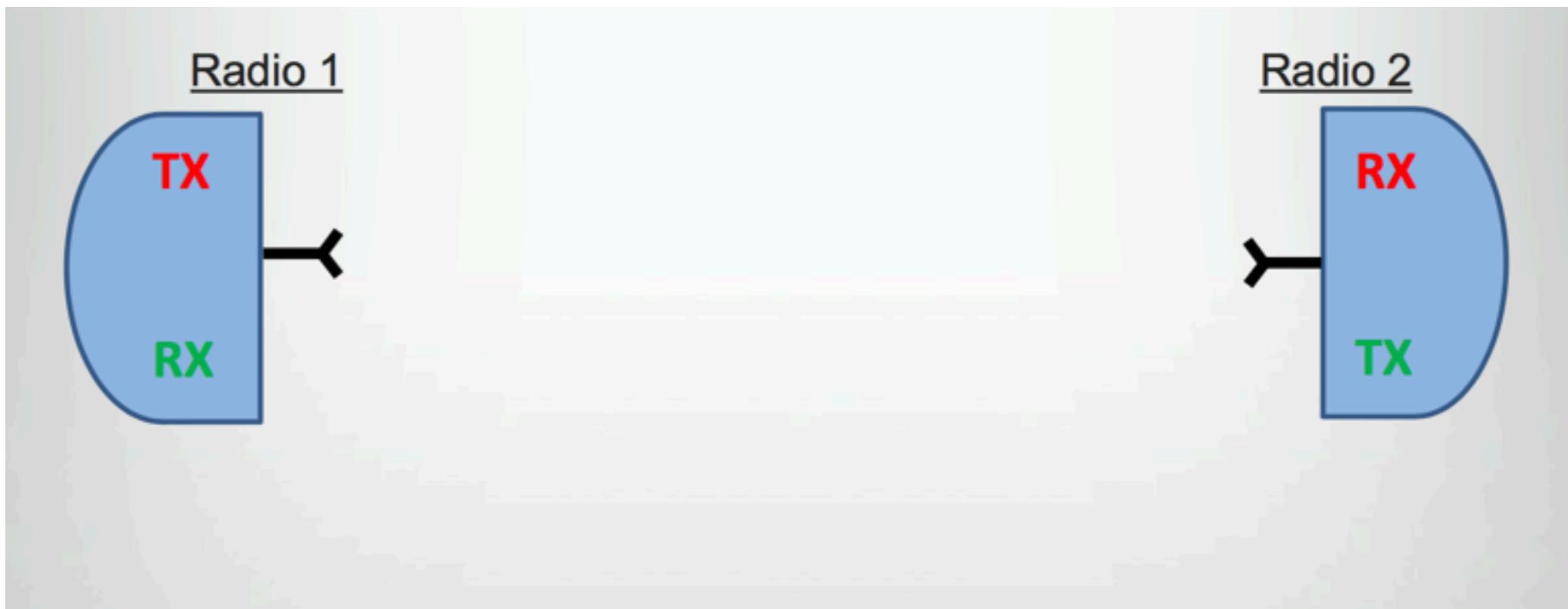


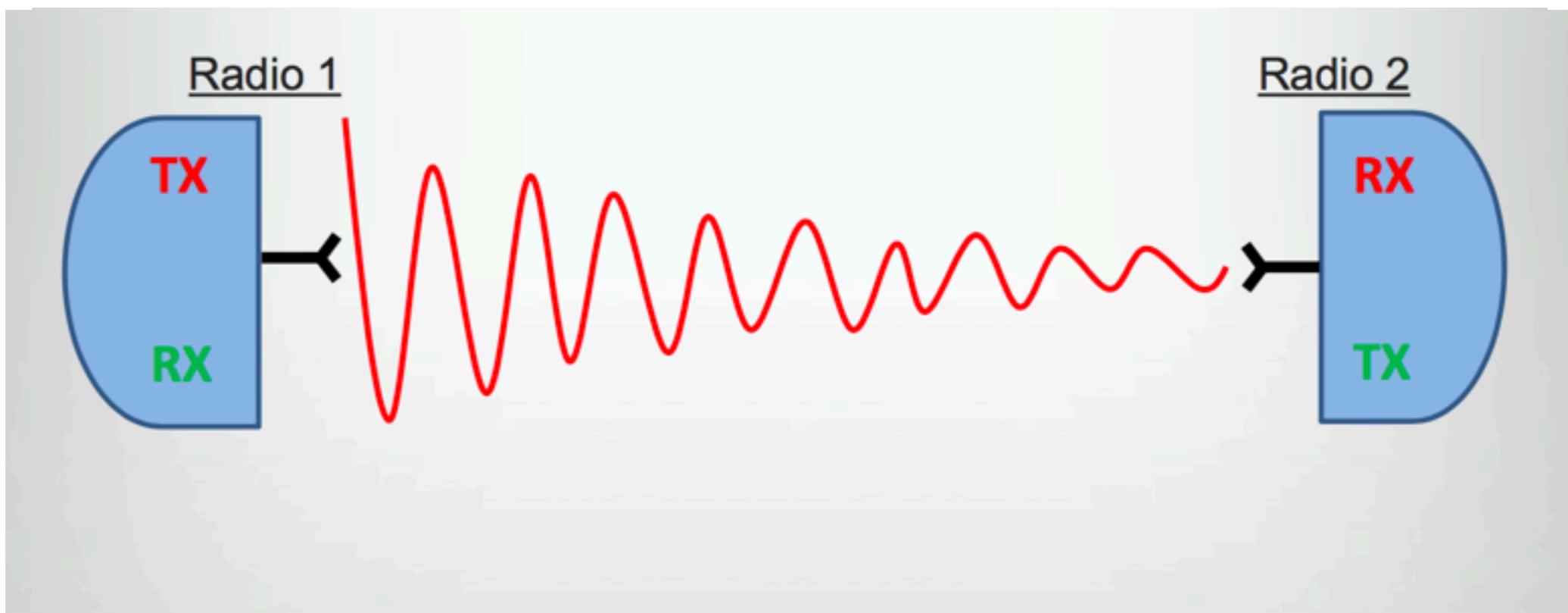
Full-Duplex Communications

Some slides adapted from: Dinesh Bharadia and Sachin Katti

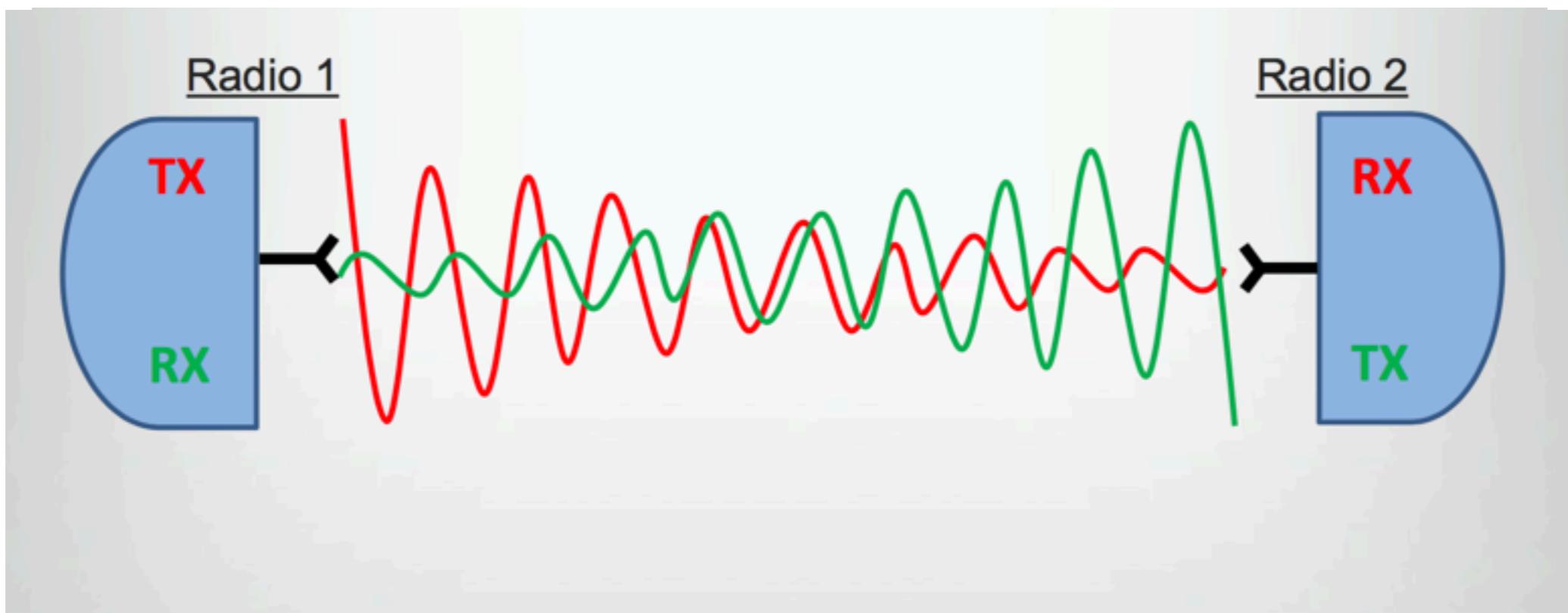
Why was full-duplex considered impossible?



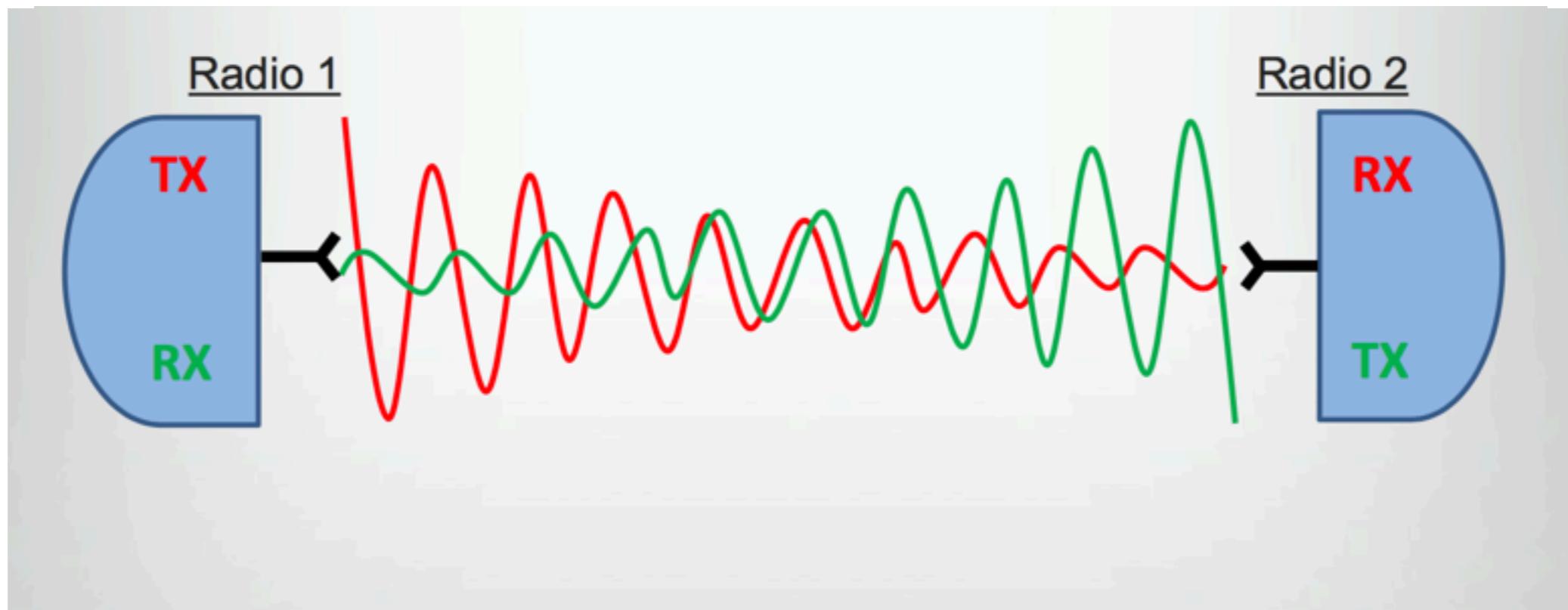
Why was full-duplex considered impossible?



Why was full-duplex considered impossible?



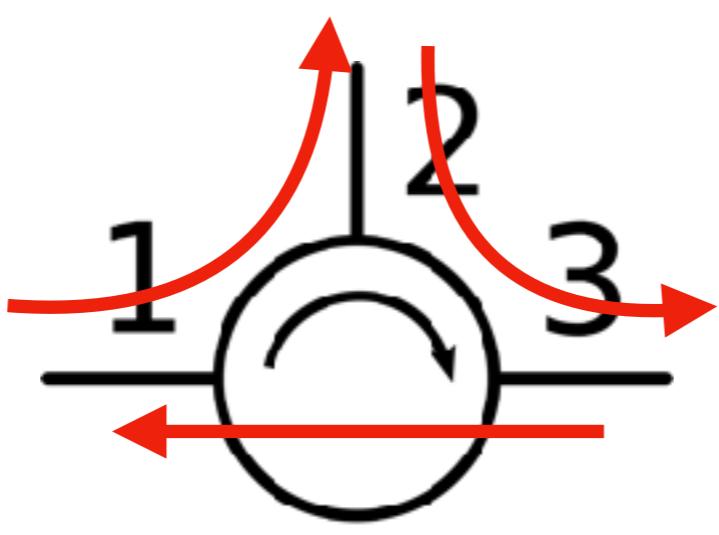
Why was full-duplex considered impossible?



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

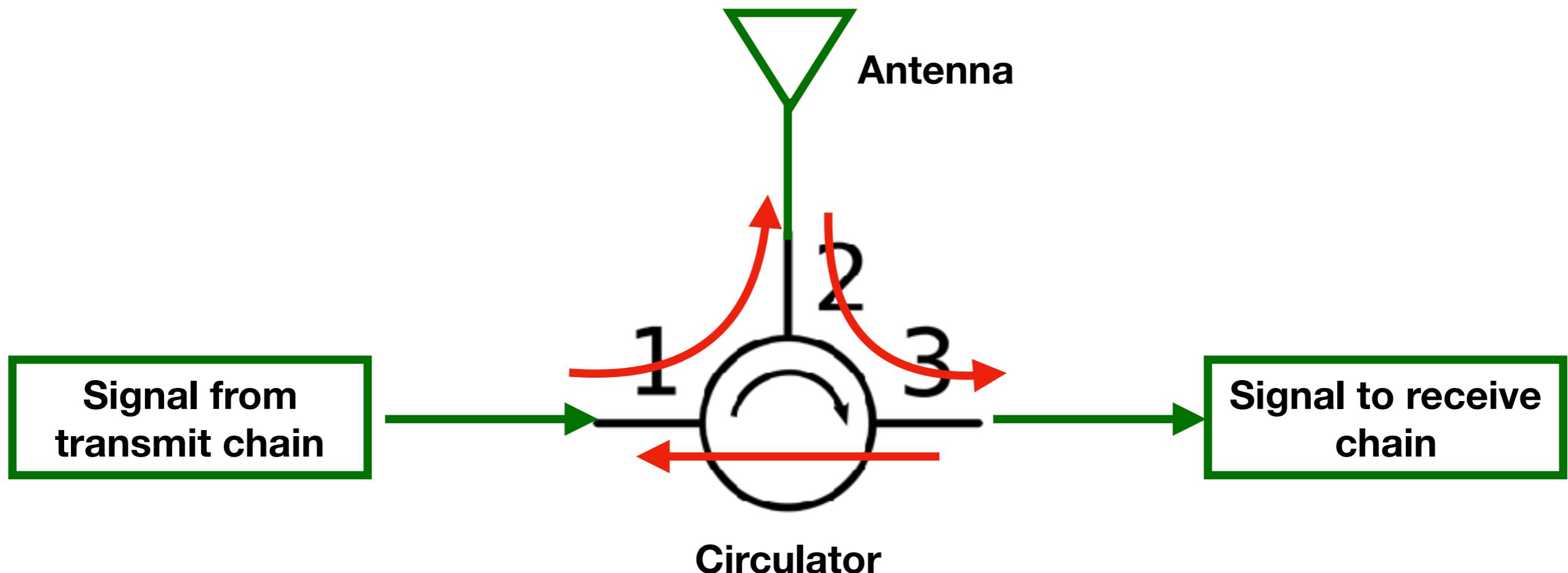
Classical technique to achieve full-duplex

- Isolate the transmitter and the receiver
- Use a circulator



Classical technique to achieve full-duplex

- Isolate the transmitter and the receiver
- Use a circulator



Problem: Can only achieve ~25dB of isolation

Idea of Recent Advances: Self-interference Cancellation

- The transmitter knows its transmitted signal
- It can simply subtract it out

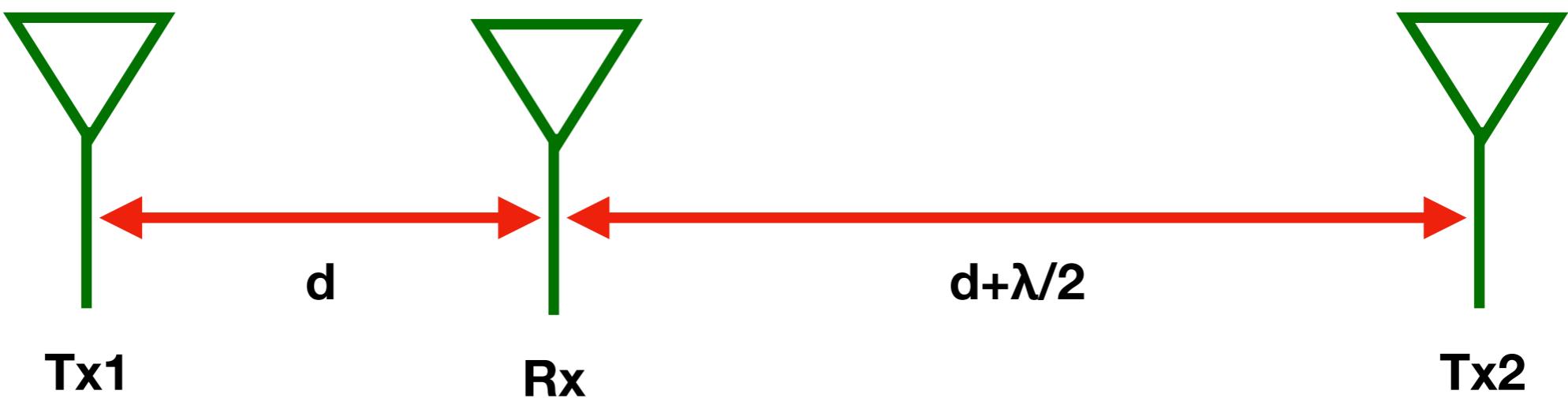
Technique #1: Digital Cancellation

- Subtract in the digital domain (similar to Zigzag)

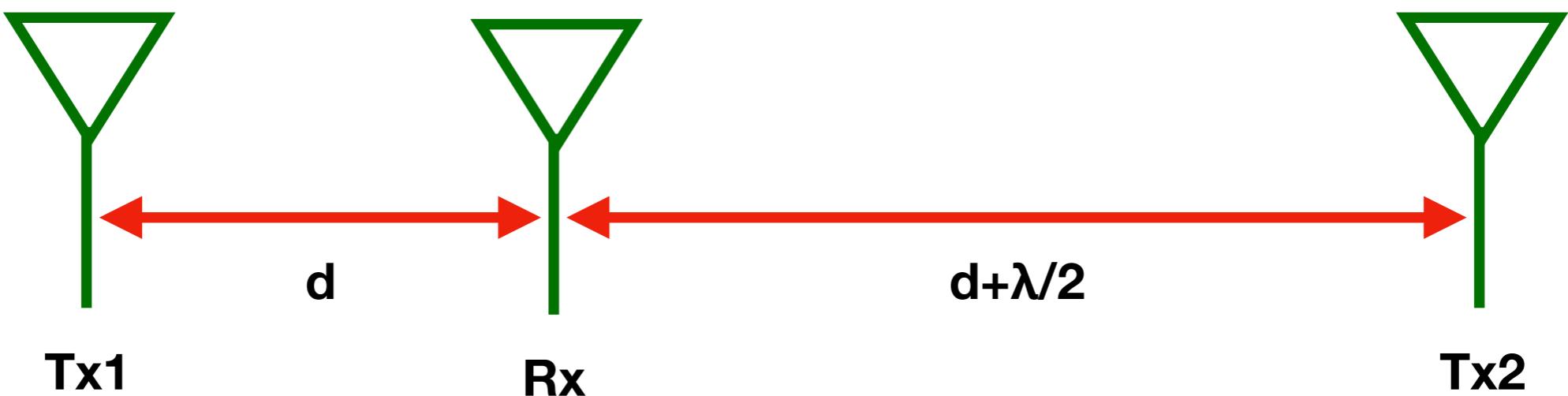
Problems?

- Limited because of ADC dynamic range

Technique #2: Antenna Cancellation



Technique #2: Antenna Cancellation

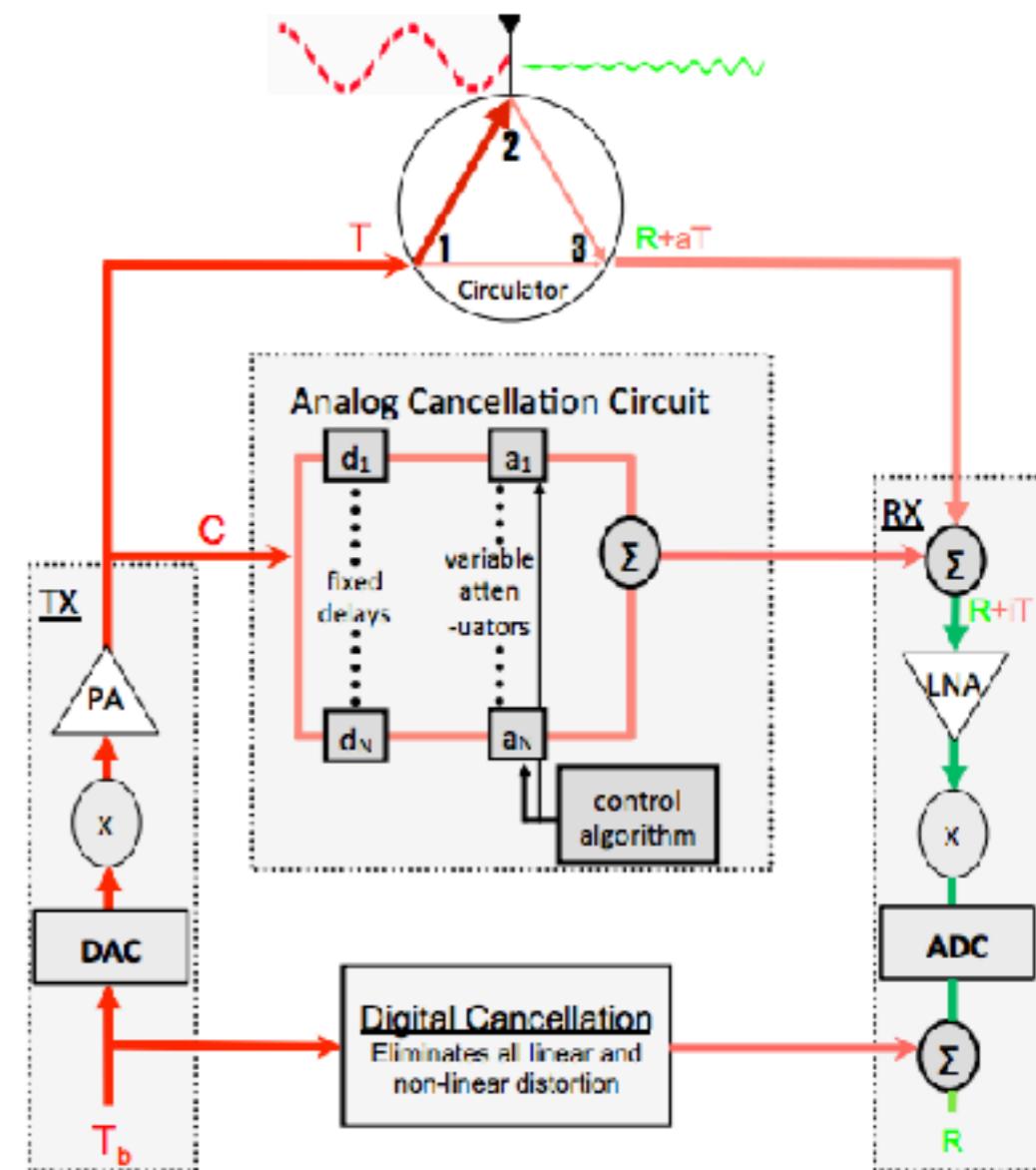


Problems?

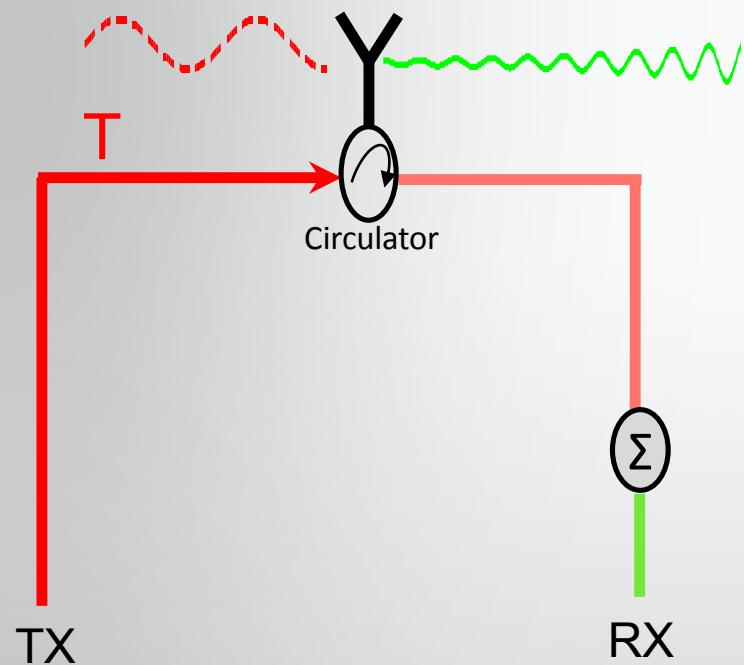
- Specific placement of antennas
- Three antennas
- Narrowband
- Multipath

Technique #3: Non-linear cancellation via filters

- Problem: non-linearities
- Solution: filter taps

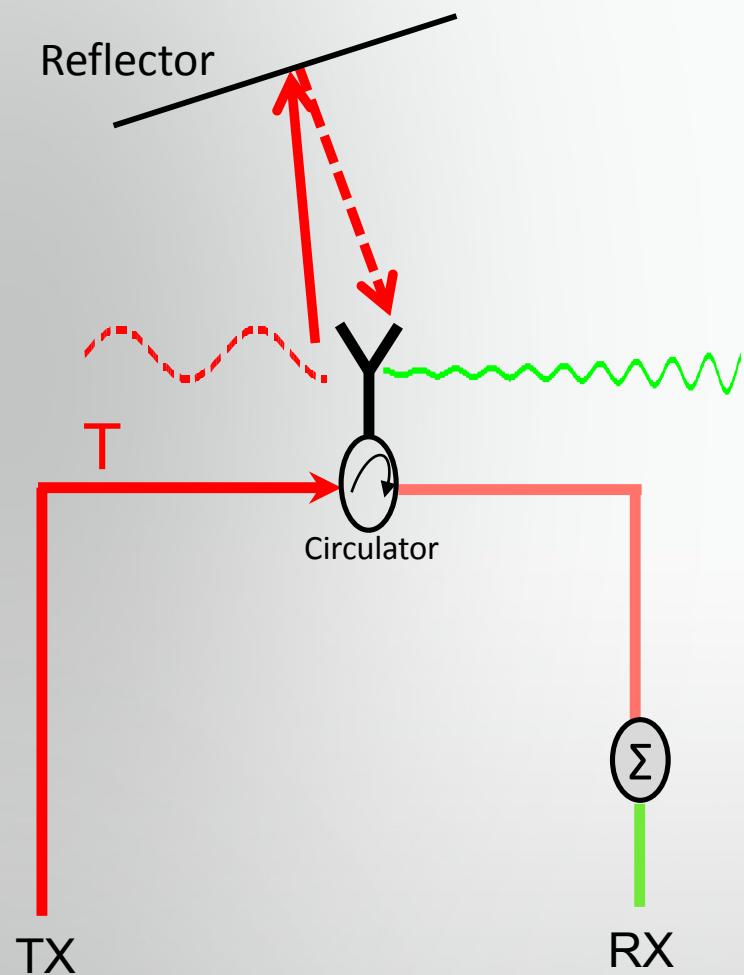


State of the Art for SISO full duplex



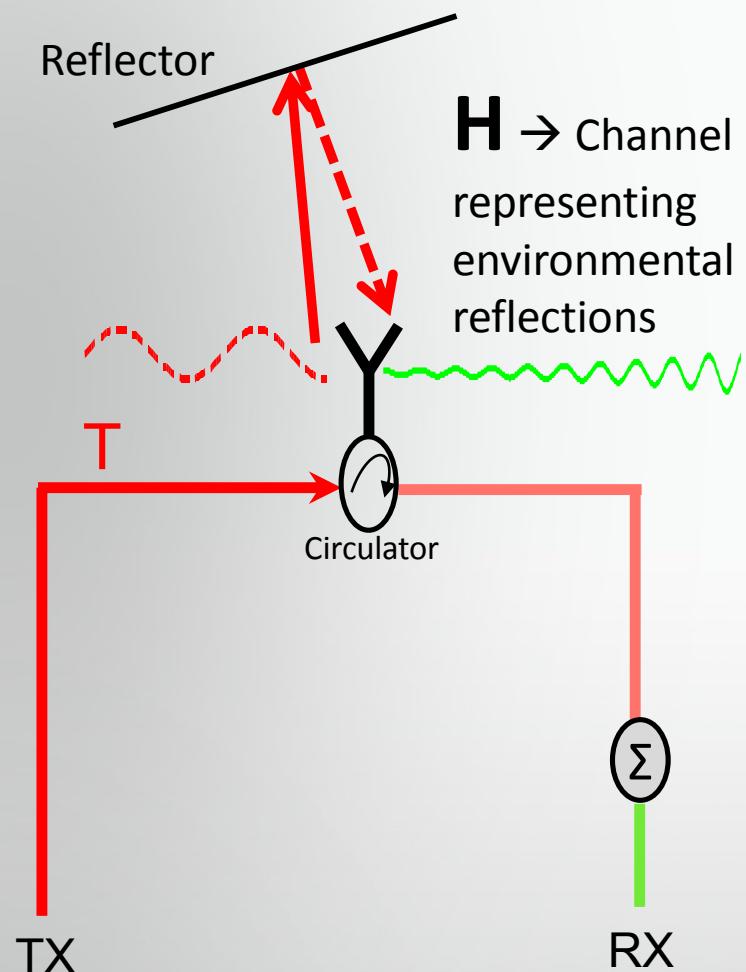
Conceptual model

State of the Art for SISO full duplex



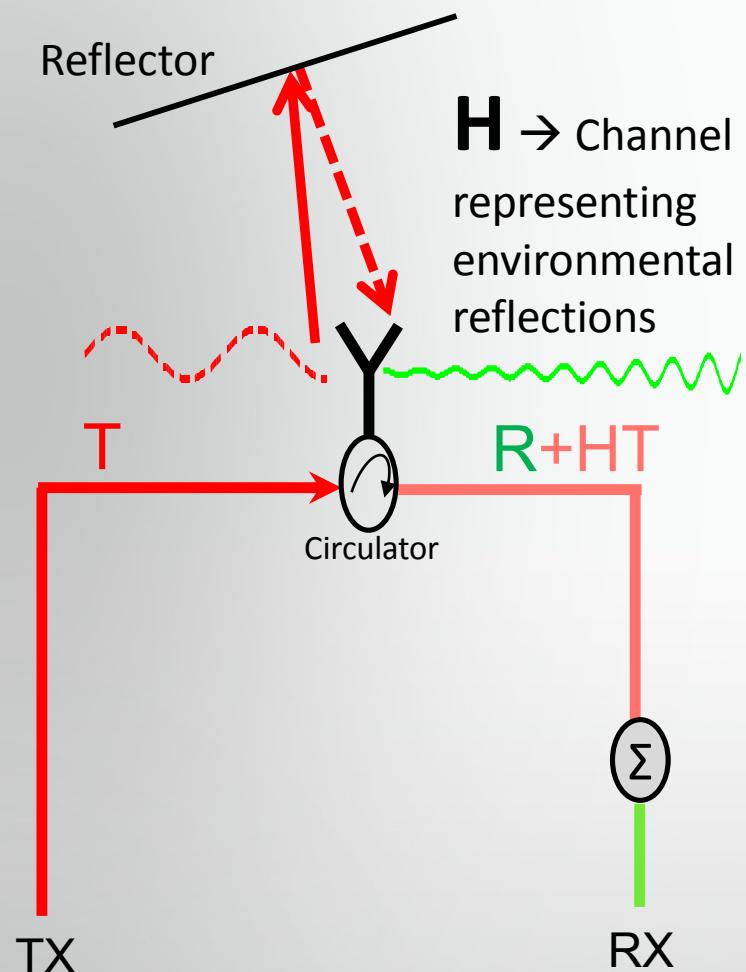
Conceptual model

State of the Art for SISO full duplex



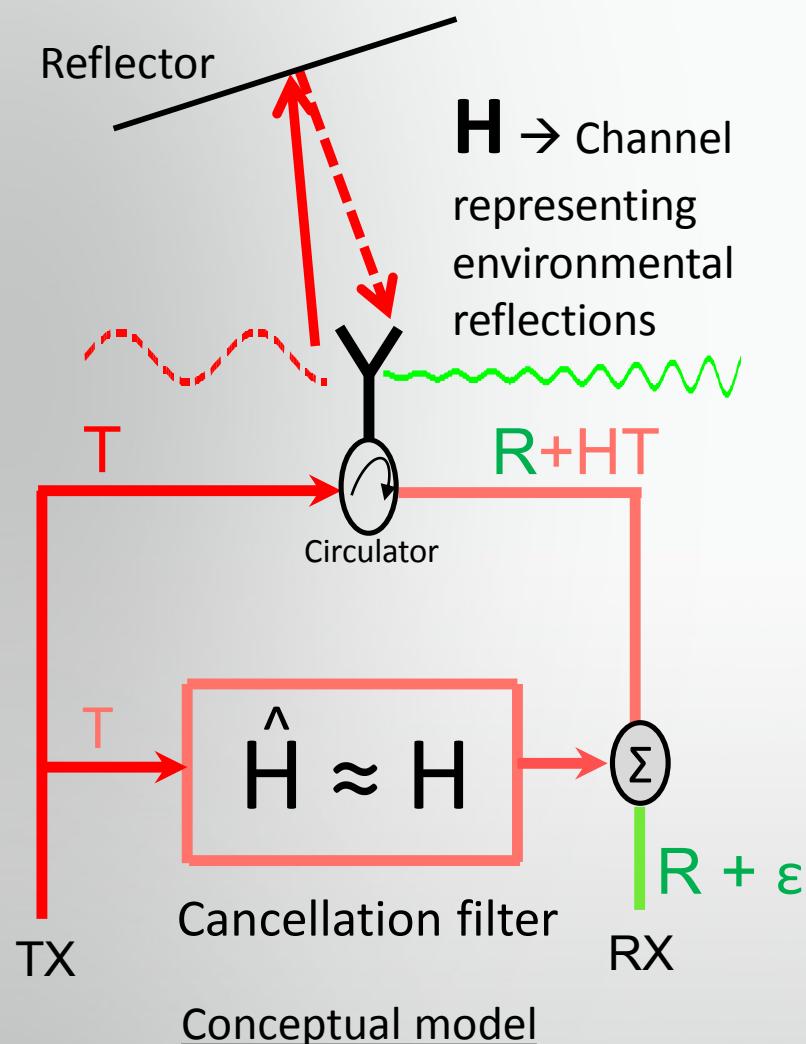
Conceptual model

State of the Art for SISO full duplex

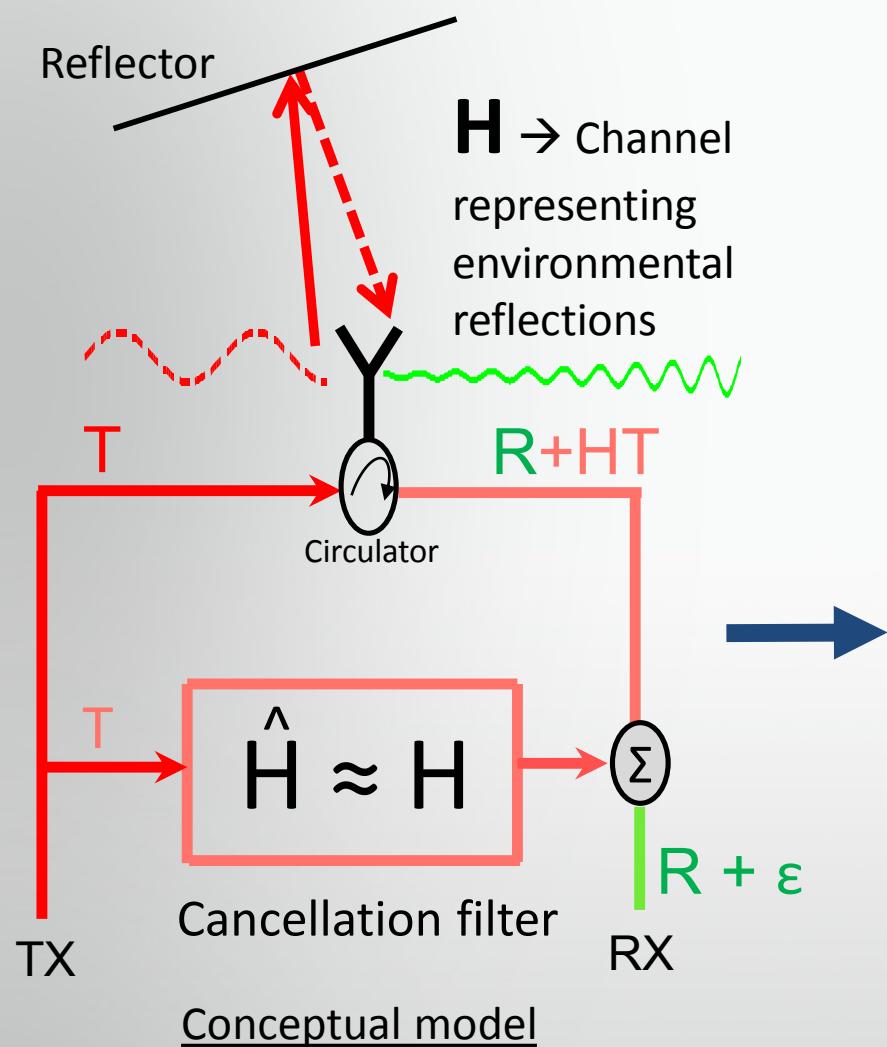


Conceptual model

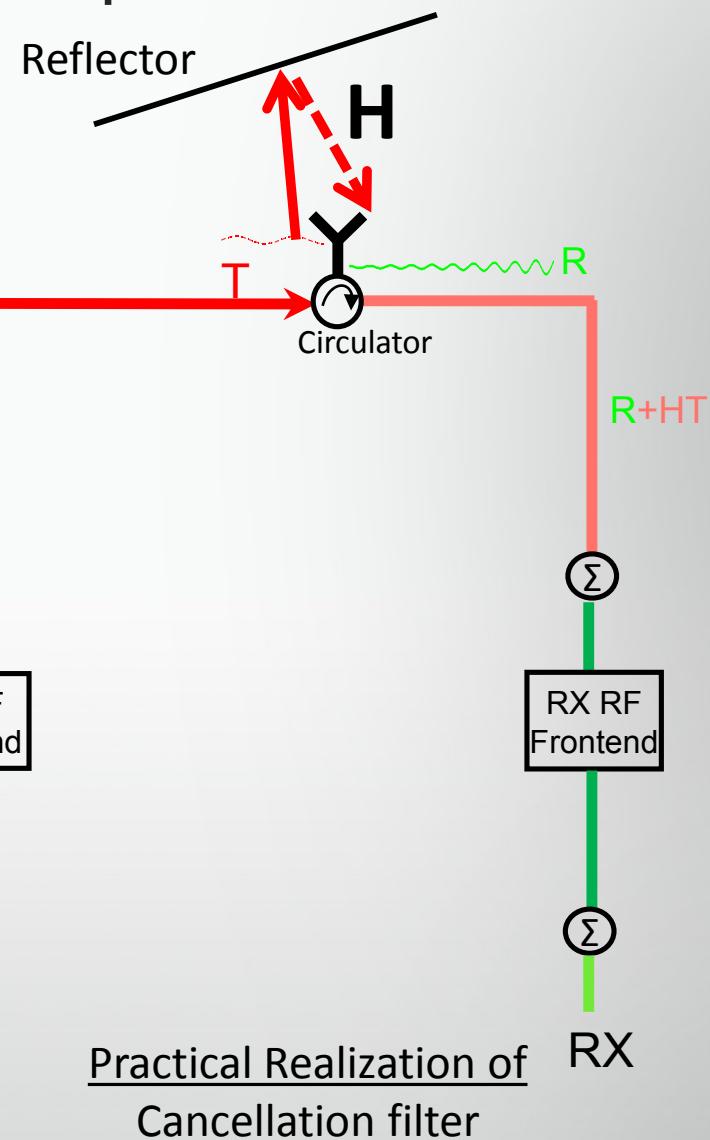
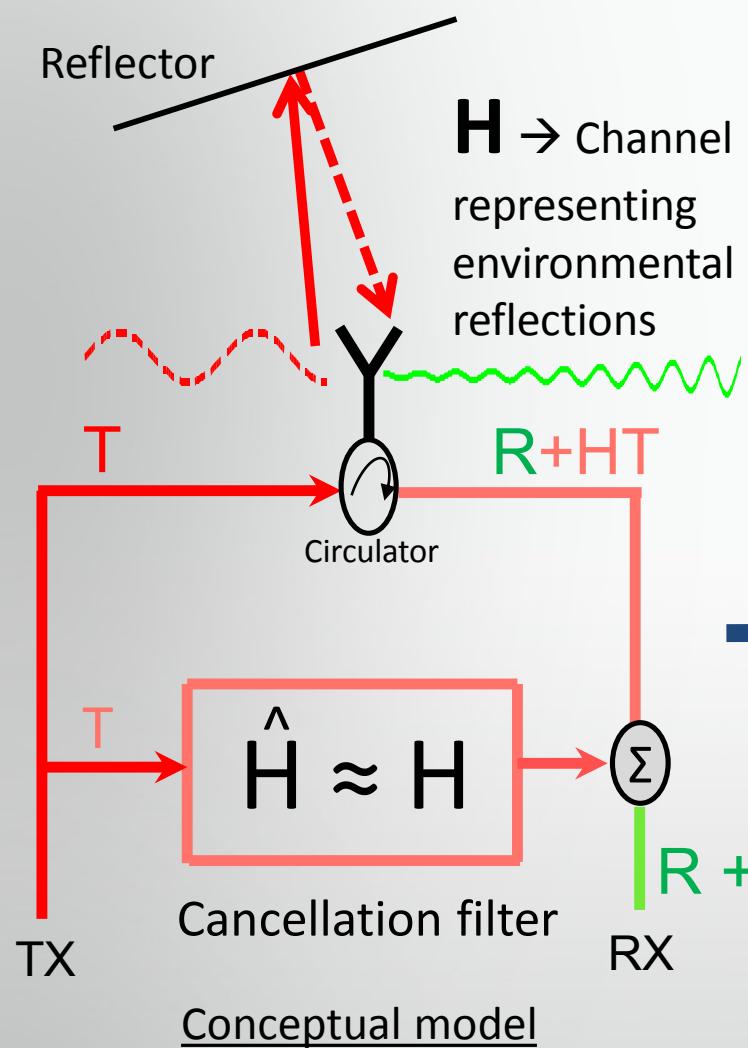
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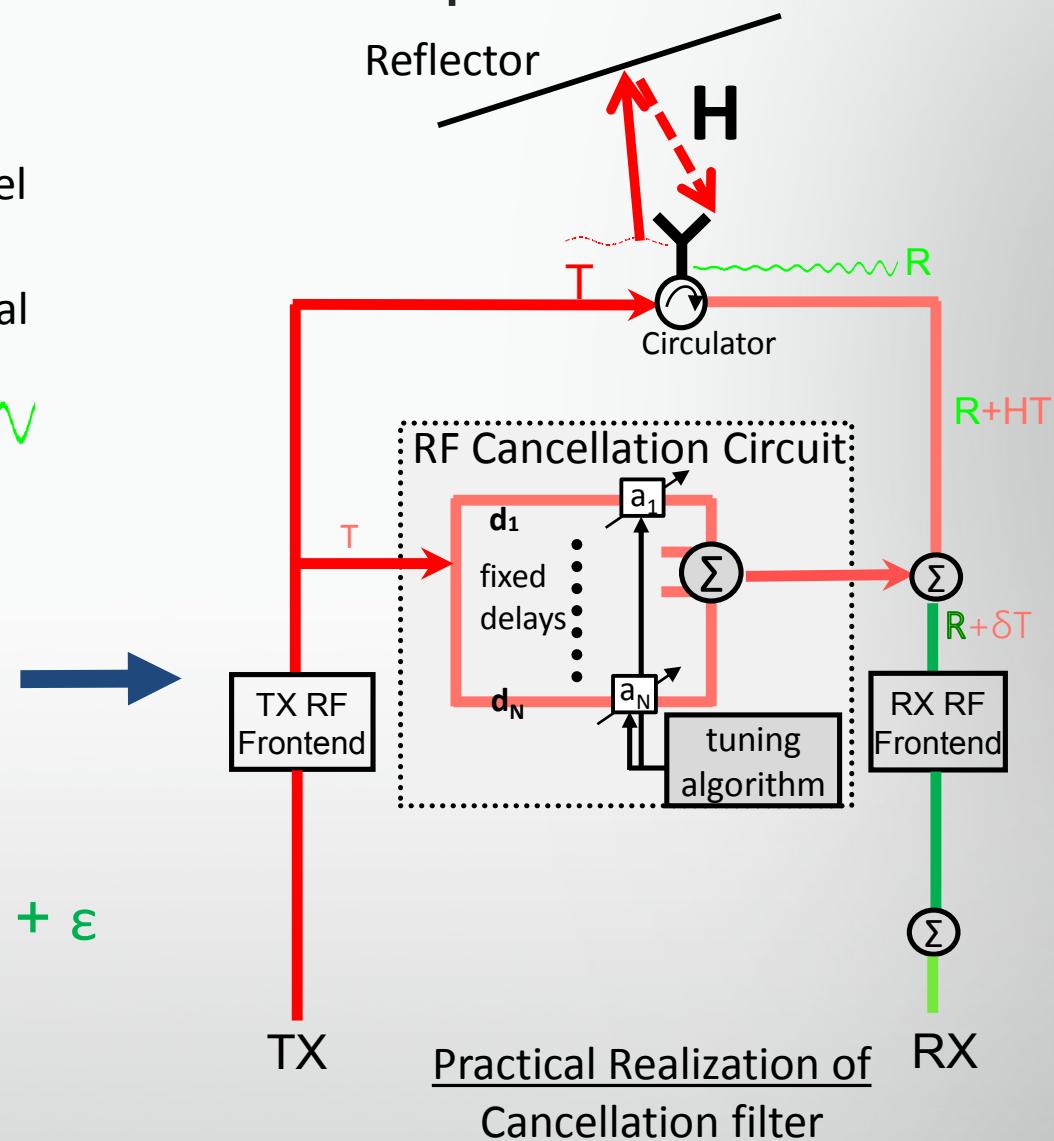
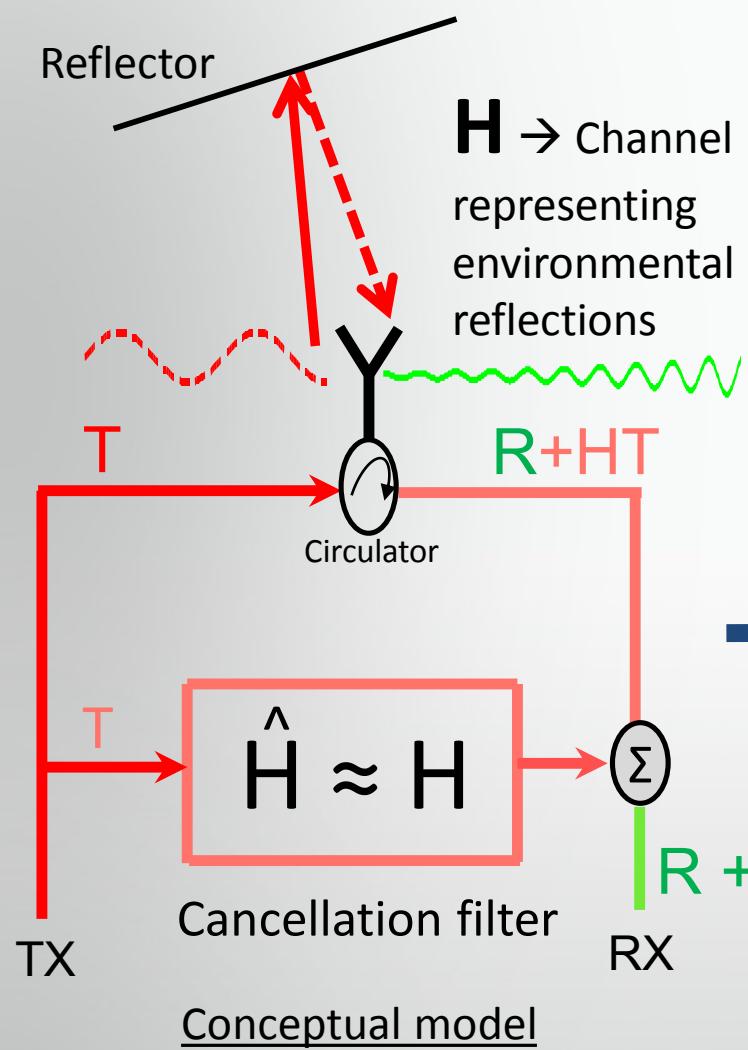
State of the Art for SISO full duplex



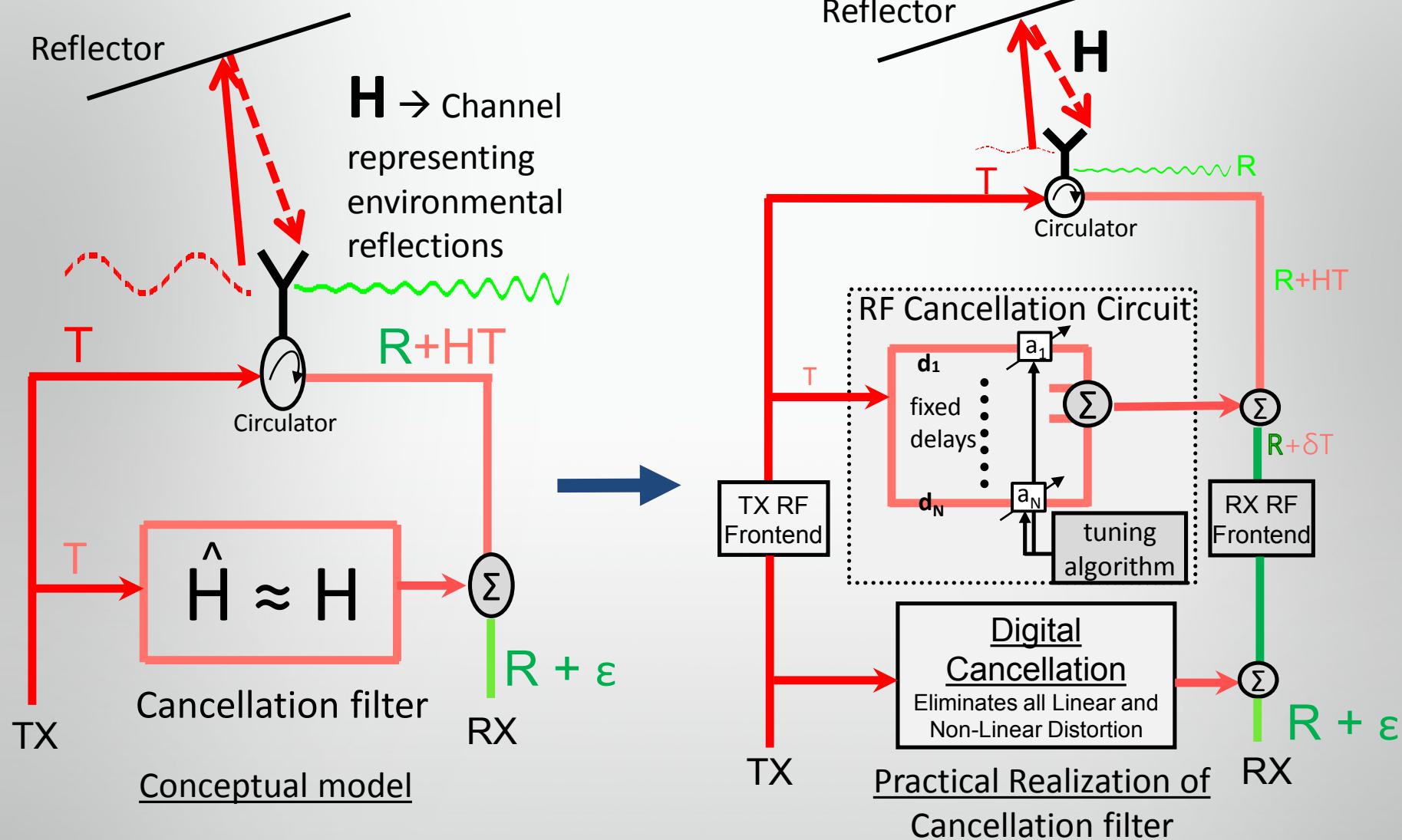
State of the Art for SISO full duplex



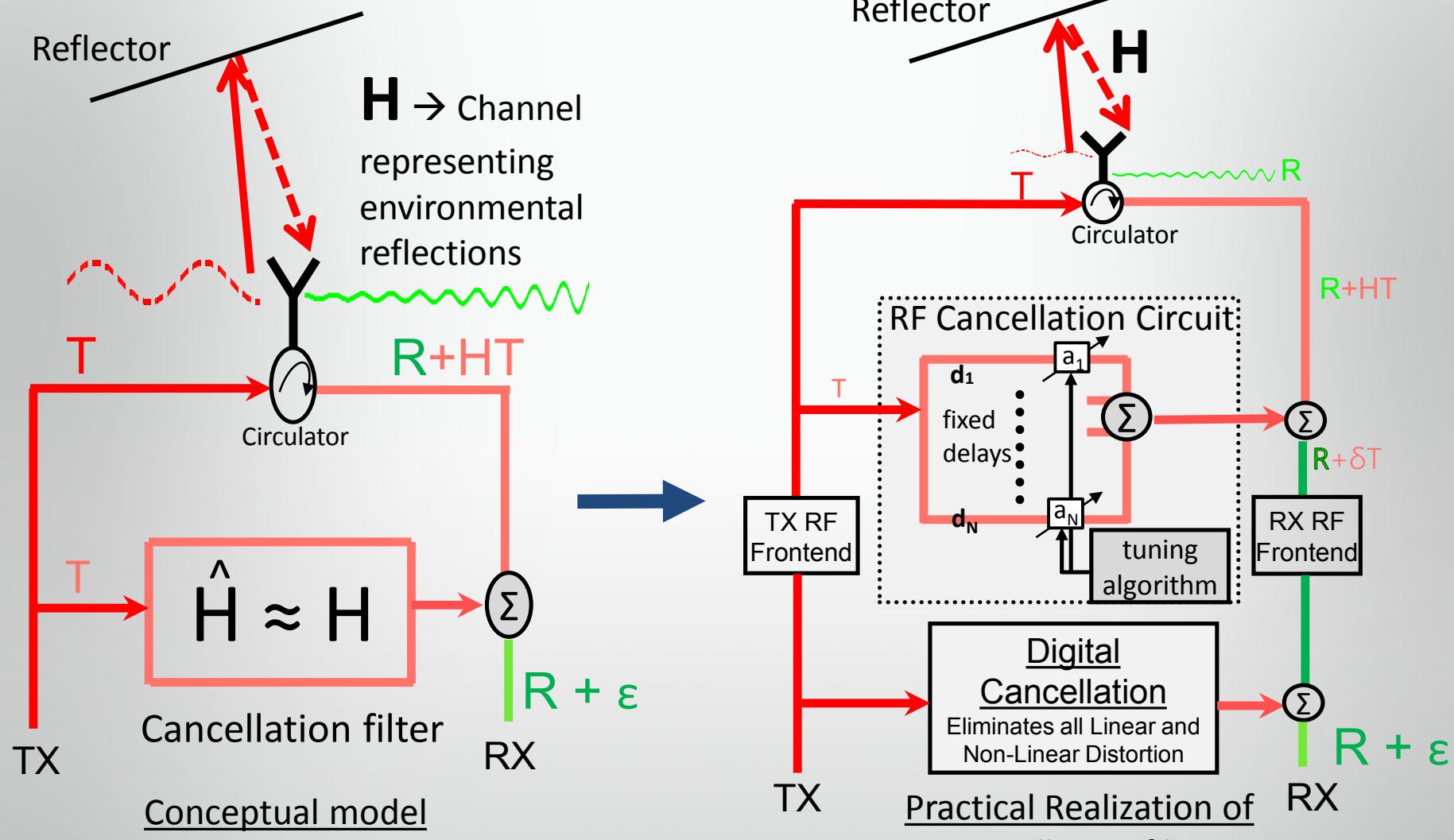
State of the Art for SISO full duplex



State of the Art for SISO full duplex

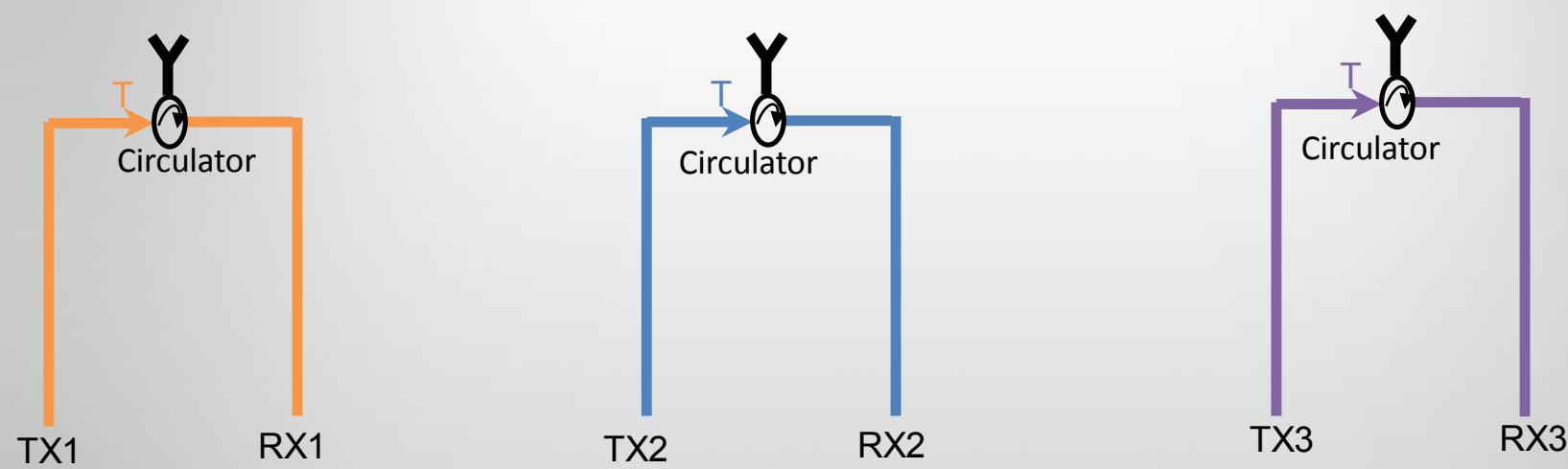


State of the Art for SISO full duplex

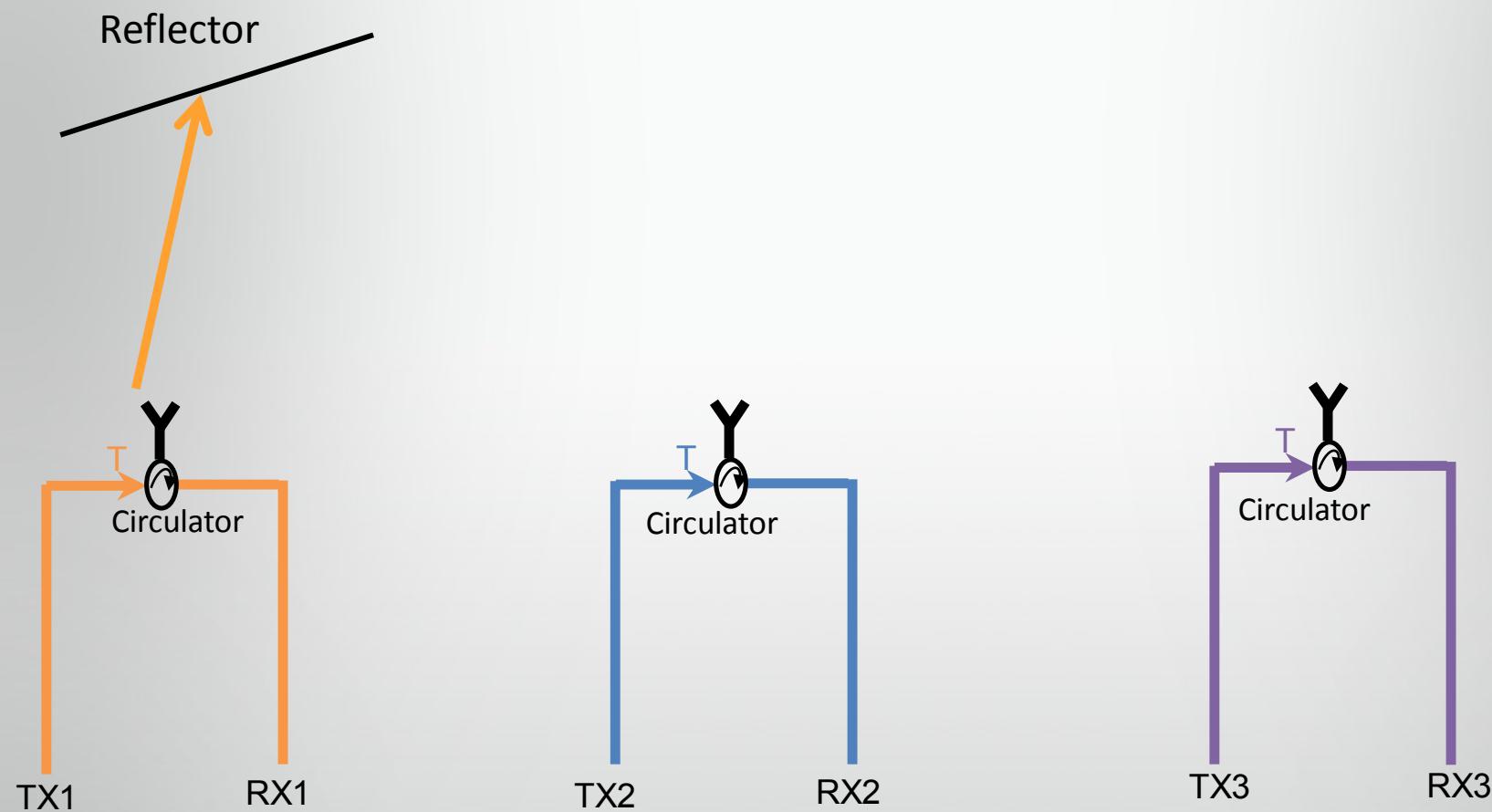


Full duplex designs are conceptually realizing an adaptive filter that closely matches the environmental

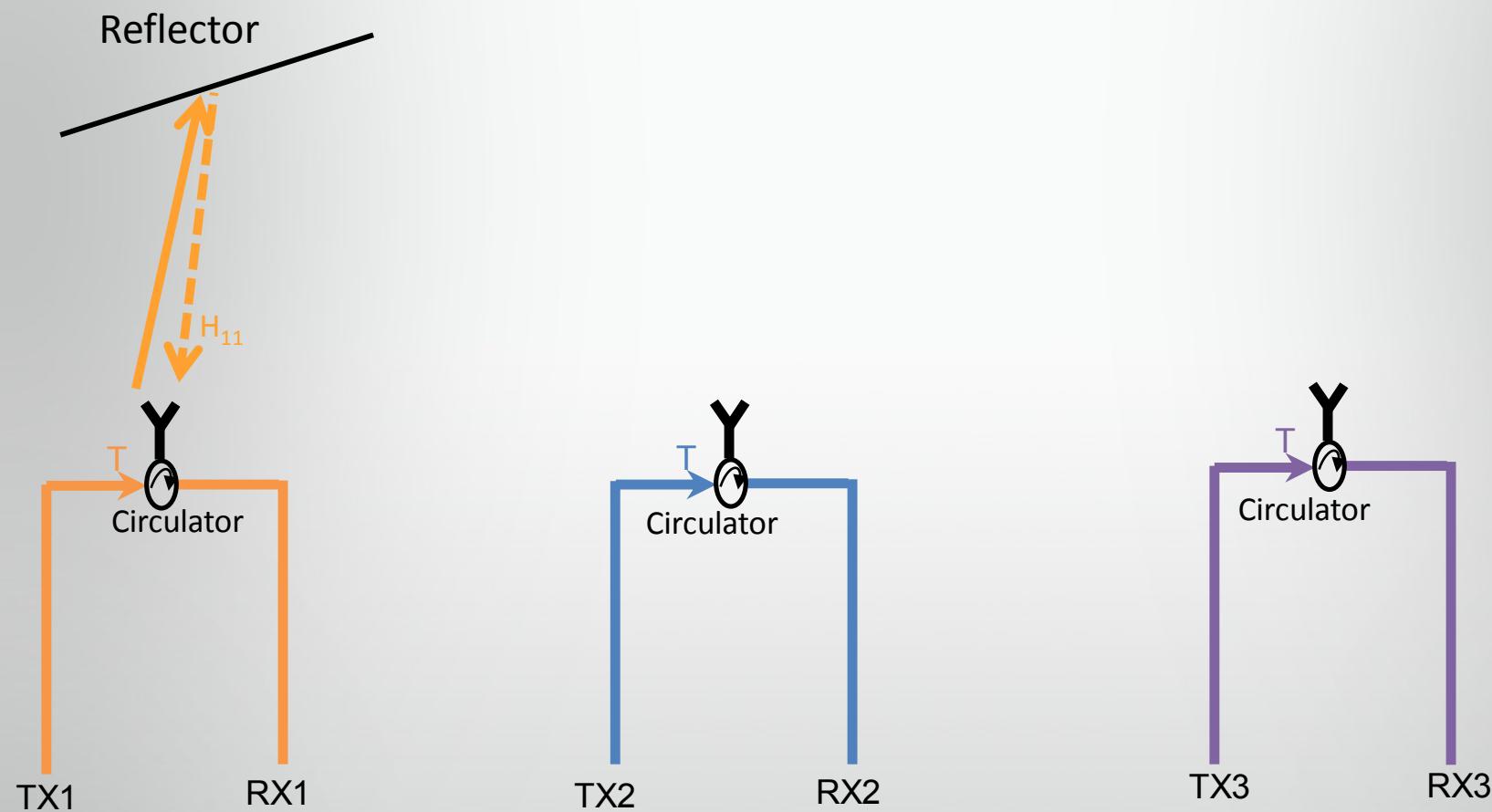
How is the MIMO full duplex problem different?



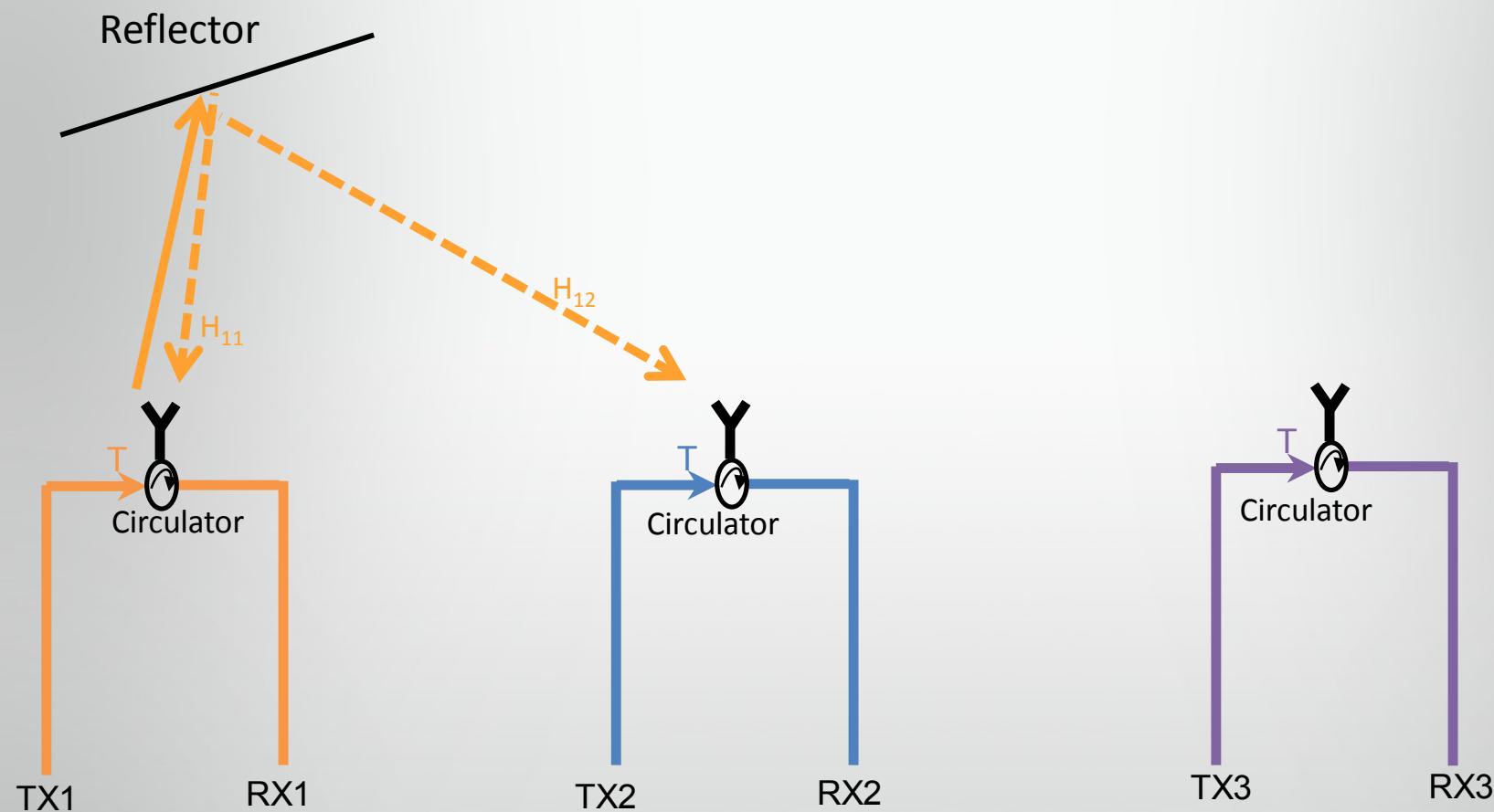
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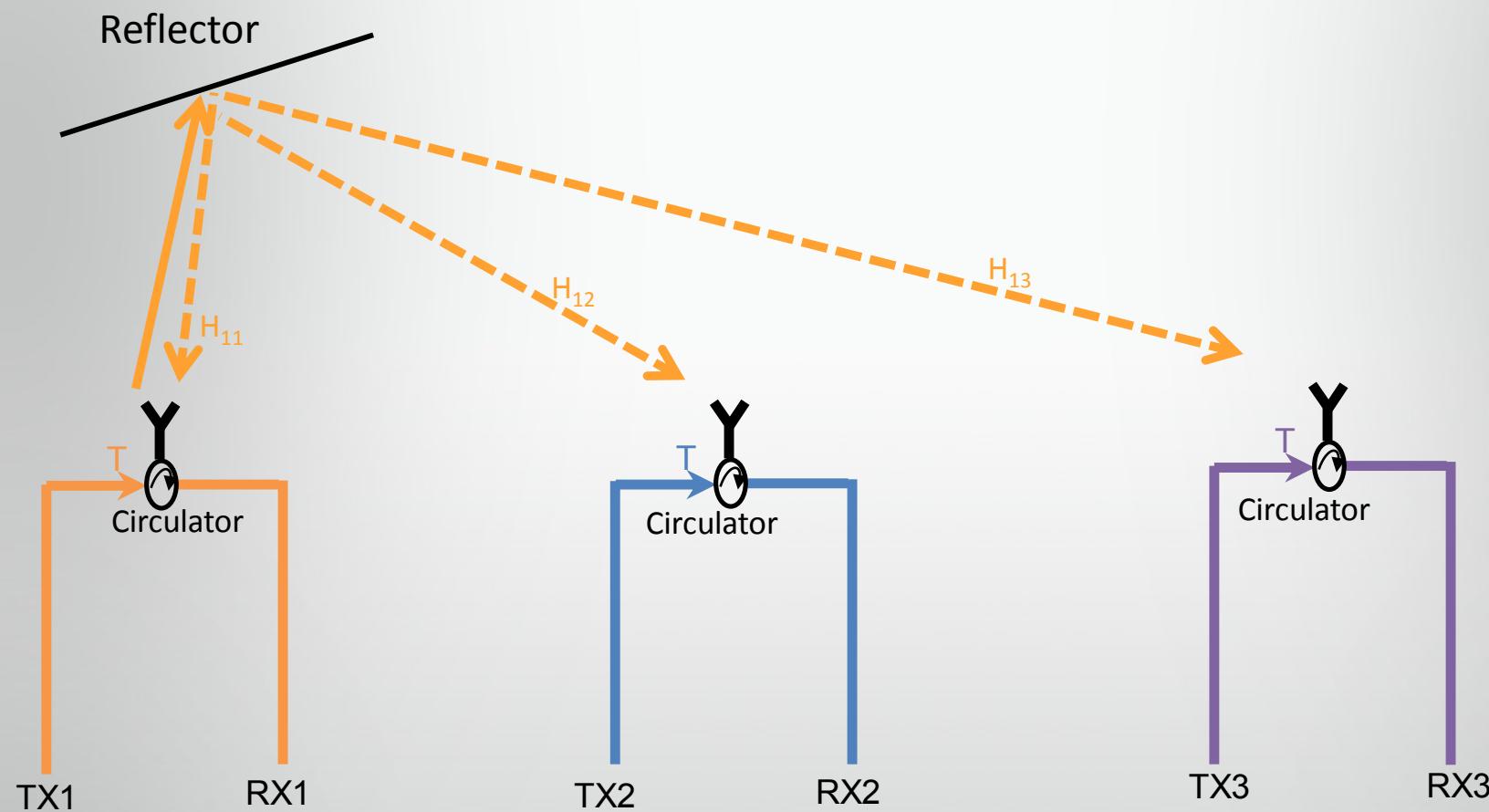
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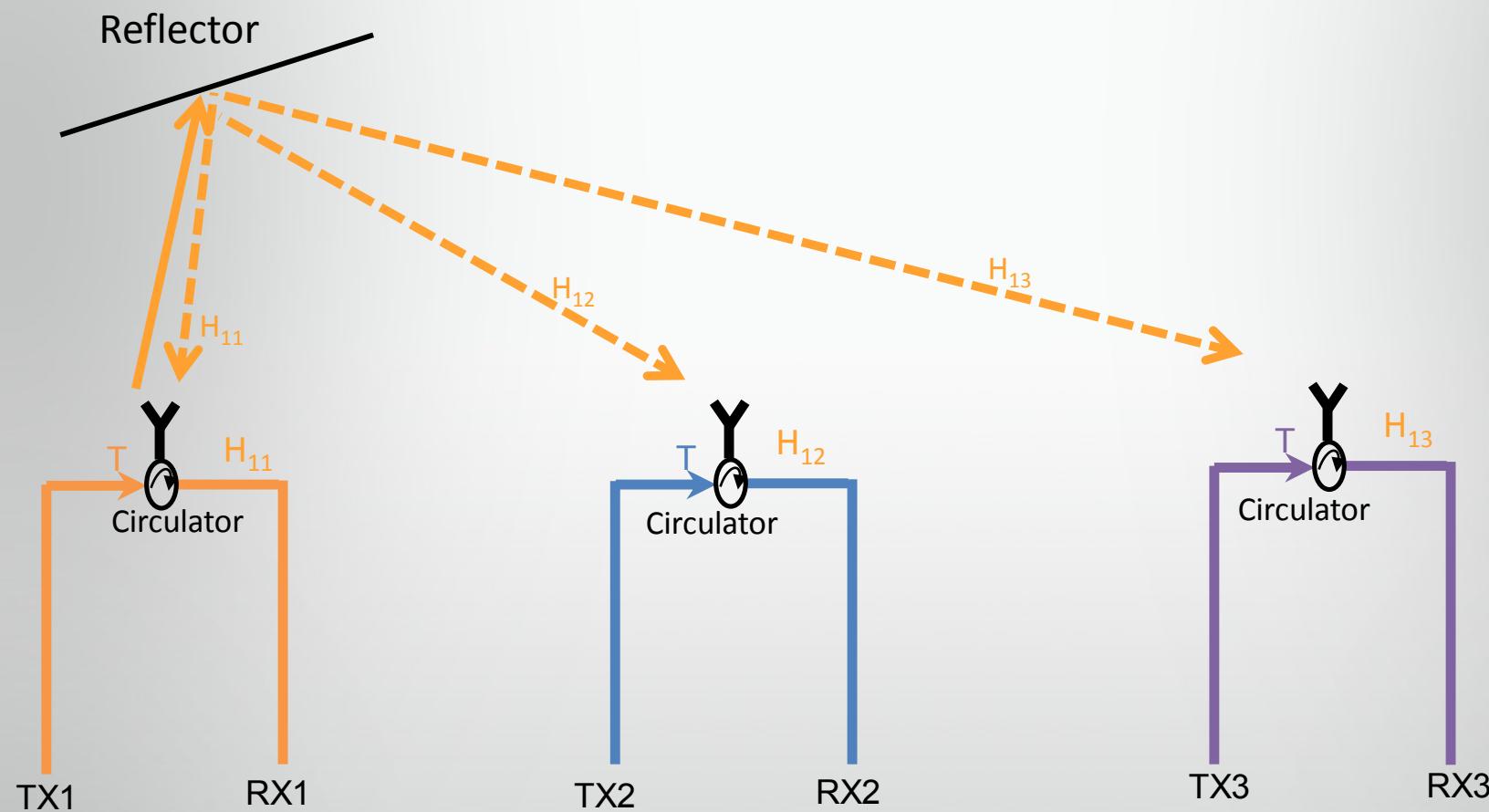
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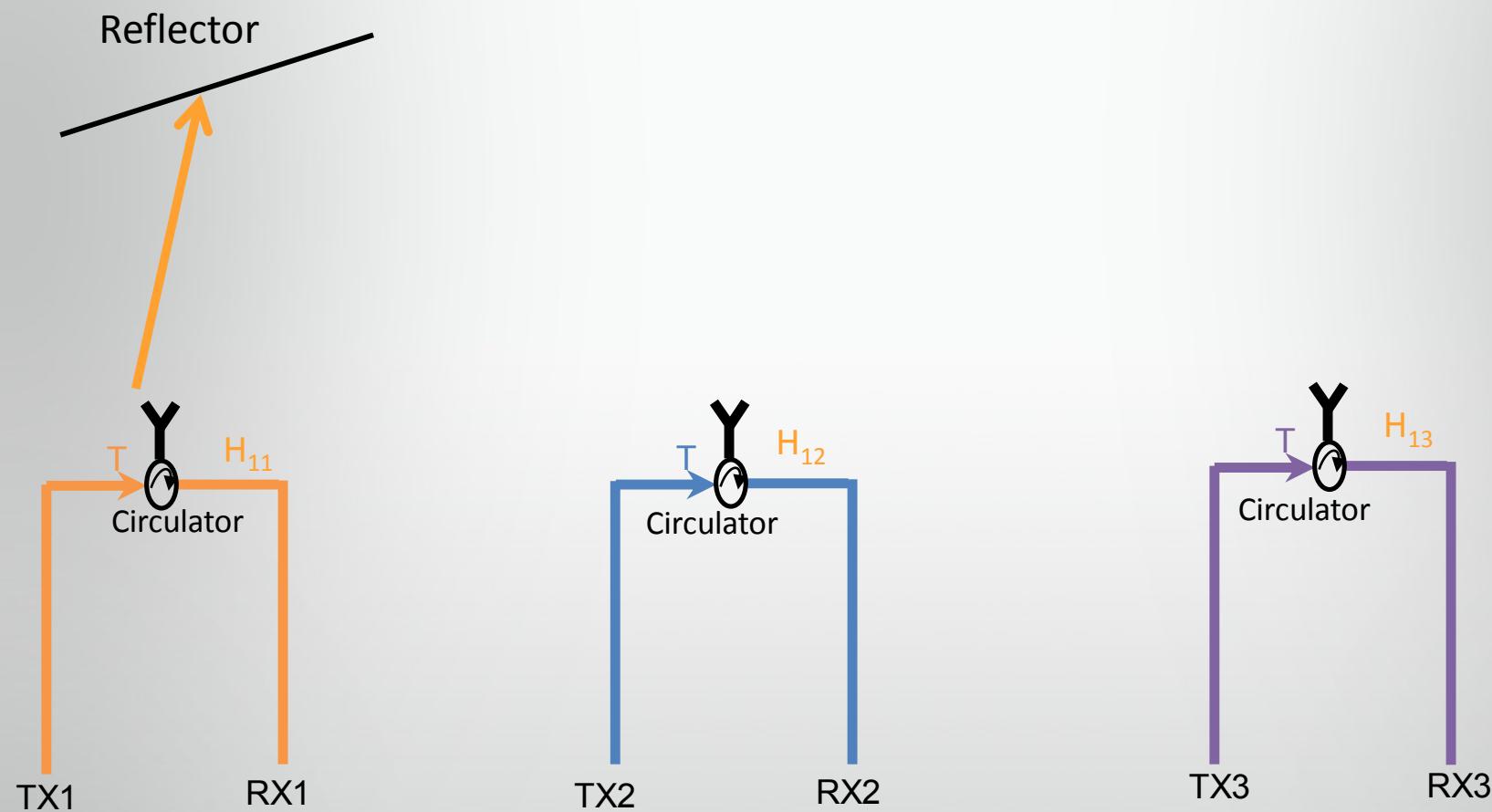
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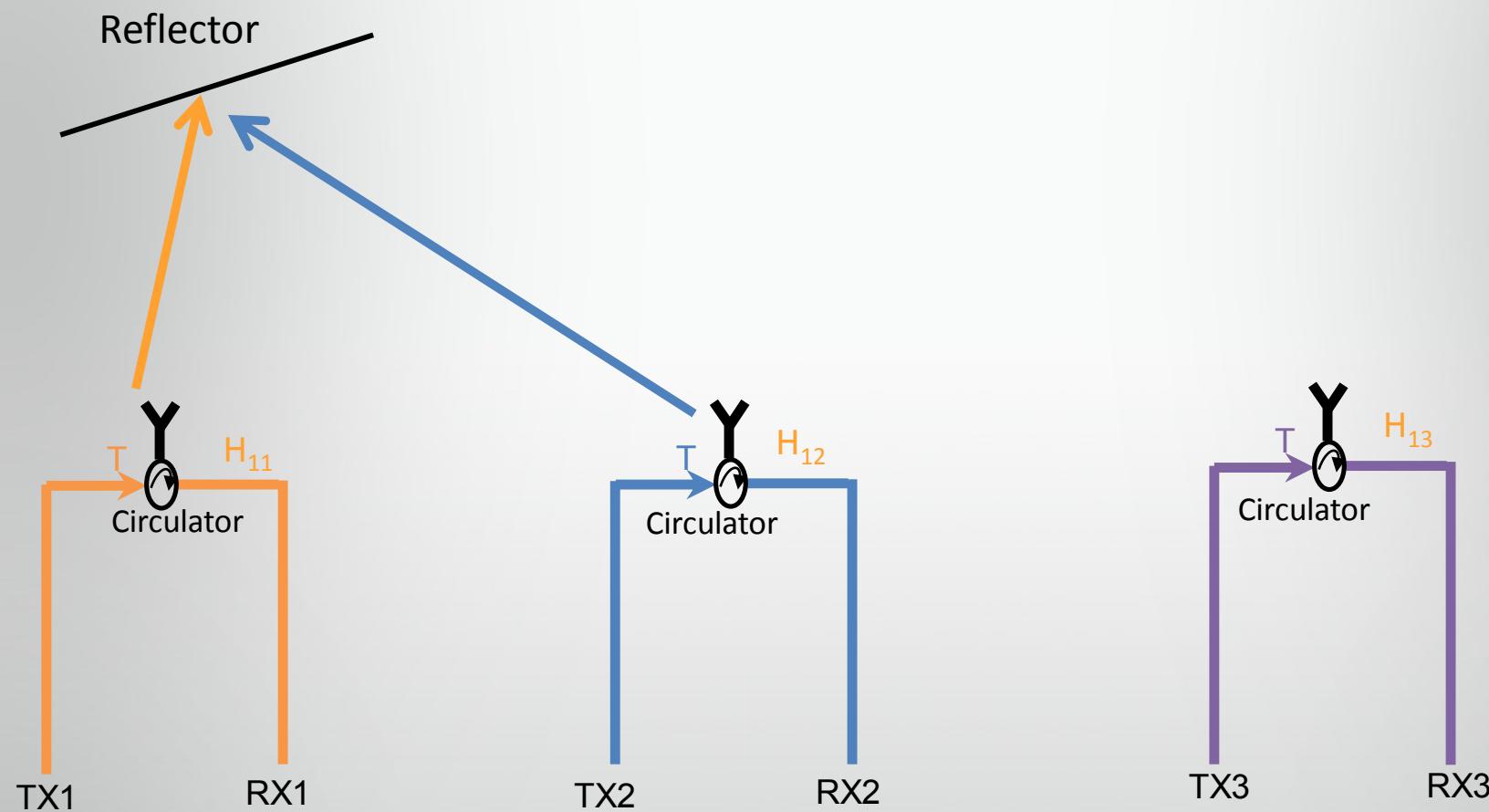
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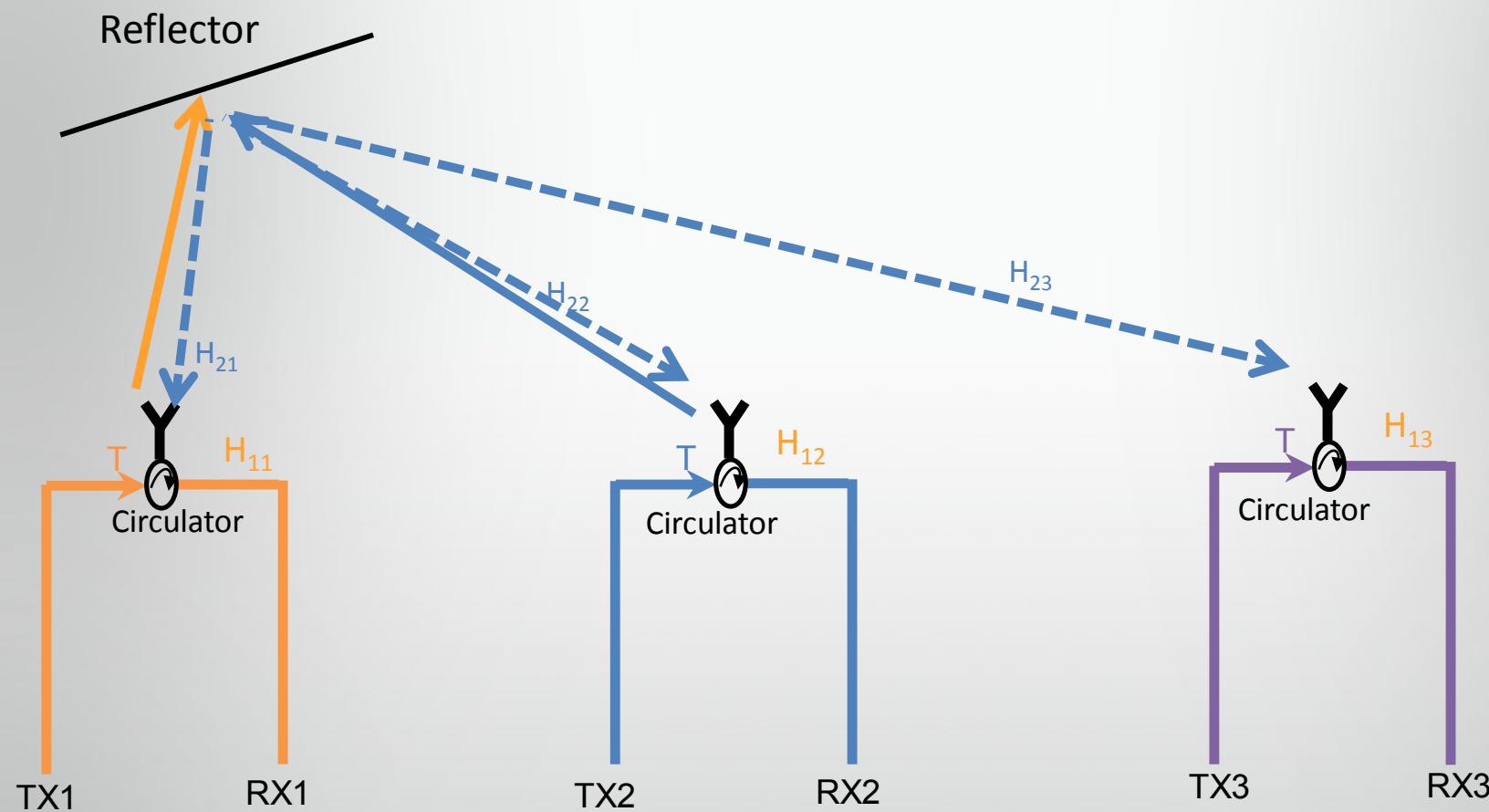
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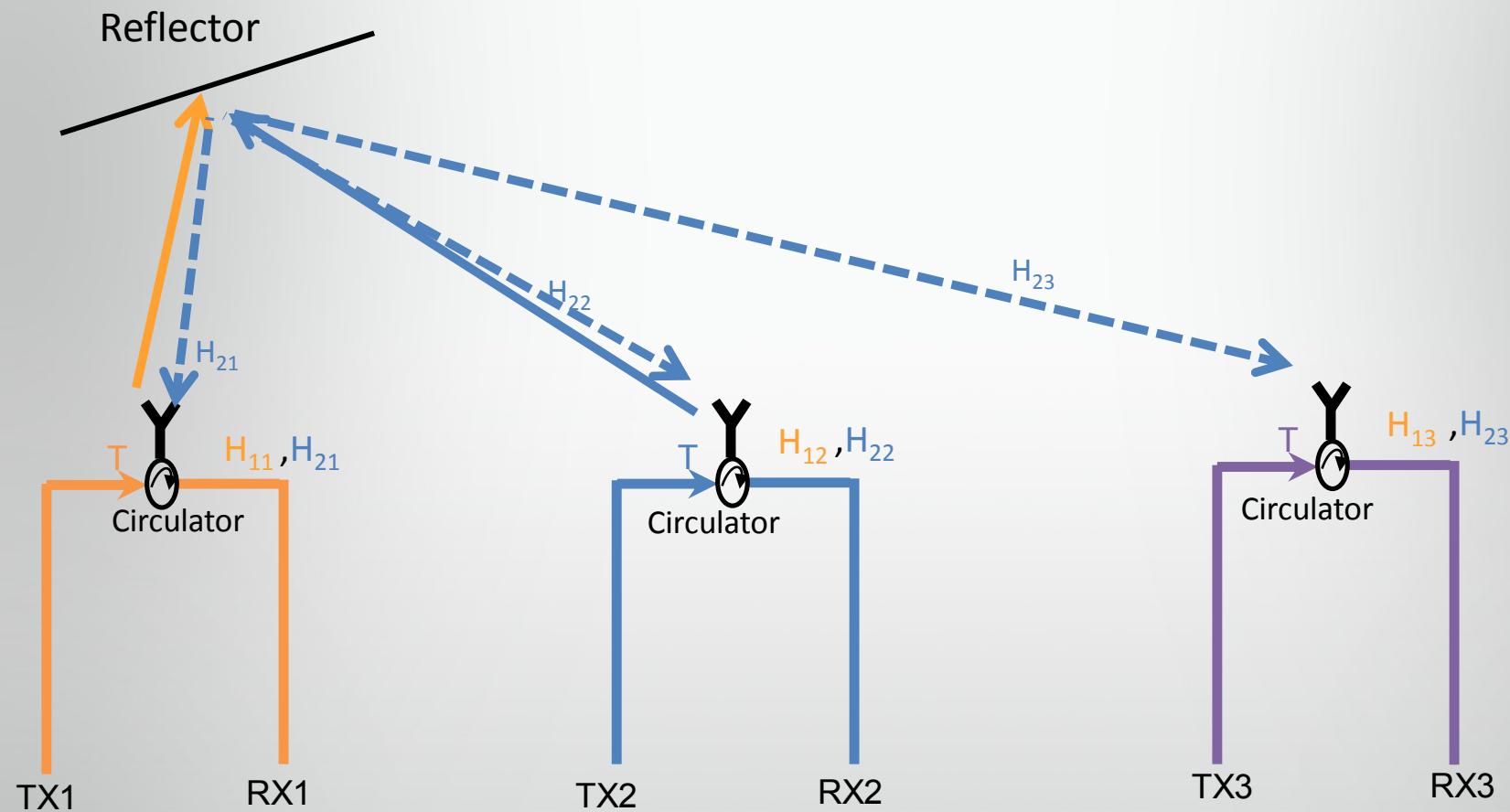
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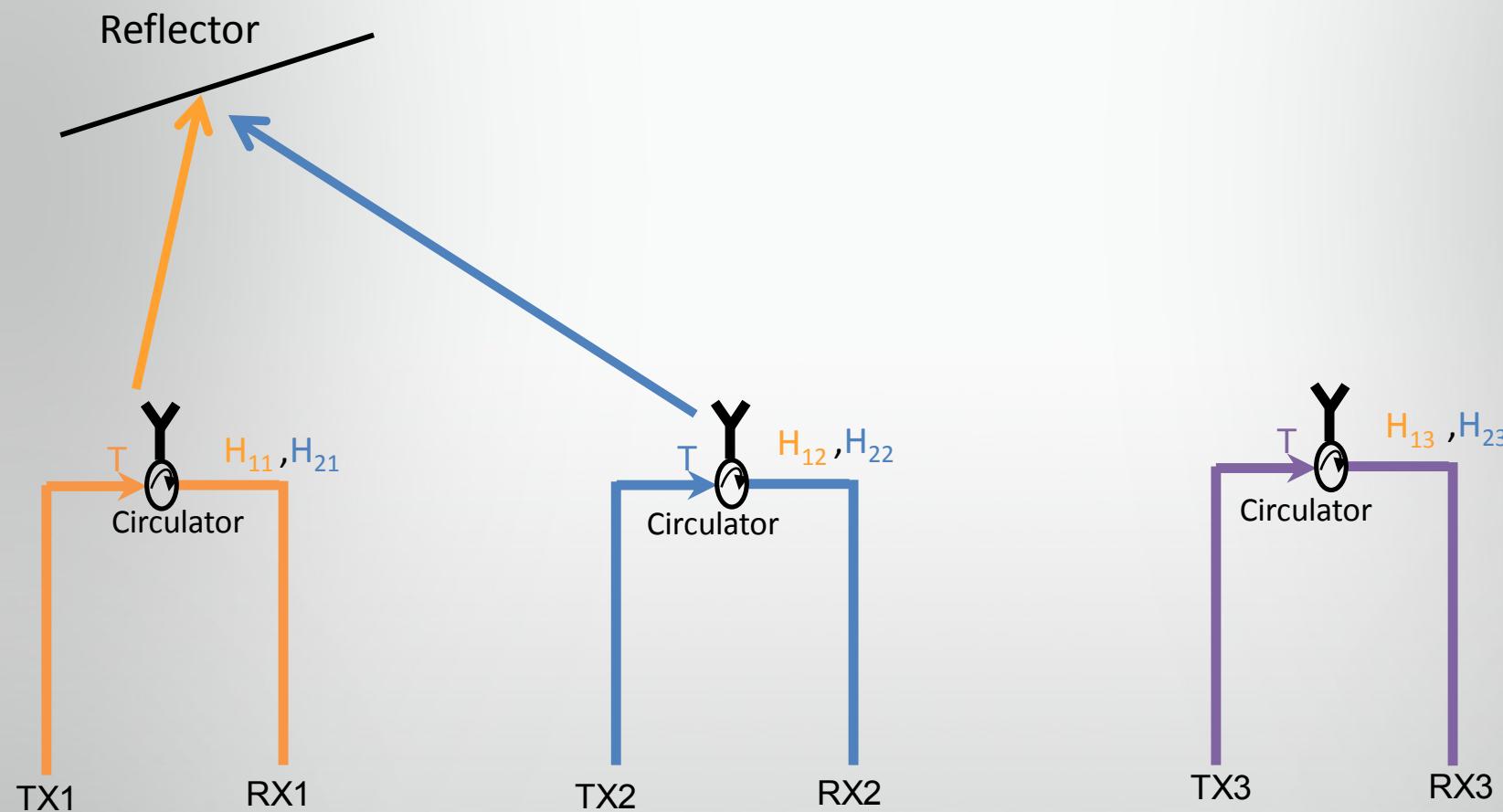
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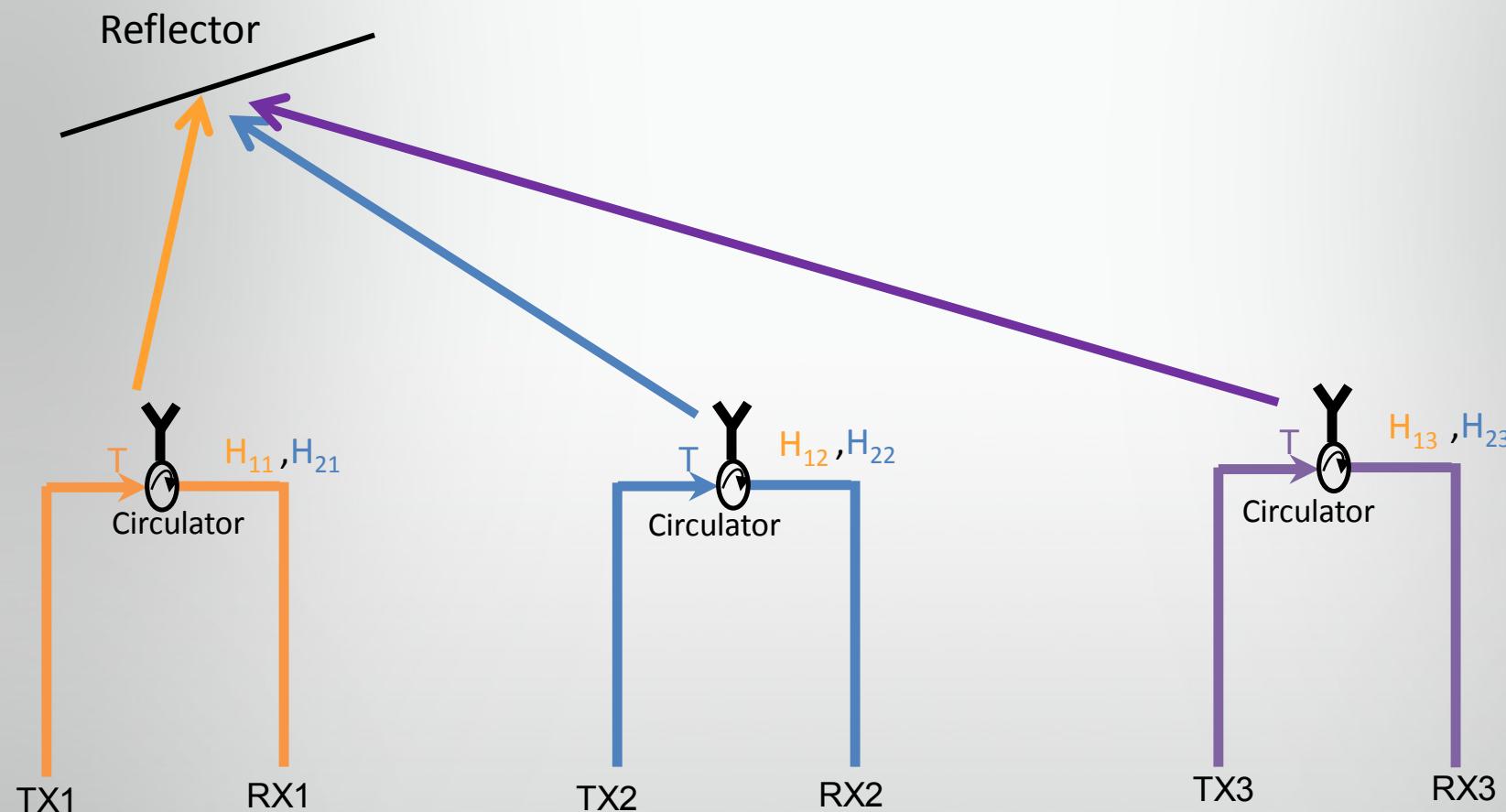
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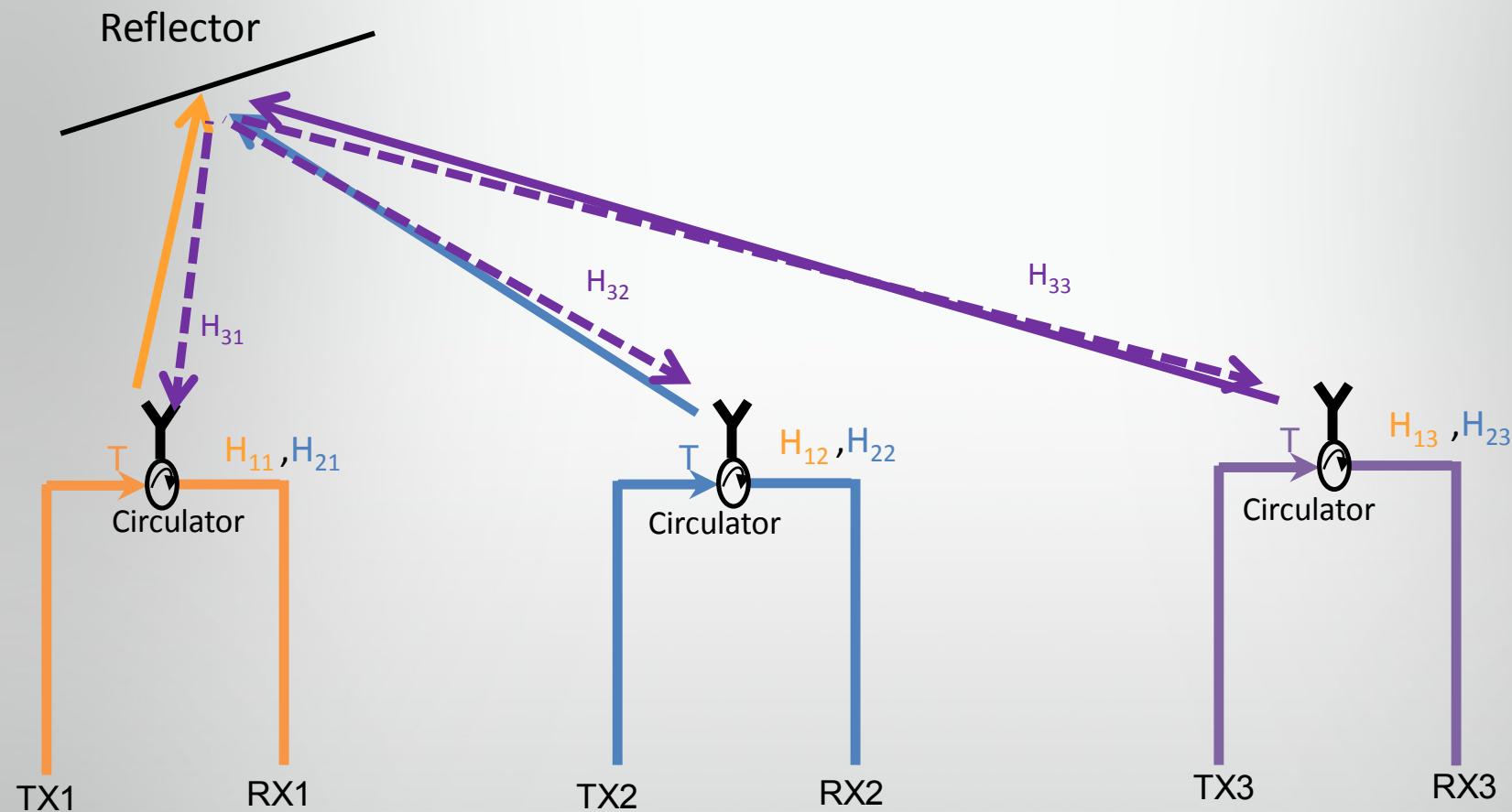
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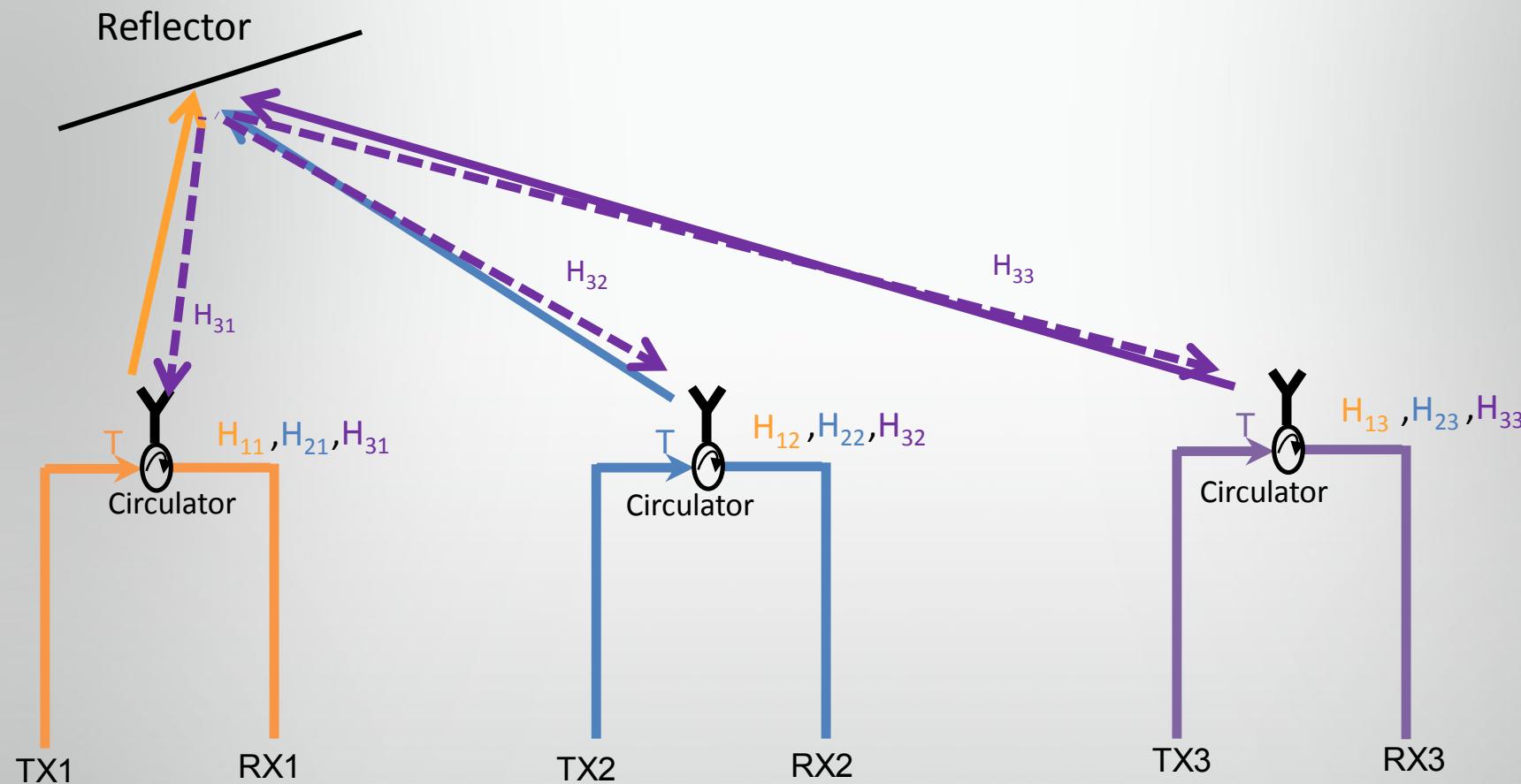
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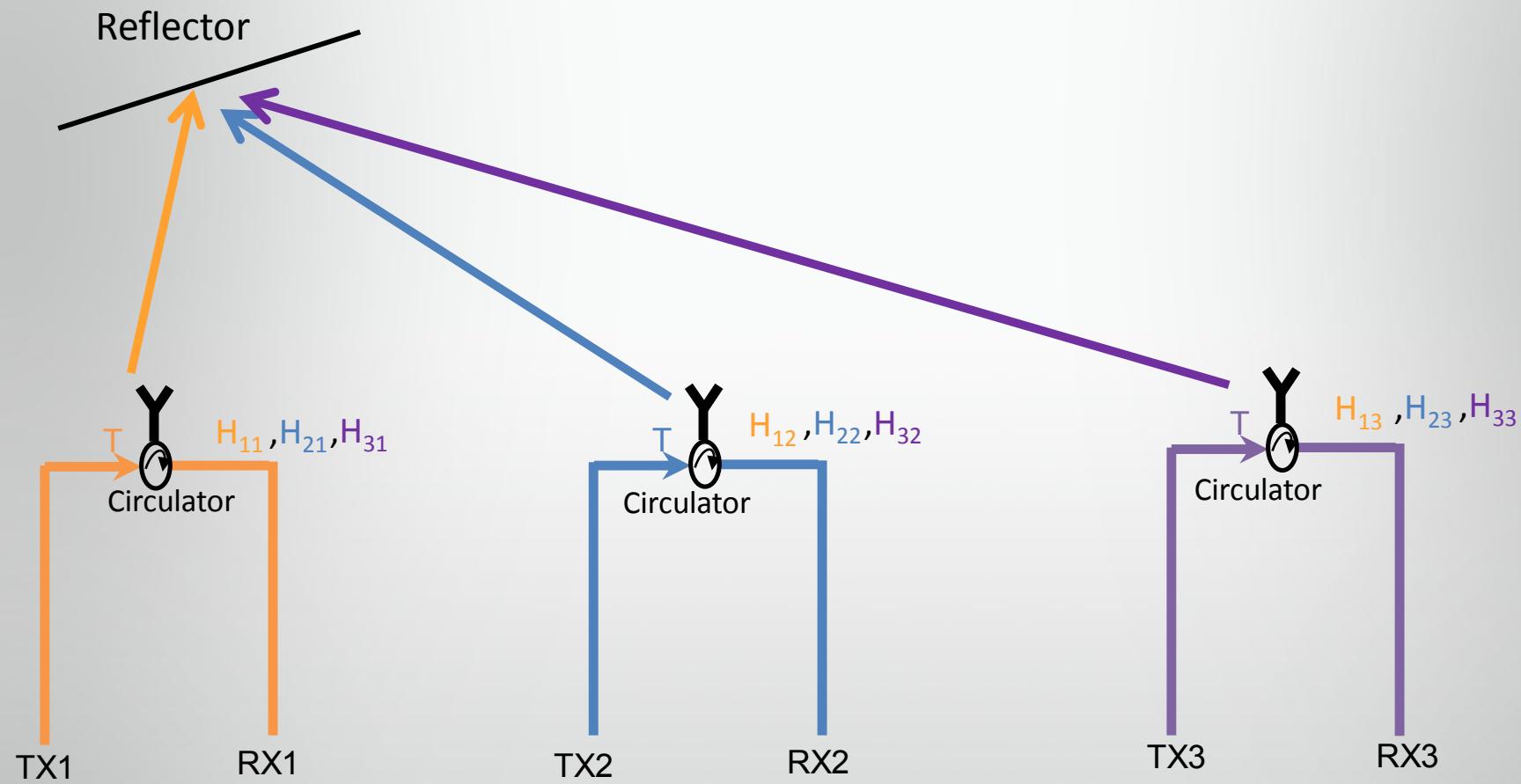
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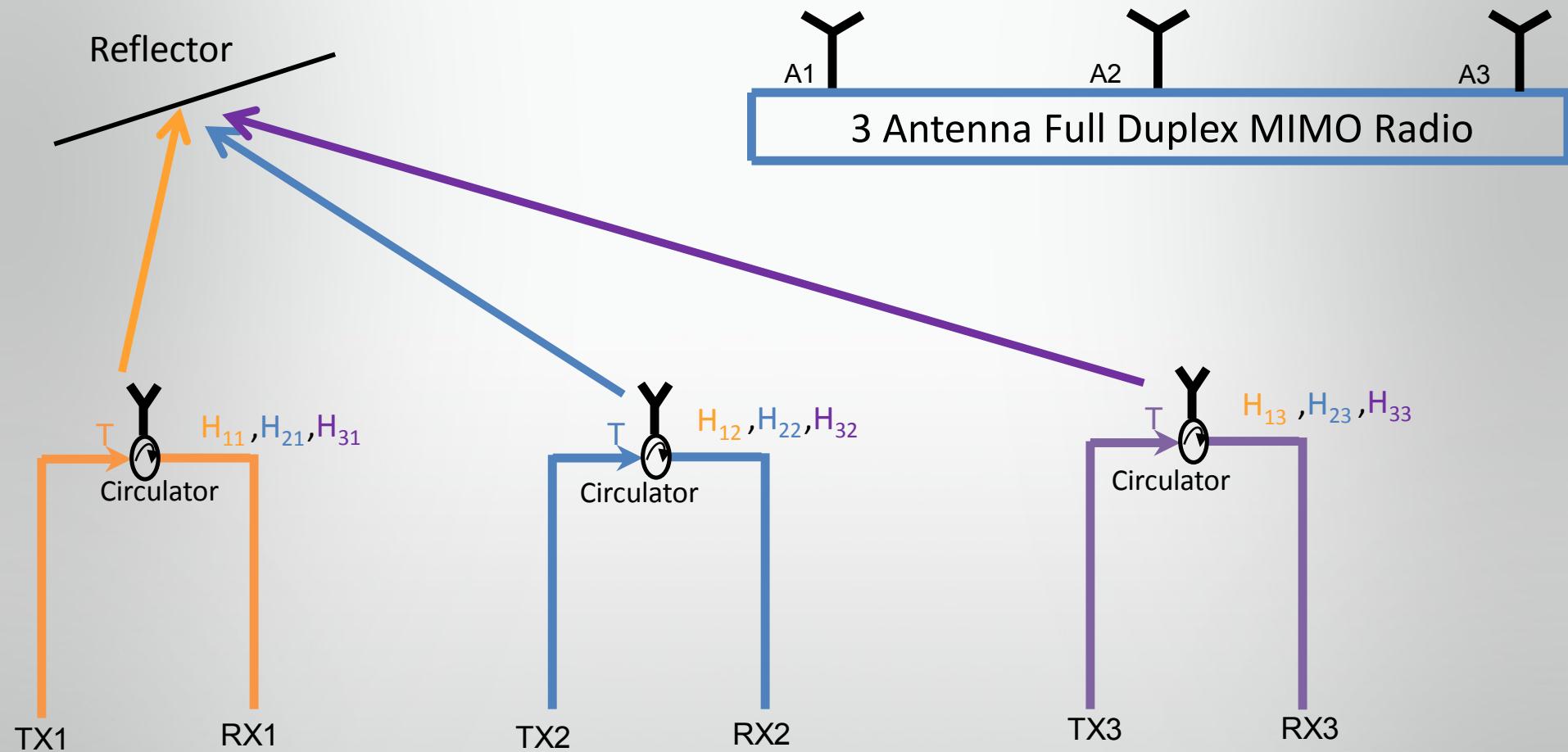
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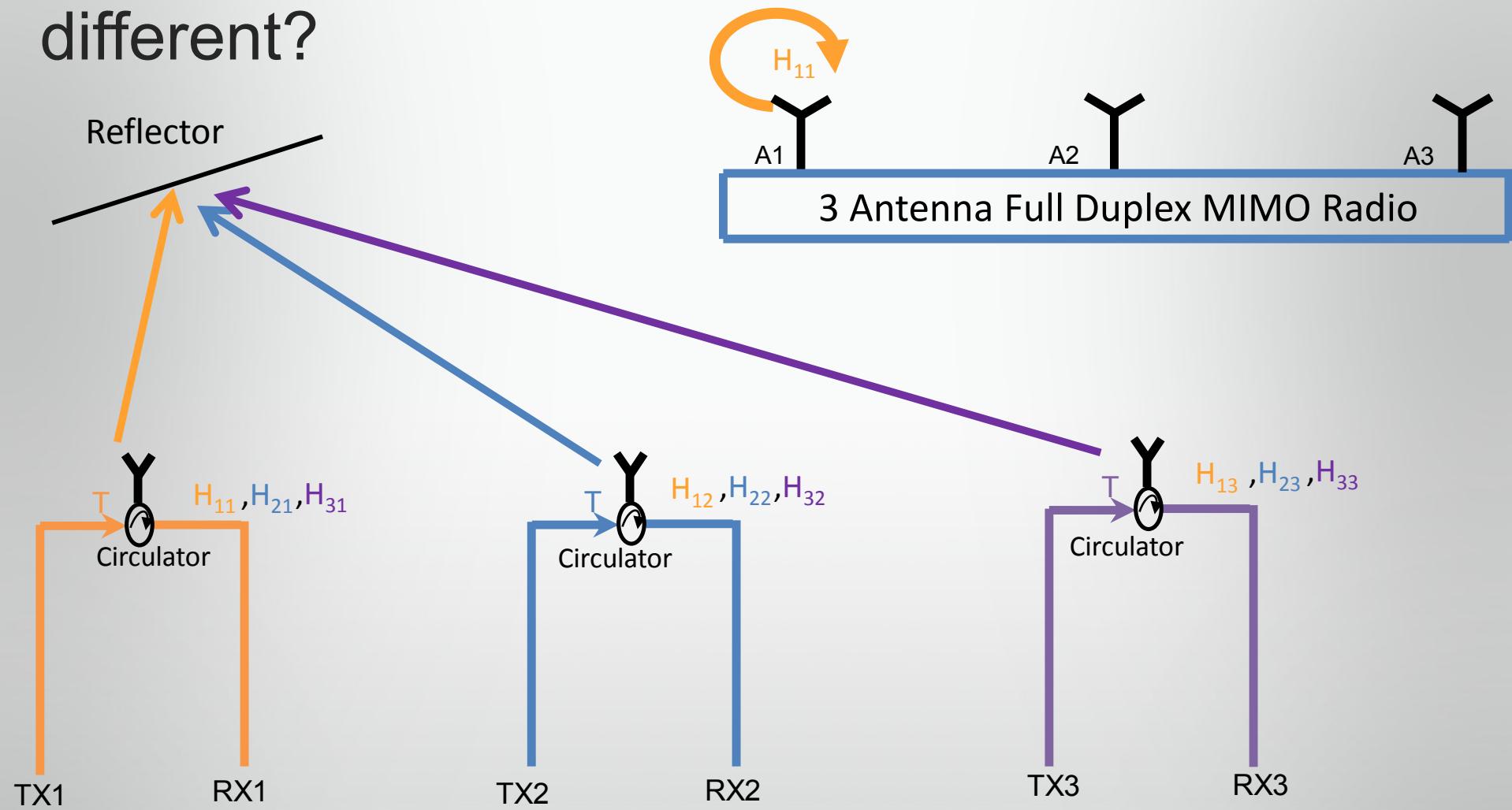
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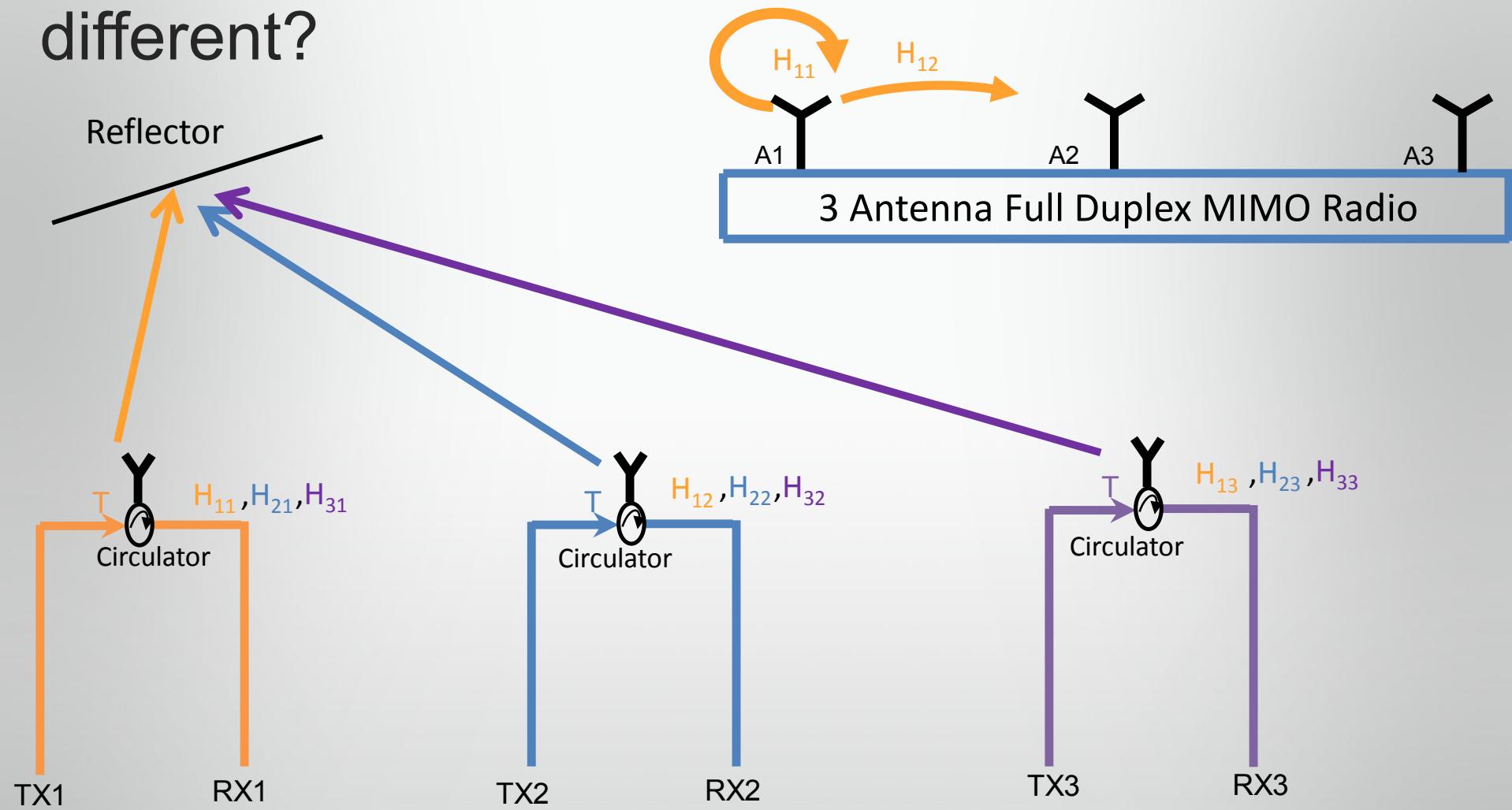
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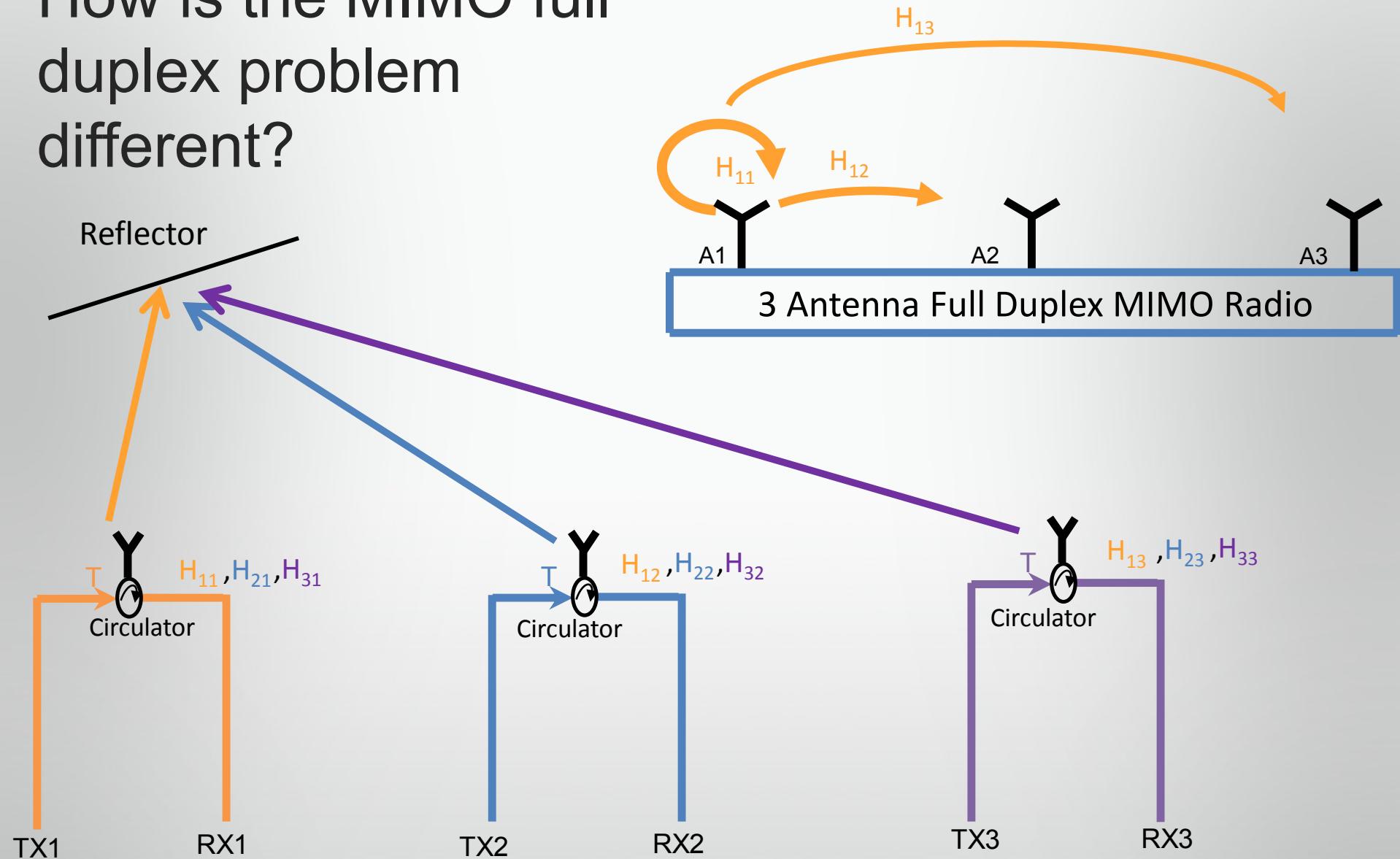
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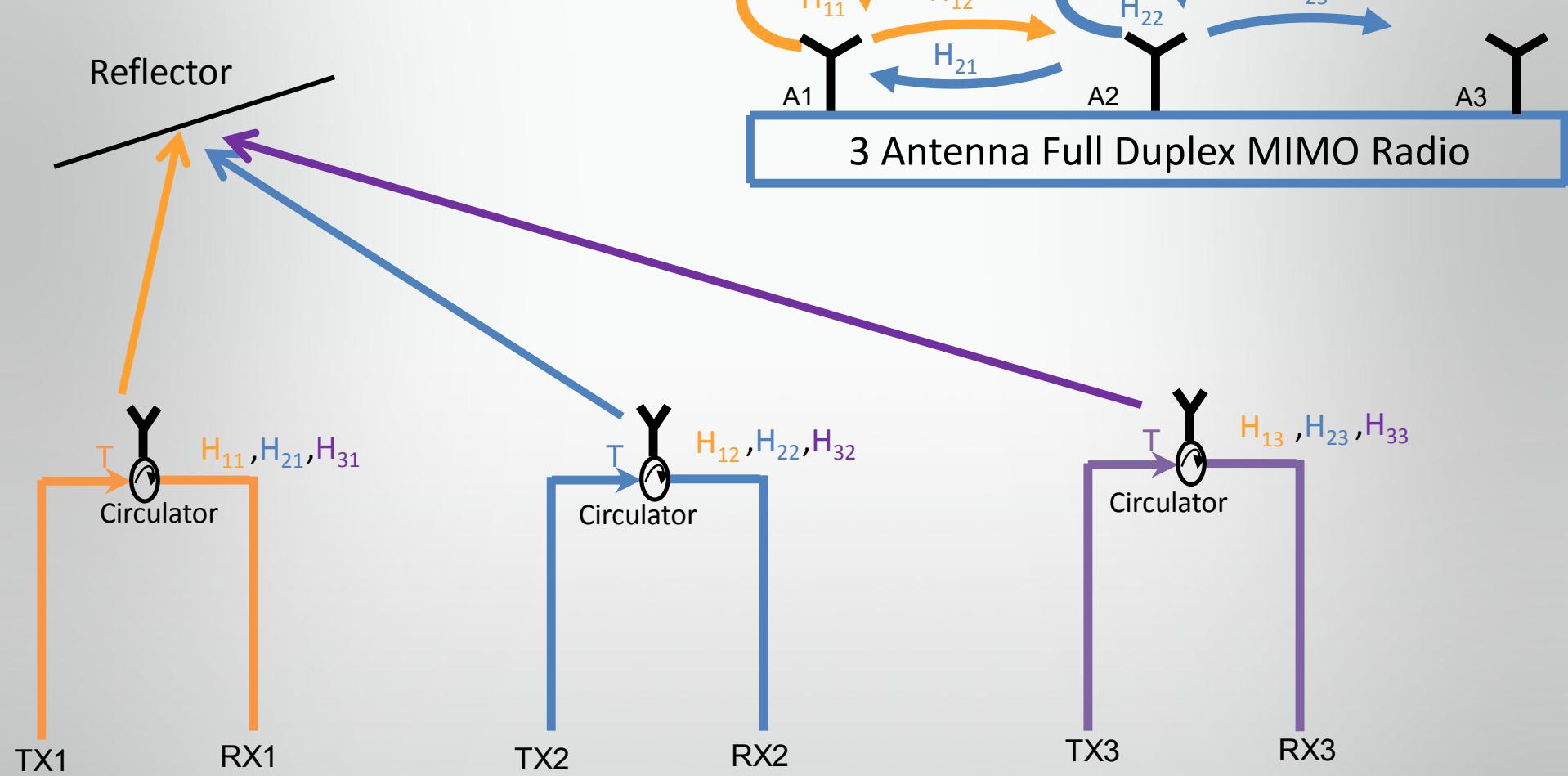
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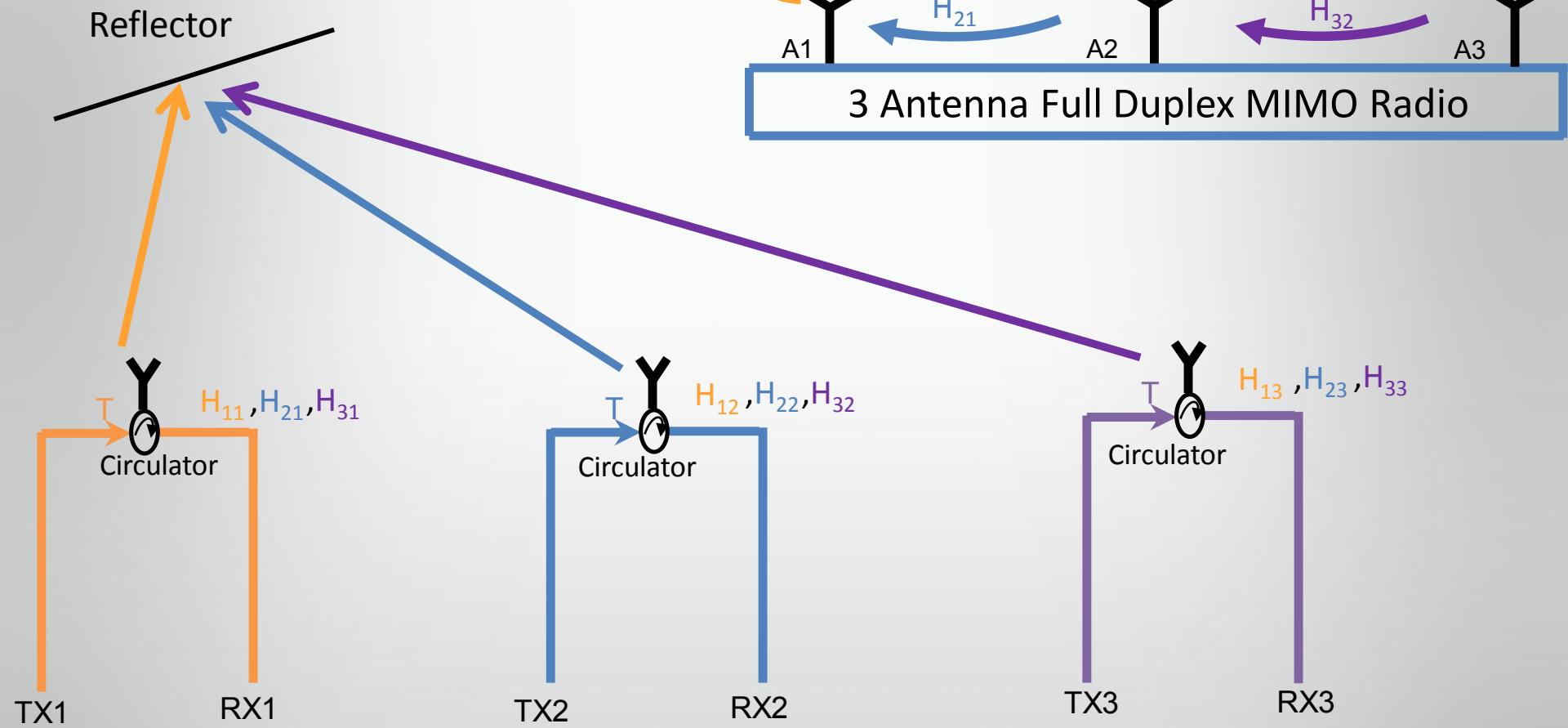
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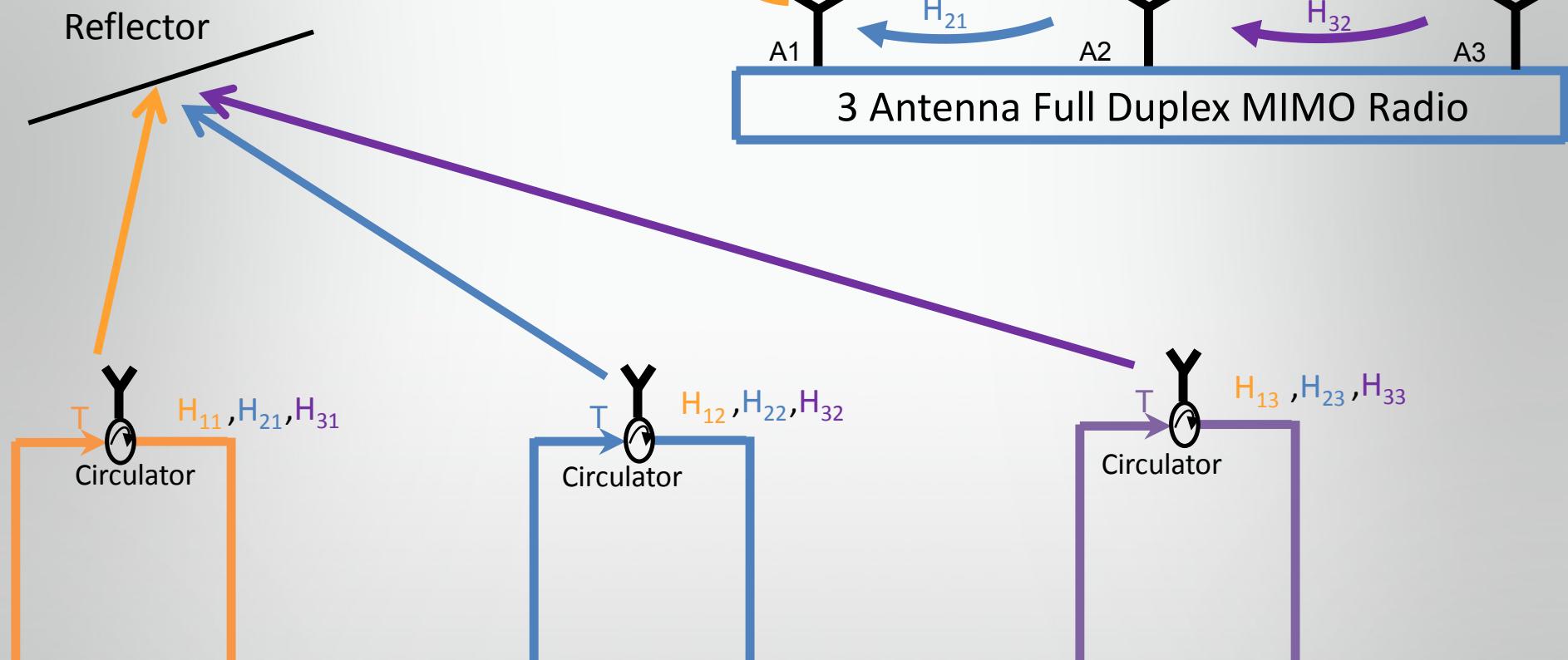
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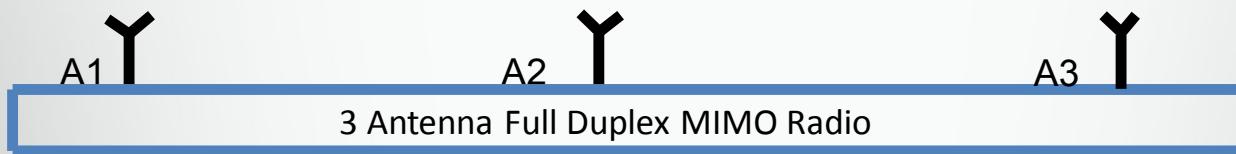
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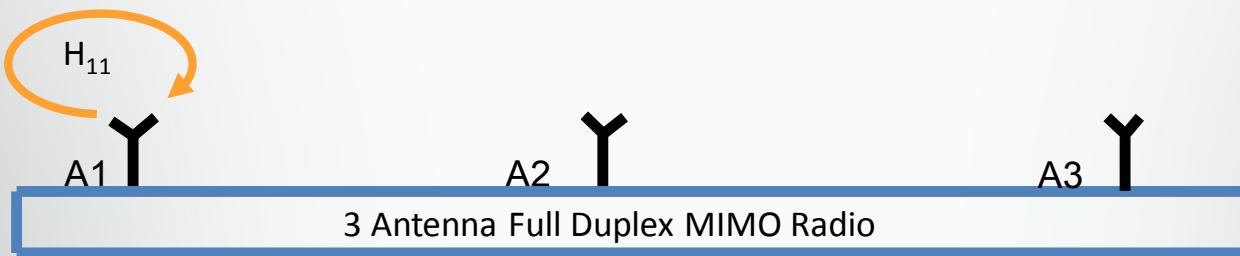
MIMO full duplex has quadratically more number of signals to cancel because of the presence of cross talk.

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

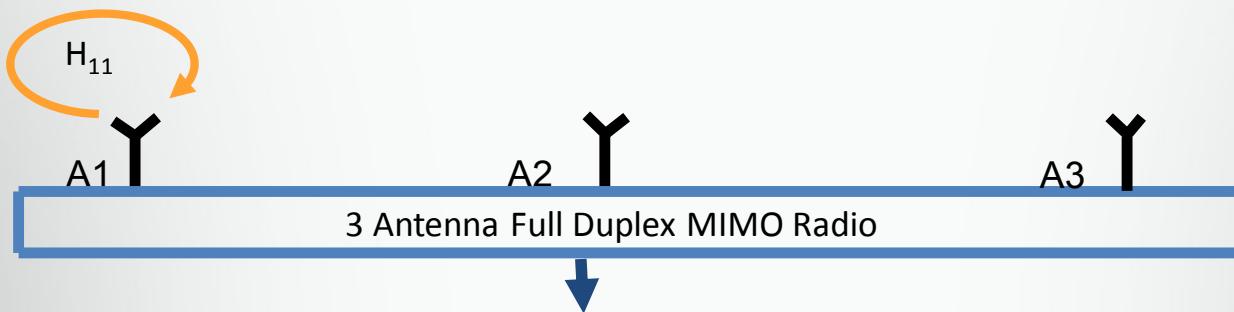
Naïve Solution: Replicates SISO design



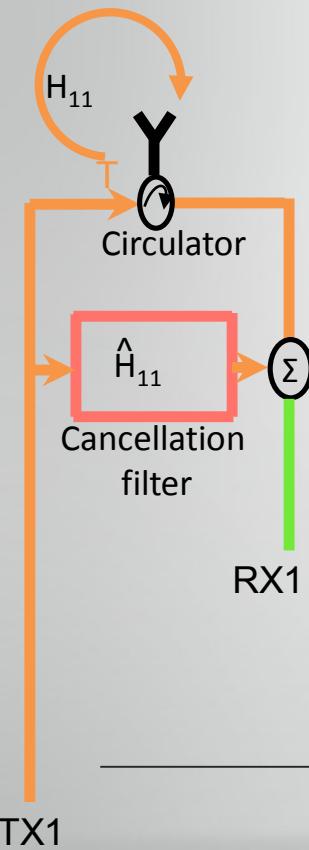
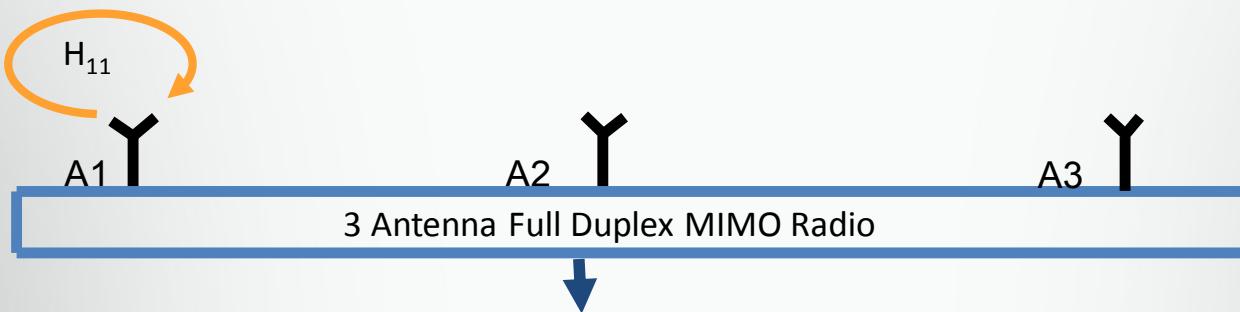
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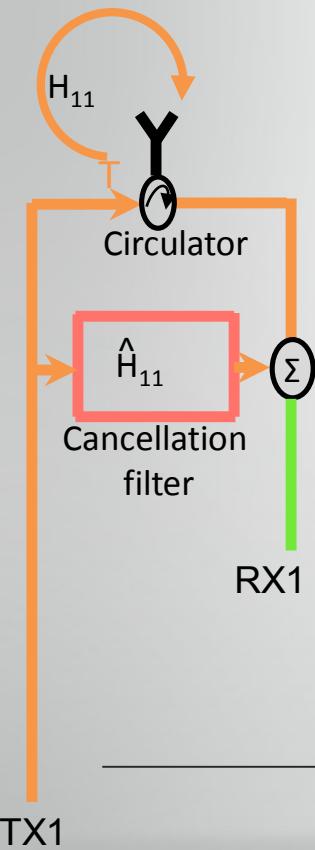
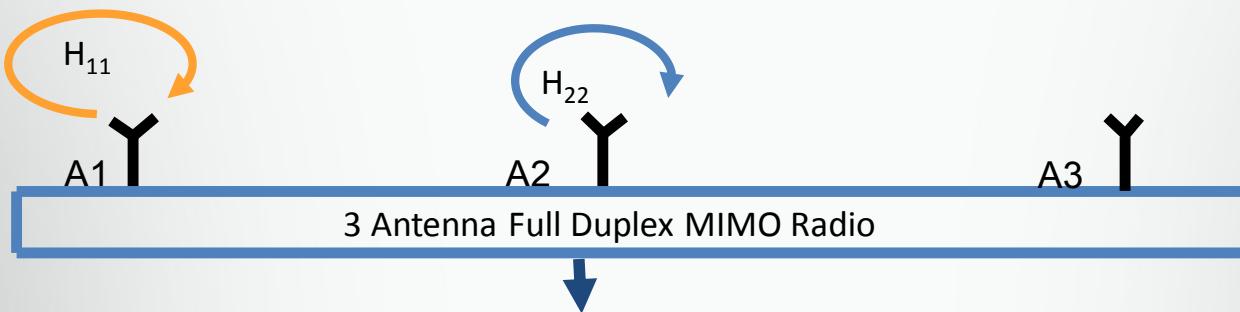
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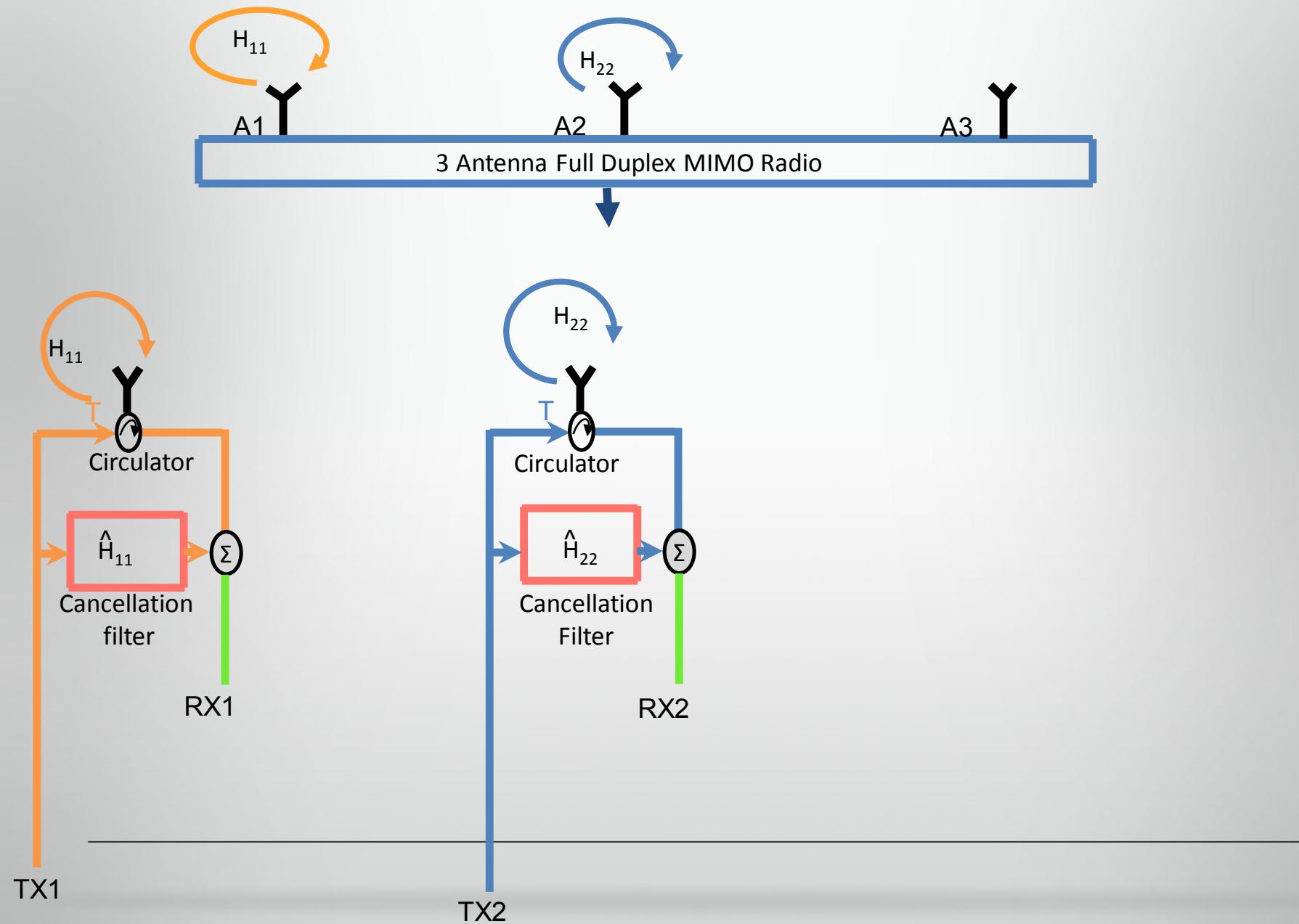
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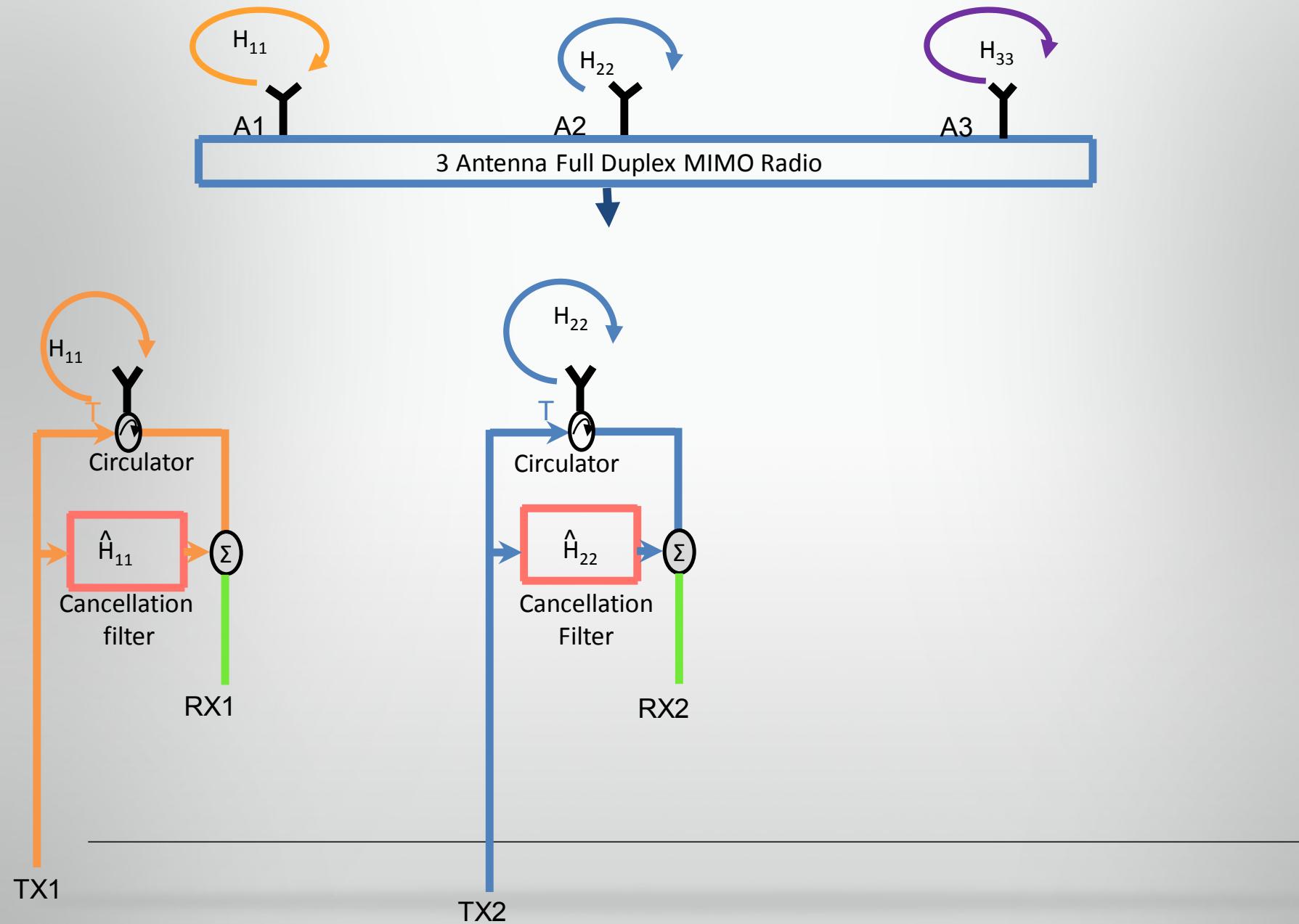
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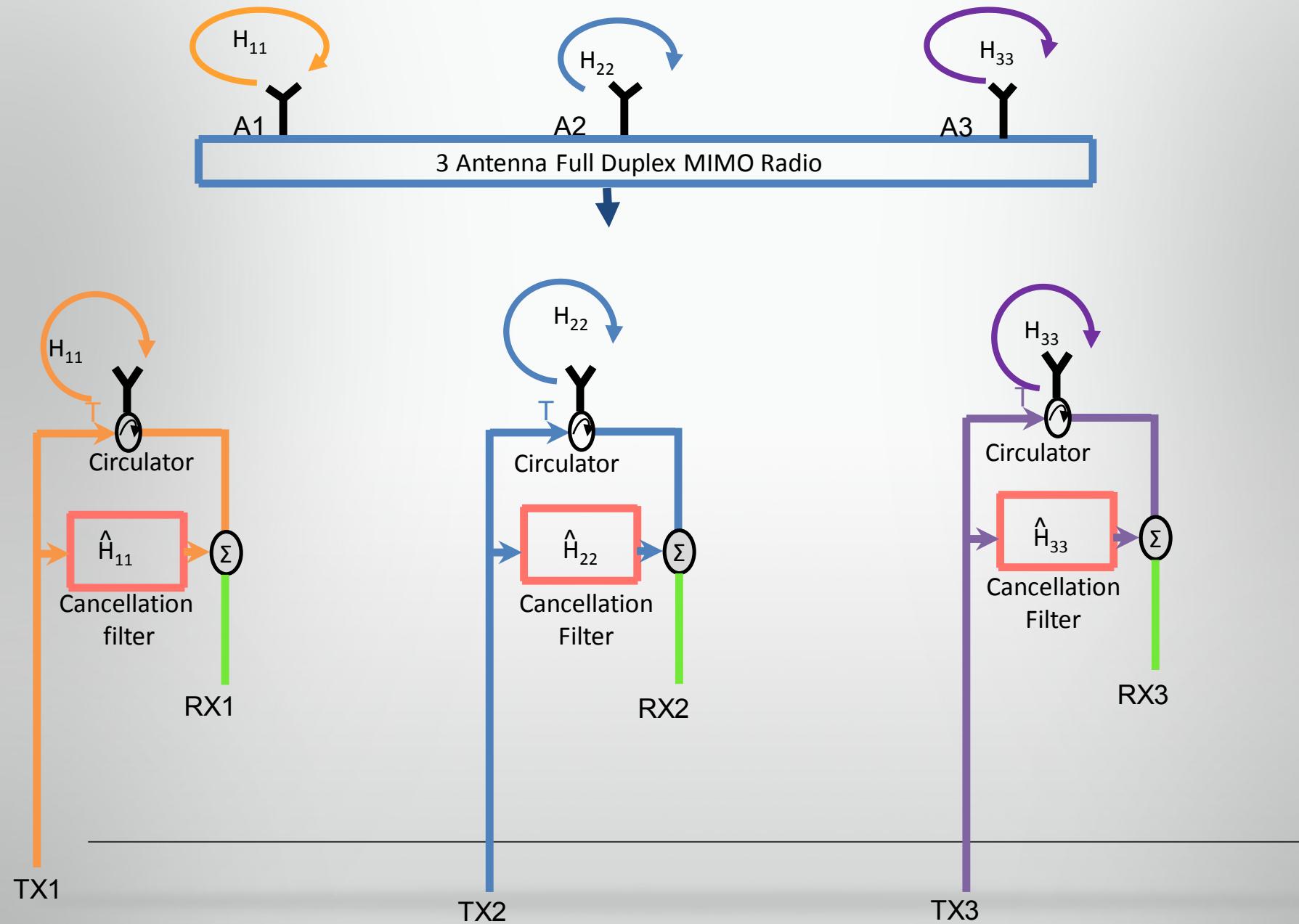
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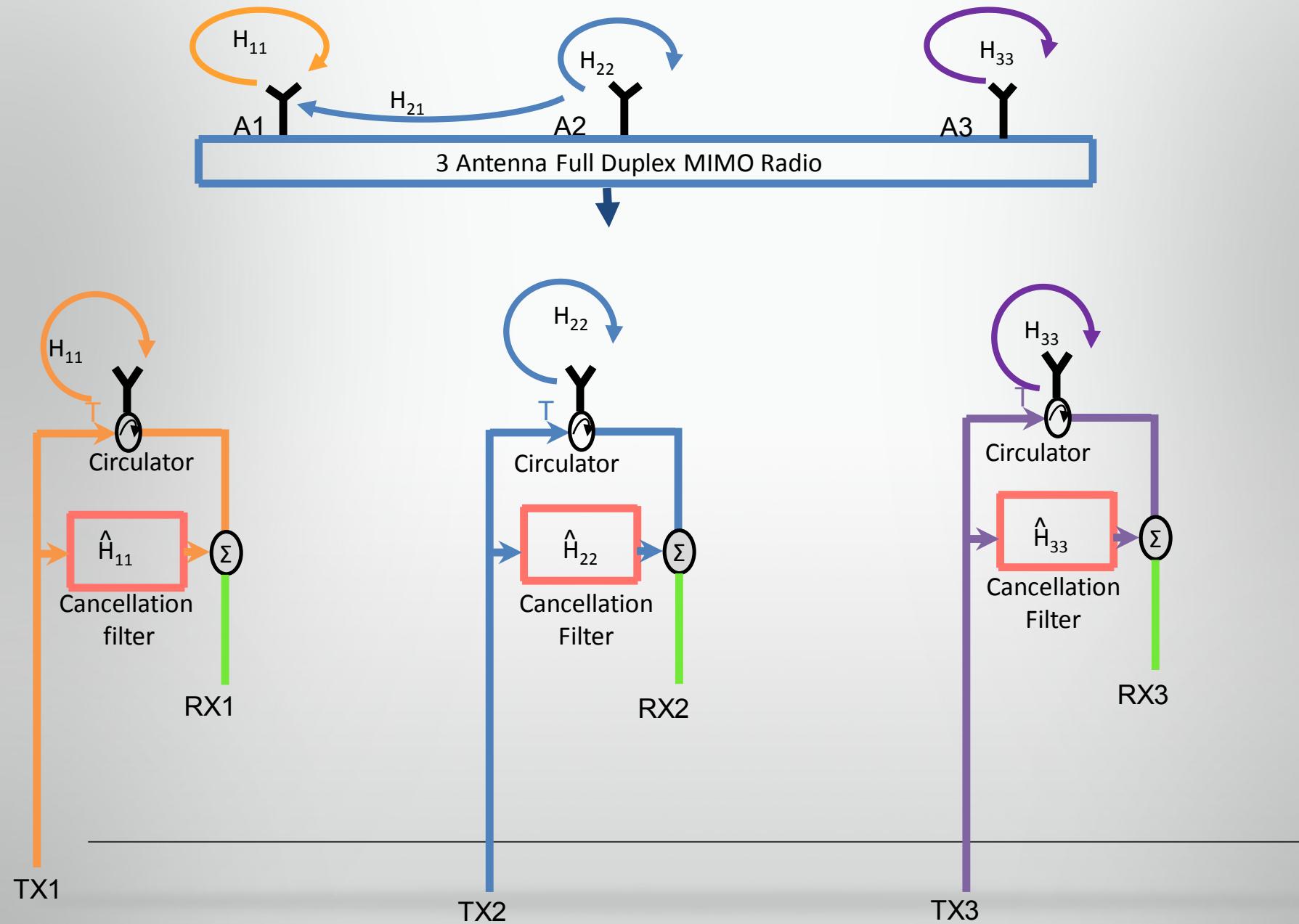
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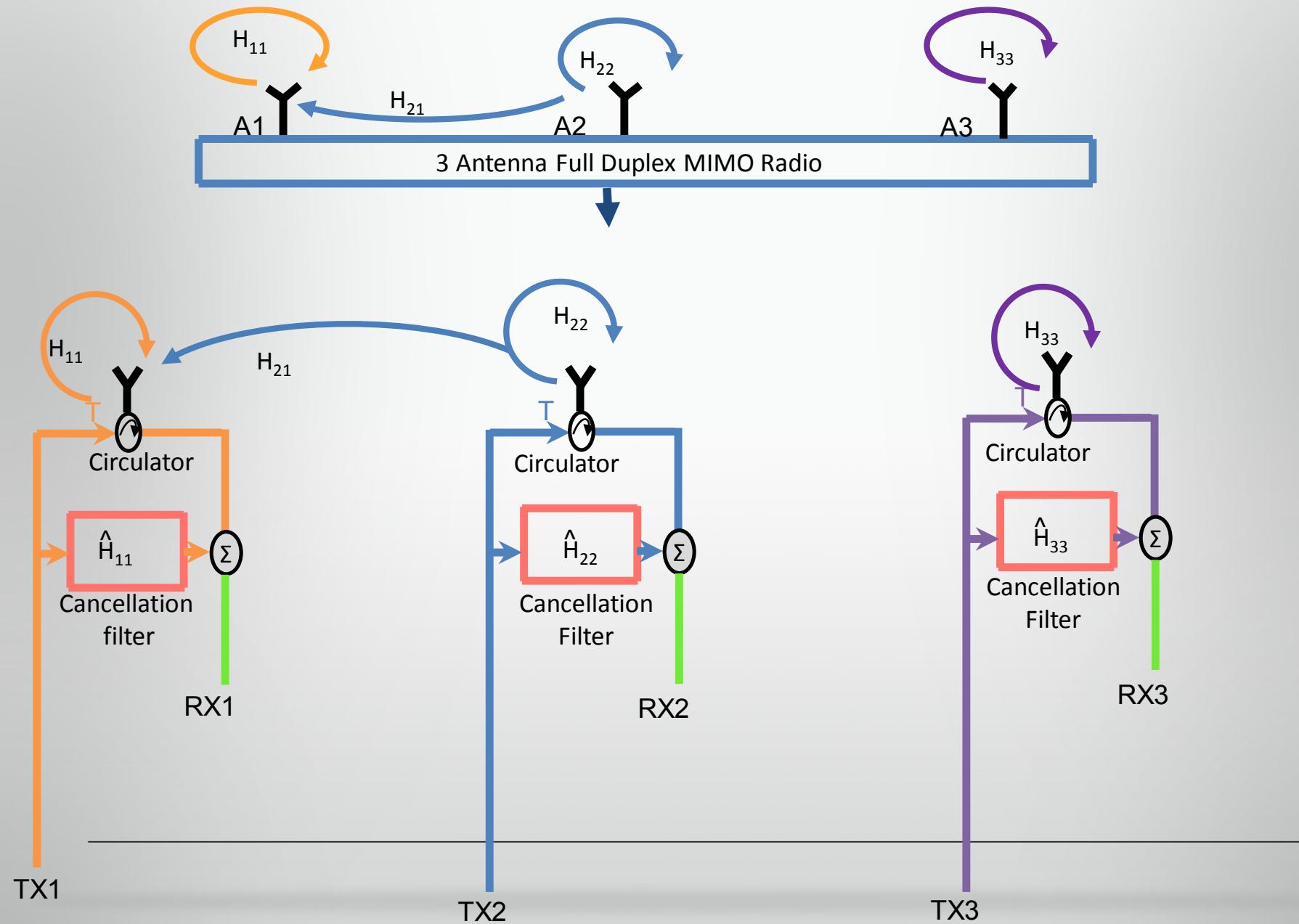
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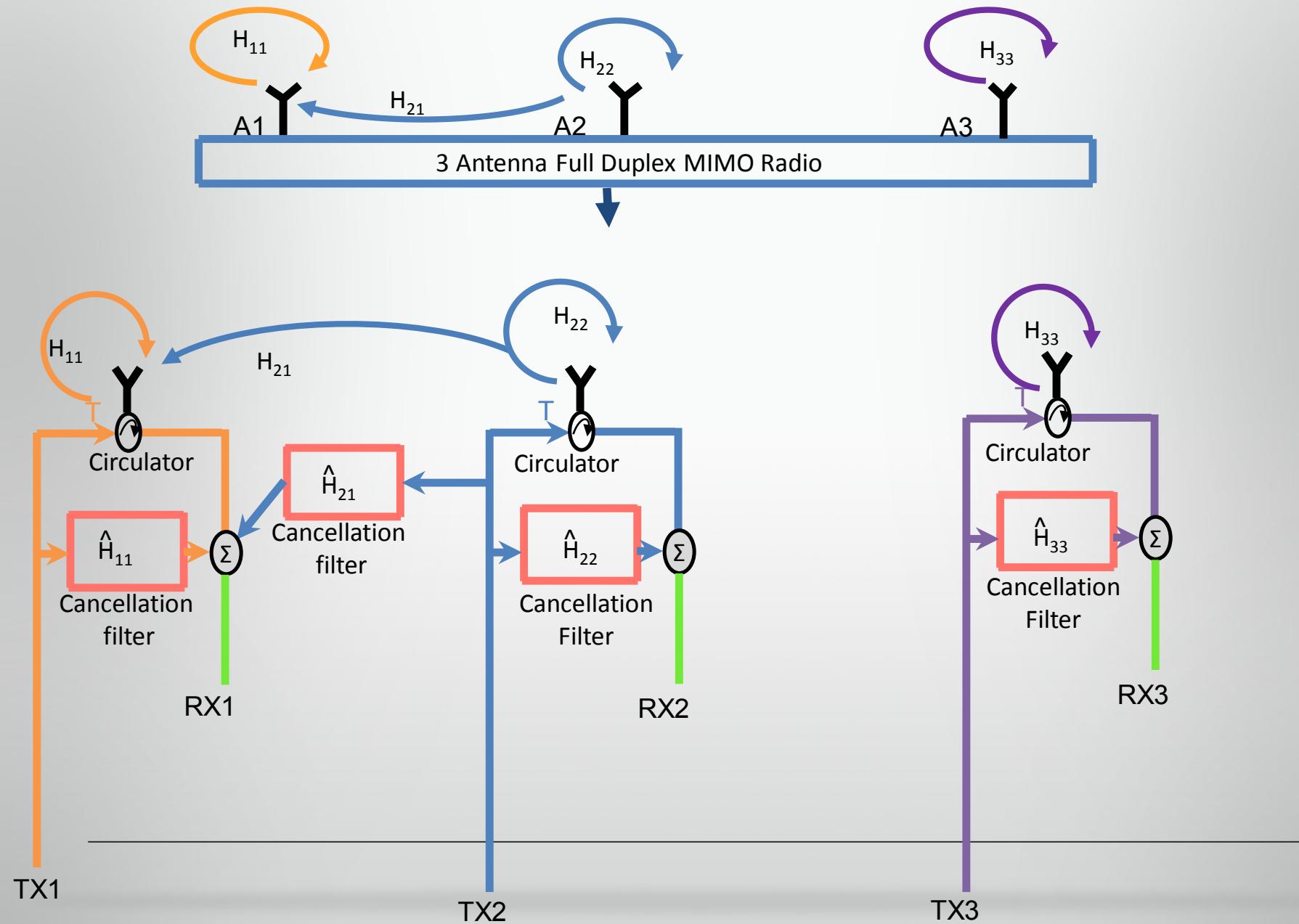
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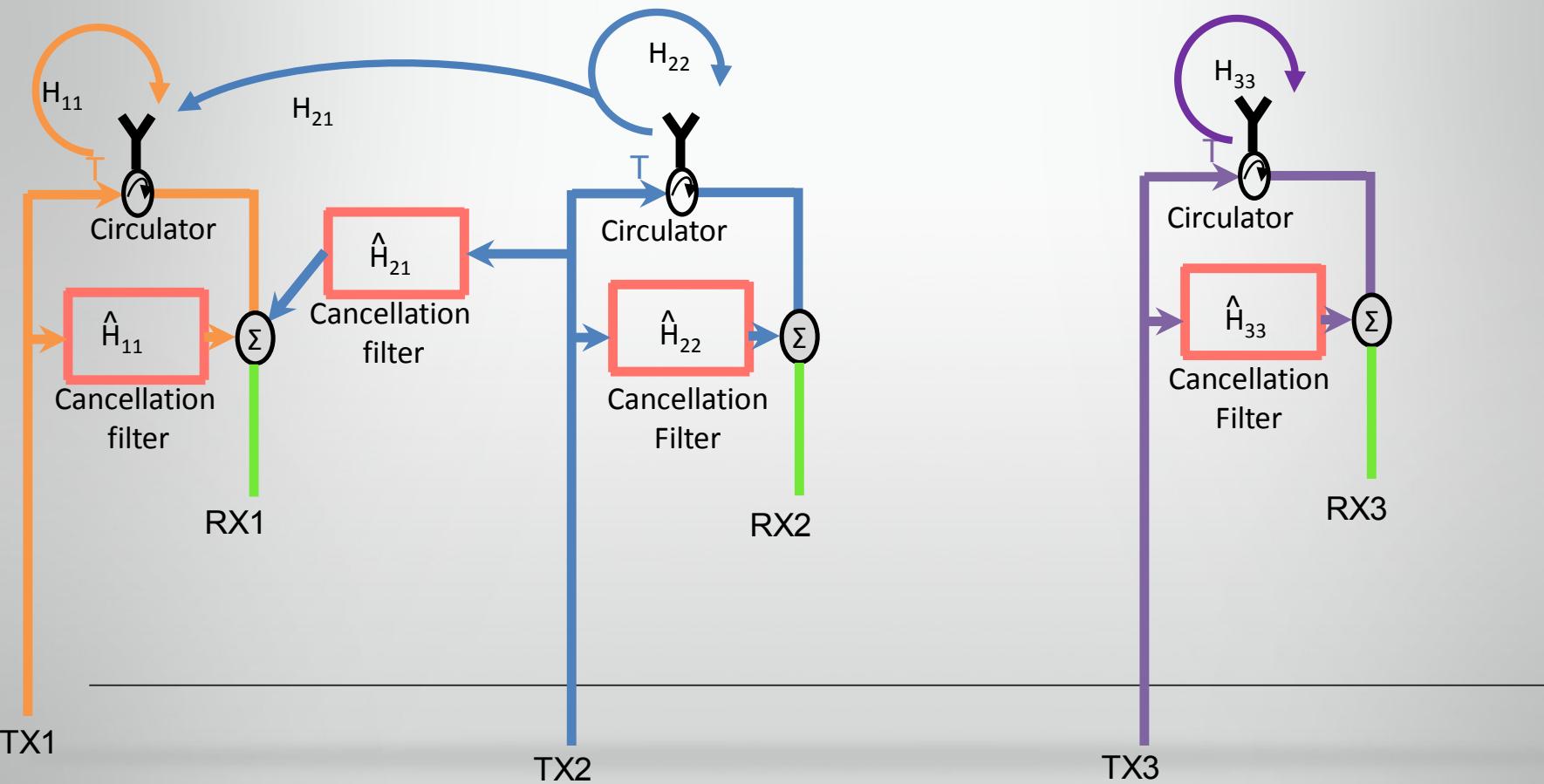
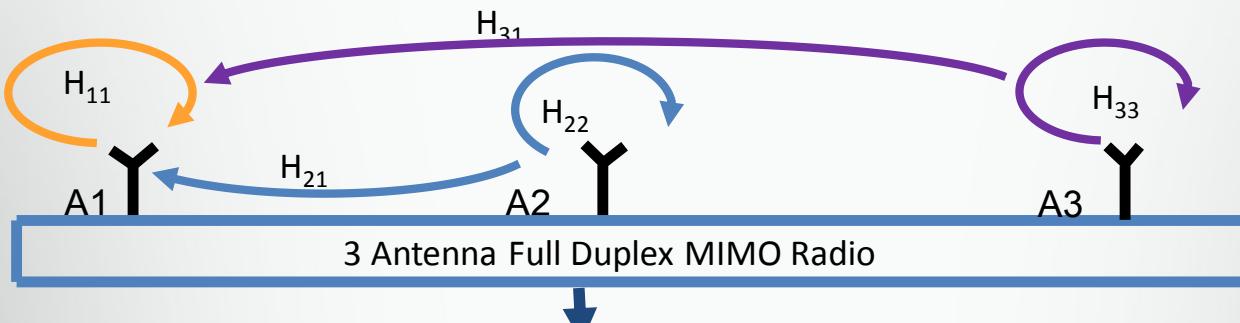
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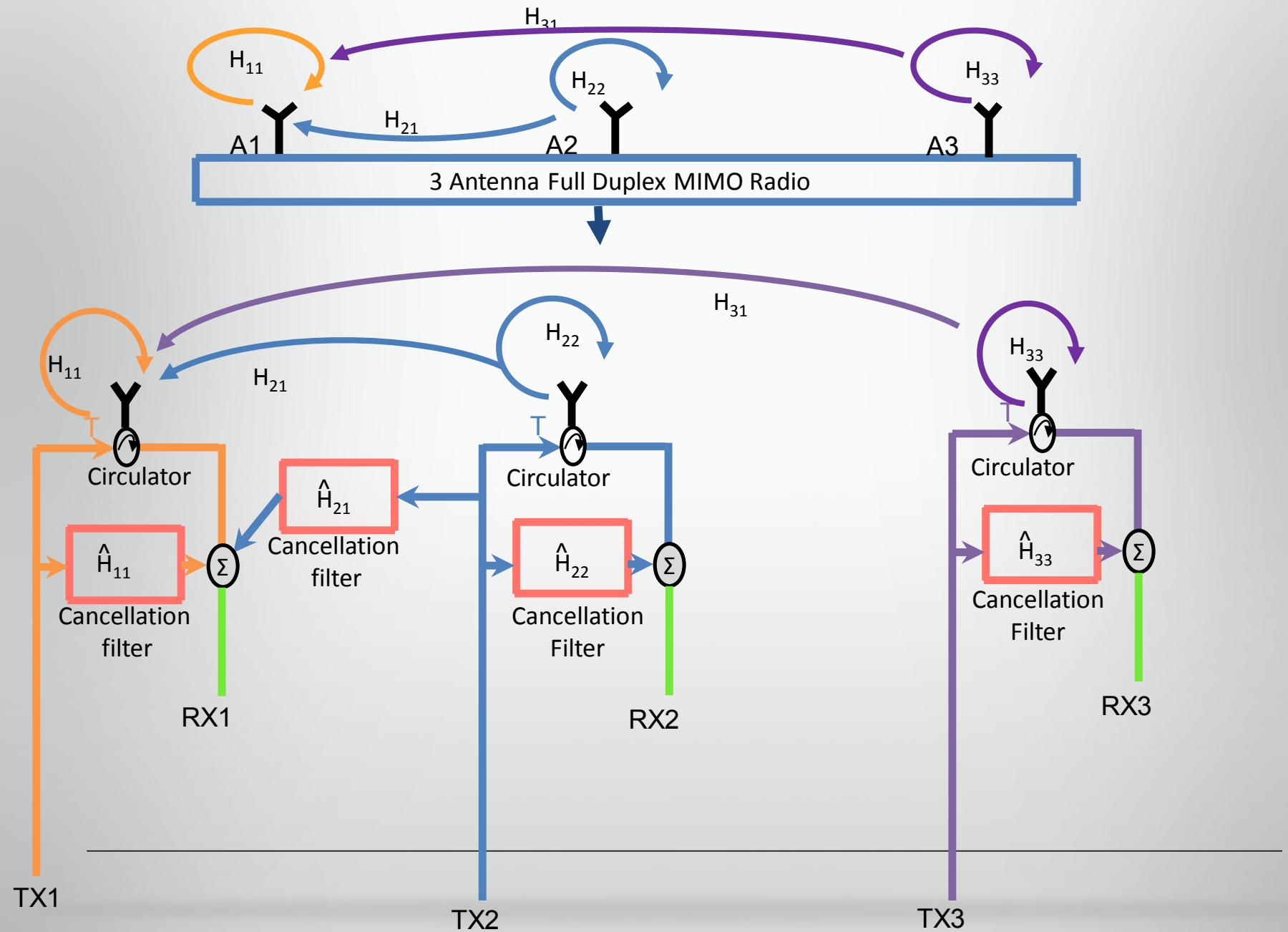
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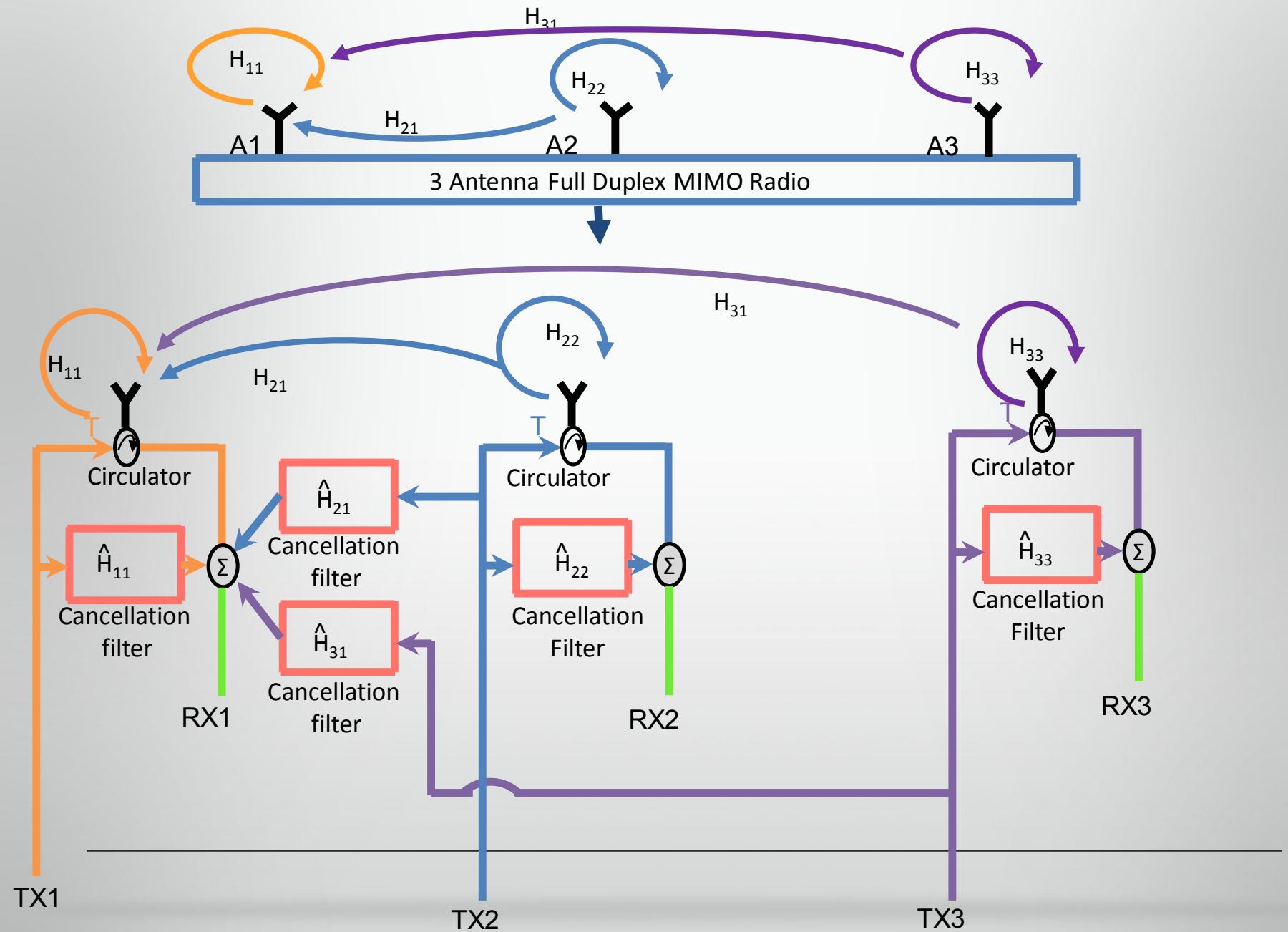
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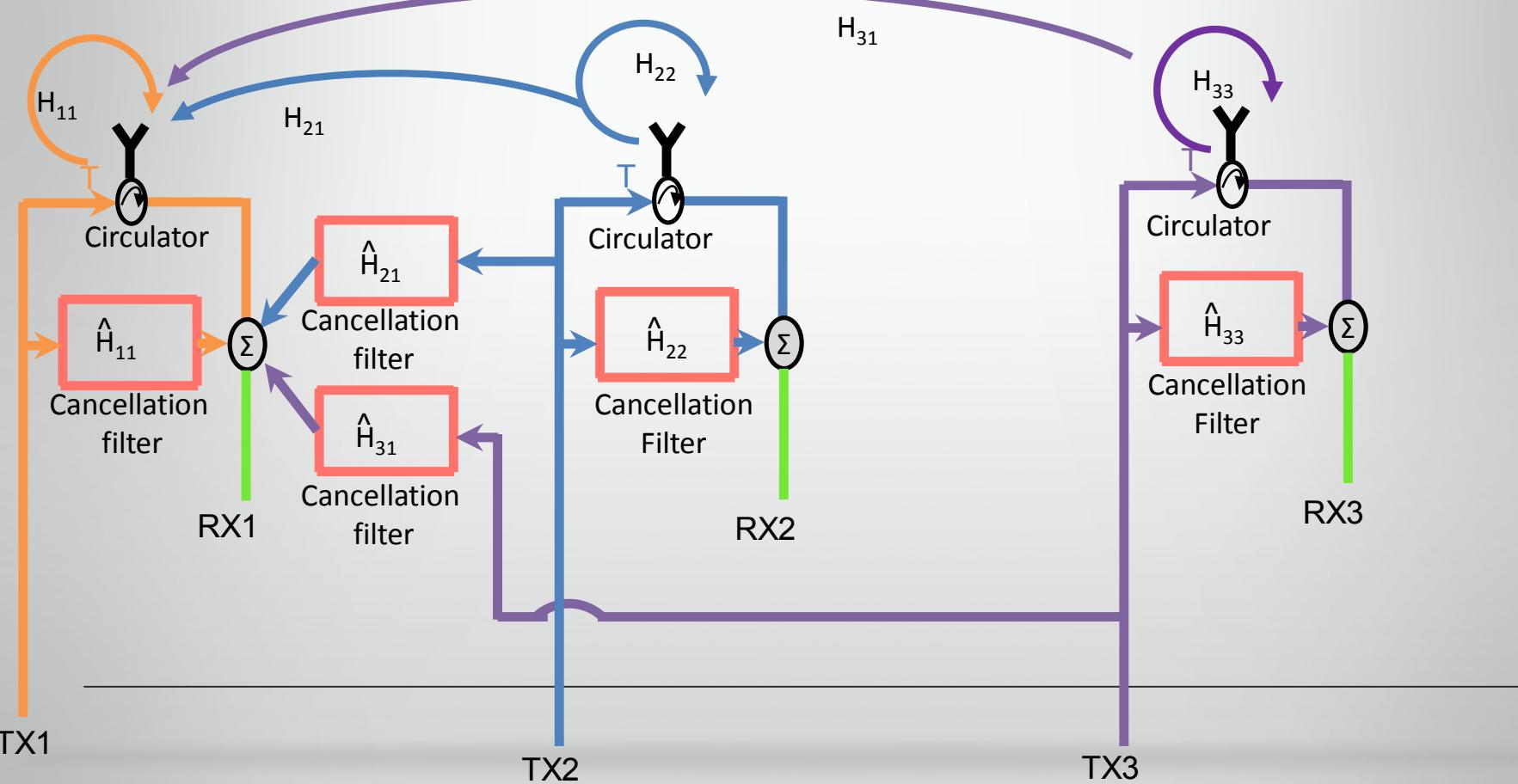
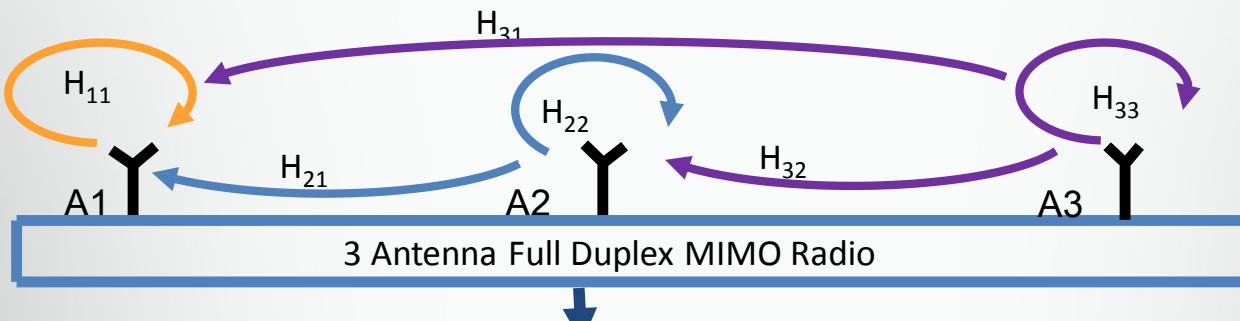
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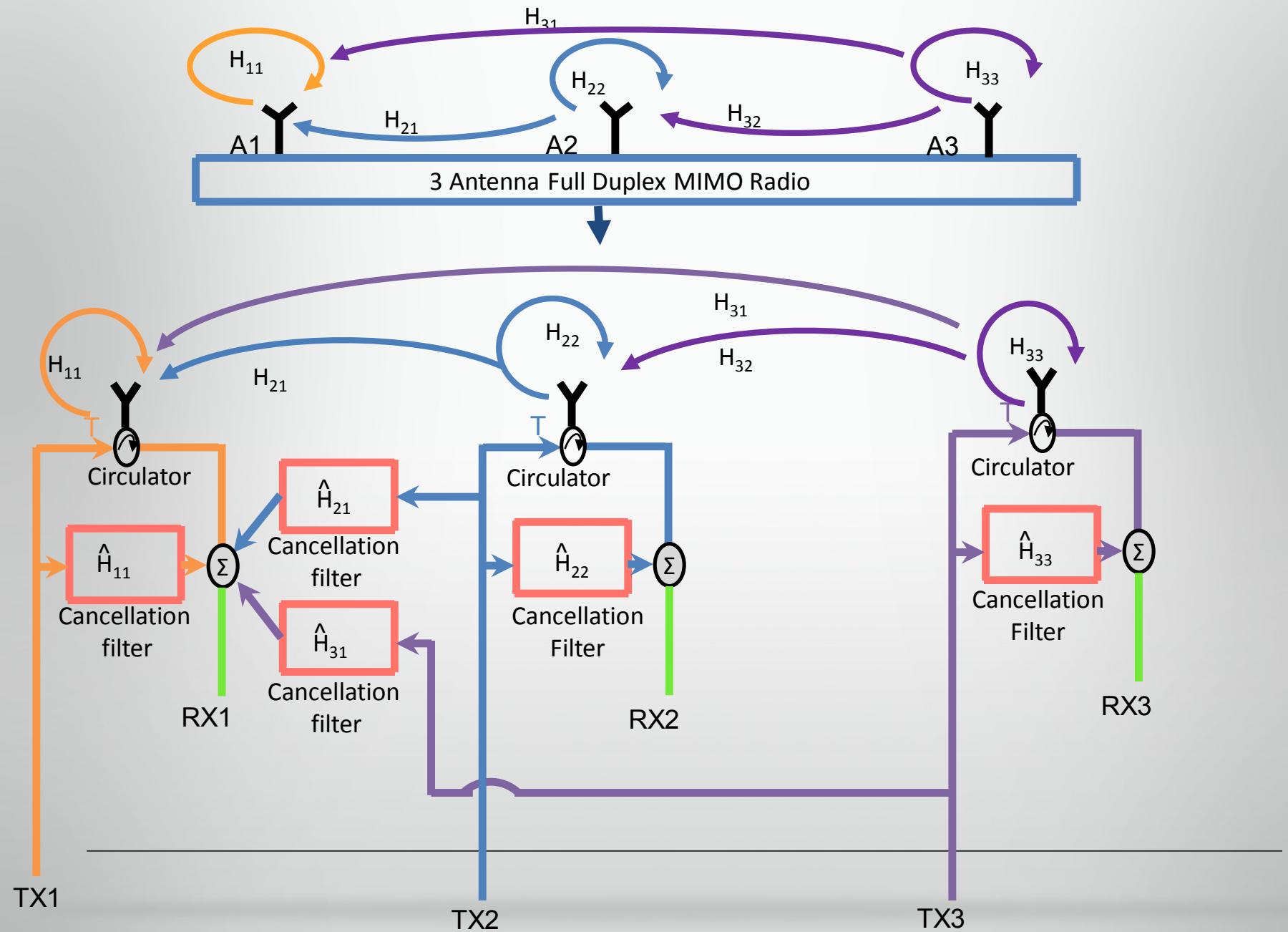
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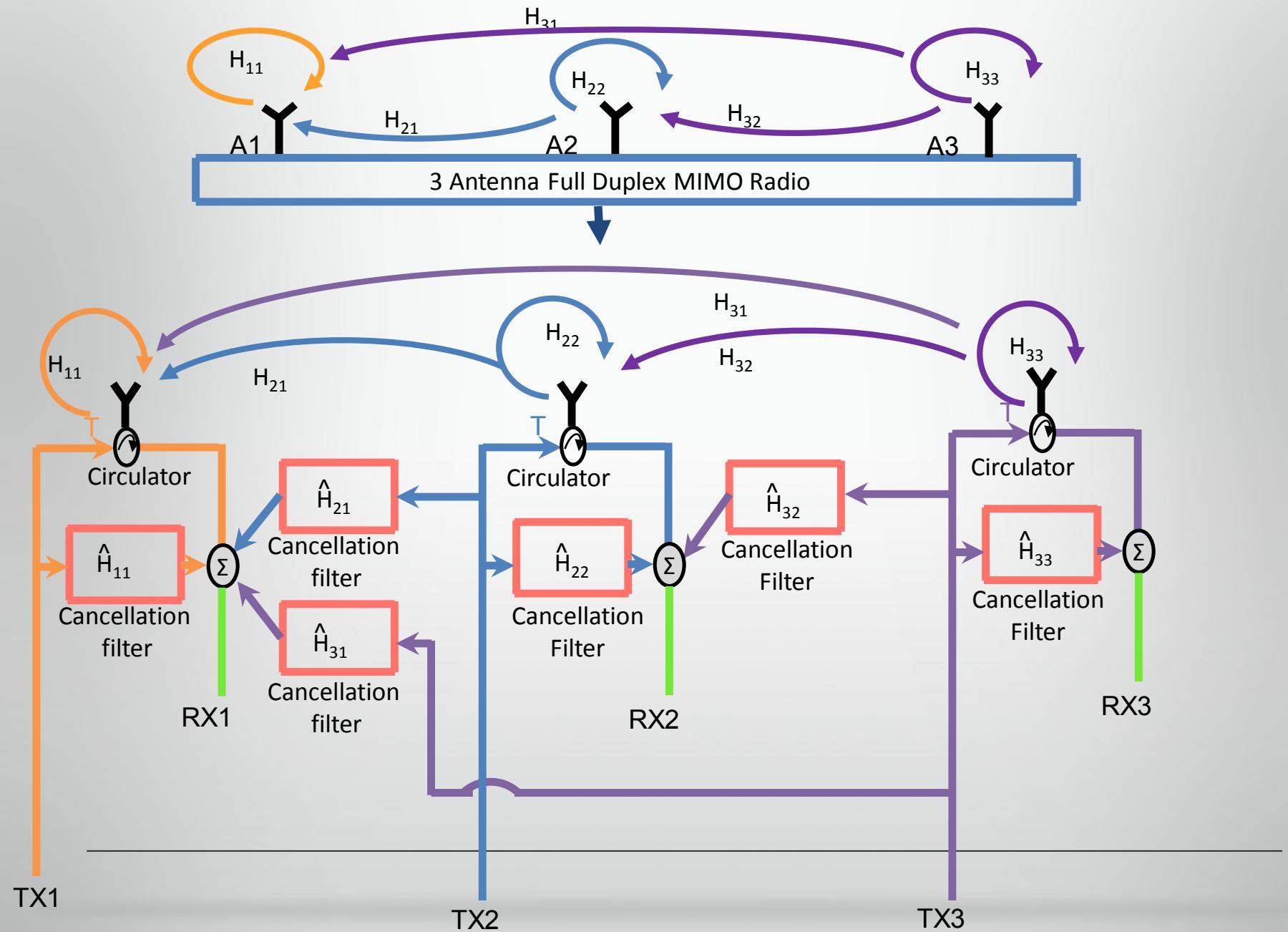
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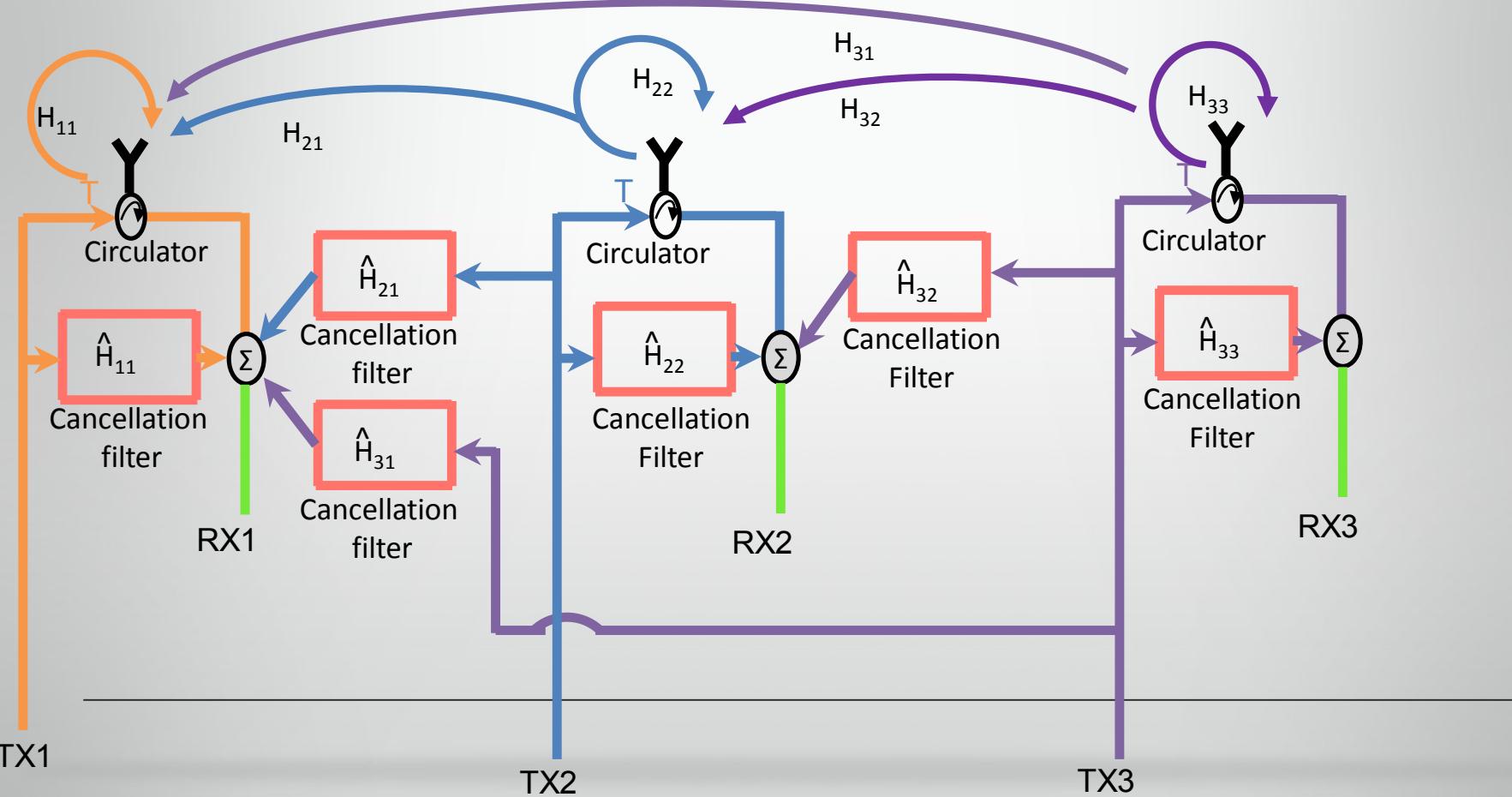
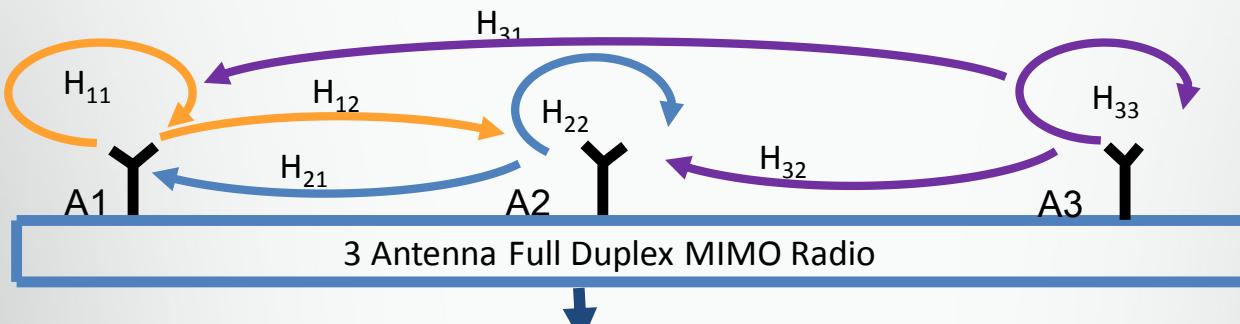
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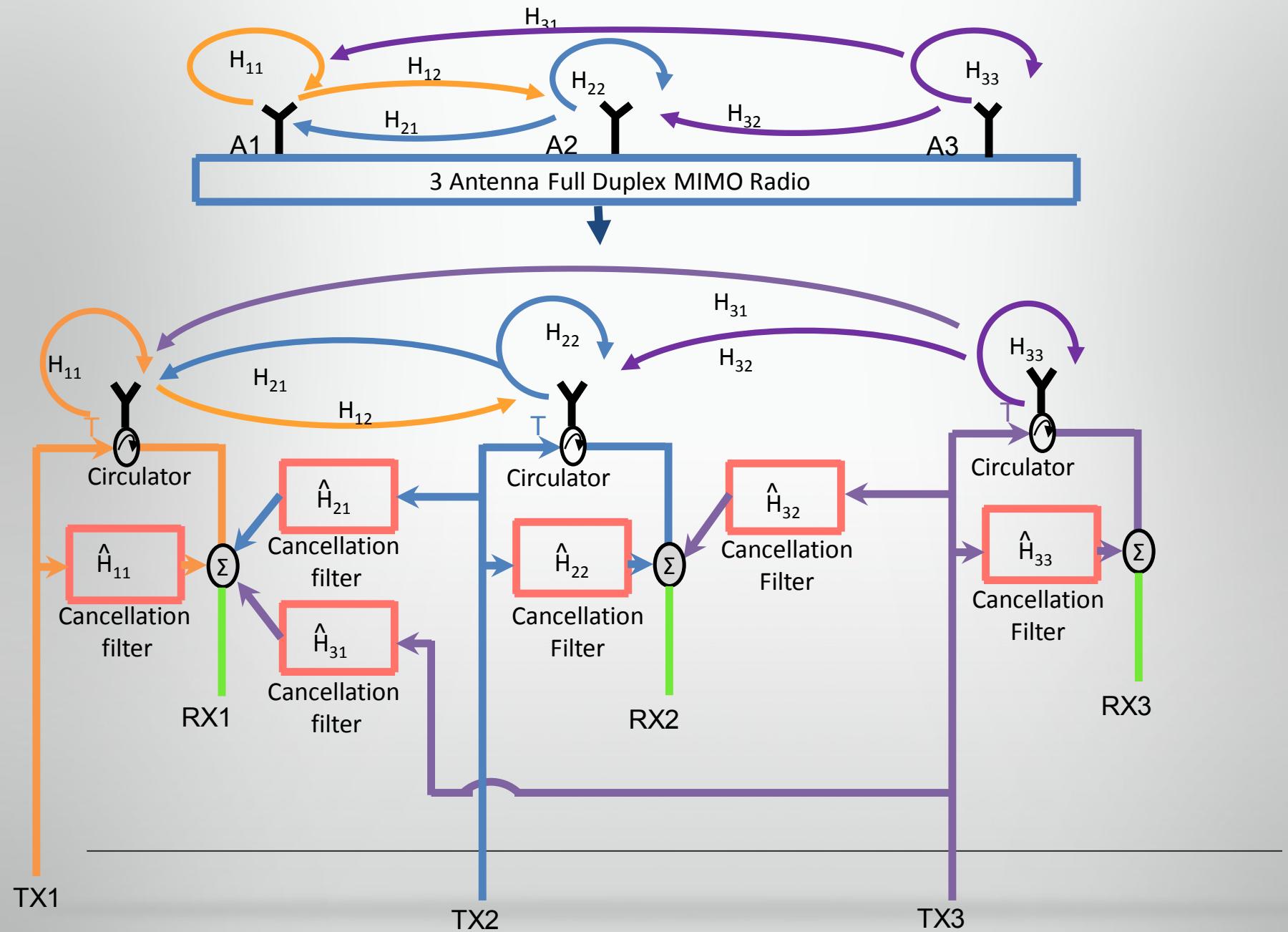
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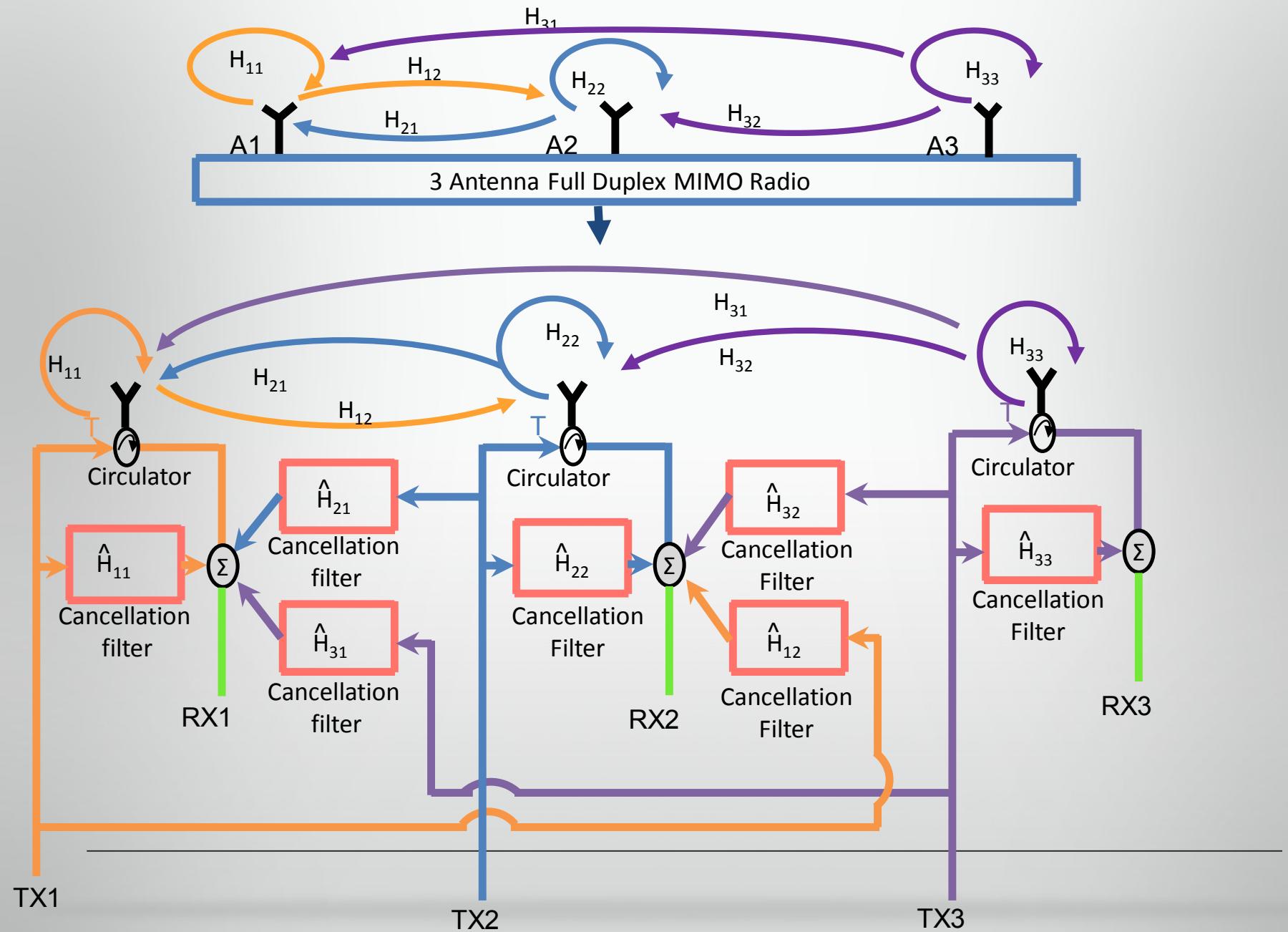
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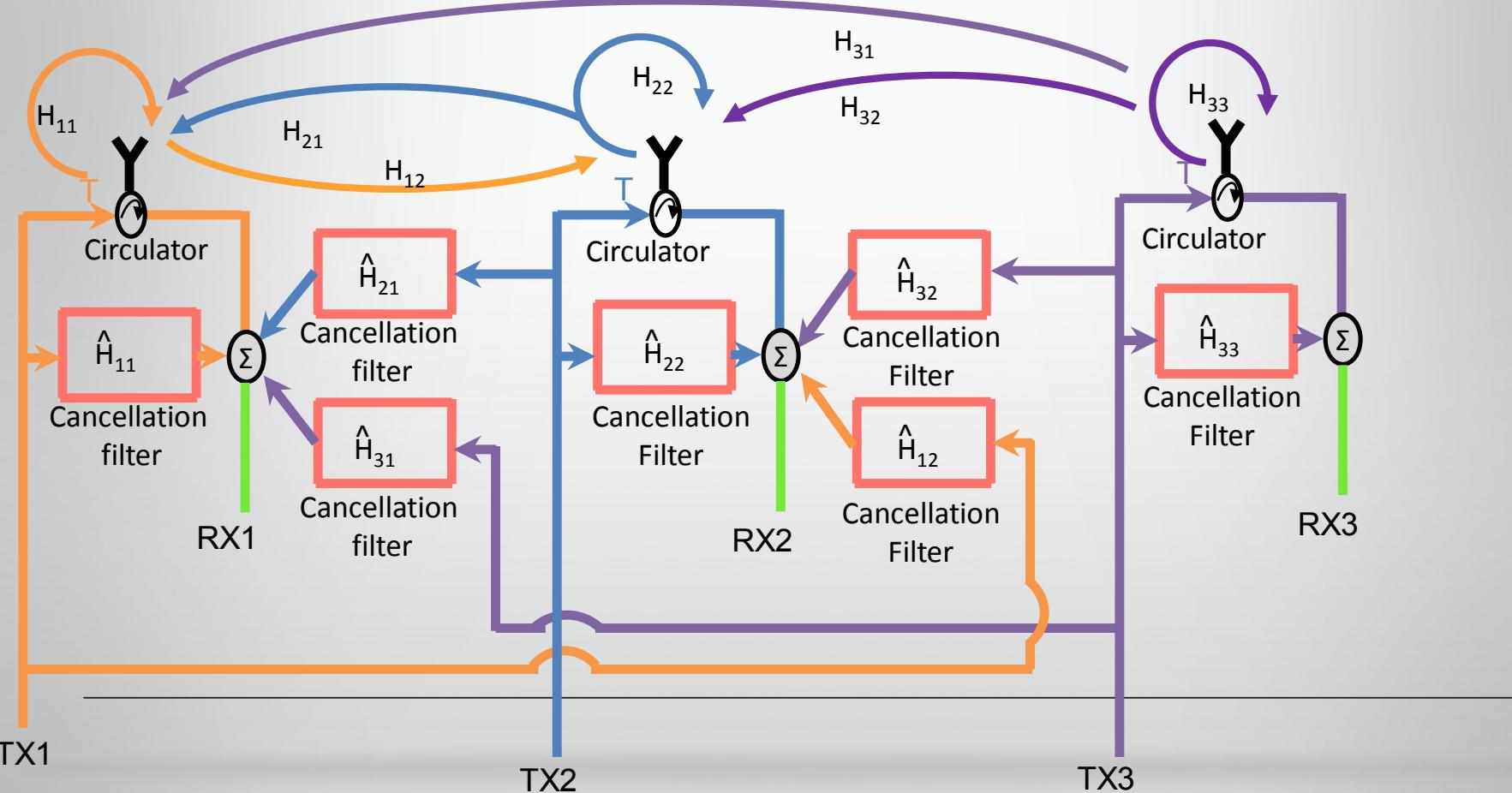
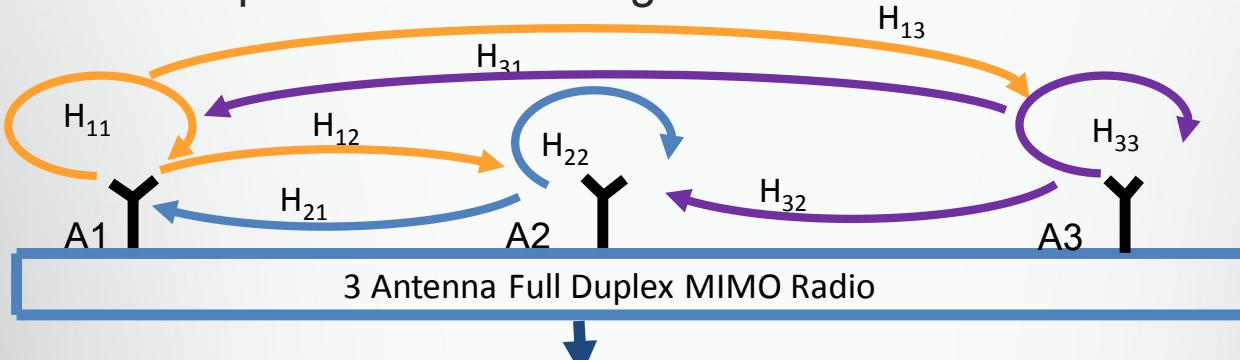
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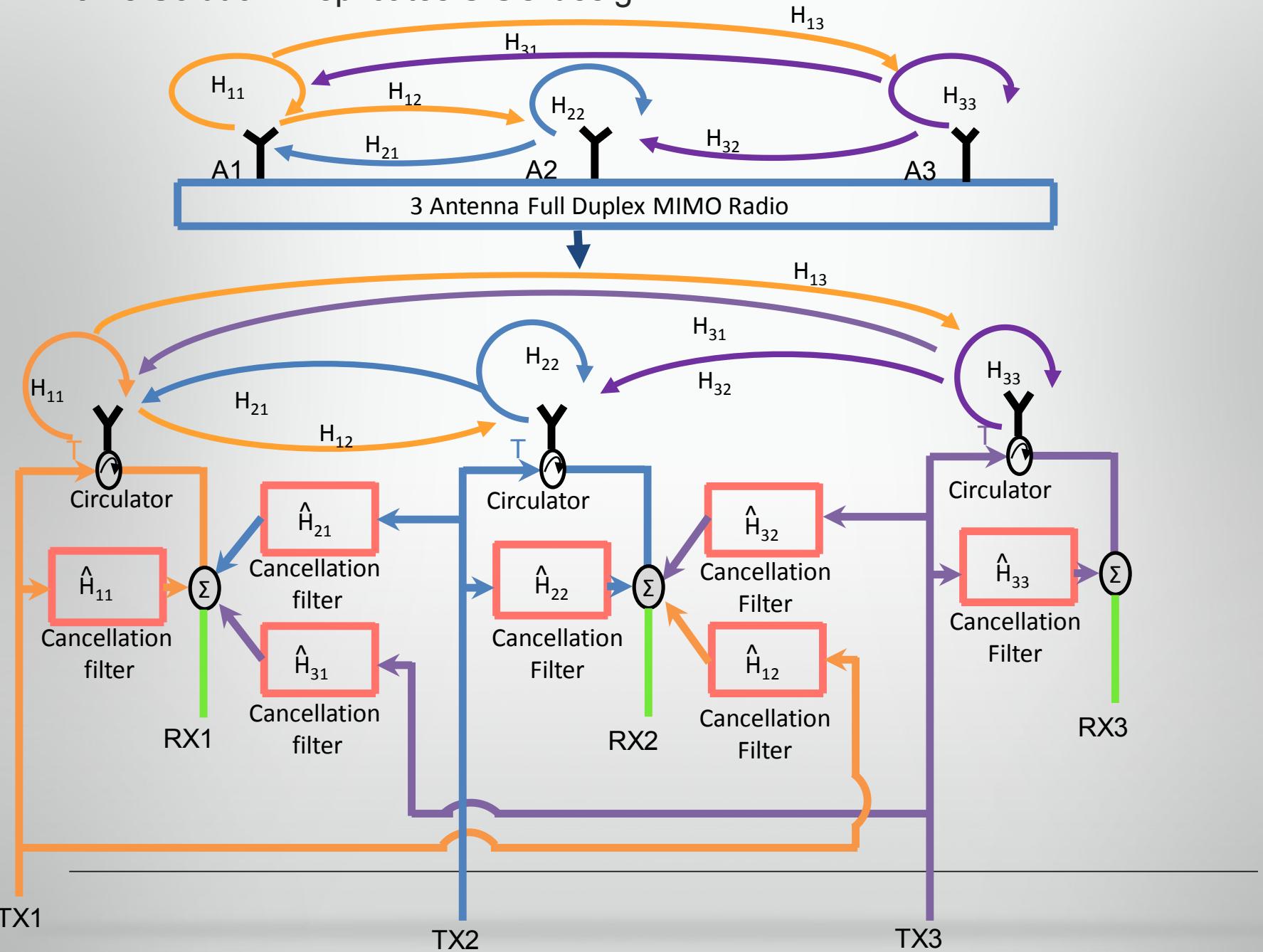
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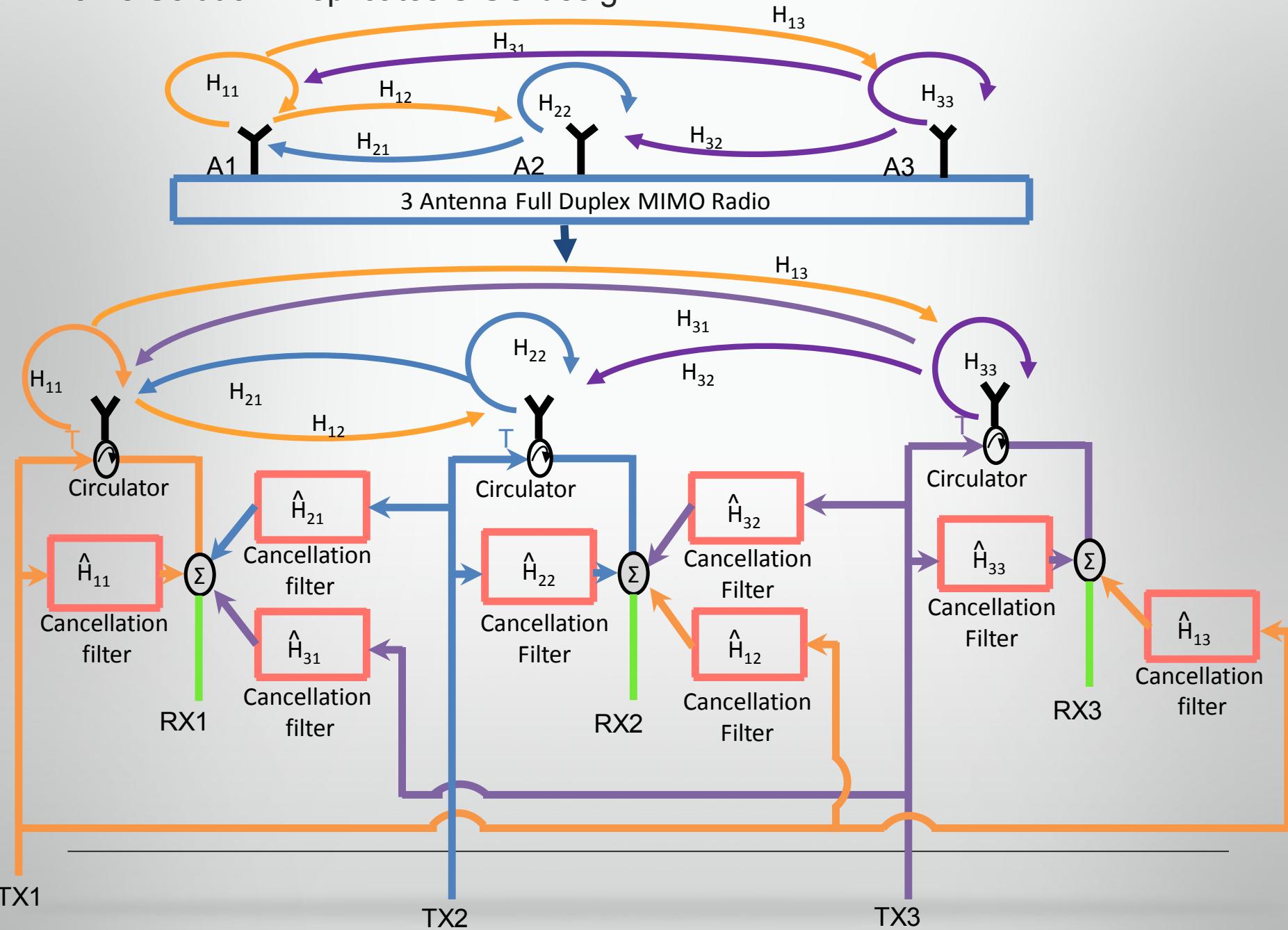
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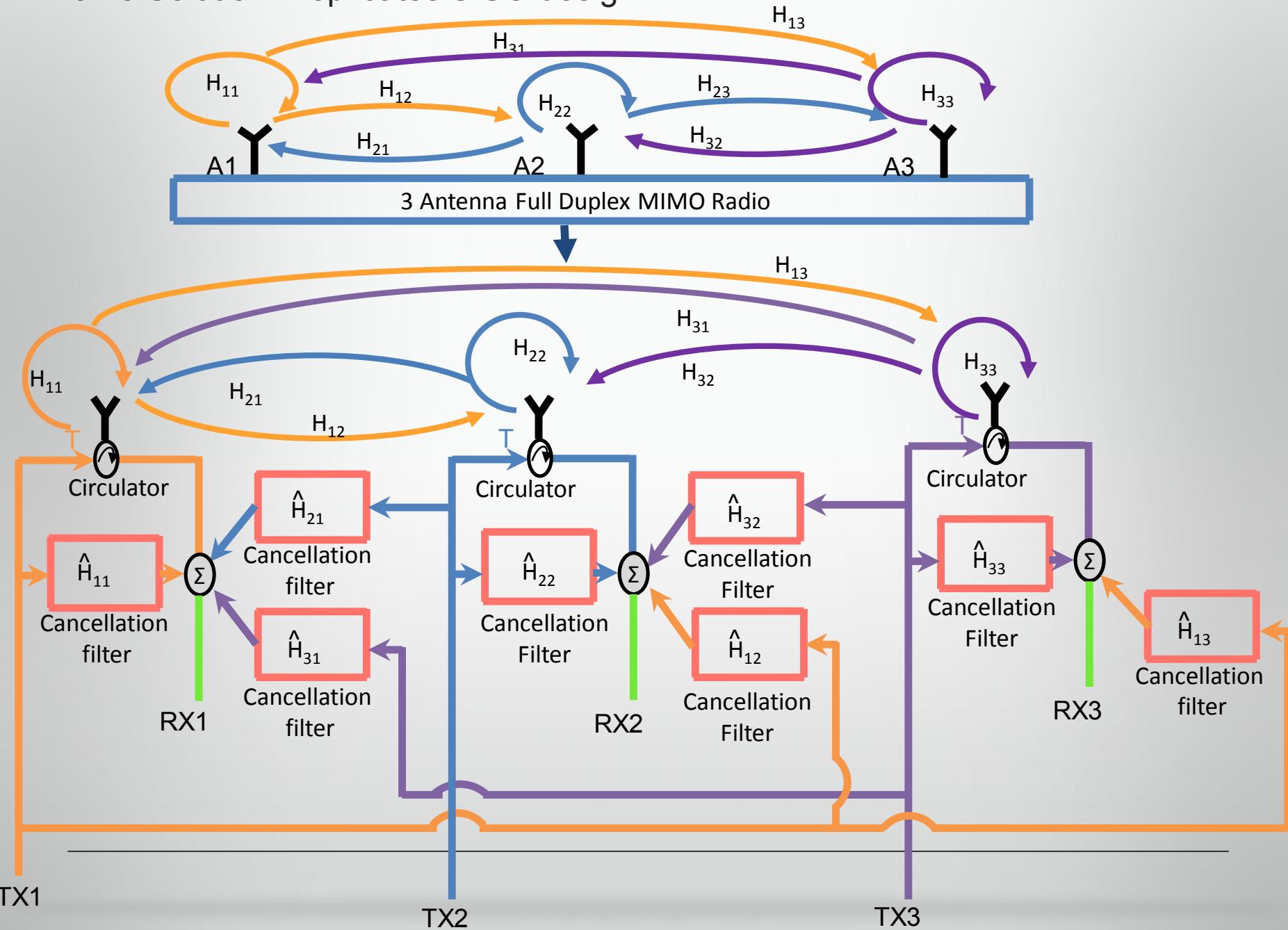
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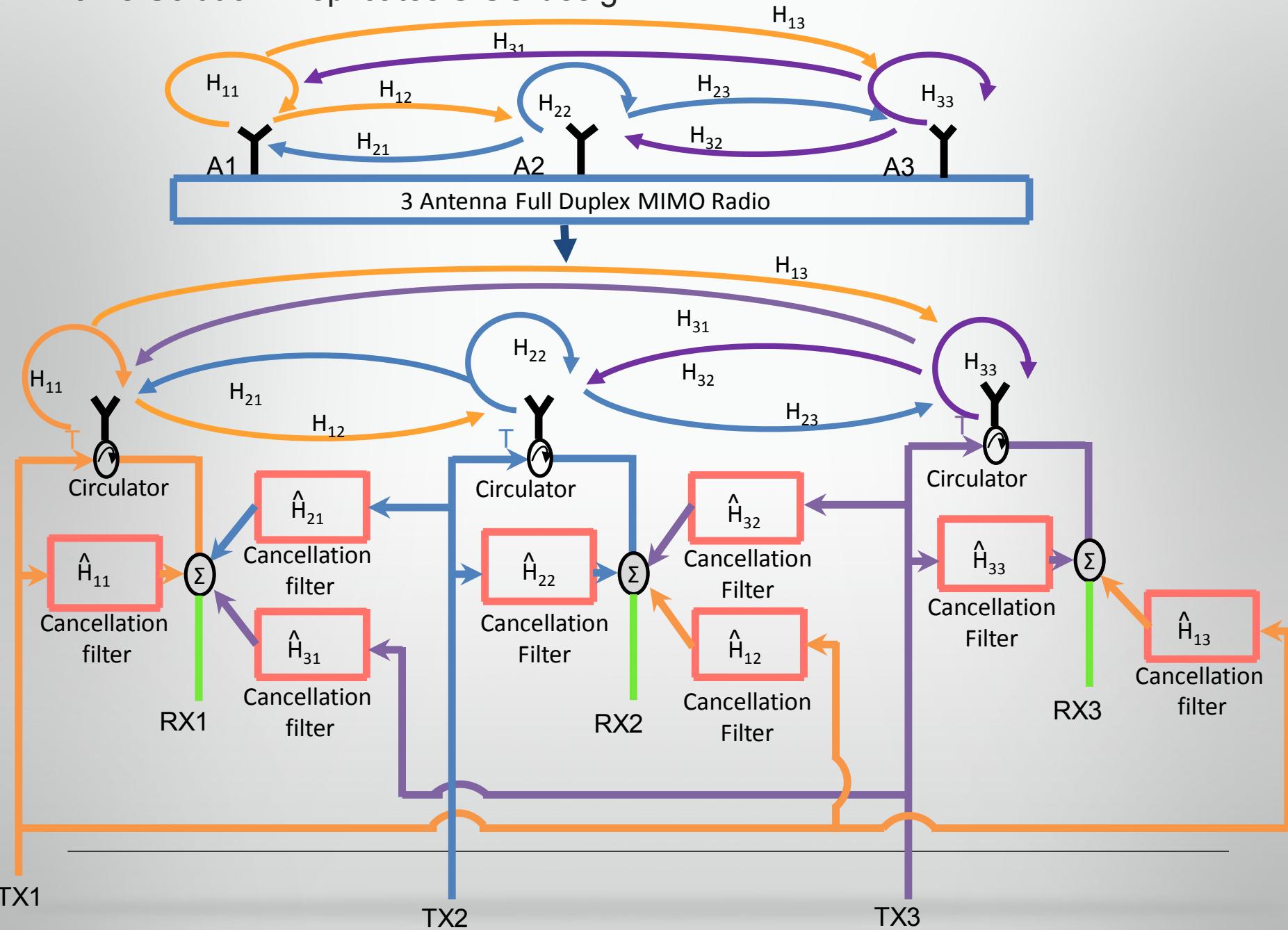
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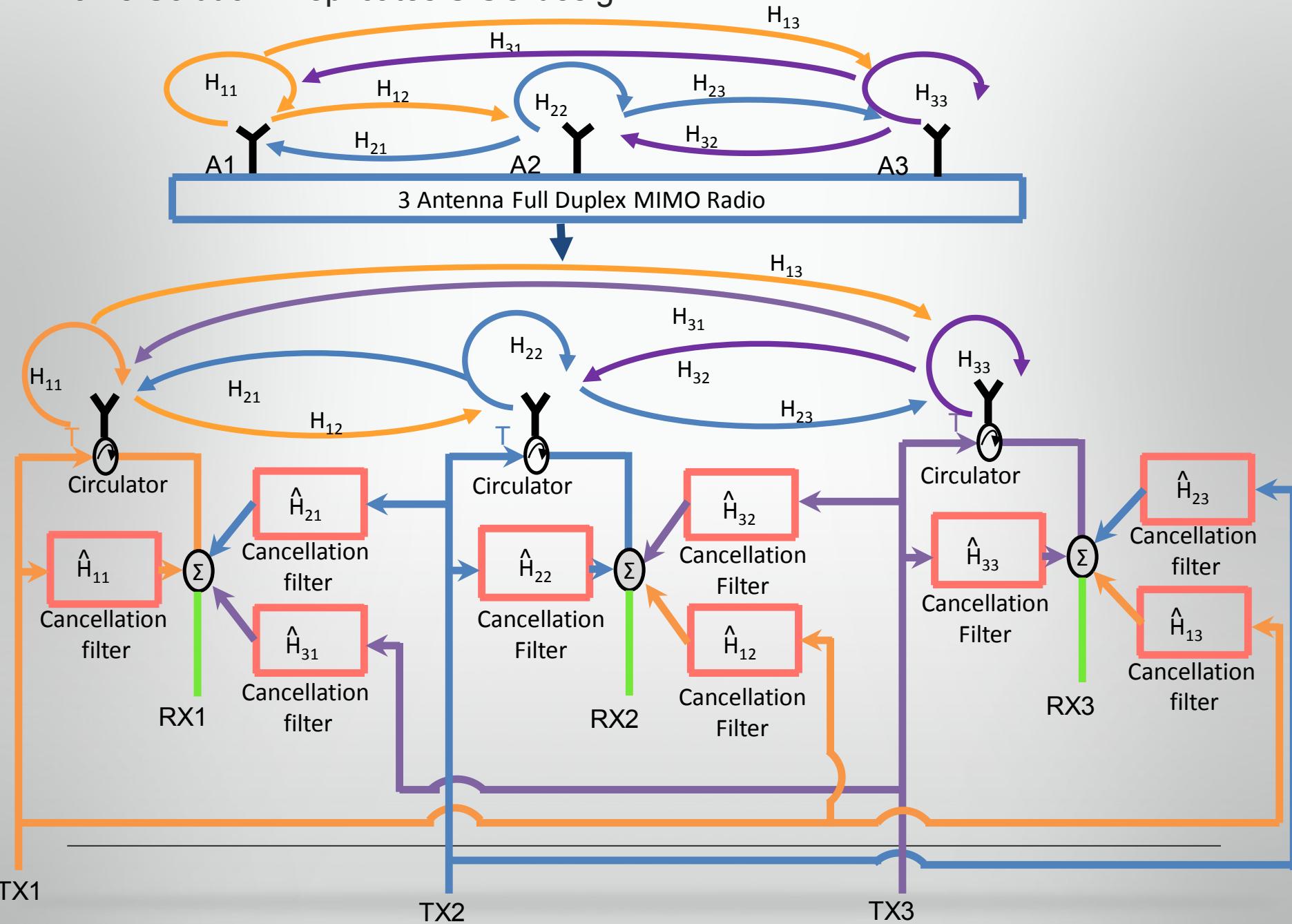
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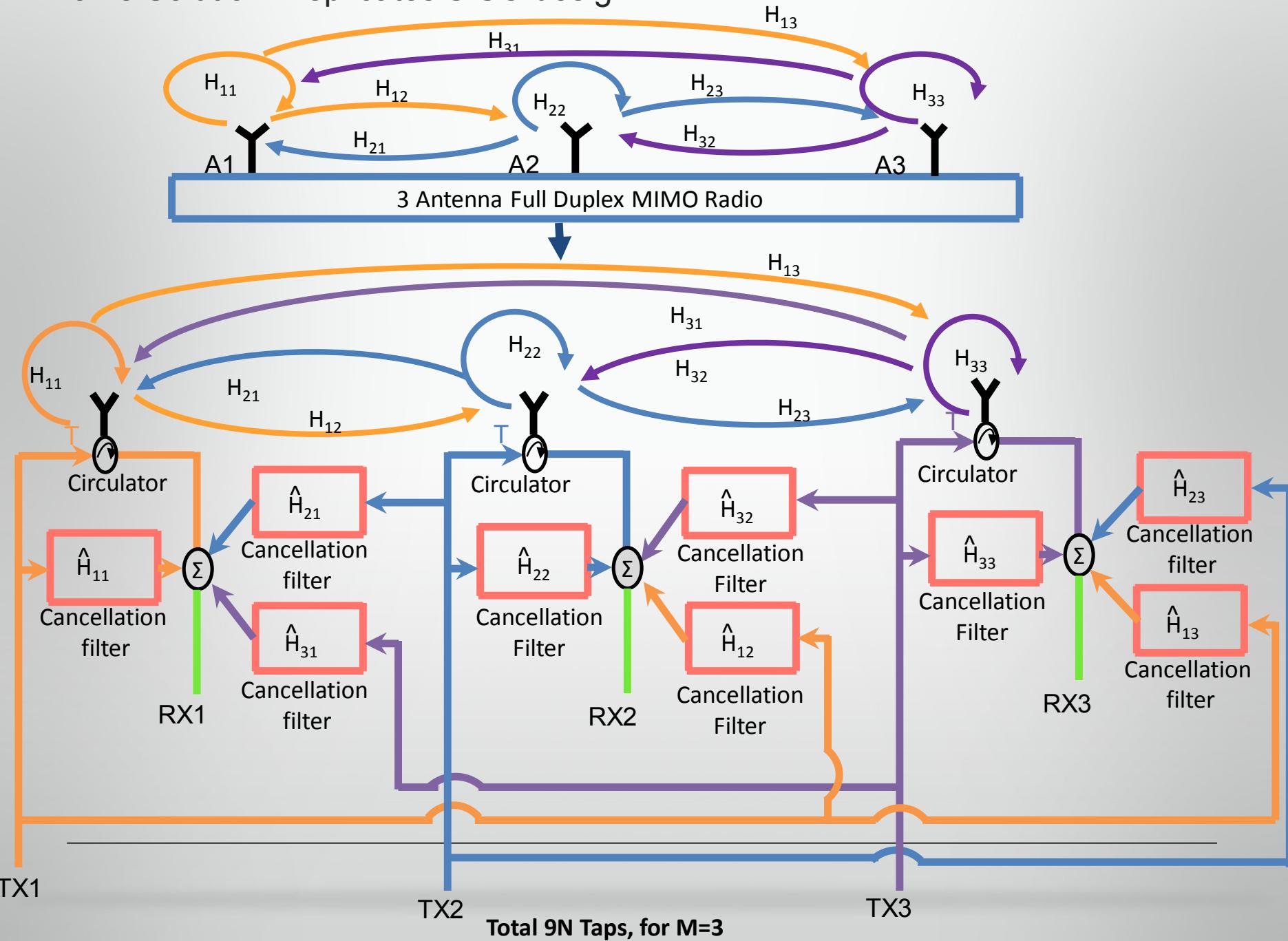
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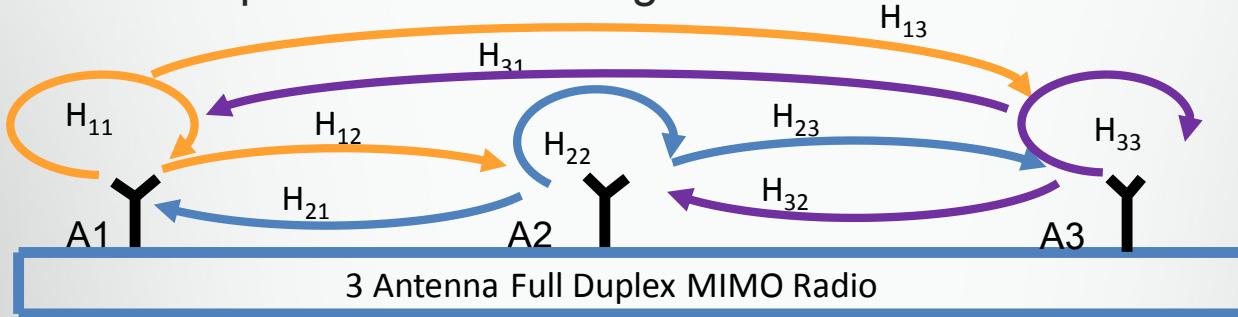
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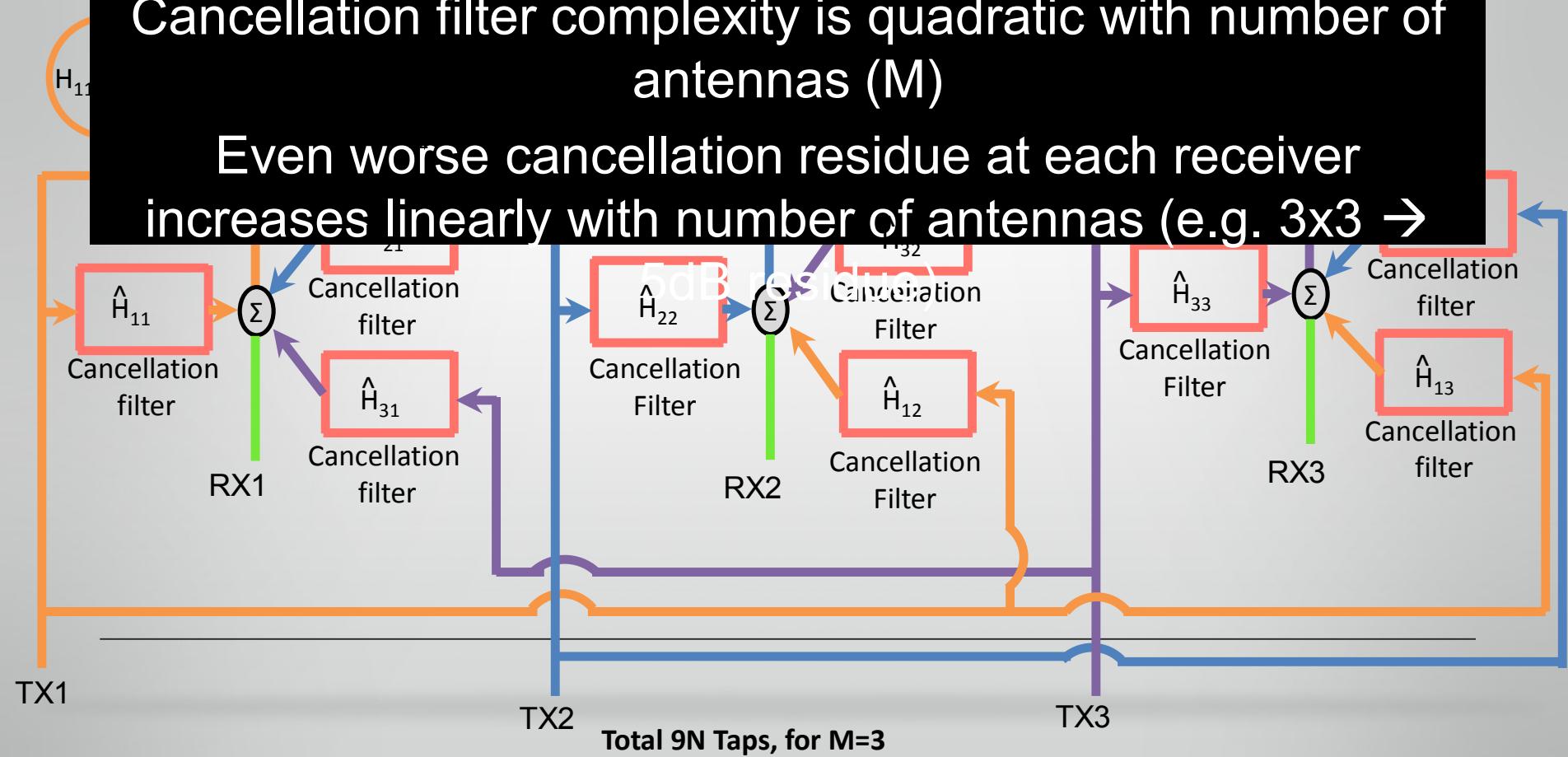


Naïve Solution: Replicates SISO design

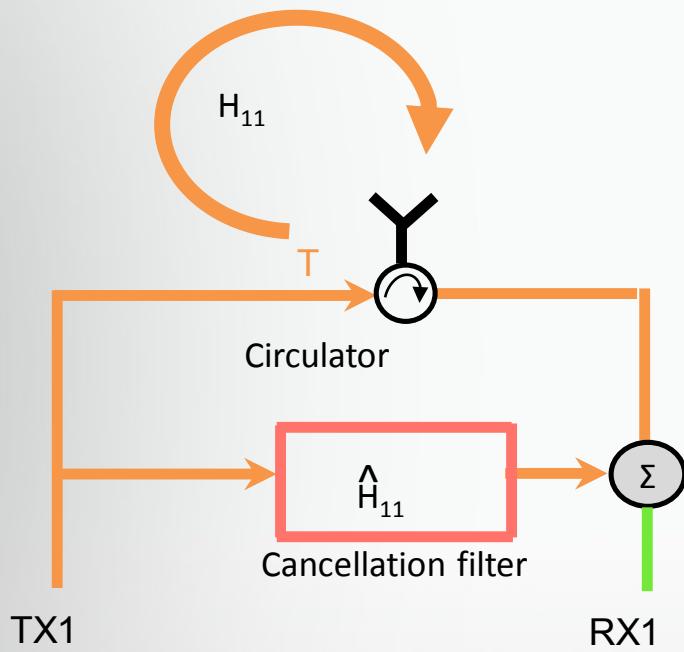


Cancellation filter complexity is quadratic with number of antennas (M)

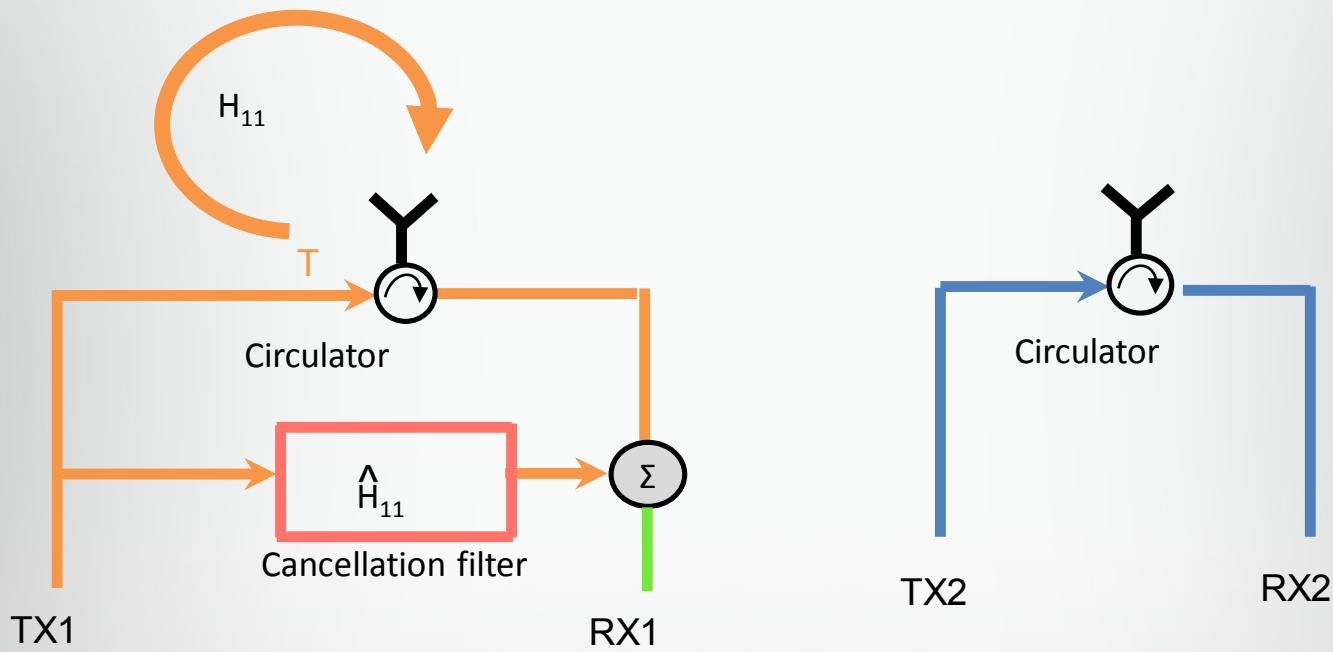
Even worse cancellation residue at each receiver increases linearly with number of antennas (e.g. 3x3 →



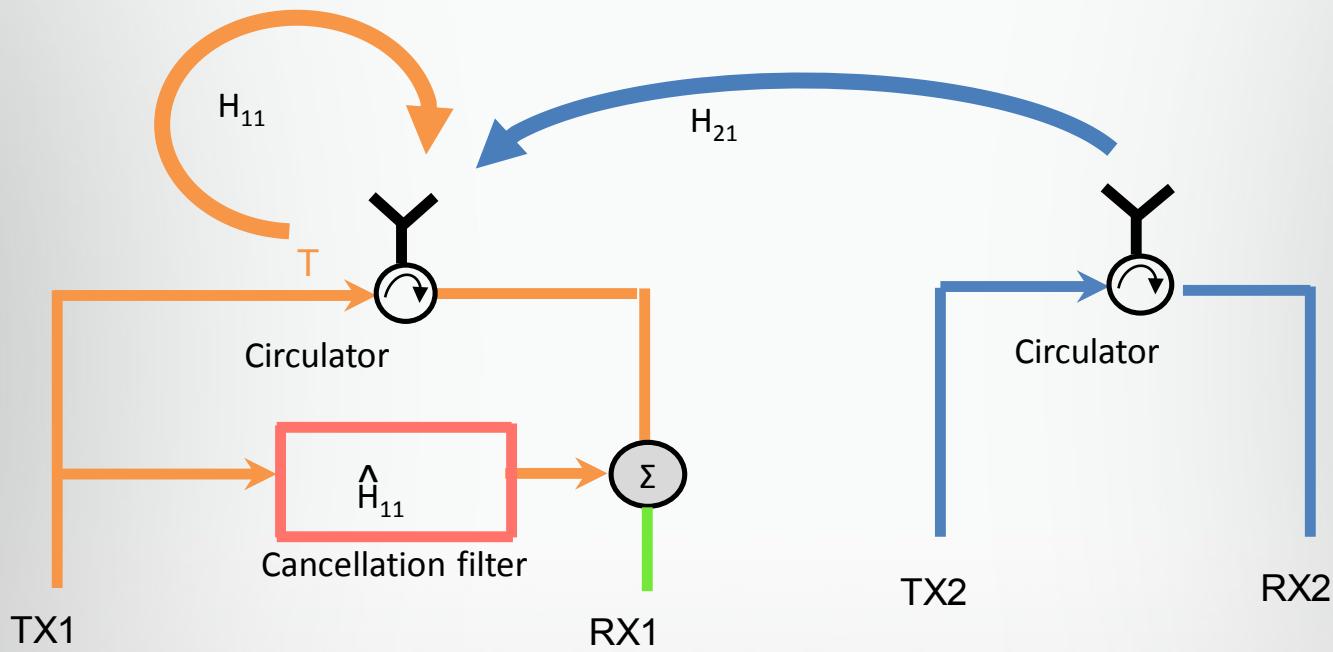
Key Idea: Reducing Complexity



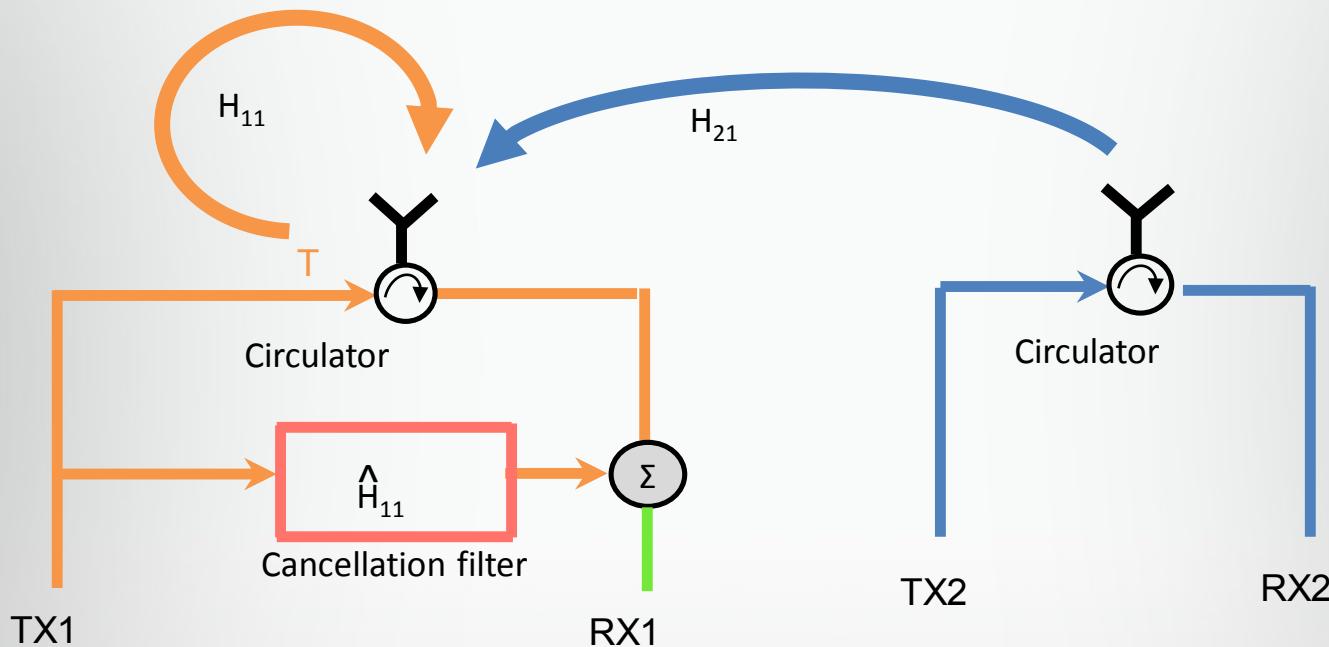
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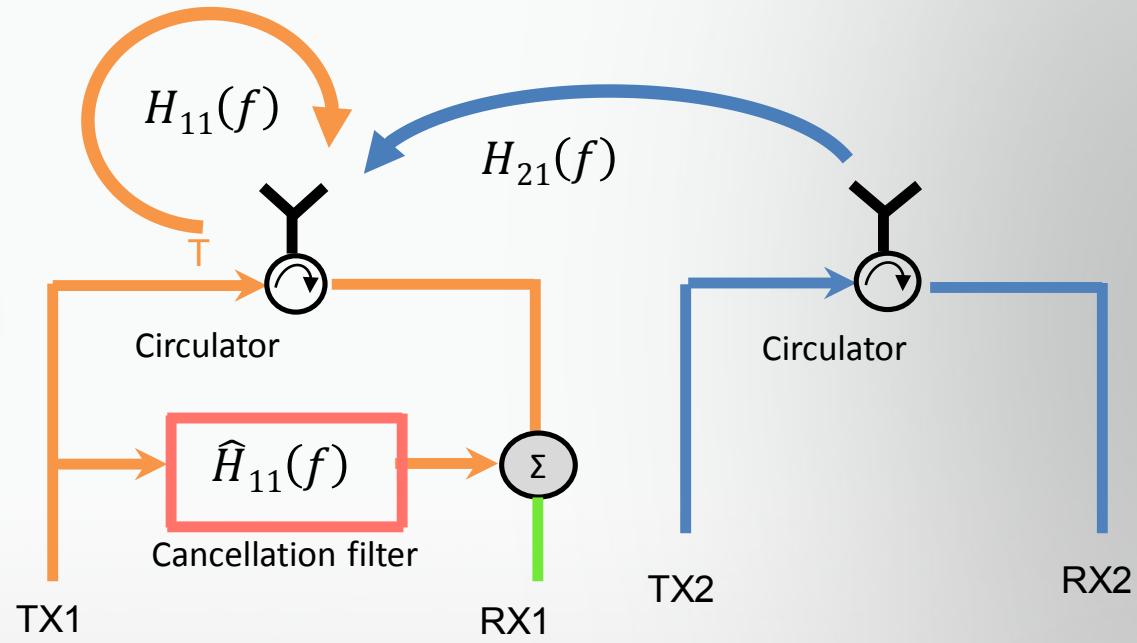


Key Idea: Reducing Complexity



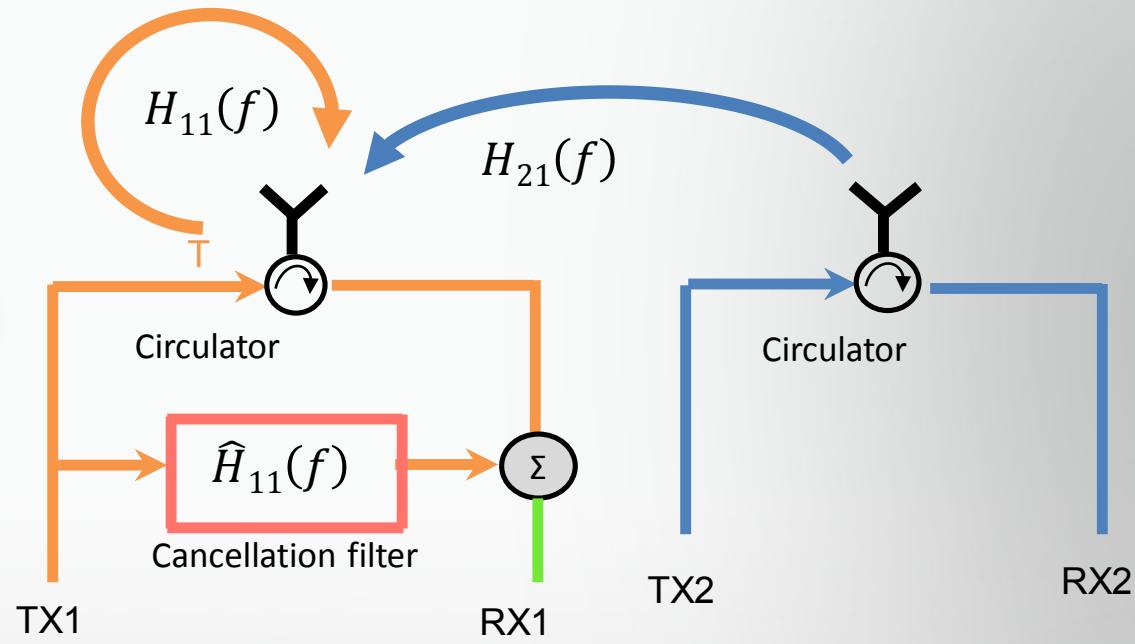
Can we reuse the self talk cancellation filter to also cancel the cross talk ?

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



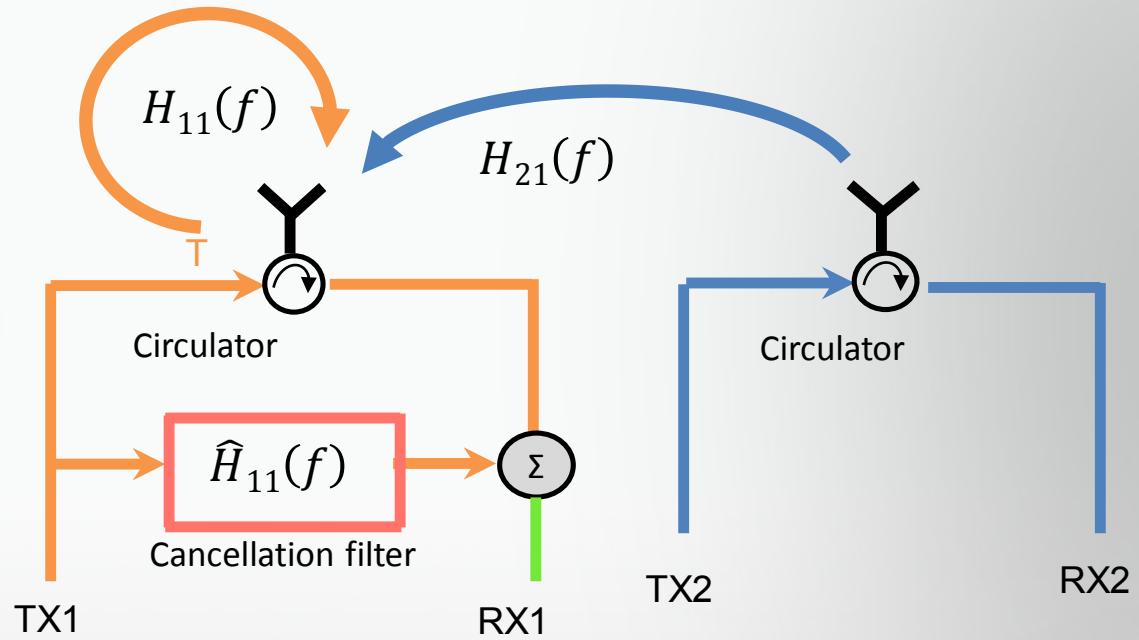
Why can self talk cancellation filter be used to partly model cross talk?

- Share Environment
- Share Reflectors



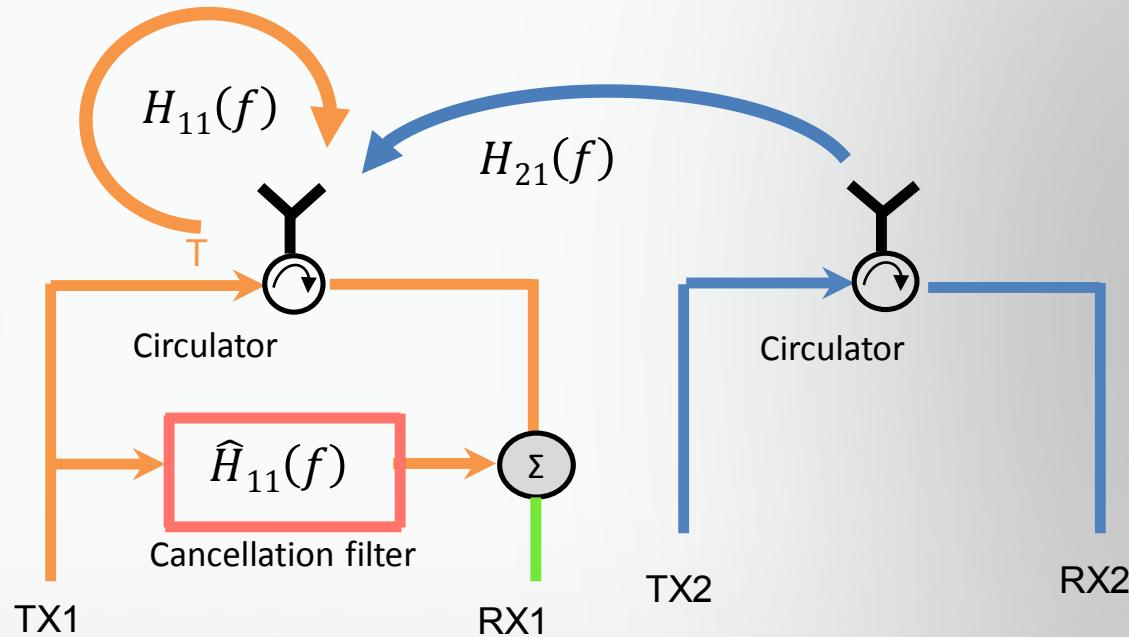
Why can self talk cancellation filter be used to partly model cross talk?

- Share Environment
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- Self talk and cross talk transfer function are related as they undergo similar environment.



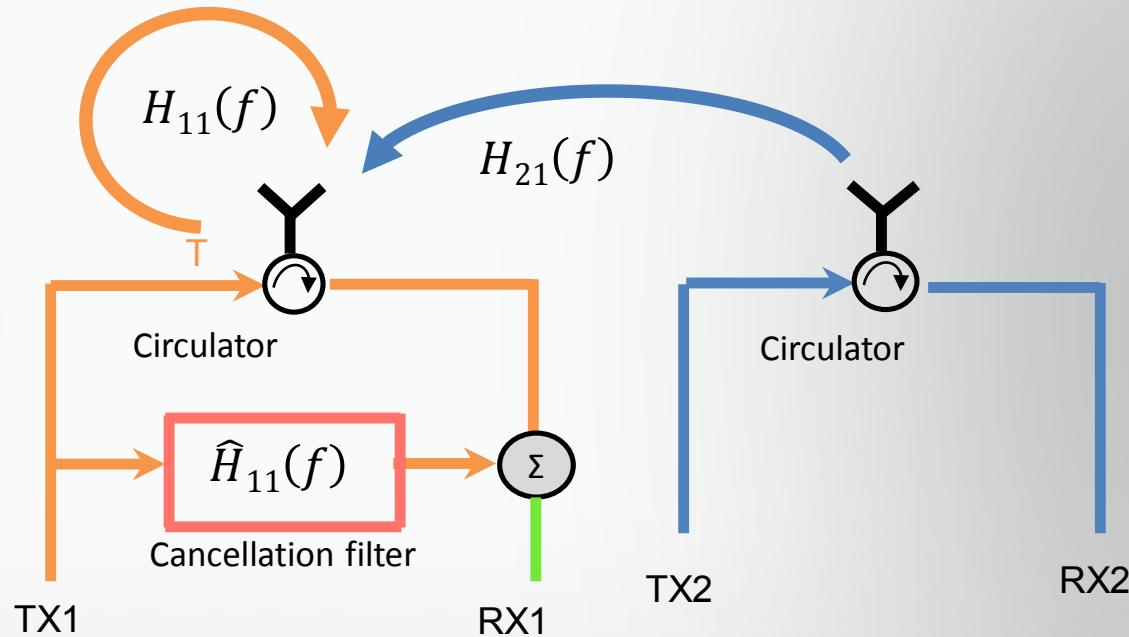
Why can self talk cancellation filter be used to partly model cross talk?

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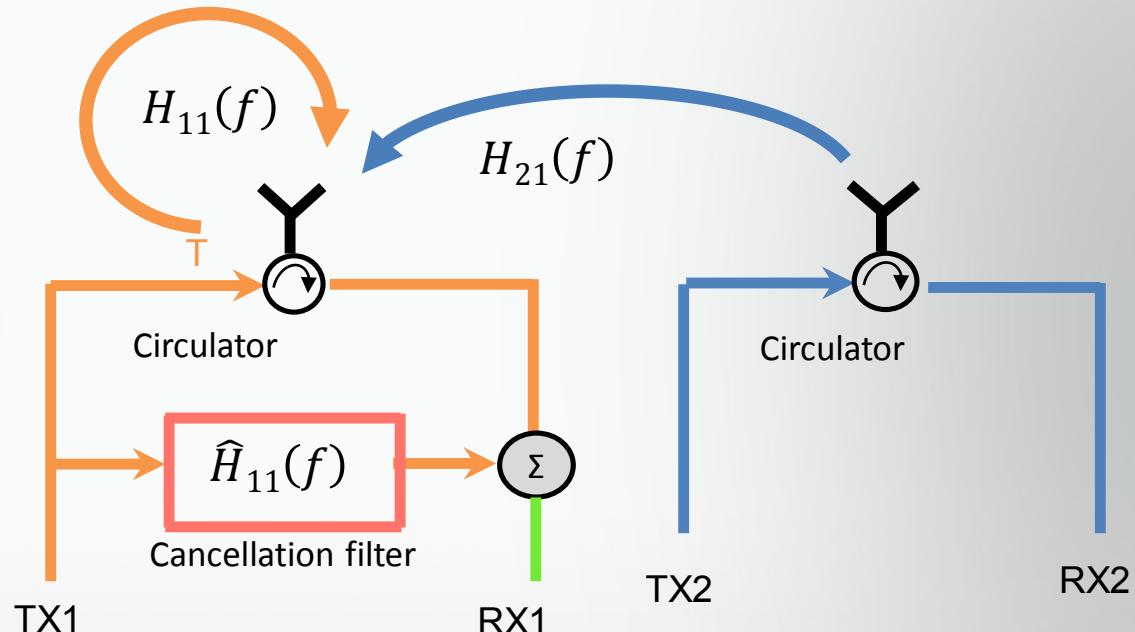
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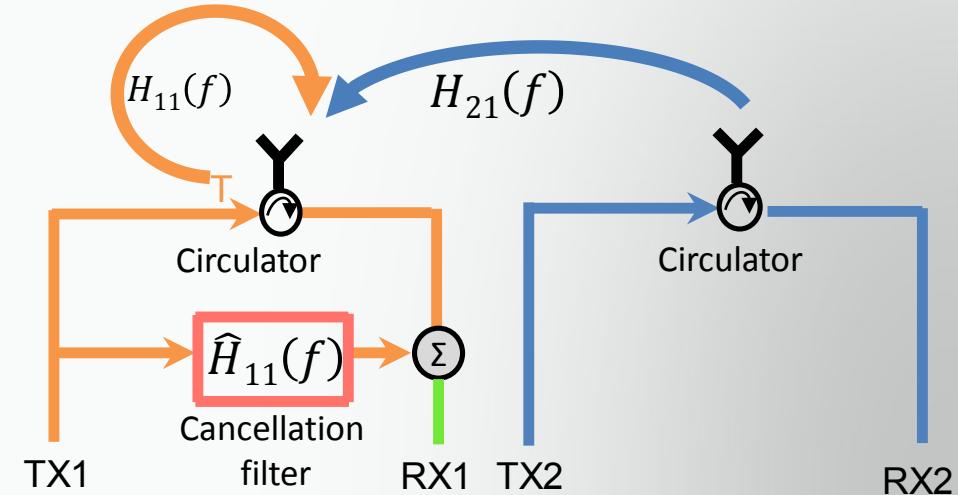
$$H_{21}(f) = H_{cas_cade}(f) \cdot H_{11}(f)$$

Can we leverage this relationship to reduce the cancellation complexity

Empirical Observation

$$H_{21}(f) = H_{cas_cade}(f) \cdot H_{11}(f)$$

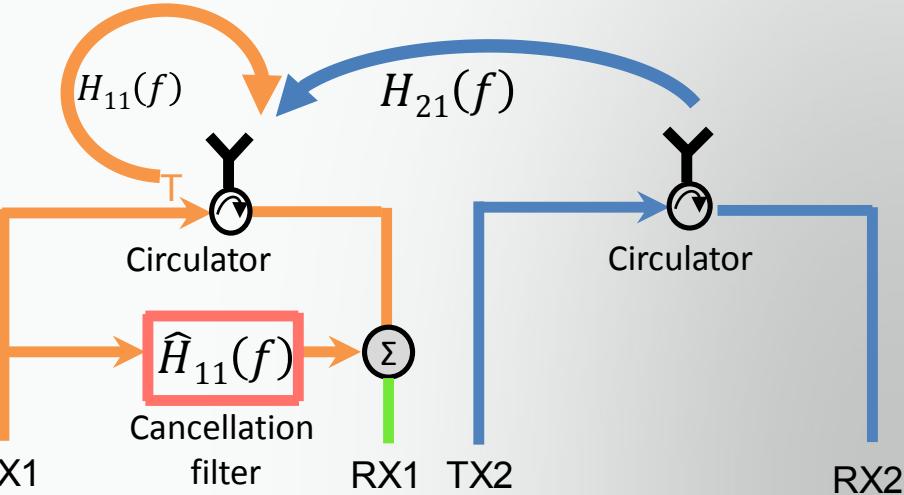
Cascade Transfer Function



Empirical Observation

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Cascade Transfer Function

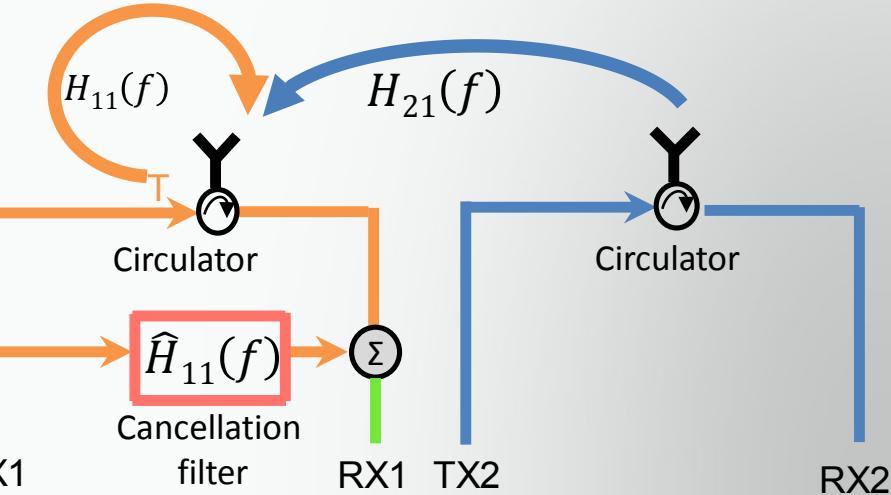


- Cascade Transfer Function
- Collect cross talk and self talk for various indoor environments

Empirical Observation

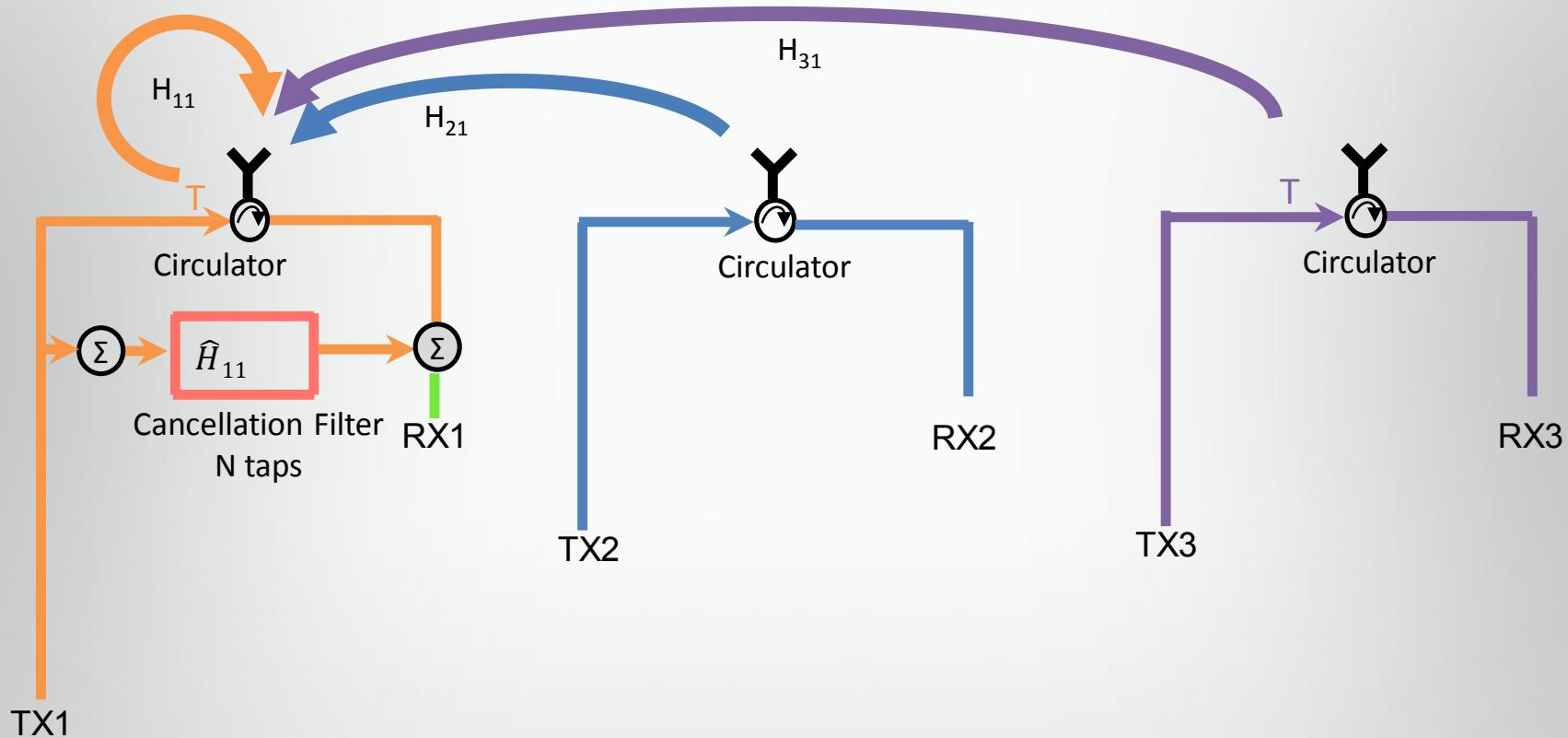
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Cascade Transfer Function

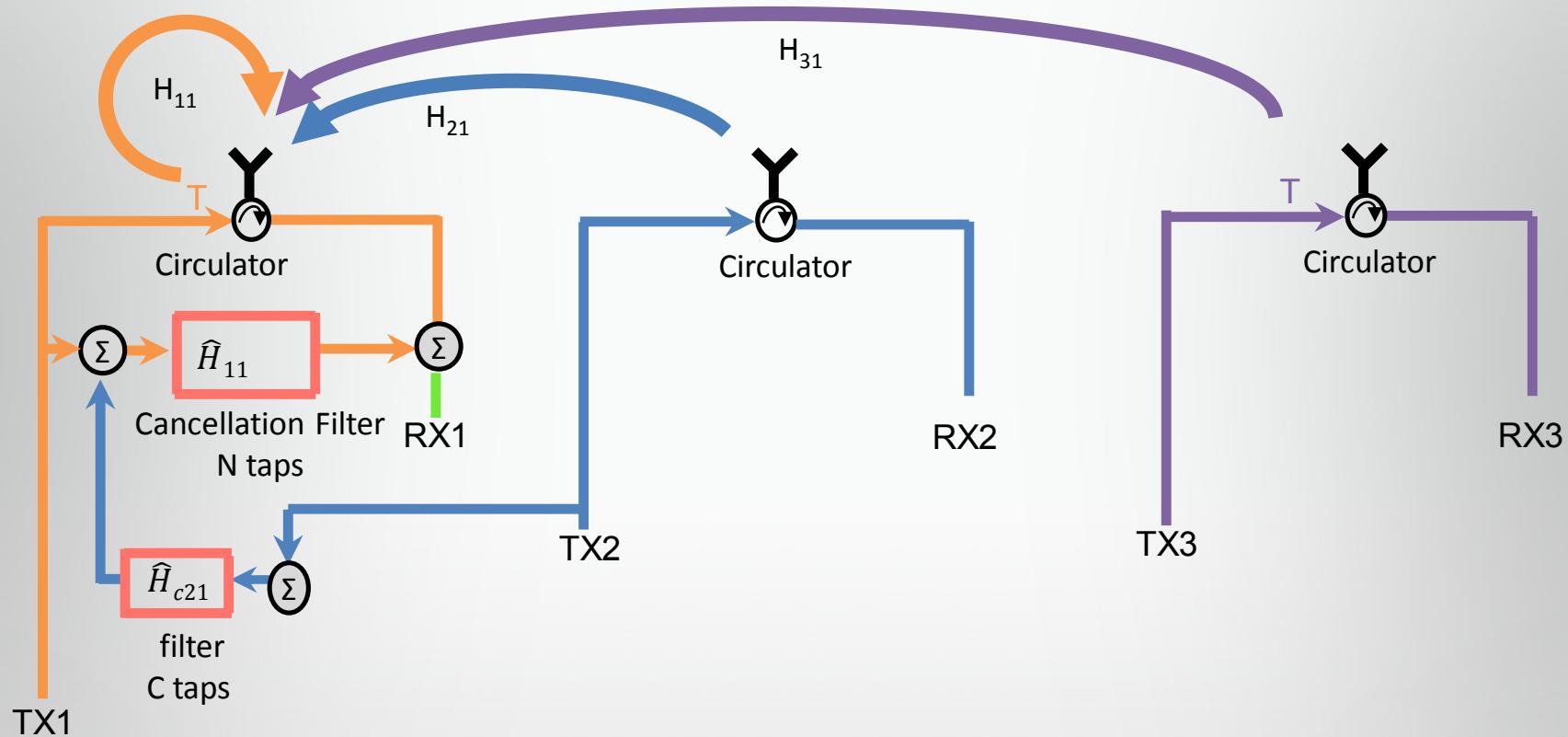


- Cascade Transfer Function
 - Collect cross talk and self talk for various indoor environments
- Learning Algorithm
 - From all the possible cascade response, calculate via optimization the best low complexity circuit which achieves the cascade transfer function (offline analysis)
 - These cascade circuits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

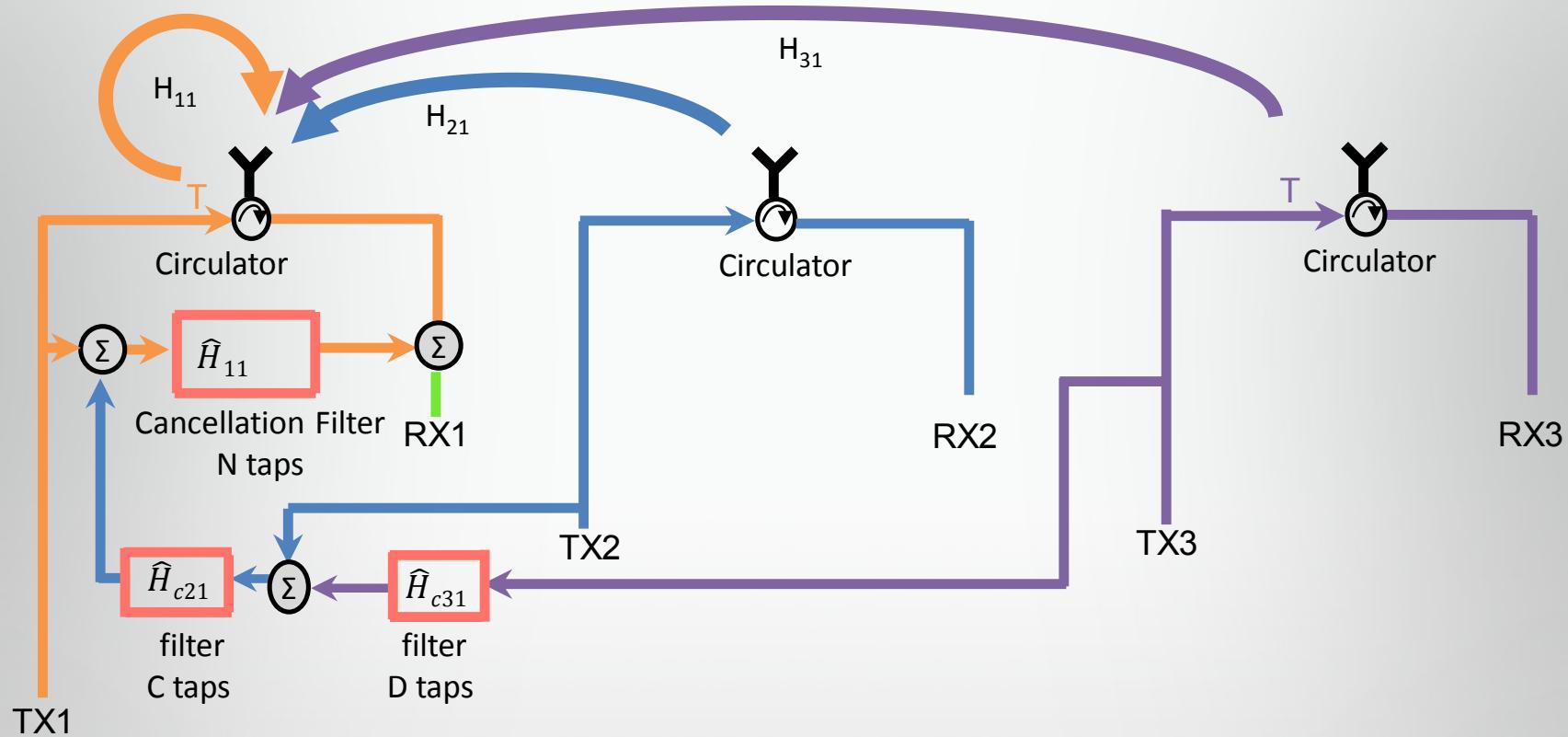
Reducing Complexity: Cascaded Cancellation



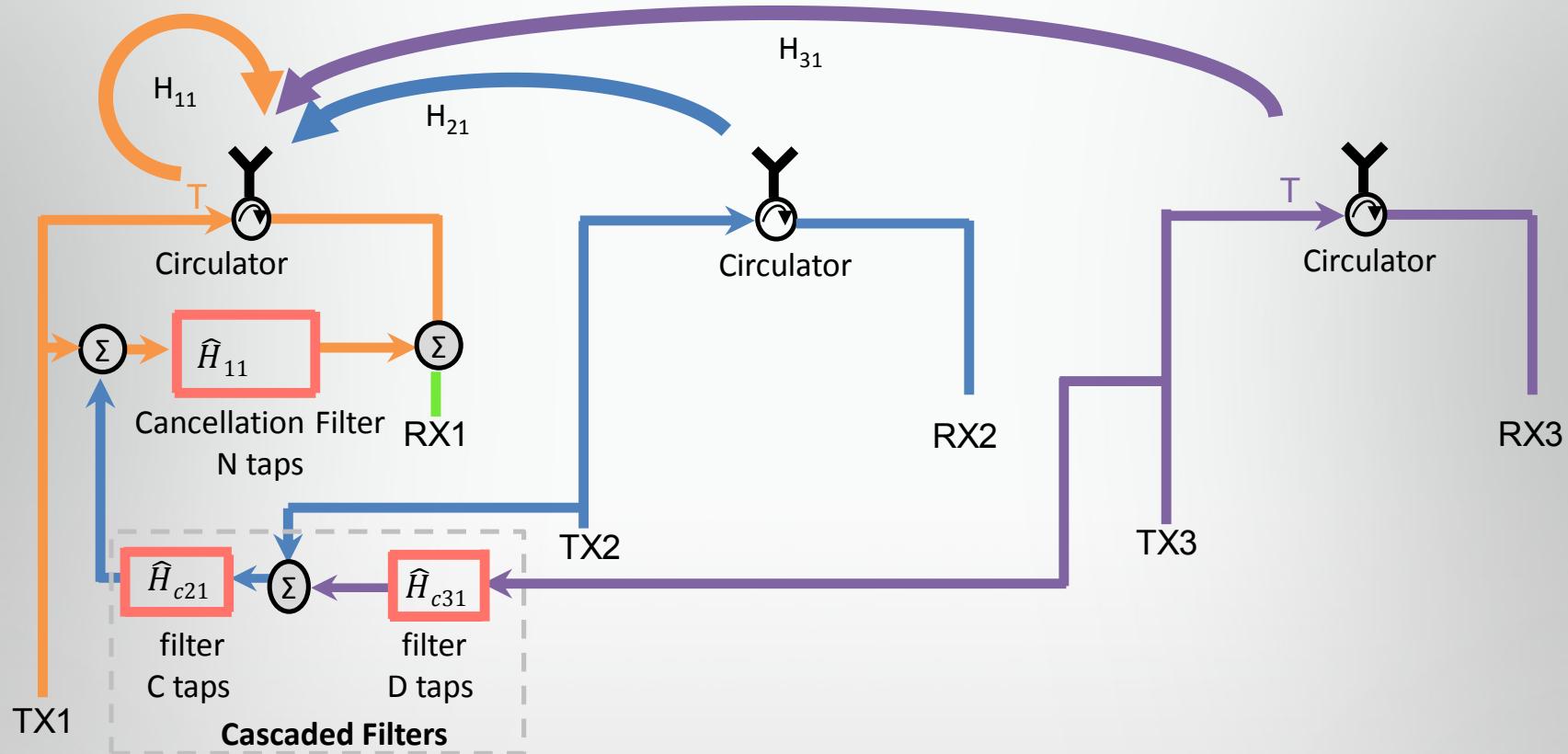
Reducing Complexity: Cascaded Cancellation



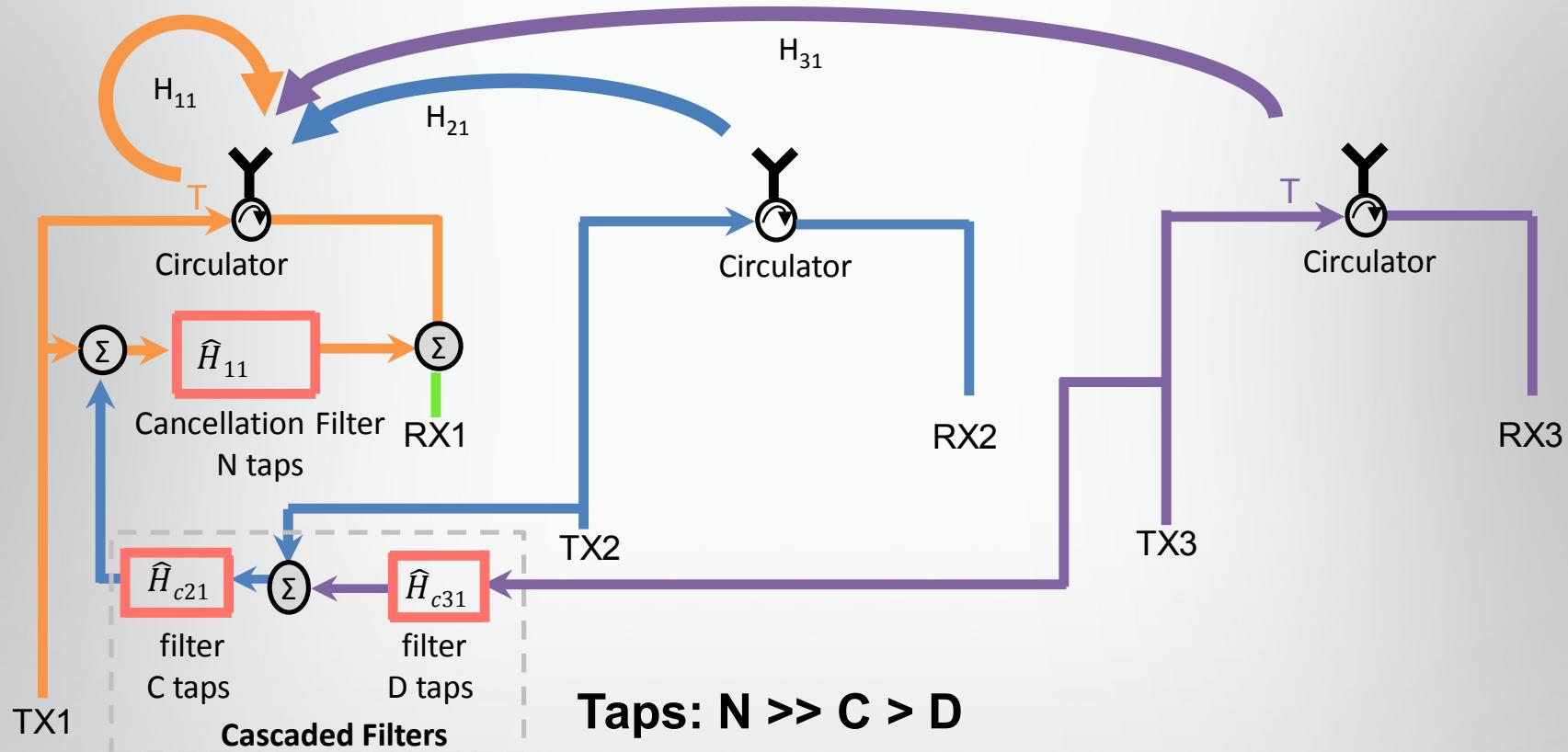
Reducing Complexity: Cascaded Cancellation



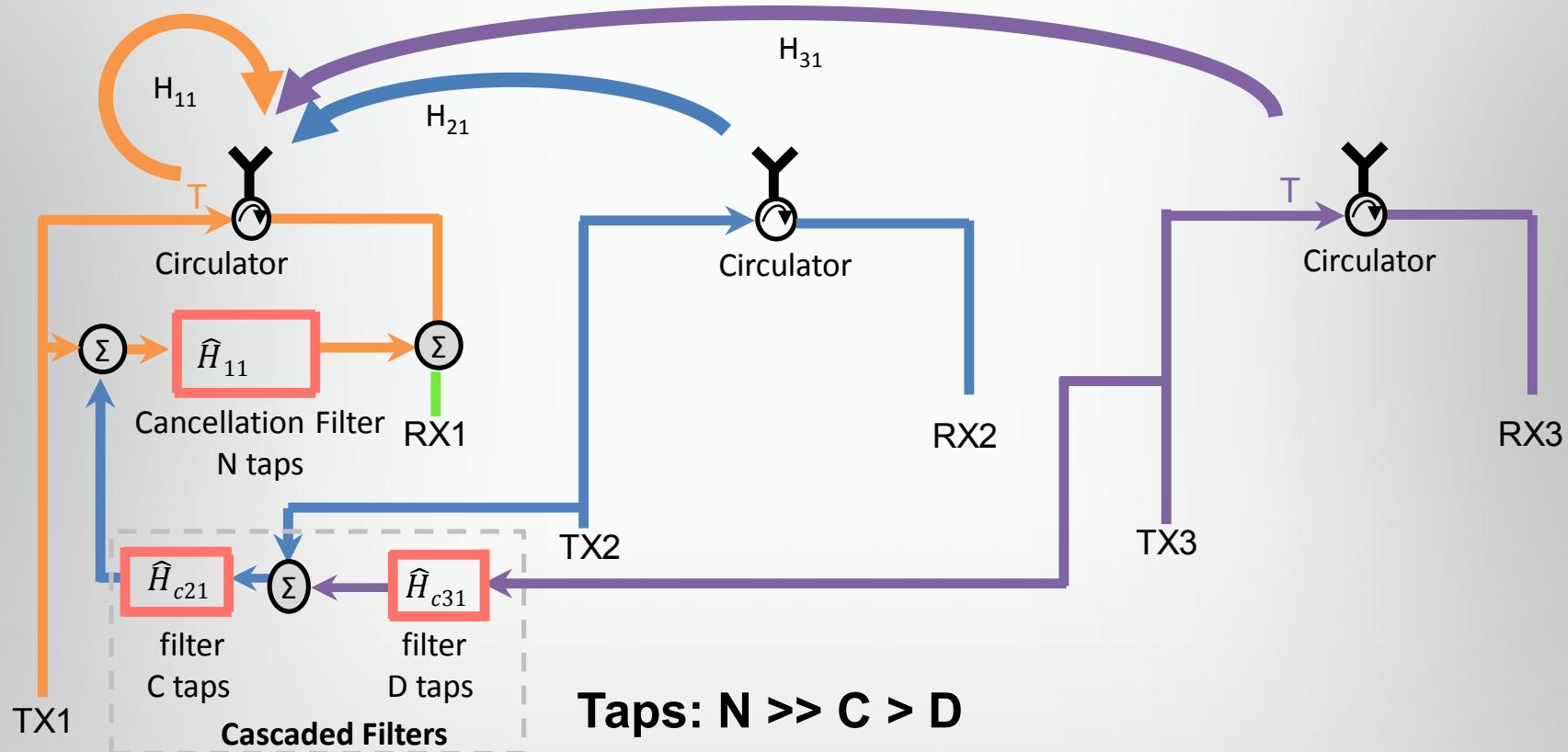
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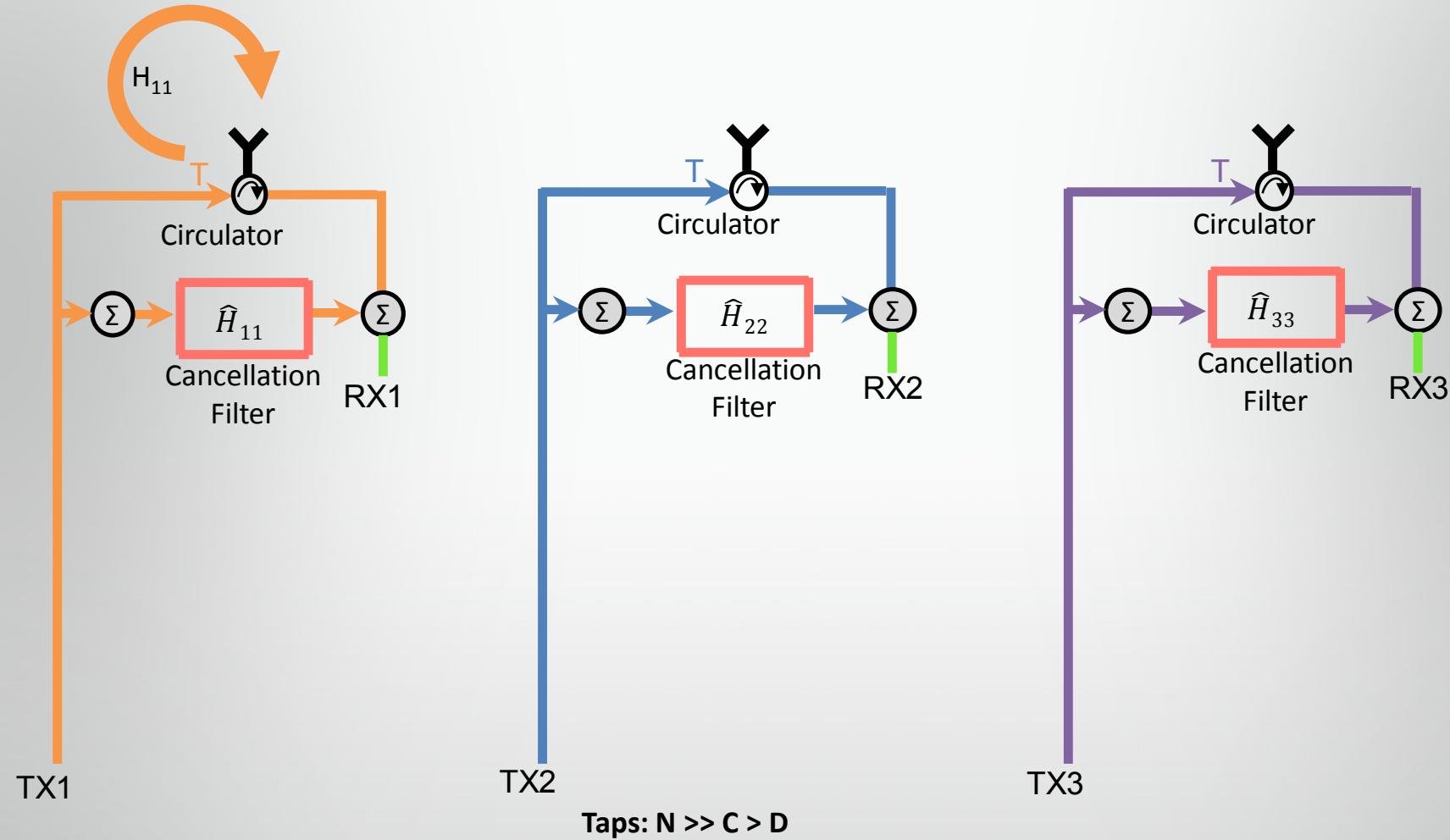
Reducing Complexity: Cascaded Cancellation



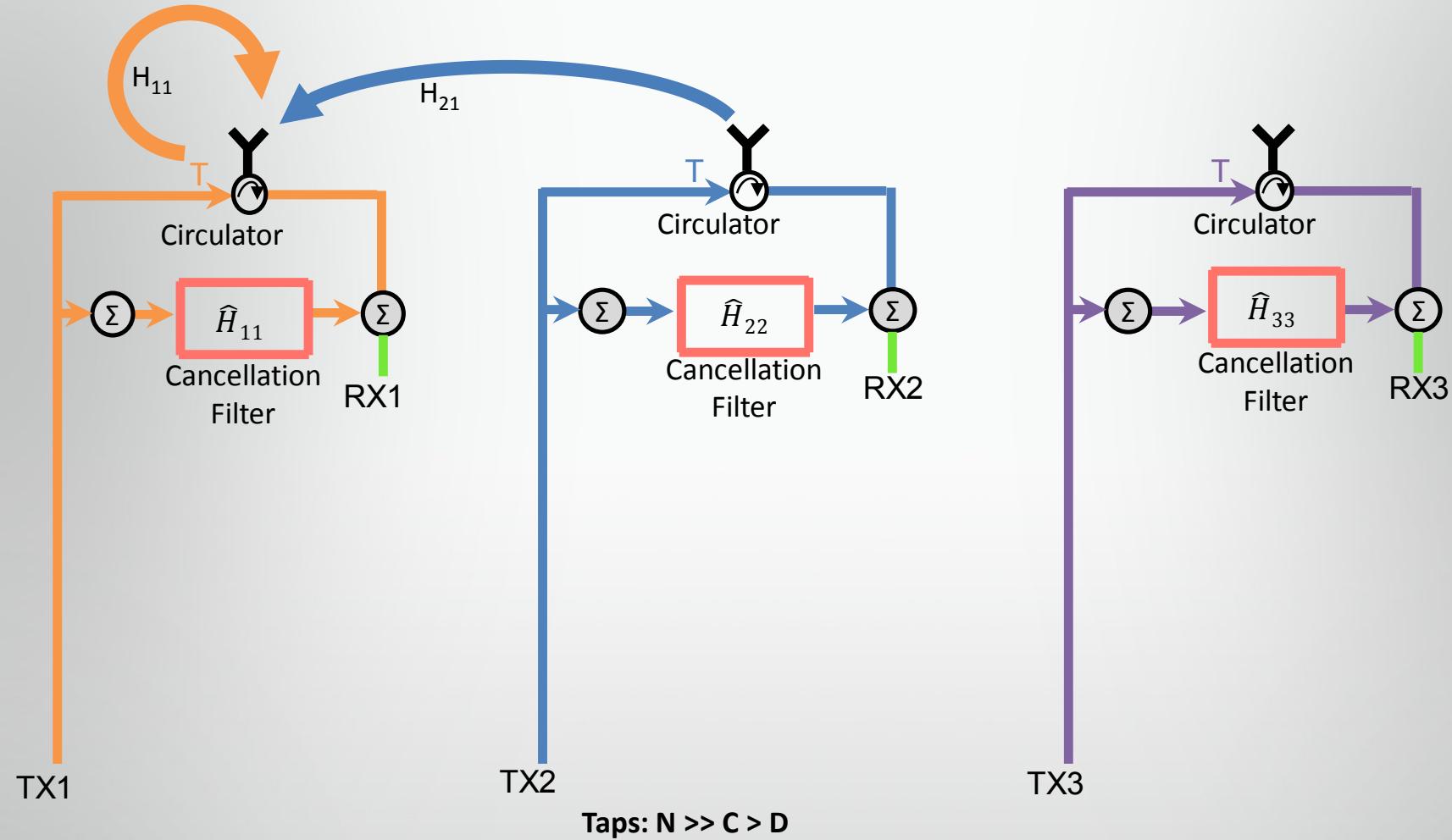
Total Taps: $N + C + D$, for Chain 1

General Complexity per chain: $\sim N \ll M.N$

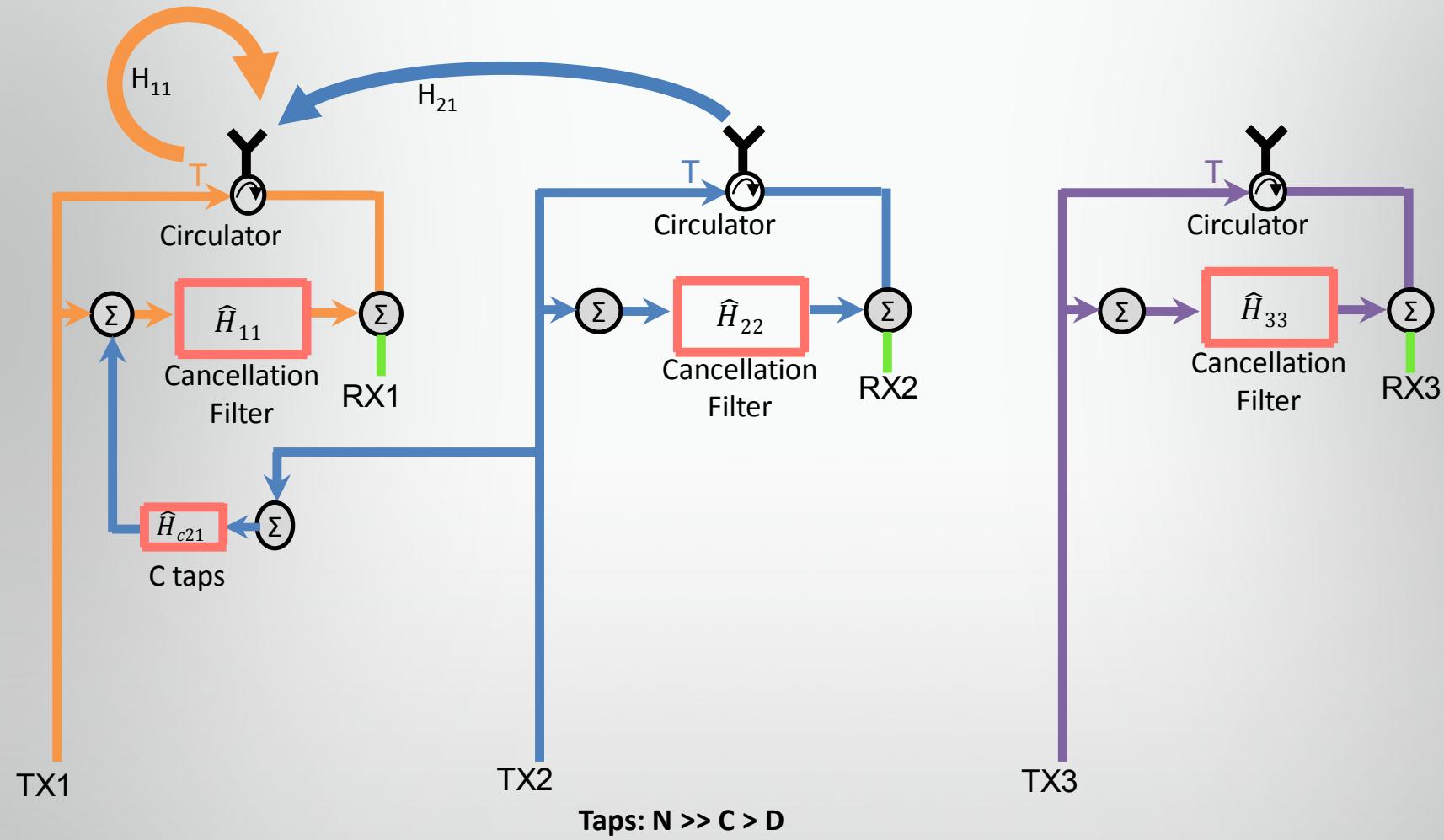
Complete Cascaded Design:



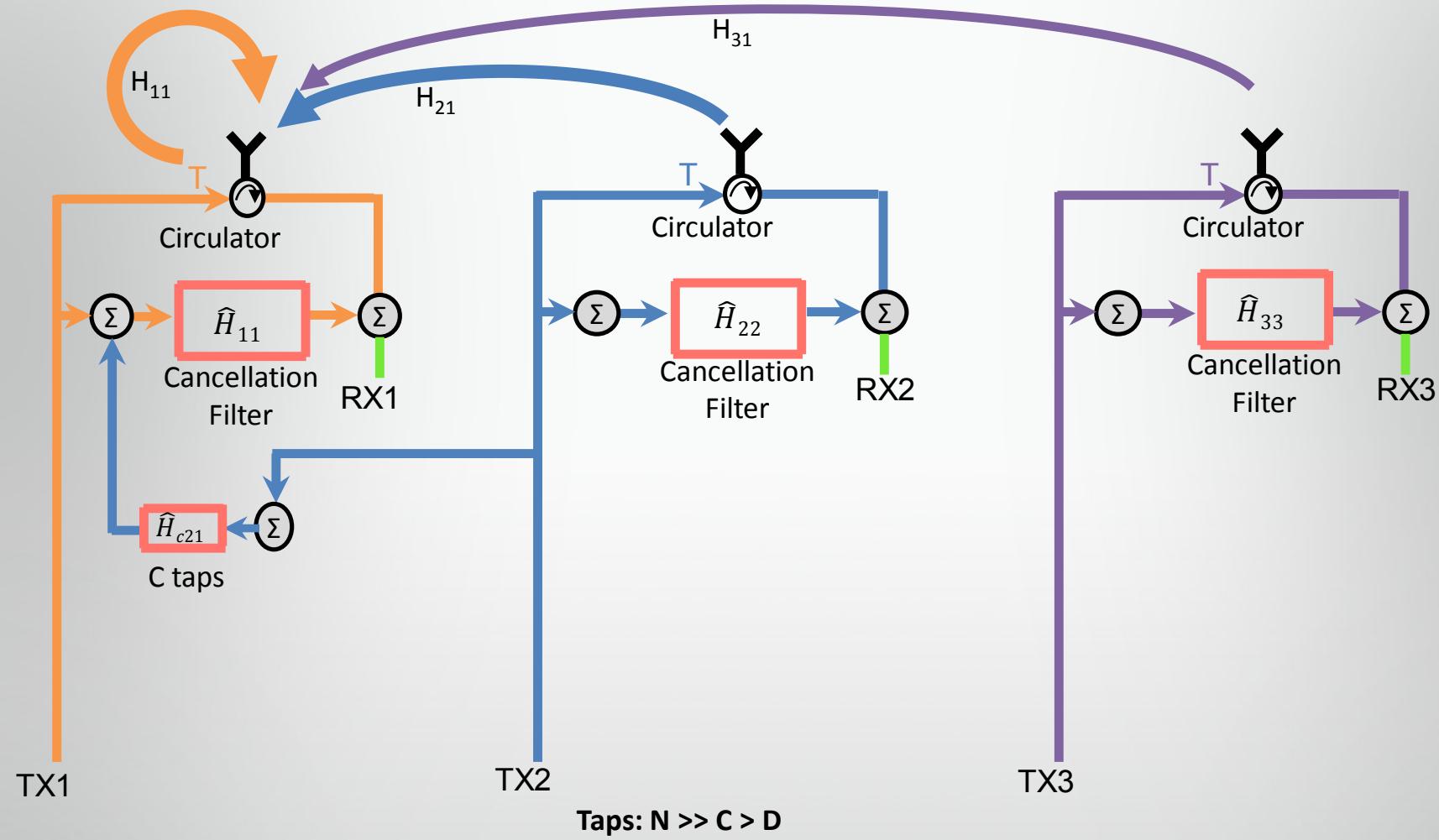
Complete Cascaded Design:



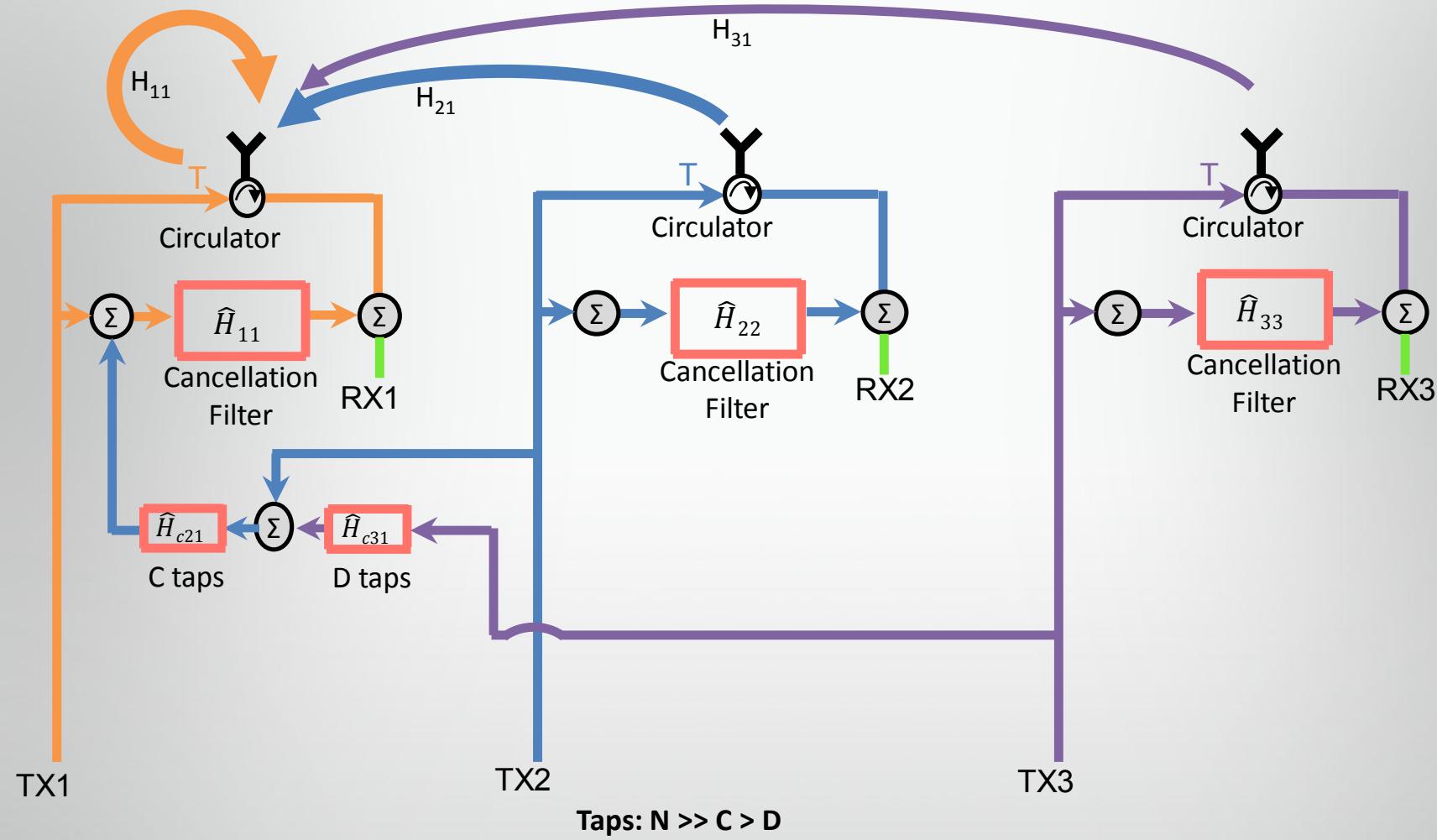
Complete Cascaded Design:



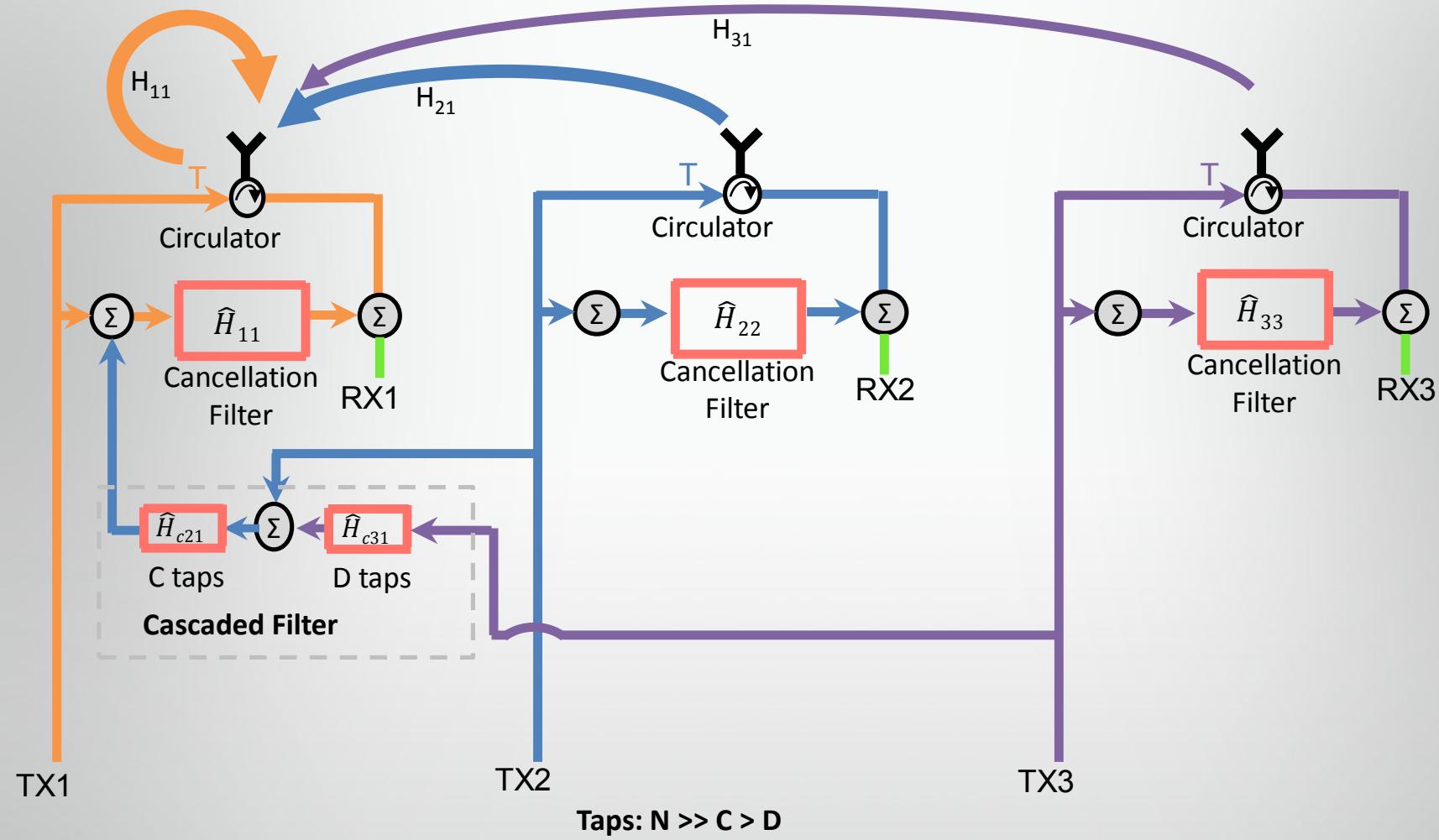
Complete Cascaded Design:



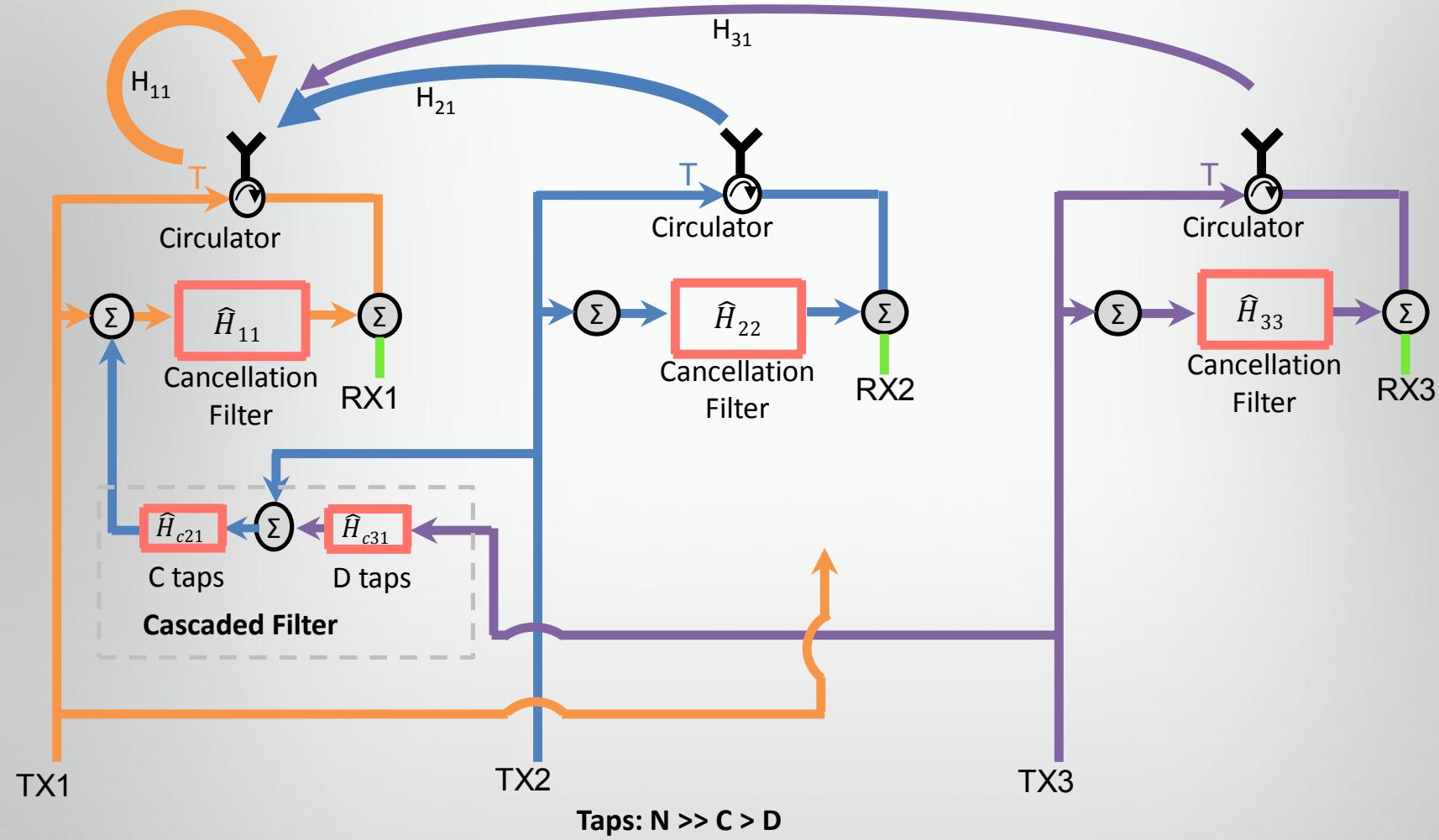
Complete Cascaded Design:



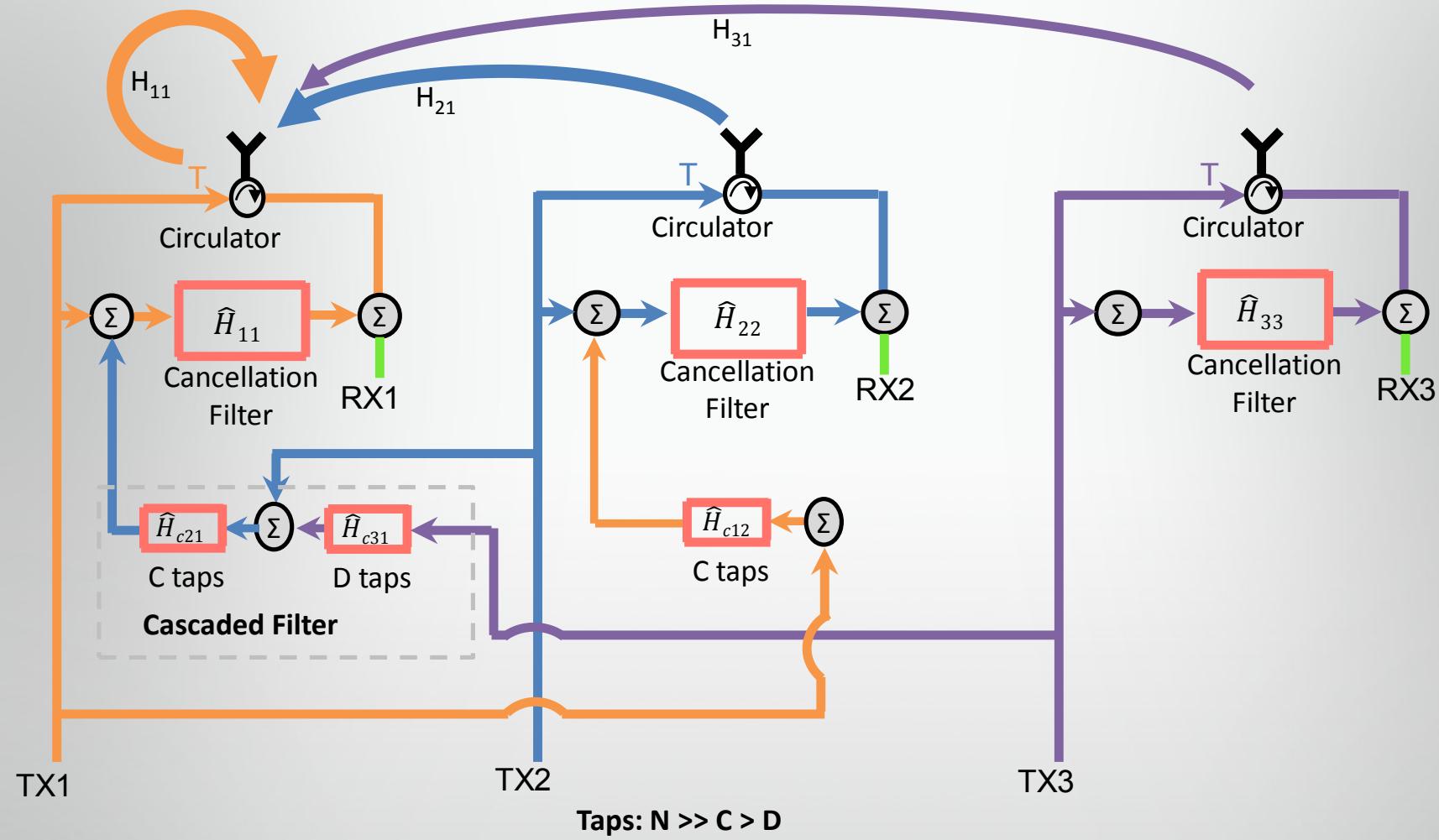
Complete Cascaded Design:



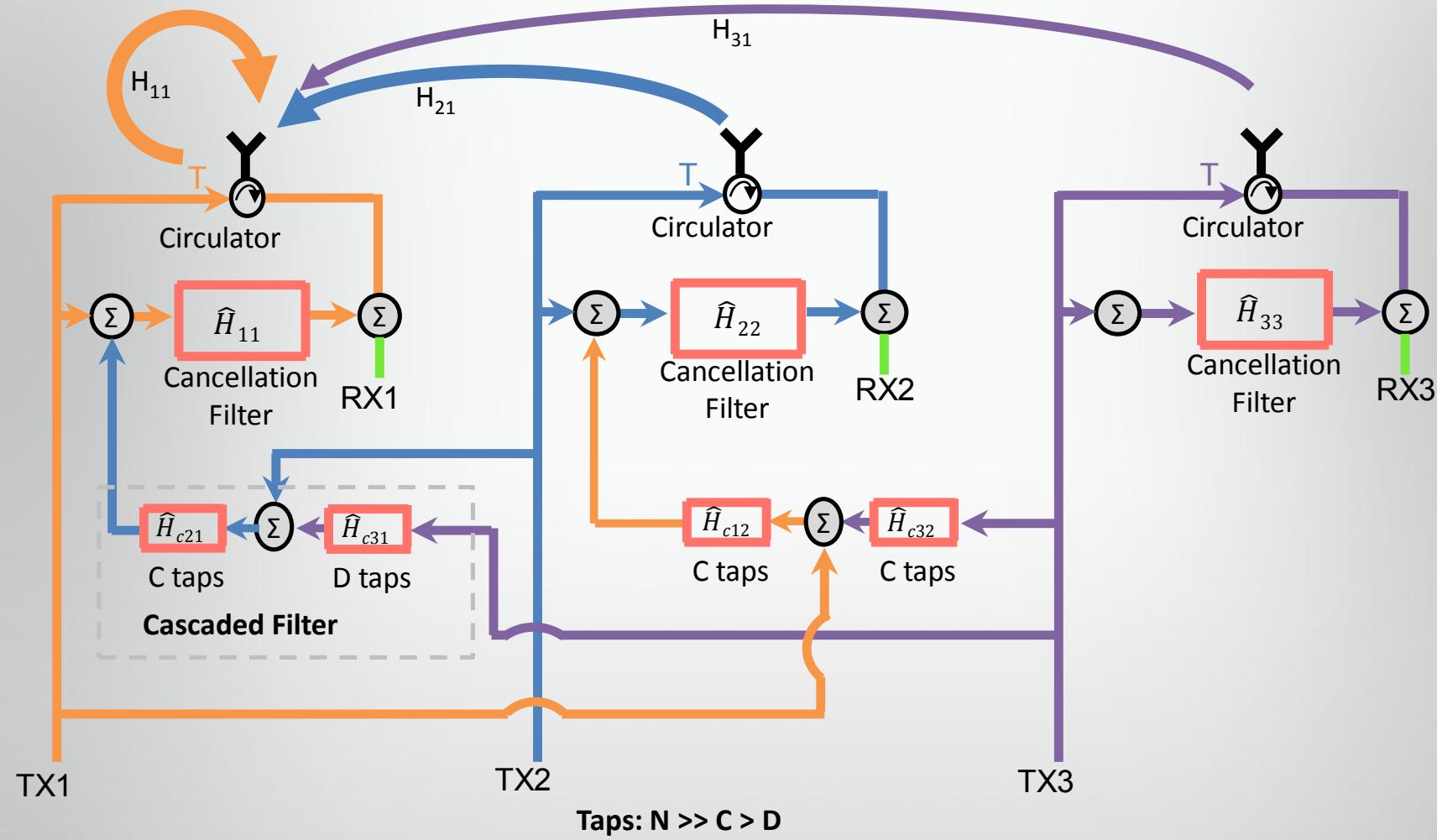
Complete Cascaded Design:



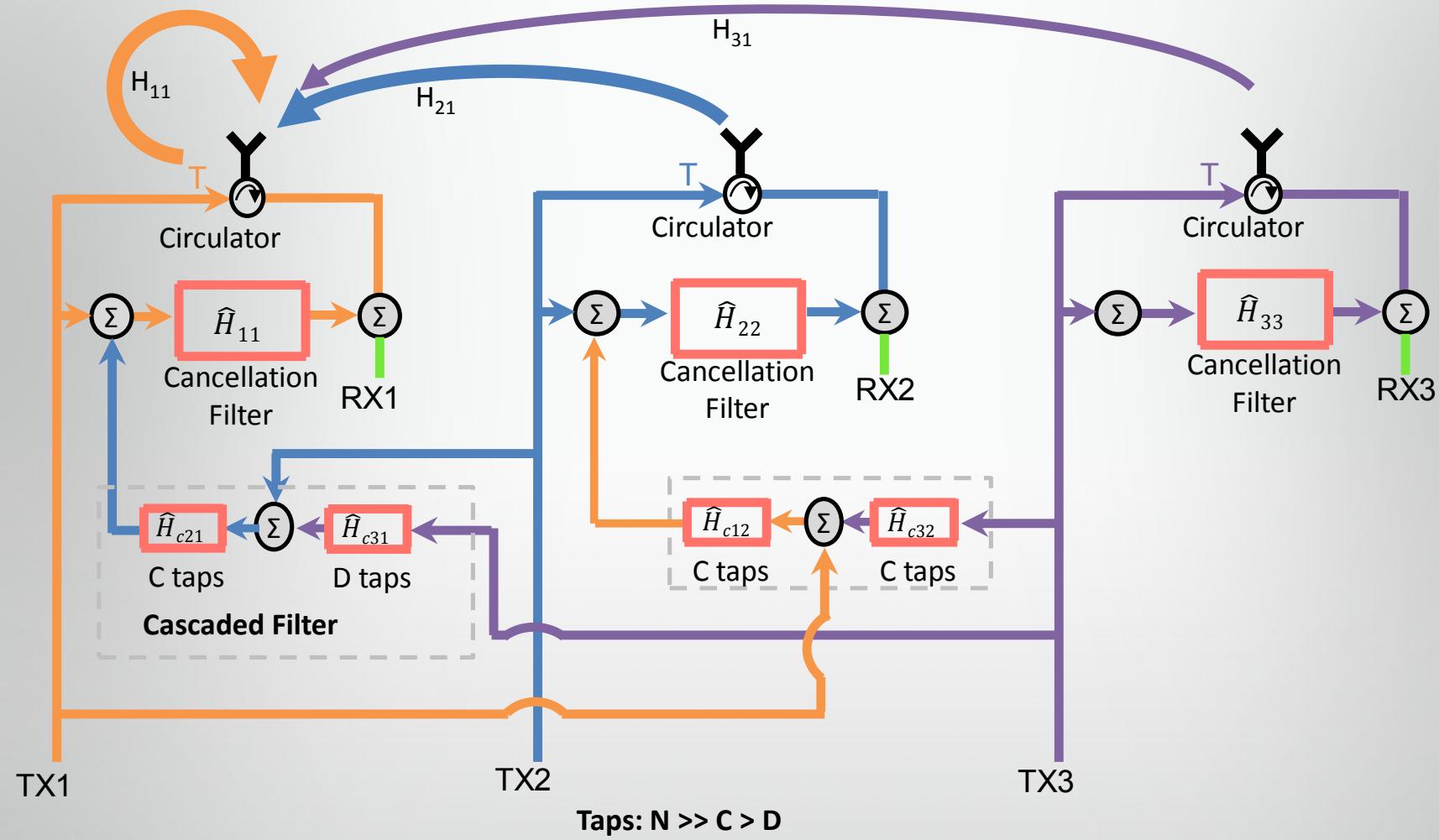
Complete Cascaded Design:



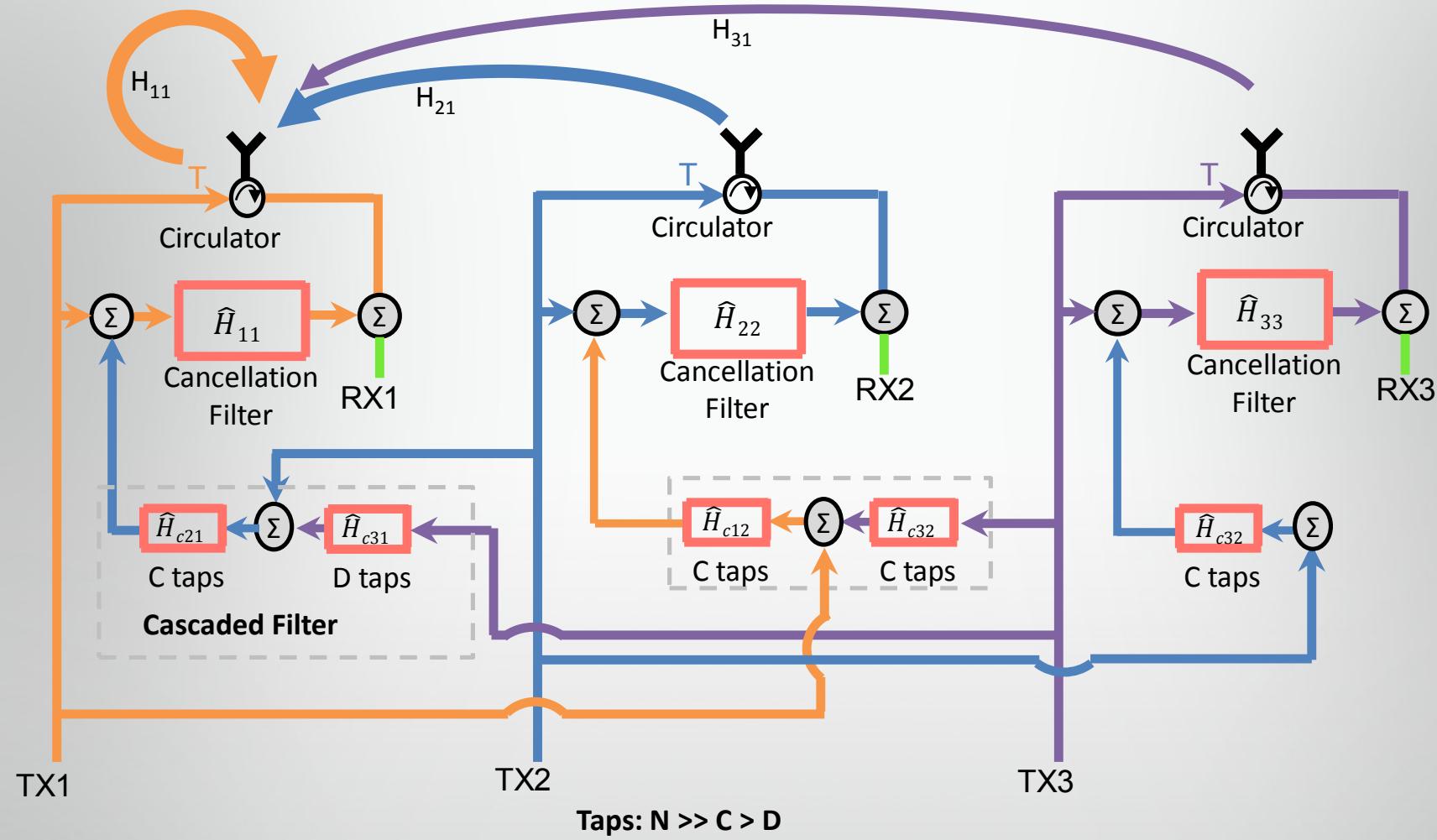
Complete Cascaded Design:



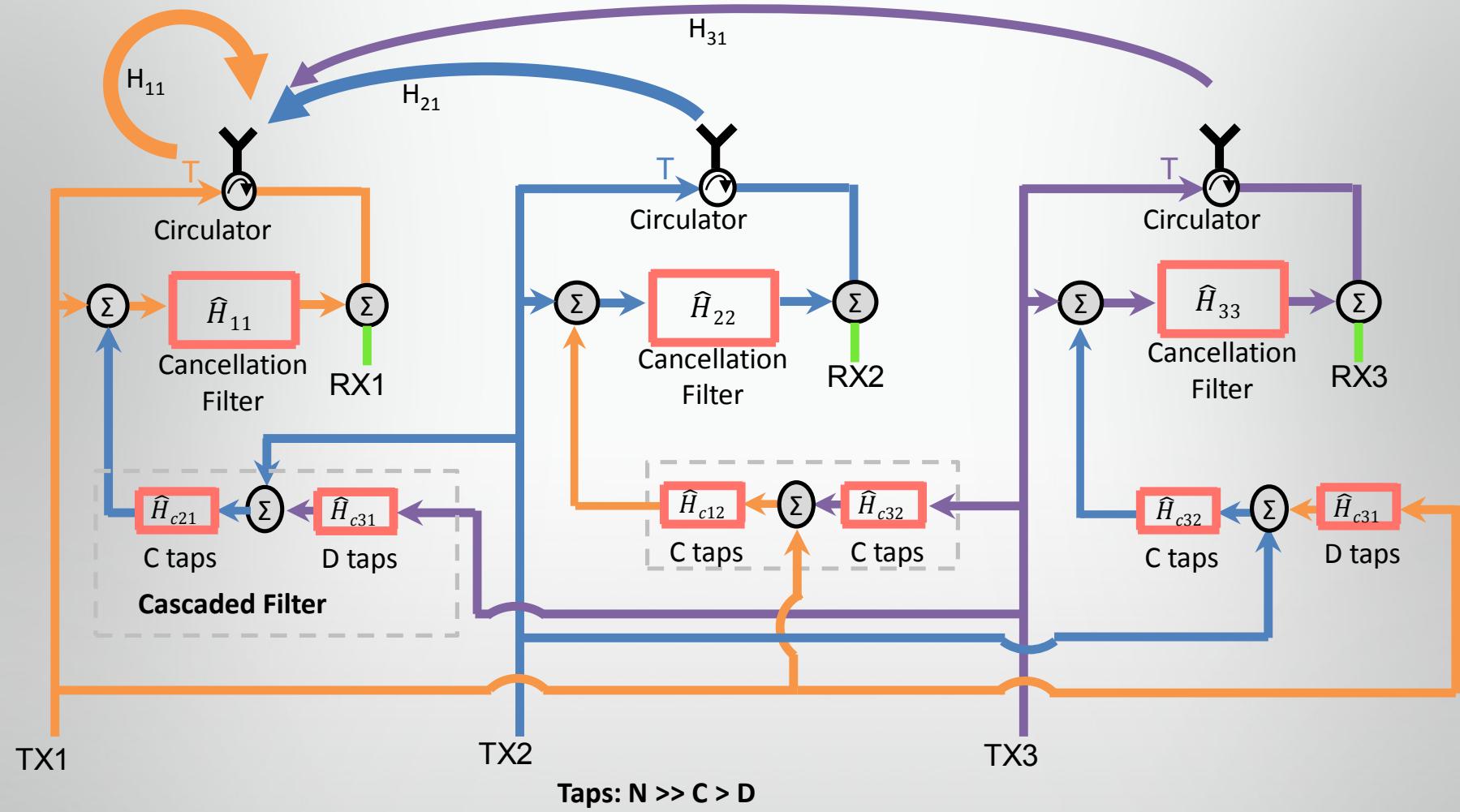
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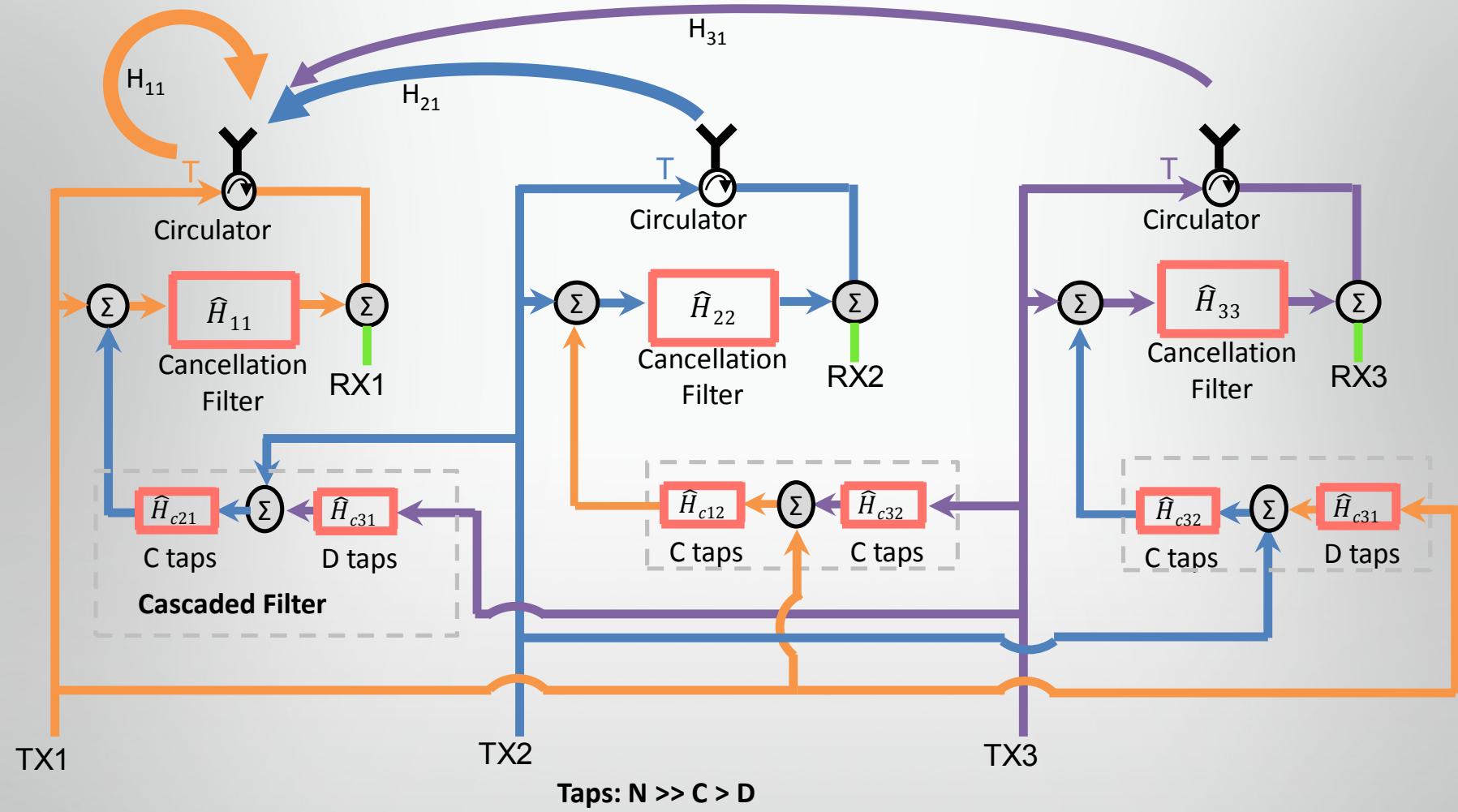
Complete Cascaded Design:



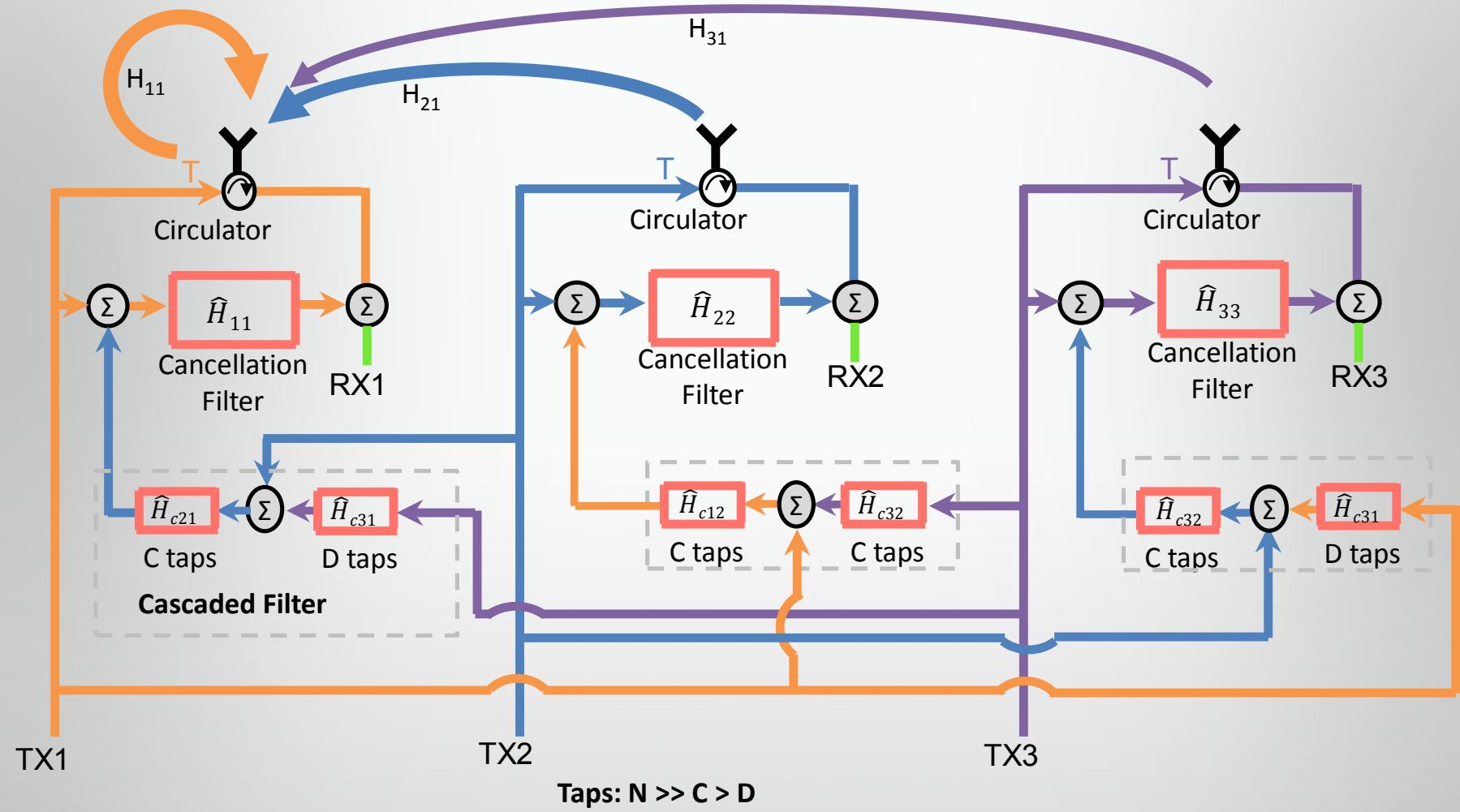
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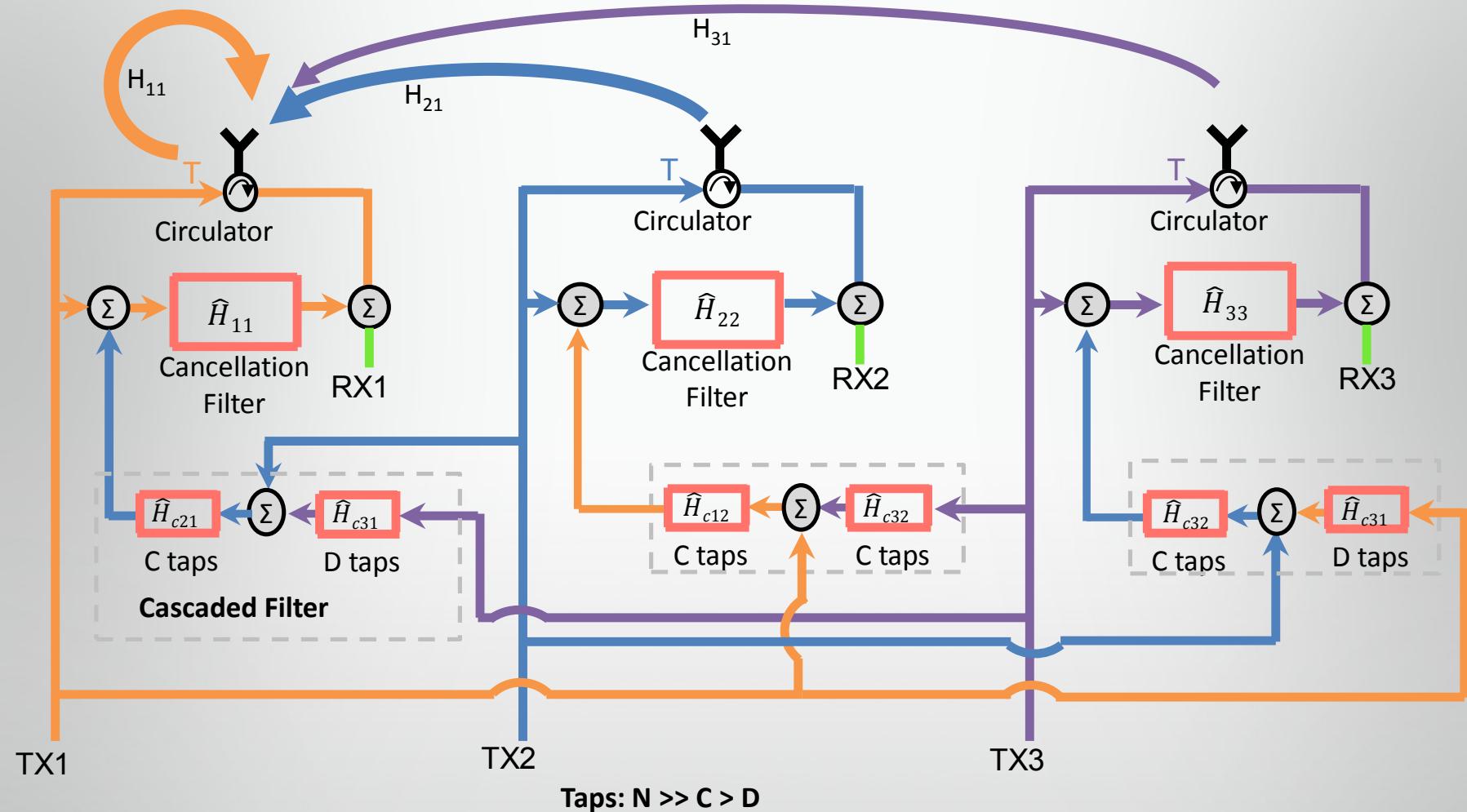
Complete Cascaded Design:



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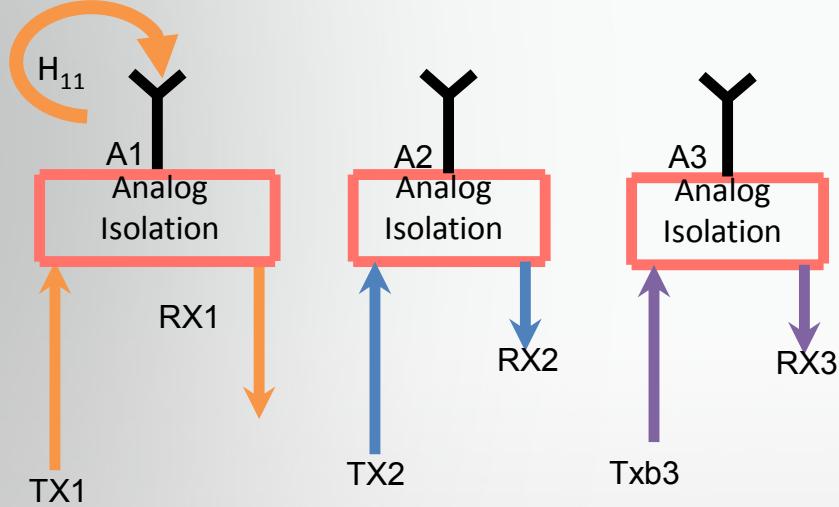


Total Taps: $3N + 4C + 2D$, for $M=3$

General Complexity: $\sim M \cdot N \ll M^2 \cdot N$

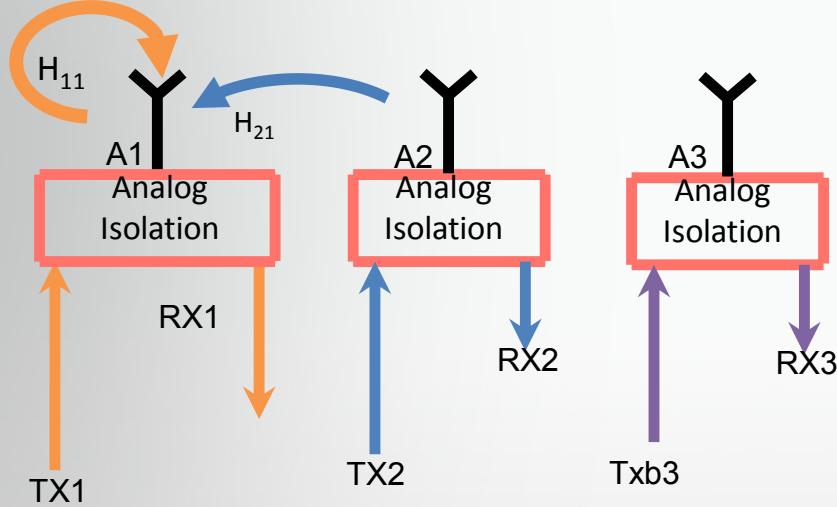
Interference Residue with Cascaded Design shows no degradation

Independent Training with SISO
Replication Design



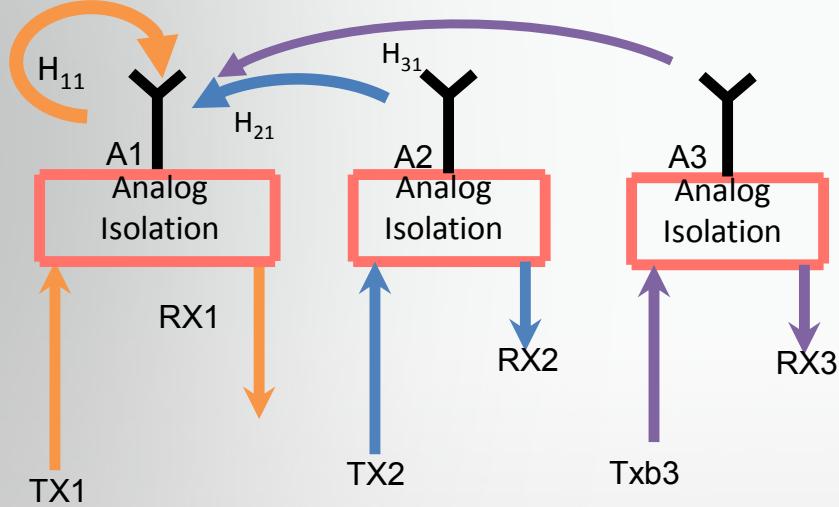
Interference Residue with Cascaded Design shows no degradation

Independent Training with SISO
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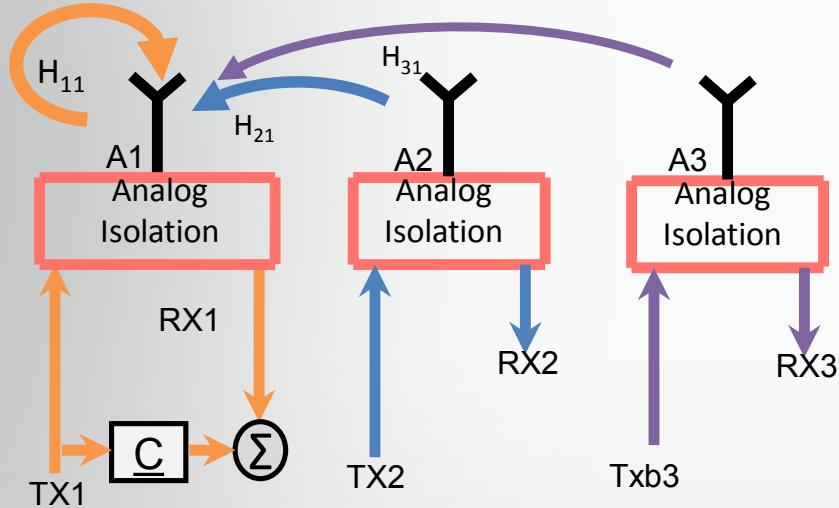
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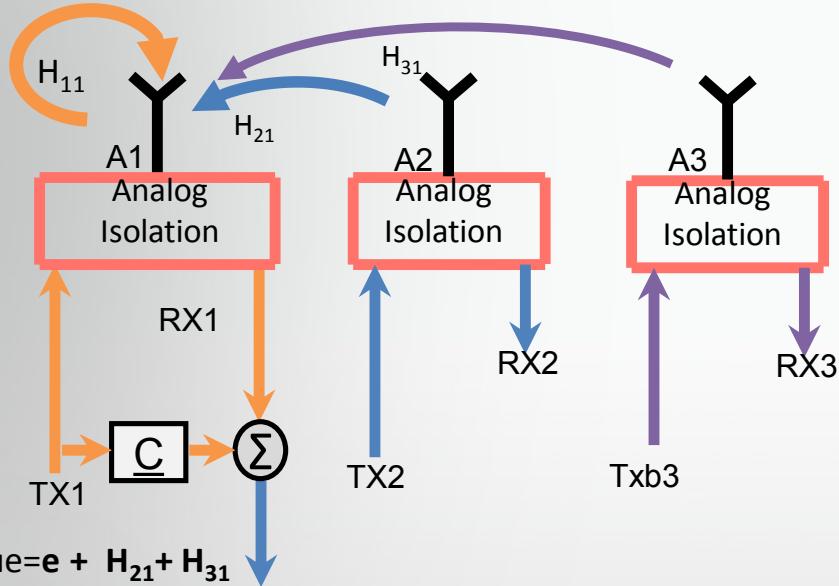
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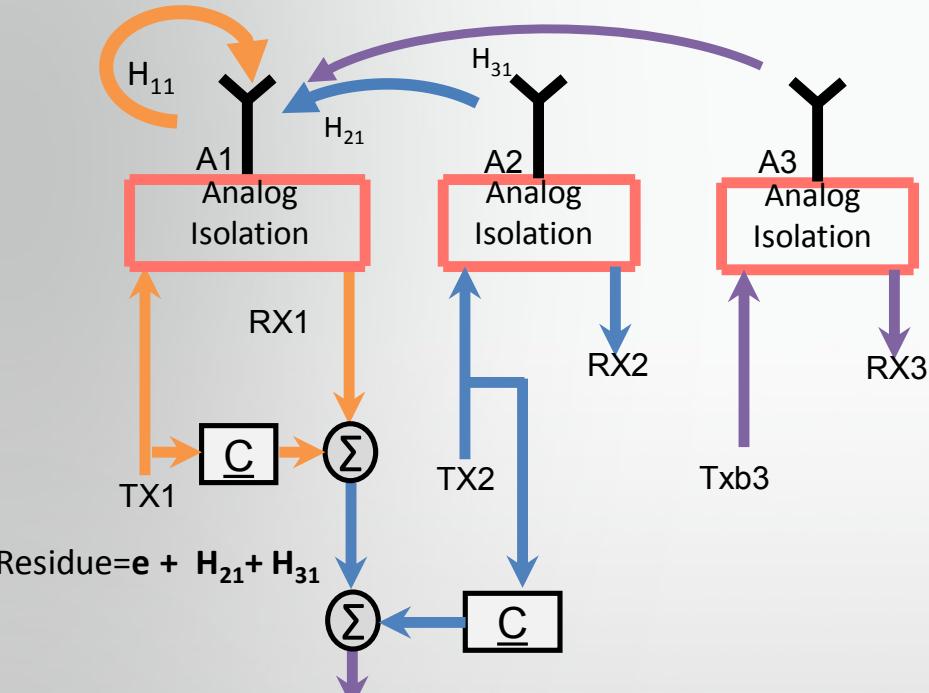
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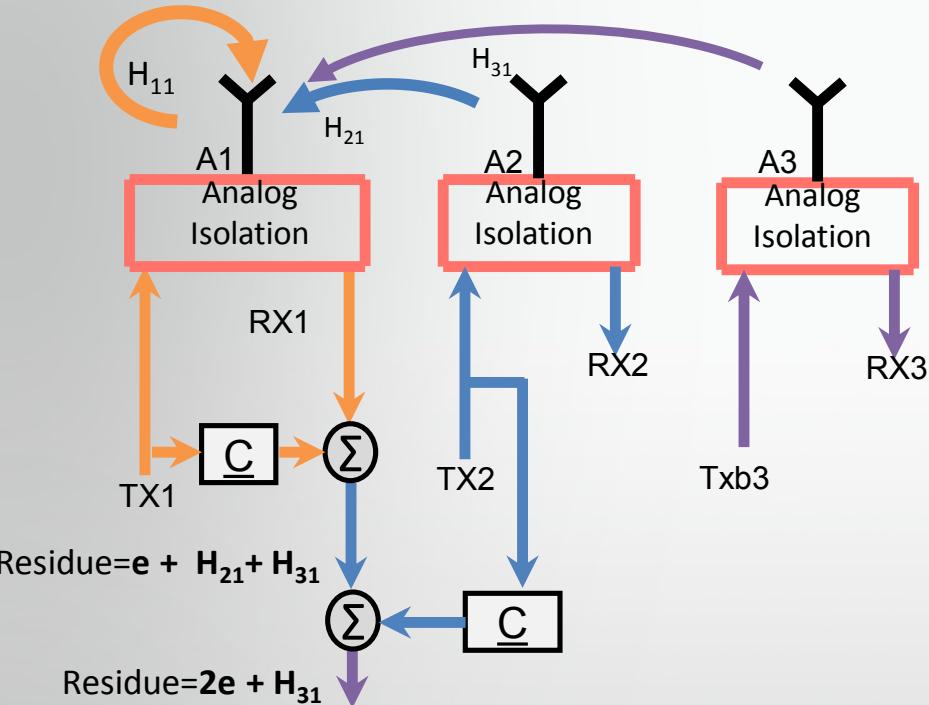
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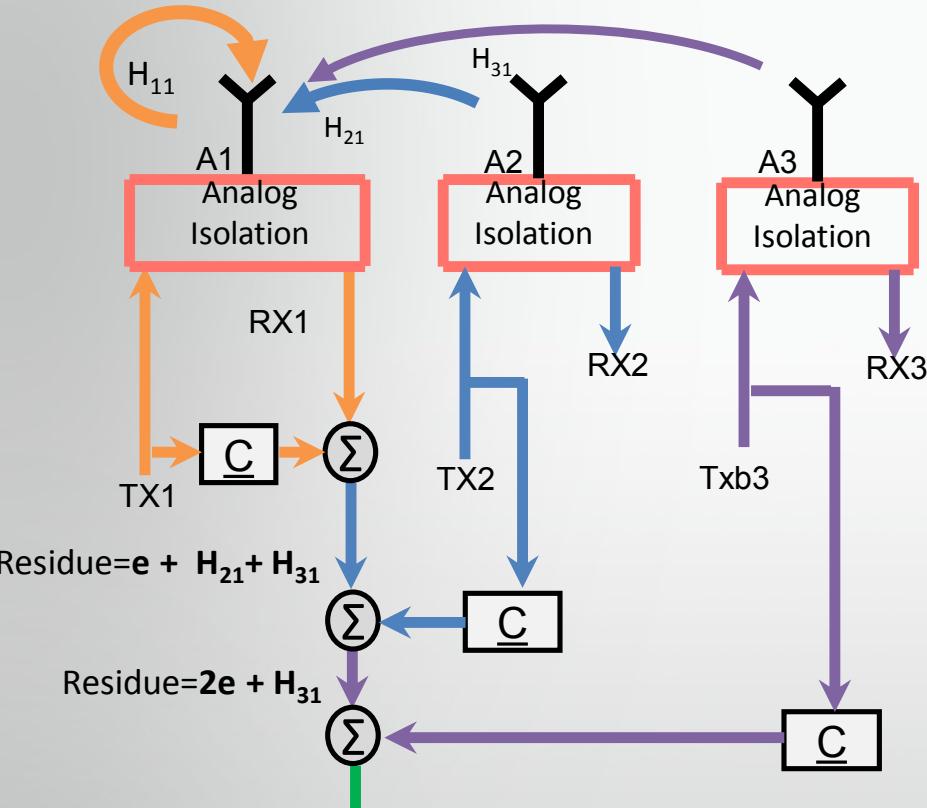
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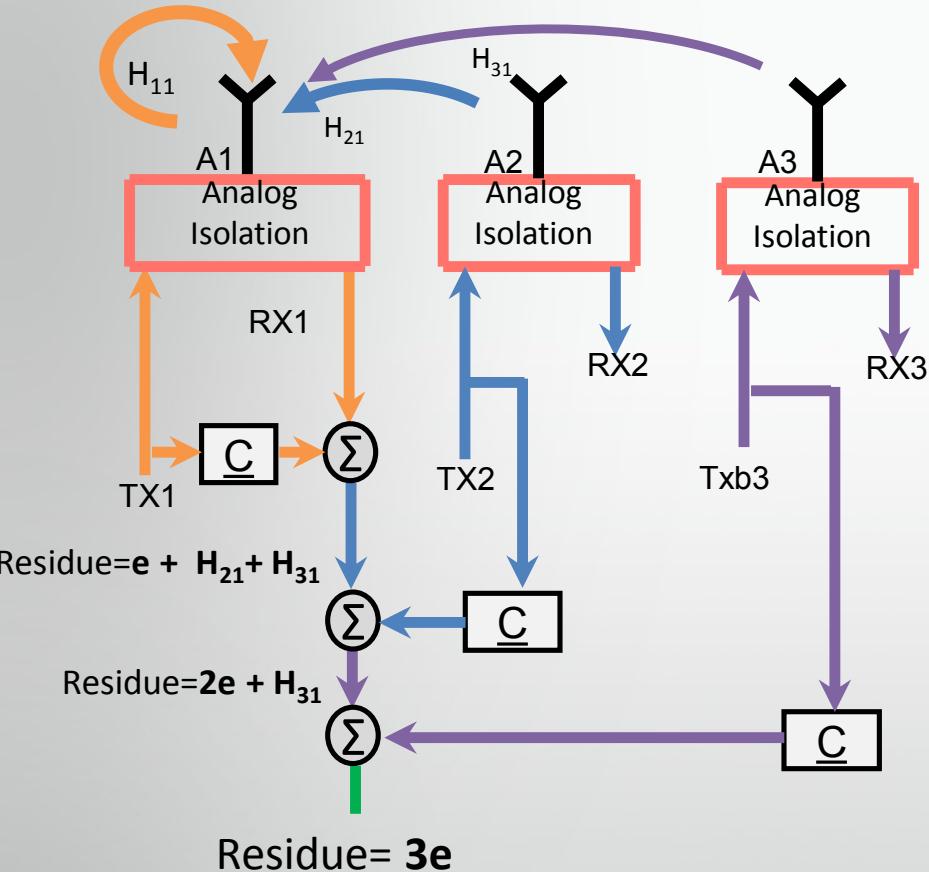
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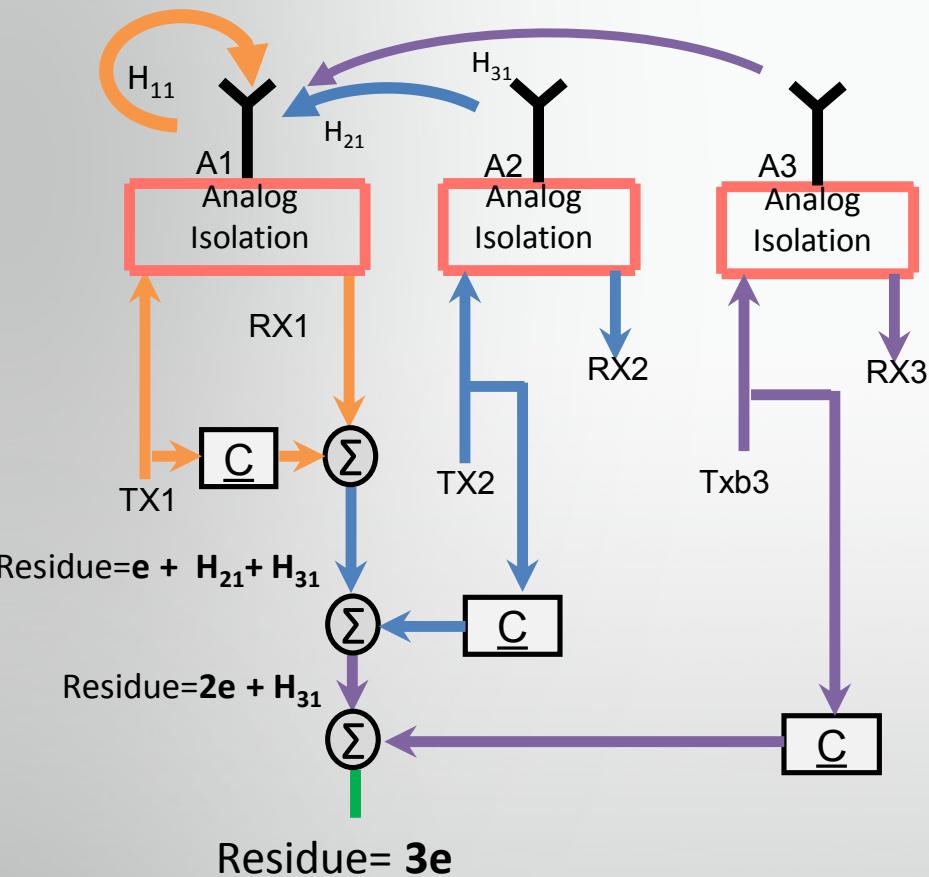
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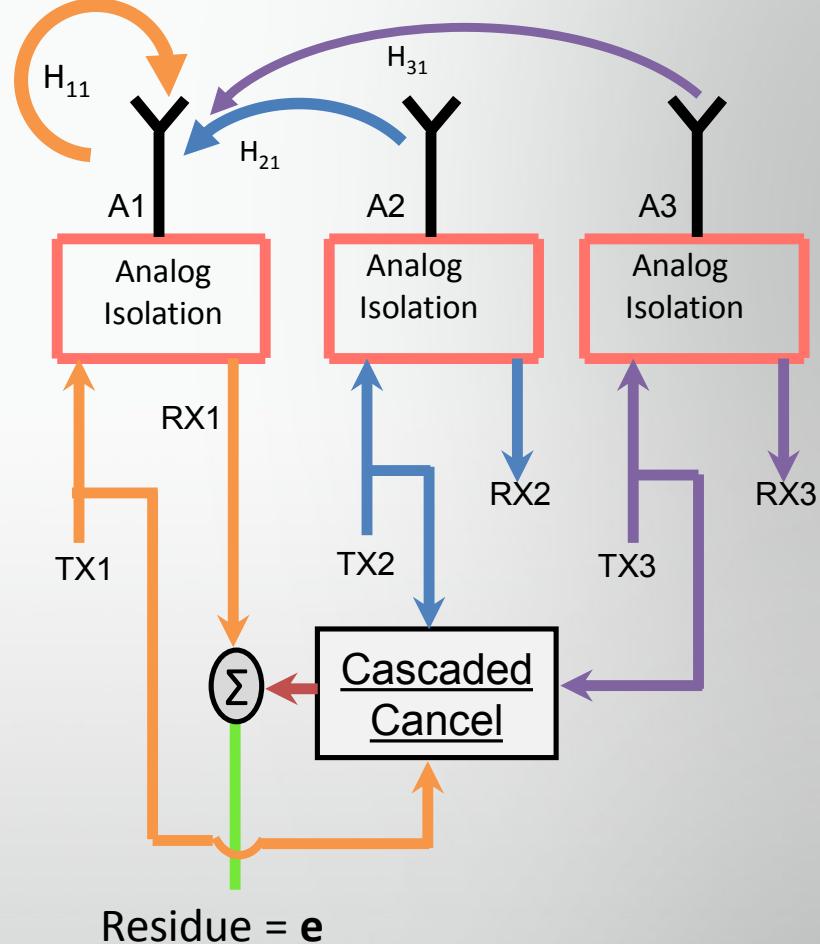


Interference Residue with Cascaded Design shows no degradation

Independent Training with SISO
Replication Design



Improved Joint Training with
Cascaded Design



Applications of Full-Duplex

- Doubling Throughput
- Hidden Terminals
- Simplified MAC
- Relays / Wireless Backhaul