FastForward: Fast and Constructive Full Duplex Relays

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The Promise of Wireless ...

Wireless link speeds have grown by two orders of magnitude in the last decade due to:

- **802.11b**: 11 Mbps
- **802.11g**: 54 Mbps
- **802.11n**: 600 Mbps
- **802.11ac**: 1.3 Gbps

- **QPSK, SISO**
- **64 QAM, SISO**
- **64 QAM, 4x4 MIMO**
- **256 QAM, 3x3 MIMO**

- **20 MHz**
- **40 MHz**
- **80 MHz**
The Promise of Wireless ...

Wireless link speeds have grown by two orders of magnitude in the last decade due to:

- **Denser Modulation/Coding**
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- **Denser Modulation/Coding**
- **MIMO**
The Promise of Wireless ...

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- **Denser Modulation/Coding**
- **MIMO**

Do we see such capacity in practice?
The Reality of Wireless...
The Reality of Wireless ...
The Reality of Wireless ...

WiFi coverage in typical home

Bitrate in Mbps (PHY layer bit rate)

26 m

9m
The Reality of Wireless ...

WiFi coverage & capacity don’t live up to the promised speeds
The Problem
The Problem

Signals experience propagation loss

Wall

Strong Signal

Weak Signal
The Problem

Signals experience propagation loss

Strong Signal

Wall

Weak Signal

AP only

Bitrates in Mbps (PHY LAYER bit rate)
The Problem

Signals experience propagation loss

Strong Signal

Wall

Weak Signal

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Bitrates in Mbps (PHY LAYER bit rate)
The Problem

Signals experience propagation loss

**Bitrates in Mbps (PHY LAYER bit rate)**

- 0
- 20
- 40
- 60
- 80
- 100
- 120
- 140

**AP only**

**Wall**

**Strong Signal**

**Weak Signal**

26 m

9 m
The Problem

Signals experience propagation loss

Can’t exploit MIMO because of correlated channels from pinholes

Correlated paths

RF pinhole

Wall

AP only

26 m

9 m

AP

Bitrates in Mbps (PHY LAYER bit rate)

0

20

40

60

80

100

120

140
The Problem

Signals experience propagation loss

Can’t exploit MIMO because of correlated channels from pinholes

![Diagram showing signals experiencing propagation loss and correlated paths due to RF pinholes.]
The Problem

Signals experience propagation loss

Can’t exploit MIMO because of correlated channels from pinholes

Correlated paths

RF pinhole

Bitrates in Mbps (PHY LAYER bit rate)

0

20

40

60

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120

140

AP only

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FastForward (FF)
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- Full duplex relay that significantly increases capacity and coverage
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- Key Idea: **Construct & forward relaying**
FastForward (FF)

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  - Tackles propagation loss → significantly increases SNR
FastForward (FF)

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  • Tackles RF pinholes → increases MIMO multiplexing
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• Experimentally achieves capacity gain of 2.3x
FastForward (FF)

- Full duplex relay that significantly increases capacity and coverage

**Key Idea:** Construct & forward relaying
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FastForward (FF)

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How does FF work at a high level?
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1. Receive signal from the source
2. Process it in RF and digital
3. Relay it simultaneously to the destination
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1. Receive signal from the source
2. Process it in RF and digital
3. Relay it simultaneously to the destination
Isn’t this easy? Just use recent work on full duplex
How to relay while receiving?

- Simultaneously TX and RX
- RF & Digital Processing
- Relayed
- Direct
- Client

AP → TX
RX → Client
Relayed → Client
Direct → Client
How to relay while receiving?

• Relaying & receiving → Simultaneous TX and RX on the same frequency
How to relay while receiving?

- Relaying & receiving → Simultaneous TX and RX on the same frequency
- Use recent work on full duplex
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![Diagram showing full duplex TX and RX](image)

-90 dBm Receiver Noise floor
-70 dBm

**20dB SNR**

Full duplex

- TX
- RX

RF & Digital Processing

AP

Direct

Client

Relayed
How to relay while receiving?

- Relaying & receiving → Simultaneous TX and RX on the same frequency
- Use recent work on full duplex

**Diagram:**
- 20 dB SNR
- 20 dBm
- 0 dBm
- -70 dBm
- -90 dBm Receiver Noise floor
- Amplify to MAX
- Relay Noise
- Relay received
- Relay transmitted
- AP
- Full duplex
- RF & Digital Processing
- TX
- RX
- Direct
- Client
How to relay while receiving?

• Relaying & receiving → Simultaneous TX and RX on the same frequency
• Use recent work on full duplex
• Receive signal, amplify and simultaneously relay

![Diagram showing relay and receiving process with SNR and power levels](chart.png)
How to relay while receiving?

• Relaying & receiving → Simultaneous TX and RX on the same frequency
• Use recent work on full duplex
• Receive signal, amplify and simultaneously relay

Are we done? No, this design has two problems:
• Amplifies noise
• Creates destructive interference
Challenge 1: Noise Amplification
Challenge 1: Noise Amplification

Source (AP) Transmitted

Direct
10dB SNR

-80dBm
-90 dBm Noise floor
Destination Received
Challenge 1: Noise Amplification

- Source (AP) Transmitted
- Transmit
  - 20dB SNR
- Direct
  - 10dB SNR
- Direct
  - -80dBm
  - -90 dBm Noise floor
  - Destination Received
Challenge 1: Noise Amplification

-90 dBm Receiver Noise floor

Relay received

-70 dBm

-90 dBm Noise floor

Destination Received

Direct

-80 dBm

10 dB SNR

20 dB SNR

Source (AP) Transmitted

Transmit

Direct
Challenge 1: Noise Amplification

-90 dBm Receiver Noise Floor

Amplify to MAX (90 dB)

-70 dBm Relay received

0 dBm Relay Noise

20 dBm Relay transmitted

20 dB SNR

Source (AP) Transmitted

Direct

10 dB SNR

-80 dBm Destination Received

-90 dBm Noise floor

Direct
Challenge 1: Noise Amplification

Amplify to MAX (90 dB)

-90 dBm Receiver Noise floor

-70 dBm Relay received

0 dBm Relay Noise

20 dBm Relay transmitted

Source (AP) Transmitted

Transmit

20 dB SNR

30 dB SNR

Direct

10 dB SNR

-80 dBm

-90 dBm Noise floor

Destination Received
Challenge 1: Noise Amplification

-90 dBm Receiver Noise floor

Amplify to MAX (90 dB)

-70 dBm

20 dBm

0 dBm

Relay Noise

Relay received

Relay transmitted

20 dB SNR

30 dB SNR

Direct

10 dB SNR

Source (AP) Transmitted

-90 dBm Noise floor

-80 dBm Relay Noise

Destination Received

-60 dBm

-80 dBm

-90 dBm
Challenge 1: Noise Amplification

-90 dBm Receiver Noise floor

-70 dBm Receiver Noise floor

-90 dBm Receiver Noise floor

0 dBm Relay Noise

10 dB SNR

20 dB SNR

30 dB SNR

Direct

-80 dBm Relay Noise

-90 dBm Noise floor

Transmit
Source (AP)
Transmitted
Challenge 1: Noise Amplification

Amplify to MAX (90 dB)
-90 dBm Receiver Noise floor
Relay received
-70 dBm
Relay Noise

20 dBm
0 dBm

Direct
10 dB SNR

20 dB SNR
30 dB SNR

Amplified noise destroys direct signal
Challenge 2: Destructive Interference

-90 dBm Noise floor
Destination Received
Challenge 2: Destructive Interference

Direct Destination Received

-90 dBm Noise floor

Destination Received
Challenge 2: Destructive Interference

-90 dBm Noise floor
Destination Received
Challenge 2: Destructive Interference
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-90 dBm Noise floor
Destination Received
Challenge 2: Destructive Interference

-90 dBm Noise floor

Destination Received
Challenge 2: Destructive Interference

Full Duplex
Max Amplify

Direct
Relayed

TX
RX

Direct + Relayed = Total

-90 dBm Noise floor
Destination Received

Destructive Interference
Construct and Forward relaying to tackle these two challenges
Construct and Forward relaying

- Full Duplex
- Max Amplify
- Direct
- Relayed
Construct and Forward relaying

Basic Idea: Filter the received signal such that noise isn’t amplified and signals add constructively at the destination
Construct and Forward filter abstraction

Full Duplex

Construct & Forward filtering

Construct & Forward filtering

TX

RX

RX

TX
Construct and Forward filter abstraction

Full Duplex

Construct & Forward filtering

Constructive amplification

Constructive rotation

Construct & Forward filtering
Construct and Forward filter abstraction

- Full Duplex
- Construct & Forward filtering
- Received signal at relay
- Constructive amplification
- Constructive rotation
- $e^{je}$
- Relayed signal
- $= TX$
Constructive amplification

Constructive rotation

Received signal at relay

Constructive amplification

Constructive rotation

Relayed signal

How does Construct and Forward calculate $A \& e^{j\theta}$?
Constructive amplification A
Constructive amplification A

Source Transmitted

20 dBm

Destination Received

-90 dBm
Noise floor

Destination Received
Constructive amplification A

Source Transmitted

20 dBm

90 dB loss

Destination Received

-90 dBm

Noise floor

-90 dBm

Destination Received
Constructive amplification A

-90 dBm Receiver Noise floor

Relay received

20 dBm

Source Transmitted

90 dB loss

-70 dBm

Destination Received

-90 dBm Noise floor
Constructive amplification A

-90 dBm Receiver Noise floor

Relay received

-70 dBm

20 dBm

Source Transmitted

90 dB loss

80 dB loss

-90 dBm Noise floor

Destination Received
Constructive amplification A

Amplify by 80 dB

-90 dBm Receiver Noise floor

Relay received

10 dBm

Relay Noise

-10 dBm

80 dB loss

-90 dBm Noise floor

Source Transmitted

20 dBm

90 dB loss

Relay Transmitted

Destination Received

-90 dBm
Constructive amplification A

-90 dBm Receiver Noise floor

Amplify by 80 dB

-70 dBm

10 dBm

-10 dBm

Relay Noise

Relay received

Relay Transmitted

80 dB loss

20 dBm

Source Transmitted

90 dB loss

-90 dBm Noise floor

-90 dBm

Relayed

-70 dBm

-90 dBm

Relay Noise

Destination Received
Constructive amplification A

-90 dBm Receiver Noise floor

Source Transmitted

Amplify by 80 dB

-70 dBm

Relay received

Relay Transmitted

10 dBm

-10 dBm

Relay Noise

80 dB loss

-90 dBm Noise floor

Relayed

-70 dBm

-90 dBm

Relay Noise

Destination Received
Constructive amplification factor $A$ can be at most the propagation loss from relay to destination.
Constructive rotation $e^{j\theta}$
Constructive rotation $e^{j\theta}$
Constructive rotation $e^{j\theta}$

- Full Duplex
- Construct & Forward Filtering
- Direct
- Relayed
- Amplify only relay
- Amplify only relay total
Constructive rotation $e^{j\phi}$
Constructive rotation $e^{j\phi}$

Full Duplex

Construct & Forward Filtering

TX

RX

Relayed

Direct

Constructive relay total

Amplify only relay total

Amplify only relay

Direct

Re

Im

Re

Im
Constructive rotation $e^{j\theta}$
Constructive rotation $e^{j\theta}$ should be as close as possible to the phase difference between the direct and the relay path’s channels.
Summary: Construct and Forward filter

Construct & Forward filtering

Full Duplex

Constructive Amplification

Constructive Rotation

Received at relay

Constructive Amplification

$e^{j\theta}$

Relayed
Summary: Construct and Forward filter

Full Duplex

Construct & Forward filtering

Constructive Amplification

Constructive Rotation

Received at relay

Constructive Amplification

$e^{j\theta}$

Relayed

Propagation loss from relay to destination
Summary: Construct and Forward filter

Full Duplex

Construct & Forward filtering

Constructive Amplification

Constructive Rotation

RX . A . \( e^{j\theta} \) = TX

Received at relay

Constructive Amplification

Constructive Rotation

Relayed

Propagation loss from relay to destination

Align the phases of the relay path and direct path at the destination
High latency leads to inter-symbol interference
High latency leads to inter-symbol interference
High latency leads to inter-symbol interference
High latency leads to inter-symbol interference.
High latency leads to inter-symbol interference.
High latency leads to inter-symbol interference
High latency leads to inter-symbol interference

Symbol1 interferes with Symbol2

Direct

Relayed

Construct & Forward Filtering

Δt

Full Duplex

TX

RX

AP

Direct

Relayed

CP Symbol1 CP Symbol2

CP Symbol1 CP Symbol2

Δt

Symbol1 interferes with Symbol2
High latency leads to inter-symbol interference

Minimize the latency of Construct & Forward filter to avoid inter symbol interference
High latency leads to inter-symbol interference

Minimize the latency of Construct & Forward filter to avoid inter symbol interference
High latency leads to inter-symbol interference

Minimize the latency of Construct & Forward filter to avoid inter symbol interference

Direct

Relayed

Full Duplex

Construct & Forward Filtering

Constructive Amplification

Constructive Rotation

Negligible Latency
High latency leads to inter-symbol interference

Minimize the latency of Construct & Forward filter to avoid inter symbol interference

Negligible Latency

How do we achieve this block with minimum latency?
Low latency constructive rotation filter

RX

Constructive rotation ($e^{j\theta}$)

TX = RX. $e^{j\theta}$
Low latency constructive rotation filter

RX

Constructive rotation ($e^{j\theta}$)

TX = RX. $e^{j\theta}$
Low latency constructive rotation filter

\[ \text{TX} = \text{RX}. \ e^{j\theta} \]

Constructive rotation \((e^{j\theta})\)
Low latency constructive rotation filter

\[ TX = RX \cdot e^{j\theta} \]
Low latency constructive rotation filter

RX = RX. $e^{j\theta}$
Low latency constructive rotation filter

RX = RX. \(e^{j\theta}\)

400 psec

300 psec

200 psec

100 psec

0 psec
Low latency constructive rotation filter

RX = RX. $e^{j\theta}$

RX

TX

400 psec

300 psec

200 psec

100 psec

0 psec
Low latency constructive rotation filter

TX = RX. $e^{j\theta}$
Low latency constructive rotation filter

RX = RX. $e^{j\theta}$

$d_1 \rightarrow a_1$
$d_2 \rightarrow a_2$
$d_3 \rightarrow a_3$
$d_4 \rightarrow a_4$

RX(a_1) = 200 psec
RX(a_2) = 300 psec
RX(a_3) = 400 psec
RX(a_4) = 700 psec
Low latency constructive rotation filter

RX = RX \cdot e^{j\phi}

- RX(d_1)
- RX(d_2)
- RX(d_3)
- RX(d_4)

Latencies:
- 0 psec for RX(d_3)
- 100 psec for RX(d_2)
- 200 psec for RX(d_1)
- 300 psec for RX(d_4)
- 400 psec
- 700 psec
Low latency constructive rotation filter

\[ RX = RX \cdot e^{j\theta} \]
Low latency constructive rotation filter

\[ \text{TX} = \text{RX} \cdot e^{j\theta} \]

RX \rightarrow TX

\( d_1 \rightarrow a_1 \)
\( d_2 \rightarrow a_2 \)
\( d_3 \rightarrow a_3 \)
\( d_4 \rightarrow a_4 \)

400 psec
700 psec

< 1 nsec

RX \( \rightarrow \text{RX}(d_1) \) 200 psec
RX \( \rightarrow \text{RX}(d_2) \) 100 psec
RX \( \rightarrow \text{RX}(d_3) \) 0 psec
RX \( \rightarrow \text{RX}(d_4) \) 300 psec

RX \( \rightarrow \text{RX. F} \)

TX \( \rightarrow \text{RX} \)
Filtering in analog achieves constructive rotation within a nanosecond.
Implementation of FastForward

Full Duplex (FD)

Analog Constructive Filter (ACNF)

Digital Constructive Filter

TX

RX

Block Diagram
Implementation of FastForward

Full Duplex (FD)

Analog Constructive Filter (ACNF)

Digital Constructive Filter

Block Diagram

Prototype

Digital CNF

Antenna
Implementation of FastForward

- Built using WARP SDR platform, designed for 802.11
Implementation of FastForward

- Built using WARP SDR platform, designed for 802.11
- Custom designed construct & forward filter boards & self-interference cancellation
- BW 20MHz, 20dBm TX power
Implementation of FastForward

• Built using WARP SDR platform, designed for 802.11
• Custom designed construct & forward filter boards & self-interference cancellation
• BW 20MHz, 20dBm TX power
• **Built 2x2 MIMO FF Prototype**
Evaluation: Coverage and Capacity of FastForward
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- Indoor office environment with five different floor plans
  - AP and relay are randomly but statically placed, and client is placed at 25 different locations in each floorplan
Evaluation: Coverage and Capacity of FastForward

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• Compared to:
Evaluation: Coverage and Capacity of FastForward

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  • AP and relay are randomly but statically placed, and client is placed at 25 different locations in each floorplan

• Compared to:
  • AP only
Evaluation: Coverage and Capacity of FastForward

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  • AP and relay are randomly but statically placed, and client is placed at 25 different locations in each floorplan

• Compared to:
  • AP only
  • AP + half duplex (HD) mesh router
Evaluation: Coverage and Capacity of FastForward

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  - AP only
  - AP + half duplex (HD) mesh router
  - AP + FF relay: same location as half duplex mesh router
Evaluation: Coverage and Capacity of FastForward

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  - AP + FF relay: same location as half duplex mesh router
- Performance metrics
  - Best bitrate is experimentally estimated for each approach at each client location
Evaluation: Coverage and Capacity of FastForward

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  - AP + FF relay: same location as half duplex mesh router
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  - Best bitrate is experimentally estimated for each approach at each client location

Relative Gain = \( \frac{\text{Bitrate of any approach}}{\text{Bitrate of AP + HD mesh router}} \)
Does FF increase coverage?

Metric: Best bitrate for all the client positions
Range of deployment: the farthest location at which the clients would see non-zero bitrate seen by mesh half duplex router.
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- **AP+ FF:** 95% of locations get at least 60Mbps
- **AP + Mesh Router:** Only 30% of locations get at least 60Mbps
Does FF increase capacity?

Metric: Relative Capacity Gain w.r.t. the AP + half duplex mesh router
Does FF increase capacity?

Metric: Relative Capacity Gain w.r.t. the AP + half duplex mesh router
Does FF increase capacity?

Metric: Relative Capacity Gain w.r.t. the AP + half duplex mesh router

![CDF Graph](image)

- AP + FF Relay
- AP only
- AP + Half Duplex Mesh Routers

Relative bitrate gains

2.3x
Does FF increase capacity?

Metric: Relative Capacity Gain w.r.t. the AP + half duplex mesh router

Our design achieves the 2.3x times the half duplex Mesh router
To Conclude

Forward signals, not packets!