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

[Diagram showing two transmission points (Tx1 and Tx2) with a receiver (Rx) placed at a distance of $d$ from Tx1 and $d+\lambda/2$ from Rx.]
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

$H \rightarrow$ Channel representing environmental reflections

Reflector
Circulator
TX  $\sum$  RX
State of the Art for SISO full duplex

Conceptual model

Reflector

\( H \rightarrow \) Channel
representing environmental reflections

Circulator

TX

Σ

RX

R+HT

4/25/2014
State of the Art for SISO full duplex

Conceptual model

Channel representing environmental reflections

\( H \rightarrow \) Channel

\( H \approx H \)
State of the Art for SISO full duplex

Conceptual model

\[
\mathbf{H} \rightarrow \text{Channel}
\]

representing environmental reflections

\[
\mathbf{H} \approx \mathbf{H}
\]

Circulator

Reflector

\[
\mathbf{R} + \mathbf{HT}
\]

TX

RX
State of the Art for SISO full duplex

Conceptual model

Practical Realization of Cancellation filter

Reflector

Channel representing environmental reflections

H ≈ H

Cancellation filter

R + HT

TX RF Frontend

RX RF Frontend
State of the Art for SISO full duplex

Channel representing environmental reflections

Circulator

Circulator

Reflector

Reflector

Conceptual model

Practical Realization of Cancellation filter

\[ H \rightarrow H \]

\[ \hat{H} \approx H \]

\[ \Sigma \]

\[ a_1 \]

\[ a_N \]

\[ \Sigma \]

\[ \Sigma \]

TX RF Frontend

TX RF Frontend

RX RF Frontend

TX

TX

RX

RX

H + HT

R + HT

R + δT

R + ε

Cancellation filter

Fixed delays

Tuning algorithm
State of the Art for SISO full duplex

\[ \hat{H} \approx H \]

Channel representing environmental reflections

Conceptual model

Reflector

Circulator

Cancellation filter

Digital Cancellation
Eliminates all Linear and Non-Linear Distortion

Practical Realization of Cancellation filter

R + HT

T

R + \varepsilon

TX

RX

TX RF Frontend

RF Cancellation Circuit

tuning algorithm

\[ \sum_{i=1}^{N} a_i d_i \]

Reflector

Circulator

R + \varepsilon

TX

RX

R + HT

T

R + \varepsilon

TX RF Frontend

Digital Cancellation
Eliminates all Linear and Non-Linear Distortion

Practical Realization of Cancellation filter
Full duplex designs are conceptually realizing an adaptive filter that closely matches the environmental reflections. Digital Cancellation eliminates all linear and non-linear distortion.
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?

Reflector

Circulator

TX1

RX1

Circulator

TX2

RX2

Circulator

TX3

RX3
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?

Reflector

H_{21}  

Circulator

H_{11}

TX1  RX1

H_{22}

Circulator

H_{12}

TX2  RX2

H_{23}

Circulator

H_{13}

TX3  RX3
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?

Reflector

TX1  H_{11}, H_{21}  RX1

Circulator

TX2  H_{12}, H_{22}  RX2

Circulator

TX3  H_{13}, H_{23}  RX3
How is the MIMO full duplex problem different?

Reflector

Circulator

TX1    RX1

H_{11}, H_{21}

Circulator

TX2    RX2

H_{12}, H_{22}

Circulator

TX3    RX3

H_{13}, H_{23}
How is the MIMO full duplex problem different?

Reflector

$H_{11}, H_{21}, H_{31}$

$H_{12}, H_{22}, H_{32}$

$H_{13}, H_{23}, H_{33}$
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?

[Diagram of a 3 Antenna Full Duplex MIMO Radio with labels T, H_{11}, H_{21}, H_{31}, H_{12}, H_{22}, H_{32}, H_{13}, H_{23}, H_{33}.]
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?

3 Antenna Full Duplex MIMO Radio

Reflector

Circulator

TX1

RX1

H_{11}, H_{21}, H_{31}

Circulator

TX2

H_{12}, H_{22}, H_{32}

Circulator

TX3

H_{13}, H_{23}, H_{33}

Circulator

RX2

RX3
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?
How is the MIMO full duplex problem different?

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

3 Antenna Full Duplex MIMO Radio
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

$H_{11}$
Naïve Solution: Replicates SISO design
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

TX1

RX1

Circulator

\( \hat{H}_{11} \)

Cancellation filter

\( H_{11} \)

\( \Sigma \)
Naïve Solution: Replicates SISO design

$H_{11}$

Circulator

$\hat{H}_{11}$

Cancellation filter

RX1

TX1

3 Antenna Full Duplex MIMO Radio
Naïve Solution: Replicates SISO design
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

**Circulator**

**Cancellation filter**

$H_{11}$

$H_{22}$

$H_{33}$

TX1

RX1

TX2

RX2
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

TX1

RX1

H_{11}

Circulator

Cancellation filter

TX2

RX2

H_{22}

Circulator

Cancellation filter

TX3

RX3

H_{33}

Circulator

Cancellation filter
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

TX1

RX1

Circulator

Circulator

Circulator

\( H_{11} \)

\( H_{21} \)

\( H_{22} \)

\( H_{33} \)

\( \hat{H}_{11} \)

\( \hat{H}_{22} \)

\( \hat{H}_{33} \)

Circulator

Circulator

Circulator

Cancellation filter

Cancellation Filter

Cancellation Filter

RX3
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

A1

\( H_{11} \)

\( H_{21} \)

\( H_{33} \)

Circulator

TX1

RX1

\( \hat{H}_{11} \)

Cancellation filter

\( \xi \)

A2

\( H_{22} \)

Circulator

TX2

RX2

\( \hat{H}_{22} \)

Cancellation filter

\( \xi \)

A3

\( H_{33} \)

Circulator

TX3

RX3

\( \hat{H}_{33} \)

Cancellation filter

\( \xi \)
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

\[ H_{11} \leftarrow H_{21} \rightarrow H_{22} \rightarrow H_{33} \]

Circulator

\[ \hat{H}_{11} \]

Cancellation filter

RX1

\[ \hat{H}_{21} \]

Cancellation filter

RX2

\[ \hat{H}_{22} \]

Cancellation filter

RX3

\[ \hat{H}_{33} \]
Naïve Solution: Replicates SISO design

Circulator

Cancellation filter

H_{11}

H_{21}

H_{31}

TX1

RX1

Circulator

Cancellation filter

H_{21}

H_{11}

H_{22}

TX2

RX2

Circulator

Cancellation filter

H_{33}

H_{22}

H_{21}

TX3

RX3

3 Antenna Full Duplex MIMO Radio
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

\[ H_{11} \]
\[ H_{21} \]
\[ H_{22} \]
\[ H_{31} \]
\[ H_{33} \]

TX1 → RX1
TX2 → RX2
TX3 → RX3

Circulator
Cancellation Filter

A1
A2
A3

\[ \hat{H}_{11} \]
\[ \hat{H}_{21} \]
\[ \hat{H}_{22} \]
\[ \hat{H}_{33} \]
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

TX1 → RX1
TX2 → RX2
TX3 → RX3

Circulator
Cancellation filter

H_{11} → A1
H_{21} → A2
H_{31} → A3

Cancellation Filter

H_{11} \tilde{H}_{11}
H_{21} \tilde{H}_{21}
H_{31} \tilde{H}_{31}
H_{22} \tilde{H}_{22}
H_{33} \tilde{H}_{33}
Naïve Solution: Replicates SISO design

A1

H_{11}

Circulator

H_{11}^\dagger

Cancellation filter

RX1

TX1

A2

H_{21}

Circulator

H_{21}^\dagger

Cancellation filter

RX2

TX2

A3

H_{31}

Circulator

H_{31}^\dagger

Cancellation filter

RX3

TX3

3 Antenna Full Duplex MIMO Radio
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

\( H_{11} \)
\( H_{21} \)
\( H_{22} \)
\( H_{31} \)
\( H_{32} \)
\( H_{33} \)

Circulator
Cancellation filter
Circulator
Cancellation filter
Circulator
Cancellation filter

RX1
RX2
RX3

TX1
TX2
TX3
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

Circulator

Cancellation filter

RX1

TX1

Circulator

Cancellation filter

RX2

TX2

Circulator

Cancellation filter

RX3

TX3
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

H_{11}  H_{12}  H_{21}  H_{22}  H_{31}  H_{32}  H_{33}

TX1  TX2  TX3

H_{11}^\dagger  H_{21}^\dagger  H_{31}^\dagger

RX1  RX2  RX3

Circulator  Cancellation filter  Cancellation filter  Cancellation filter  Cancellation filter  Cancellation Filter  Cancellation Filter  Cancellation Filter
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

Circulator

Cancellation filter

RX1

TX1

Cancellation filter

H12

H21

H31

H32

H33

Circulator

Cancellation filter

RX2

TX2

Cancellation Filter

H11

H22

H31

H32

H33

Circulator

Cancellation Filter

RX3

TX3
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

Circulator
Circulator
Circulator

Cancellation filter
Cancellation filter
Cancellation Filter

RX1
RX2
RX3

TX1
TX2
TX3

\( H_{11} \)
\( H_{12} \)
\( H_{12} \)

\( H_{21} \)
\( H_{21} \)
\( H_{21} \)

\( H_{22} \)
\( H_{22} \)
\( H_{22} \)

\( H_{31} \)
\( H_{31} \)
\( H_{31} \)

\( H_{32} \)
\( H_{32} \)
\( H_{32} \)

\( H_{33} \)
\( H_{33} \)
\( H_{33} \)
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

Circulator

Cancellation filter

RX1

TX1

H_{11}

H_{12}

H_{21}

H_{22}

H_{31}

H_{32}

H_{33}

A1

A2

A3

Circulator

Cancellation filter

RX2

TX2

Circulator

Cancellation filter

RX3

TX3
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

TX1

RX1

TX2

RX2

TX3

RX3
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

Circulator

Cancellation filter

The diagram shows a 3 antenna full duplex MIMO radio system with various cancellation filters and circulators.
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

\[ H_{11} \]  
\[ H_{12} \]  
\[ H_{21} \]  
\[ H_{22} \]  
\[ H_{23} \]  
\[ H_{31} \]  
\[ H_{32} \]  
\[ H_{33} \]  

\[ \Sigma \]  

\[ T \]  

\[ \hat{H}_{11} \]  
\[ \hat{H}_{21} \]  
\[ \hat{H}_{31} \]  
\[ \hat{H}_{22} \]  
\[ \hat{H}_{32} \]  
\[ \hat{H}_{33} \]  

\[ A_1 \]  
\[ A_2 \]  
\[ A_3 \]  

\[ \text{Circulator} \]  
\[ \text{Cancellation filter} \]  
\[ \text{Cancellation filter} \]  
\[ \text{Circulator} \]  
\[ \text{Cancellation filter} \]  
\[ \text{Cancellation filter} \]  
\[ \text{Circulator} \]  
\[ \text{Cancellation filter} \]  
\[ \text{Cancellation filter} \]  

\[ TX_1 \]  
\[ RX_1 \]  
\[ TX_2 \]  
\[ RX_2 \]  
\[ TX_3 \]  
\[ RX_3 \]
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

Circulator

Circulator

Circulator

RX1

RX2

RX3

TX1

TX2

TX3

A1

A2

A3
Naïve Solution: Replicates SISO design

3 Antenna Full Duplex MIMO Radio

Total 9N Taps, for M=3
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 → 5dB residue)
Key Idea: Reducing Complexity

\[ H_{11} \]

Circulator

\[ \hat{H}_{11} \]

Cancellation filter

TX1 → Circulator → RX1

\[ T \]
Key Idea: Reducing Complexity

$H_{11}$

Circulator

$\hat{H}_{11}$

Cancellation filter

TX1 → RX1

TX2 → RX2

Circulator
Key Idea: Reducing Complexity

TX1 → Circulator → Cancellation filter \(\hat{H}_{11}\) → \(T\) → Circulator → RX1

TX2 → Circulator → RX2

\(H_{11}\) → \(T\) → \(H_{21}\)
Can we reuse the self talk cancellation filter to also cancel the cross talk?

Key Idea: Reducing Complexity
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
- Share Reflectors
- 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?

- Share Environment
- Share Reflectors
- Self talk and cross talk transfer function are related as they undergo similar environment.
- A lot of work for modeling self-talk is already done, we need to create only the difference in self talk and cross talk.
Why can self talk cancellation filter be used to partly model cross talk?

- Share Environment
- Share Reflectors
- Self talk and cross talk transfer function are related as they undergo similar environment.
- A lot of work for modeling self-talk is already done, we need to create only the difference in self talk and cross talk.

\[
H_{21}(f) = H_{\text{cas}}(f) \cdot H_{11}(f)
\]
Why can self talk cancellation filter be used to partly model cross talk?

- Share Environment
- Share Reflectors
- Self talk and cross talk transfer function are related as they undergo similar environment.
- A lot of work for modeling self-talk is already done, we need to create only the difference in self talk and cross talk.

\[ H_{21}(f) = H_{\text{cas}}(f) \cdot H_{11}(f) \]

Can we leverage this relationship to reduce the cancellation complexity?
Empirical Observation

\[ H_{21}(f) = H_{\text{cas}}(f) \cdot H_{11}(f) \]

Cascade Transfer Function
Empirical Observation

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

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

\[ H_{21}(f) = H_{\text{cascade}}(f) \cdot H_{11}(f) \]

Cascade Transfer Function

- Cascade Transfer Function
- Learning Algorithm
- Complexity Reduction

Collect cross talk and self talk for various indoor environments

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
Reducing Complexity: Cascaded Cancellation

Circulator

\[ H_{11} \]

\[ H_{21} \]

\[ H_{31} \]

Circulator

Circulator

\[ H_{11} \] Cancellation Filter N taps

TX1

TX2

TX3

RX1

RX2

RX3
Reducing Complexity: Cascaded Cancellation

\[
\begin{align*}
\hat{H}_{11} & \quad \text{Circulator} \\
\hat{H}_{c21} & \quad \text{filter C taps} \\
\end{align*}
\]

\[
\begin{align*}
\Sigma & \quad \text{N taps} \\
\end{align*}
\]
Reducing Complexity: Cascaded Cancellation

- $H_{11}$
- $H_{21}$
- $H_{31}$

Circulator

Cancellation Filter
- N taps
- C taps
- D taps

$\hat{H}_{11}$
$\hat{H}_{c21}$
$\hat{H}_{c31}$
Reducing Complexity: Cascaded Cancellation

TX1 \xrightarrow{\Sigma} \hat{H}_{11} \xrightarrow{\Sigma} RX1

Circulator

Circulator

\begin{align*}
\hat{H}_1 &= H_{11} \\
\hat{H}_2 &= H_{21} \\
\hat{H}_3 &= H_{31}
\end{align*}

RX2 \xrightarrow{T} TX3

RX3

Cascaded Filters

\begin{align*}
\hat{H}_{c21} &= \text{filter C taps} \\
\hat{H}_{c31} &= \text{filter D taps}
\end{align*}
Reducing Complexity: Cascaded Cancellation

\[ H_{11} \quad H_{21} \quad H_{31} \]

Cascaded Filters

\[ \hat{H}_{11} \quad \hat{H}_{c21} \quad \hat{H}_{c31} \]

Taps: \( N >> C > D \)
Reducing Complexity: Cascaded Cancellation

Total Taps: N+ C + D, for Chain 1
General Complexity per chain: \( \sim N \ll M \cdot N \)
Complete Cascaded Design:

\[ H_{11} \]

\[ \sum \]

Circulator

\[ \hat{H}_{11} \]

Circulator

\[ \sum \]

Circulator

\[ \sum \]

Circulator

\[ \hat{H}_{22} \]

Circulator

\[ \sum \]

Circulator

\[ \sum \]

Circulator

\[ \hat{H}_{33} \]

Circulator

\[ \sum \]

TX1

RX1

TX2

RX2

TX3

RX3

\[ T \]

\[ T \]

\[ T \]

\[ T \]

\[ H_{11} \]

\[ H_{22} \]

\[ H_{33} \]

\[ T \]

Taps: \( N \gg C \gg D \)
Complete Cascaded Design:

TX1 \rightarrow H_{11} \rightarrow RX1

TX2 \rightarrow H_{22} \rightarrow RX2

TX3 \rightarrow H_{33} \rightarrow RX3

Taps: N >> C > D
Complete Cascaded Design:

\[ H_{11} \rightarrow H_{21} \rightarrow \hat{H}_{22} \rightarrow H_{33} \rightarrow \hat{H}_{33} \]

Circulator

Cancellation Filter

TX1  \( \rightarrow \)  RX1

TX2  \( \rightarrow \)  RX2

TX3  \( \rightarrow \)  RX3

Taps: \( N \gg C > D \)
Complete Cascaded Design:

Taps: $N >> C > D$
Complete Cascaded Design:

\[ H_{11} \]
\[ H_{21} \]
\[ H_{31} \]

Taps: N >> C > D
Complete Cascaded Design:

- Circulator
- Cancellation Filter
- C taps
- D taps
- Cascaded Filter

$H_{11}$, $H_{21}$, $H_{31}$

TX1 $\rightarrow$ RX1 $\rightarrow$ TX2 $\rightarrow$ RX2 $\rightarrow$ TX3

Taps: $N >> C > D$
Complete Cascaded Design:

- Circulators: $\Sigma$
- Cancellation Filters: $\hat{H}_{11}$, $\hat{H}_{22}$, $\hat{H}_{33}$
- C taps: $\hat{H}_{c21}$, $\hat{H}_{c31}$
- D taps: $\Sigma$
- TX1, RX1, TX2, RX2, TX3
- Taps: $N >> C > D$
Complete Cascaded Design:

\[ H_{11} \]
\[ H_{21} \]
\[ H_{31} \]

Circulator

TX1

Cascaded Filter

\[ \hat{H}_{c21} \]

\[ \hat{H}_{c31} \]

RX1

D taps

Taps: N >> C > D

TX2

C taps

TX3

RX2

TX3

RX3

Cascaded Filter

Cancellation Filter

Filter

Filter

Filter
Complete Cascaded Design:

Taps: N >> C > D

Taps: N >> C > D
Complete Cascaded Design:

- **TX1**
  - Circulator
  - $\tilde{H}_{11}$
  - Cancellation Filter
  - $H_{c21}$
  - C taps

- **RX1**
  - Circulator
  - $H_{31}$
  - Cancellation Filter
  - $H_{c31}$
  - D taps

- **TX2**
  - Circulator
  - $H_{21}$
  - Cancellation Filter
  - $H_{c12}$
  - C taps

- **RX2**
  - Circulator
  - $H_{32}$
  - Cancellation Filter
  - $H_{c32}$
  - C taps

- **TX3**
  - Circulator
  - $H_{33}$
  - Cancellation Filter

- **RX3**

**Taps:** $N >> C > D$
Complete Cascaded Design:

\[
\begin{align*}
\hat{H}_{11} & \quad H_{21} \\
\hat{H}_{22} & \quad H_{31} \\
\hat{H}_{33} &
\end{align*}
\]

Circulator
Circulator
Circulator

\[
\begin{align*}
\sum & \quad \hat{H}_{11} \\
\sum & \quad \hat{H}_{22} \\
\sum & \quad \hat{H}_{33}
\end{align*}
\]

Cancellation Filter
Cancellation Filter
Cancellation Filter

\[
\begin{align*}
\hat{H}_{c21} & \quad \hat{H}_{c31} \\
\hat{H}_{c12} & \quad \hat{H}_{c32}
\end{align*}
\]

Cascaded Filter
Cascaded Filter
Cascaded Filter

TX1
TX2
TX3

RX1
RX2
RX3

Taps: N >> C > D
Complete Cascaded Design:

- $H_{11}$
- $H_{21}$
- $H_{31}$

Circulator

TX1

Circulator

RX1

Circulator

RX2

Circulator

RX3

Cascaded Filter

$\hat{H}_{11}$

$\hat{H}_{22}$

$\hat{H}_{33}$

$H_{c21}$

$H_{c31}$

$H_{c12}$

$H_{c32}$

$H_{c31}$

C taps

D taps

C taps

C taps

D taps

Taps: $N >> C > D$
Complete Cascaded Design:

Taps: N >> C > D
Complete Cascaded Design:

- TX1 → Circulator → Cancellation Filter $\hat{H}_{11}$ → RX1
- TX2 → Circulator → Cancellation Filter $\hat{H}_{22}$ → RX2
- TX3 → Circulator → Cancellation Filter $\hat{H}_{33}$ → RX3

Cascaded Filter:
- $\hat{H}_{c21}$ C taps → $\hat{H}_{c31}$ D taps
- $\hat{H}_{c12}$ C taps → $\hat{H}_{c32}$ C taps
- $\hat{H}_{c31}$ D taps

Taps: $N >> C > D$
Complete Cascaded Design:

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

$H_{11}$

TX1

RX1

A1 Analog Isolation

TX2

RX2

A2 Analog Isolation

Txb3

RX3

A3 Analog Isolation
Interference Residue with Cascaded Design shows no degradation

Independent Training with SISO Replication Design

\[ H_{11} \]

\[ H_{21} \]

A1 Analog Isolation

A2 Analog Isolation

A3 Analog Isolation

TX1

RX1

TX2

RX2

Txb3

RX3
Interference Residue with Cascaded Design shows no degradation

Independent Training with SISO Replication Design
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$$\text{Residue} = e + H_{21} + H_{31}$$
Interference Residue with Cascaded Design shows no degradation

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Residue = \( e + H_{21} + H_{31} \)
Interference Residue with Cascaded Design shows no degradation

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Residue = \( e + H_{21} + H_{31} \)

Residue = \( 2e + H_{31} \)
Interference Residue with Cascaded Design shows no degradation

Independent Training with SISO Replication Design
Interference Residue with Cascaded Design shows no degradation

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Residue = \(3e\)
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