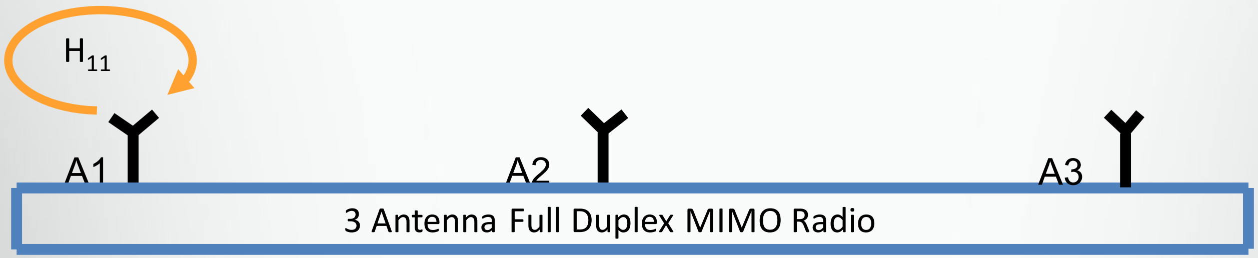

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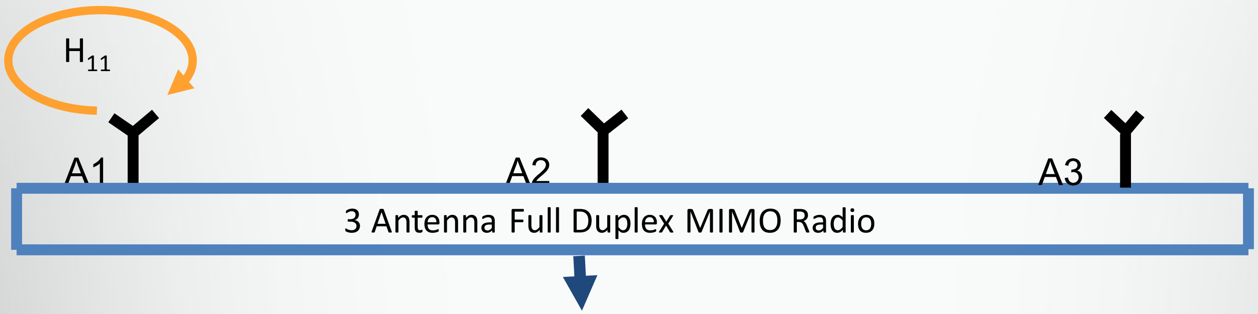

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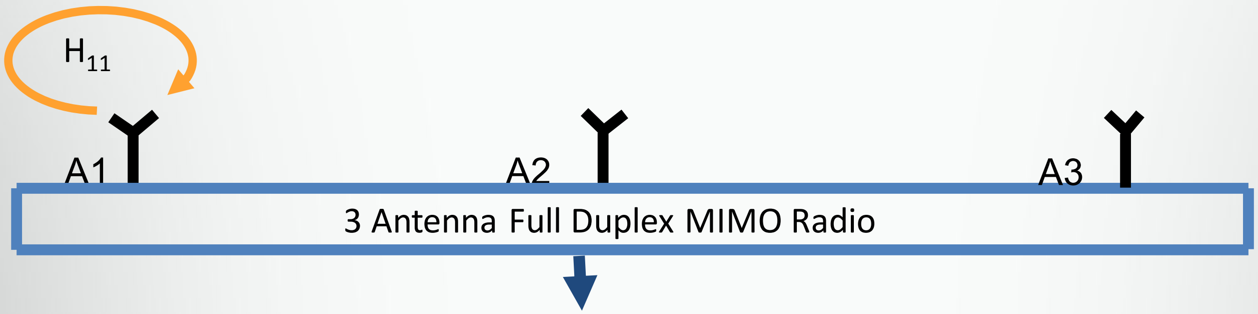

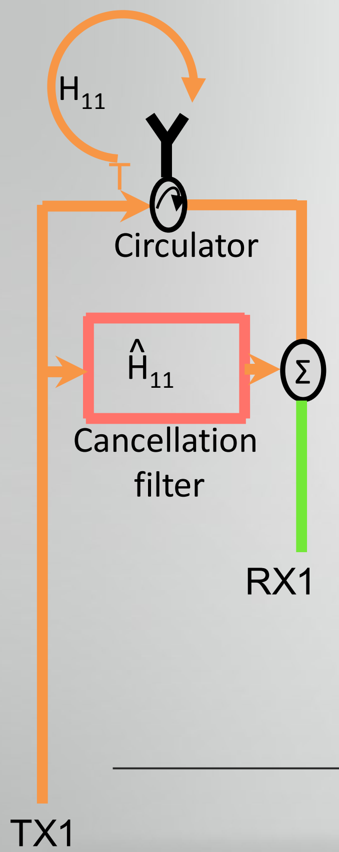

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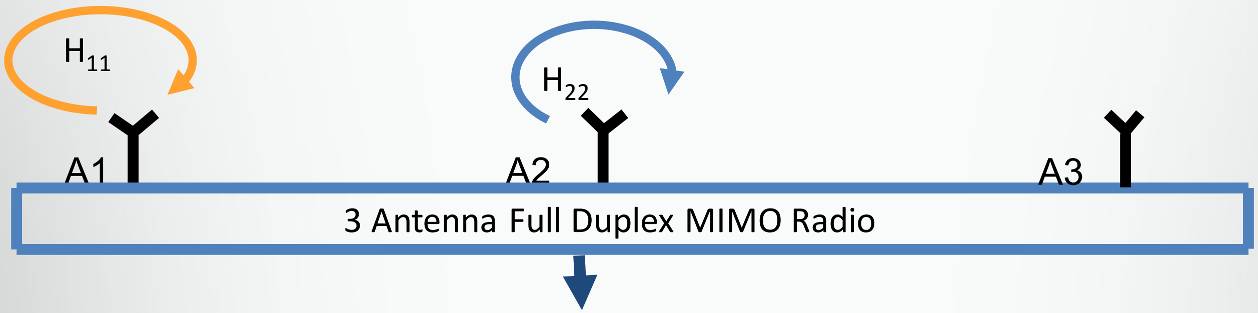

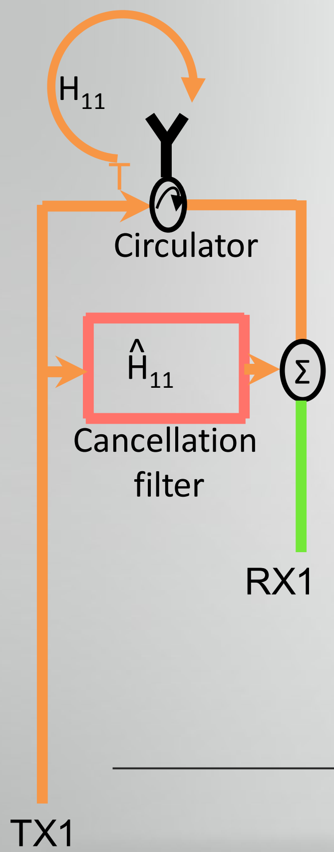

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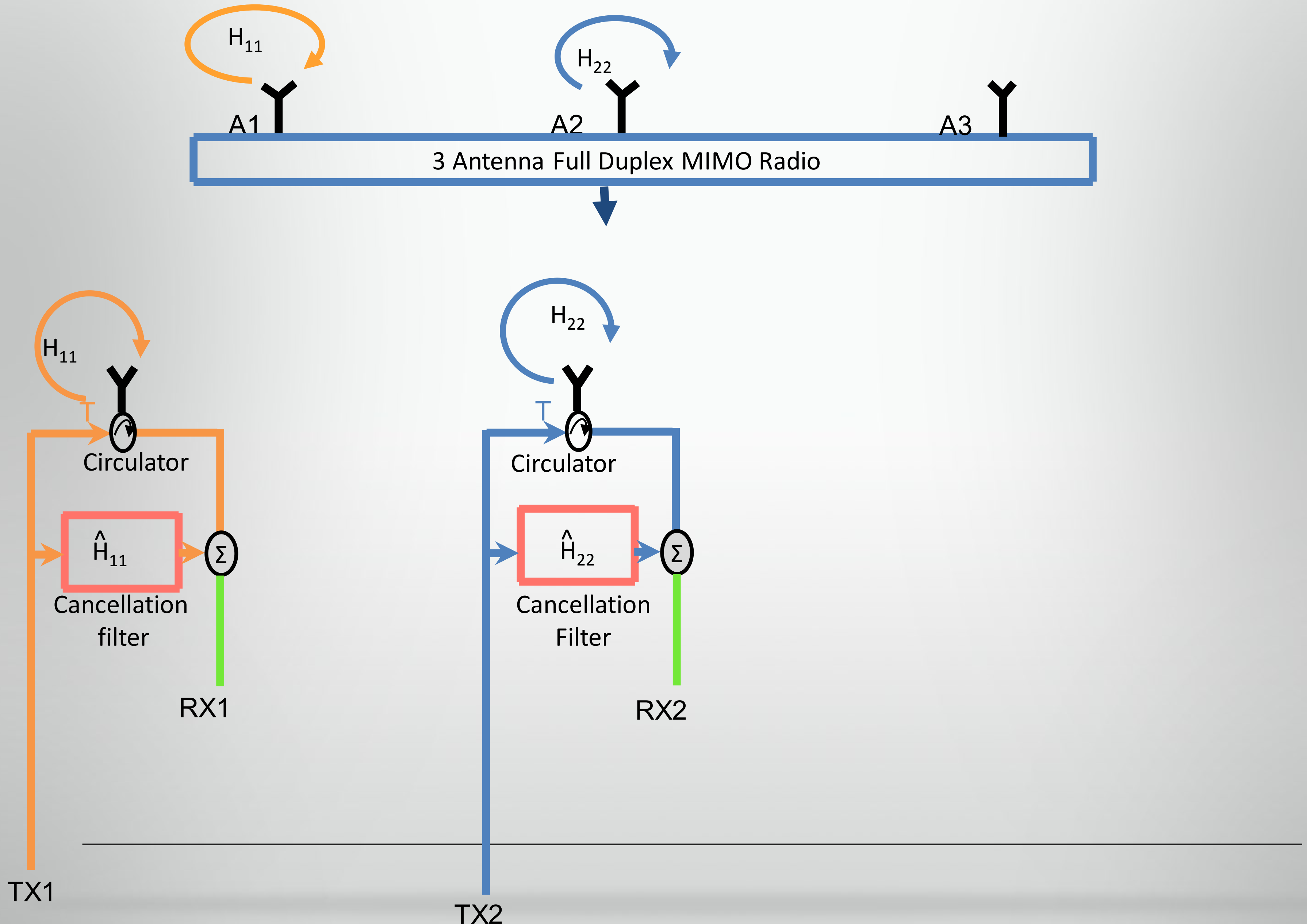

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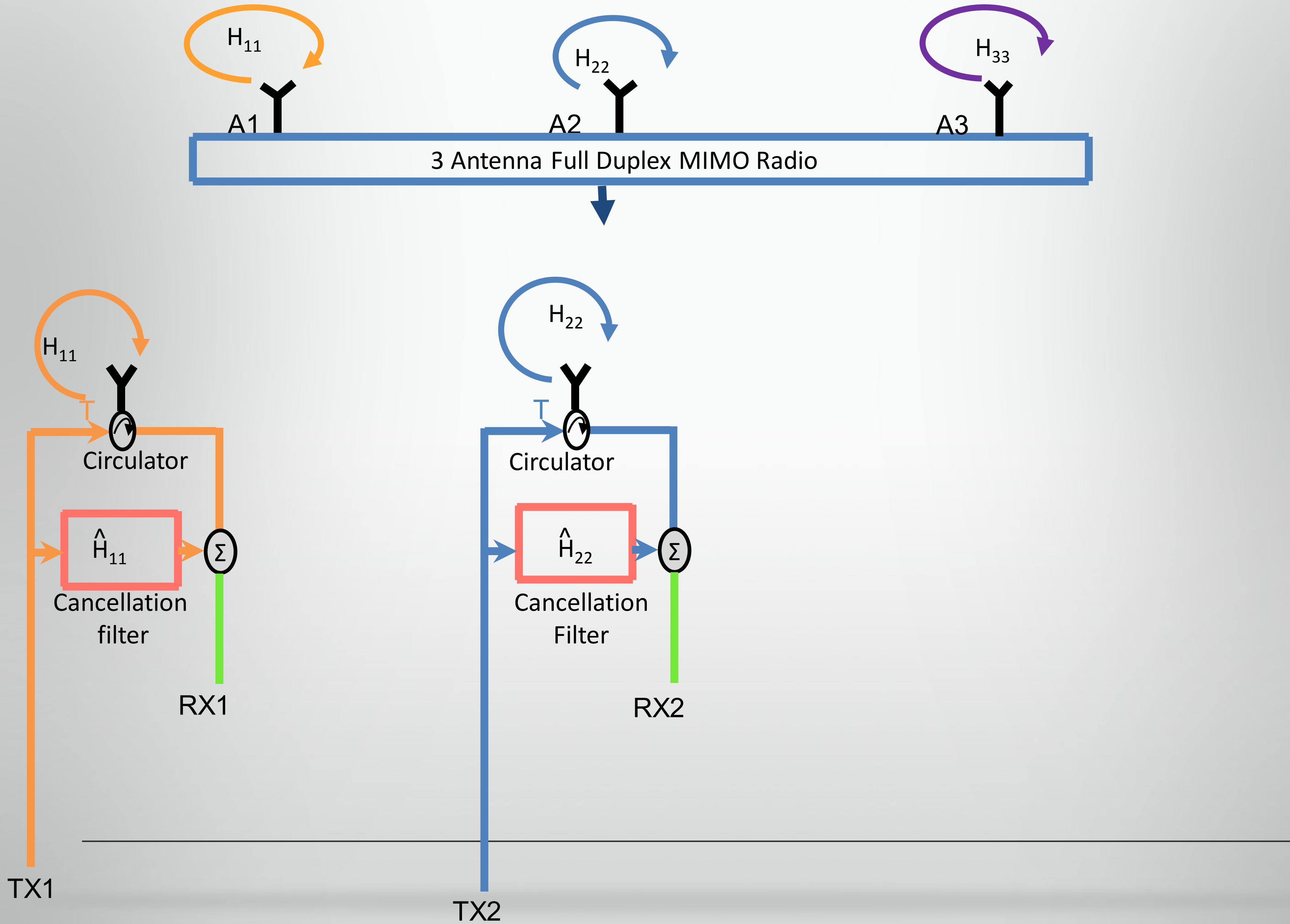

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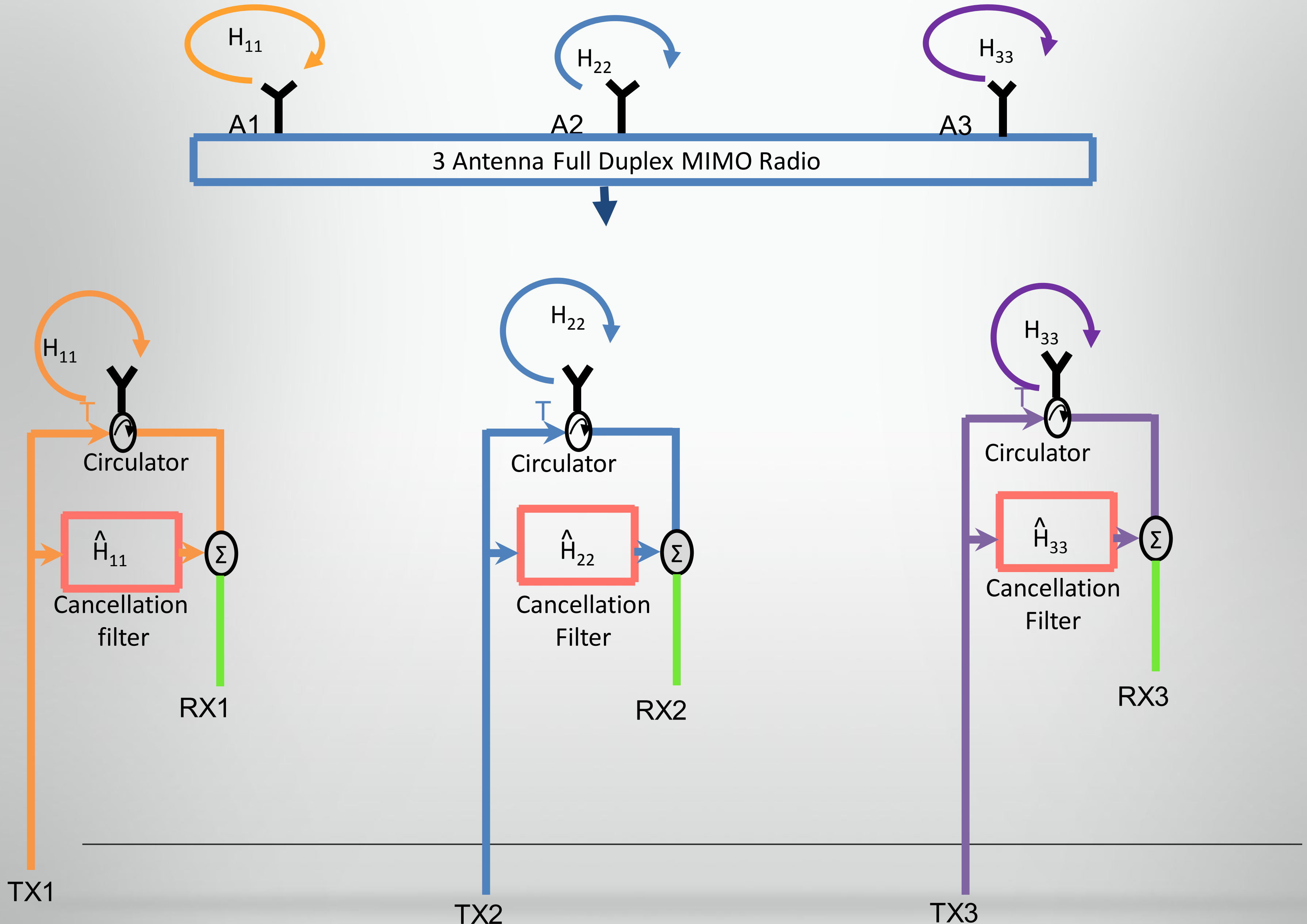

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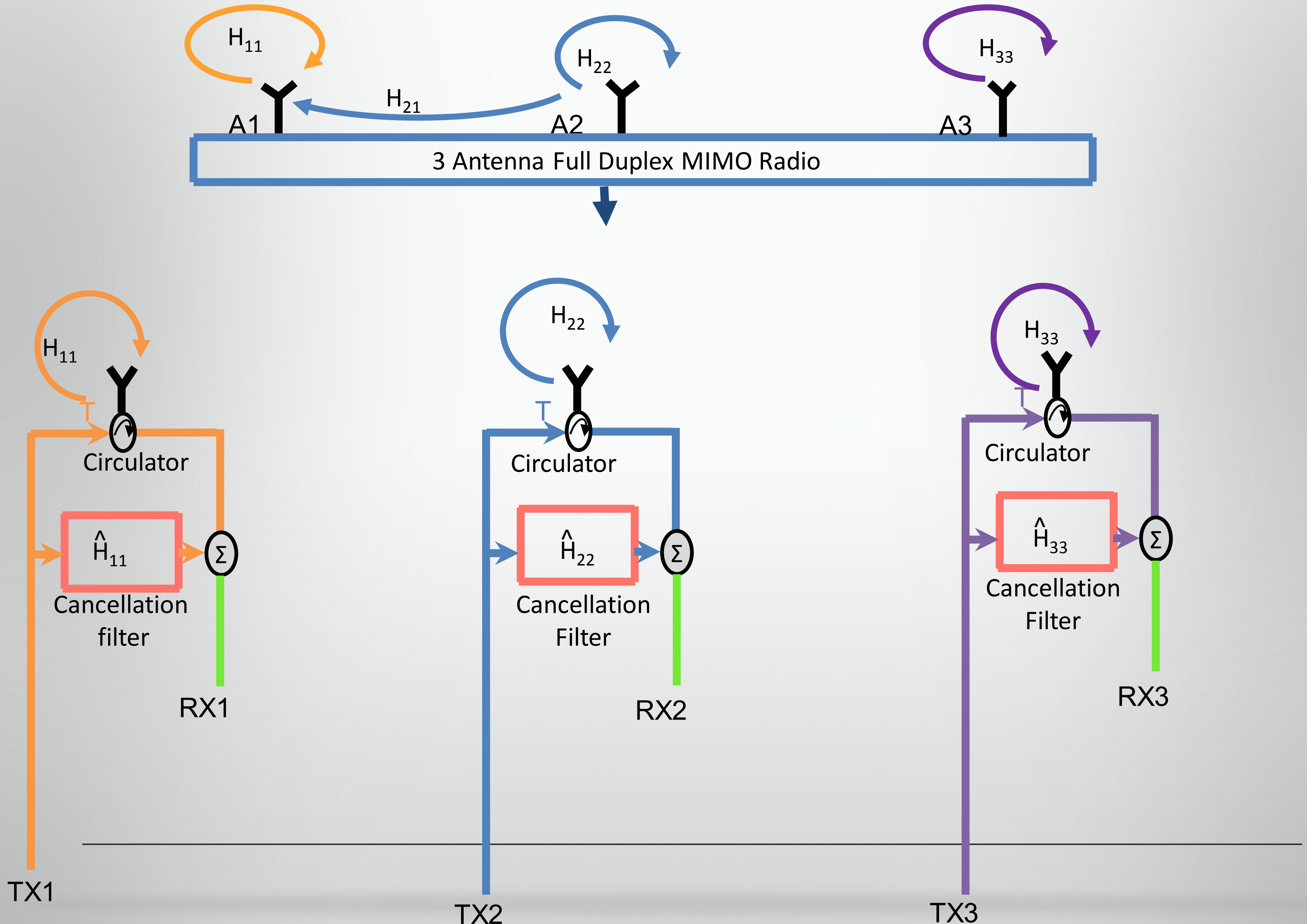

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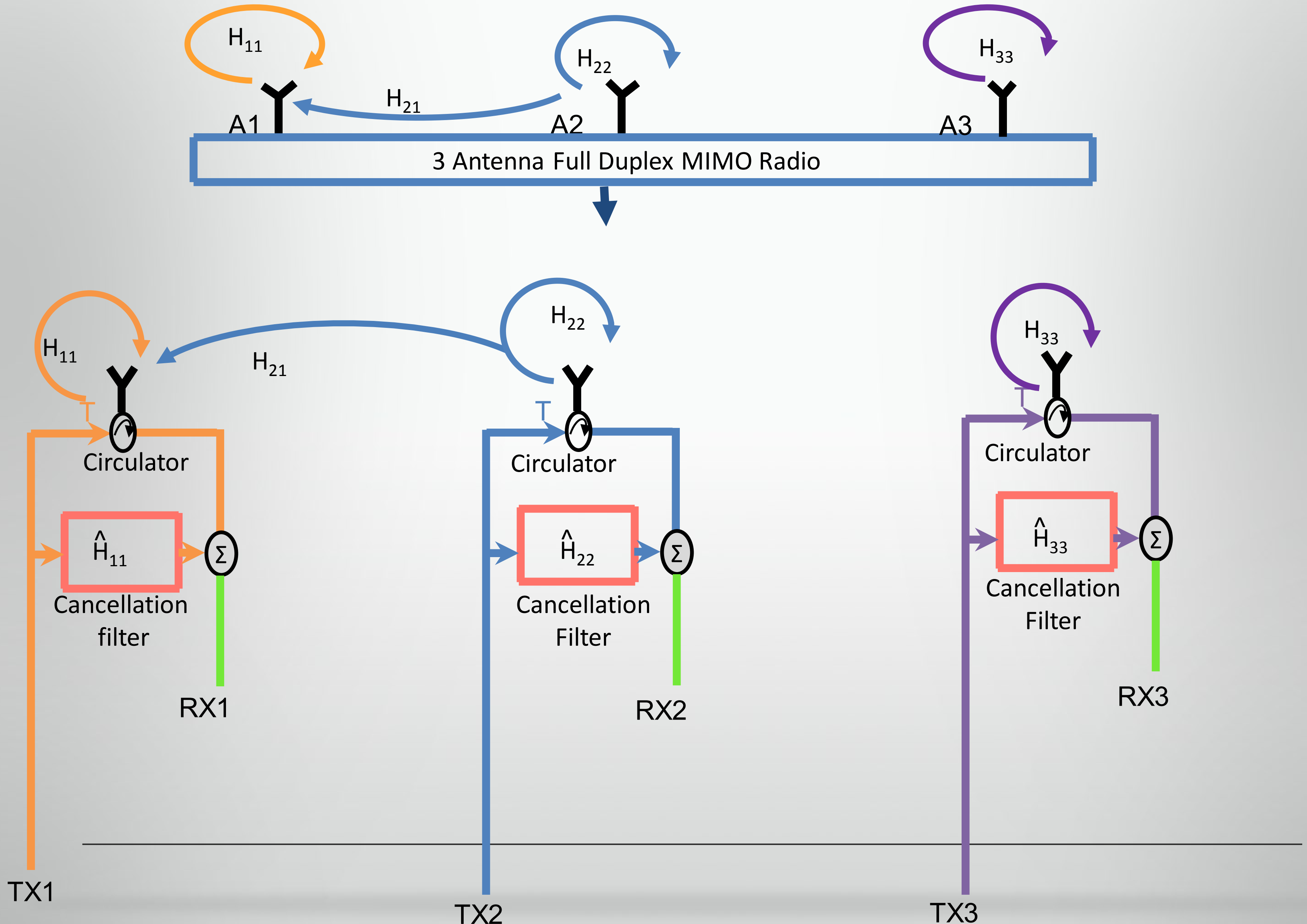

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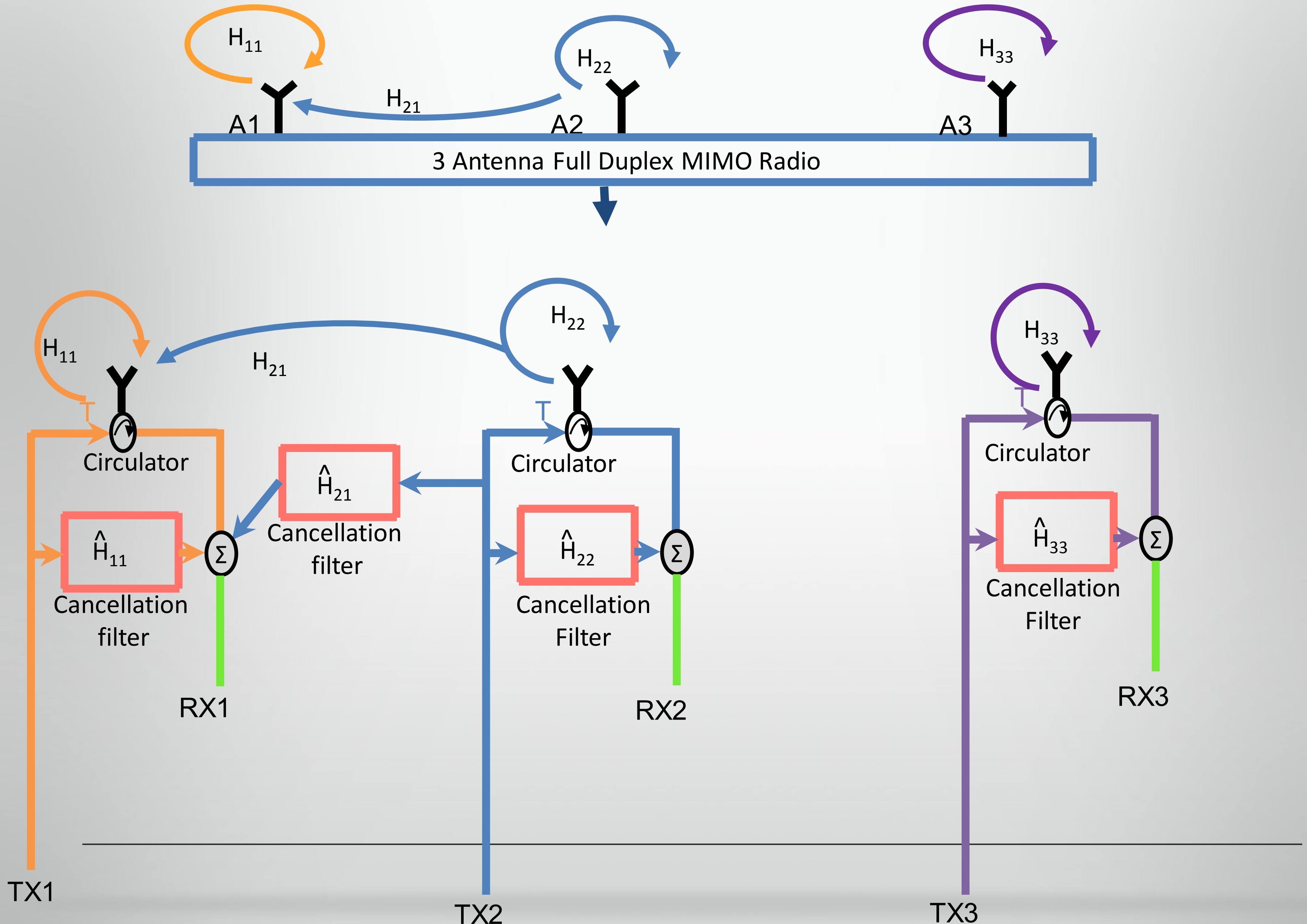

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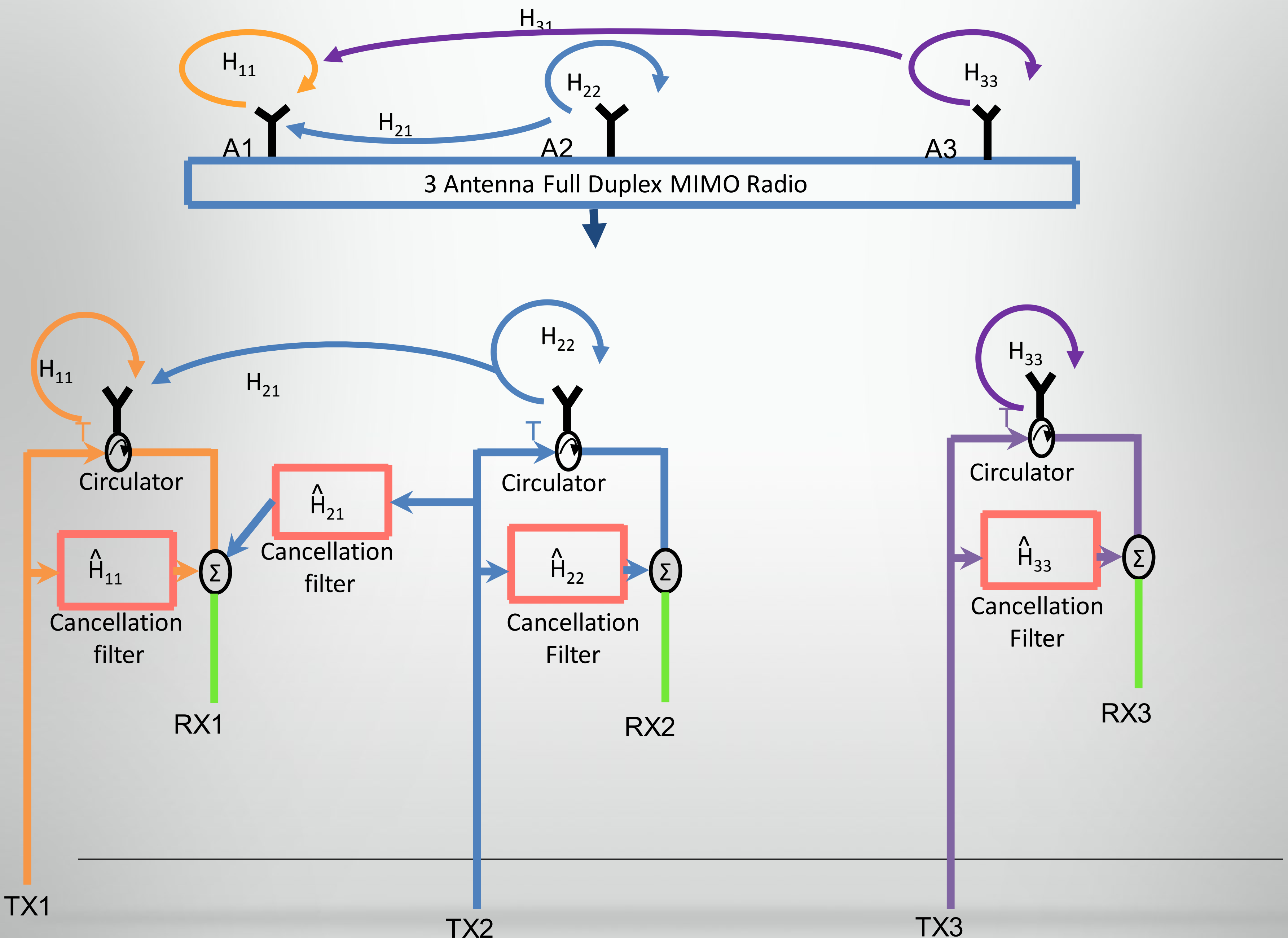

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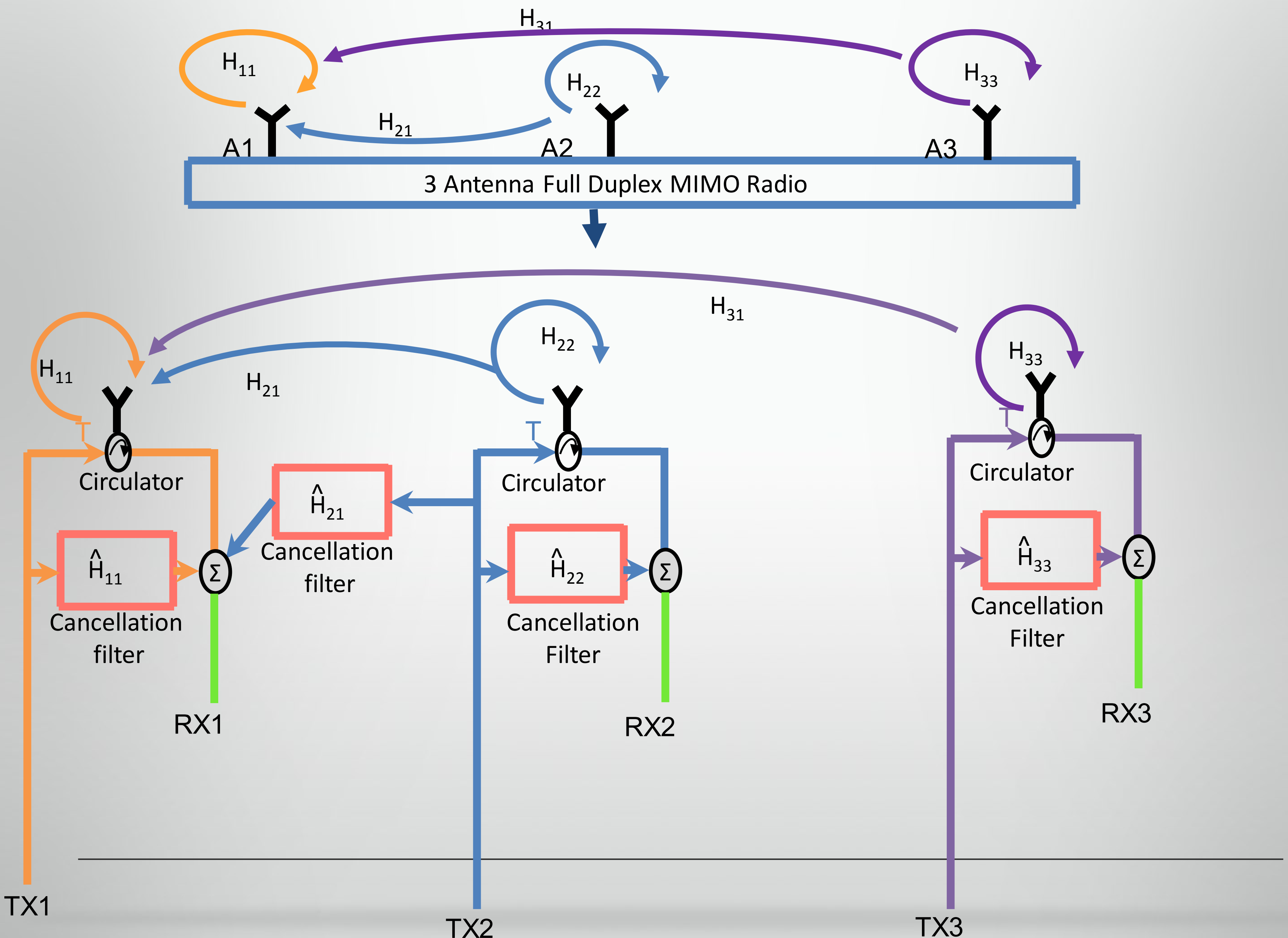

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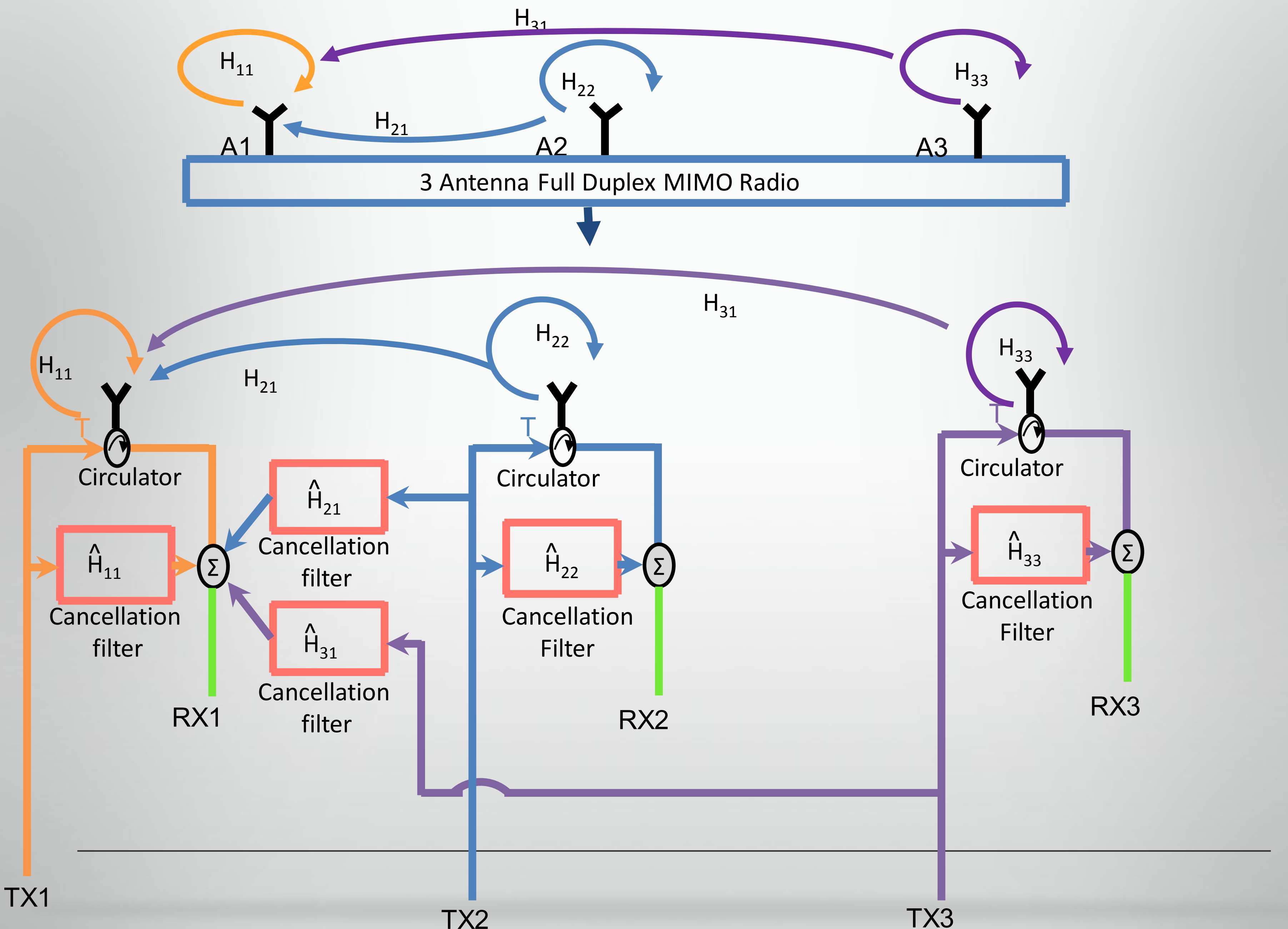

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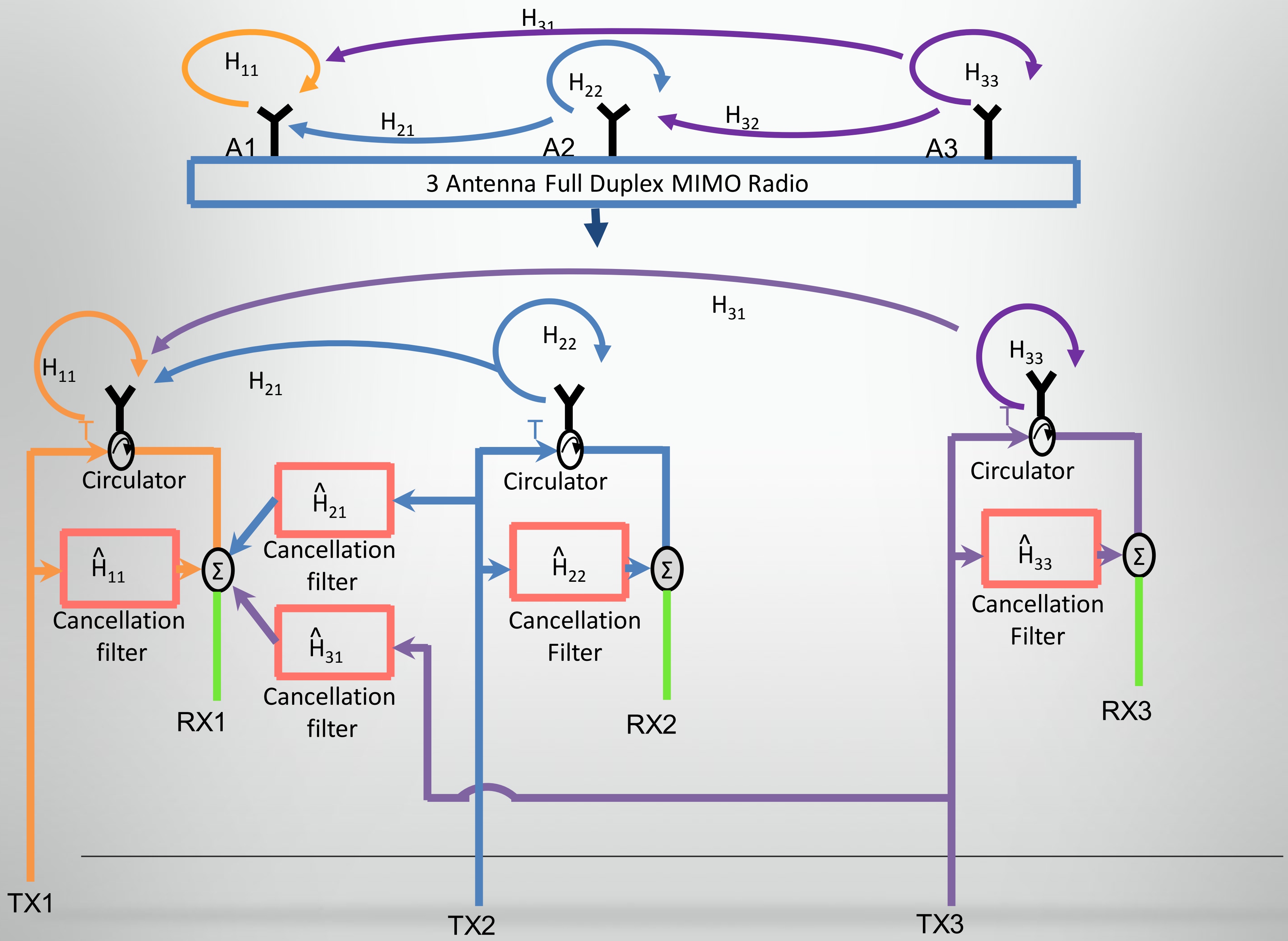

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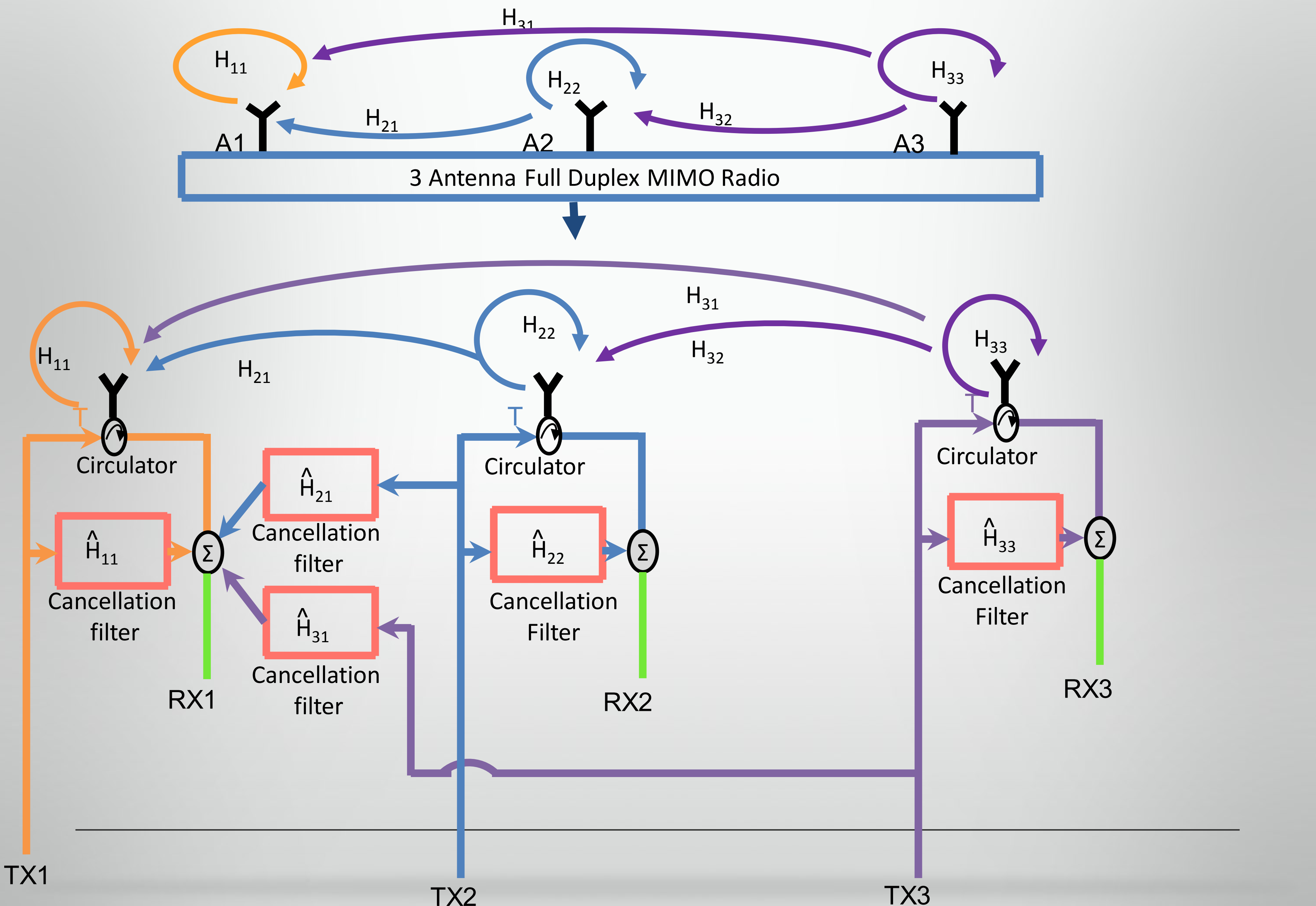

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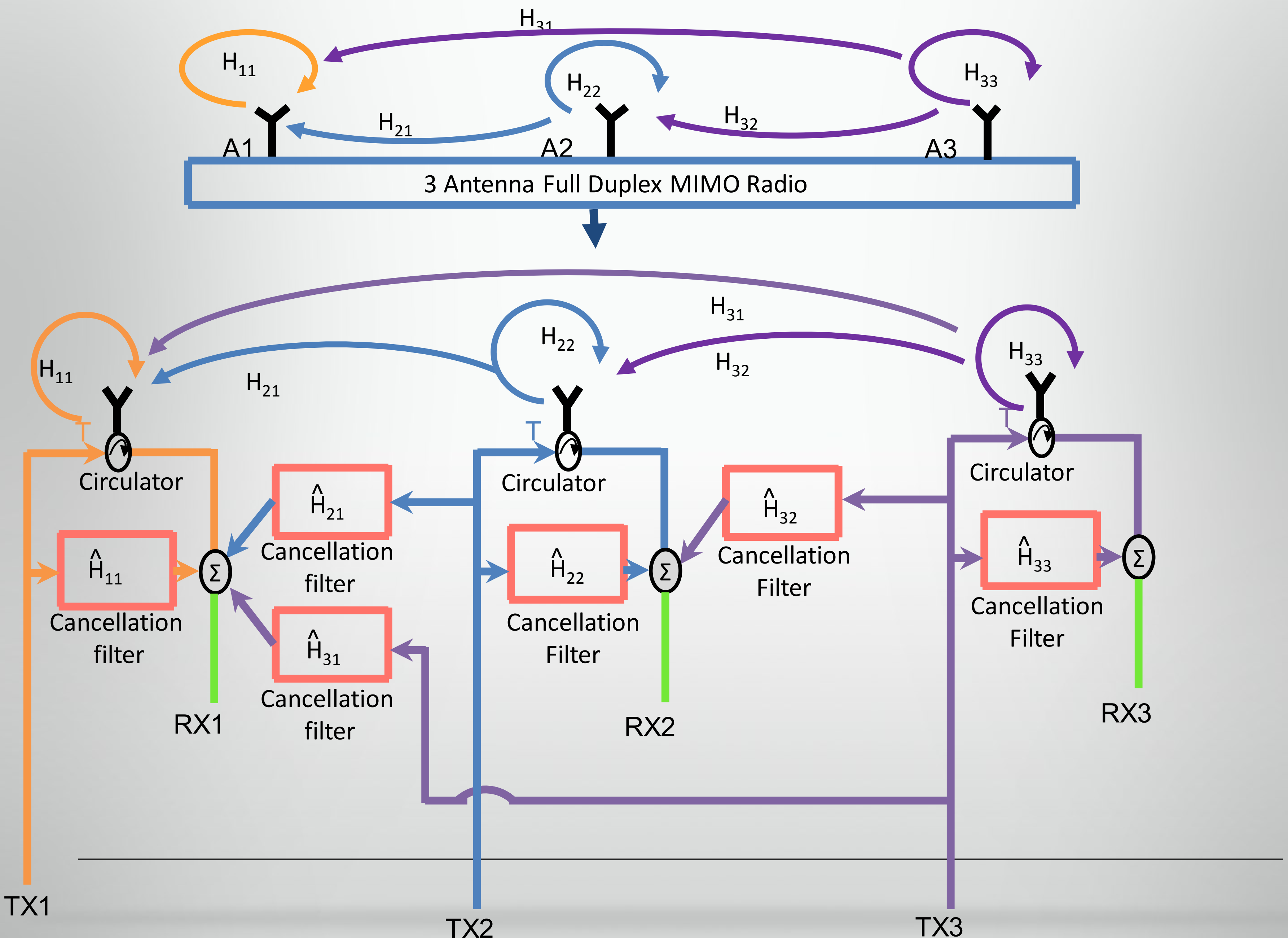

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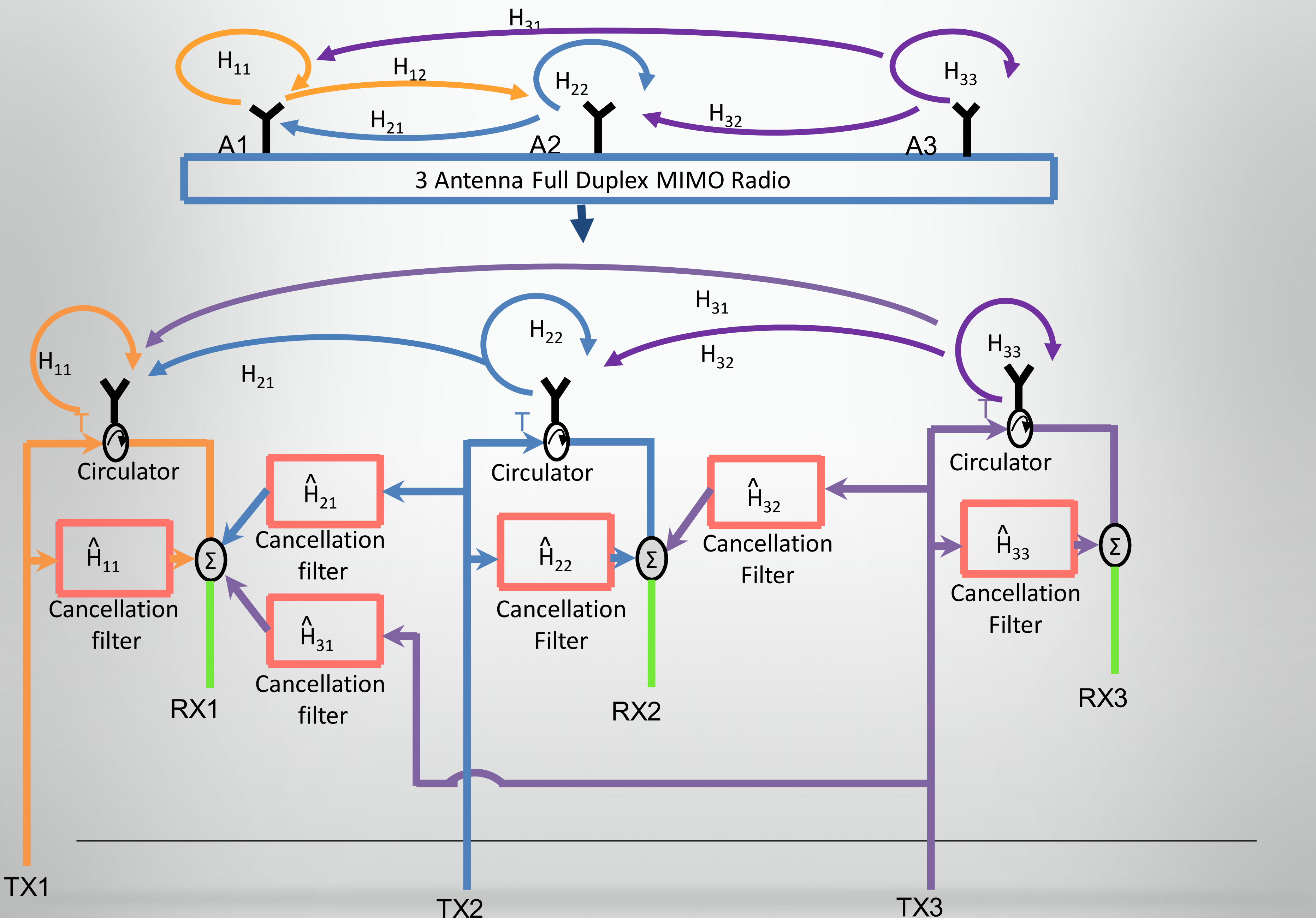

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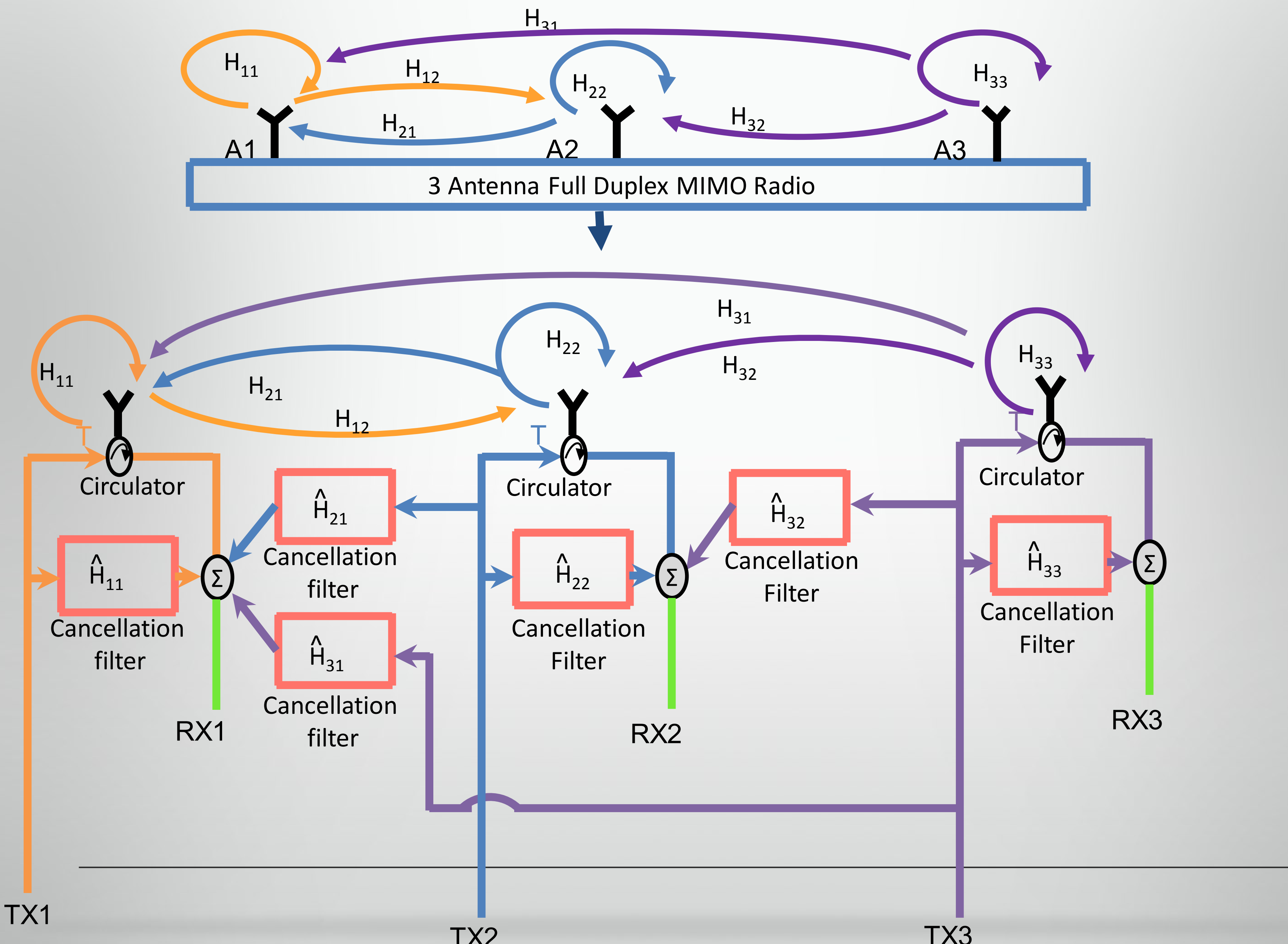

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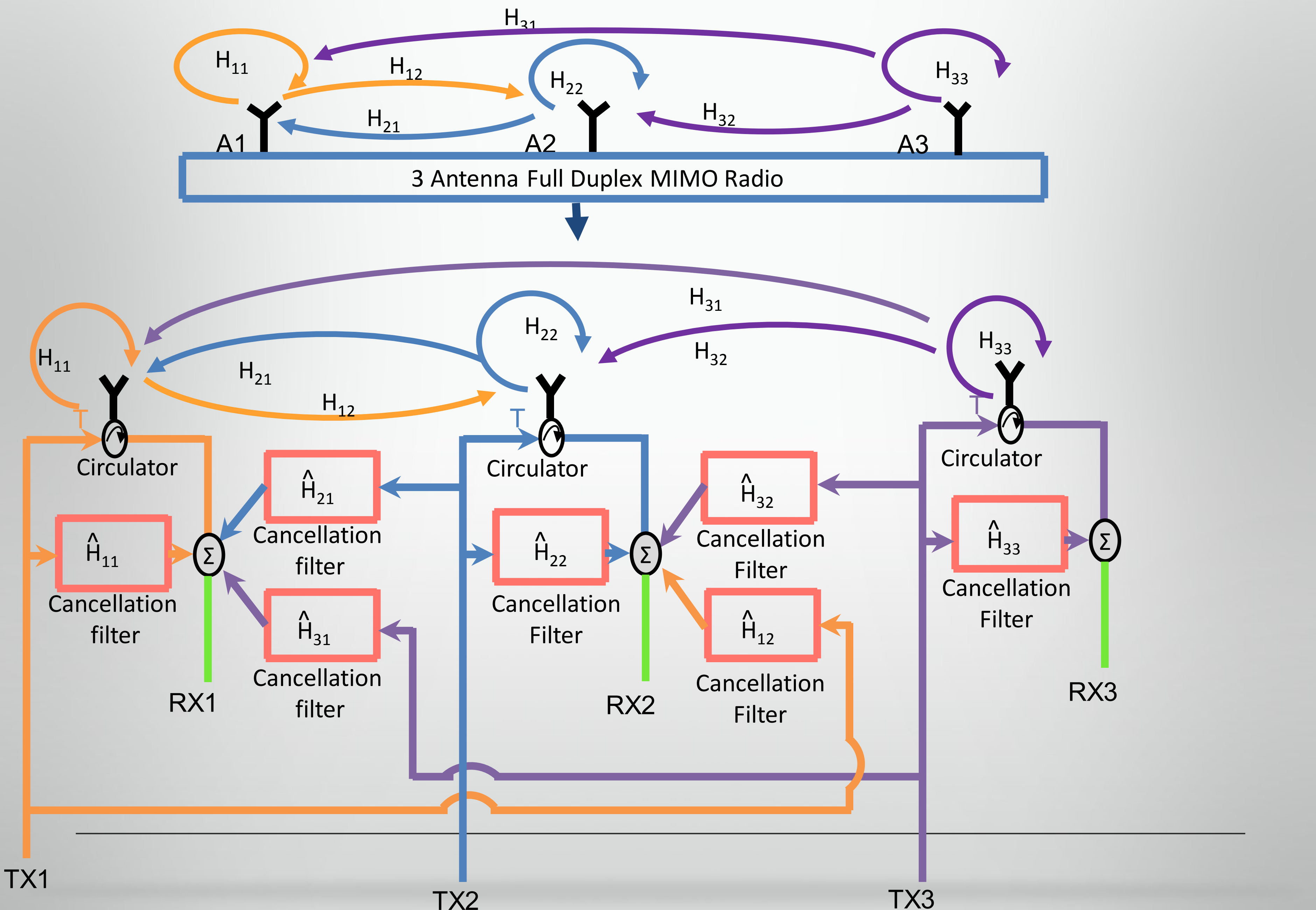

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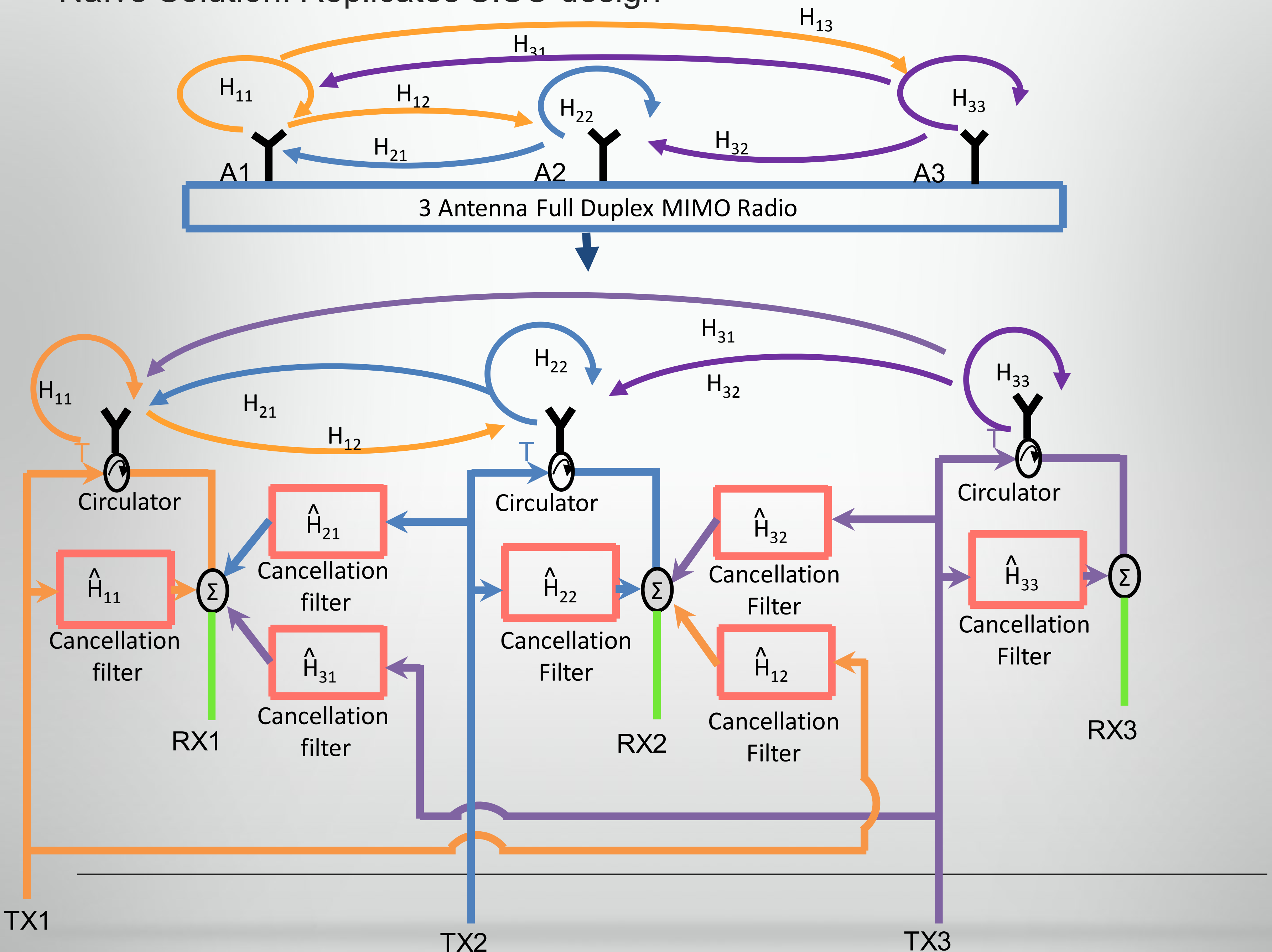

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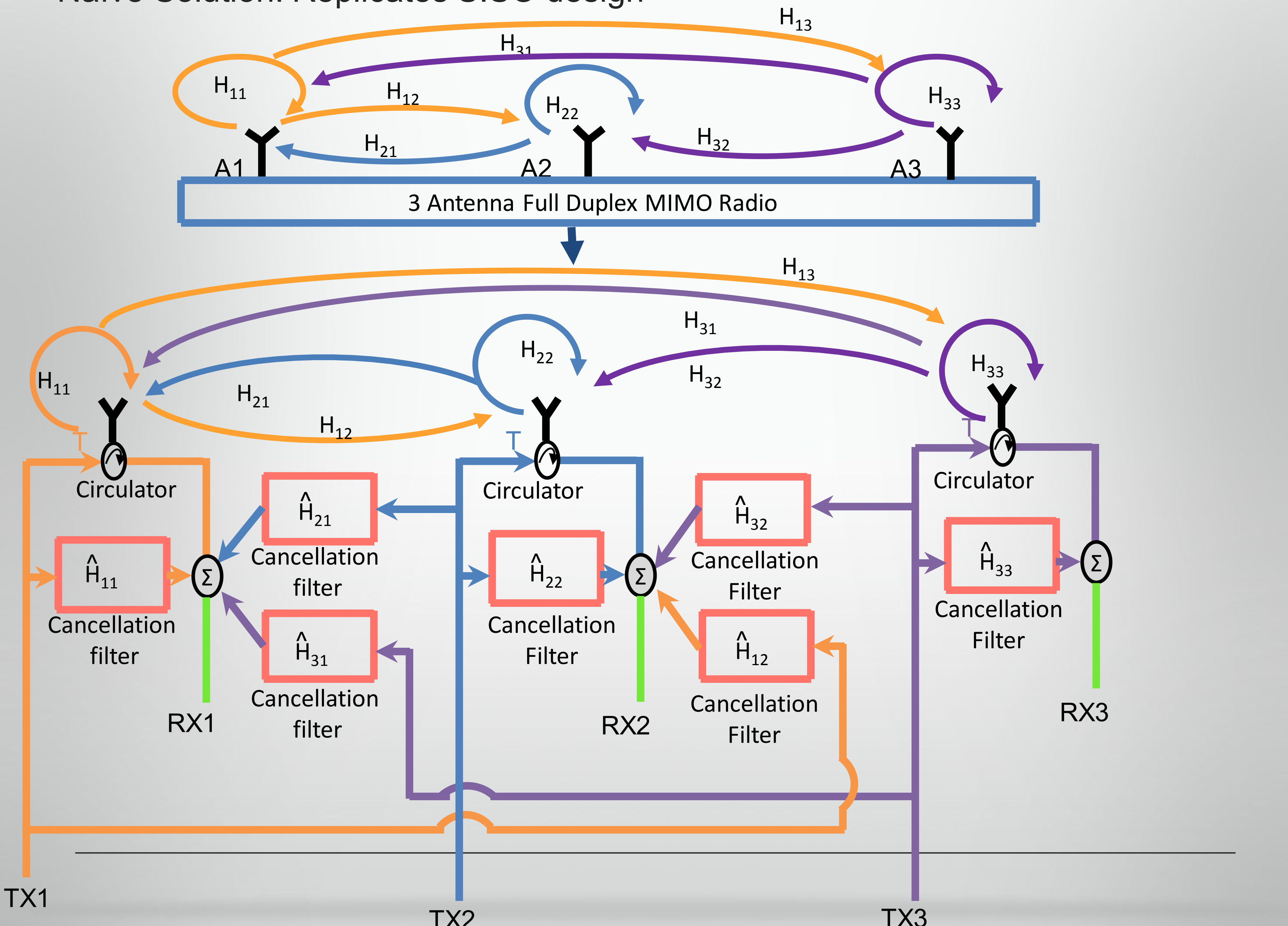

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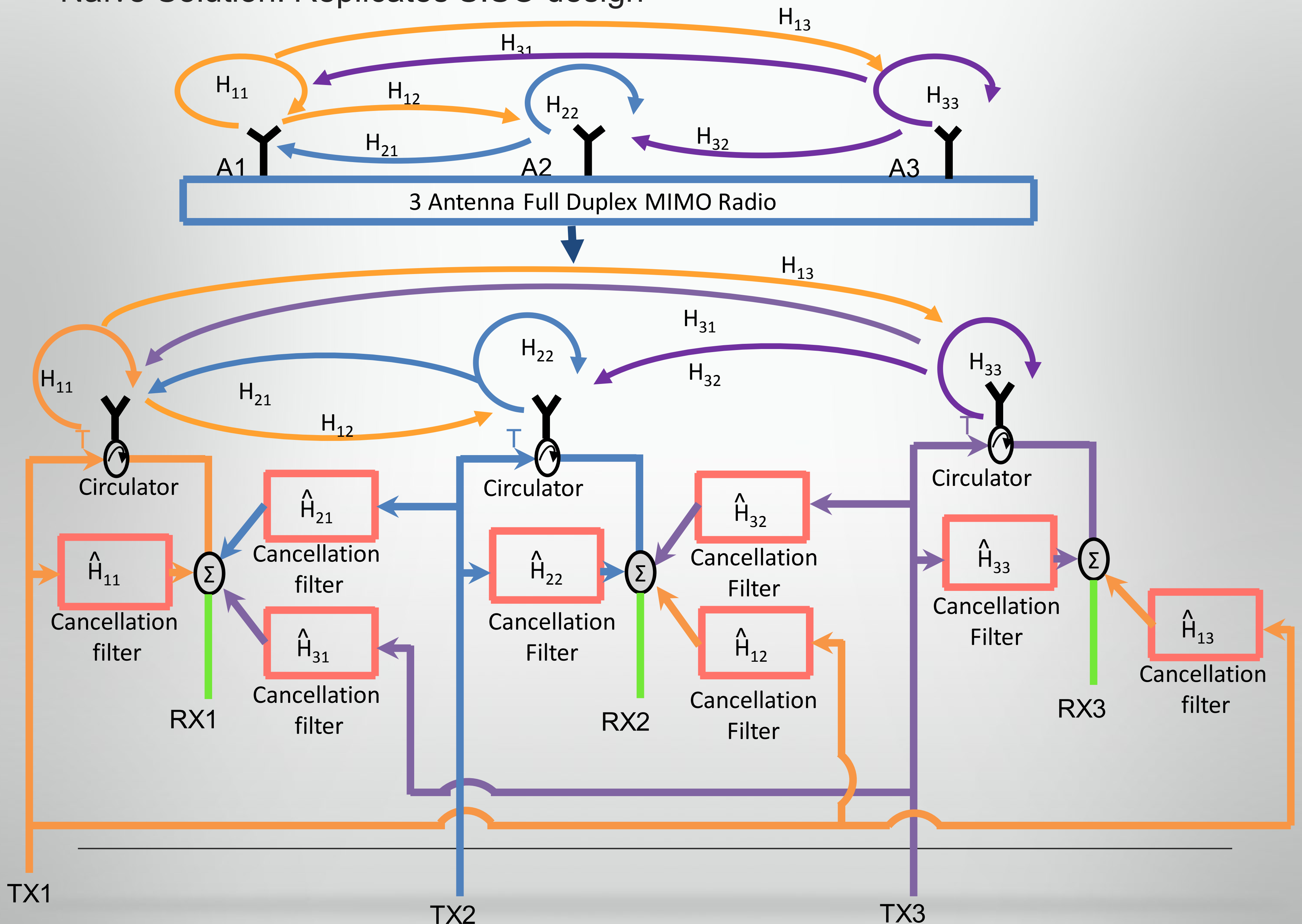

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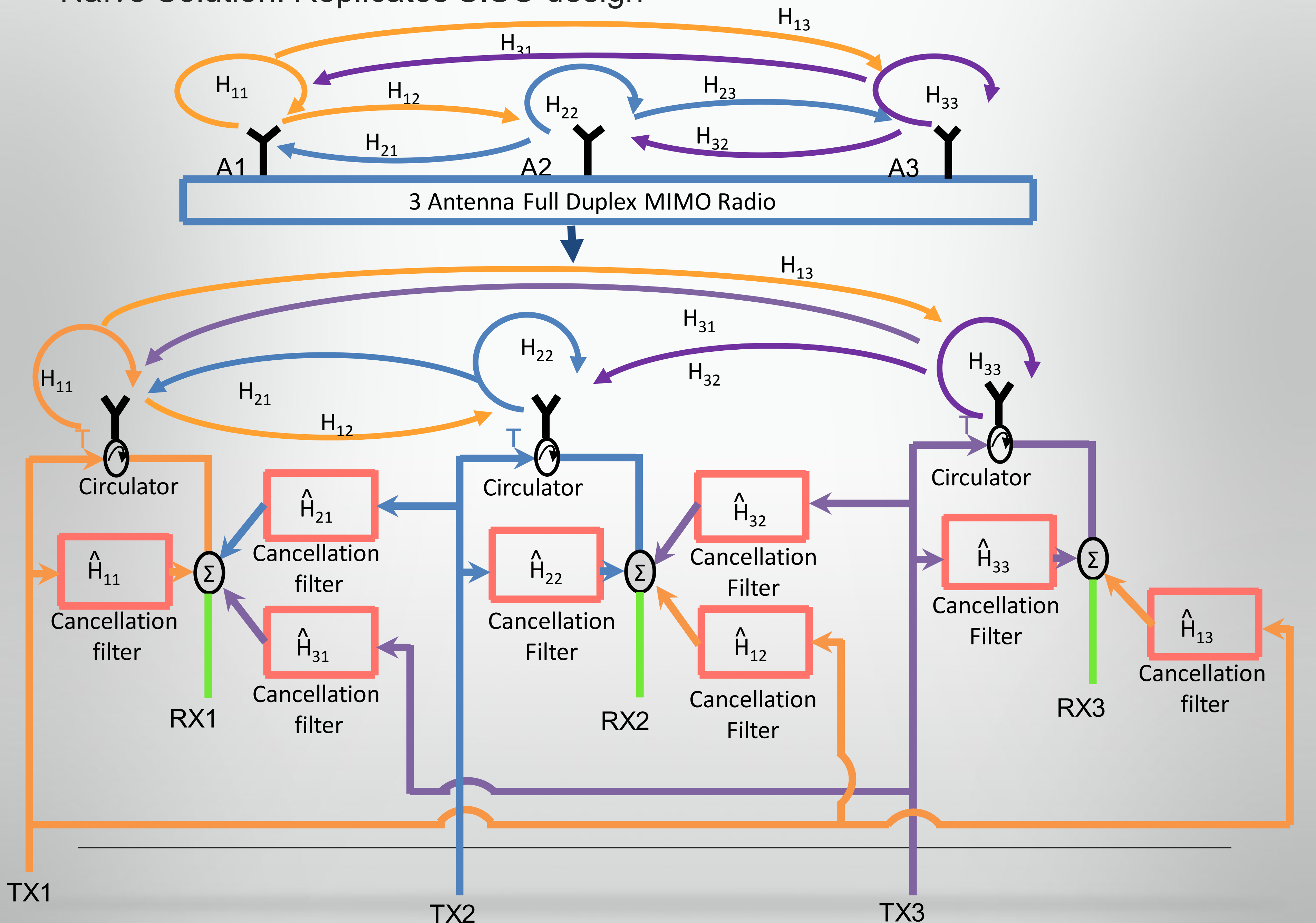

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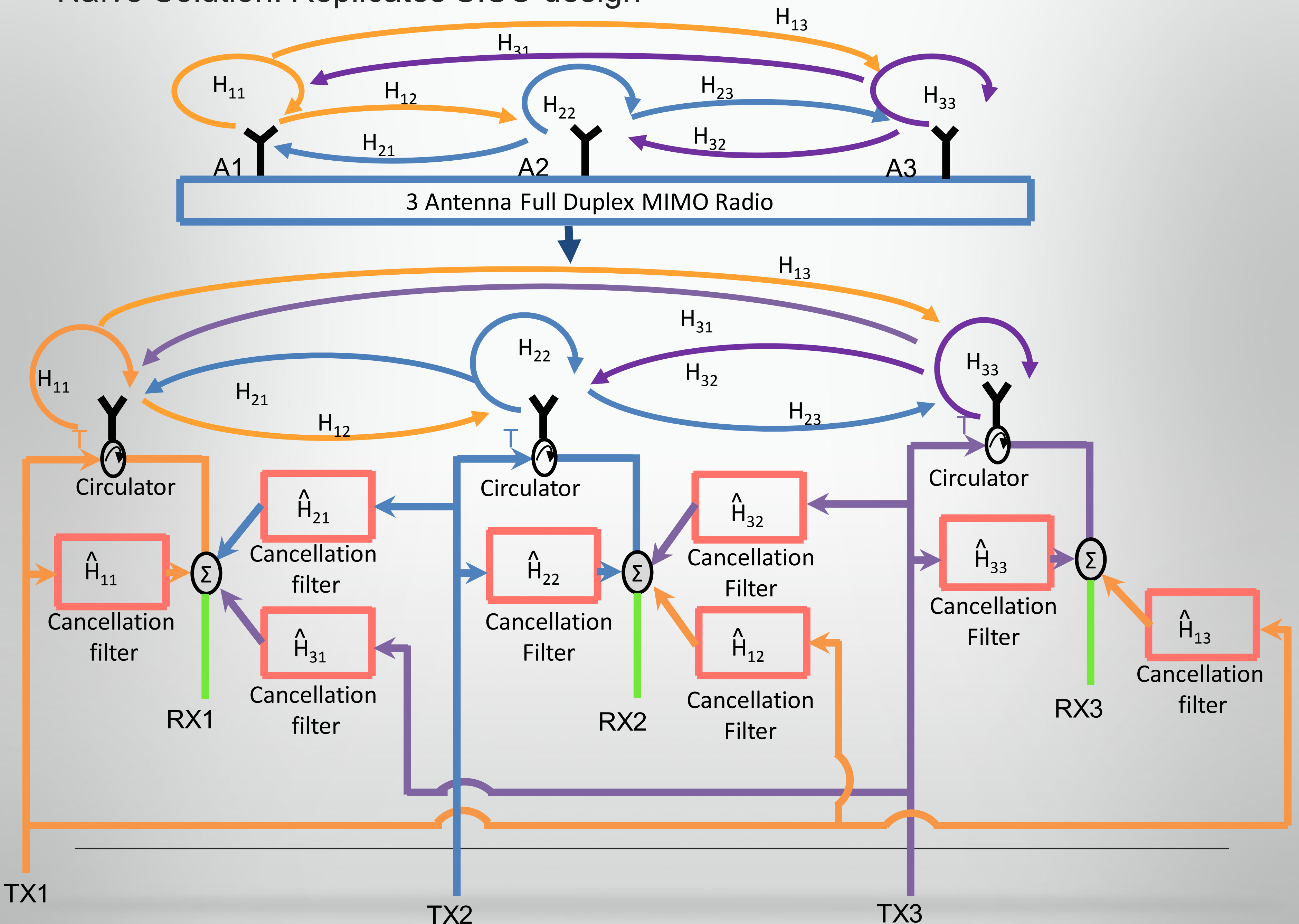

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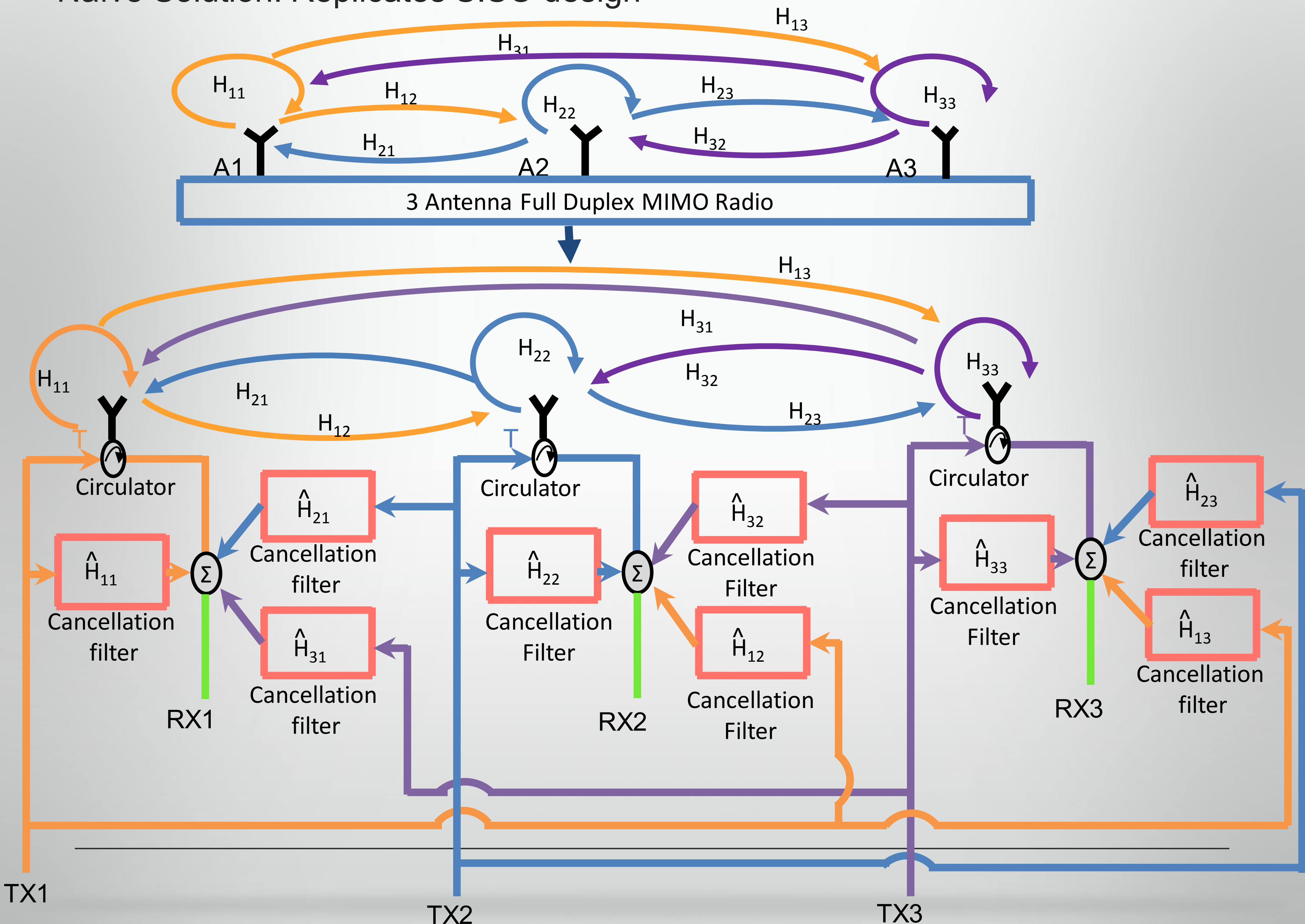

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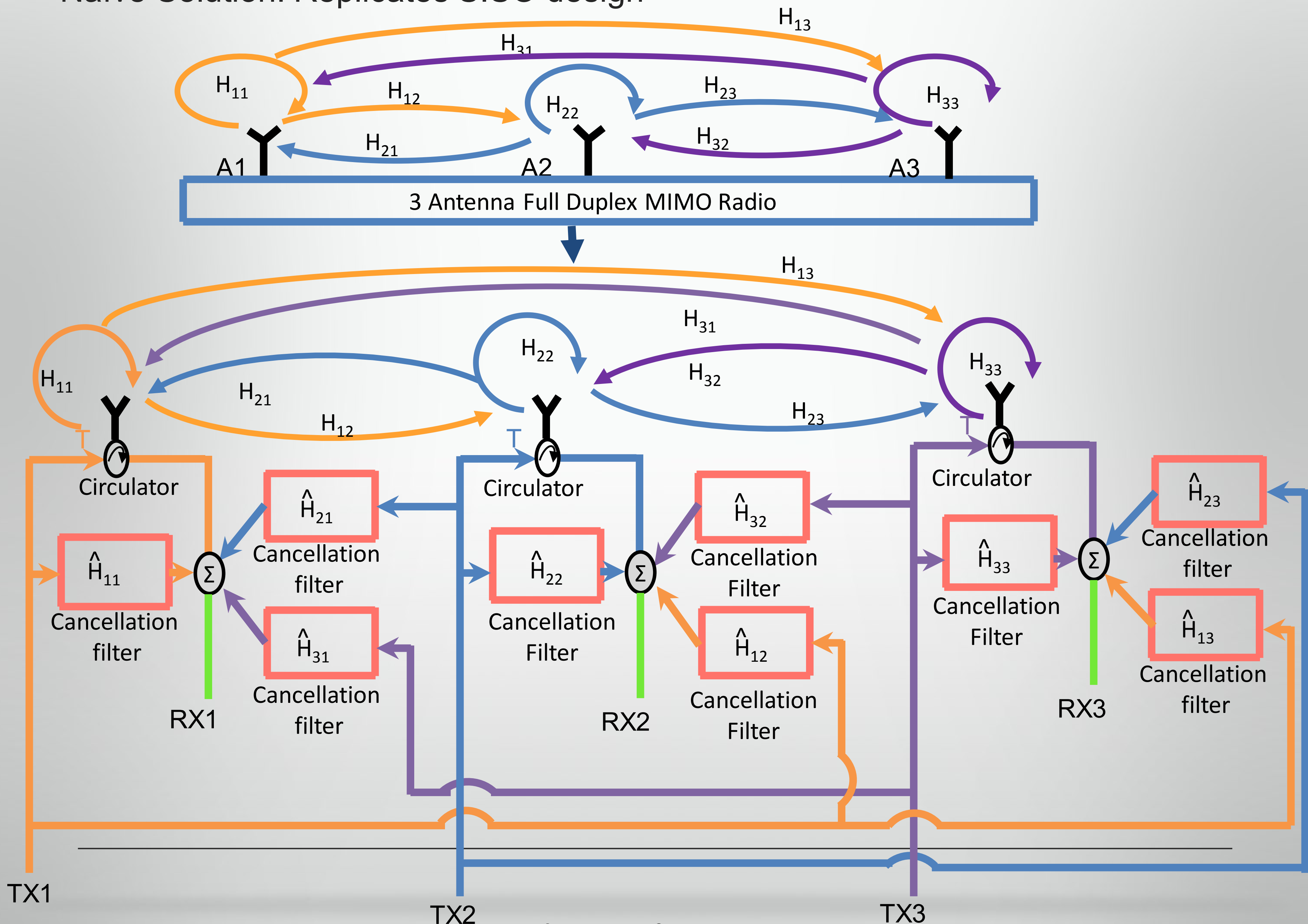

Total 9N Taps, for M=3

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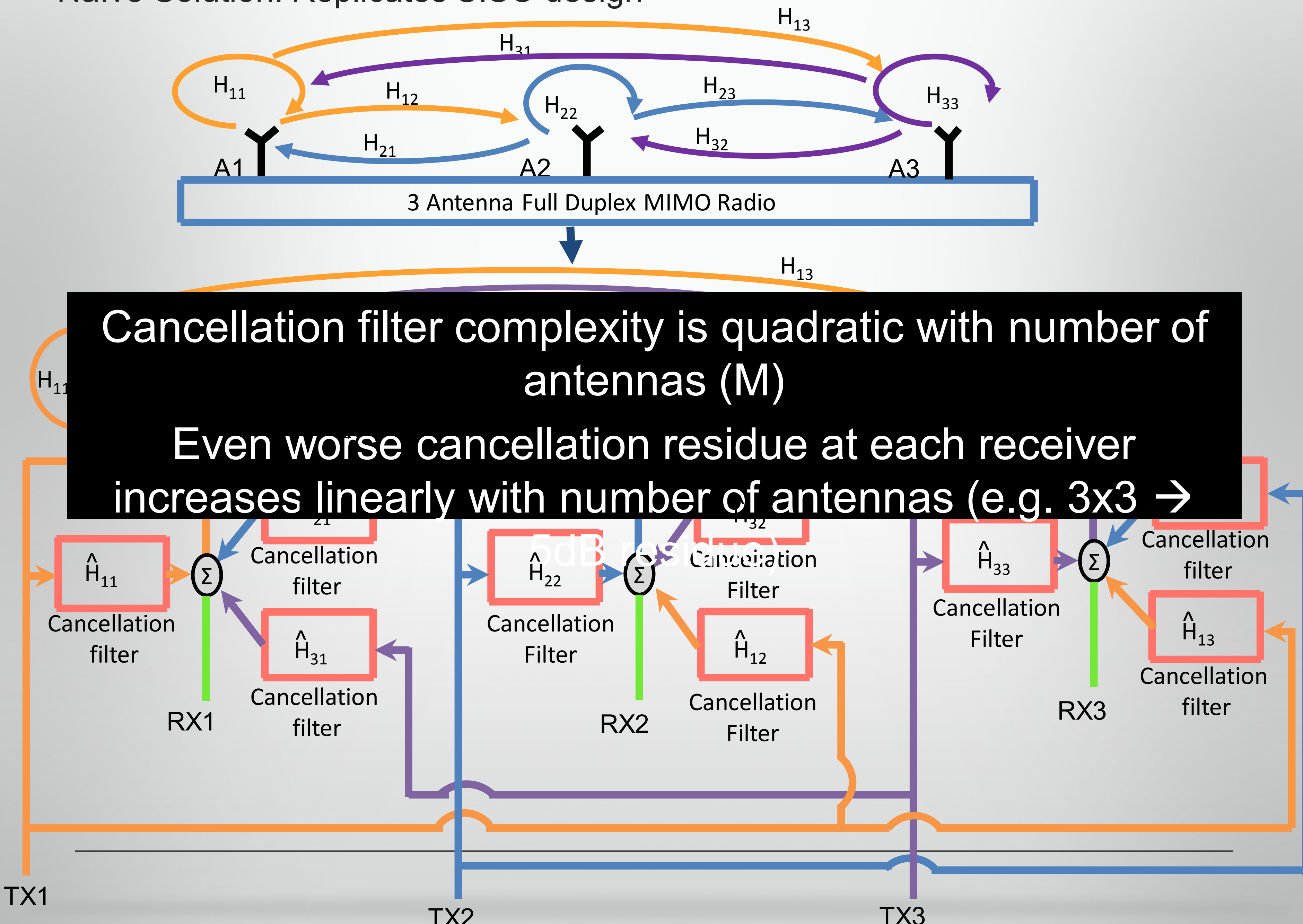


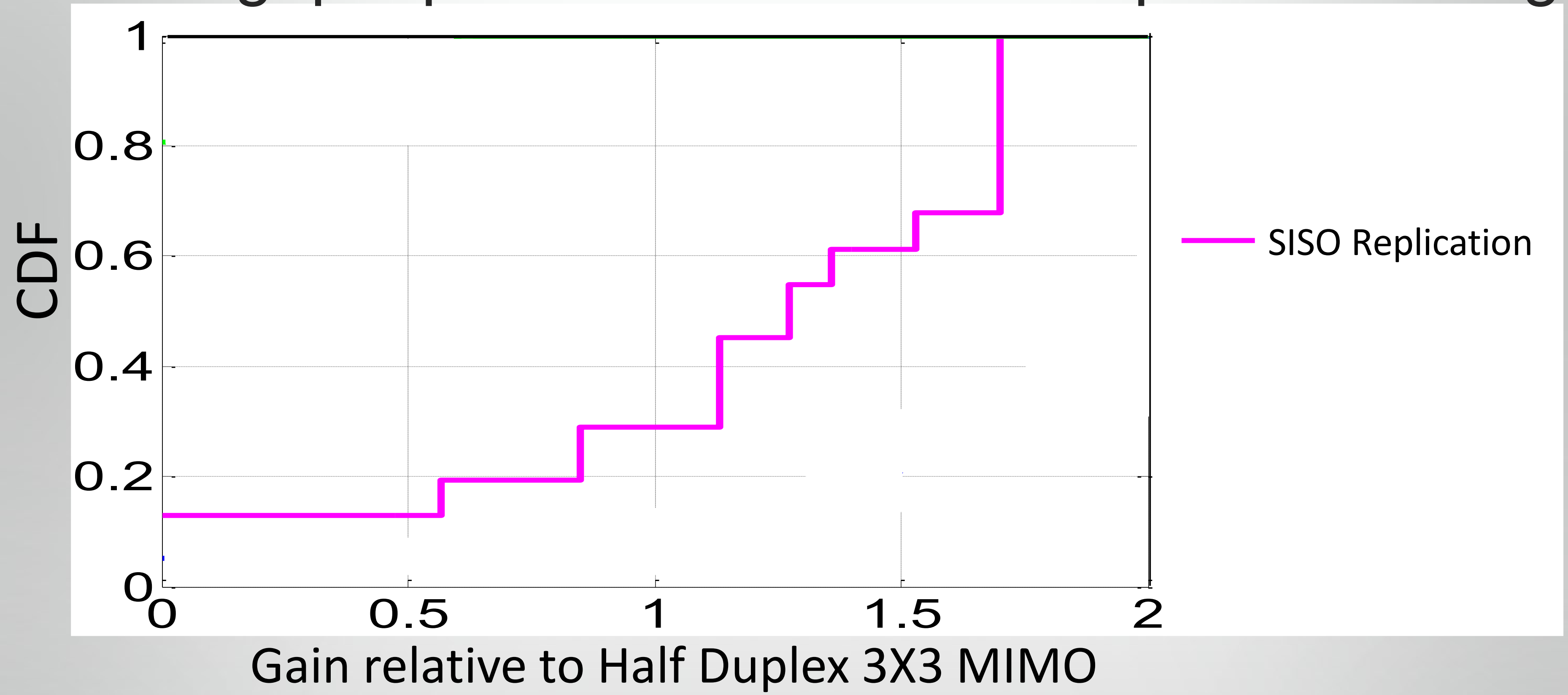
Cancellation filter complexity is quadratic with number of antennas (M)

Even worse cancellation residue at each receiver increases linearly with number of antennas (e.g. 3x3 → 5dB residue)

Total 9N Taps, for M=3

Why does the increase in cancellation residue matter?

Throughput performance of SISO replication design



Median throughput gain is not close to 2x because of large interference residue

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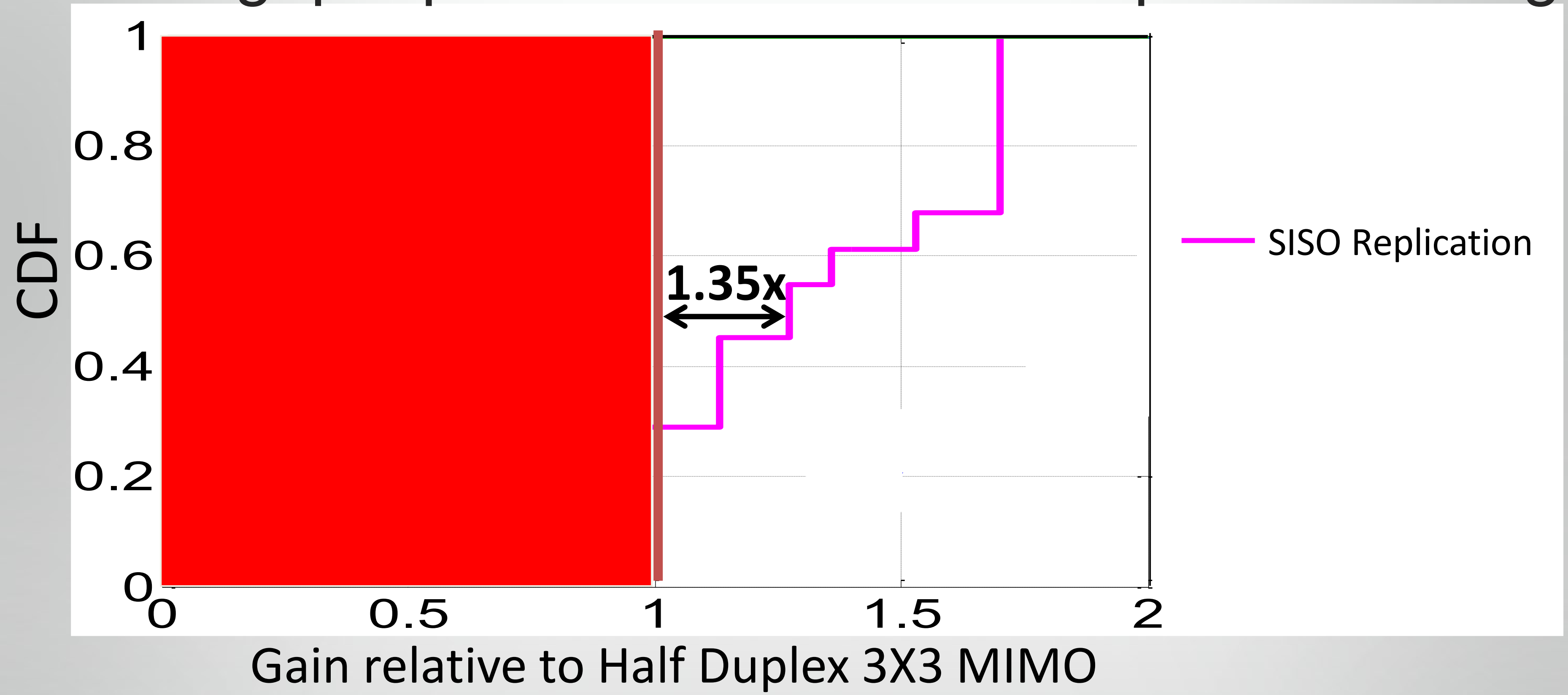

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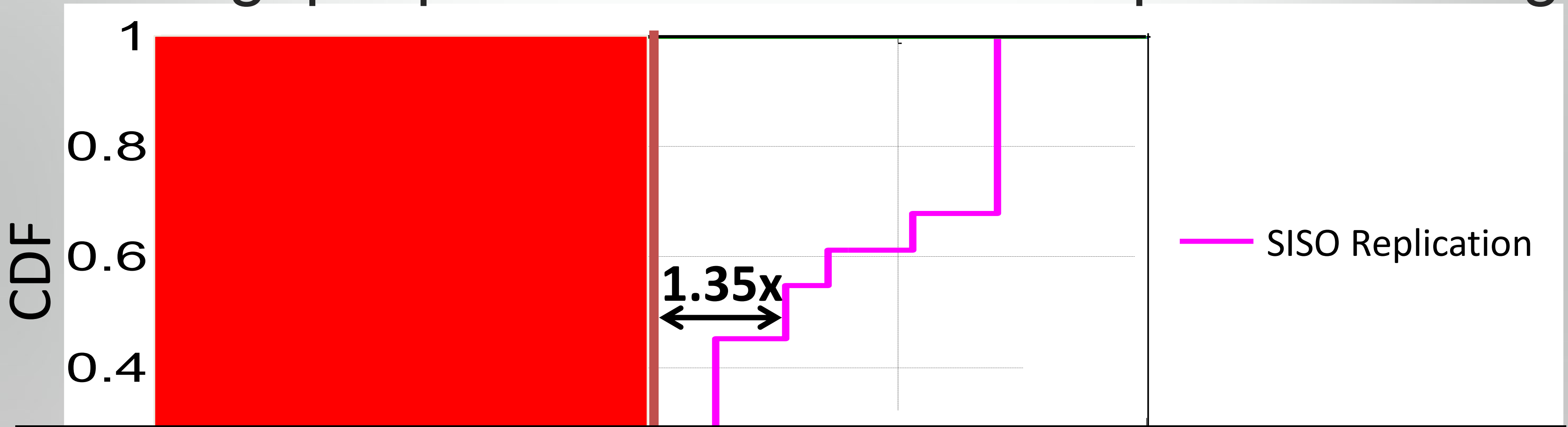

Ideal Solution:

- Cancellation filter complexity scales linearly with number of antennas (M)
- Cancellation Residue same as SISO and should not be impacted by number of MIMO antennas

Technical Contributions

Designed & implemented a near-ideal MIMO in-band full duplex radio

- Hybrid (analog & digital) cross and self-talk cancellation circuits & algorithms that completely eliminate interference to the noise floor

Prototype 3x3 MIMO full duplex radios using off-the-shelf WiFi radios

- Experimental indoor evaluation which demonstrates that our design practically achieves close to the 2x theoretically expected throughput gain

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- Cancellation residue is the same as the SISO full duplex, i.e. it does not degrade with increasing number of antennas.

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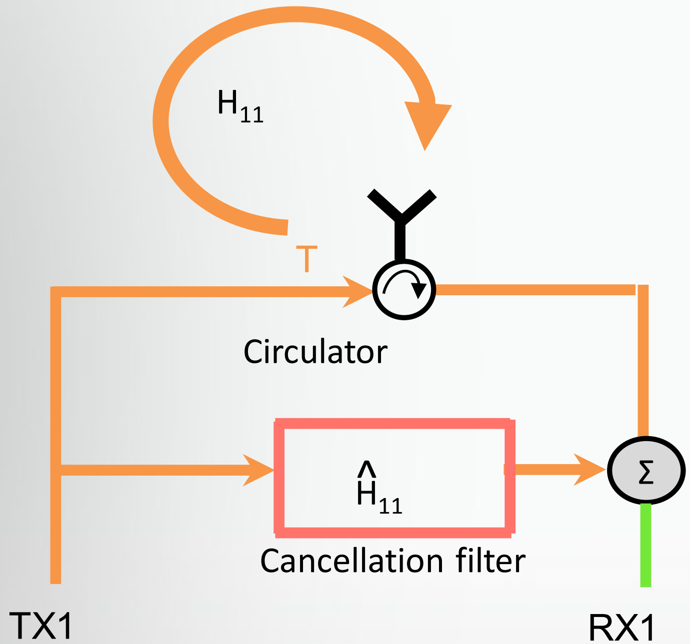
Key Idea: Reducing Complexity



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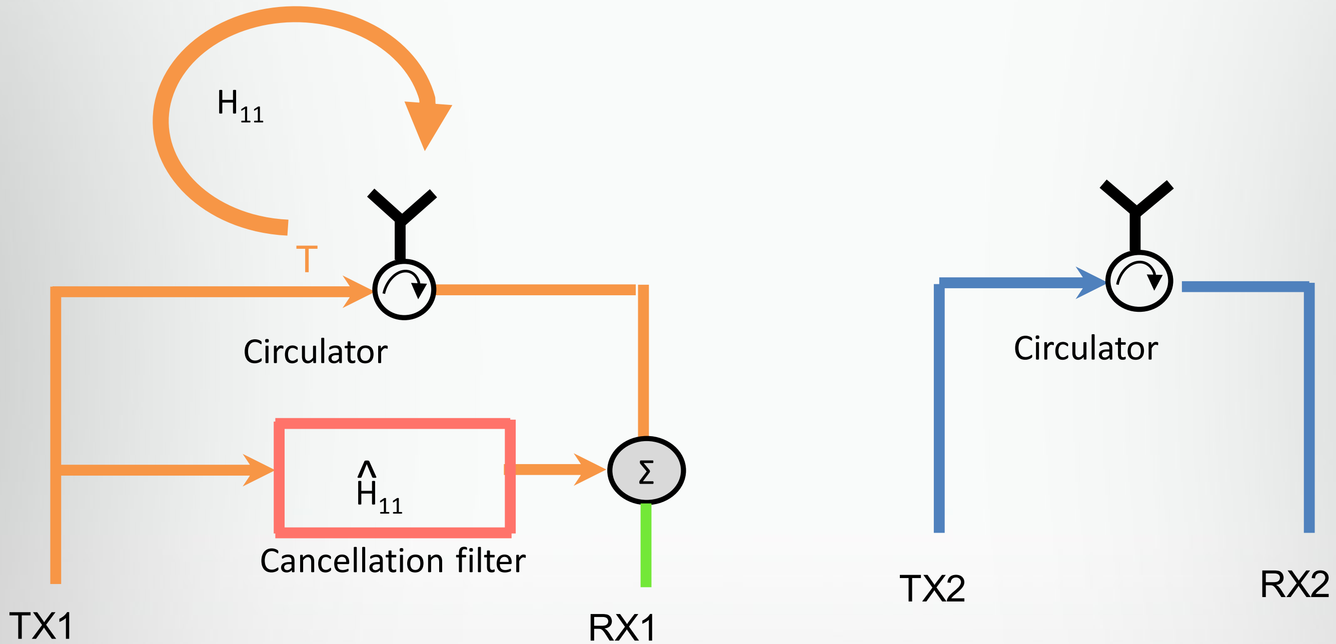

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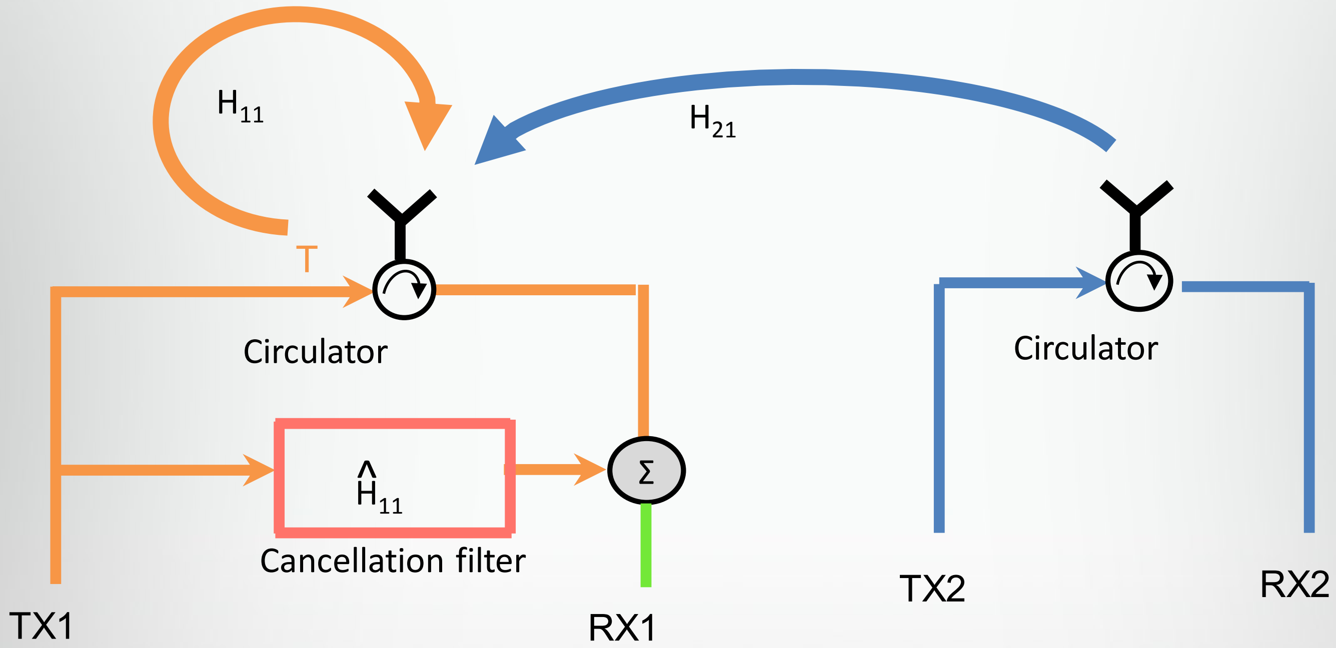

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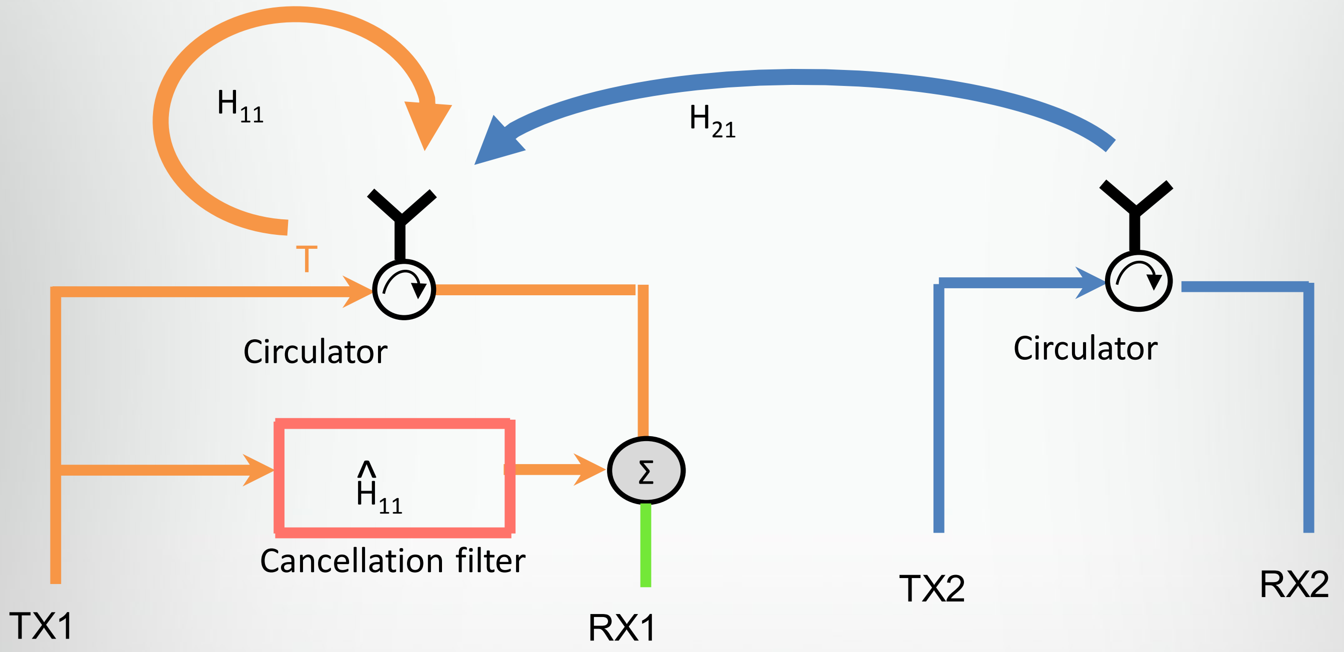
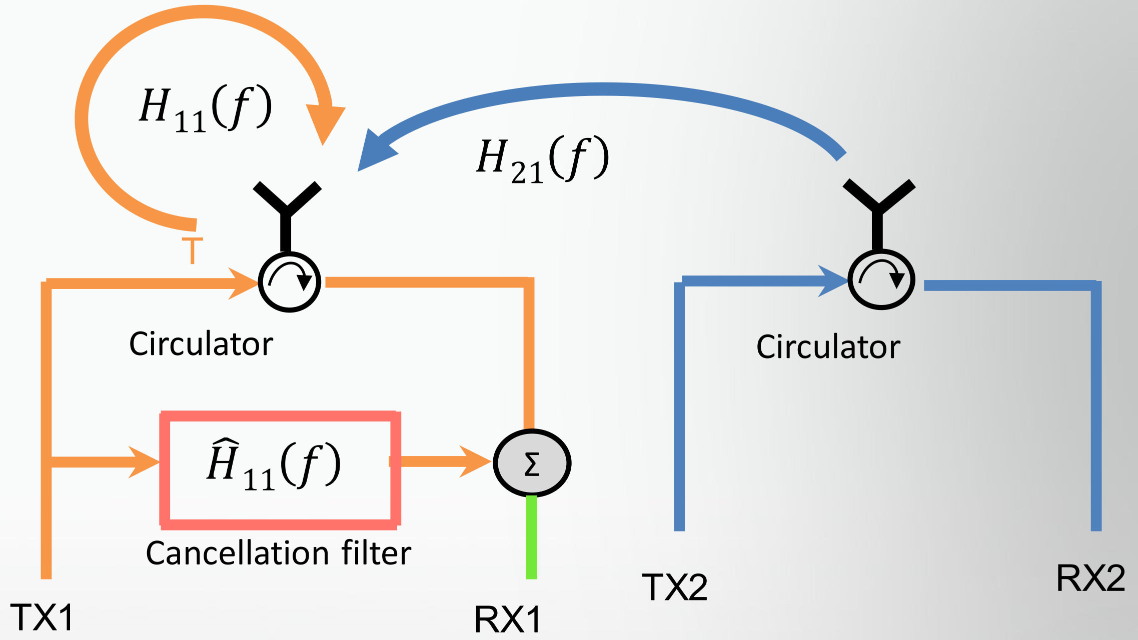


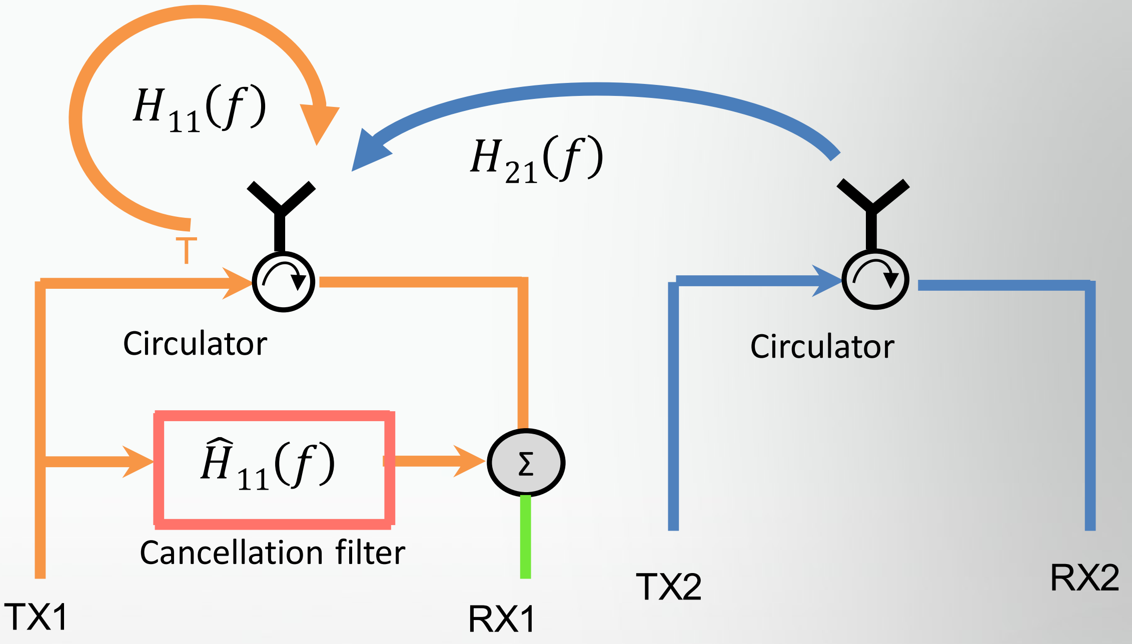
Can we reuse the self talk cancellation filter to also cancel the cross talk ?

Why can self talk cancellation filter be used to partly model cross talk?



Why can self talk cancellation filter be used to partly model cross talk?

- Share Environment
- Share Reflectors



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- Share Environment
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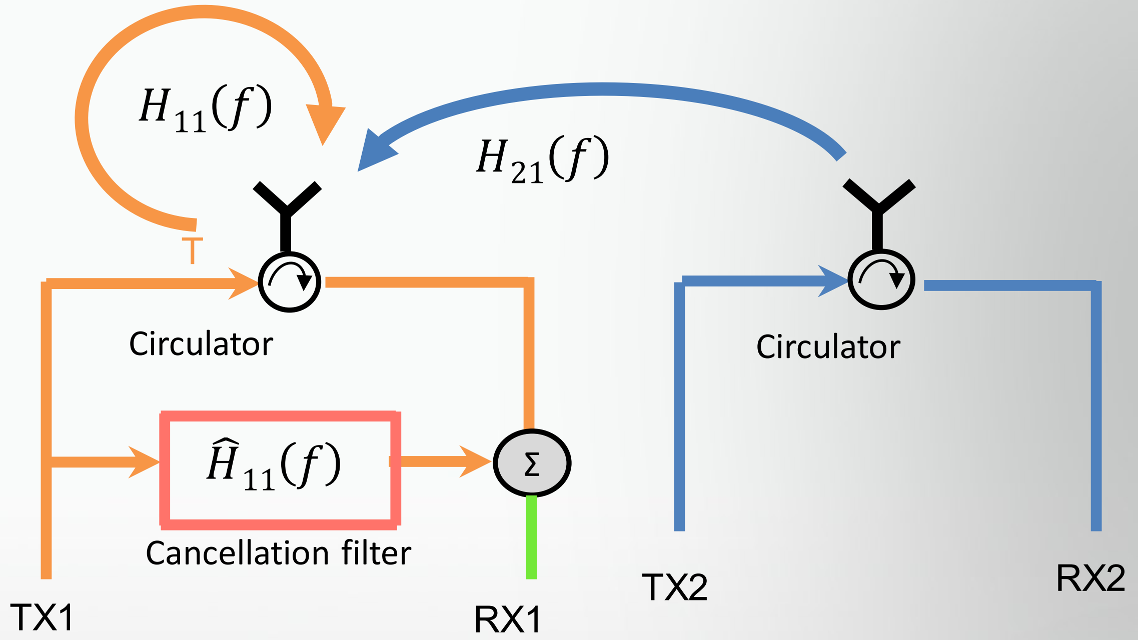

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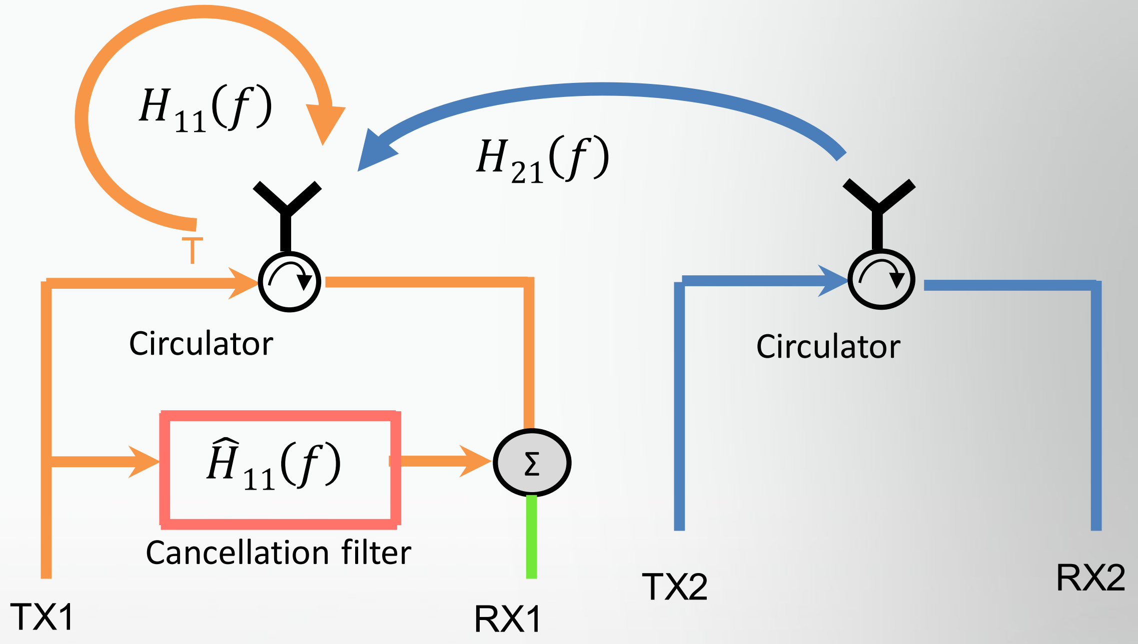

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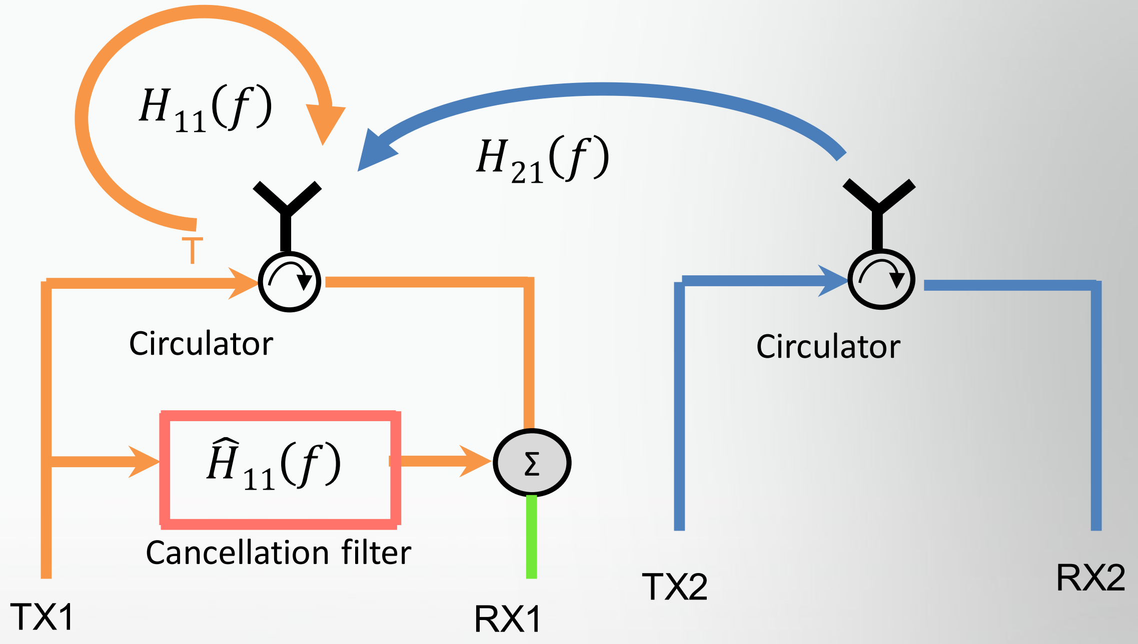

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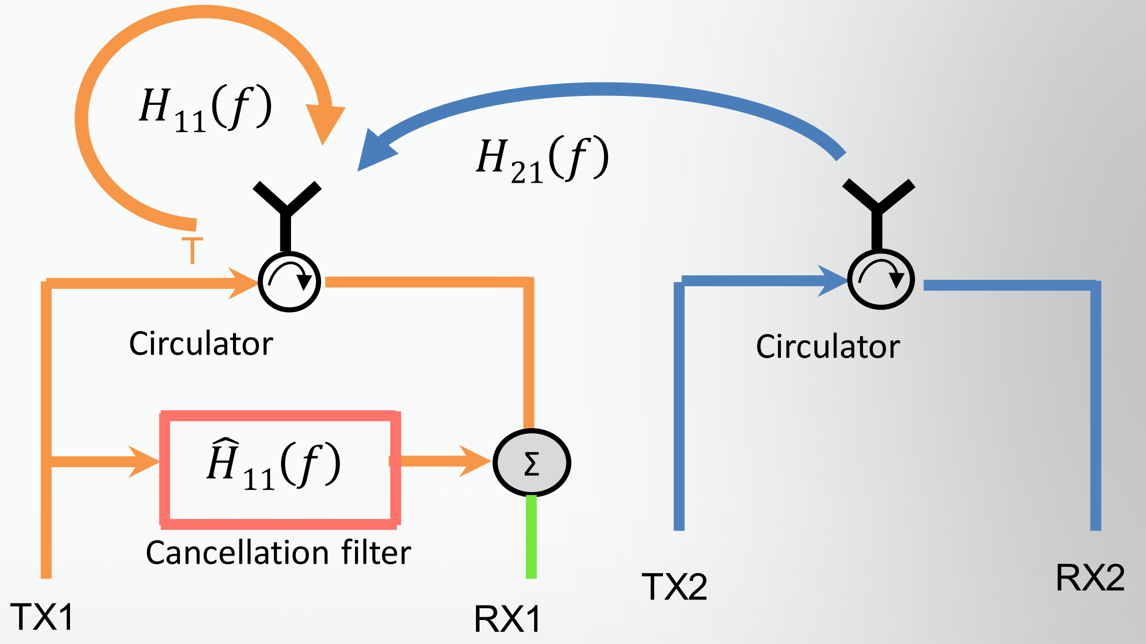


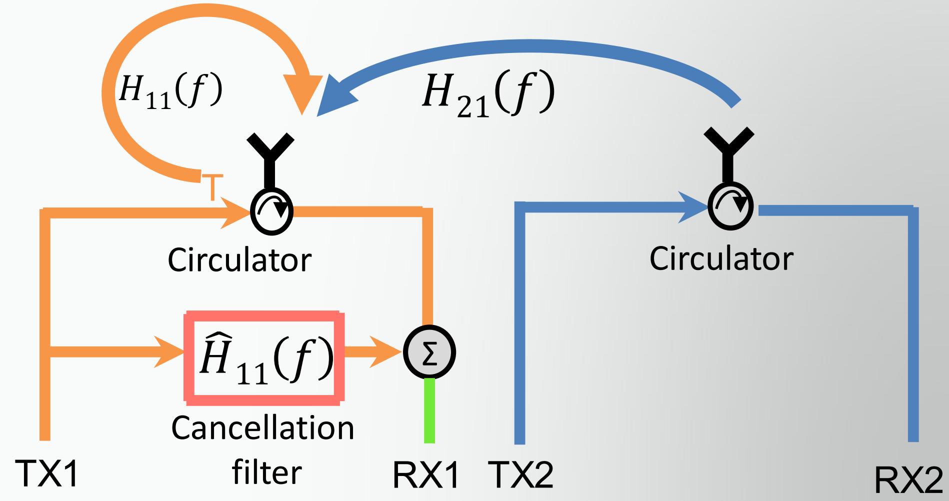
$$H_{21}(f) = Hcas_{cade}(f)\,.\,H_{11}(f)$$

Can we leverage this relationship to reduce the cancellation complexity

Empirical Observation

$$H_{21}(f) = \underbrace{Hcas_{cade}(f)}_{} \, . H_{11}(f)$$

Cascade Transfer Function



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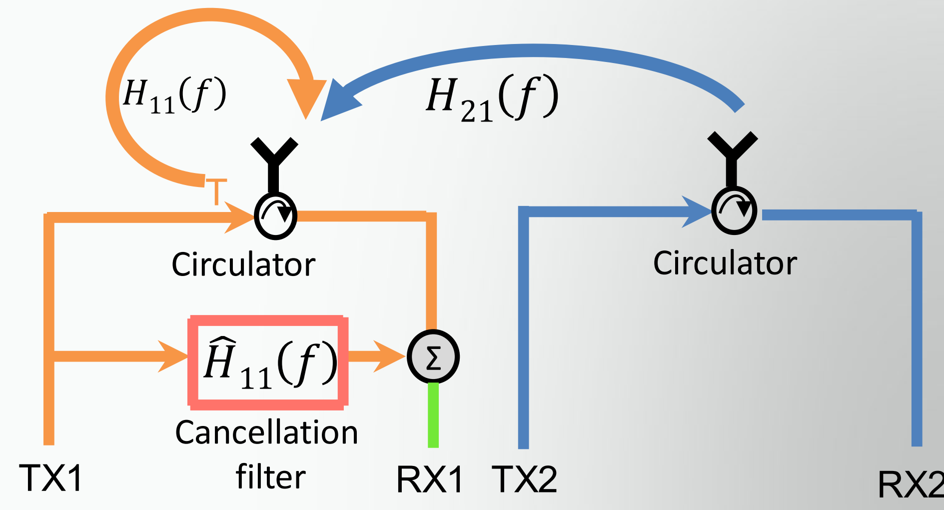

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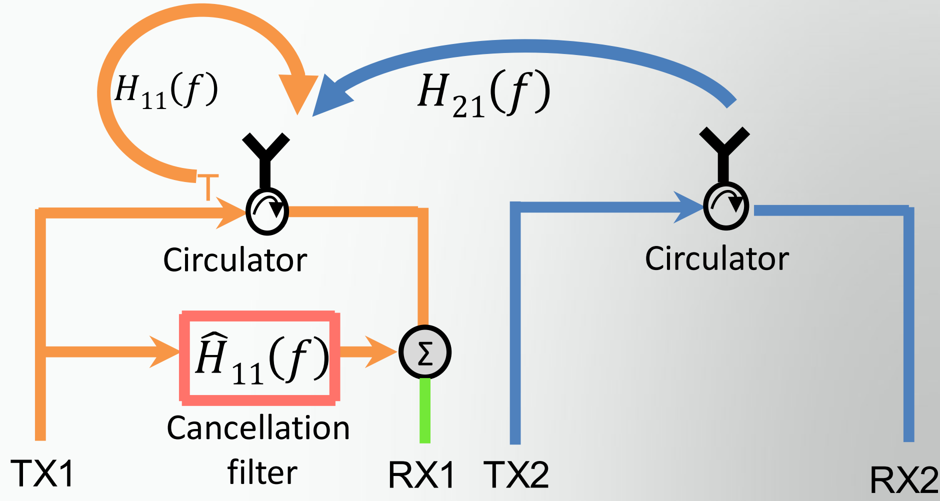
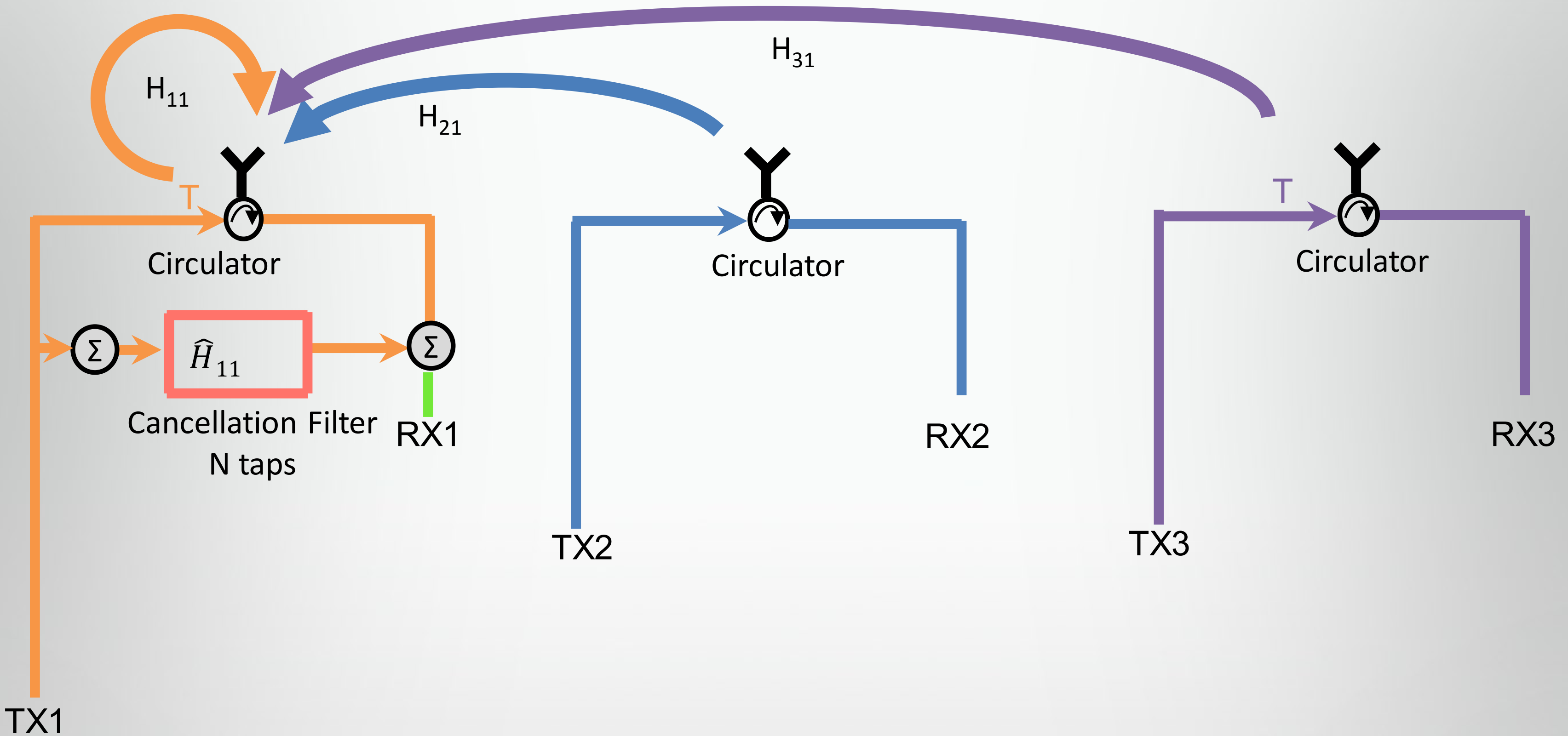
Cascade Transfer Function



- Cascade Transfer Function
- Collect cross talk and self talk for various indoor environments
- Learning Algorithm
- From all the possible cascade response, calculate via optimization the best low complexity circuit which achieves the cascade transfer function (offline analysis)
- Complexity Reduction
- These cascade circuits are very low complexity, thus allowing us to get close to linear complexity

Reducing Complexity: Cascaded Cancellation



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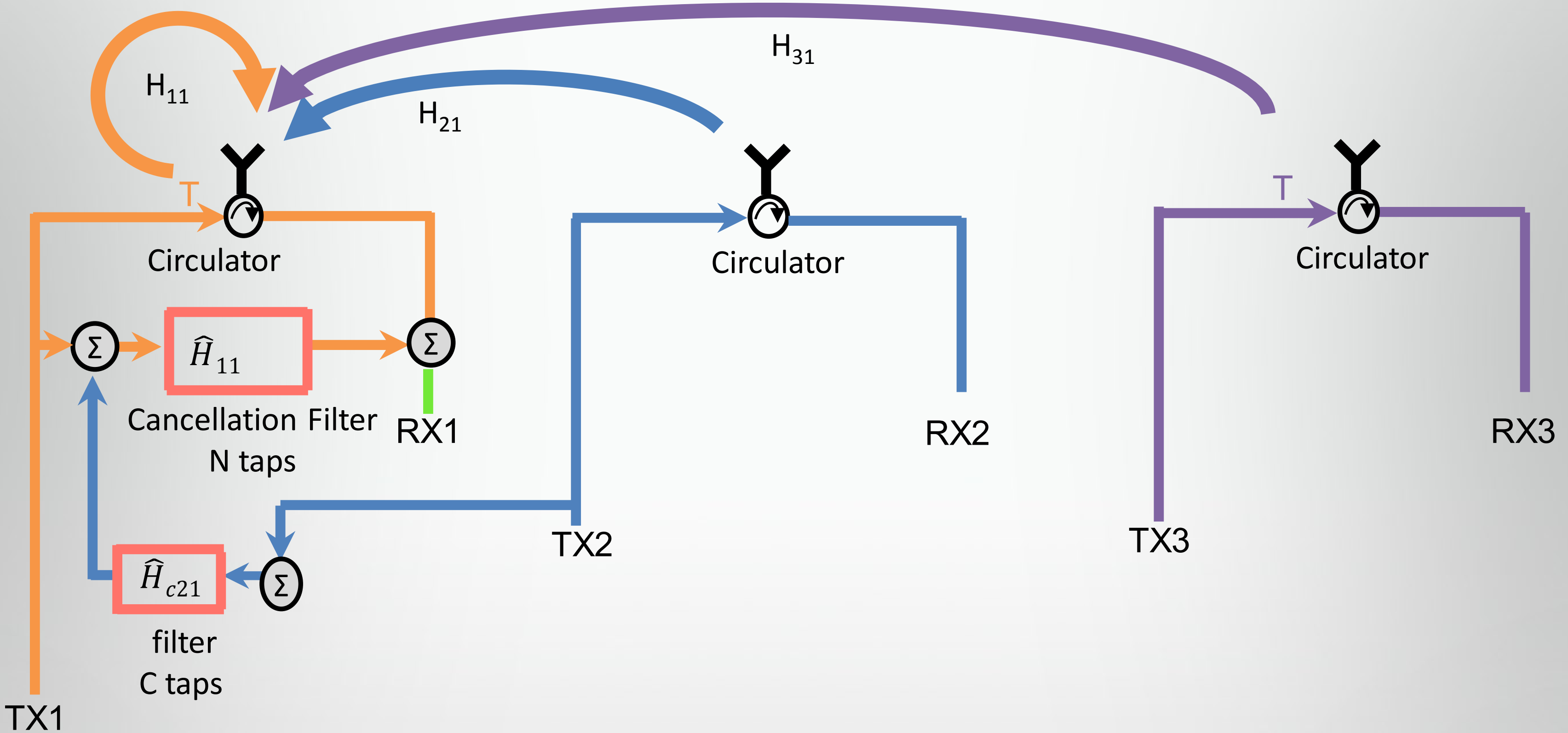

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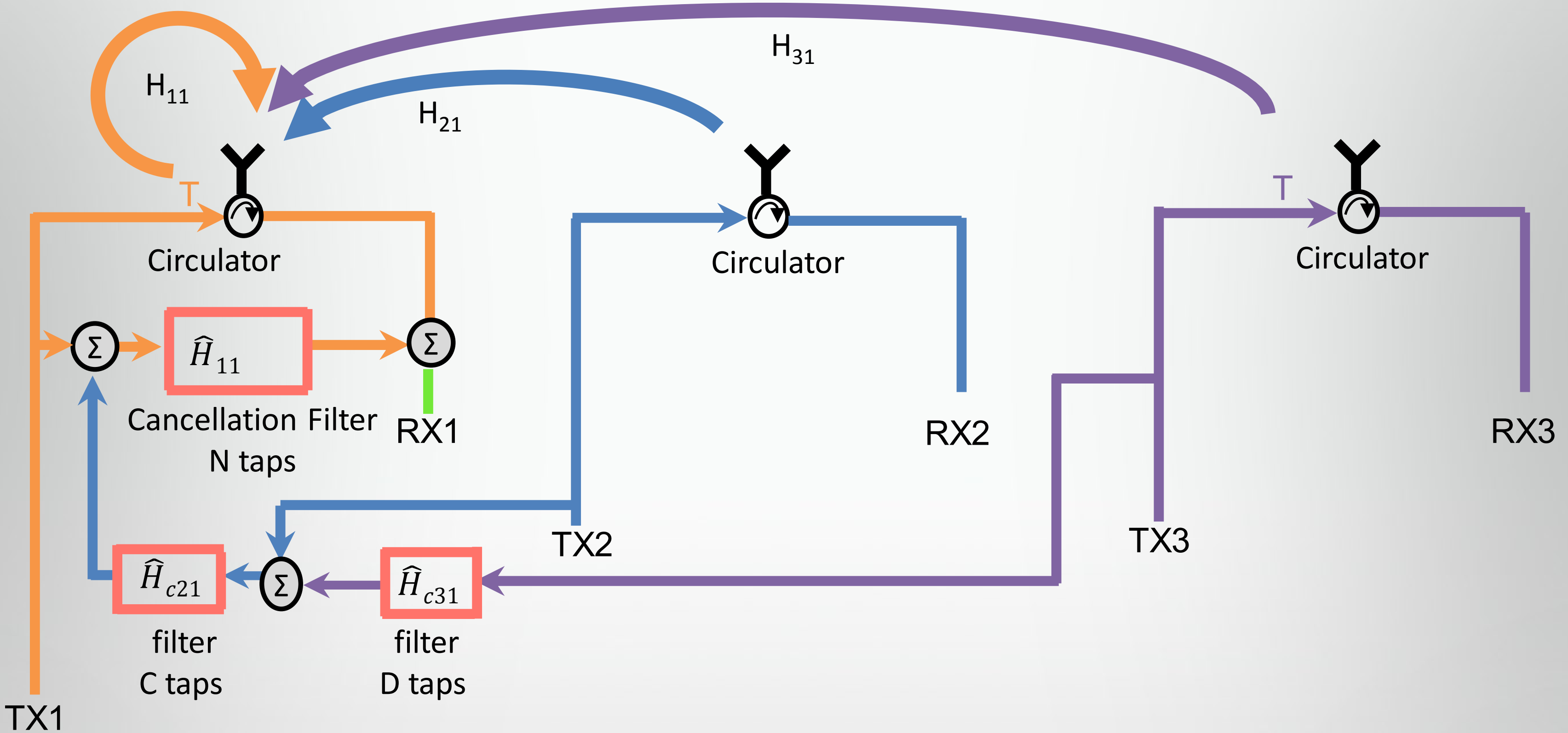

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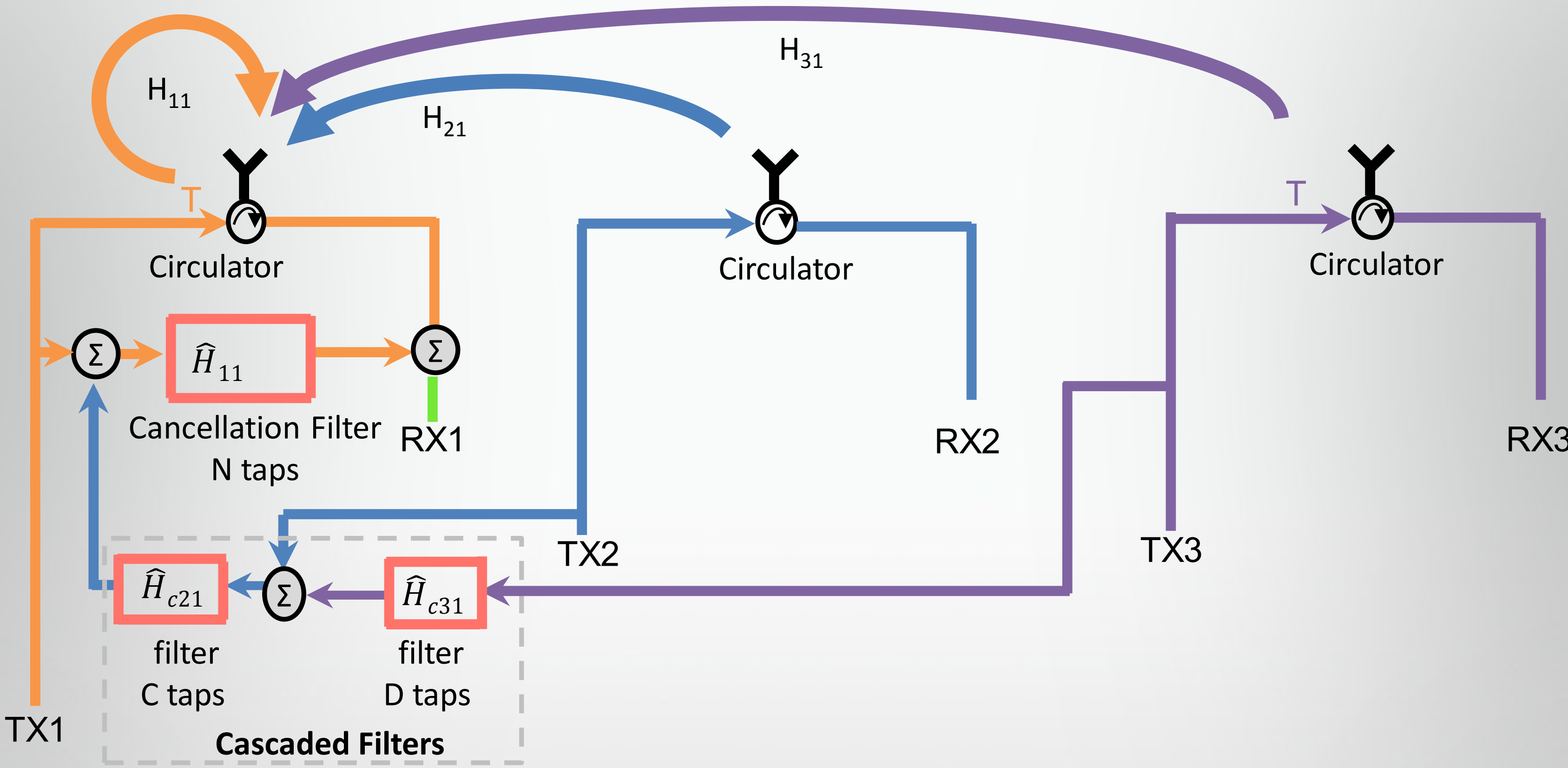

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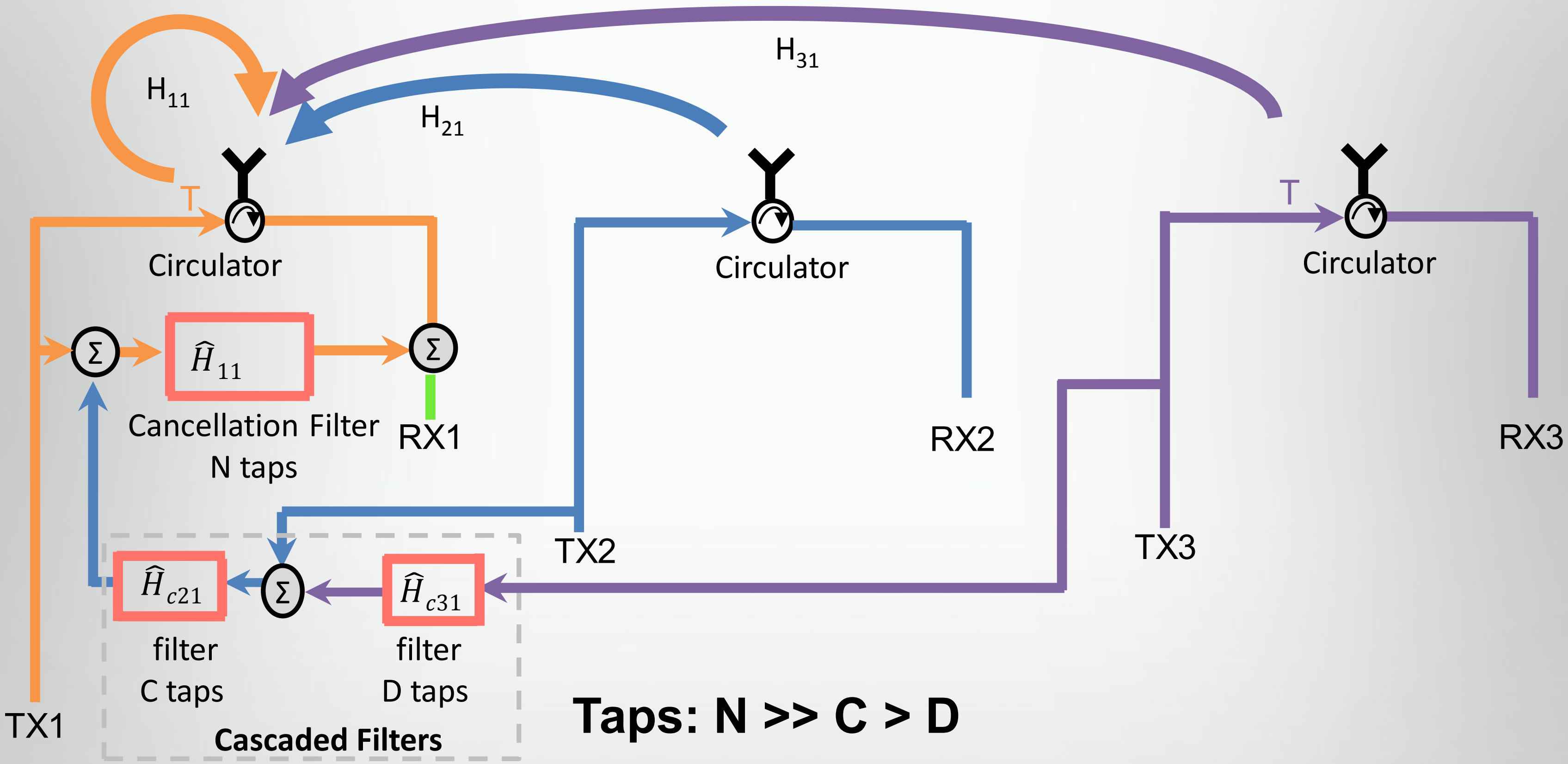

Taps: N >> C > D

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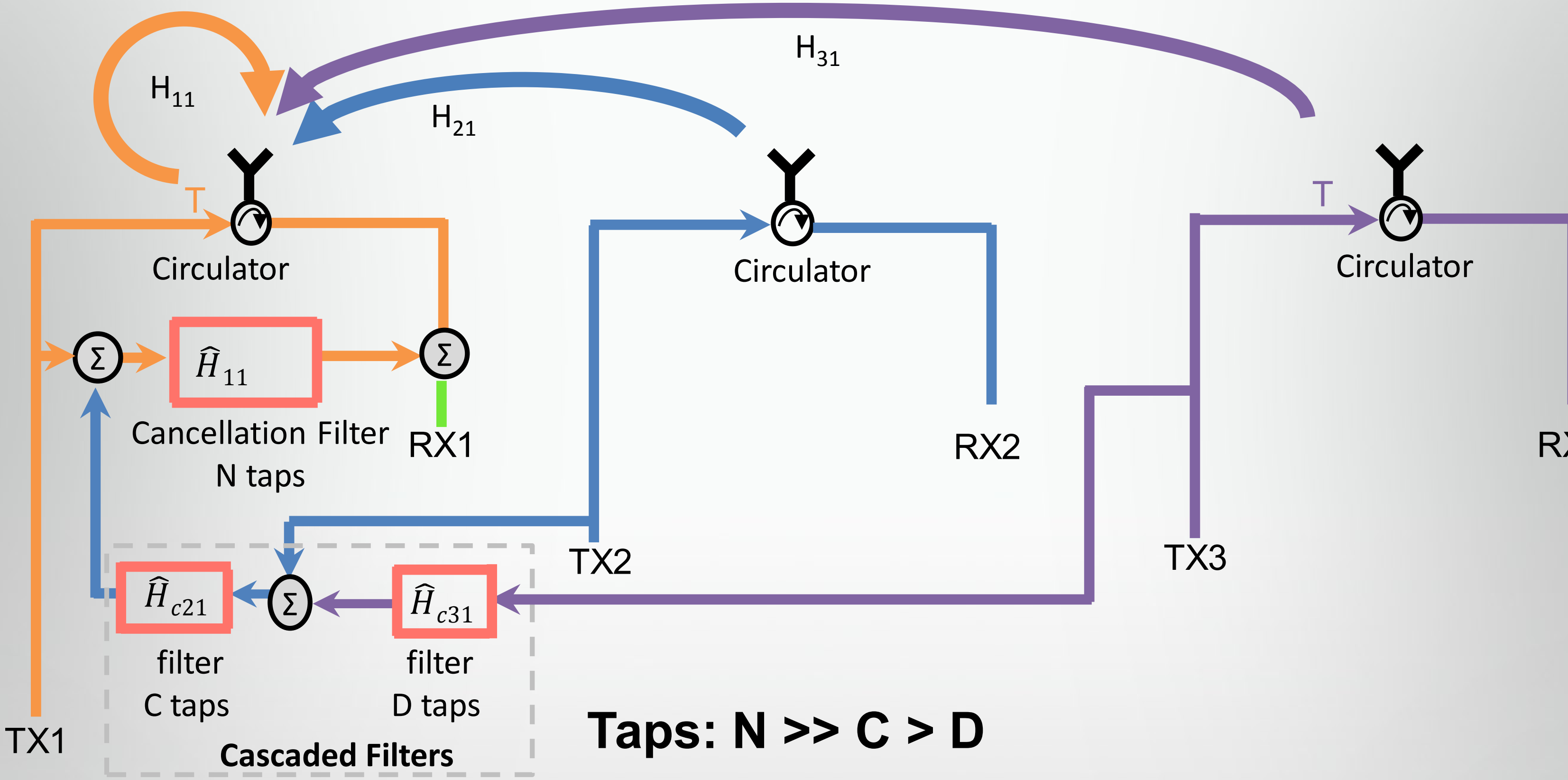
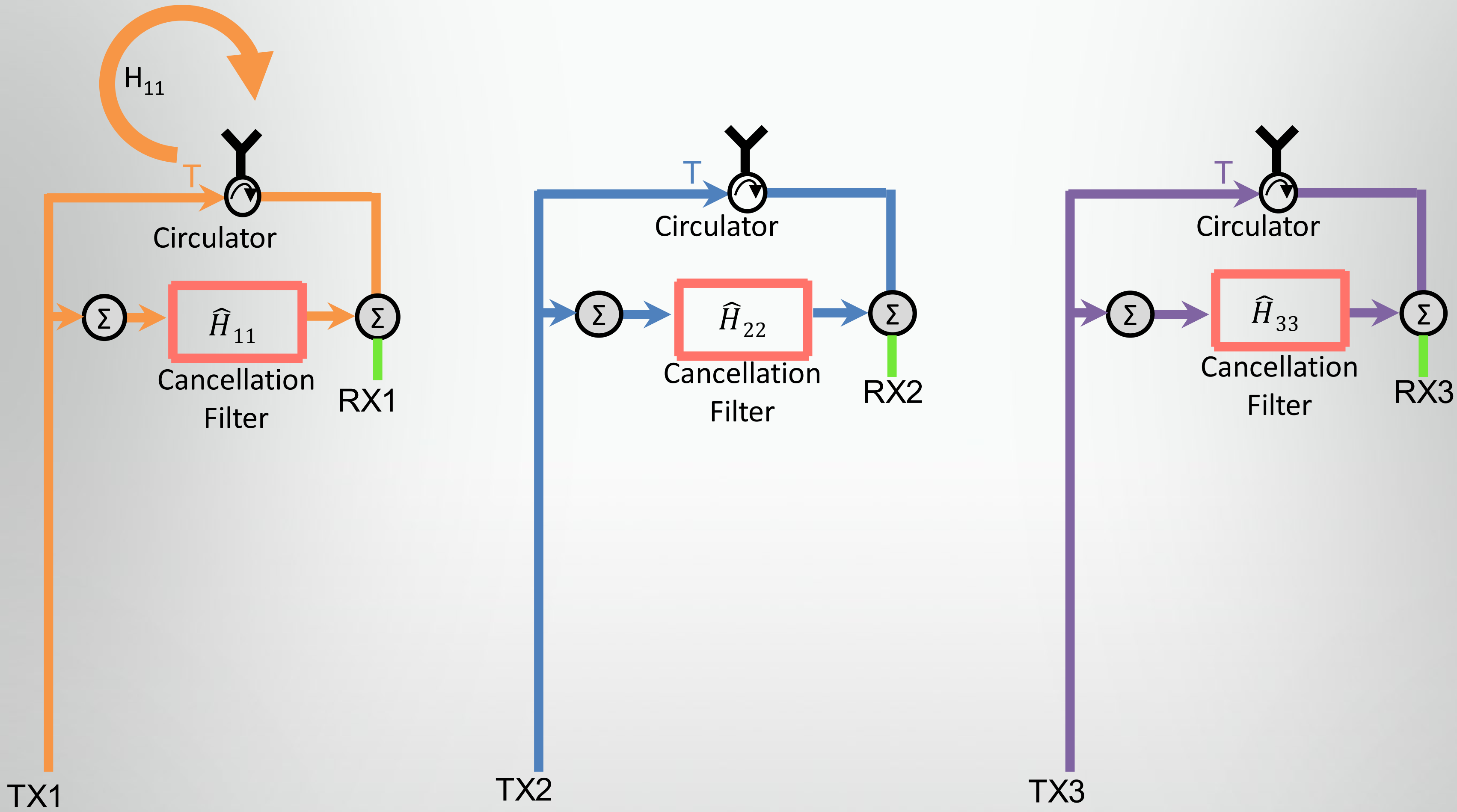


Taps: N >> C > D

Total Taps: N+ C + D, for Chain 1

General Complexity per chain: ~N << M.N

Complete Cascaded Design:



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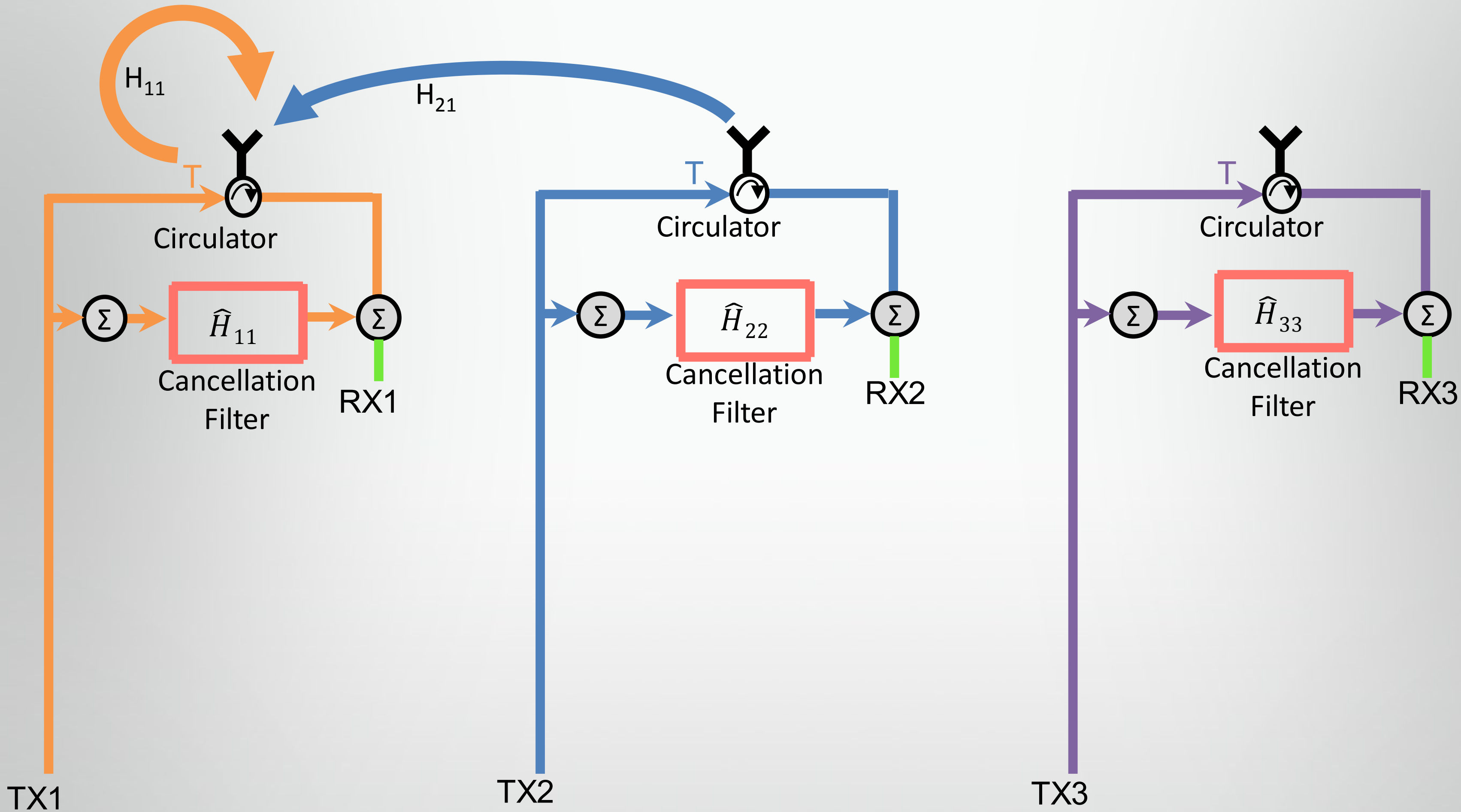

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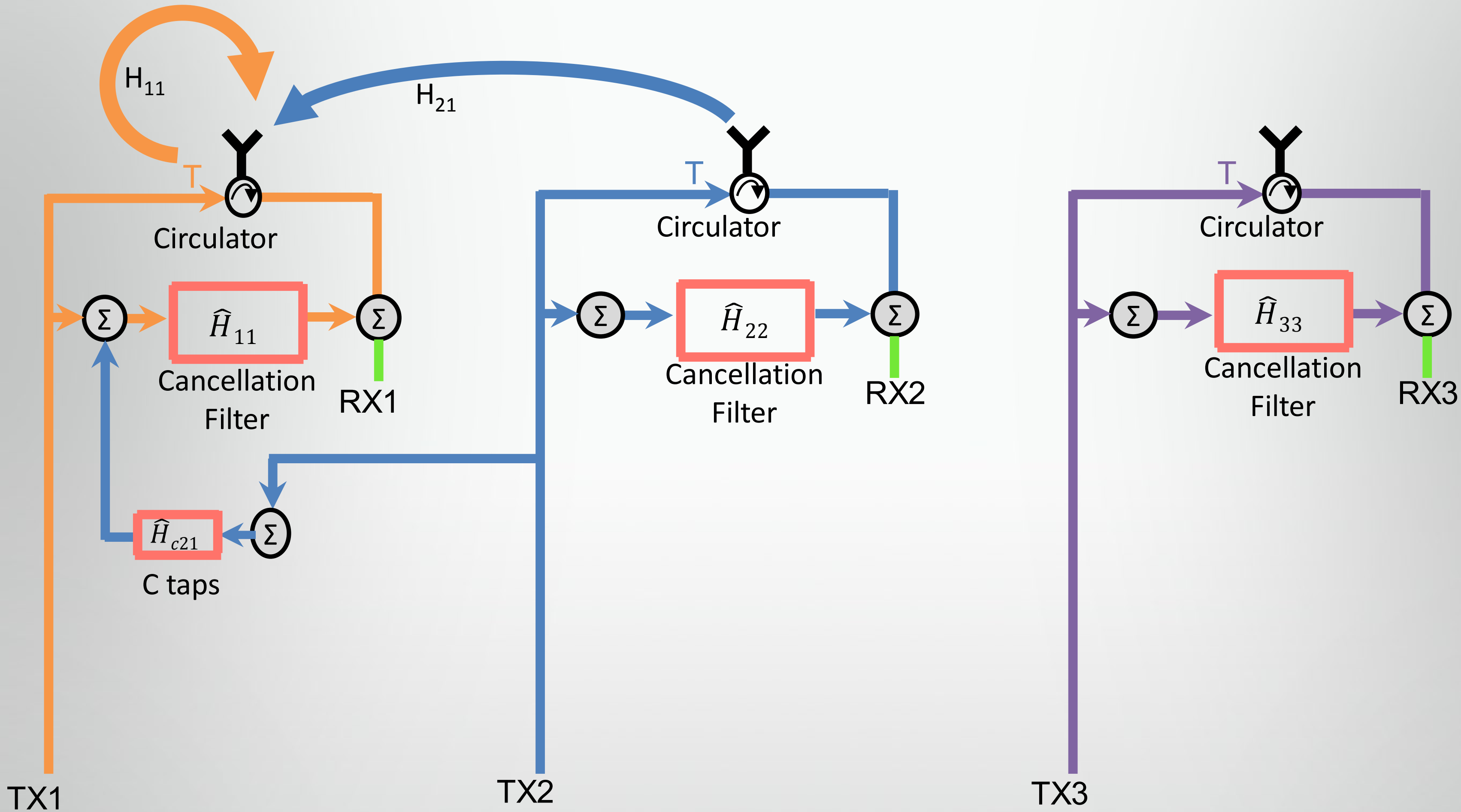

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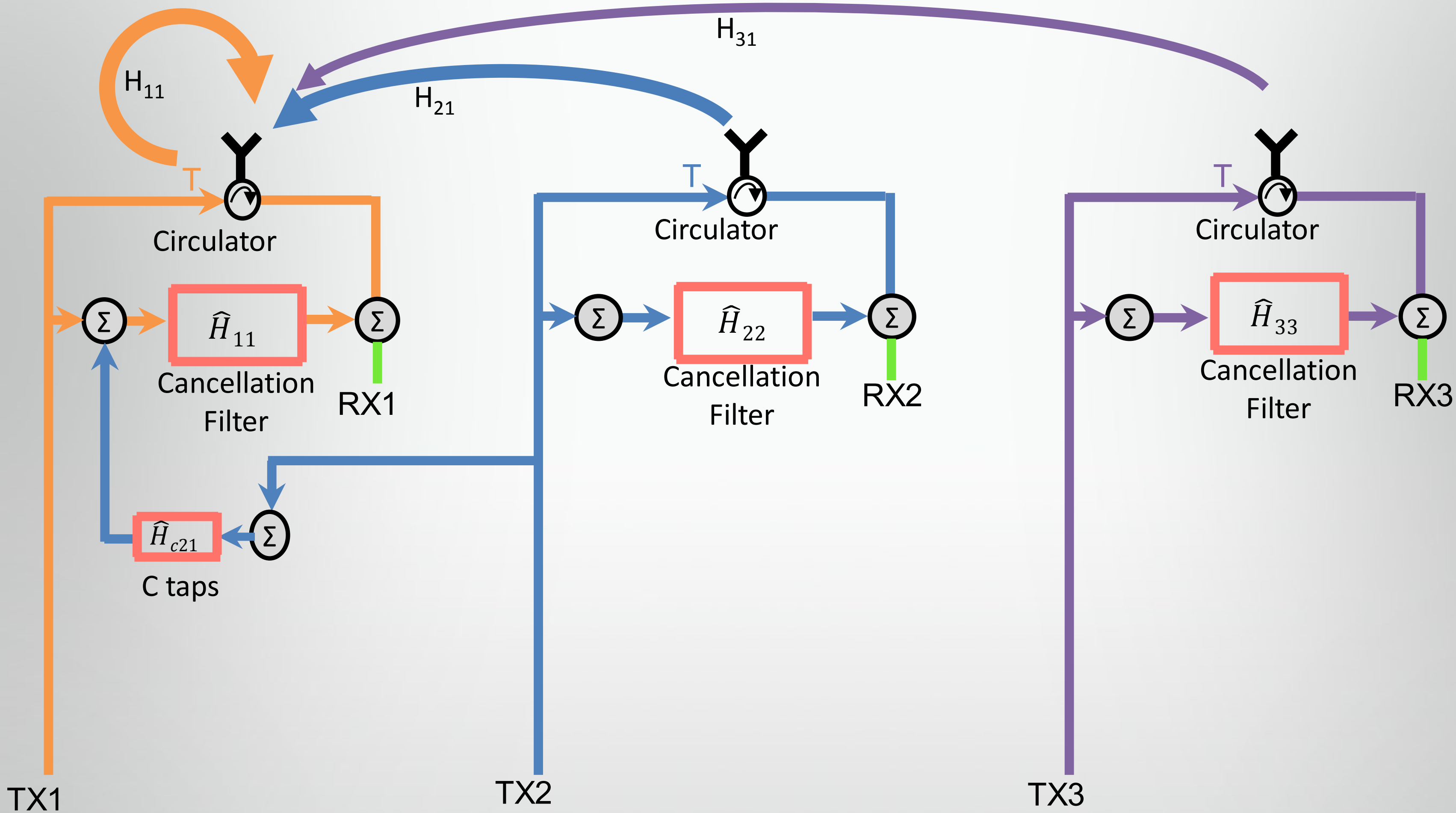

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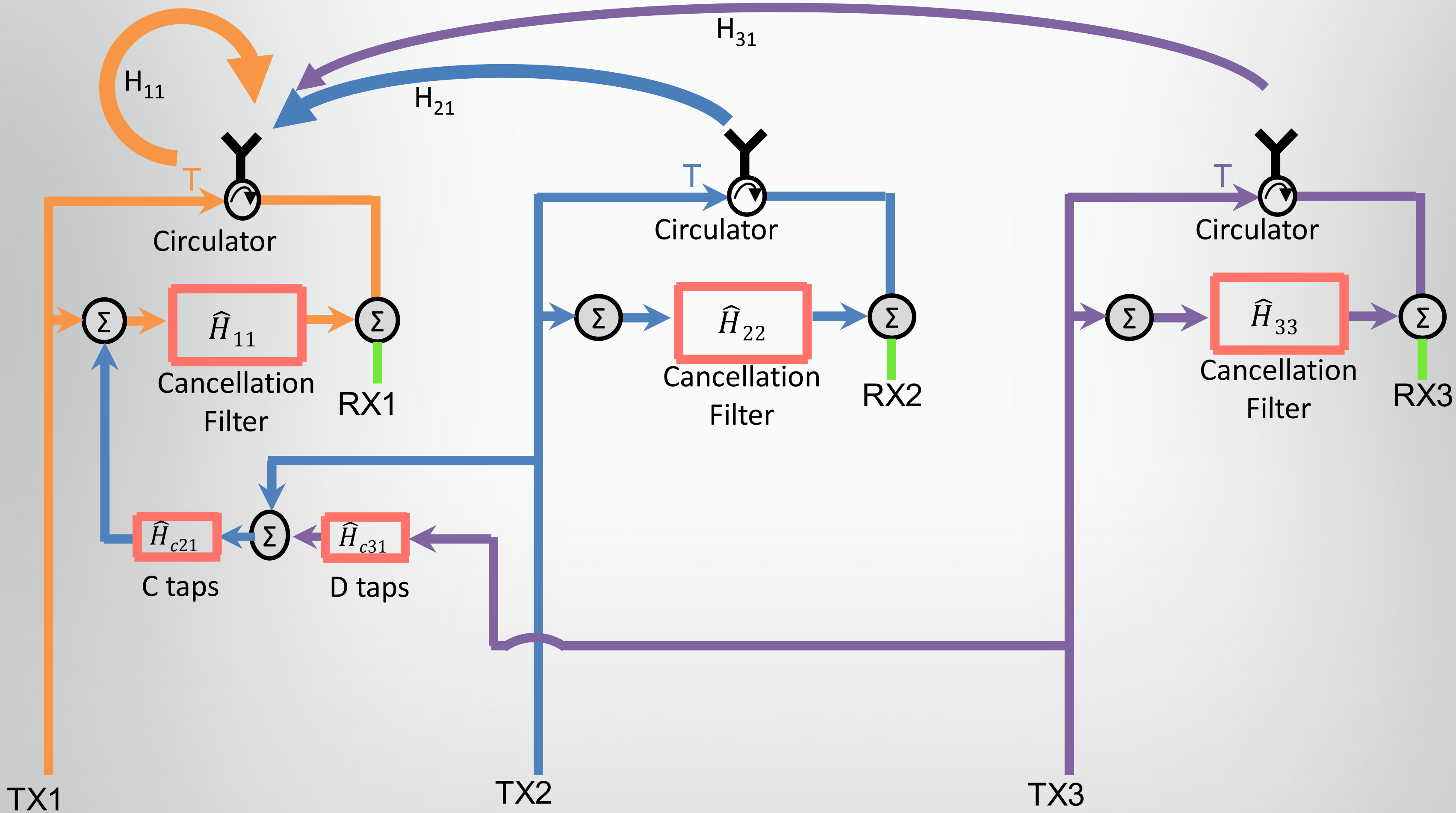

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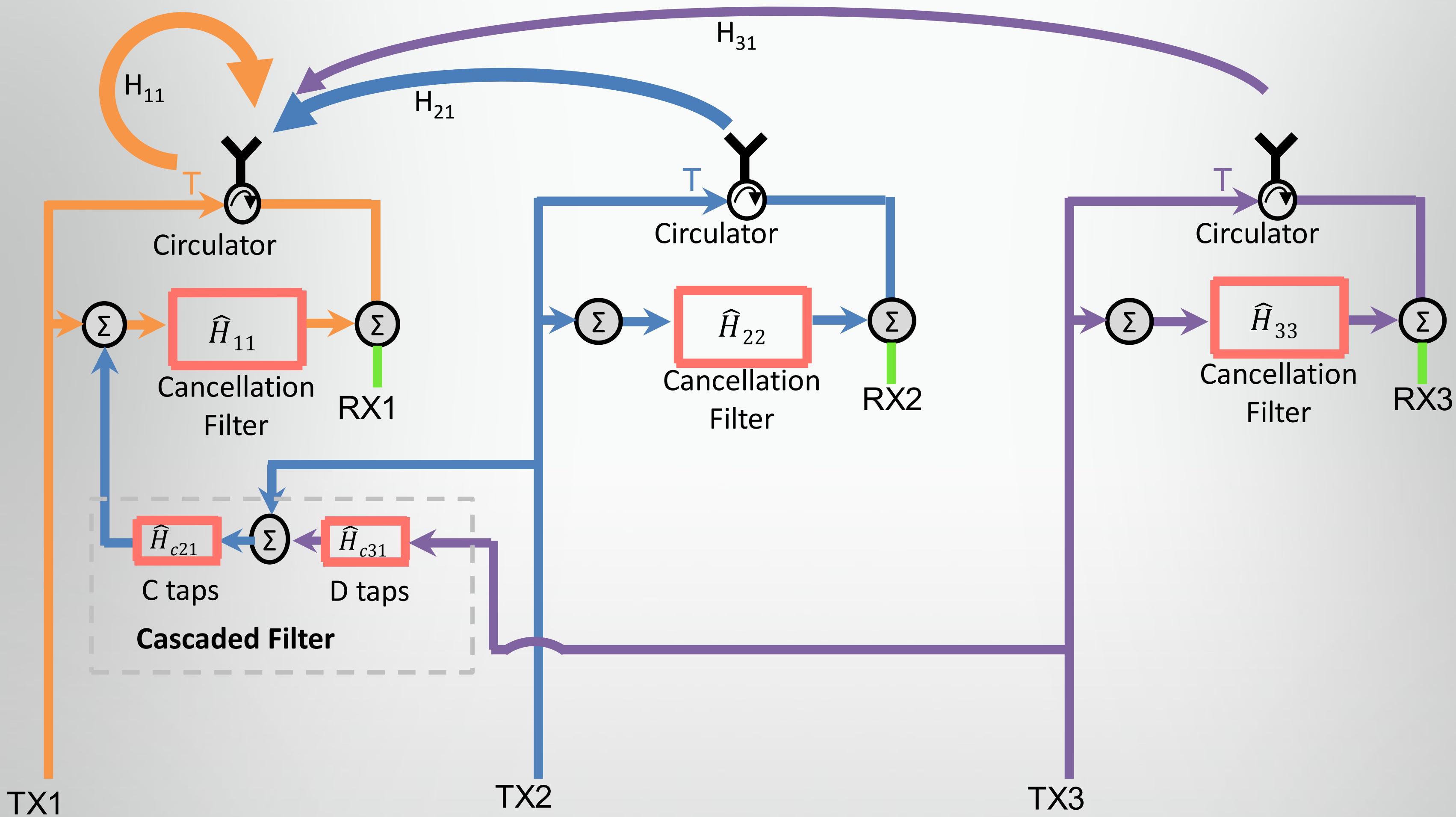

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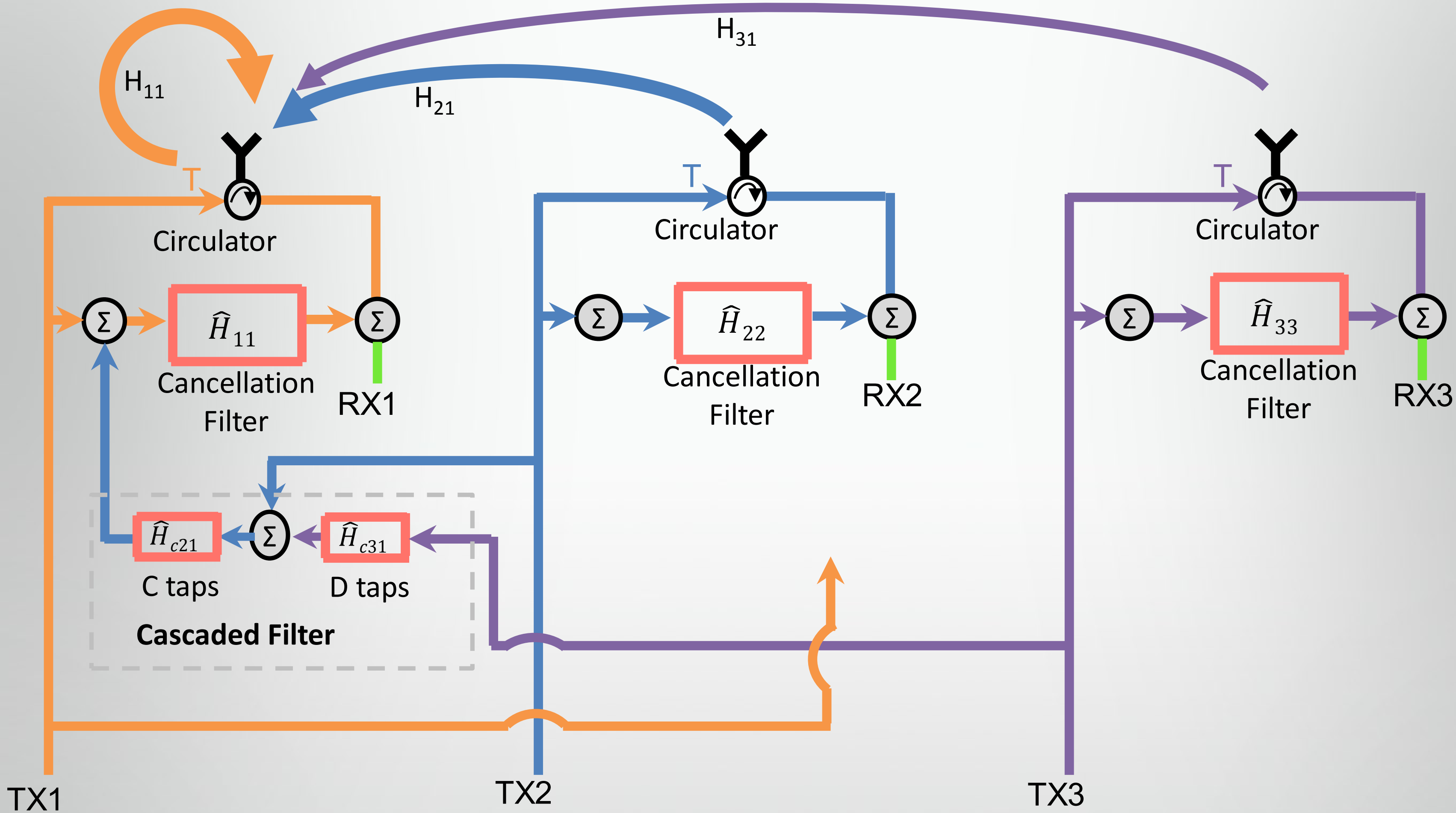

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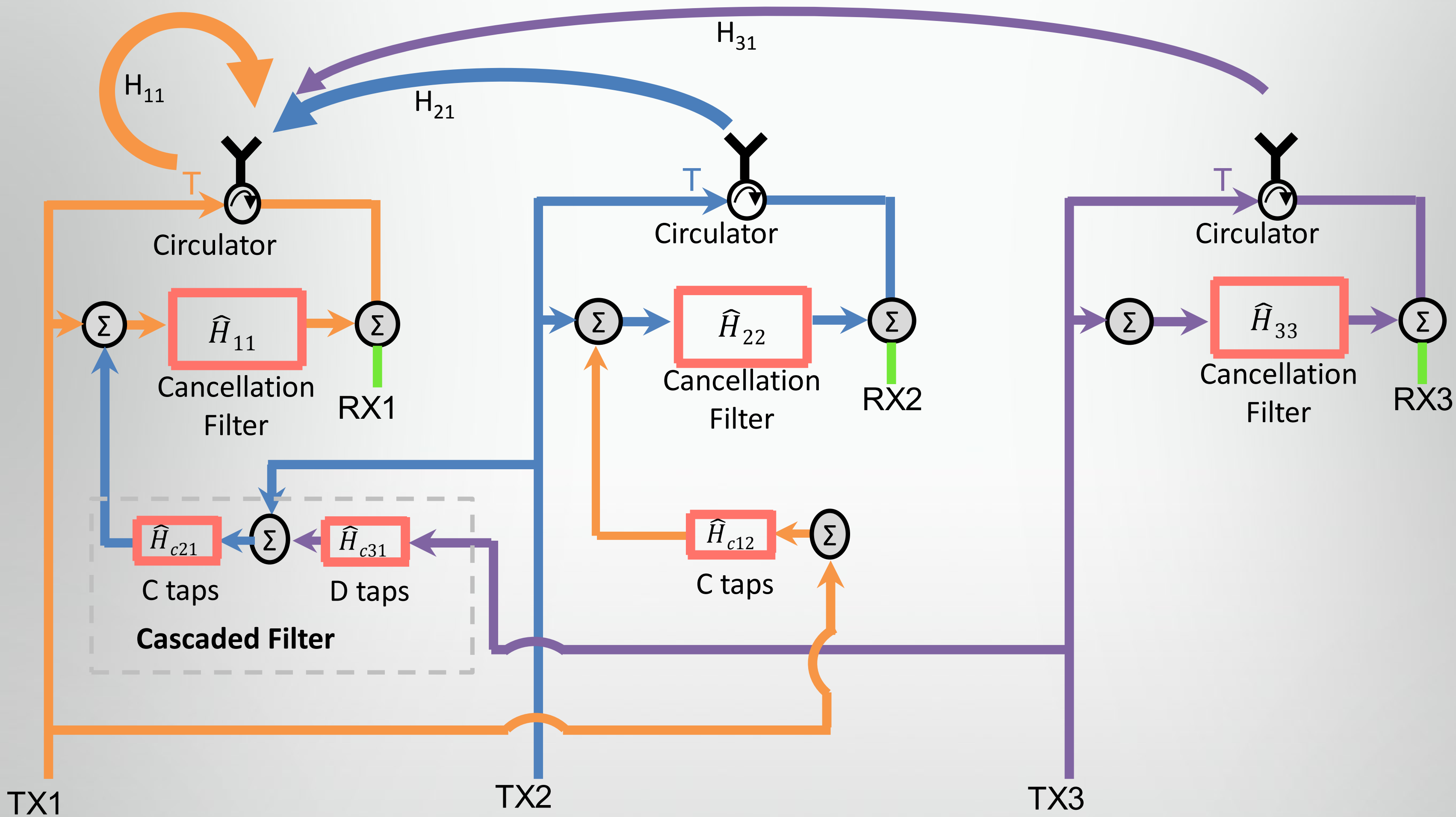

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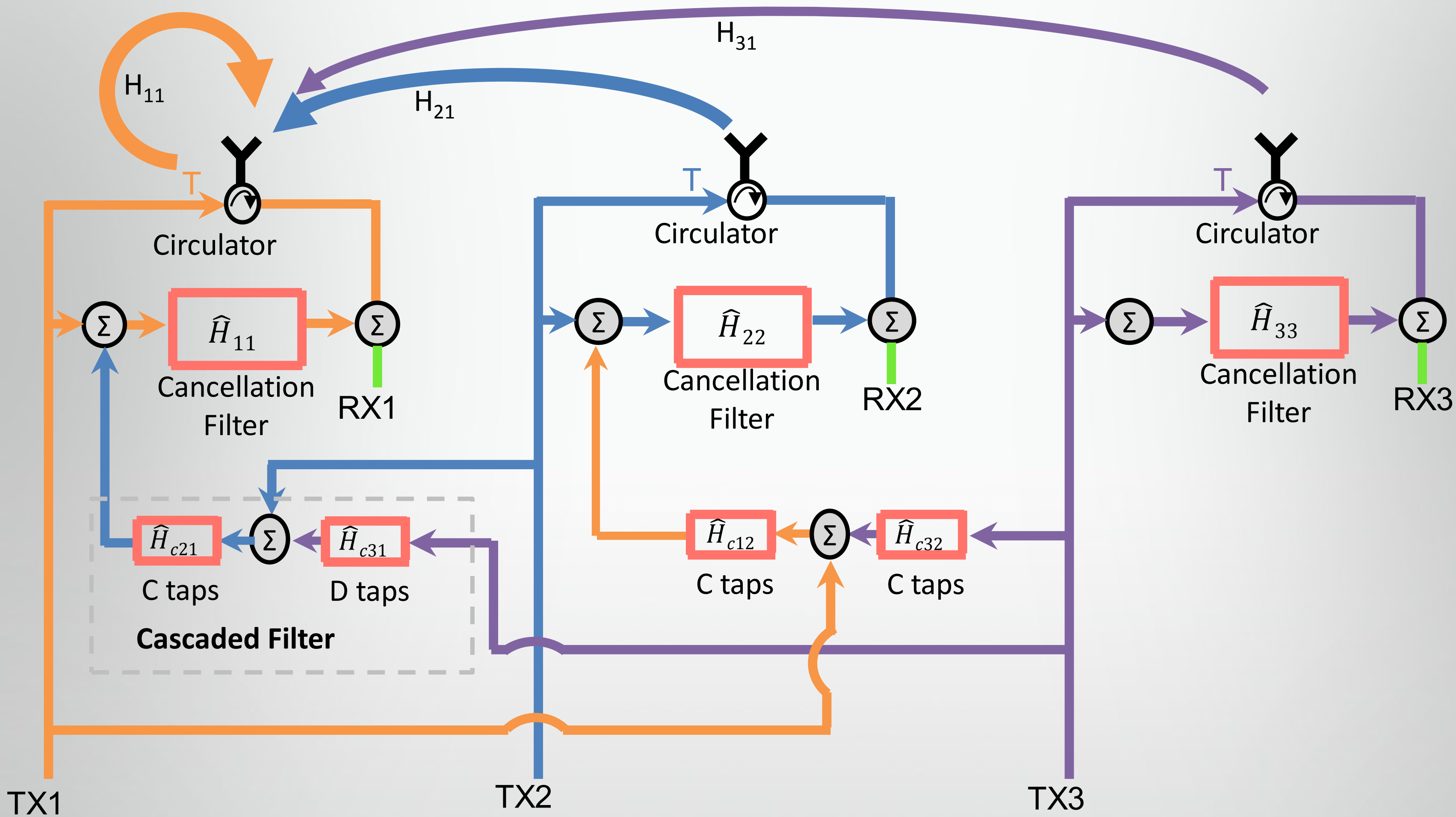

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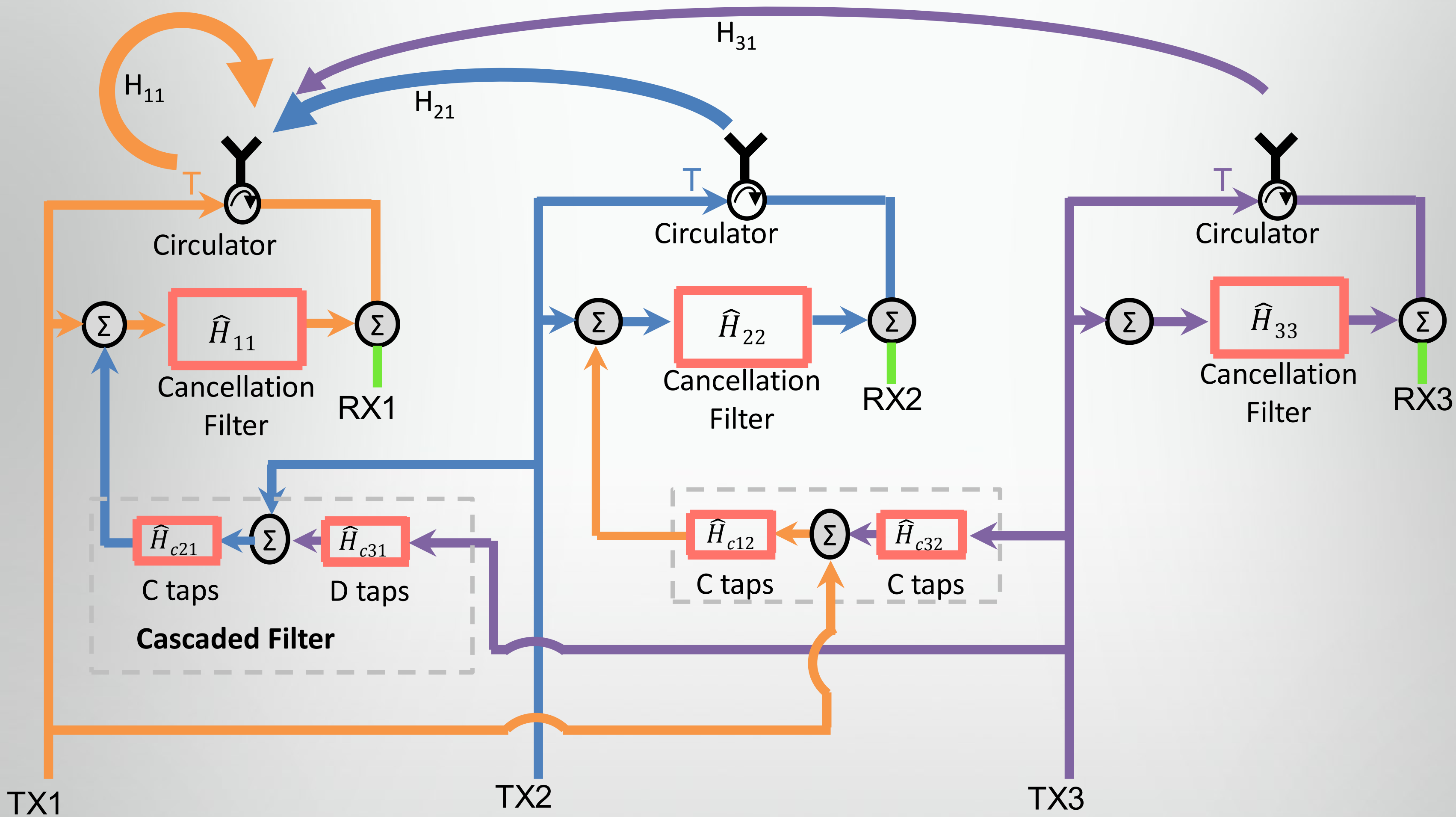

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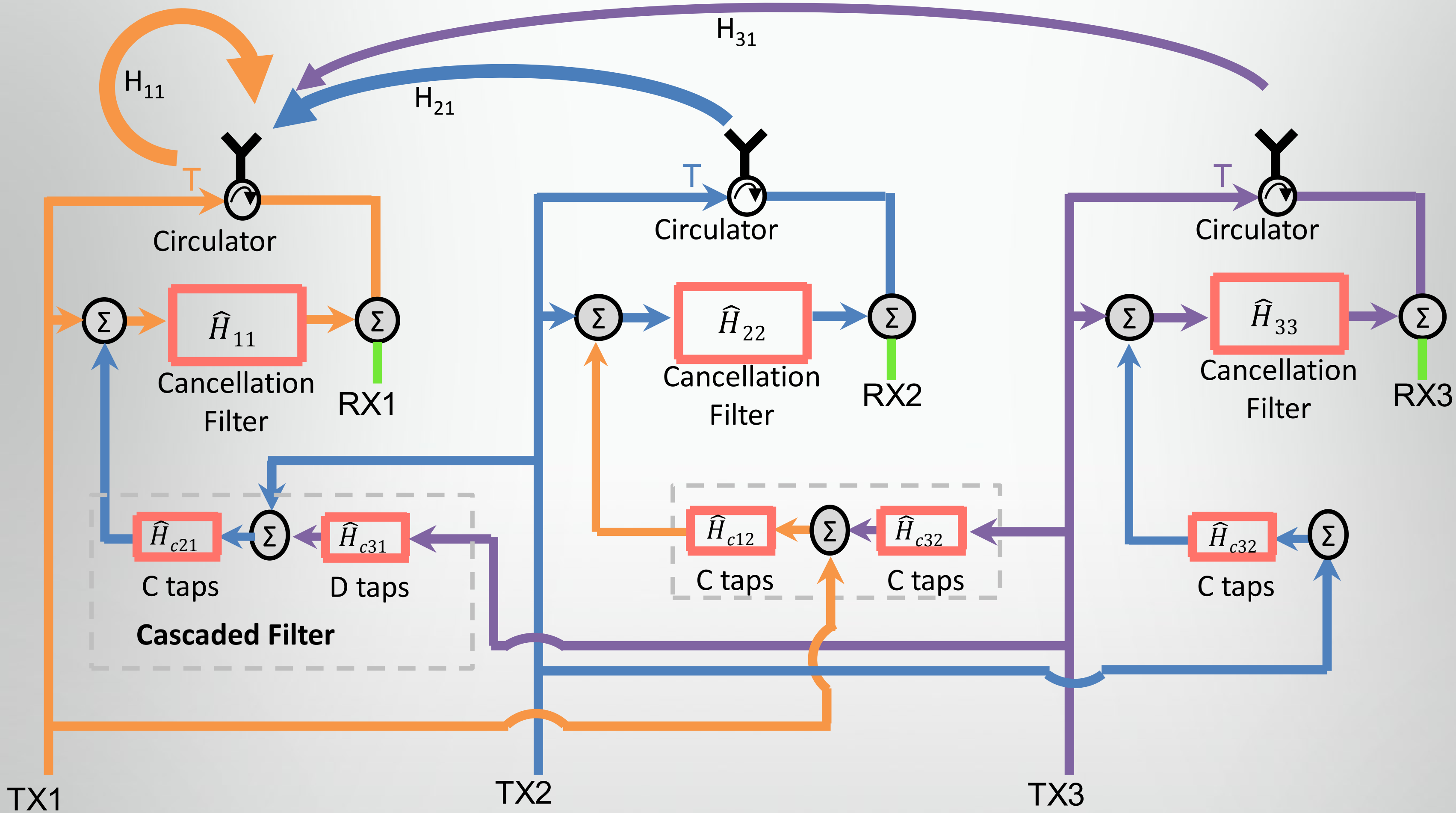

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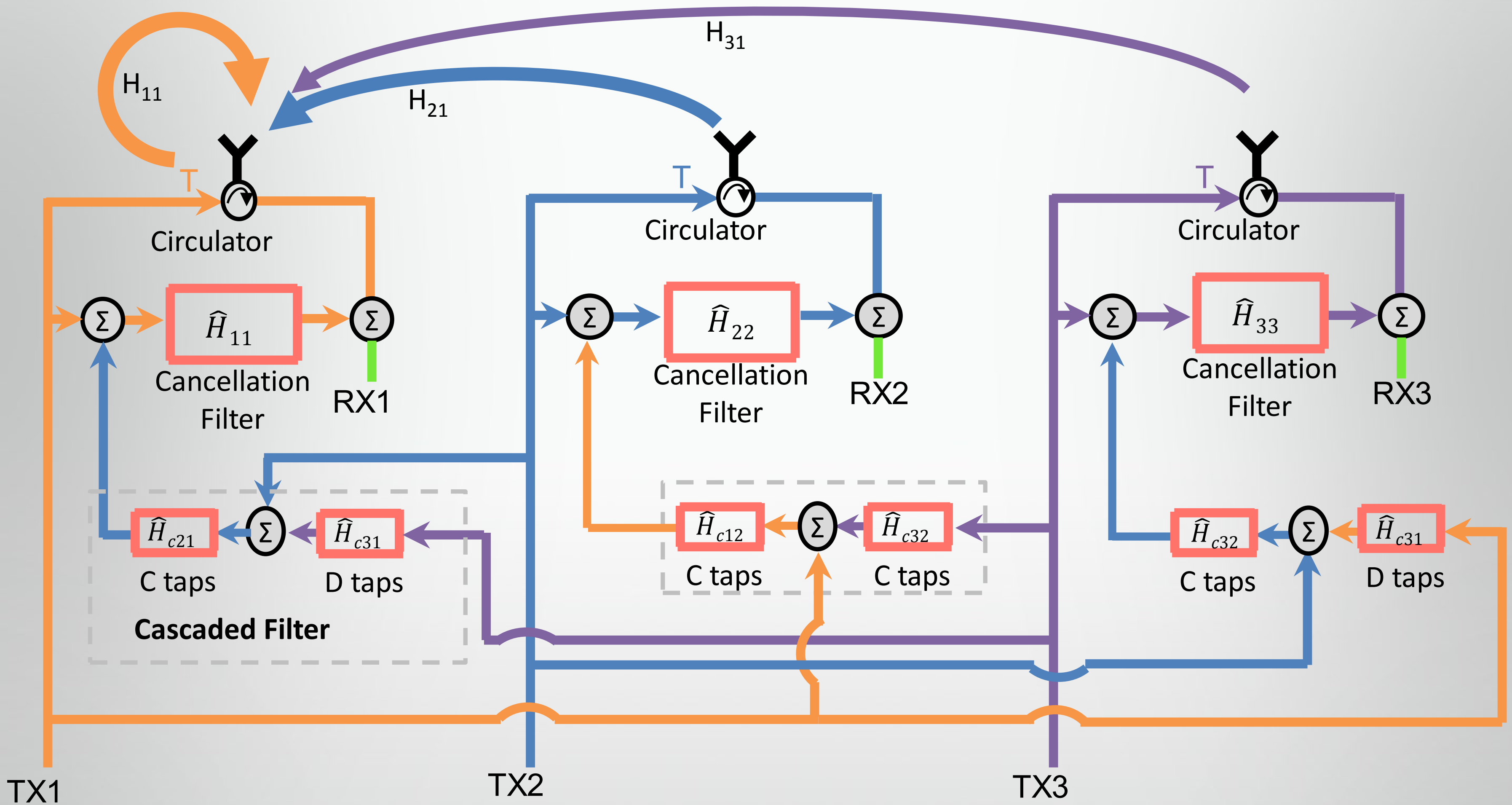

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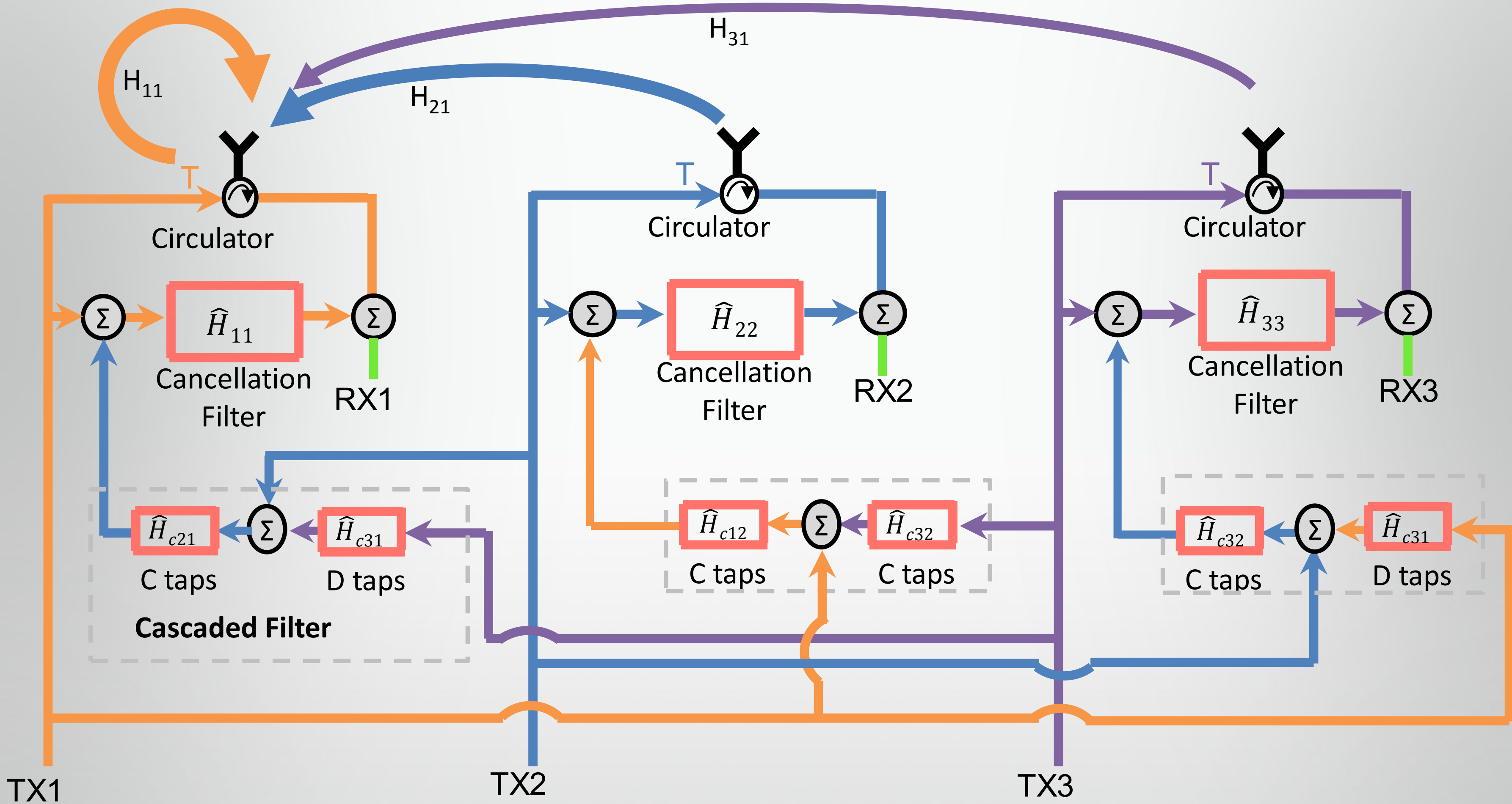

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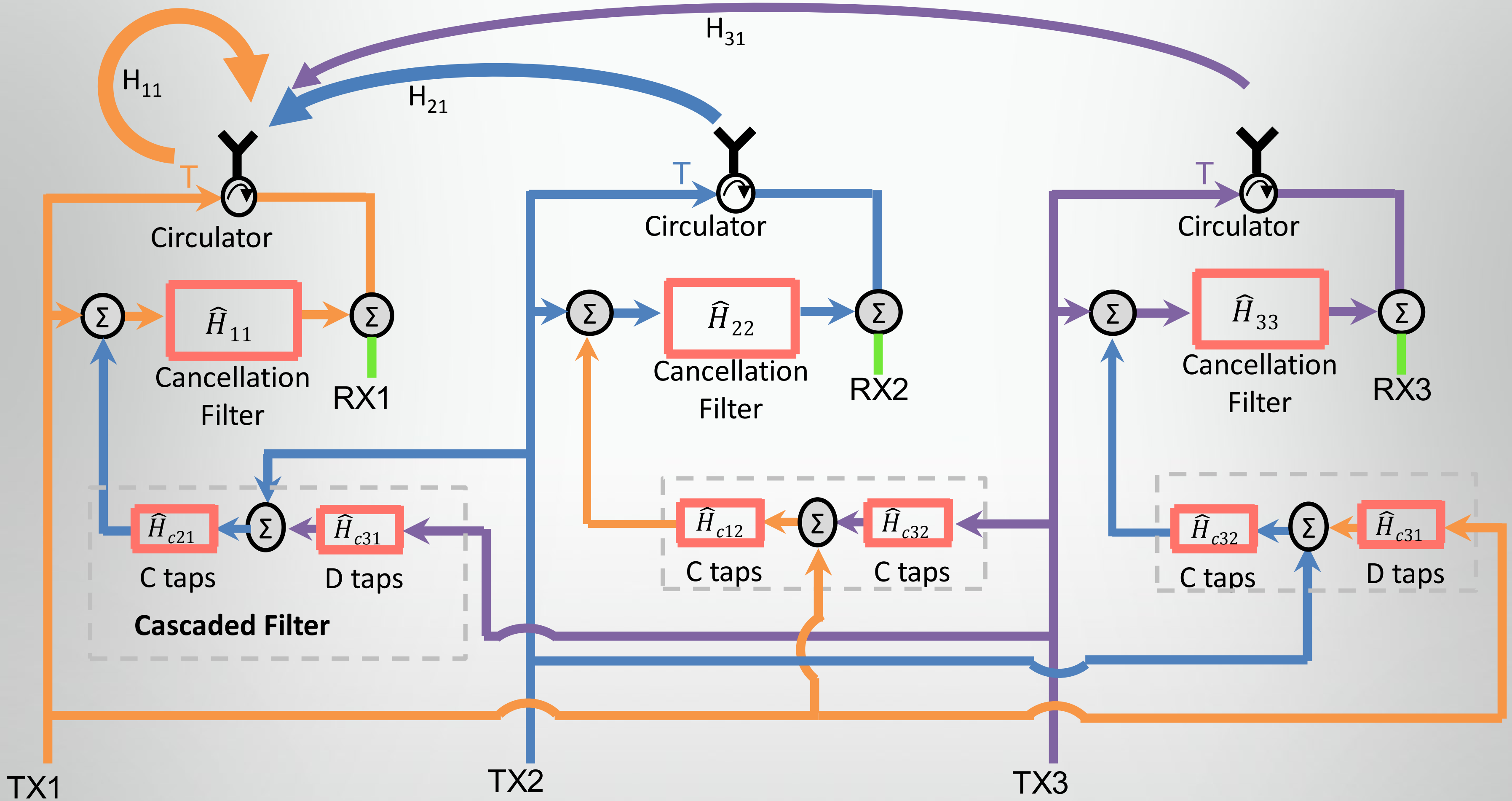

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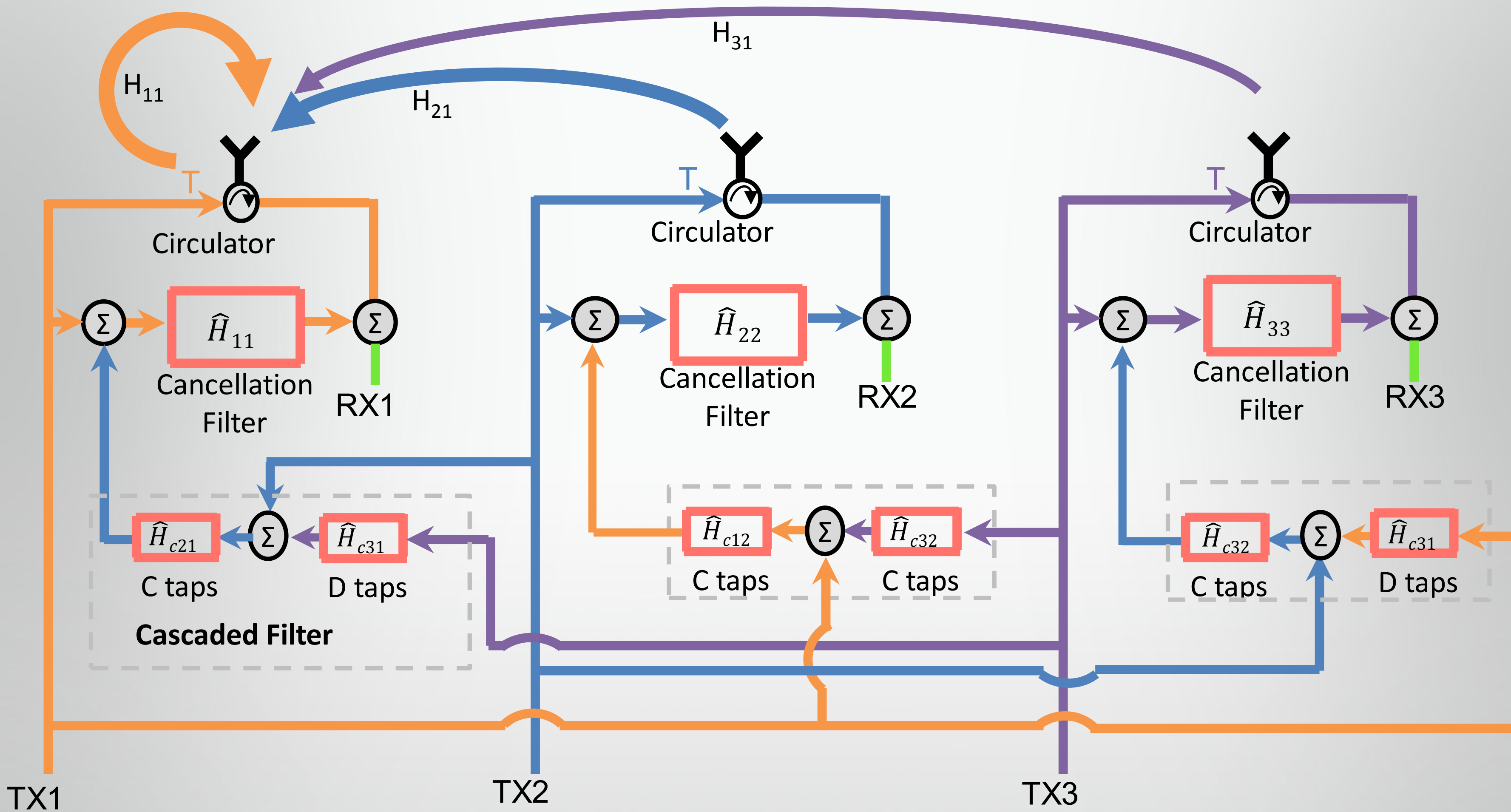


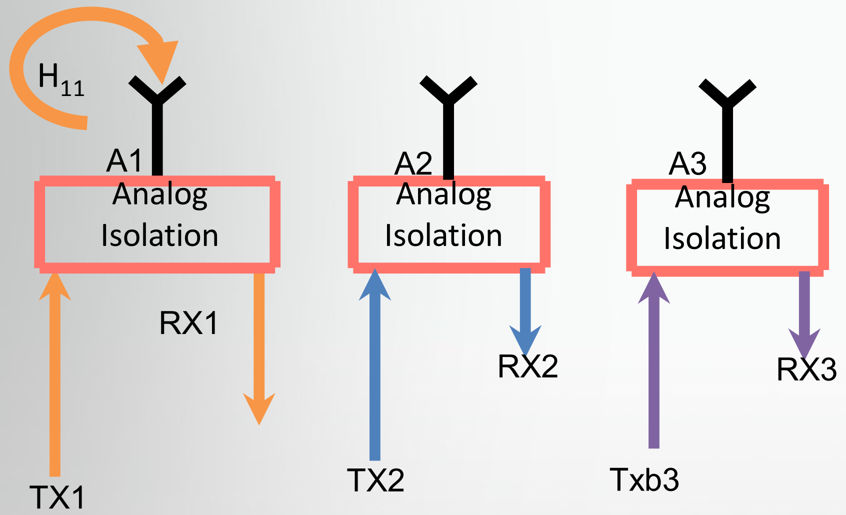
Taps: N >> C > D

Total Taps: 3N+ 4C + 2D, for M=3

General Complexity: ~ M.N << M².N

Interference Residue with Cascaded Design shows no degradation

Independent Training with SISO Replication Design



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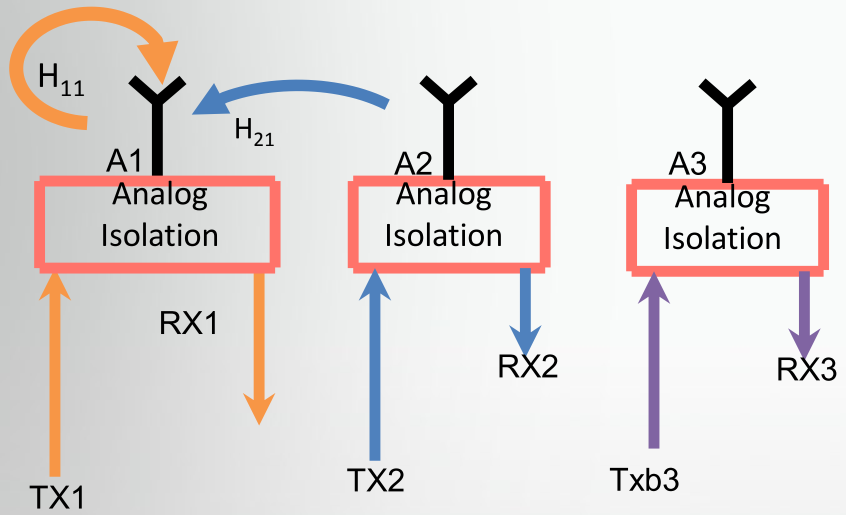

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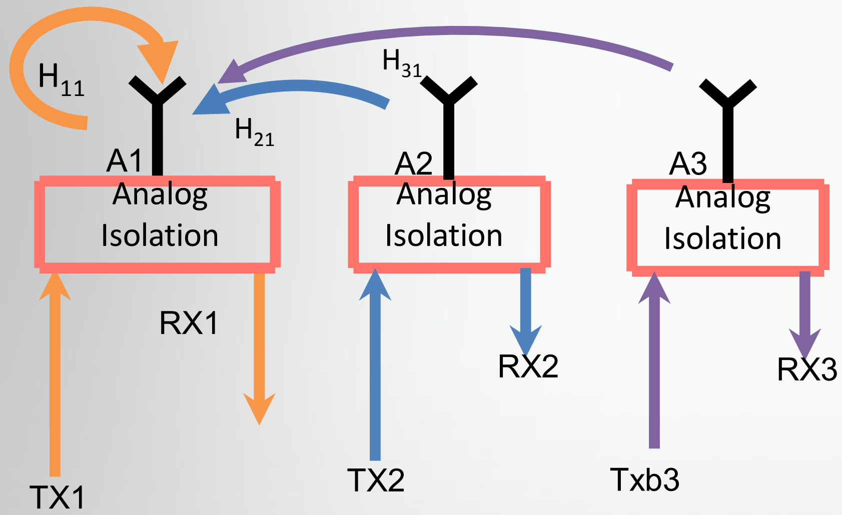

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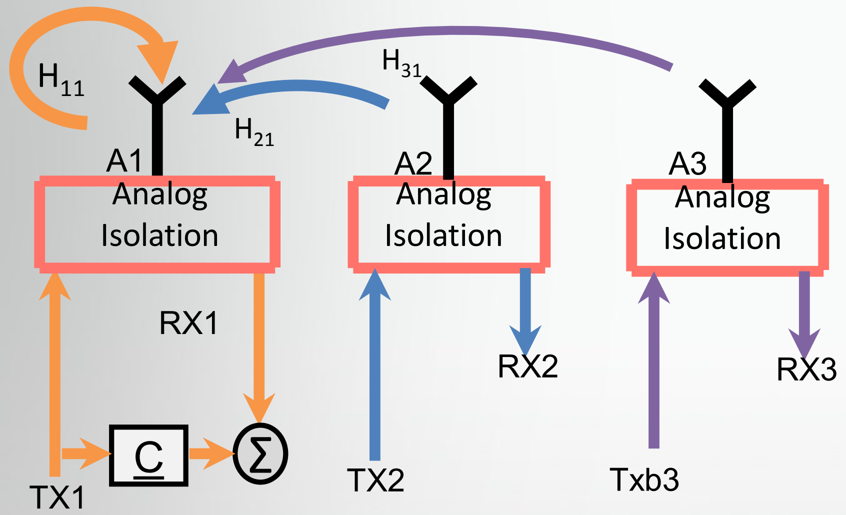

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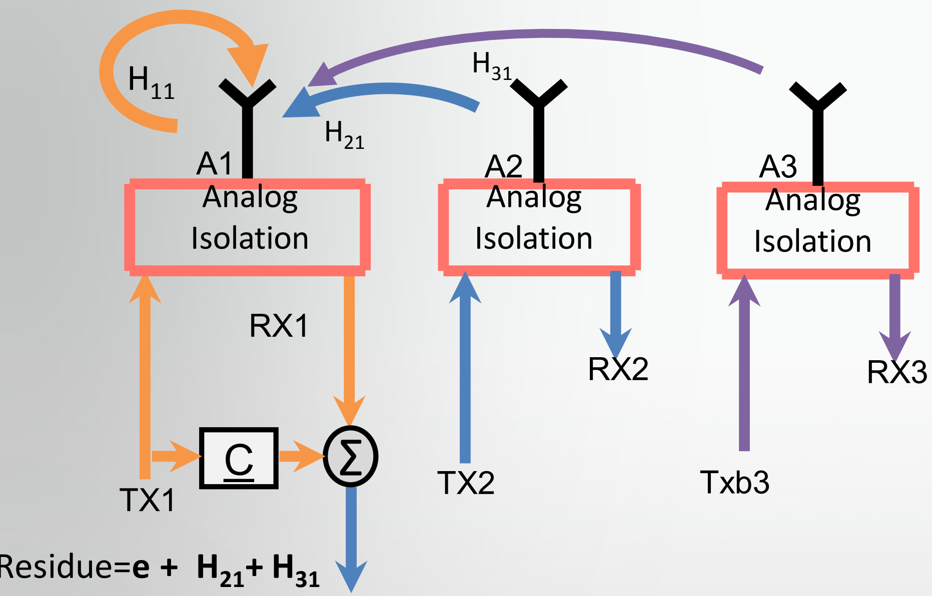

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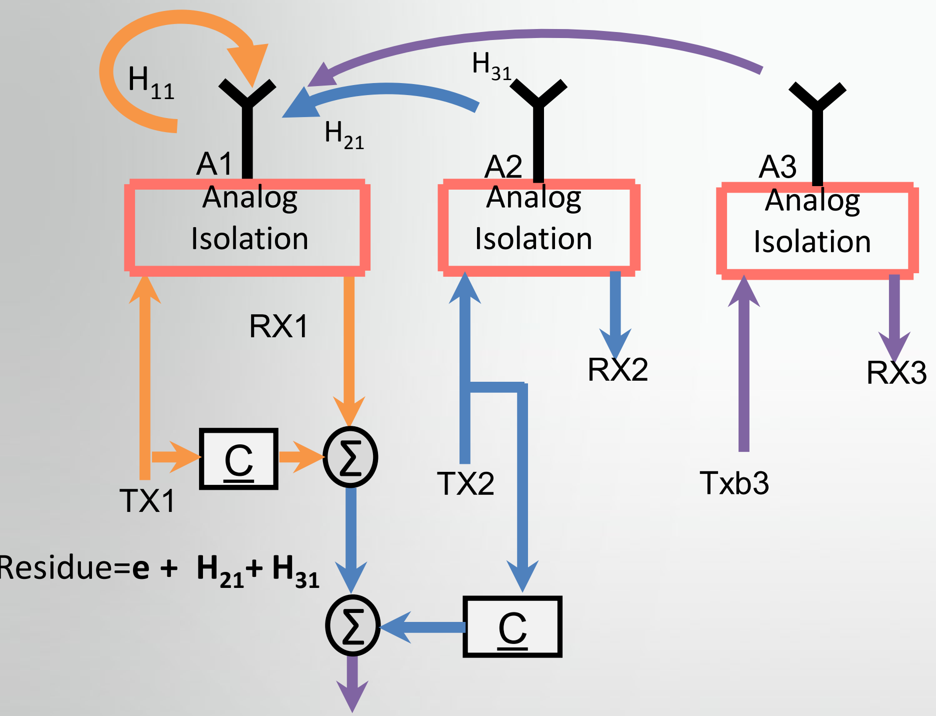

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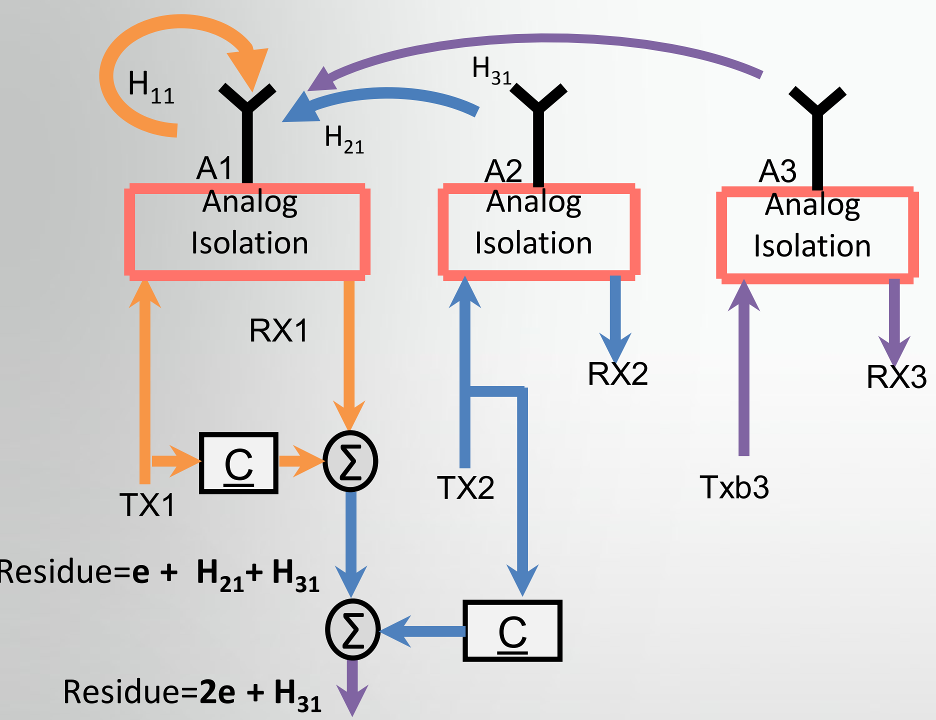

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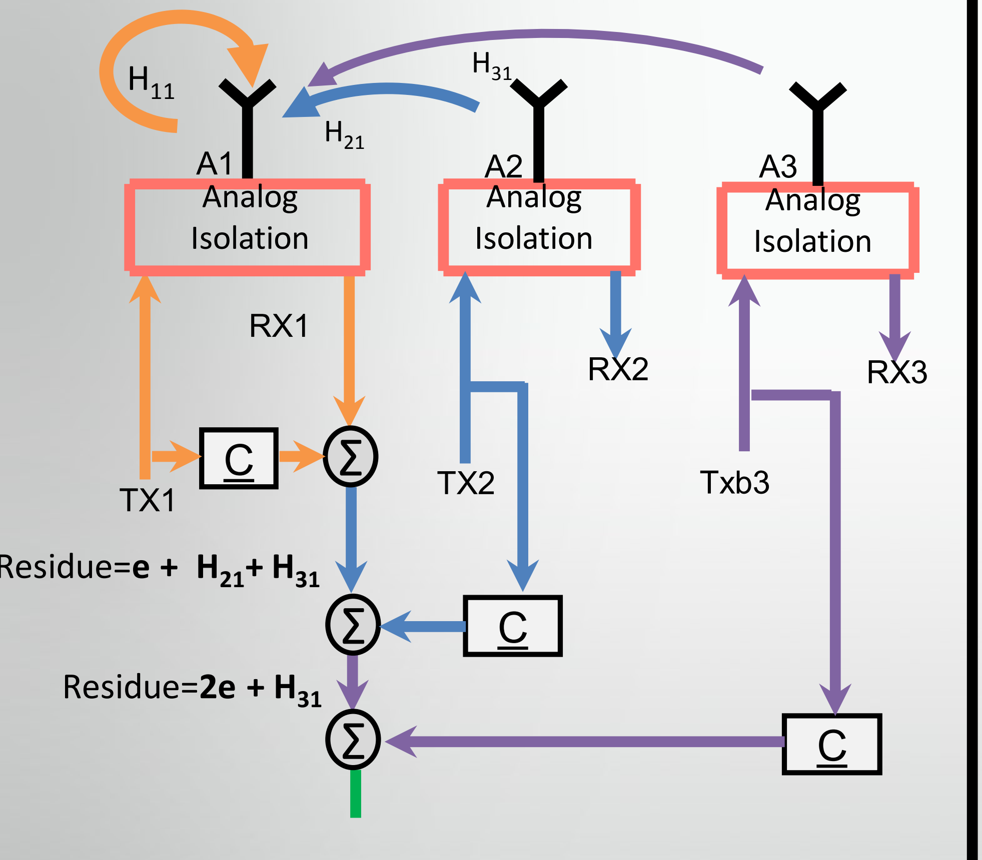

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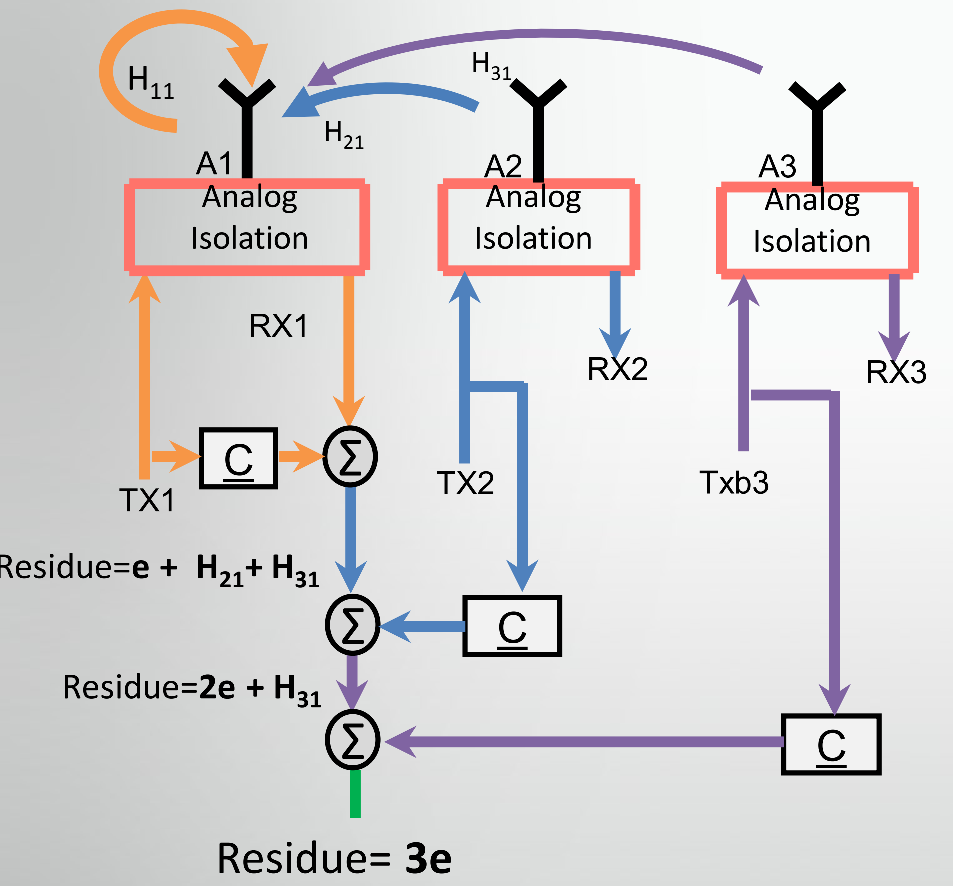
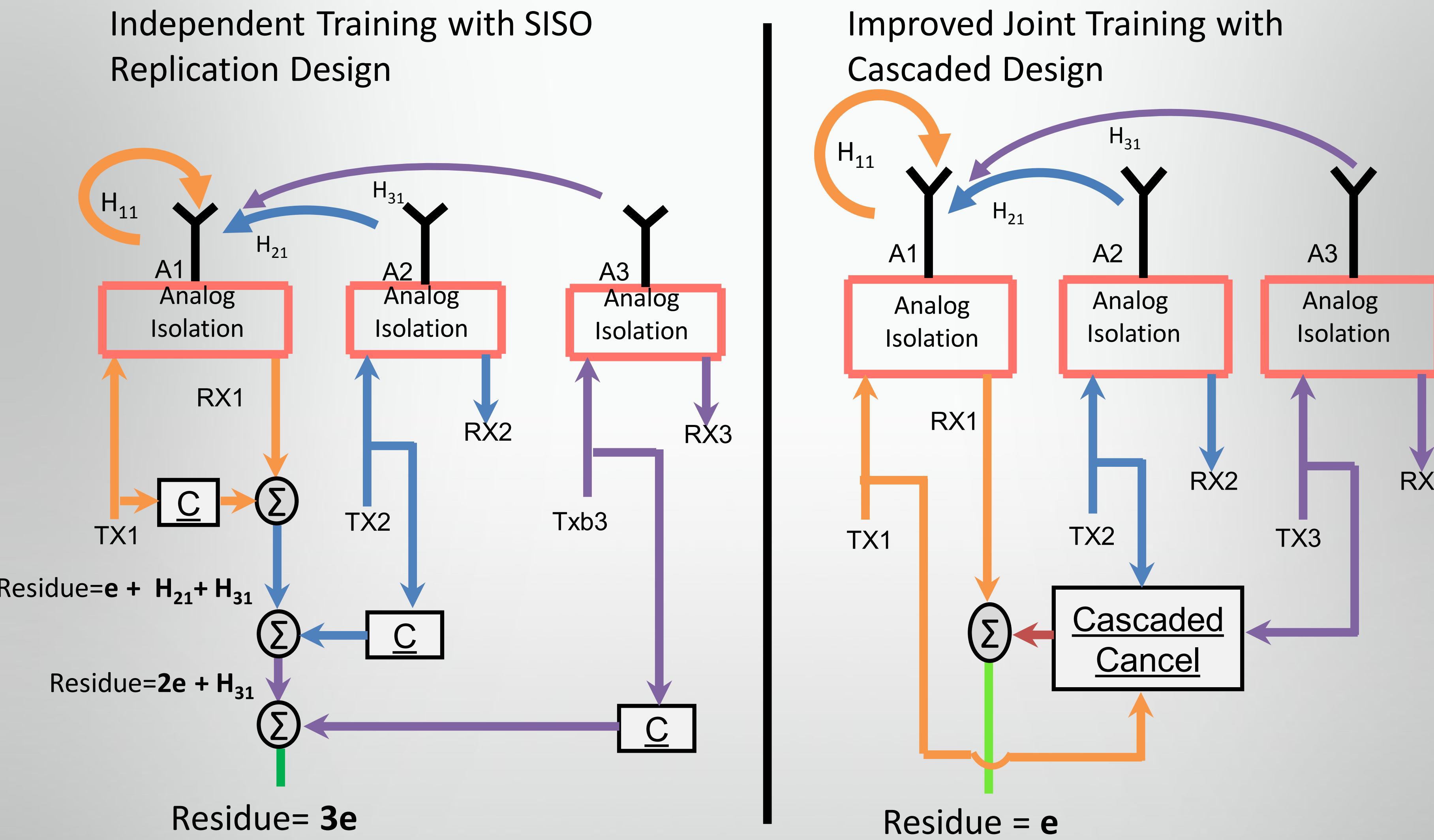
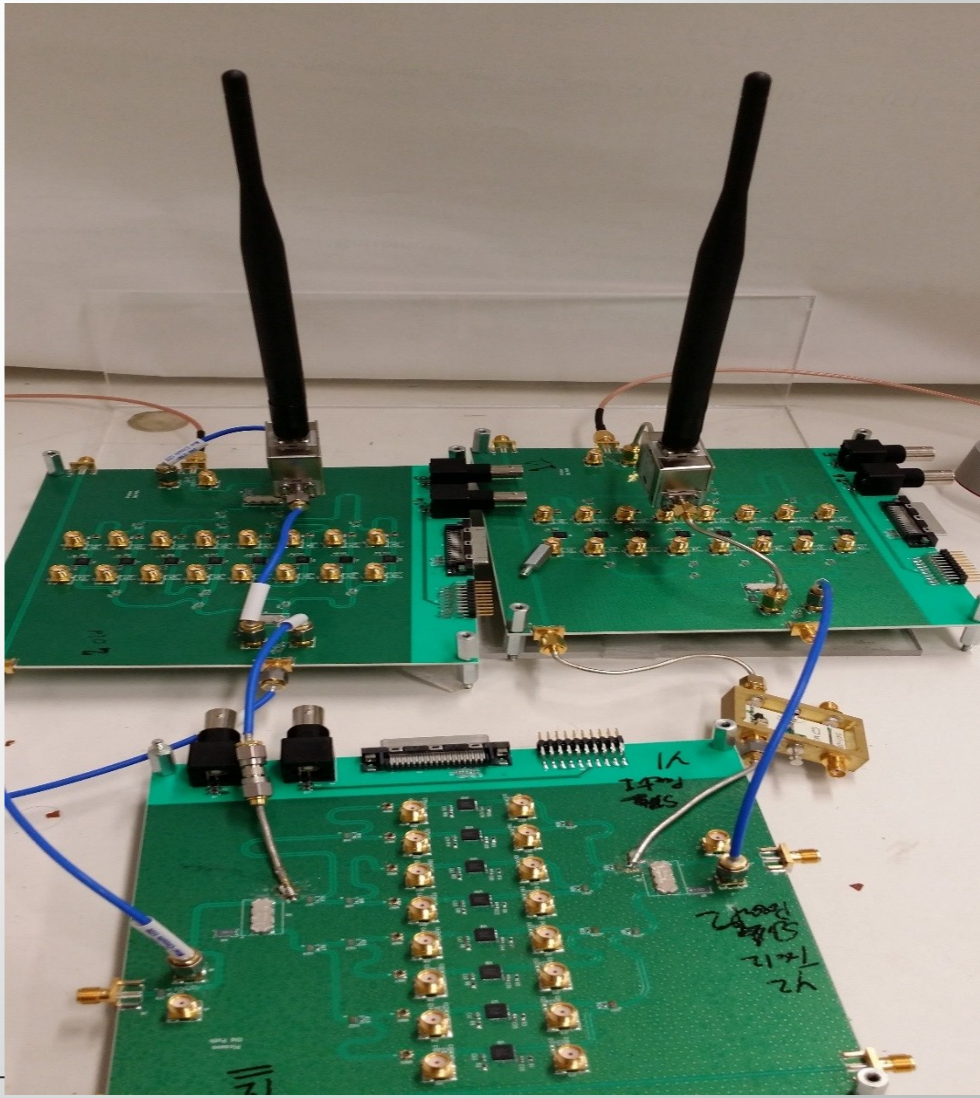


Interference Residue with Cascaded Design shows no degradation



Evaluation Q1: Does it work with commodity radios?



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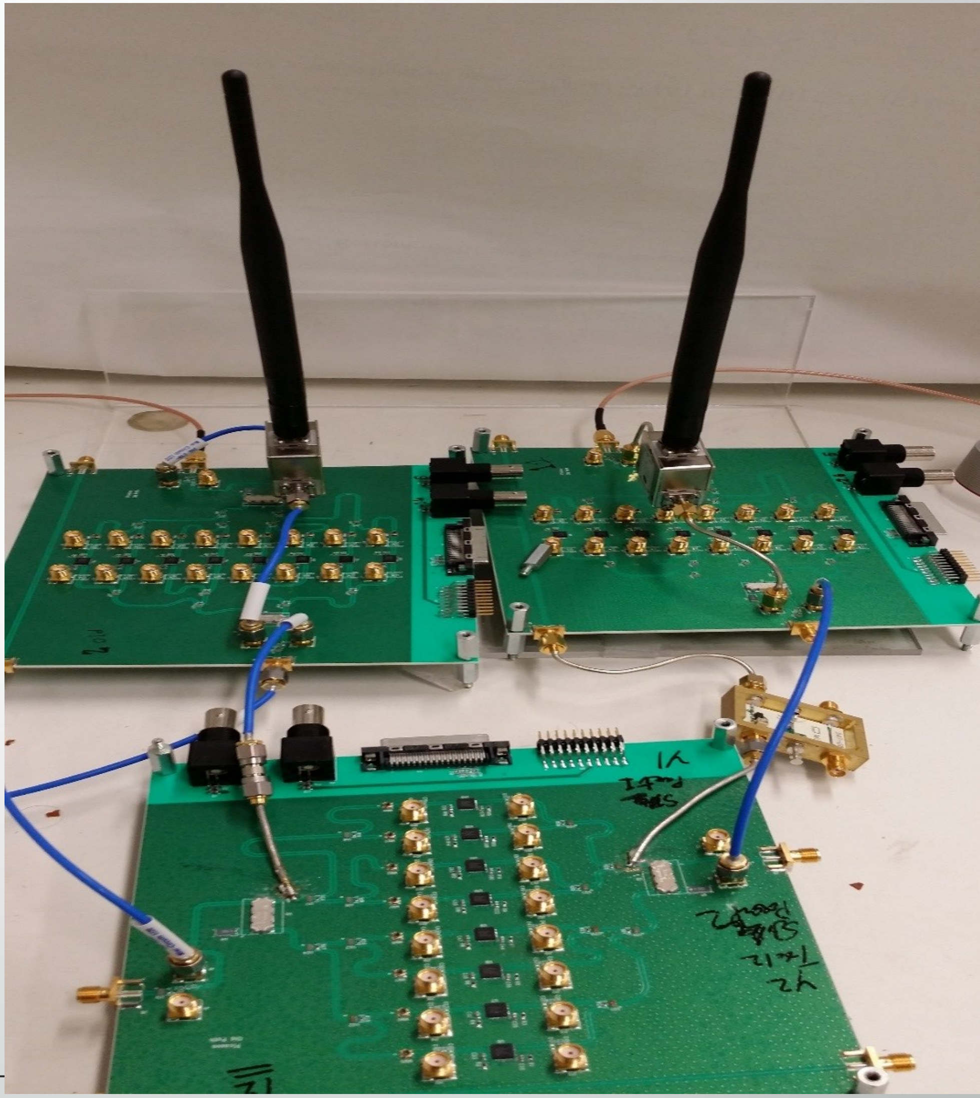
Goal: Build 3X3 MIMO full duplex radio using commodity software radios.



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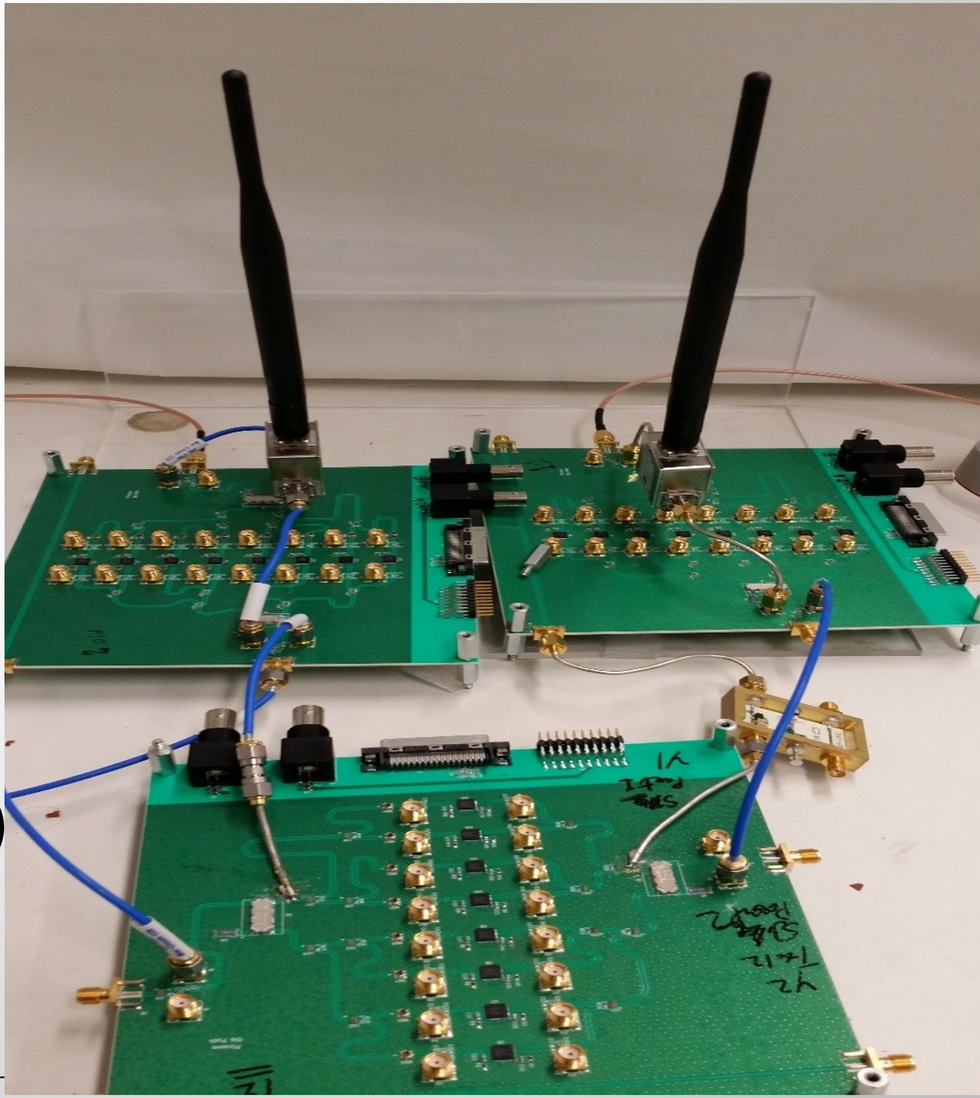

- Maxim transceiver
- Challenge: **Extremely high transmitter noise and non-linearities**
- 20MHz BW (transceiver limitation)
- 20 dBm max TX power
- WiFi 802.11n PHY

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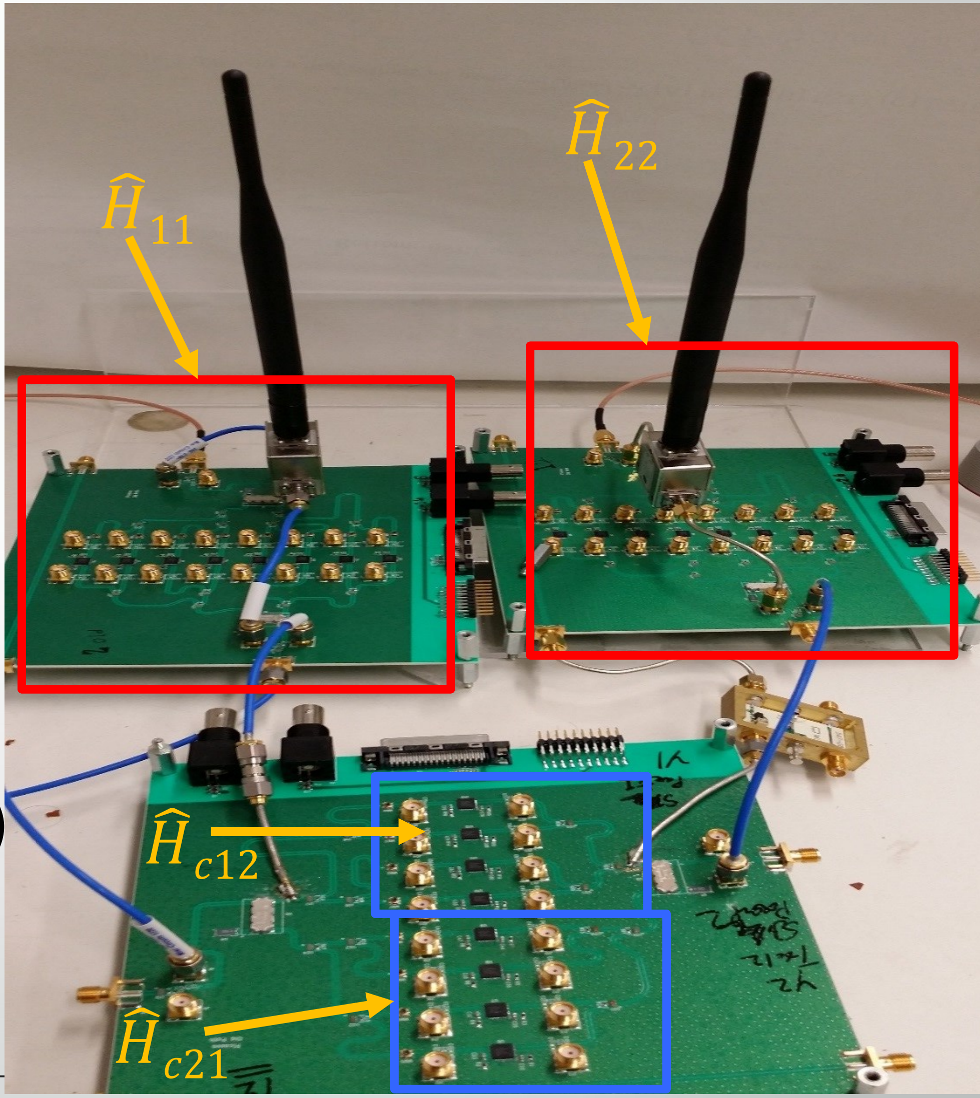

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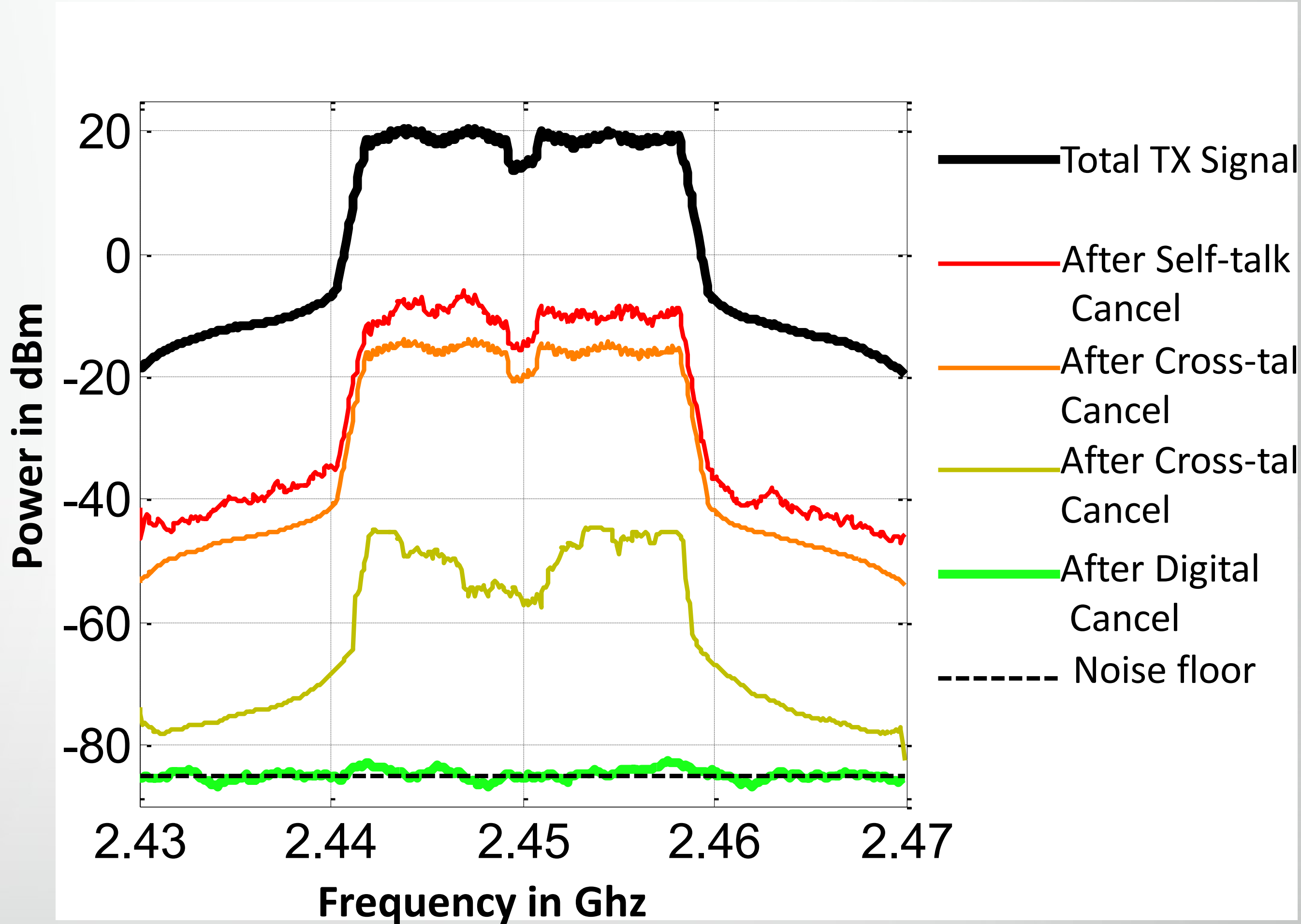
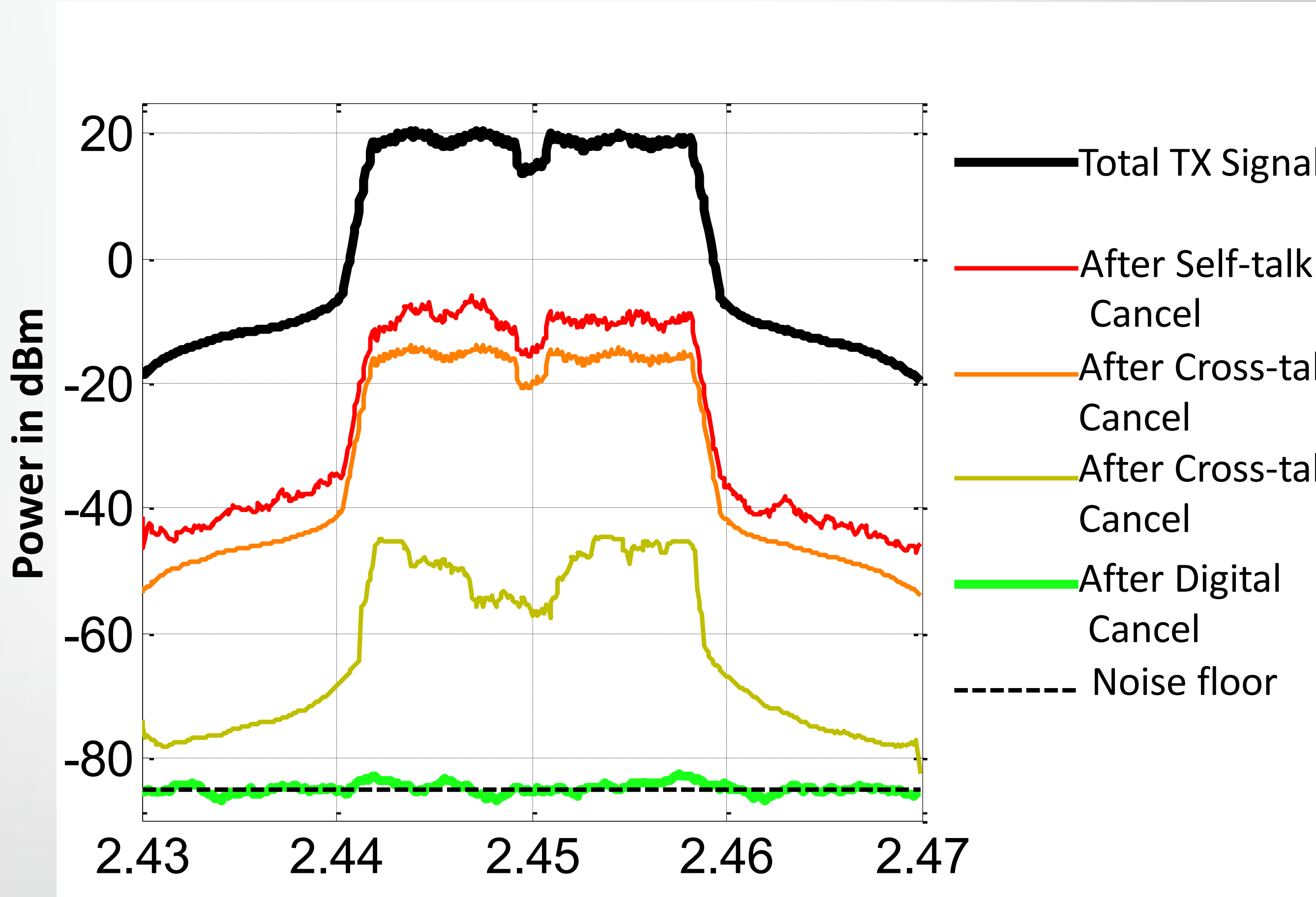


Evaluation Q1: Does it work with commodity radios?

- Indoor noisy office environment
- Tunes to environmental changes within 8us, needs to be re-tuned every 60 ms



Prototype implementation completely cancels interference to noise floor for a 3x3 MIMO radio

Evaluation Q2: Does it have linear Complexity Scaling ?

Resource Comparison between SISO replication and our design

	SISO replication design	Our design
Analog Cancellation taps (3X3)	108	56 (reduced by 1.92x)
Digital Cancellation taps (3X3)	1188	485 (reduced by 2.45x)
Tuning time (3X3)	9 ms	.024 ms (reduced by 375x)

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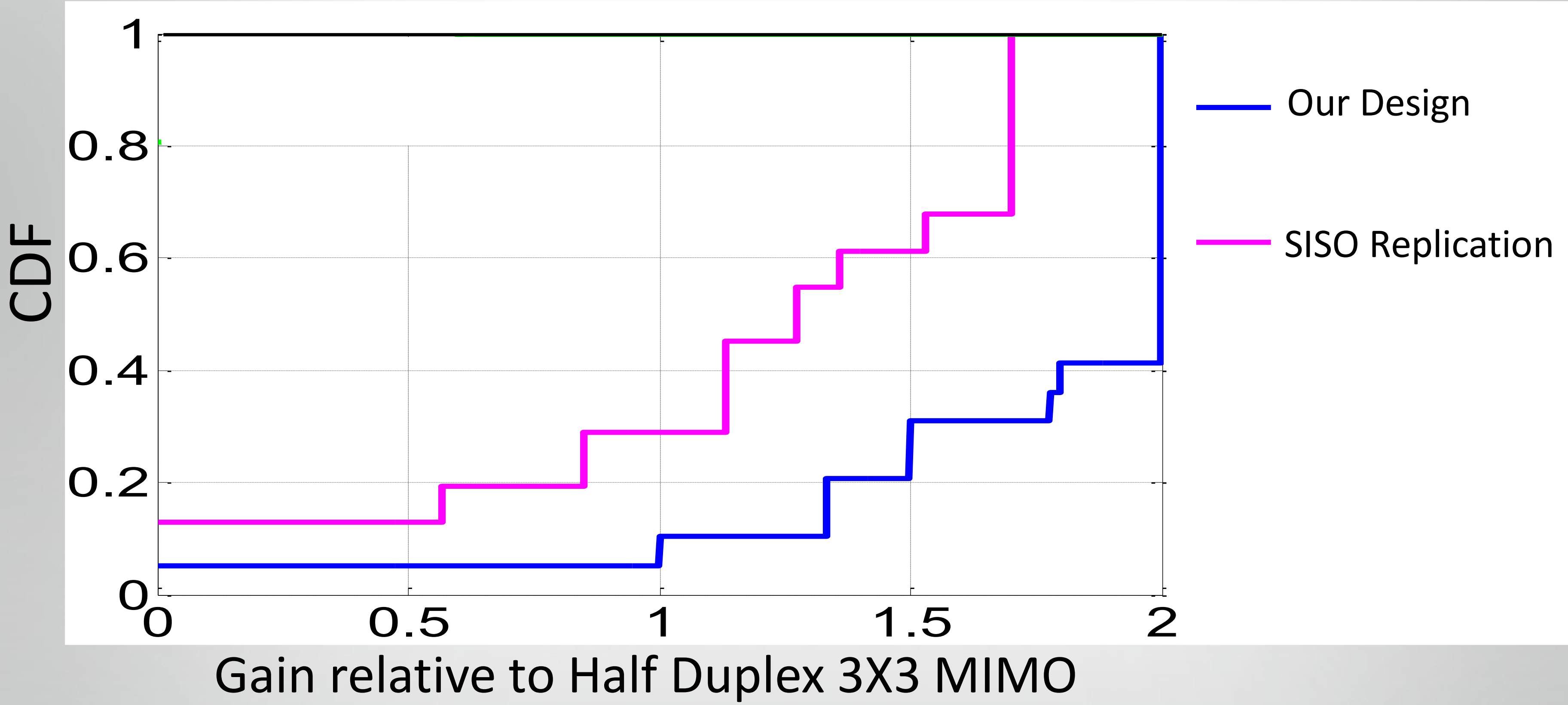
Complexity of both Analog and Digital Cancellation, scales linearly as number of antennas increases

Evaluation Q4: Does that translate to doubling of throughput in practice?



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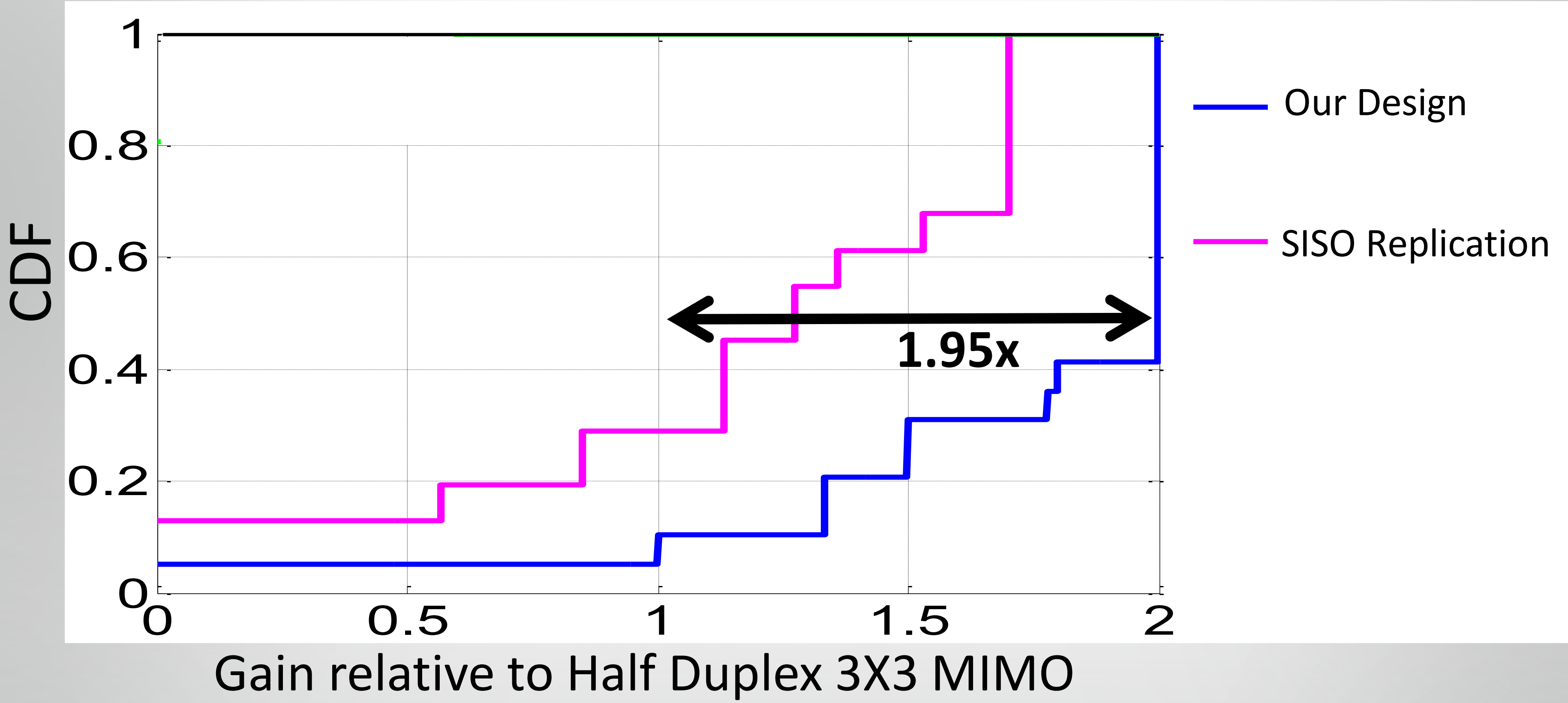

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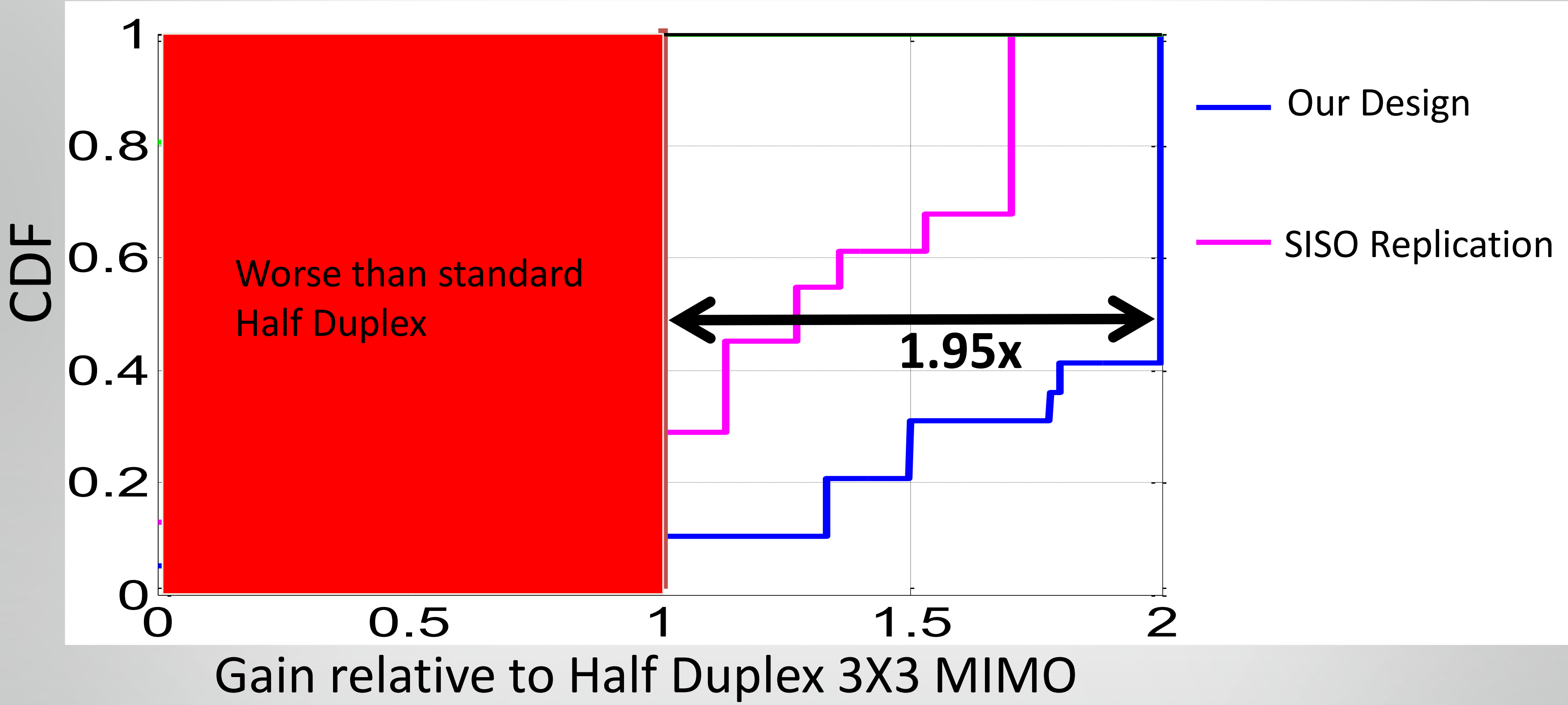

Our design practically achieves the theoretical throughput doubling

Conclusion

- Design and implementation of a near-ideal complexity and performance full duplex MIMO radio
  - Shows that full duplex and MIMO can operate concurrently
- Has applications to many other problems
  - Radio slicing, backscatter, imaging etc
- Many implications for MAC layer design
  - Feedback, beamforming, MU-MIMO