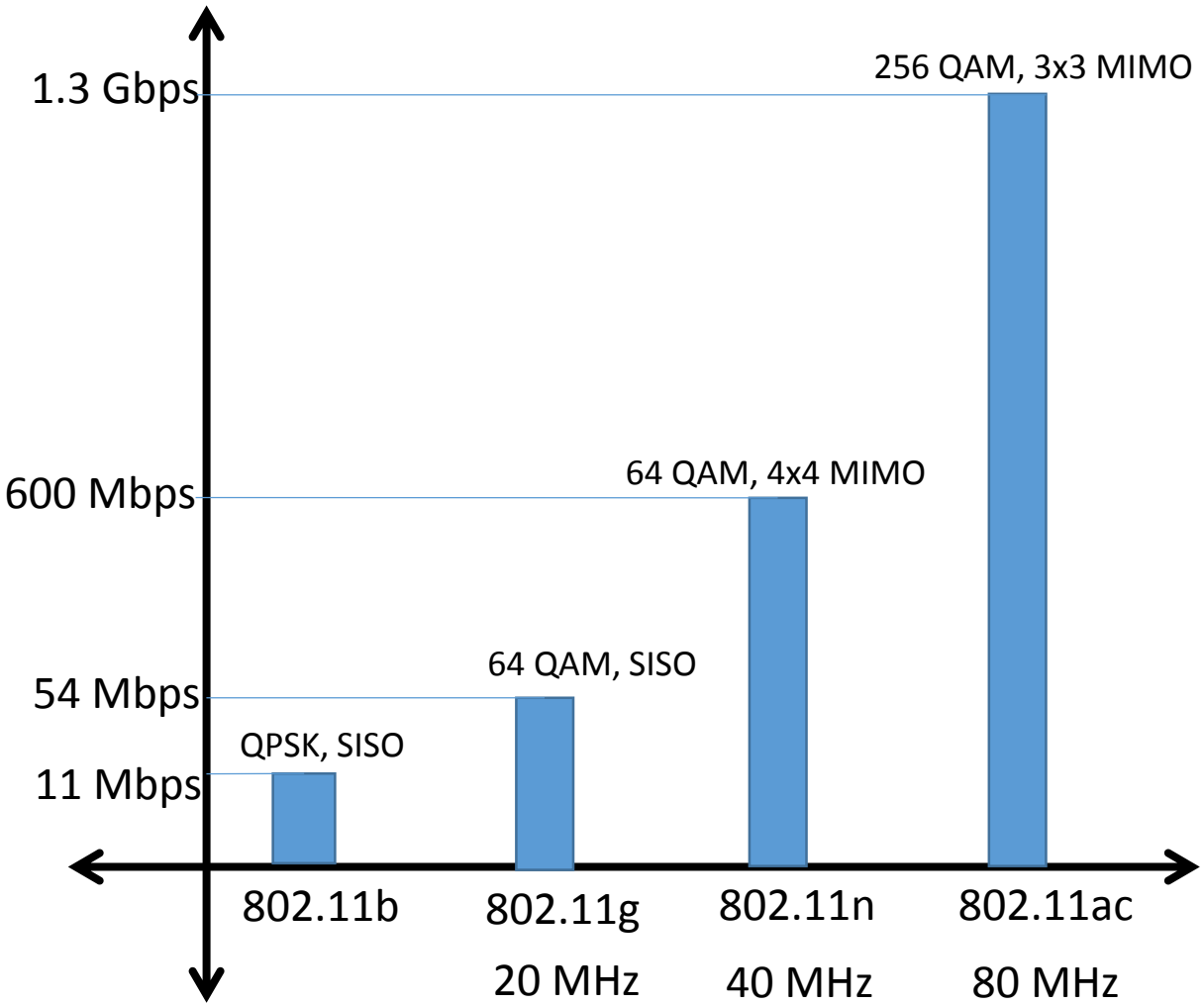
FastForward: Fast and Constructive Full Duplex Relays

Dinesh Bharadia and Sachin Katti
Stanford University & Kumu Networks

The Promise of Wireless …

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



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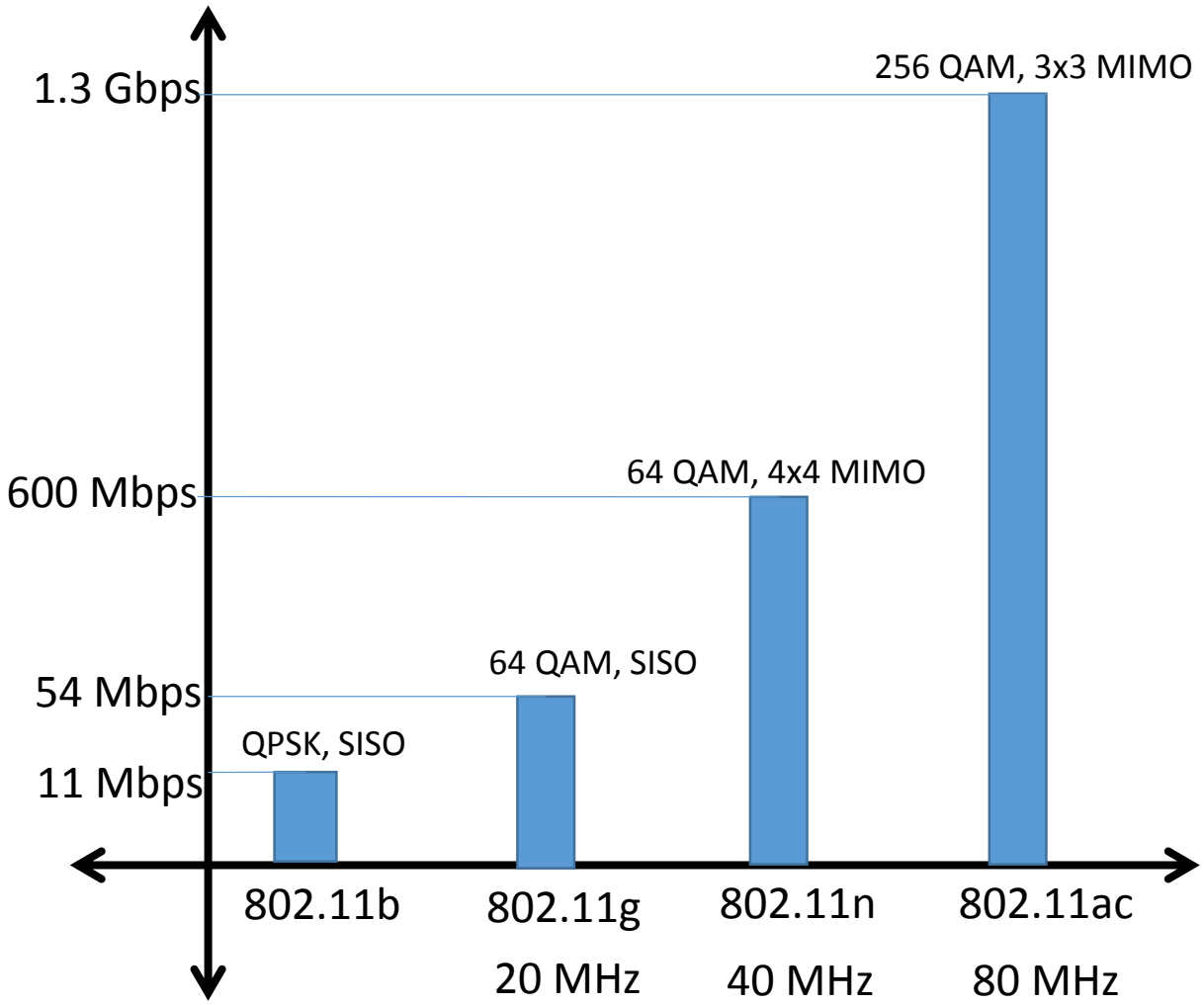

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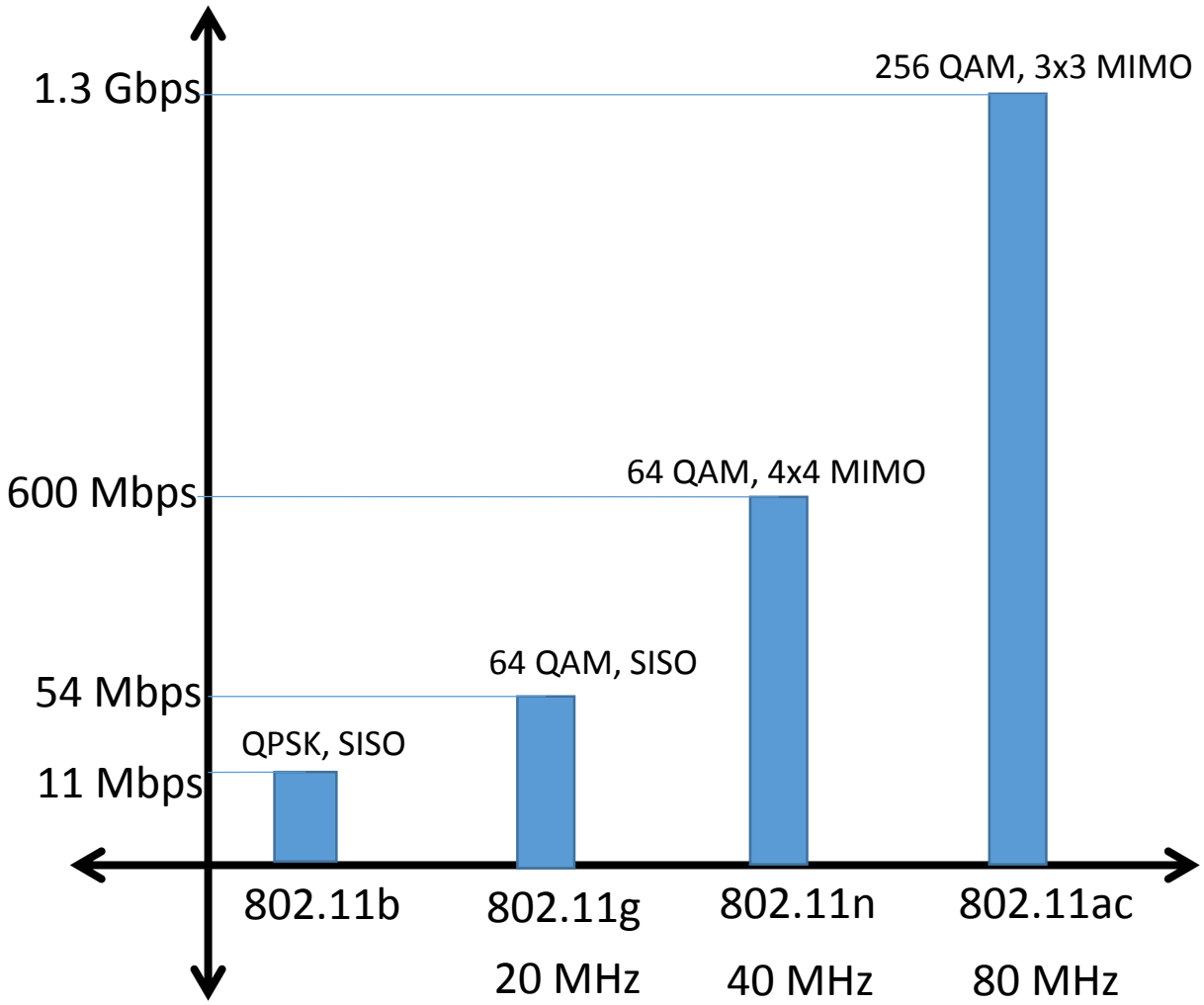

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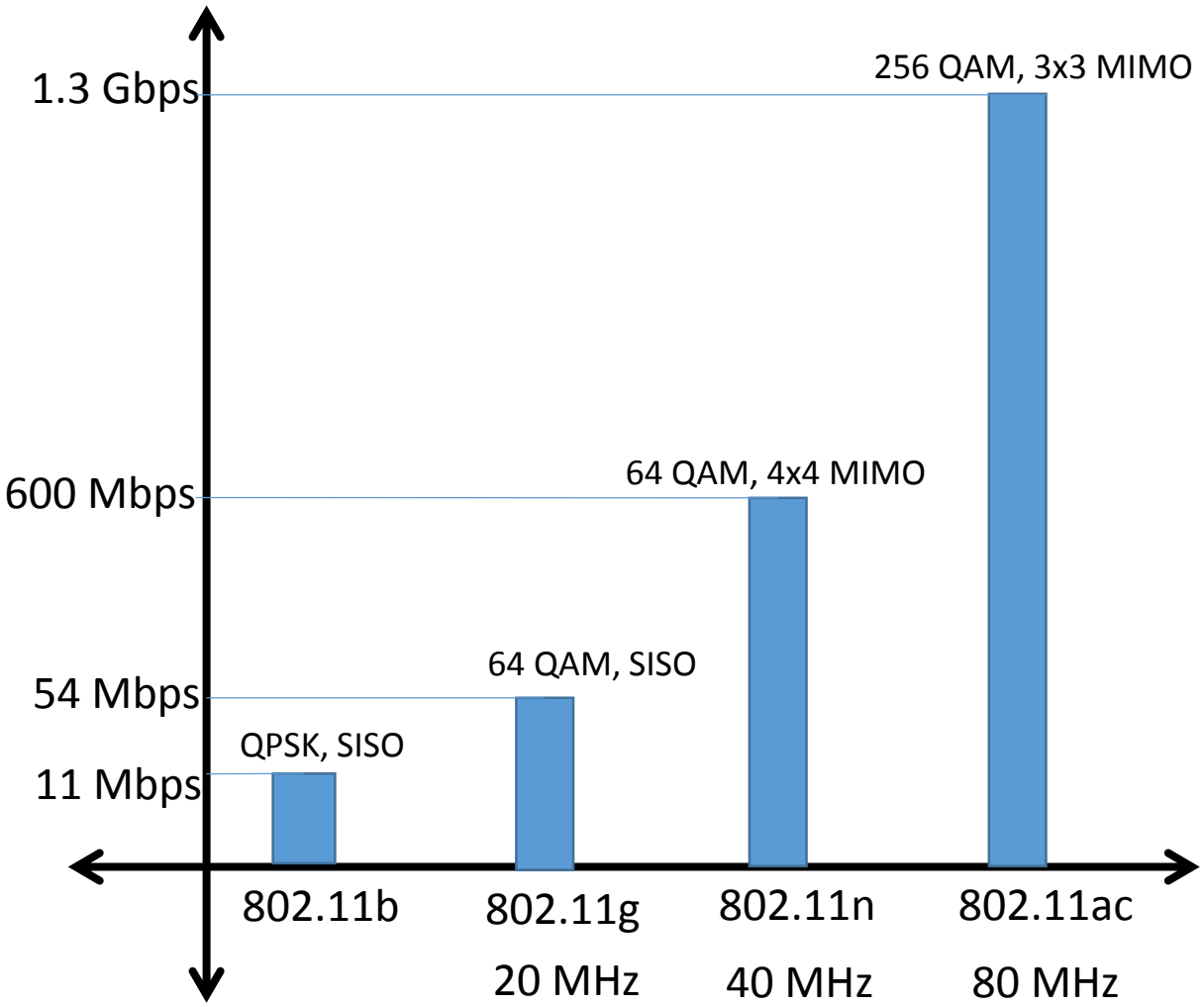

Do we see such capacity in practice?

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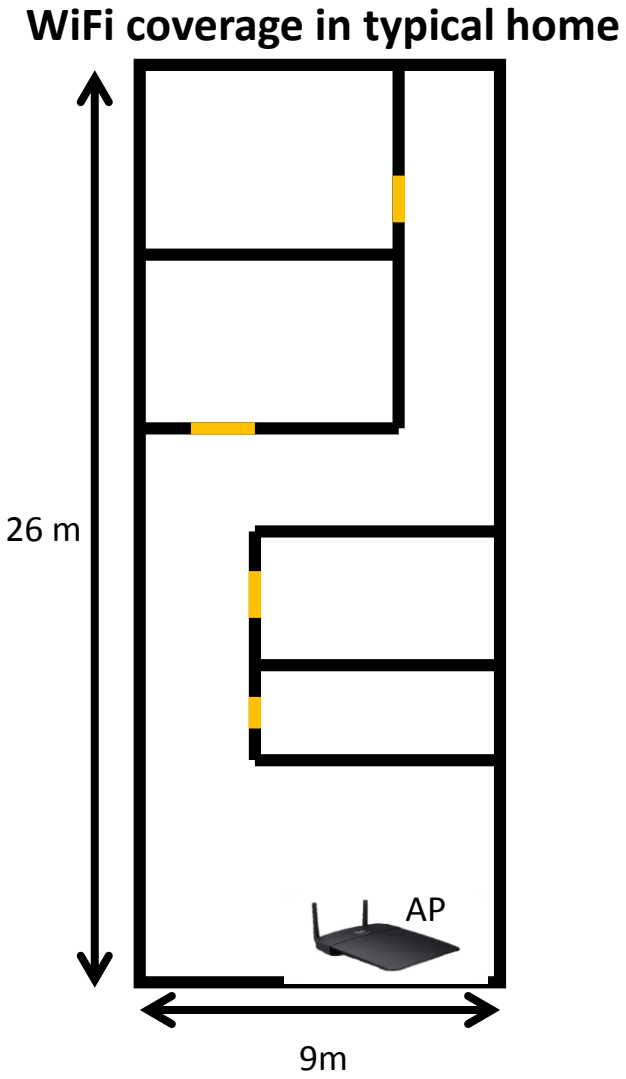

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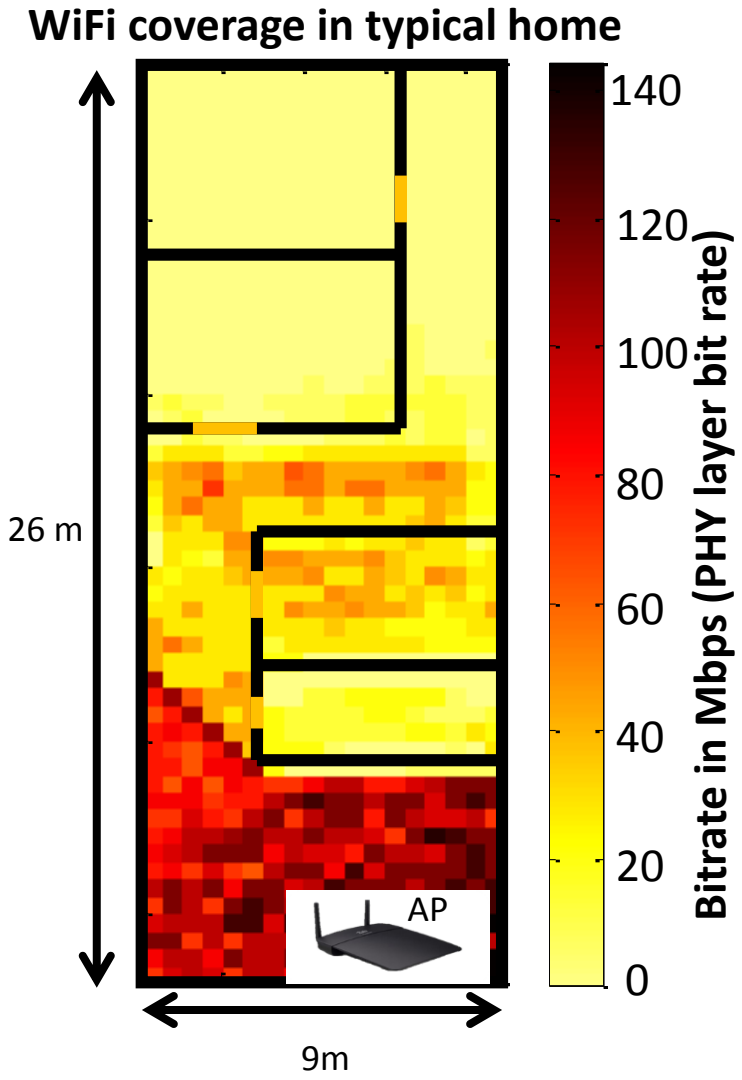

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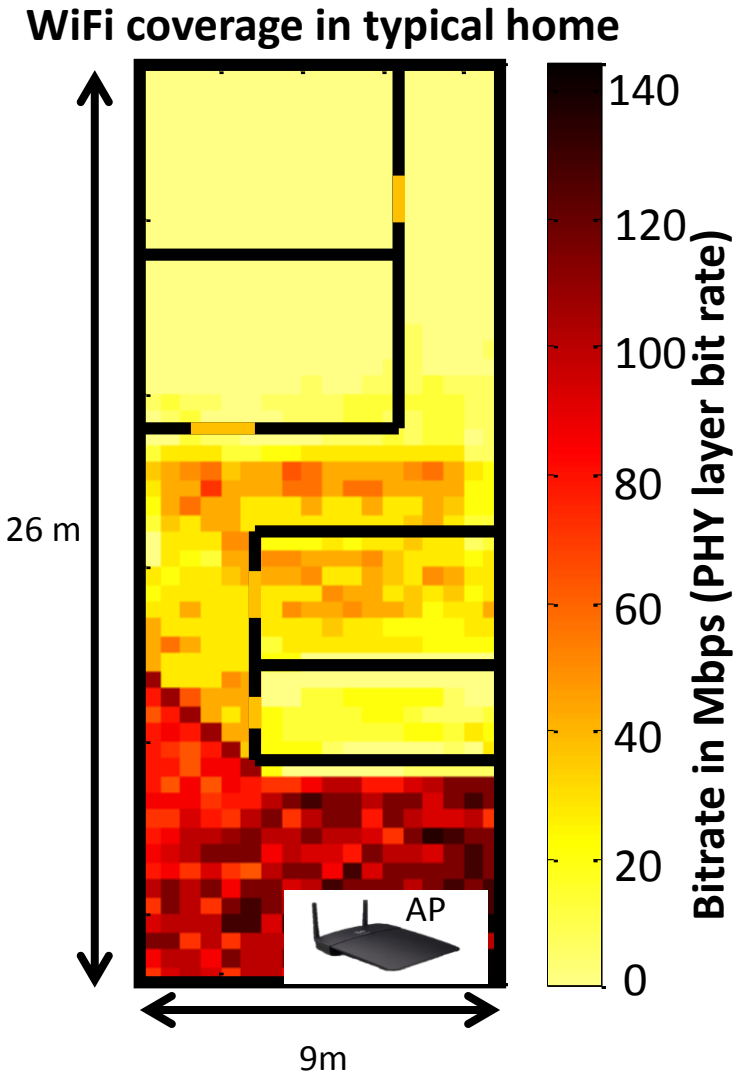
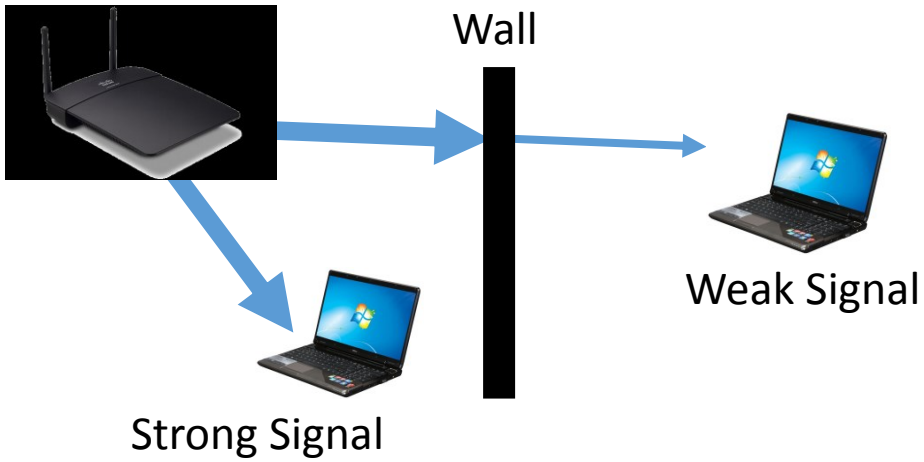


WiFi coverage & capacity don’t live up to the promised speeds

The Problem

The Problem

Signals experience propagation loss



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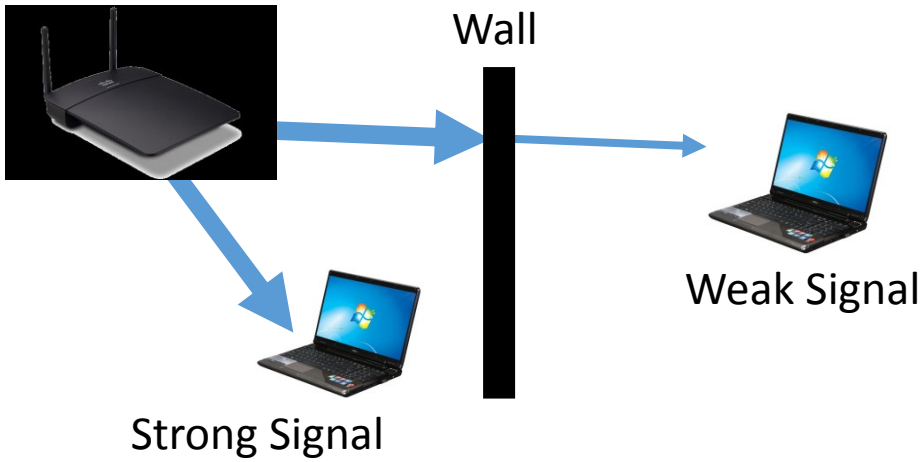

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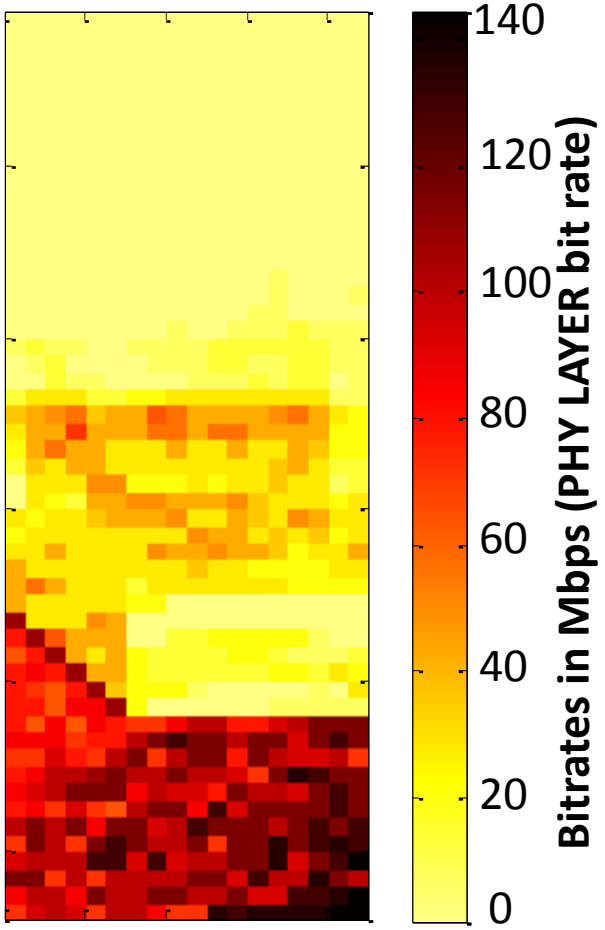

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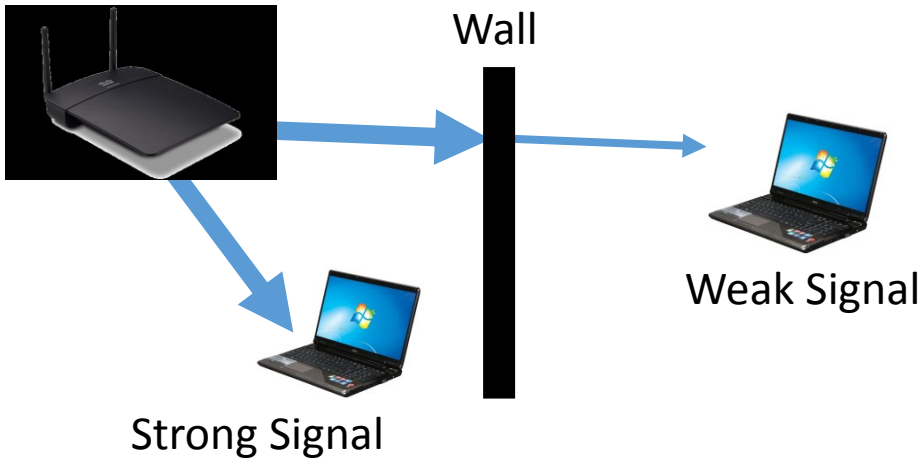

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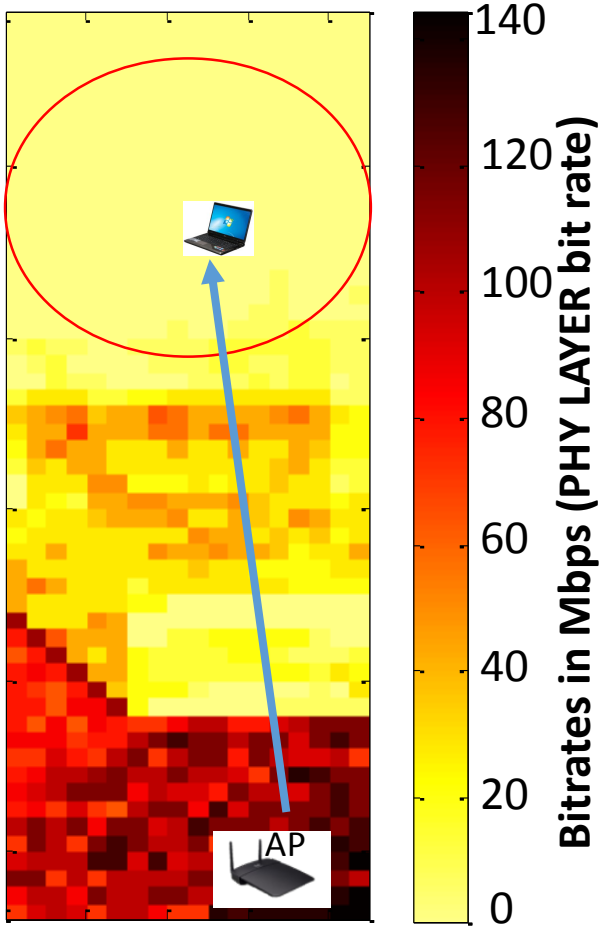

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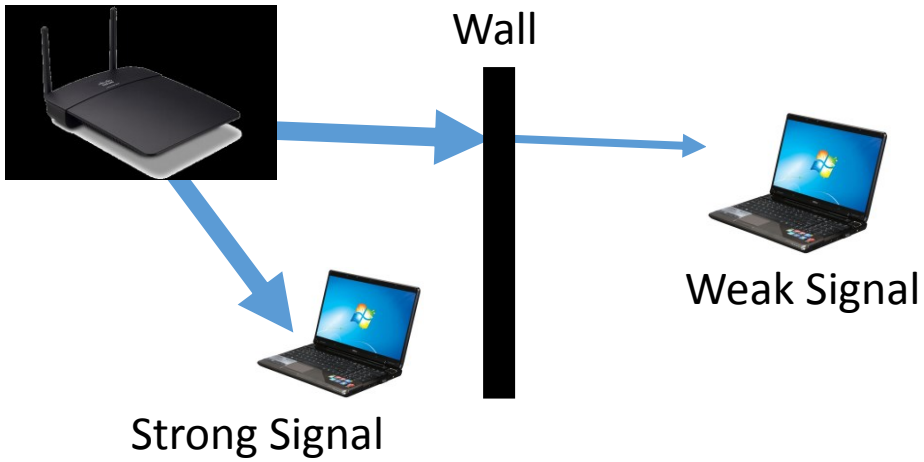

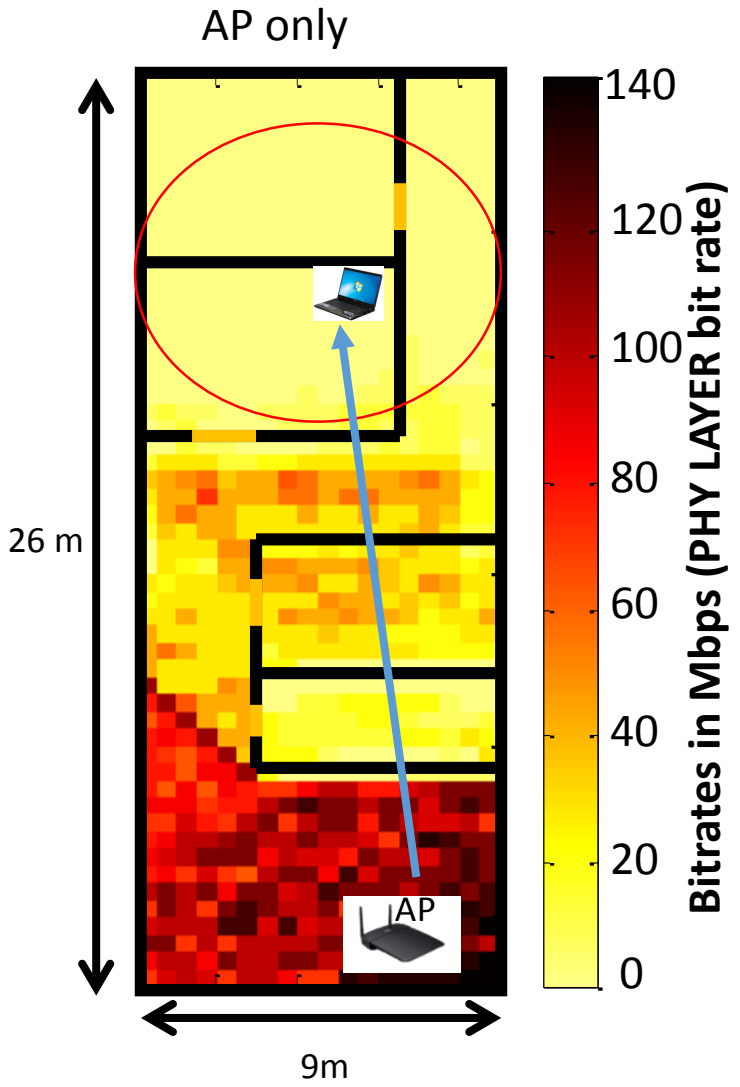

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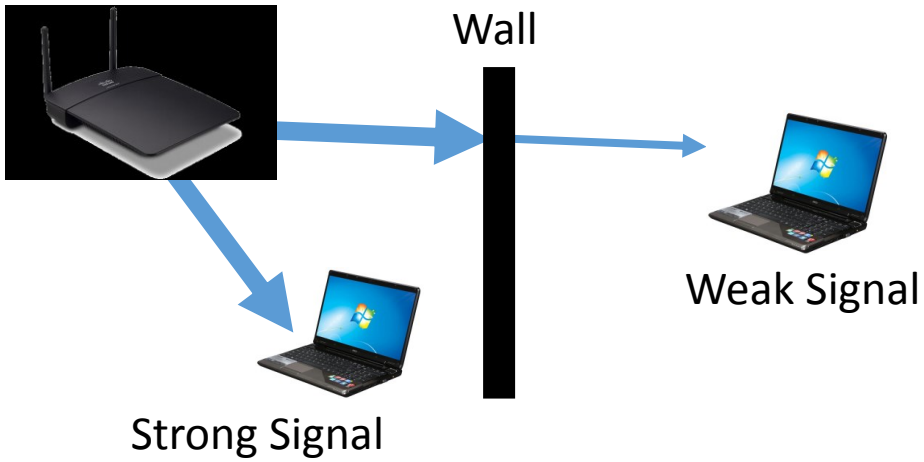

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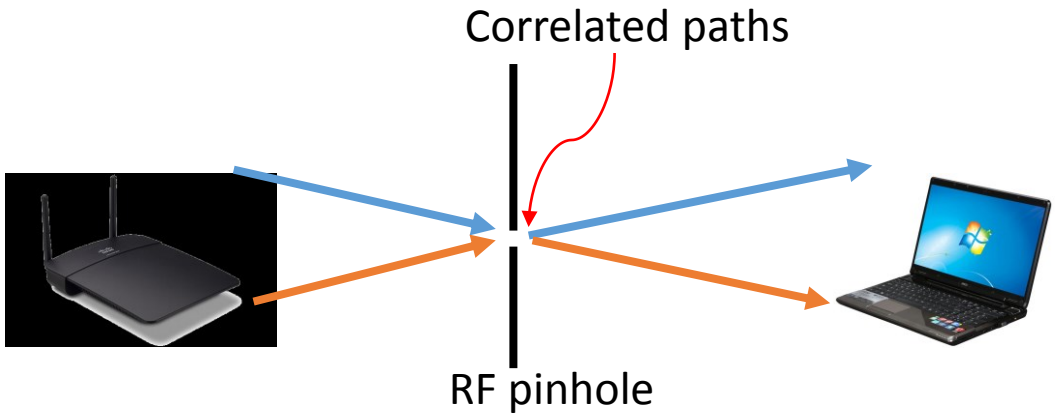

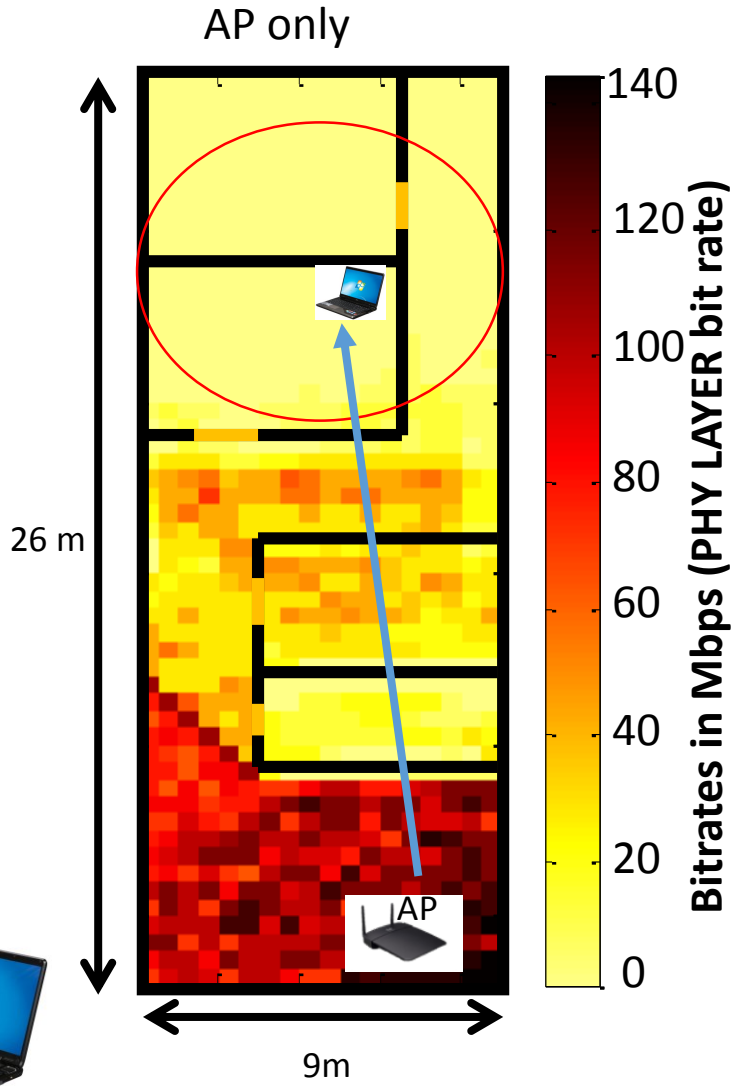

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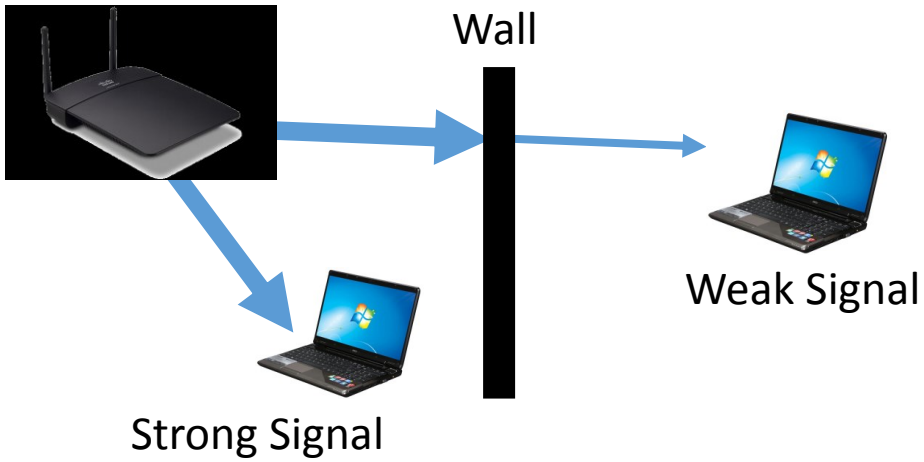

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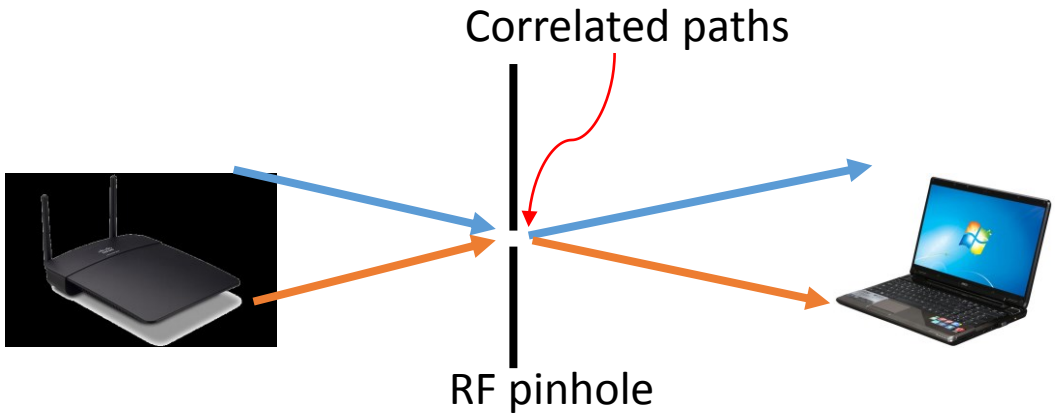

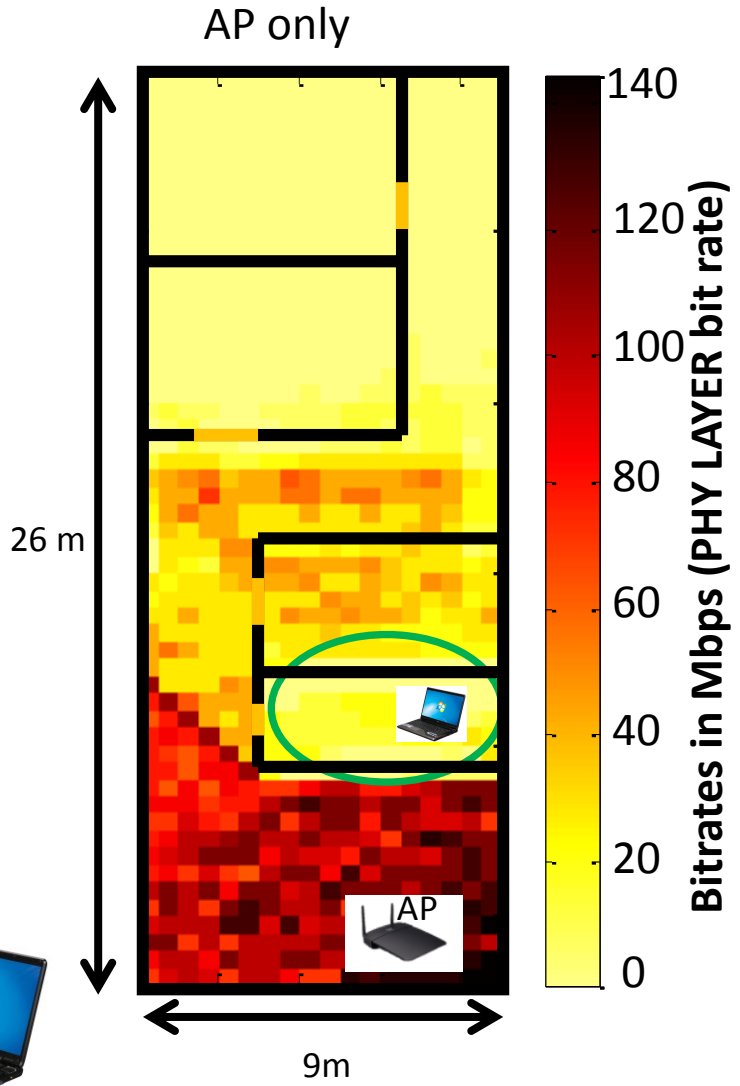

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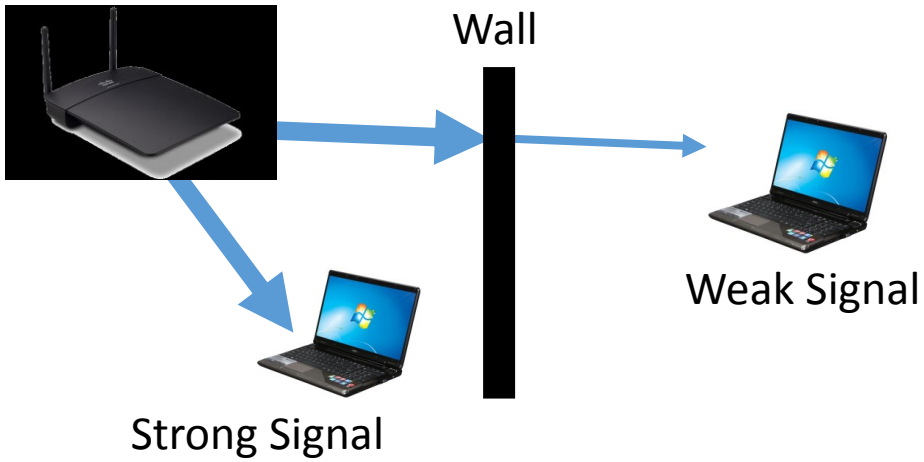

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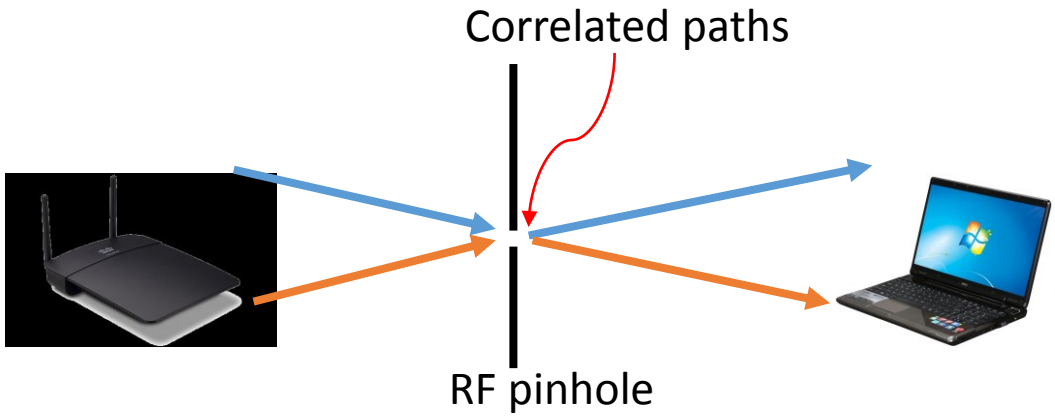

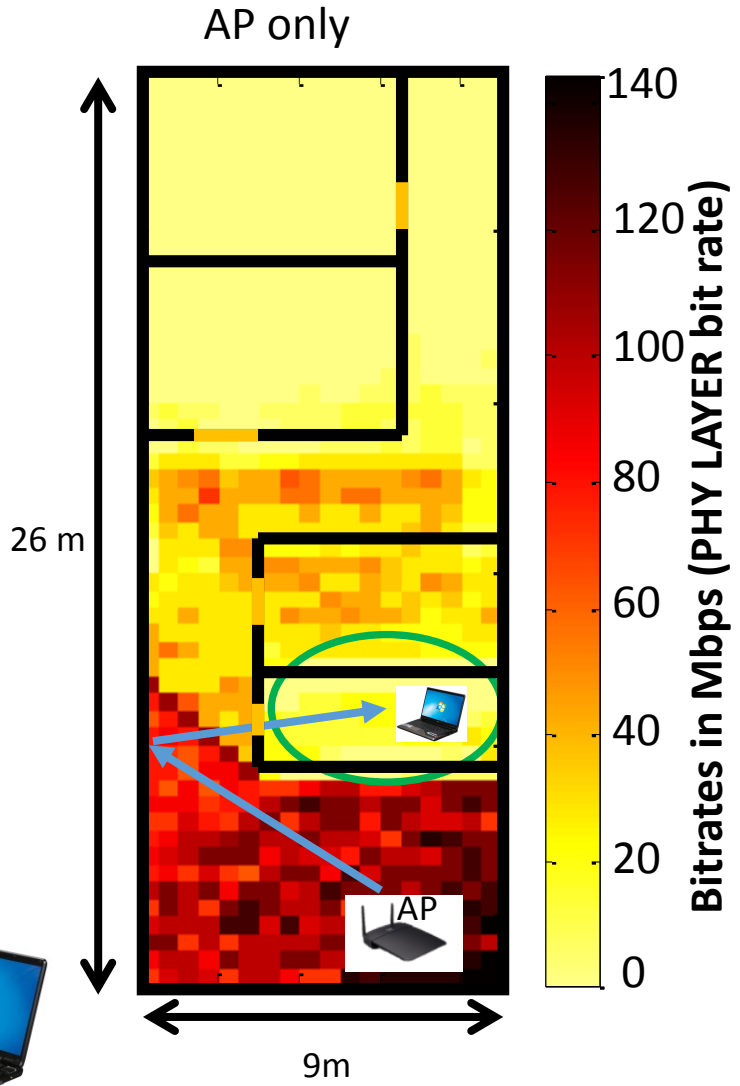

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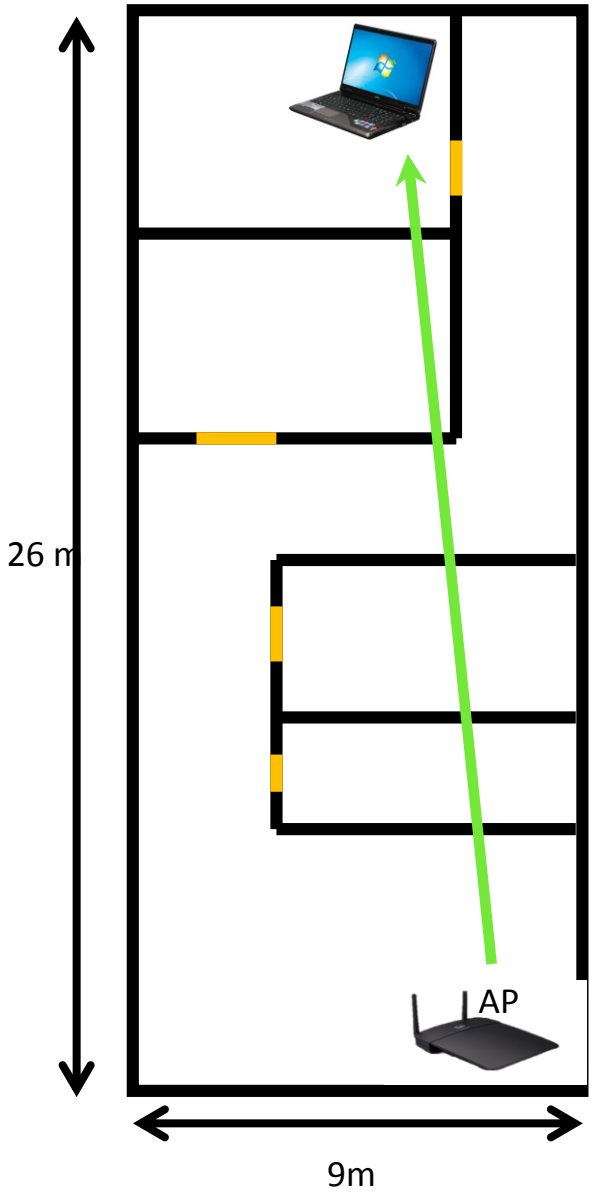

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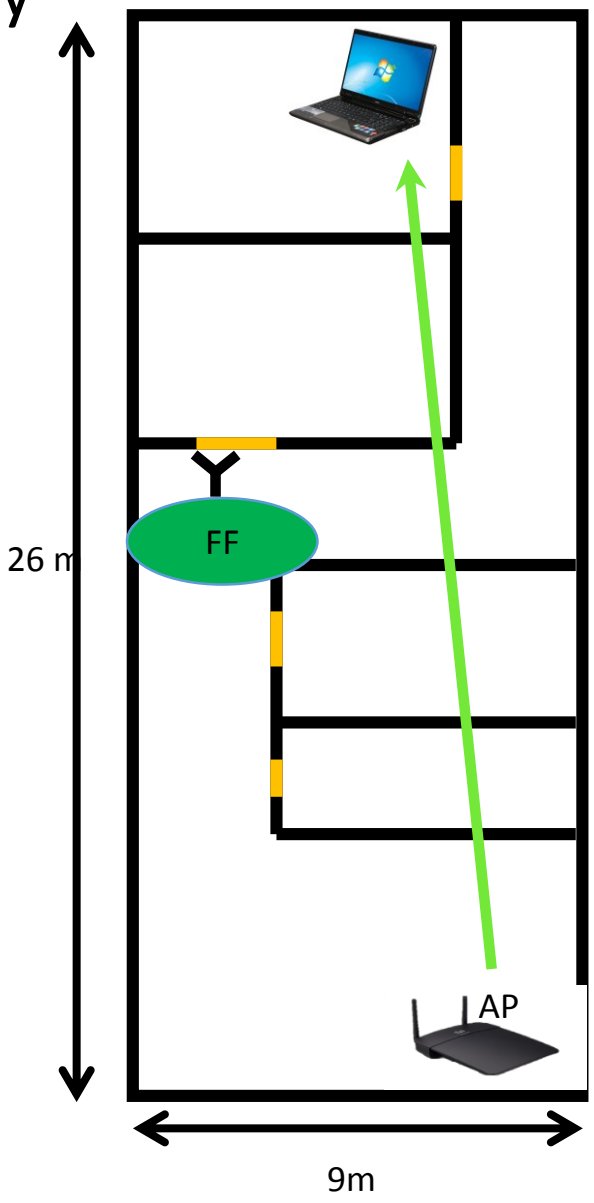
- Full duplex relay that significantly increases capacity and coverage



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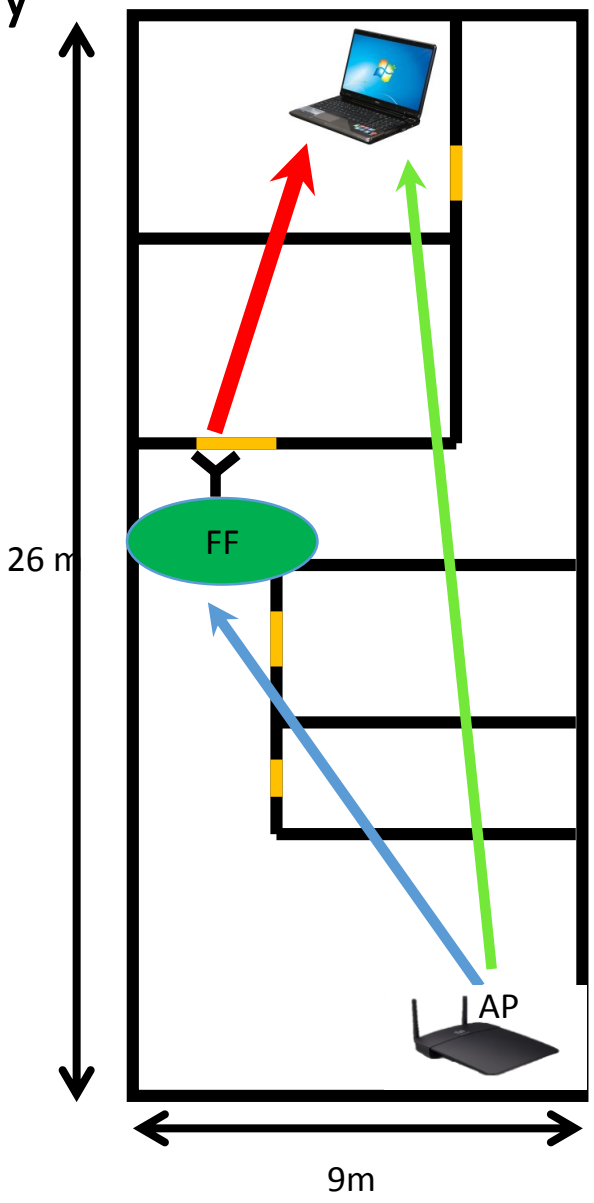

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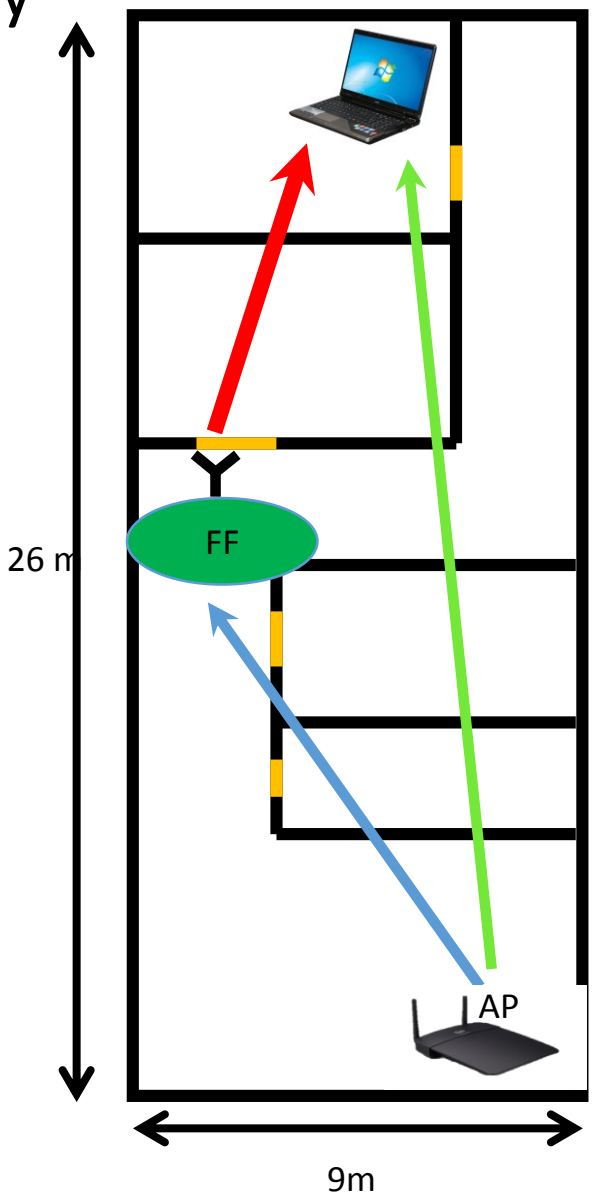

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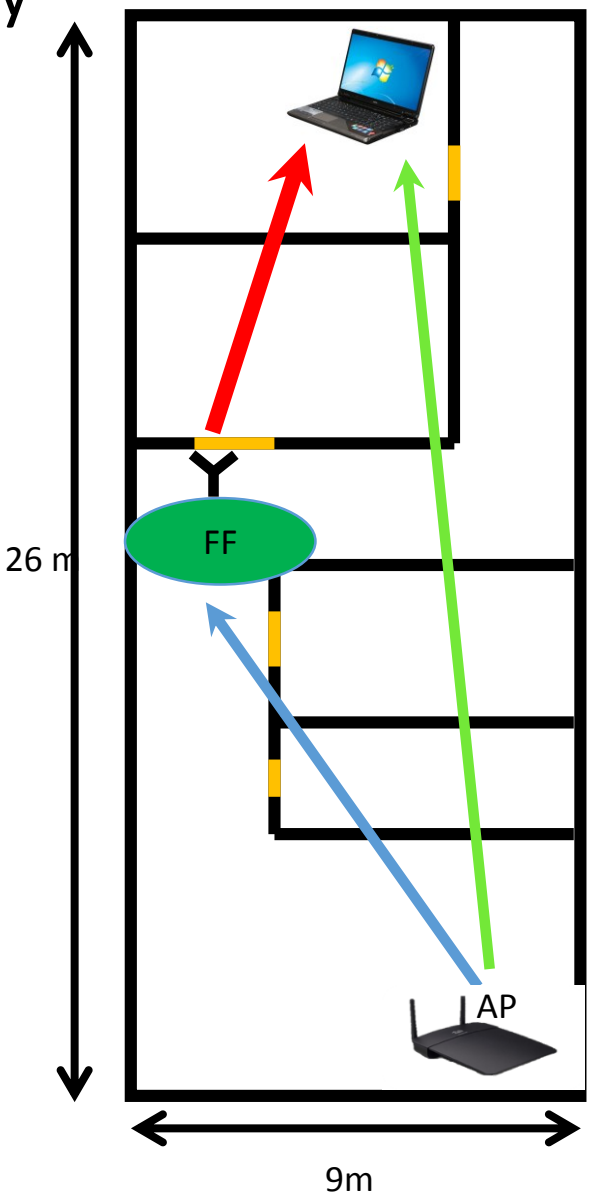

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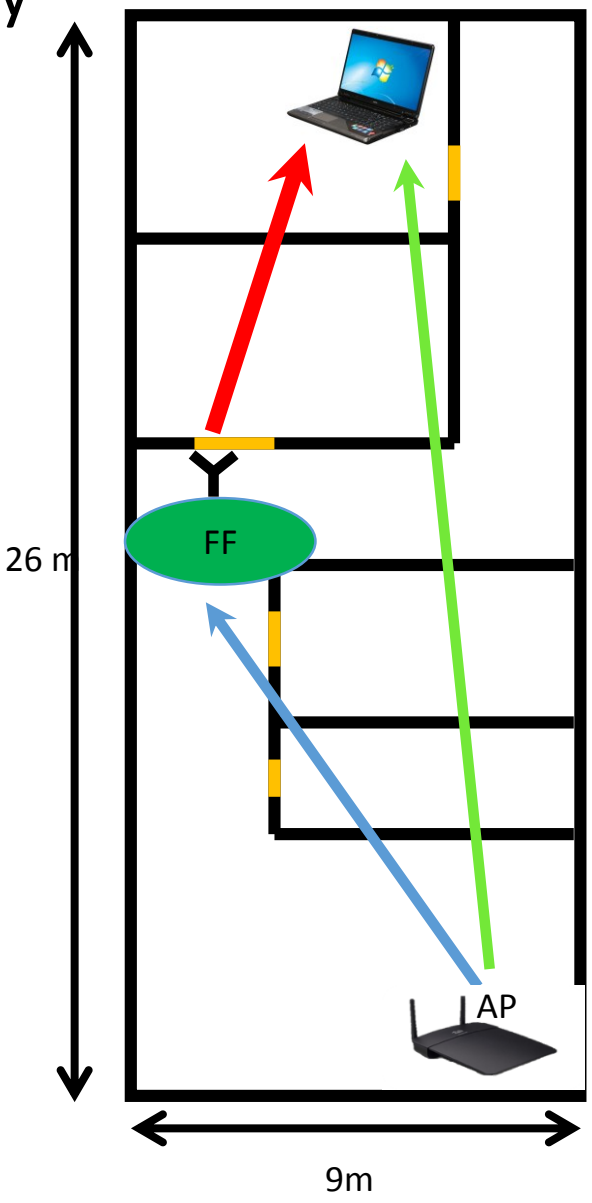

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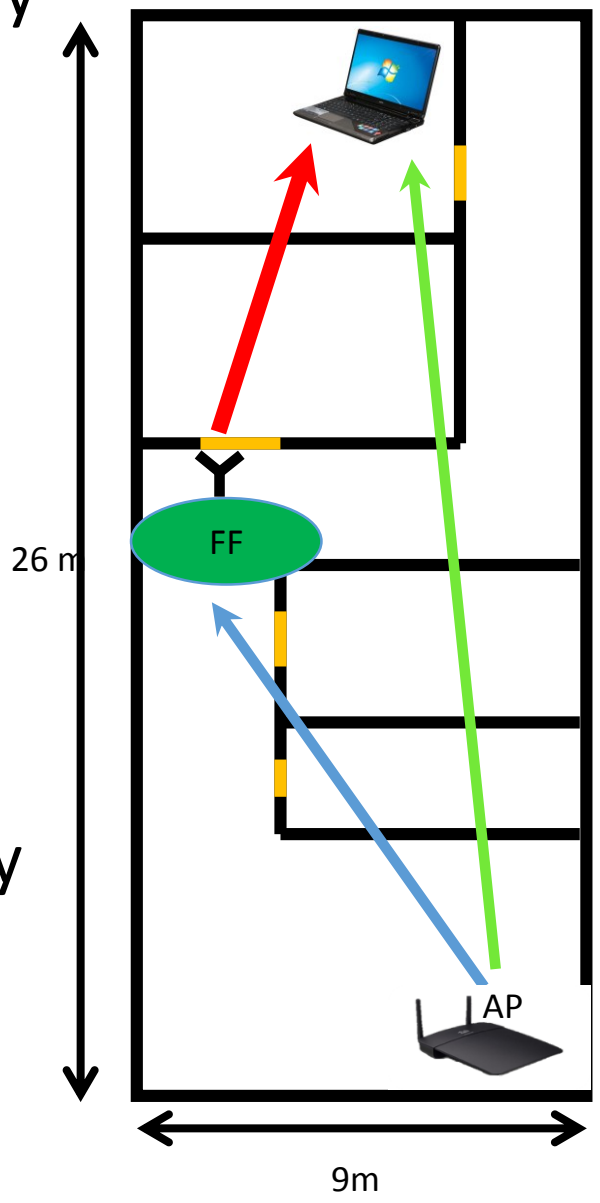

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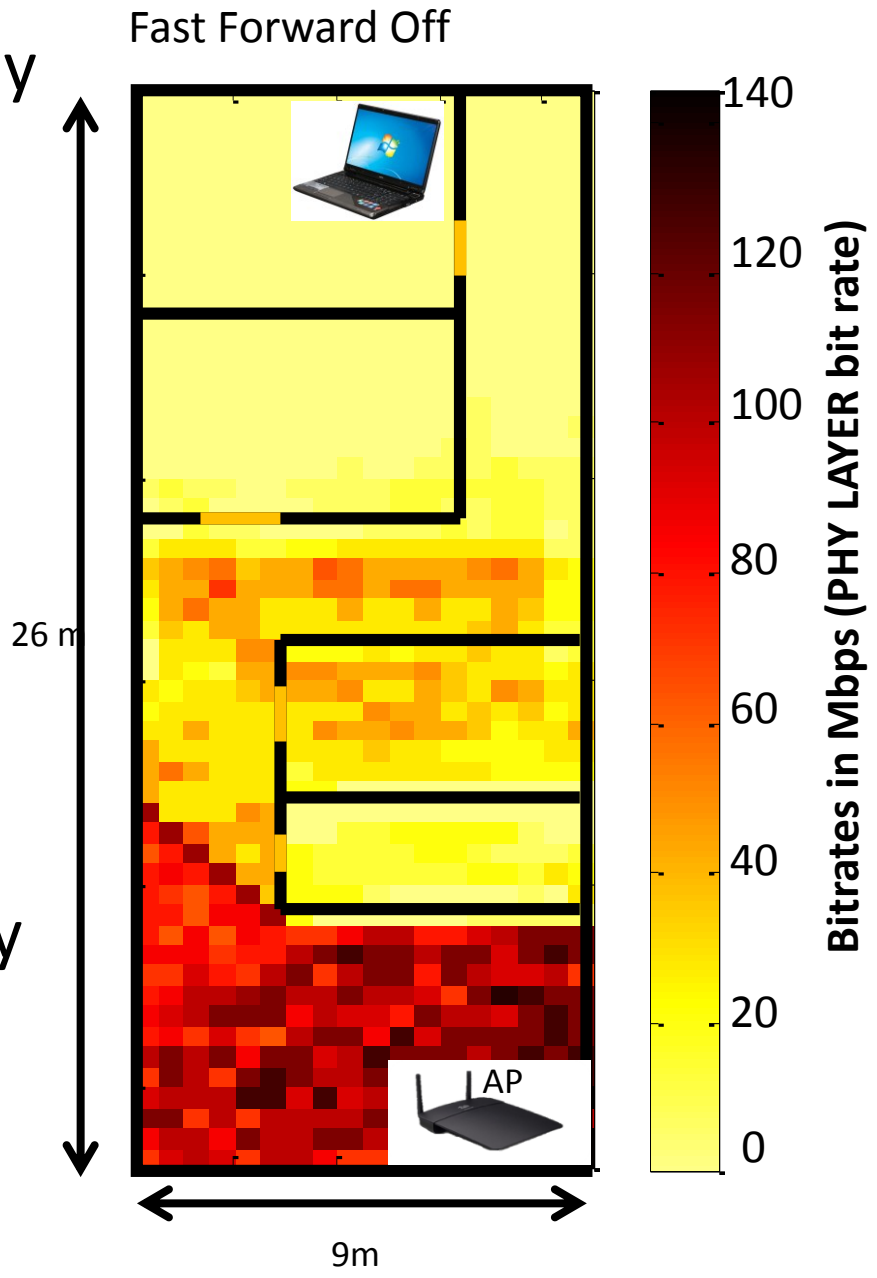

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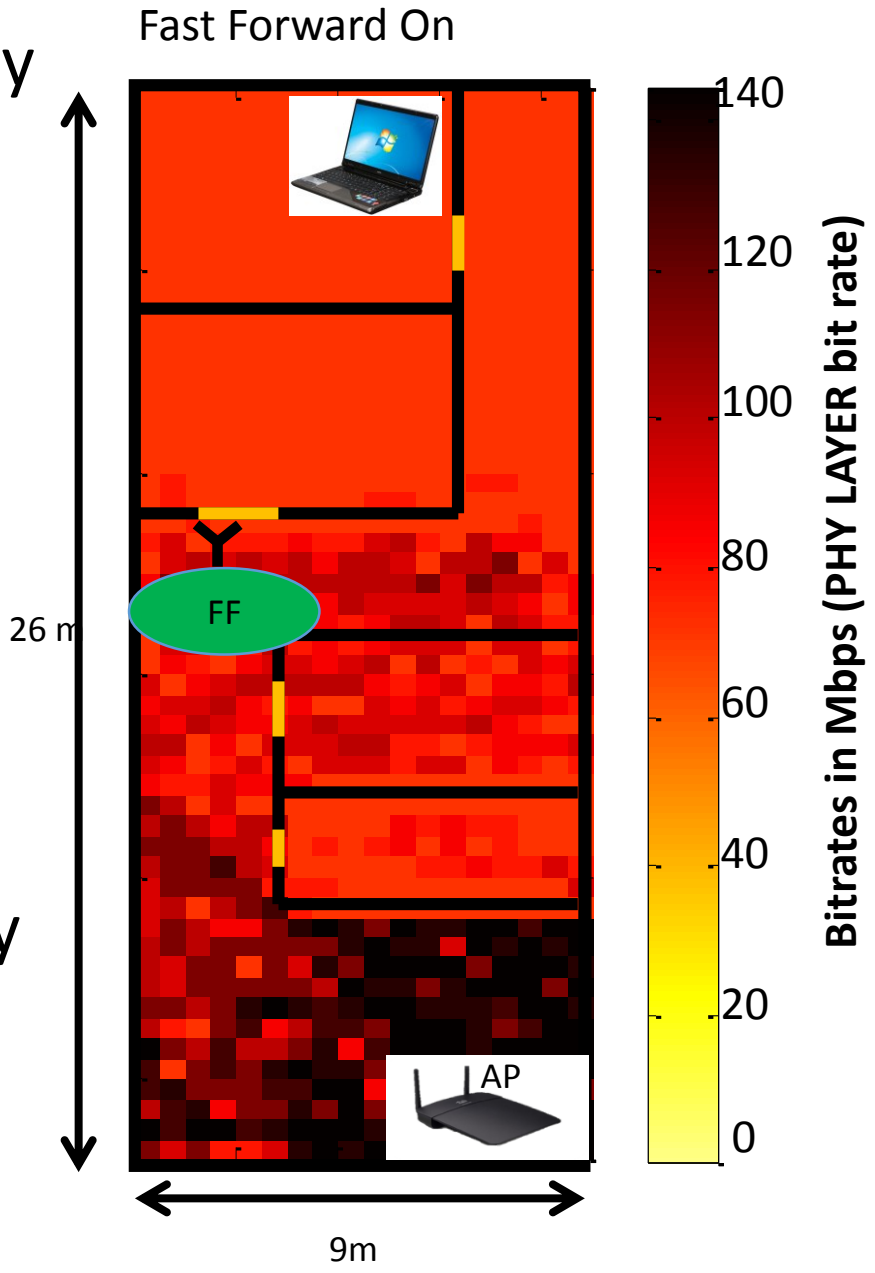

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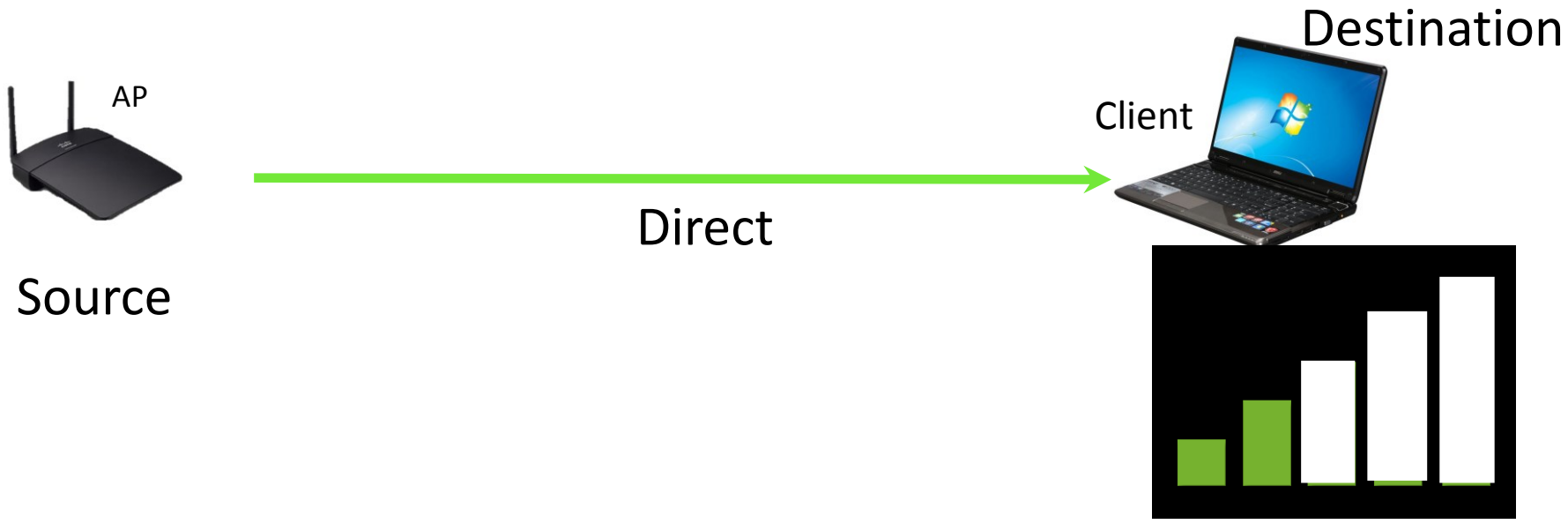

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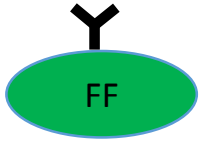
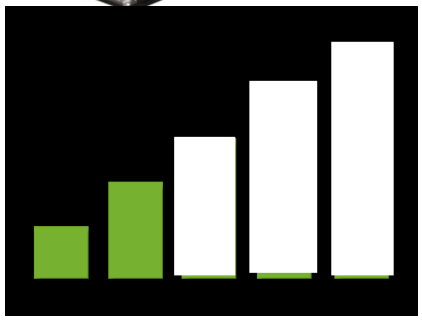


Source

Direct

Destination

Client



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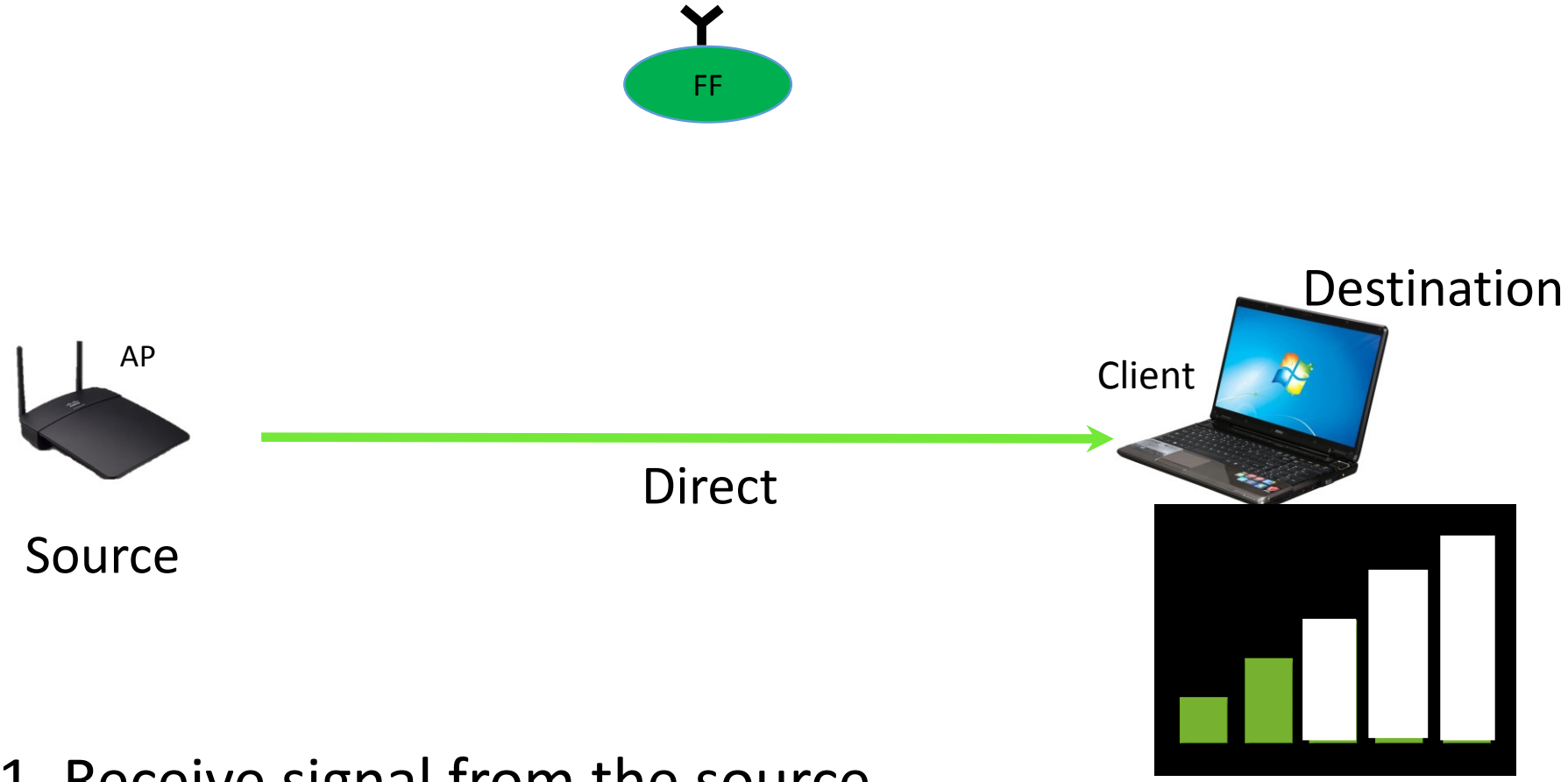

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2. Process it in RF and digital
3. Relay it simultaneously to the destination

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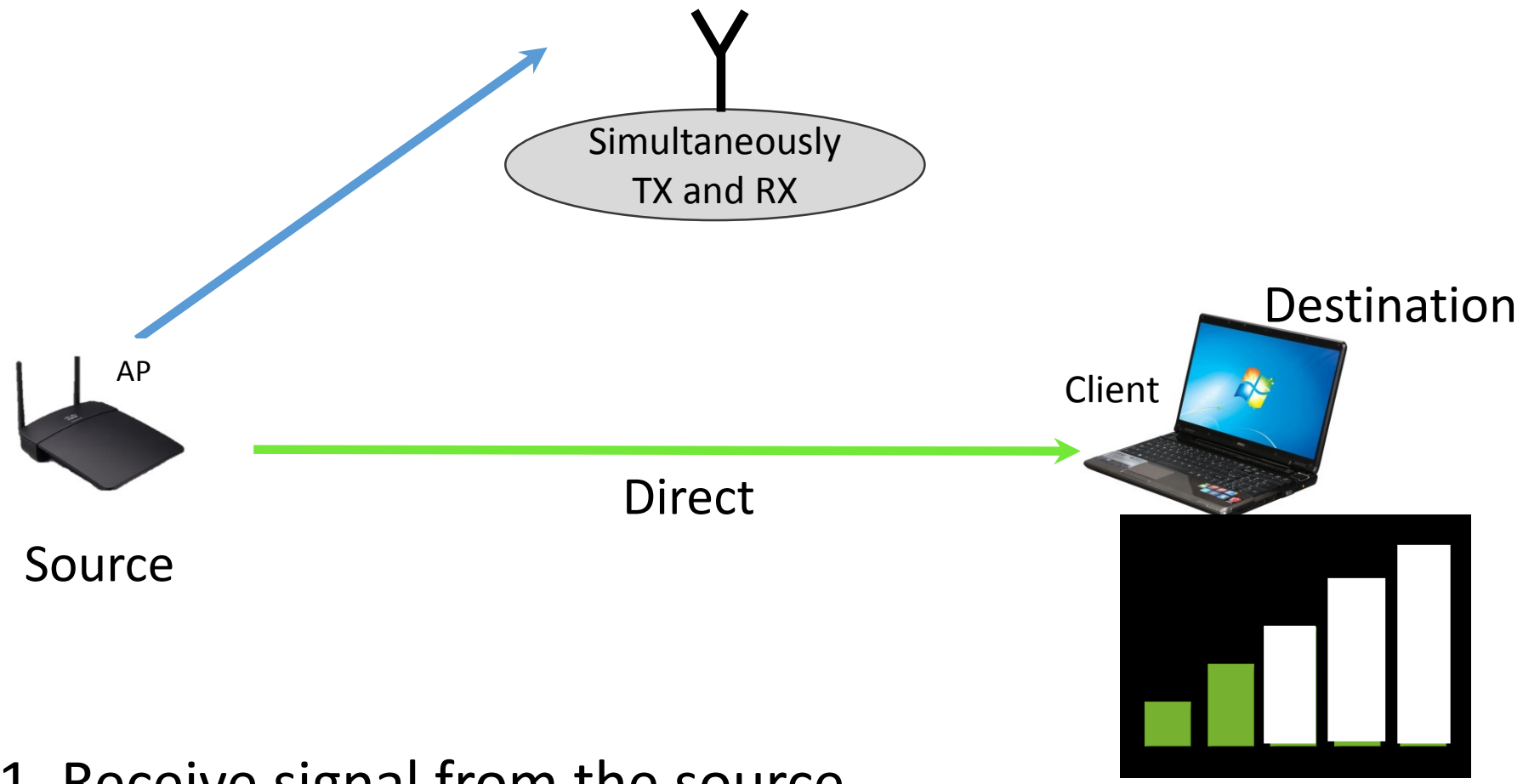

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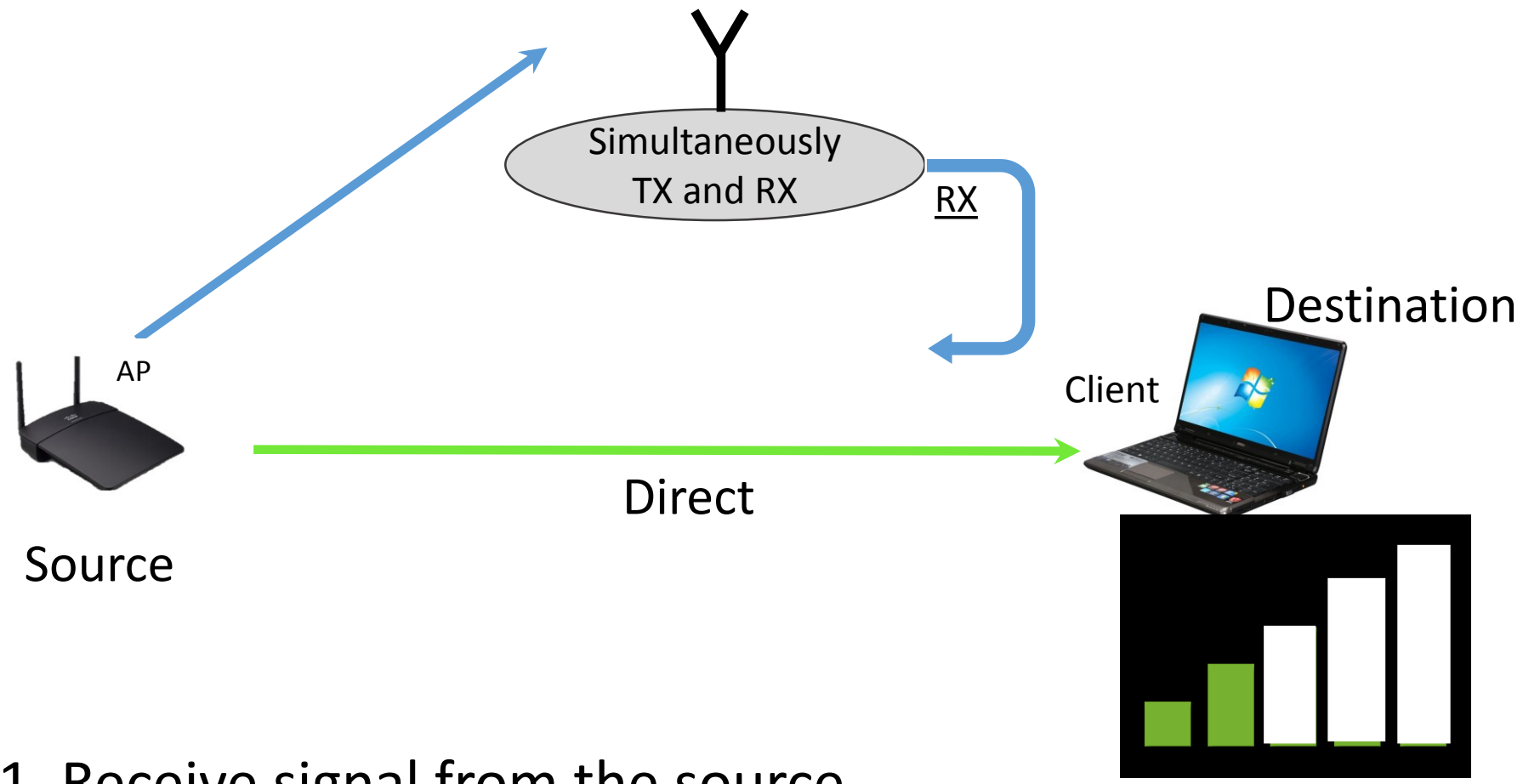

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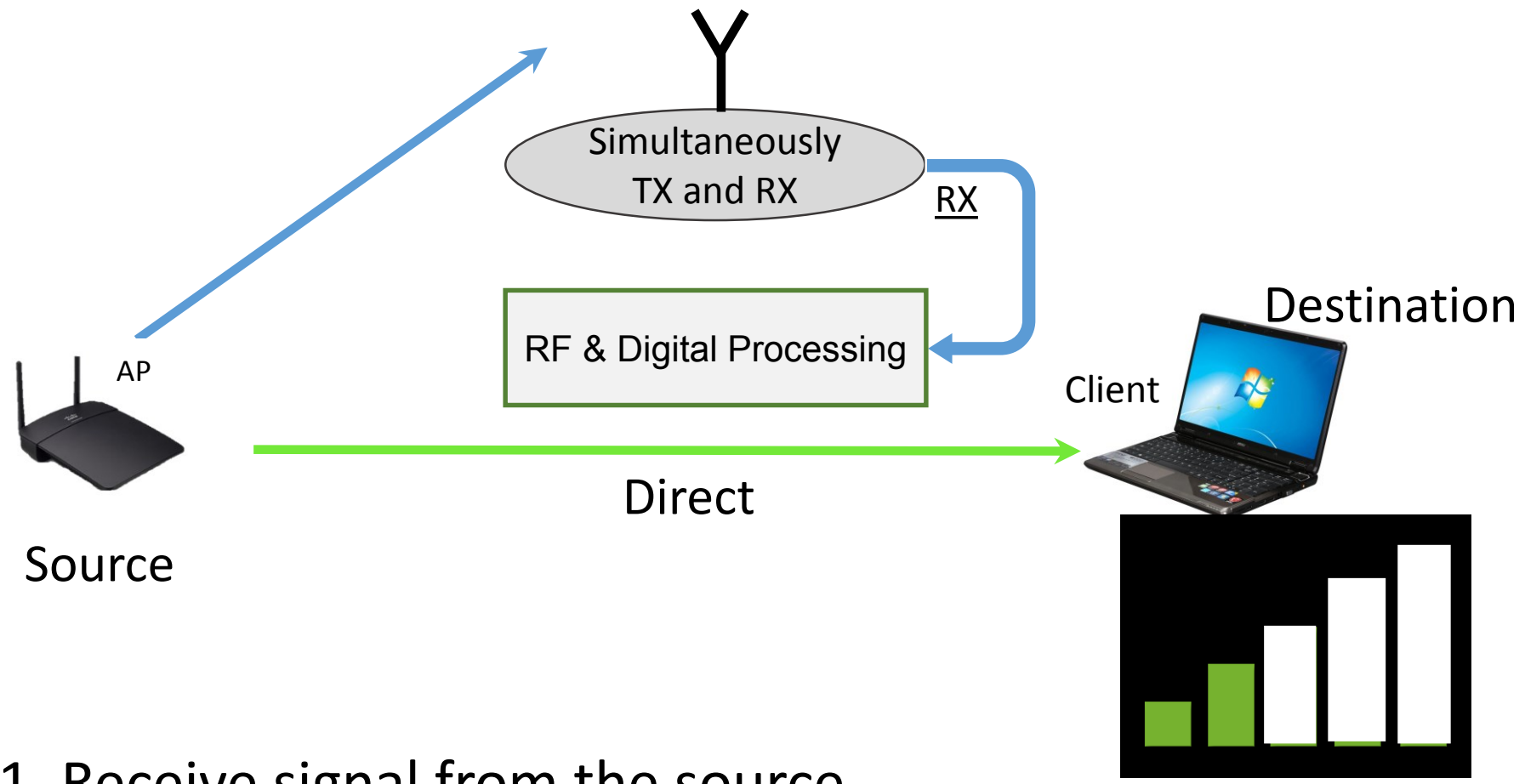

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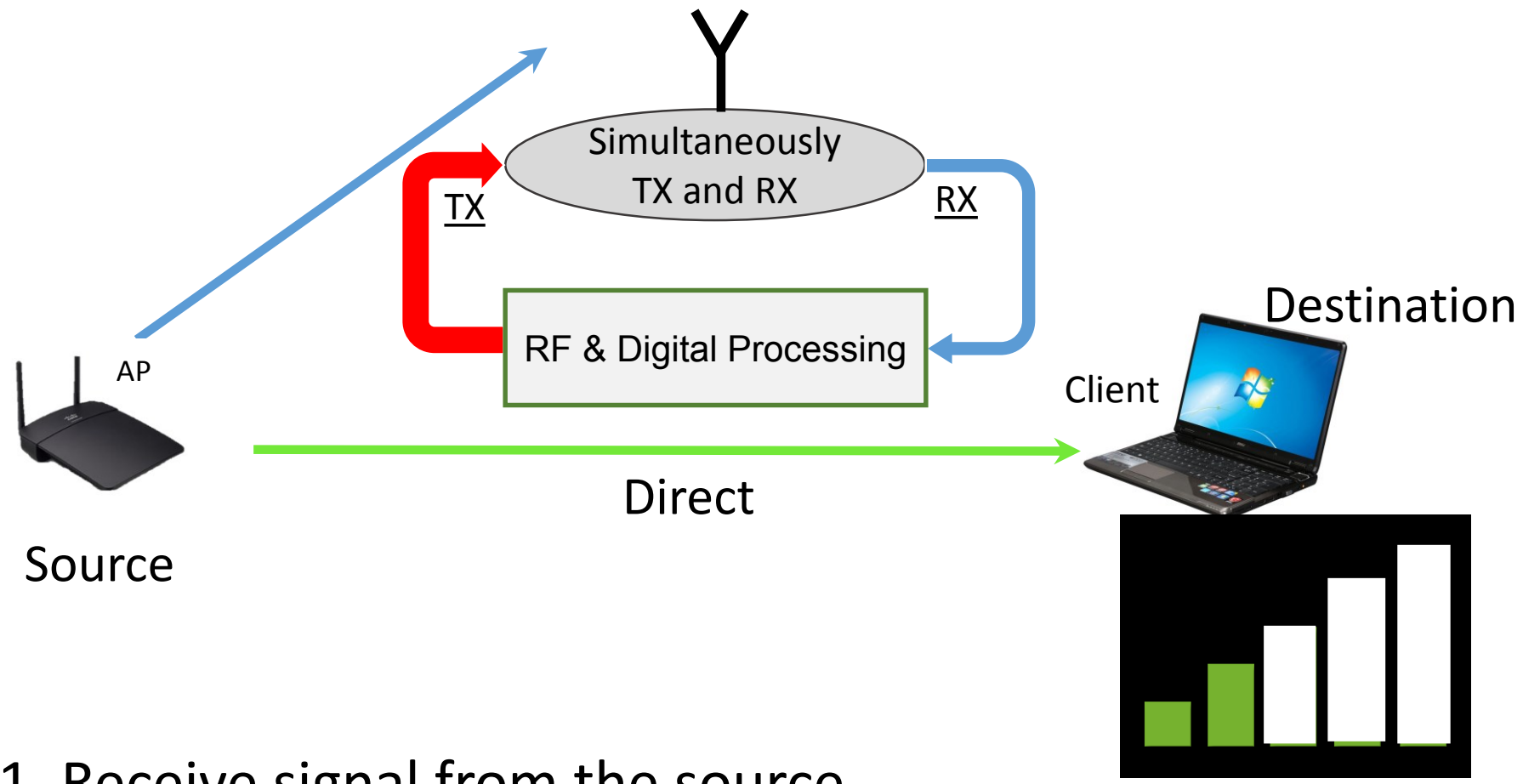

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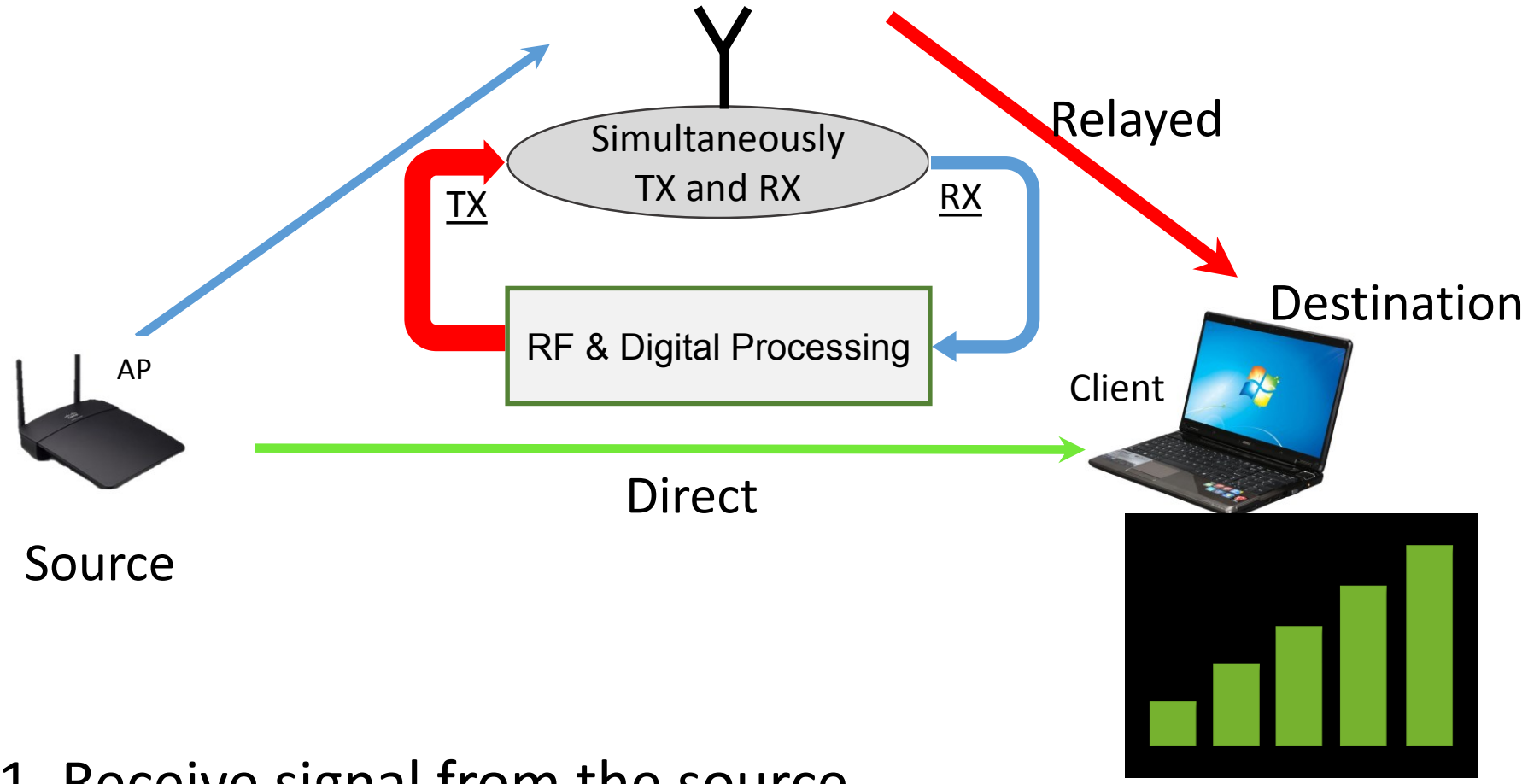

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Isn’t this easy? Just use recent work on full duplex

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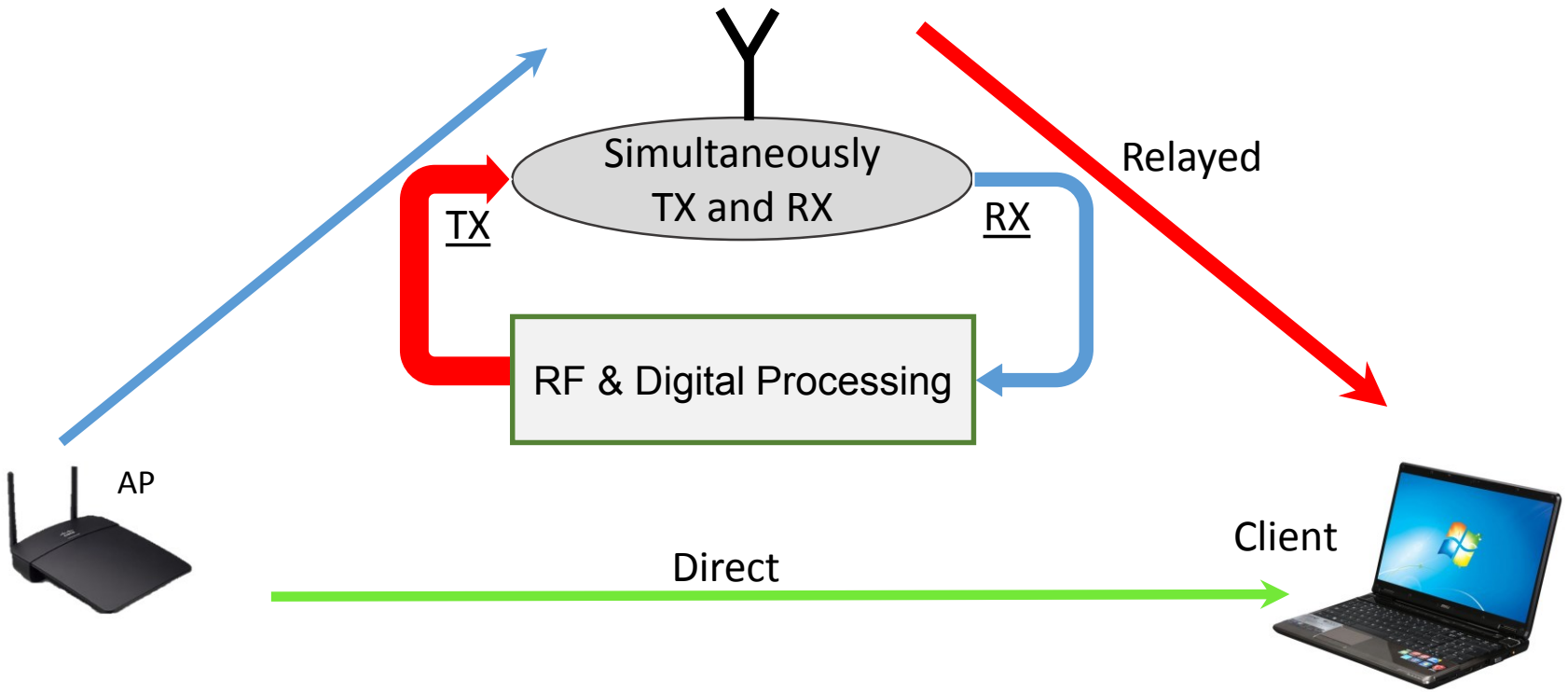

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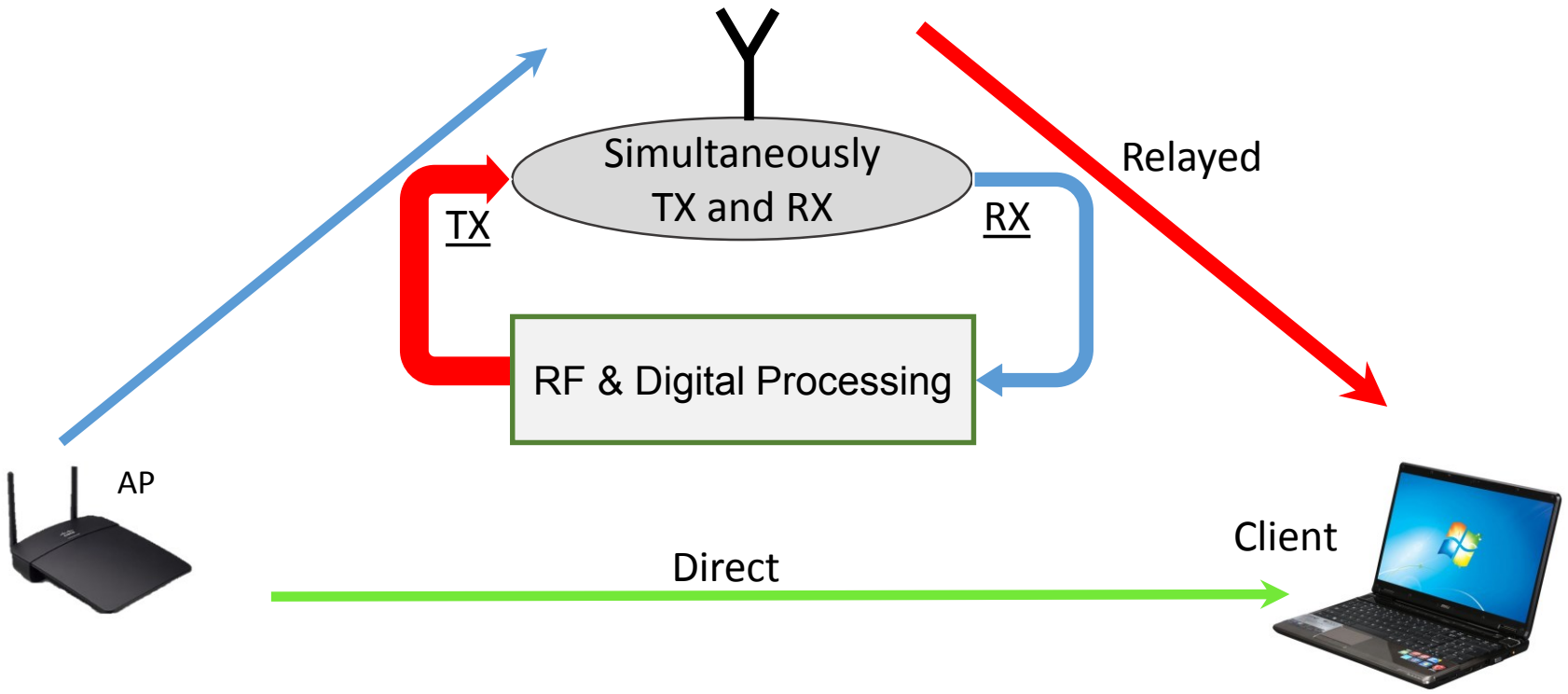

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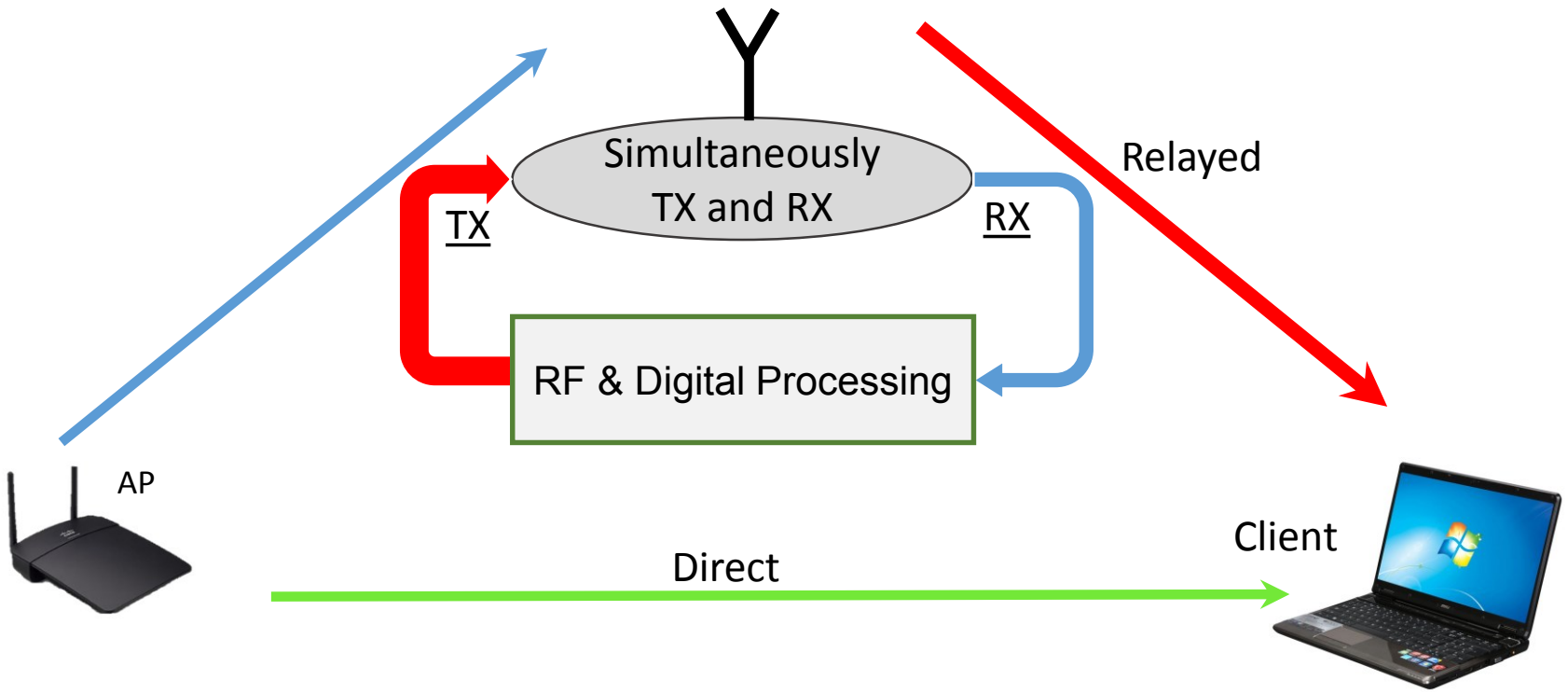

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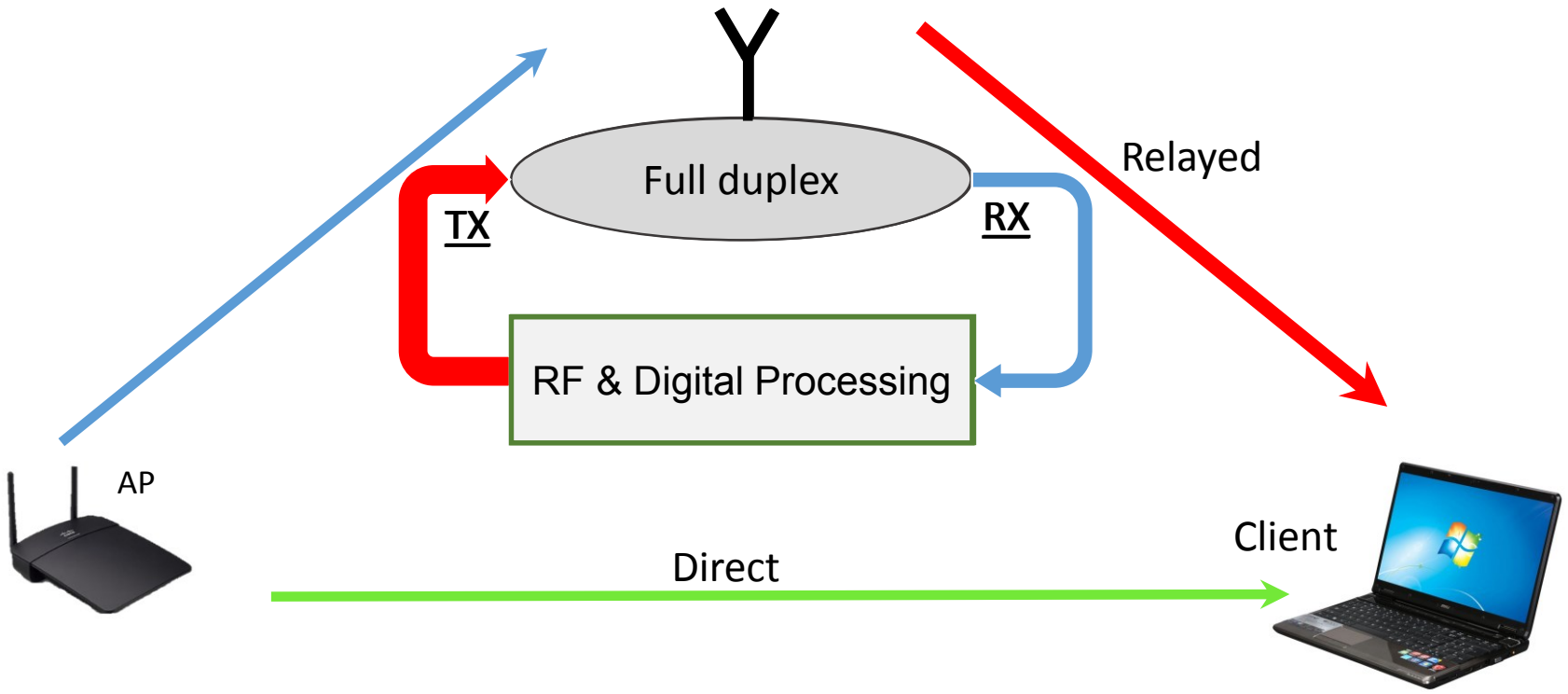

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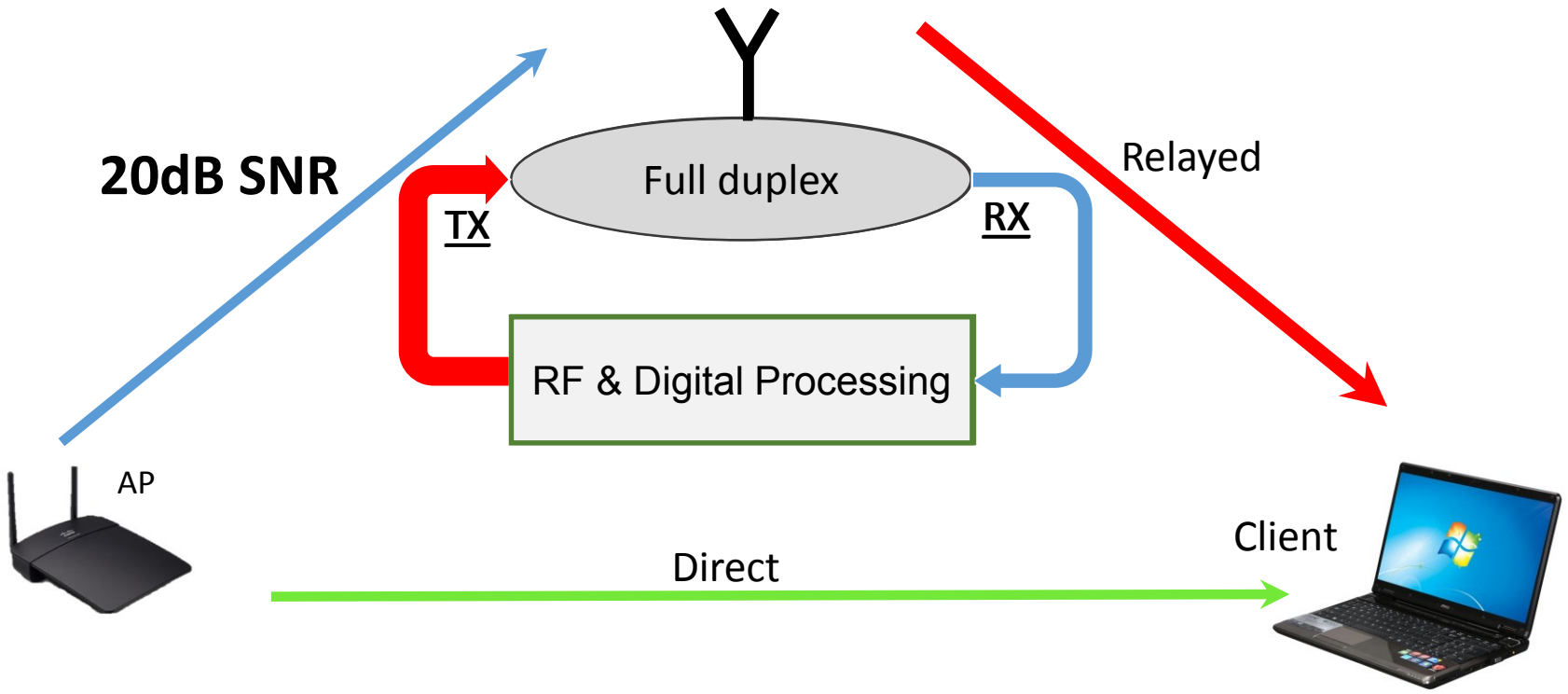
- Use recent work on full duplex



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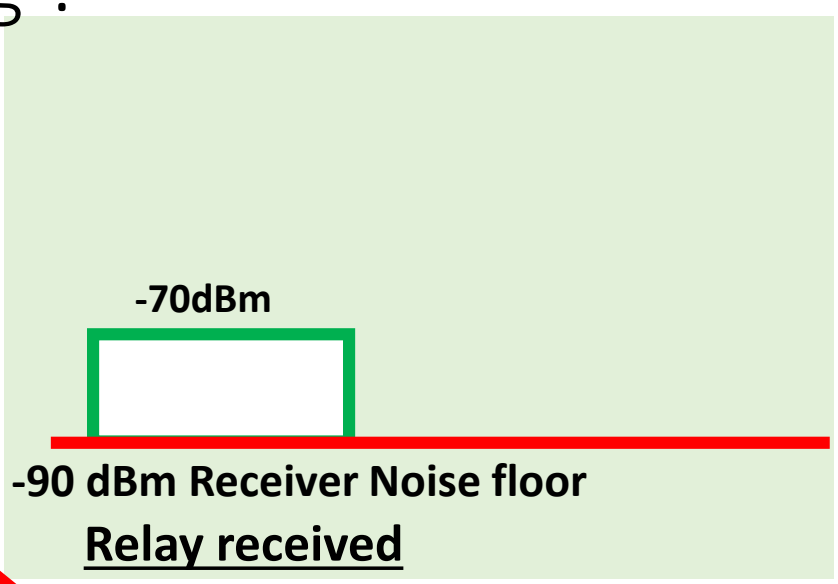

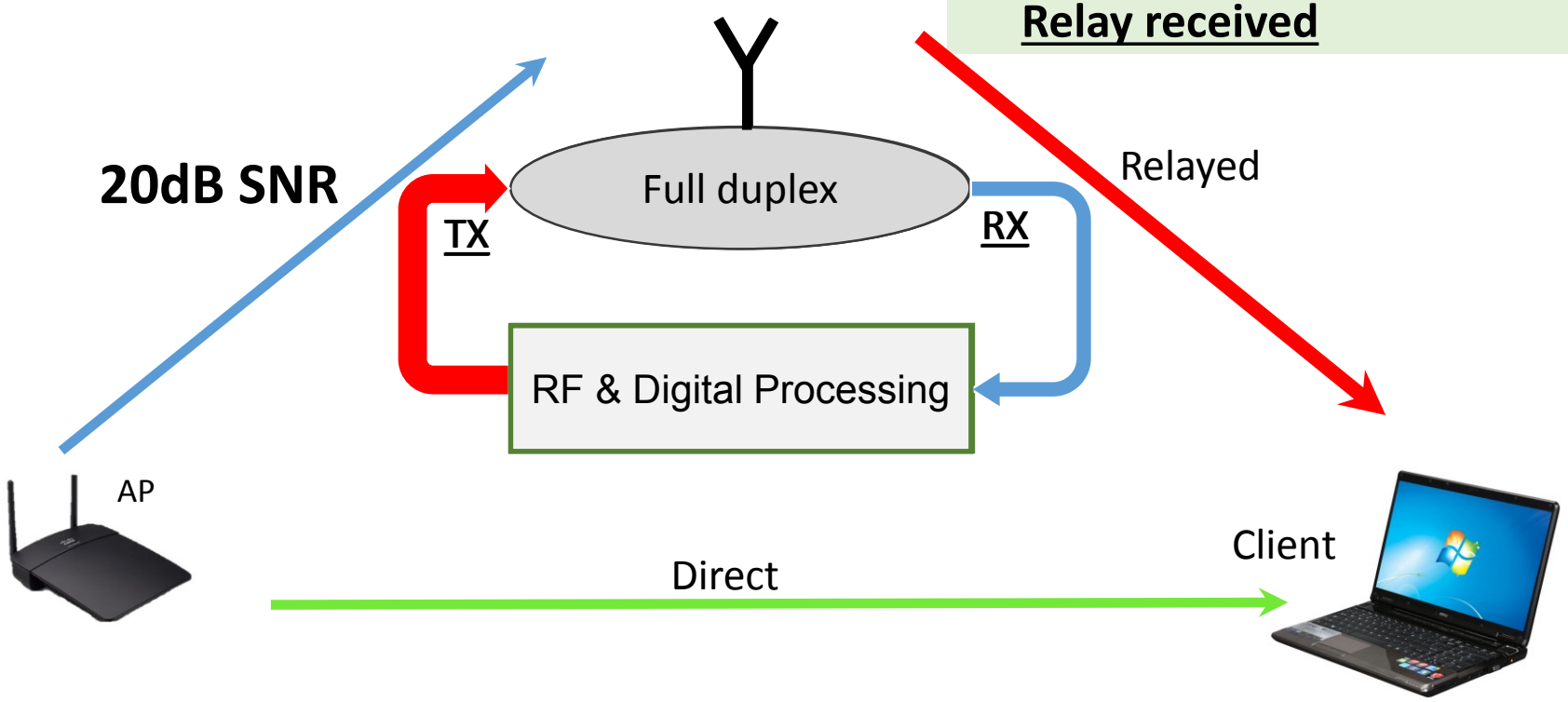

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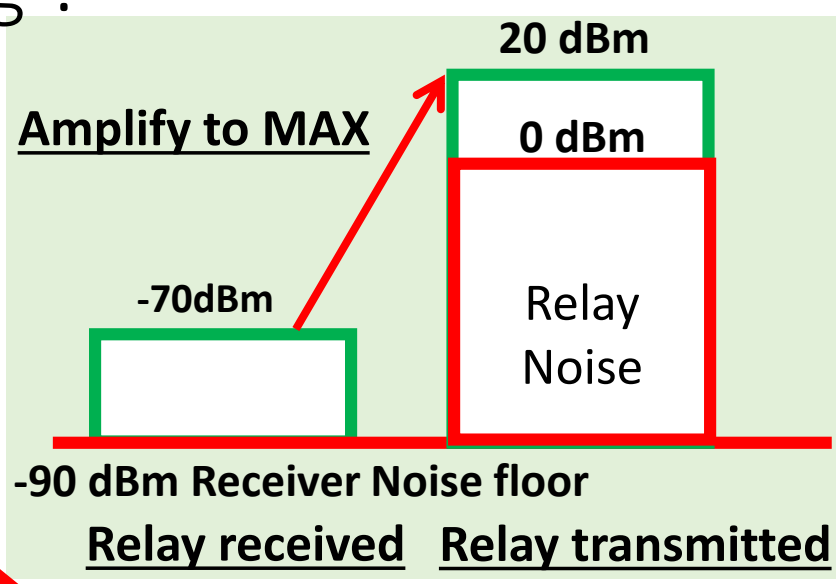

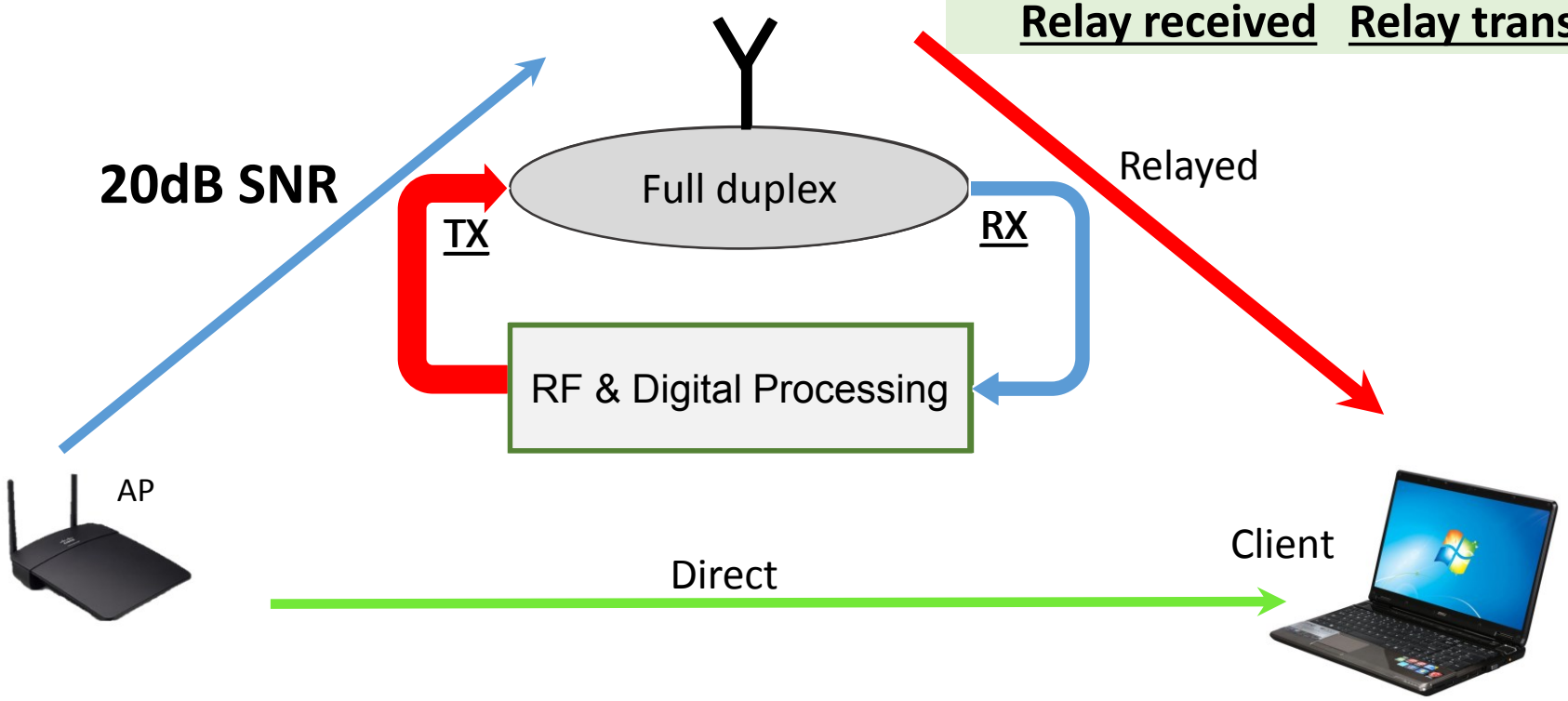

How to relay while receiving ?

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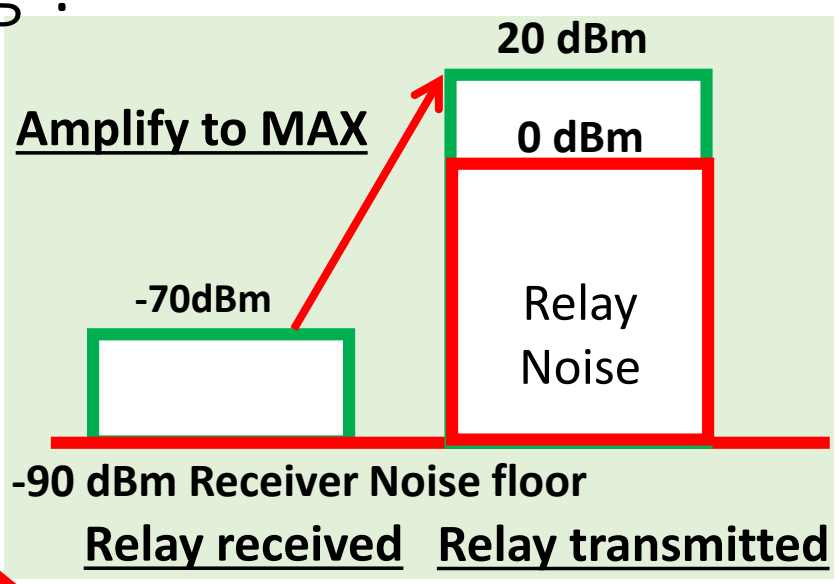
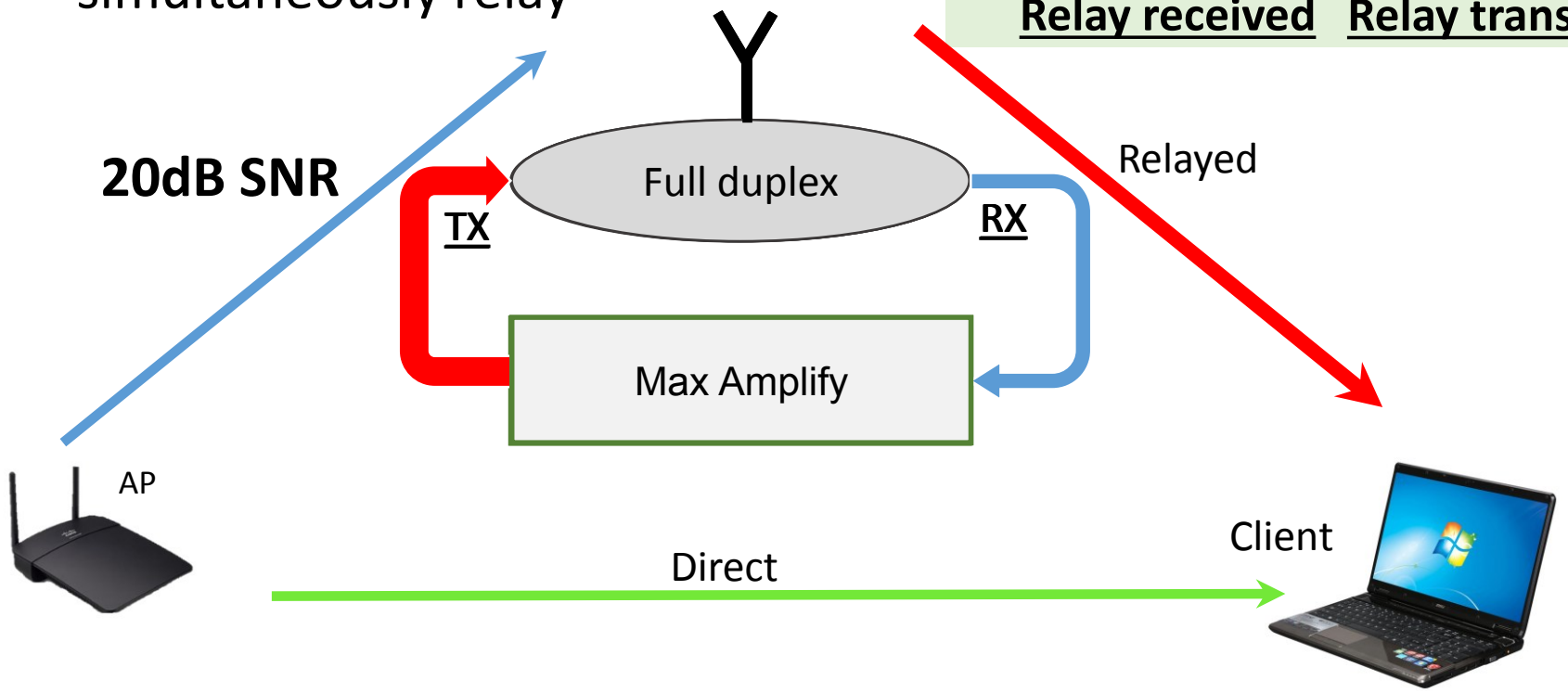
- Receive signal, amplify and simultaneously relay





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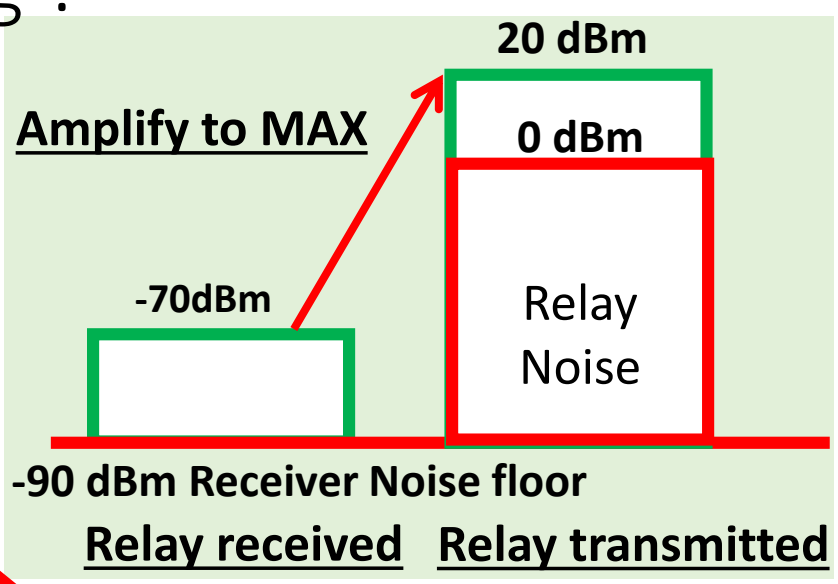

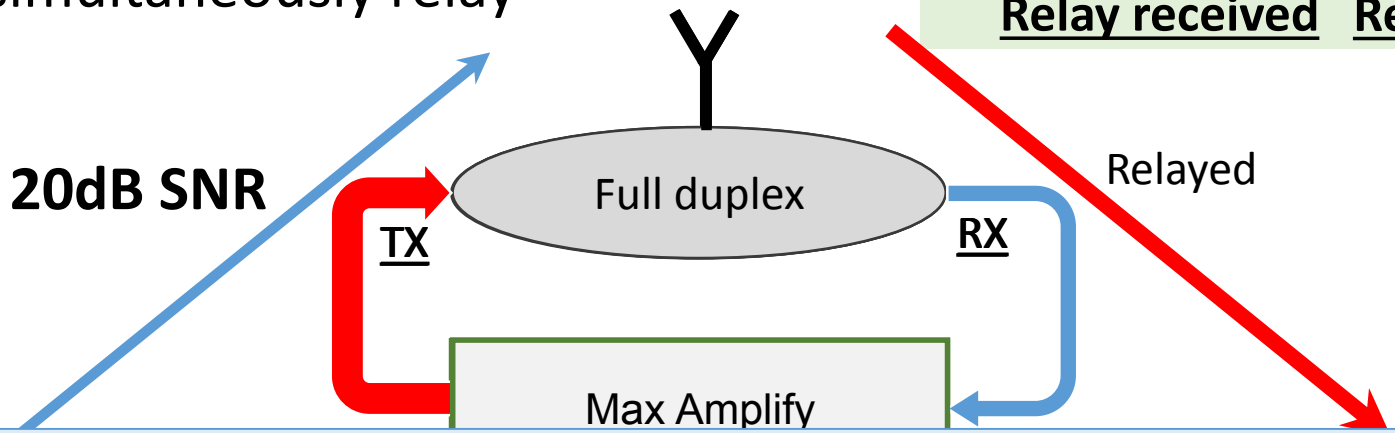

Are we done? No, this design has two problems:

- Amplifies noise
- Creates destructive interference

Challenge 1: Noise Amplification

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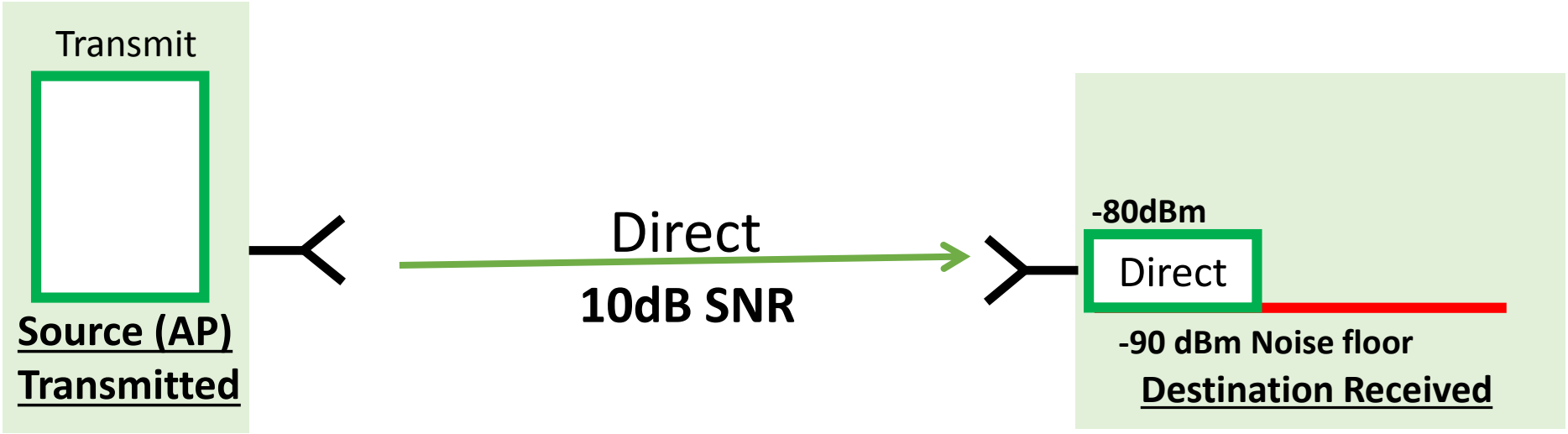

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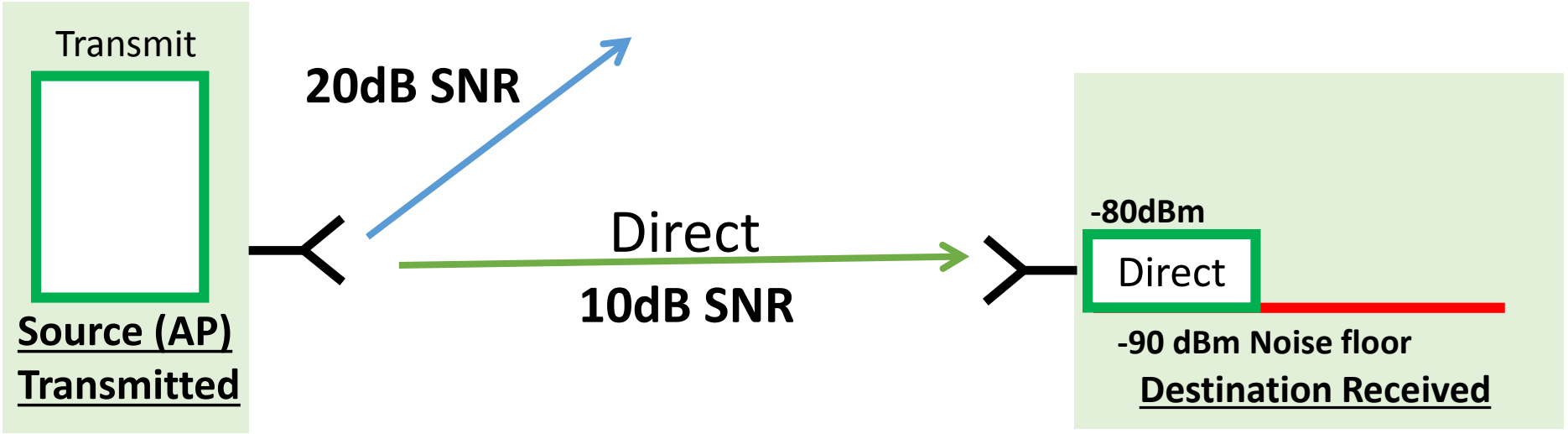

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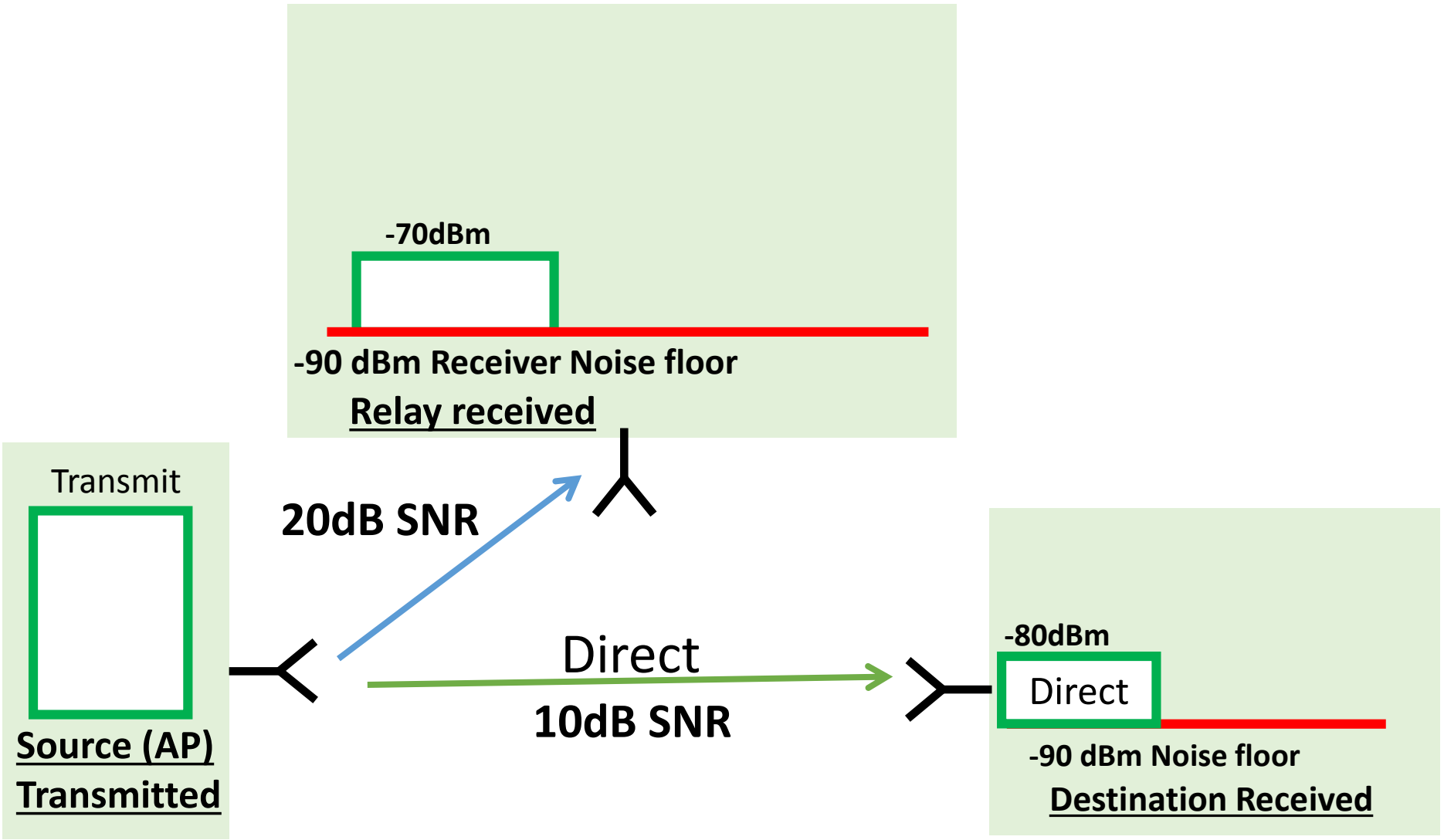

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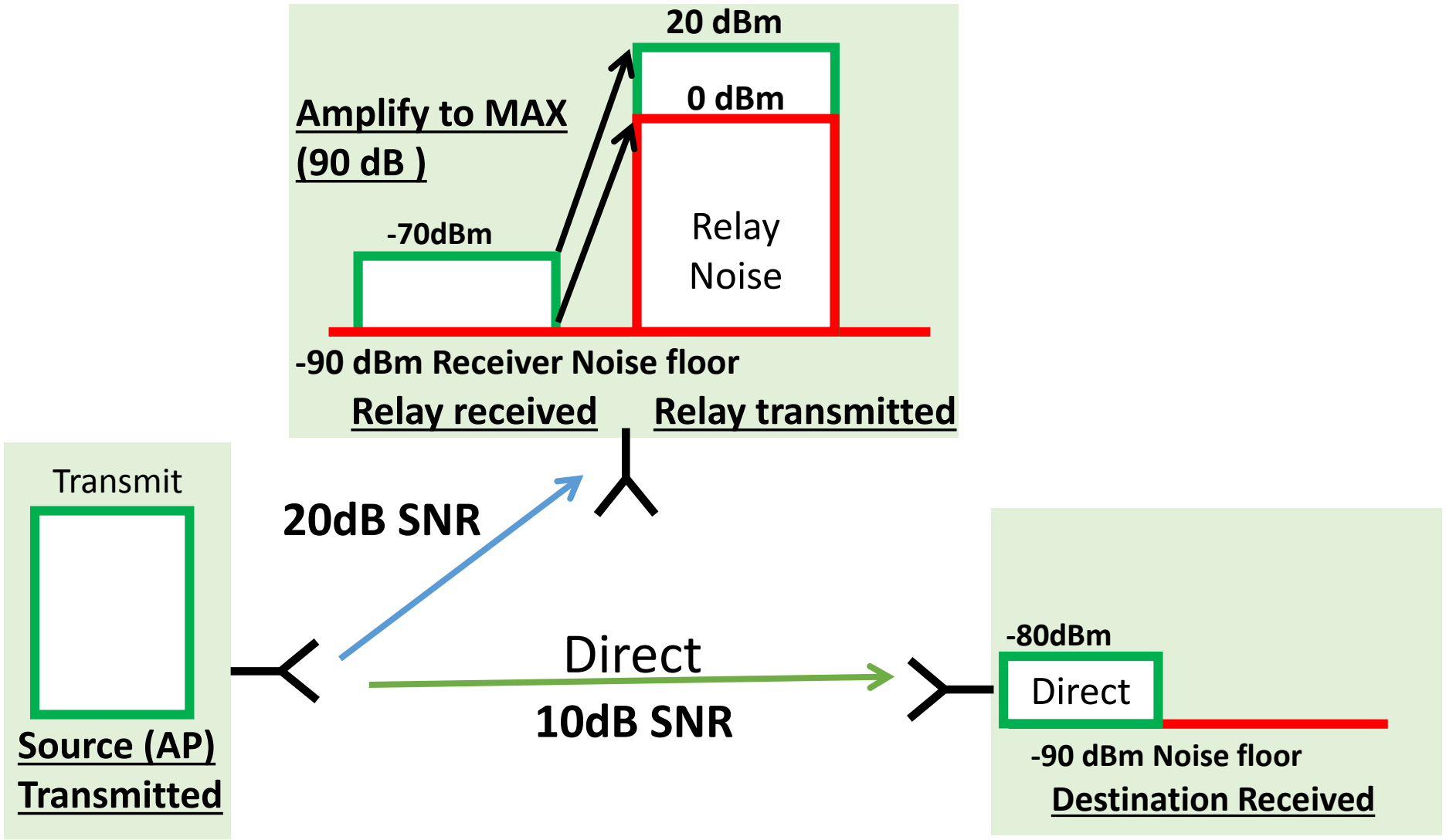

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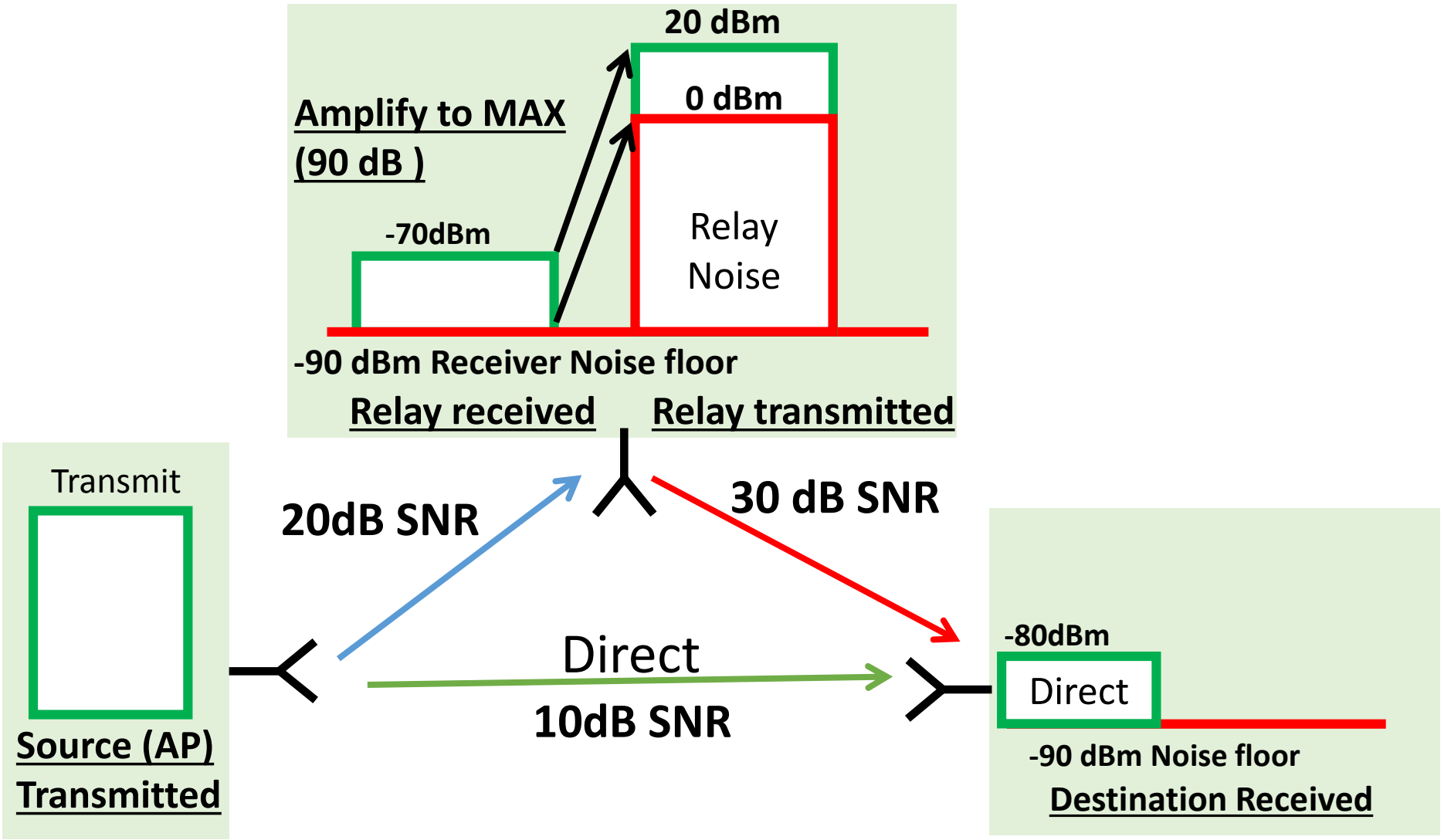

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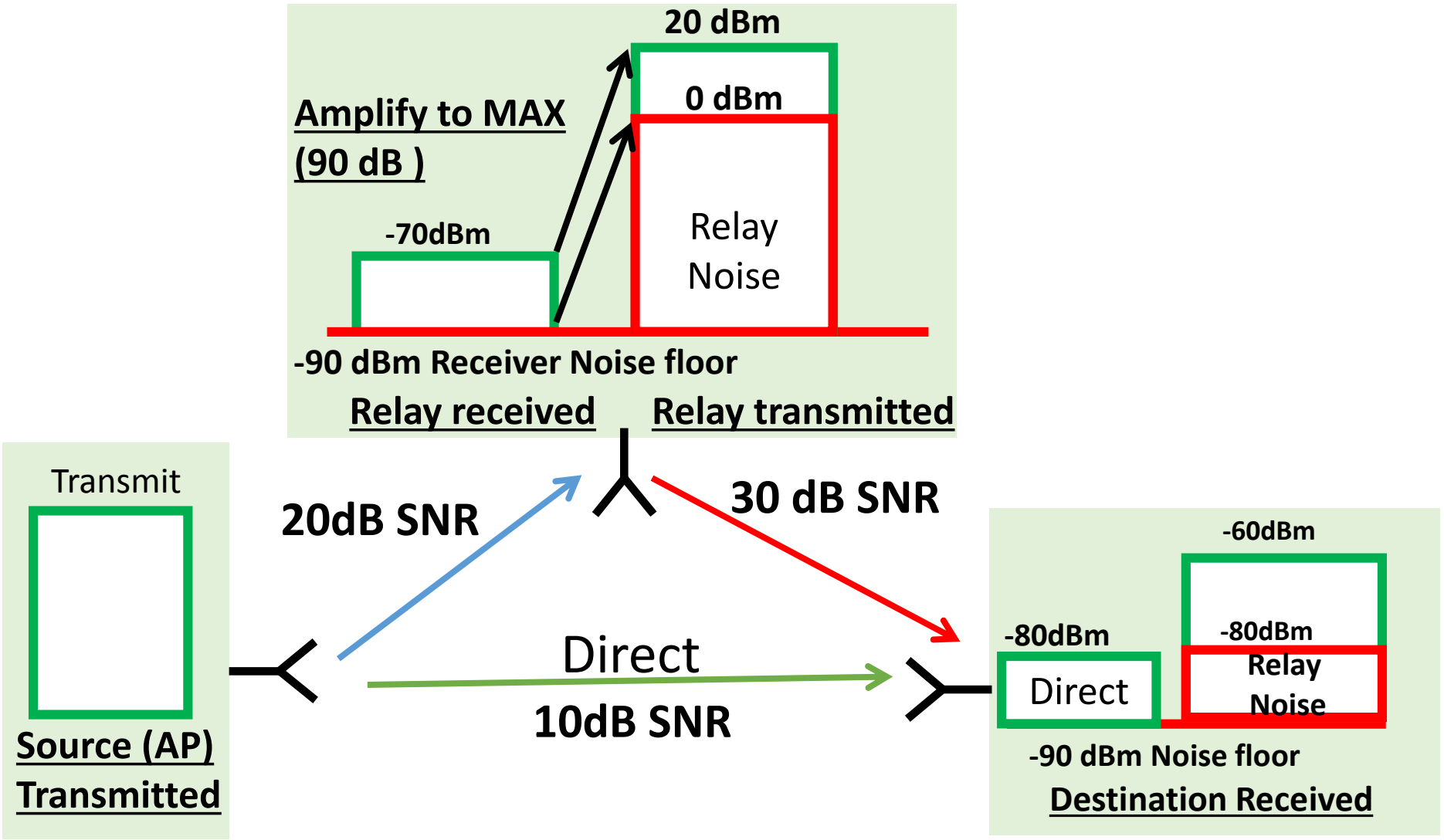

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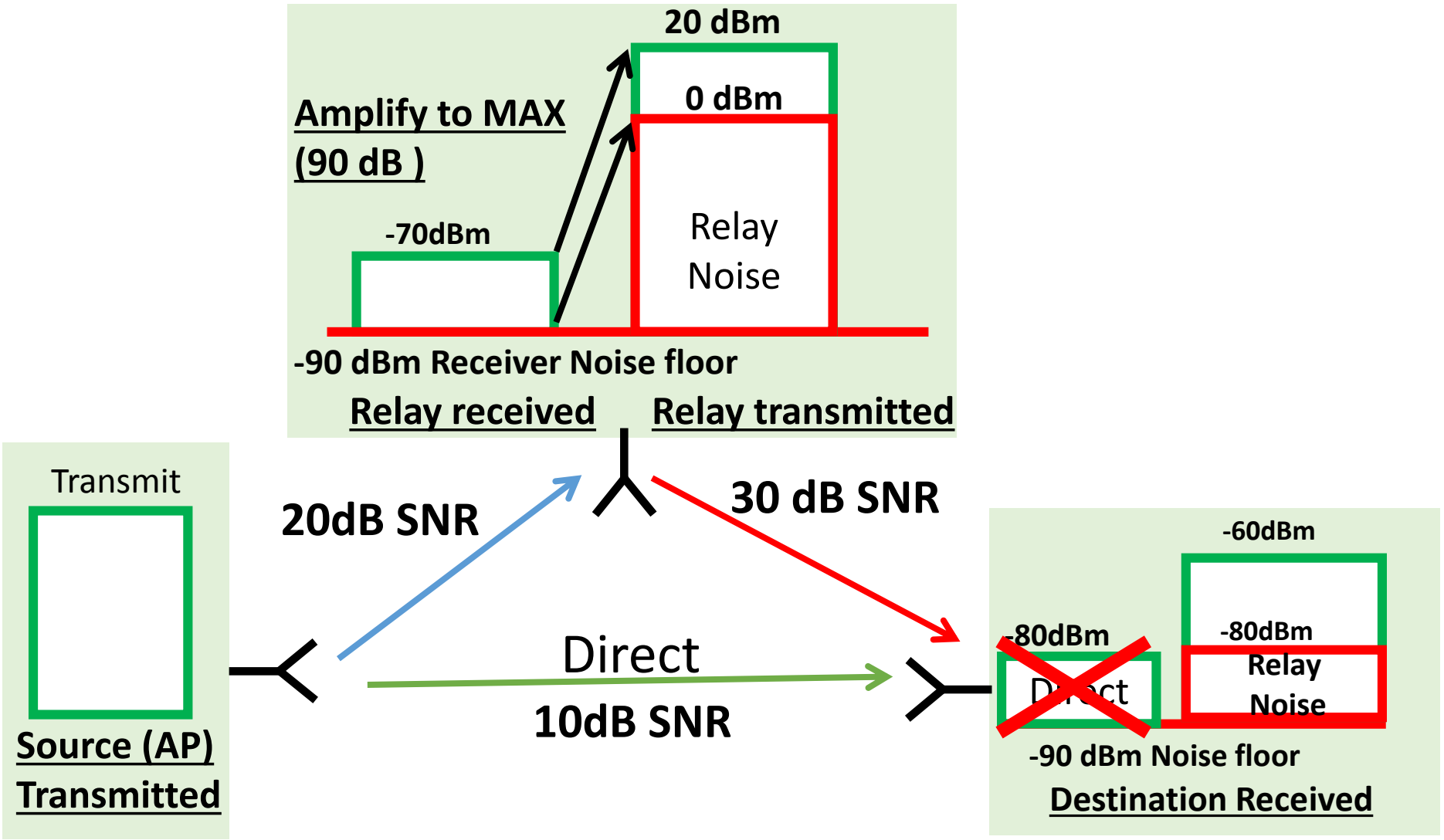

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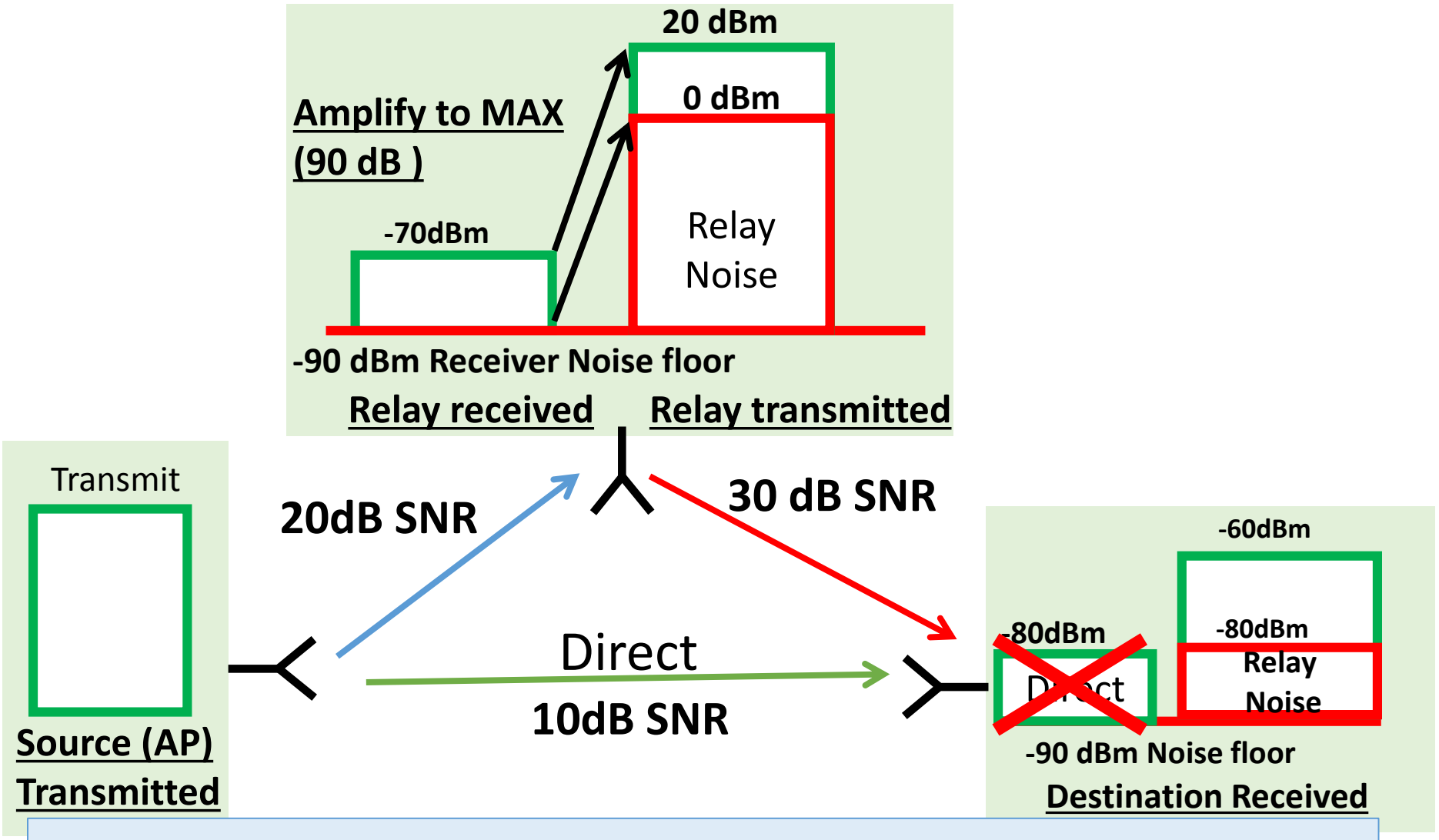
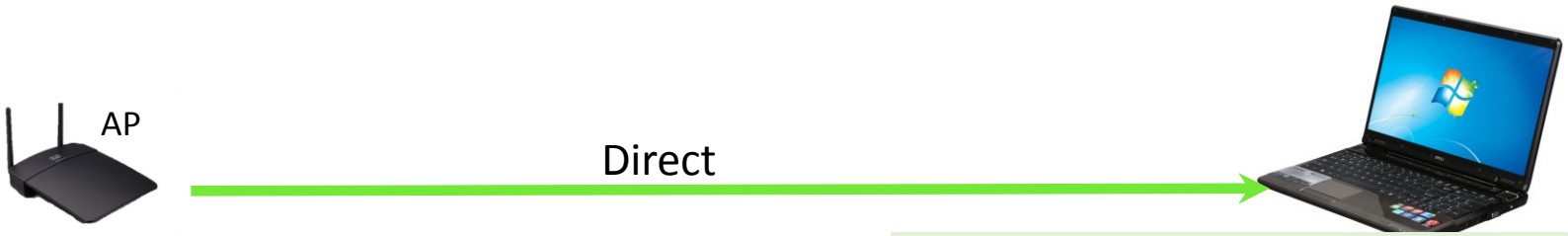


Amplified noise destroys direct signal

Challenge 2: Destructive Interference

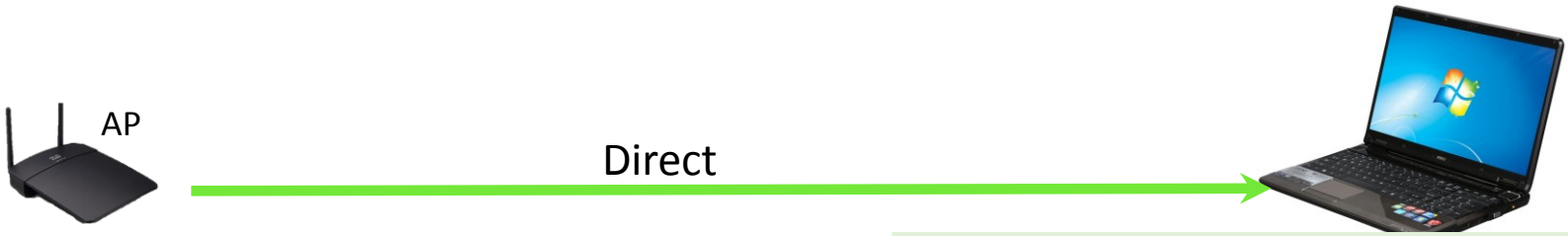


Direct

-90 dBm Noise floor

Destination Received

Challenge 2: Destructive Interference



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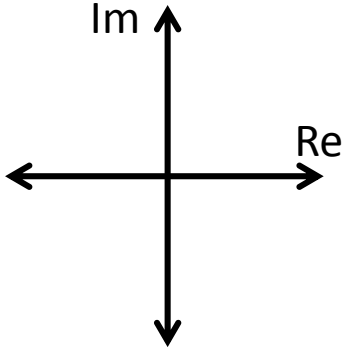

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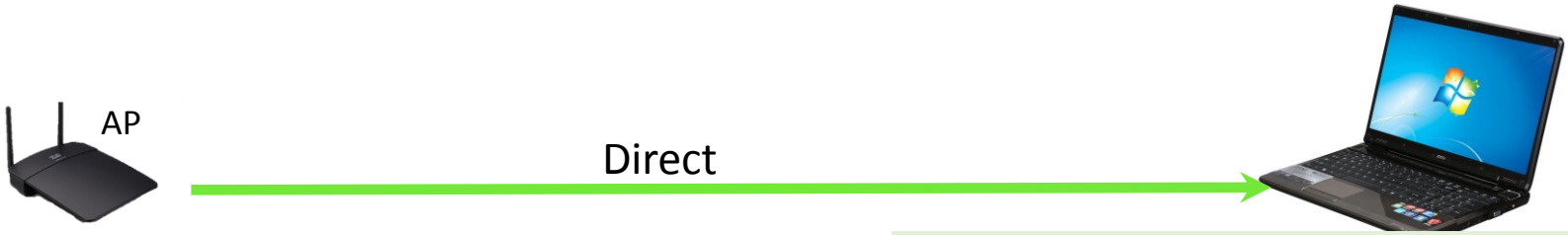

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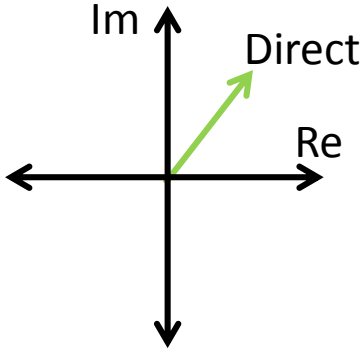

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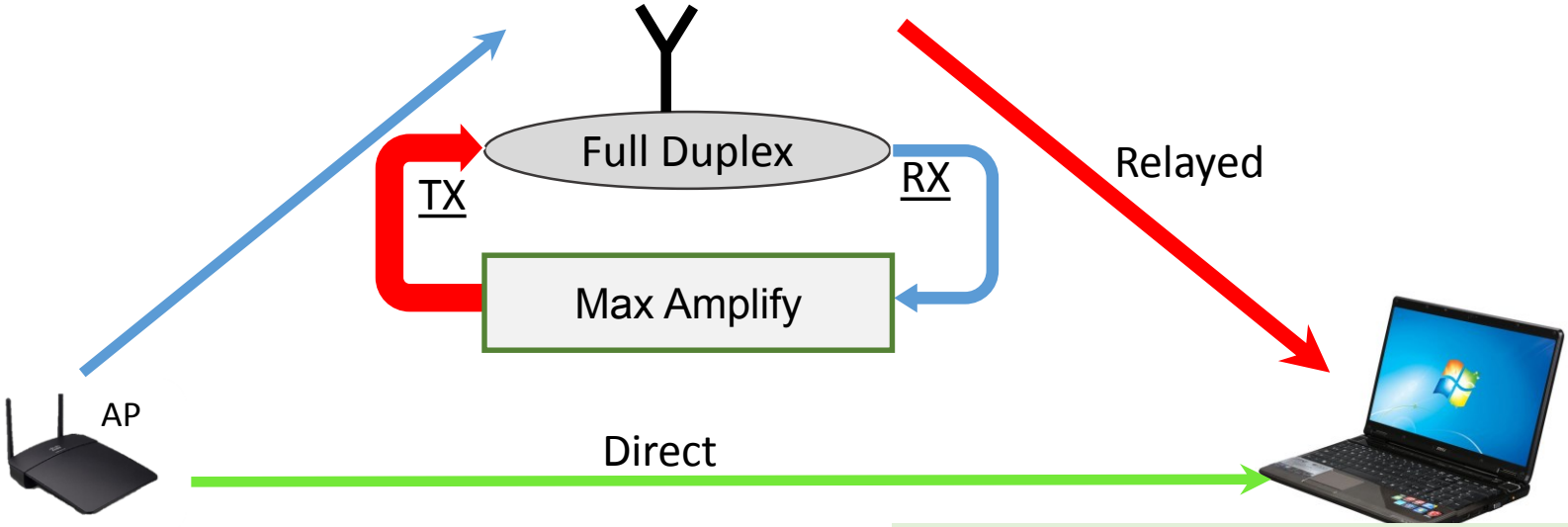

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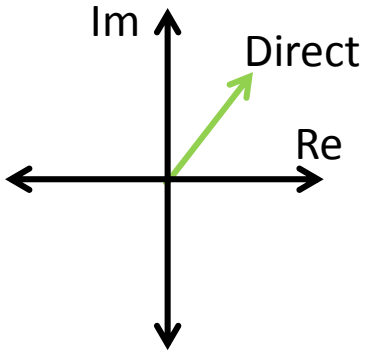

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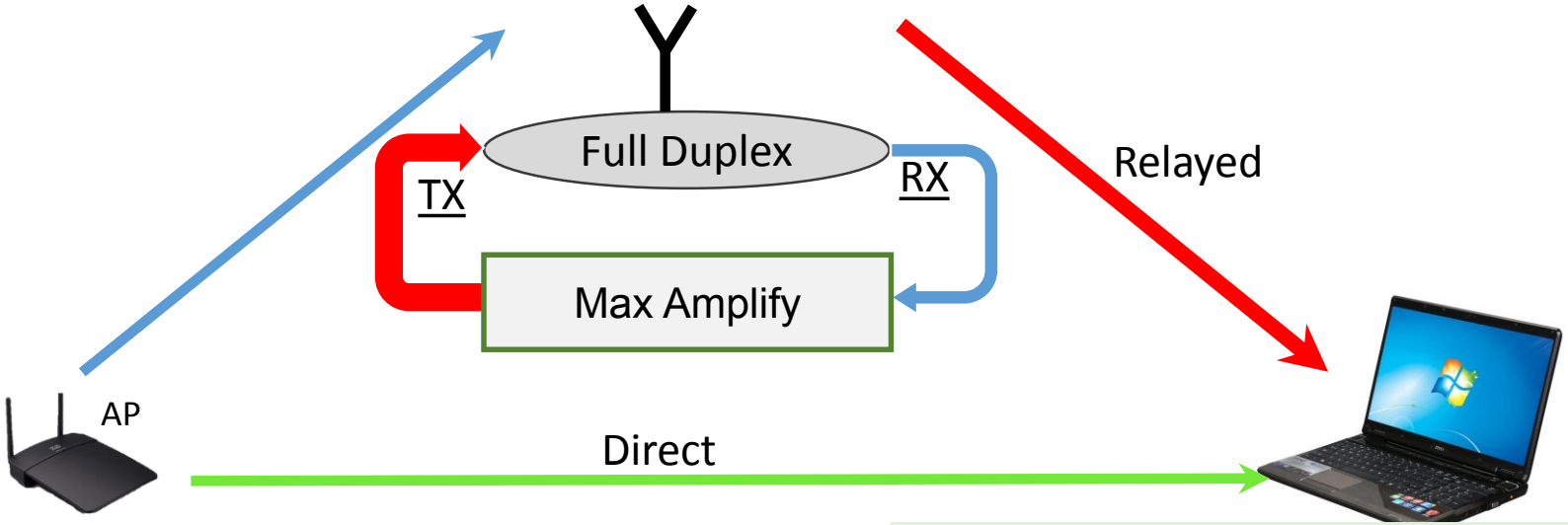

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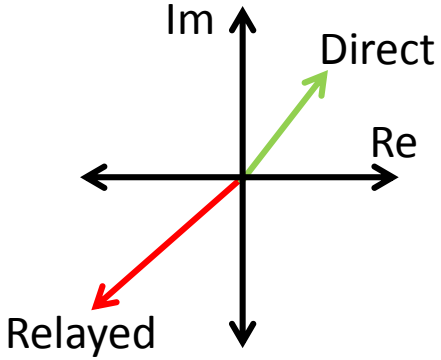

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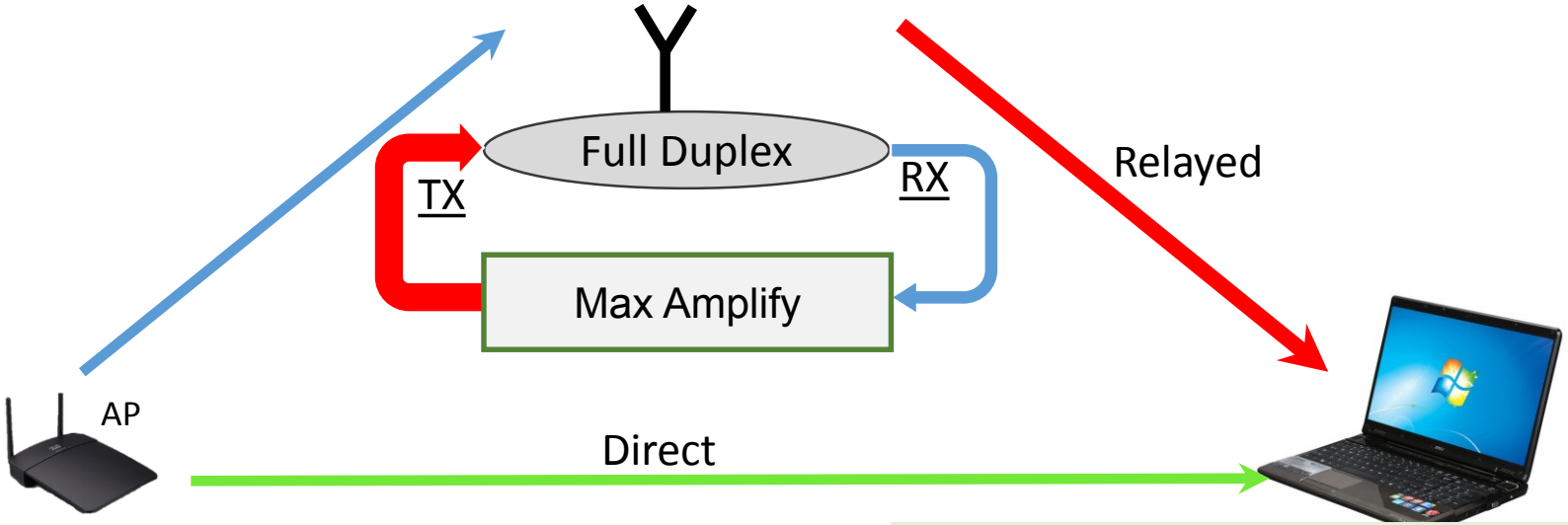
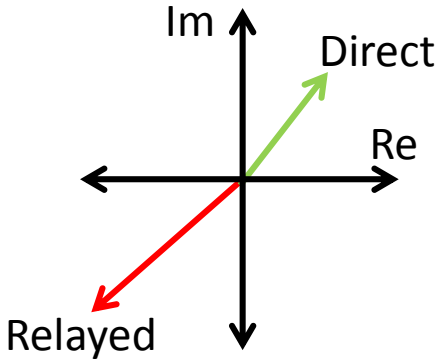


Direct + Relayed

-90 dBm Noise floor

Destination Received



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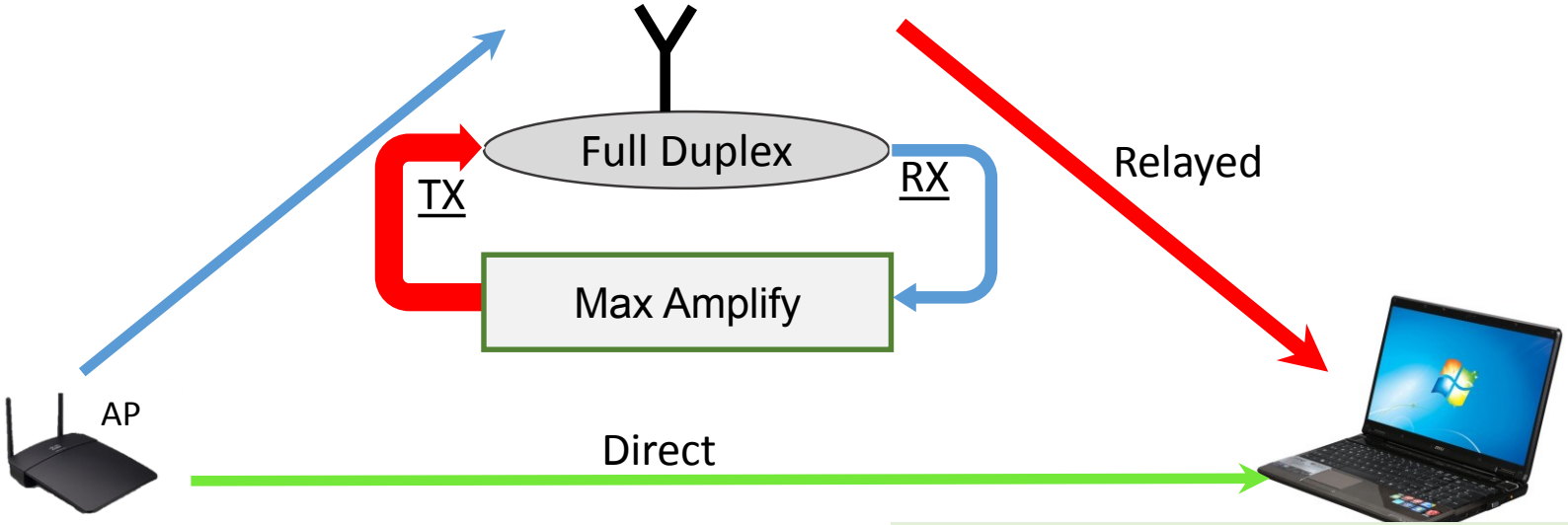
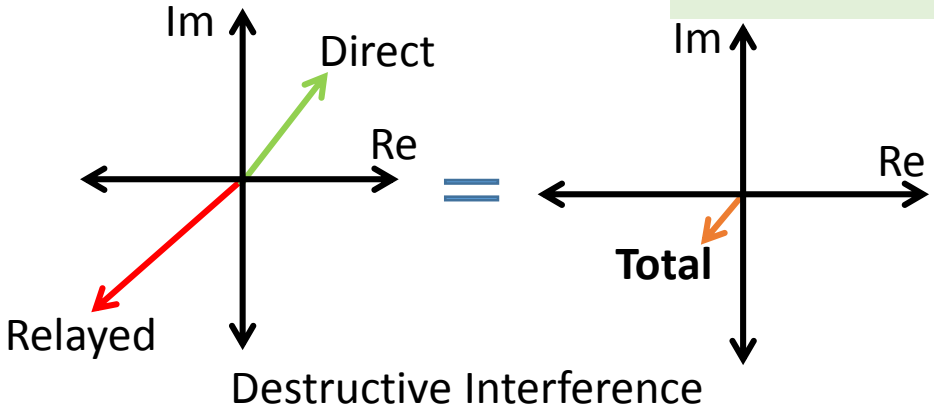


Direct + Relayed = Total

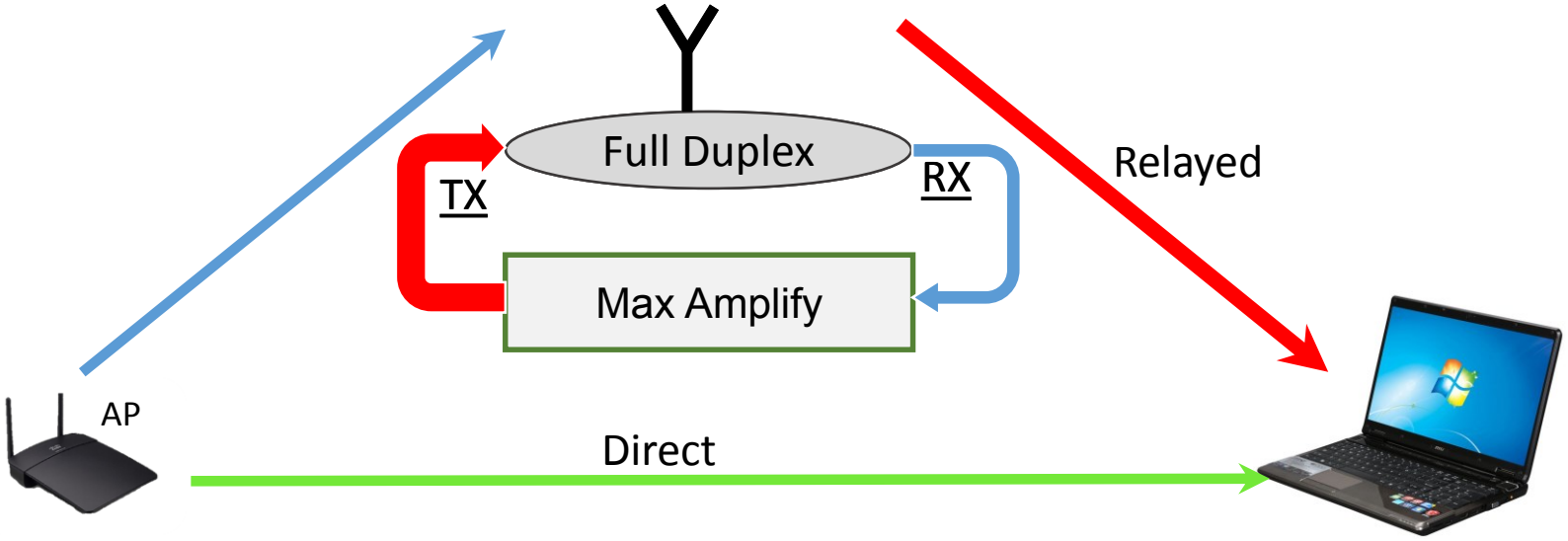
-90 dBm Noise floor

Destination Received

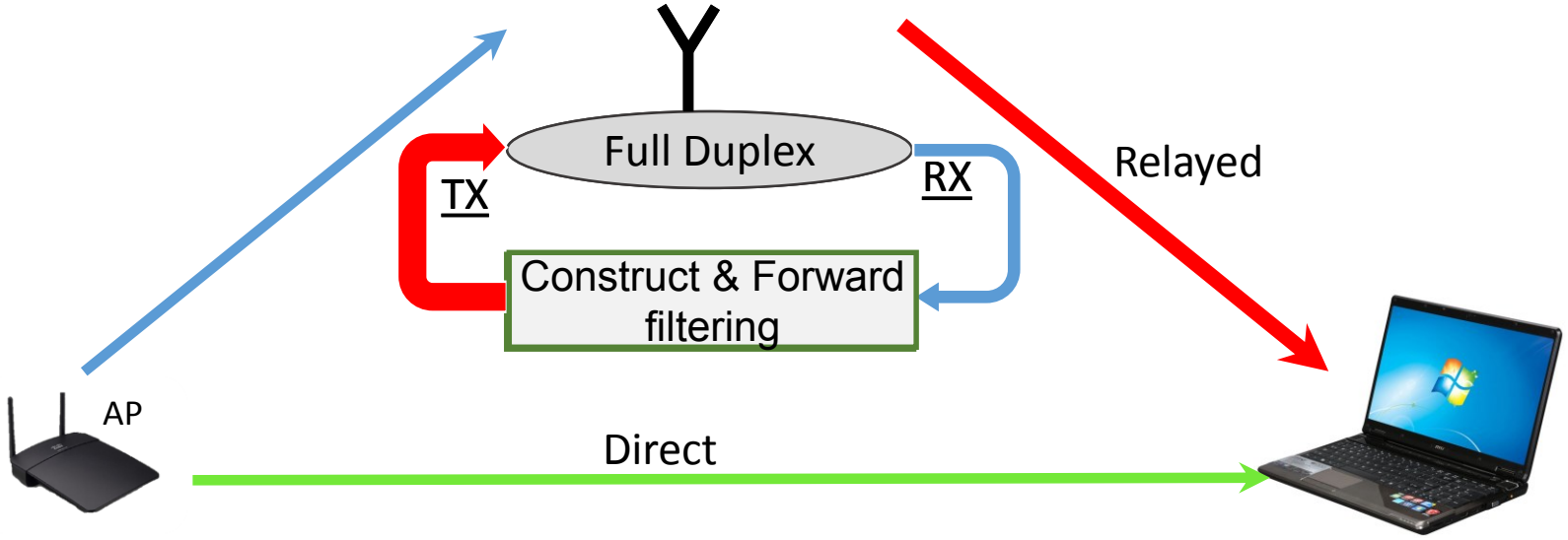


Construct and Forward relaying to tackle these two challenges

Construct and Forward relaying

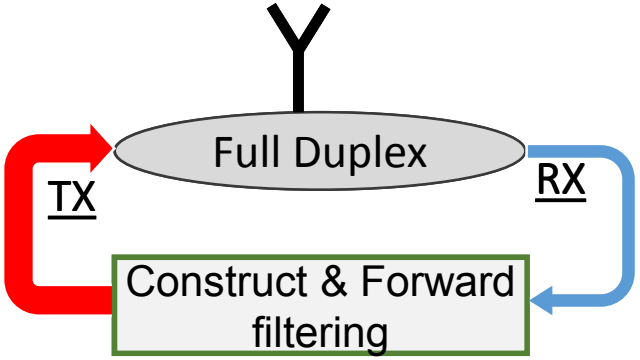


Construct and Forward relaying



Basic Idea: Filter the received signal such that noise isn't amplified and signals add constructively at the destination

Construct and Forward filter abstraction



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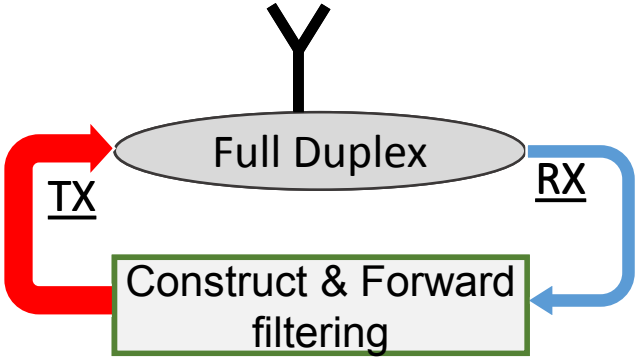

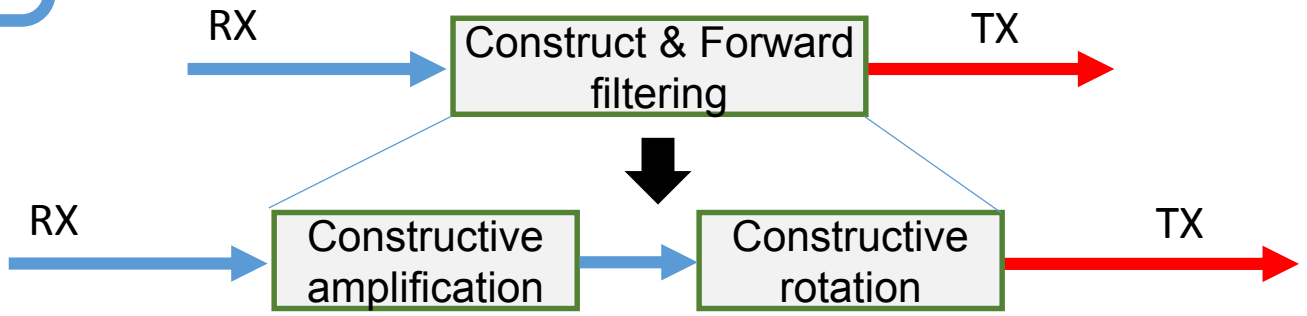

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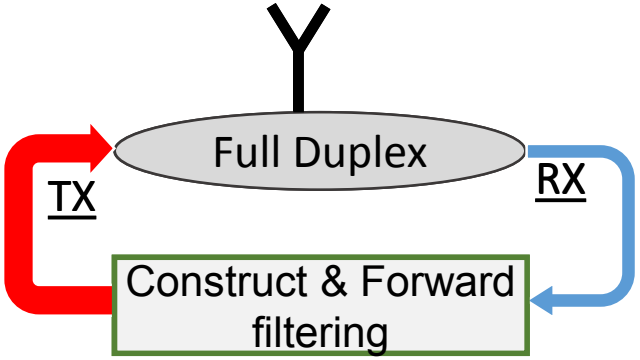
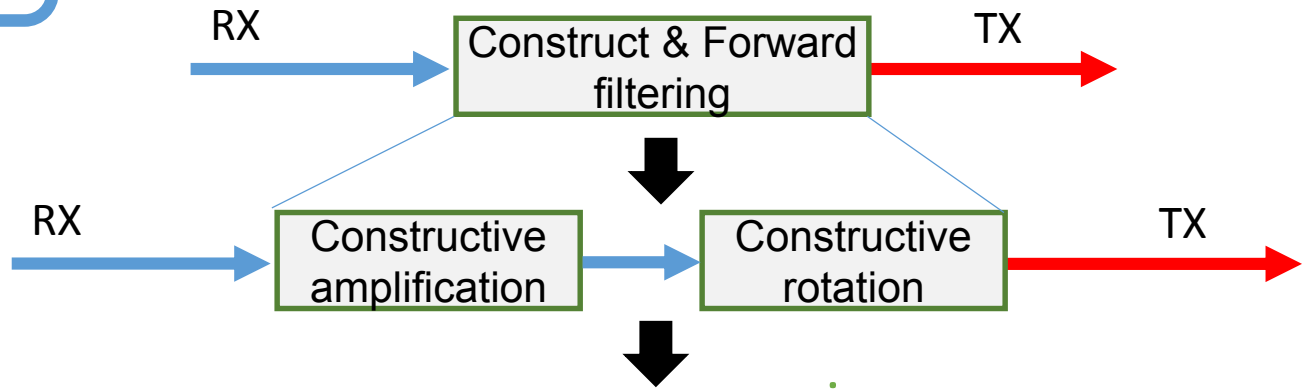




$RX \cdot A \cdot e^{j\theta} = TX$

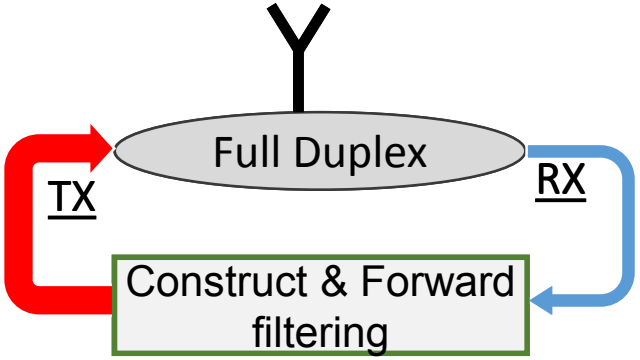
Received signal at relay

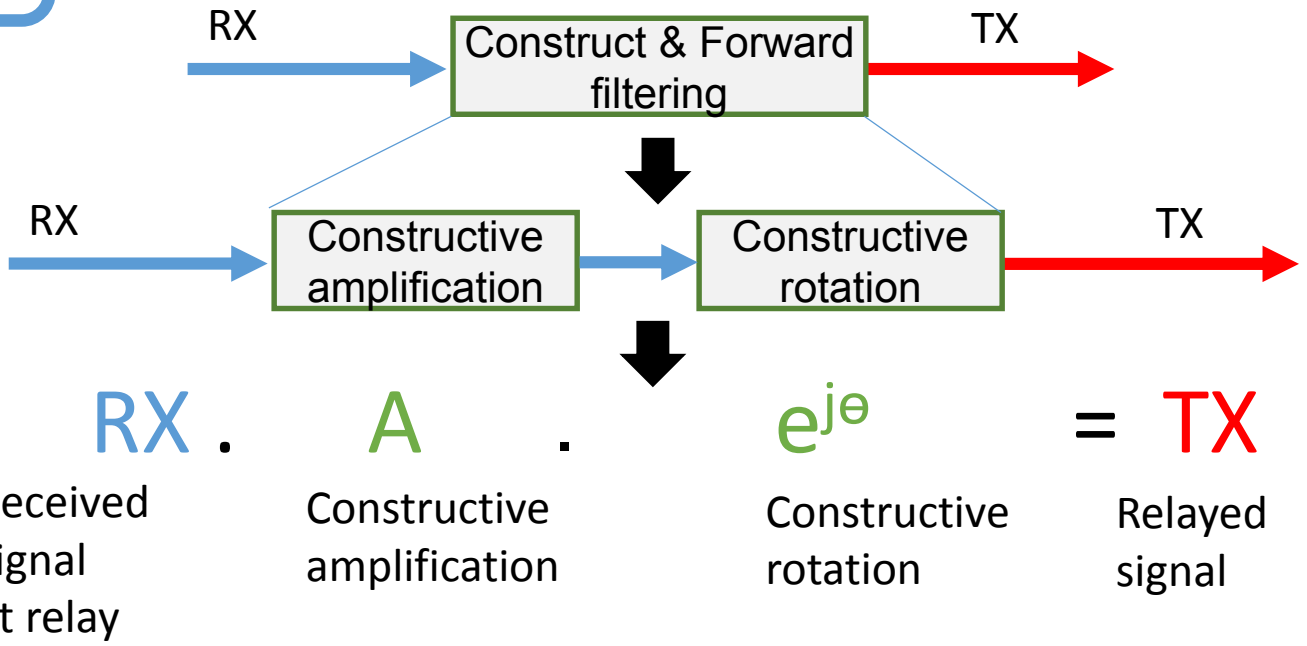
Constructive amplification

Constructive rotation

Relayed signal

Construct and Forward filter abstraction



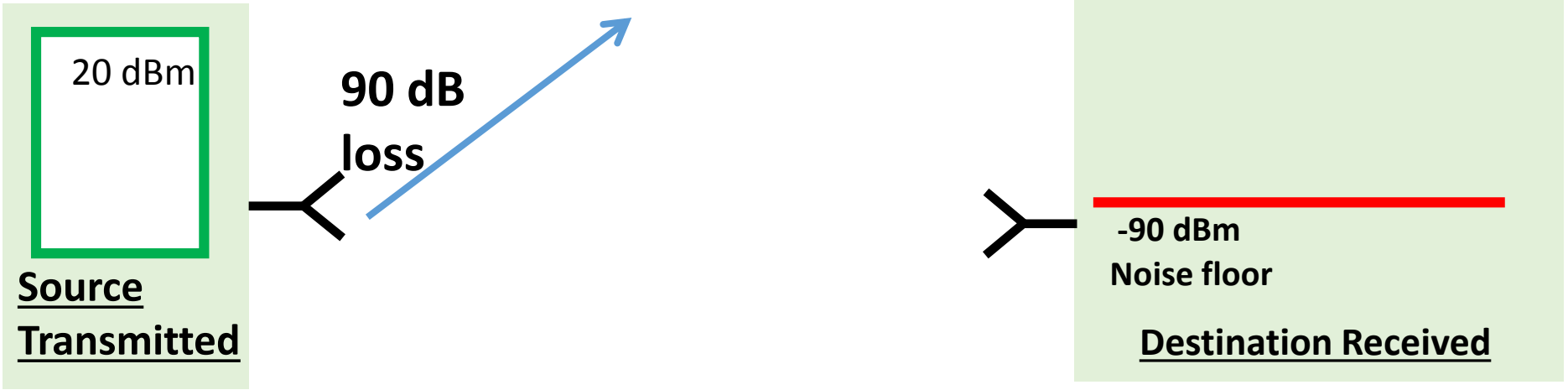


How does Construct and Forward calculate A & $e^{j\theta}$?

Constructive amplification A

Constructive amplification A

Constructive amplification A



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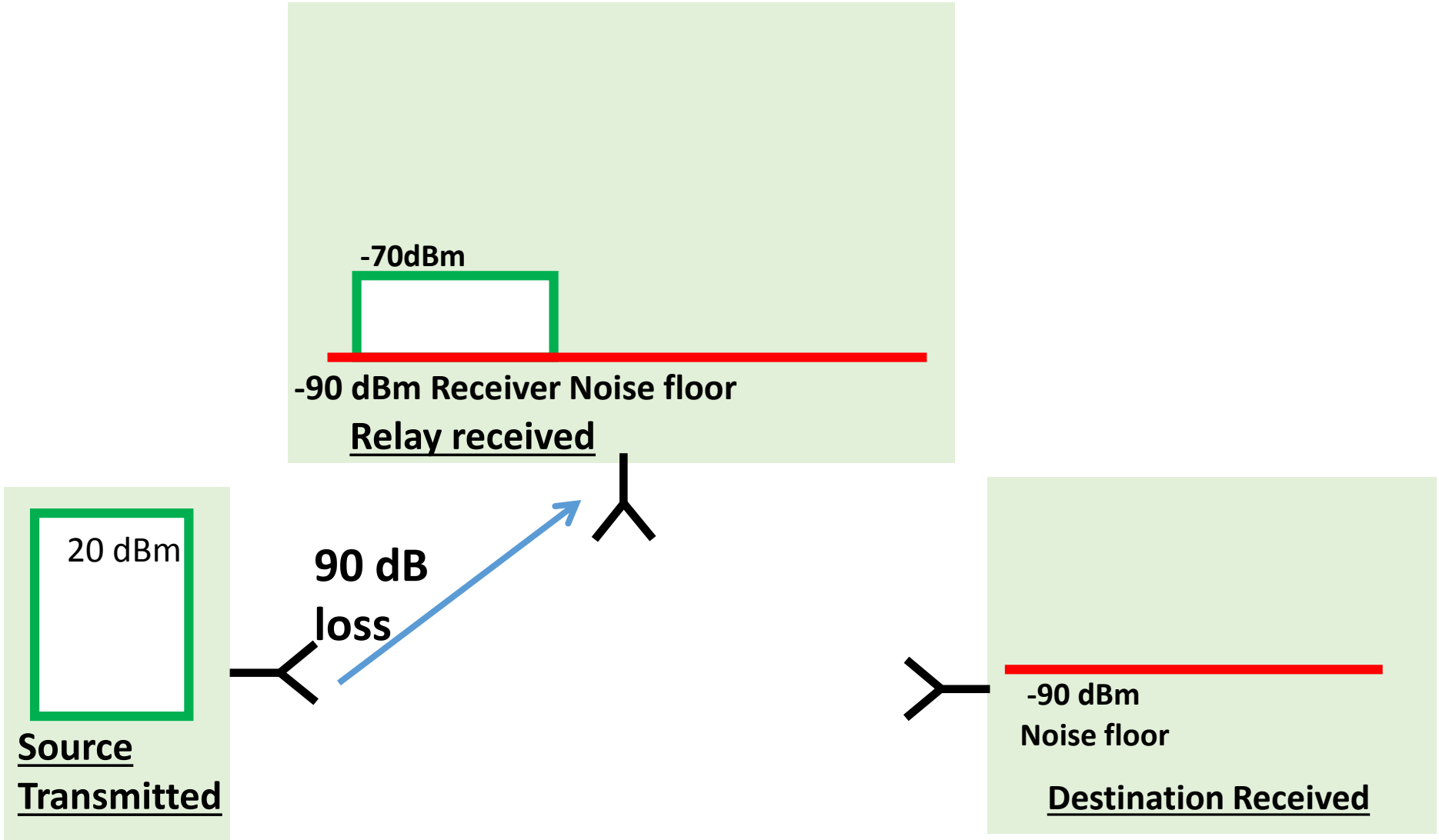

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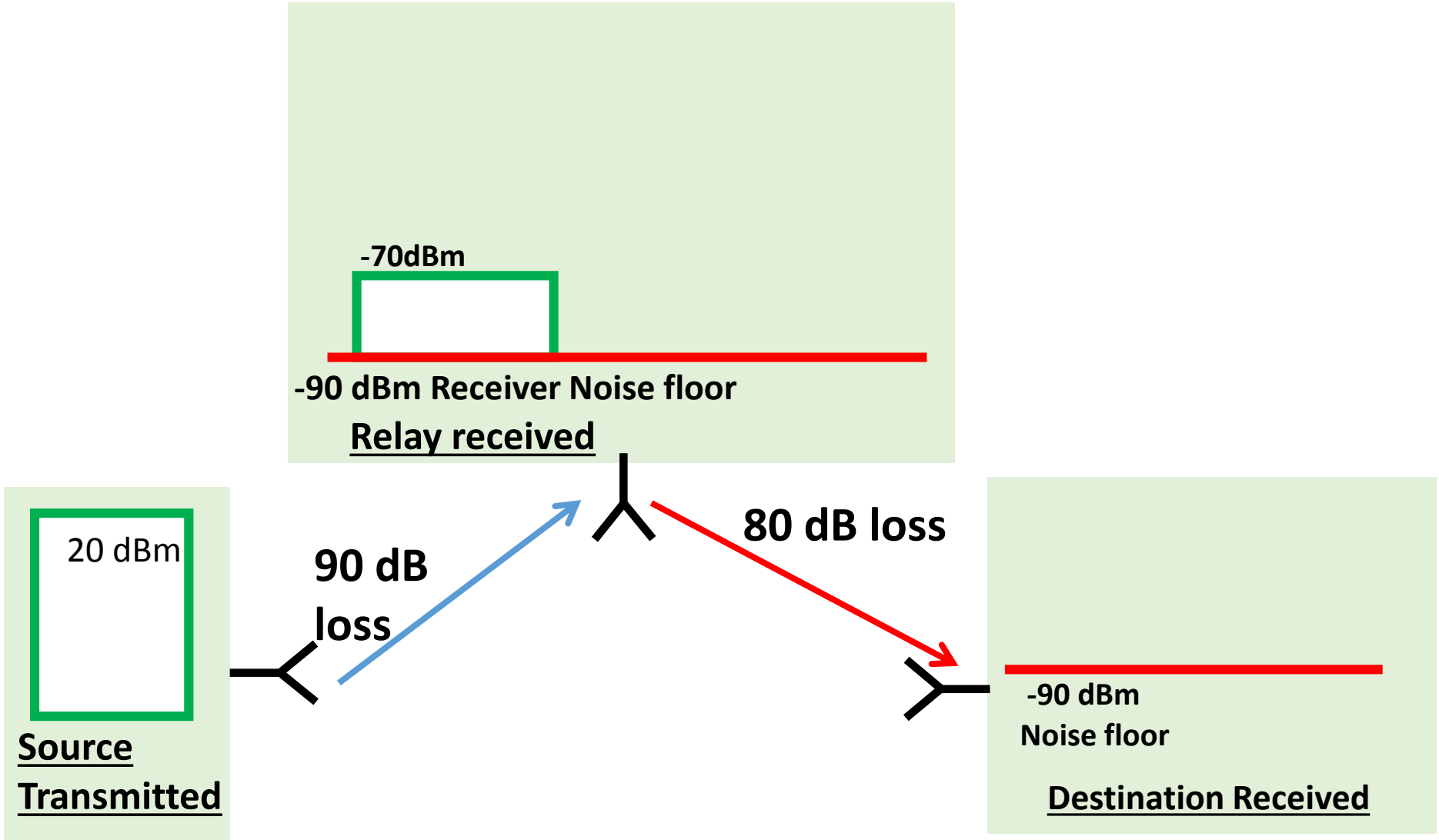
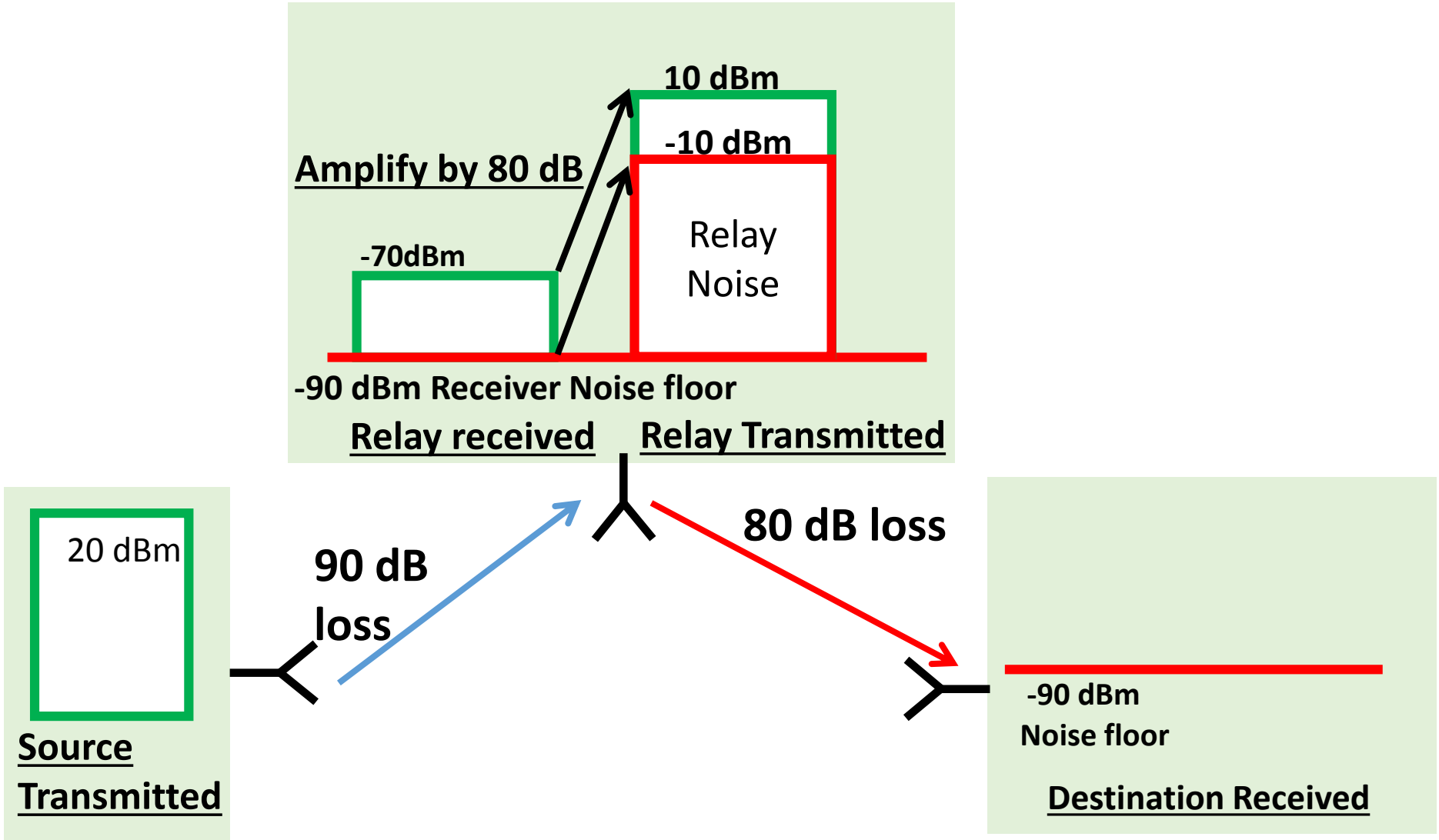
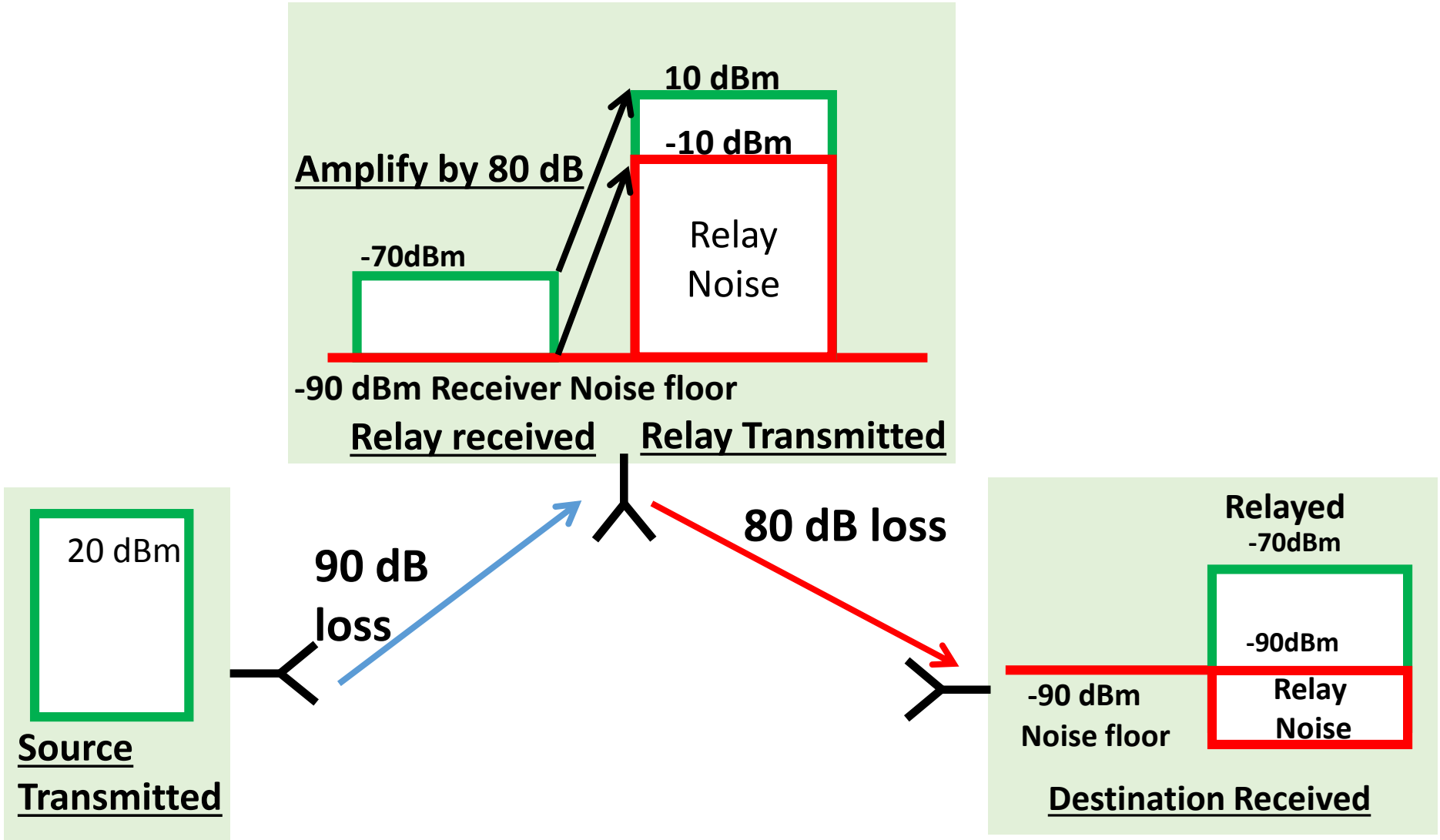


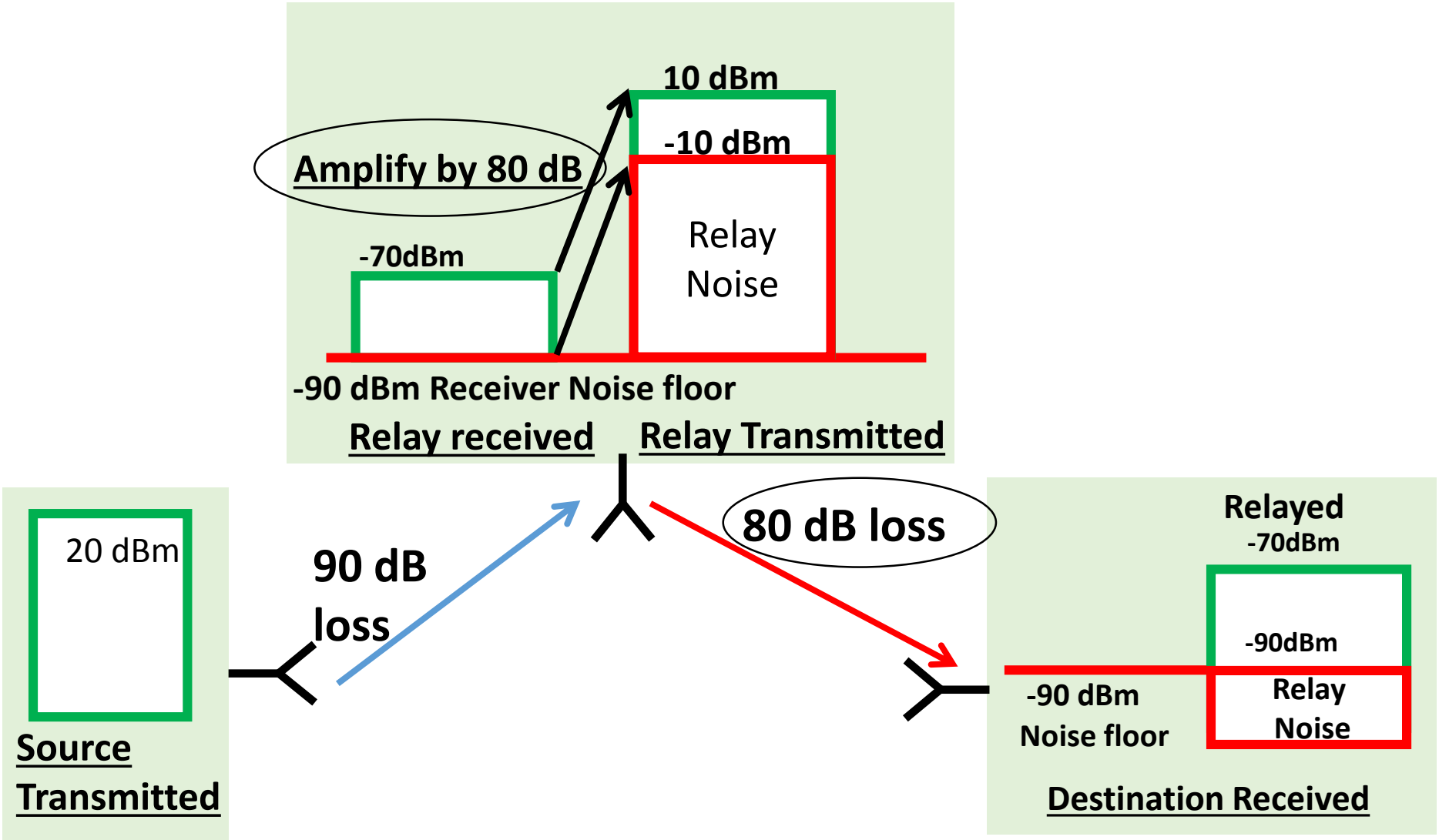
Constructive amplification A



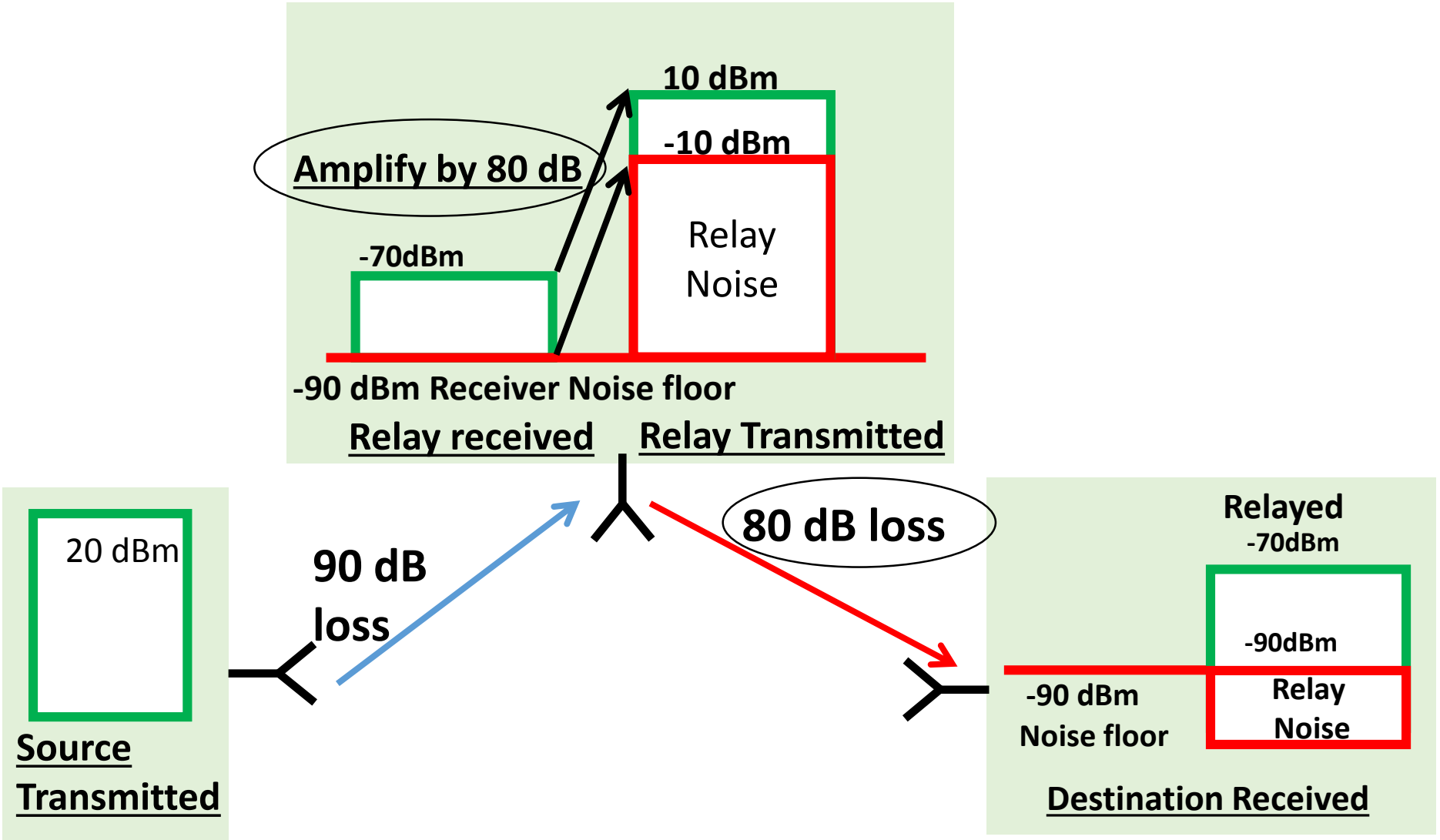
Constructive amplification A



Constructive amplification A

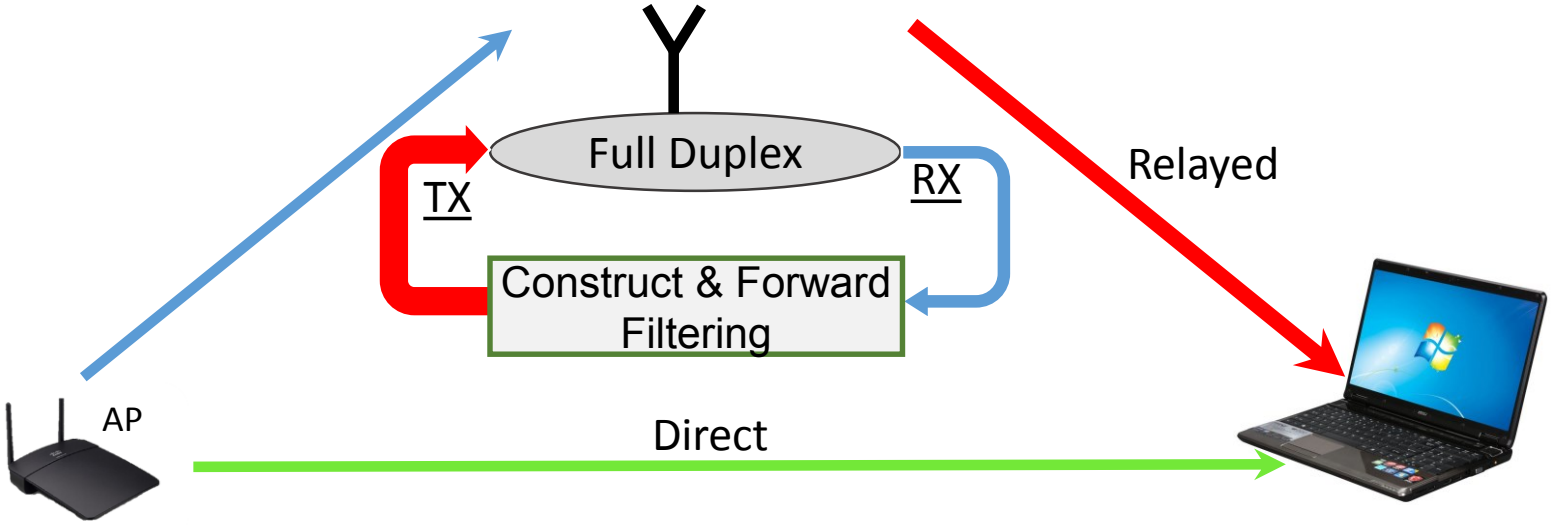


Constructive amplification A

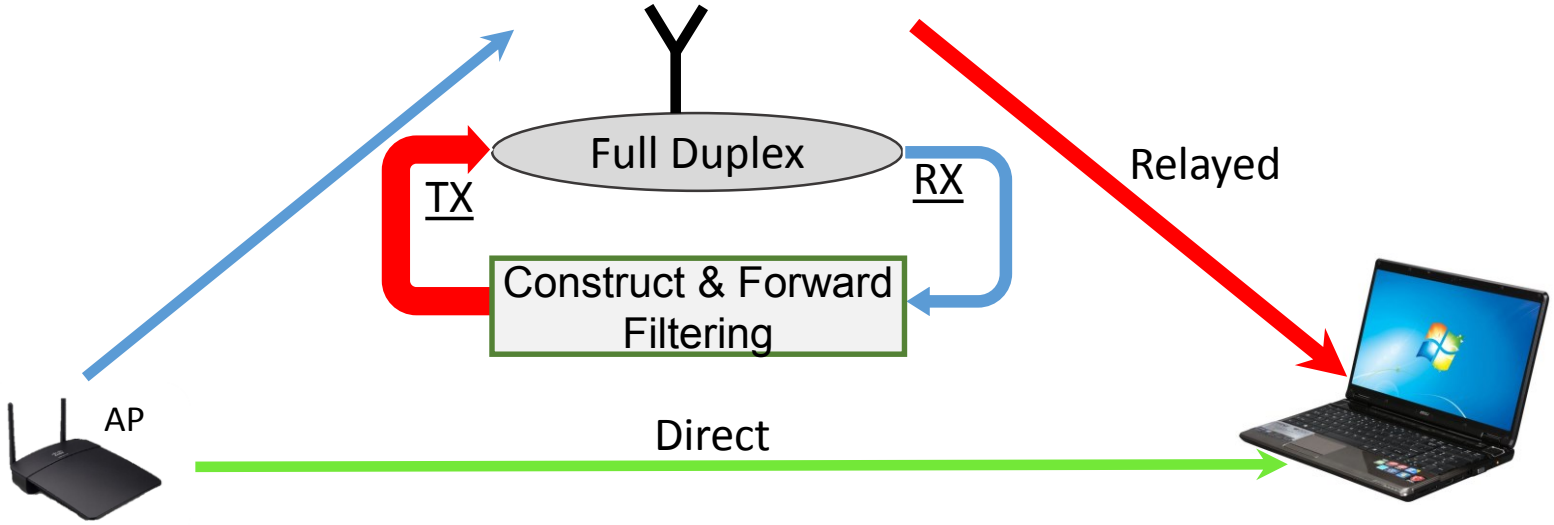


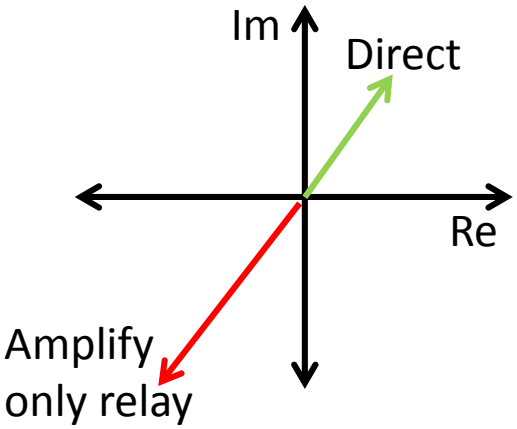
Constructive amplification factor A can be at most the propagation loss from relay to destination

Constructive rotation $e^{j\theta}$

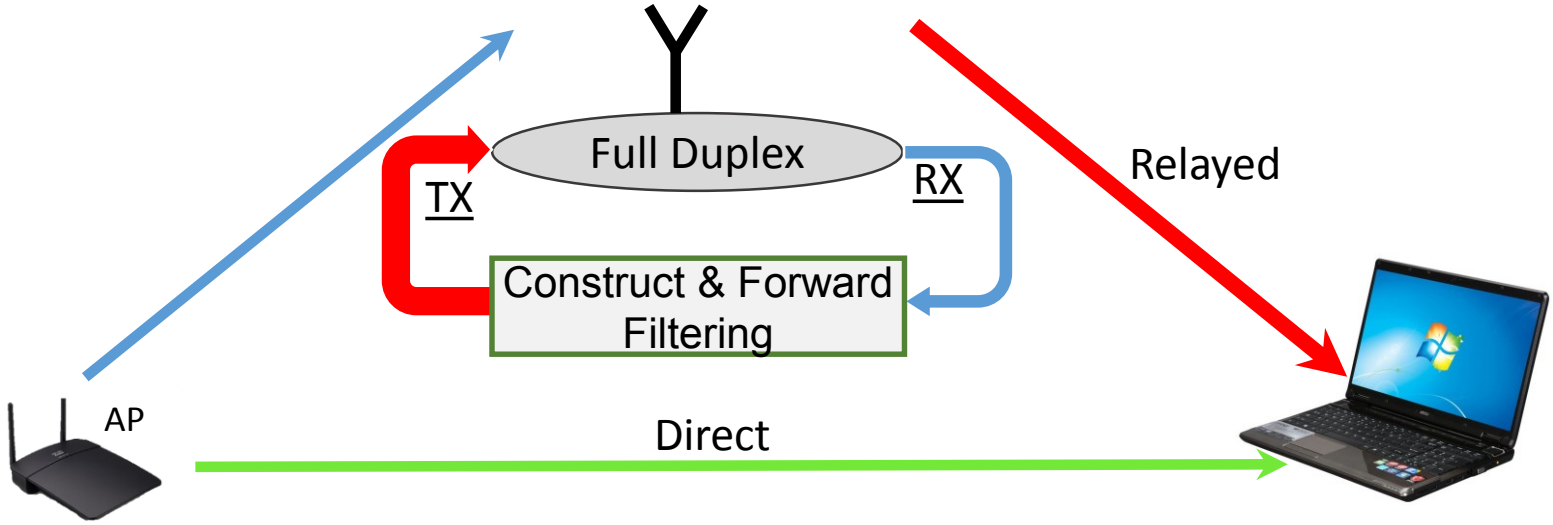


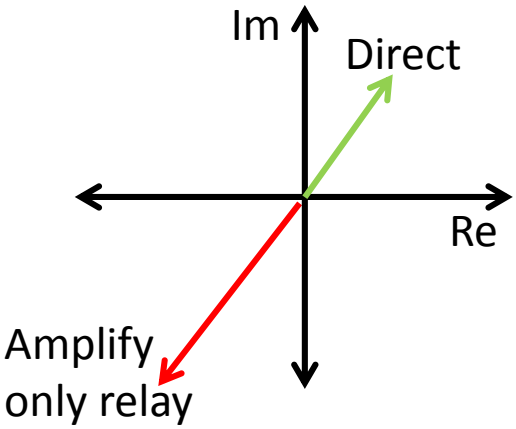
Constructive rotation $e^{j\theta}$

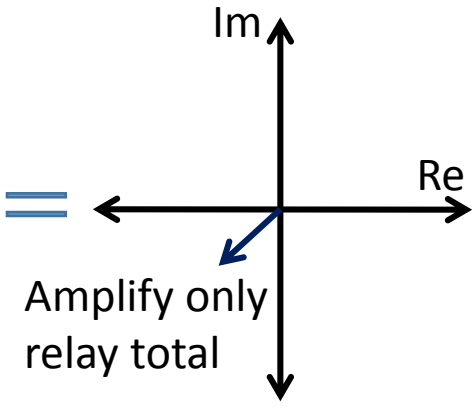




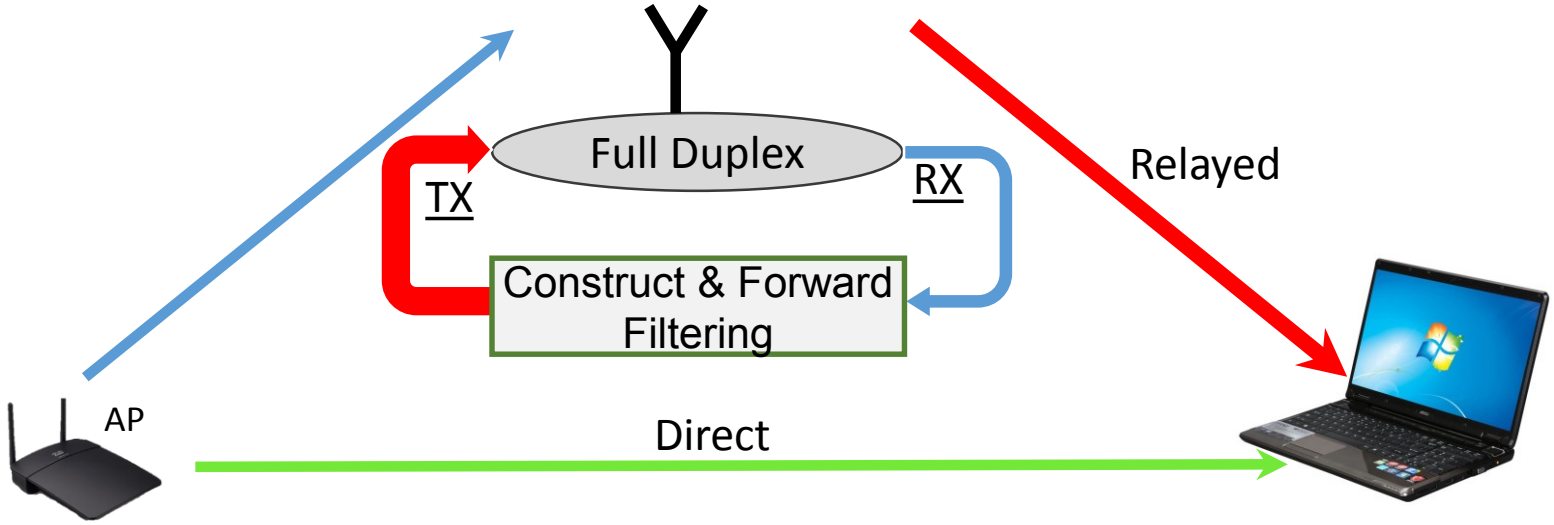
Constructive rotation $e^{j\theta}$

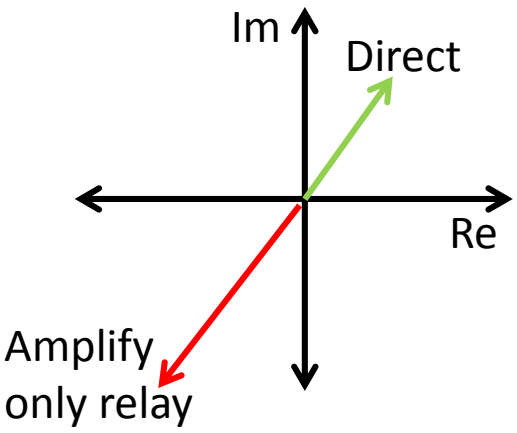


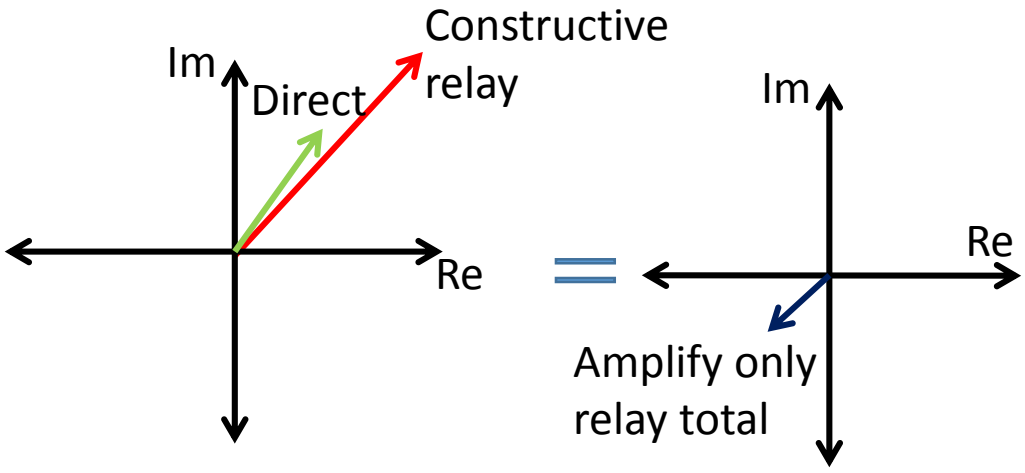




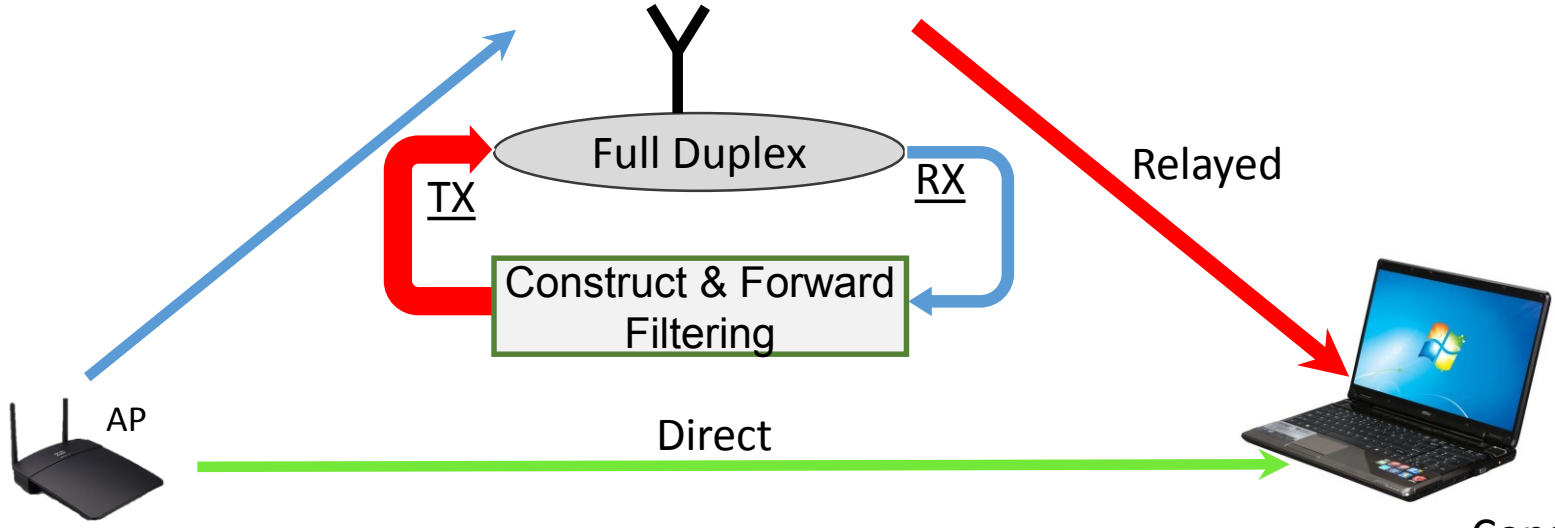
Constructive rotation $e^{j\theta}$

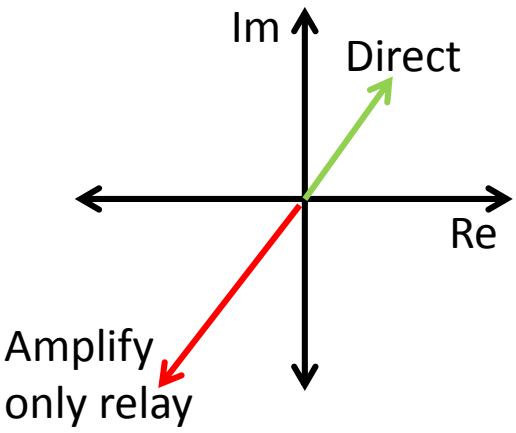


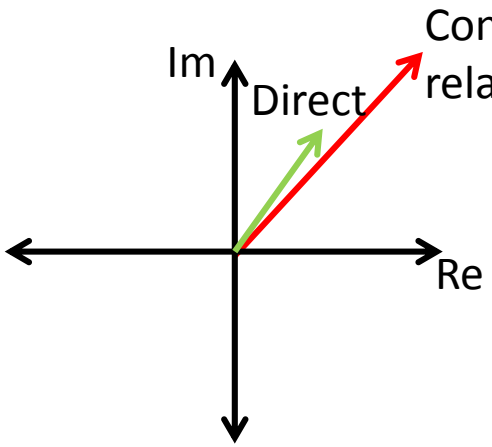


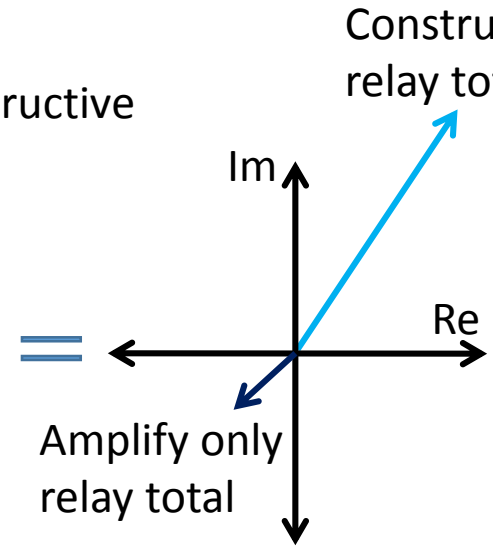


Constructive rotation $e^{j\theta}$

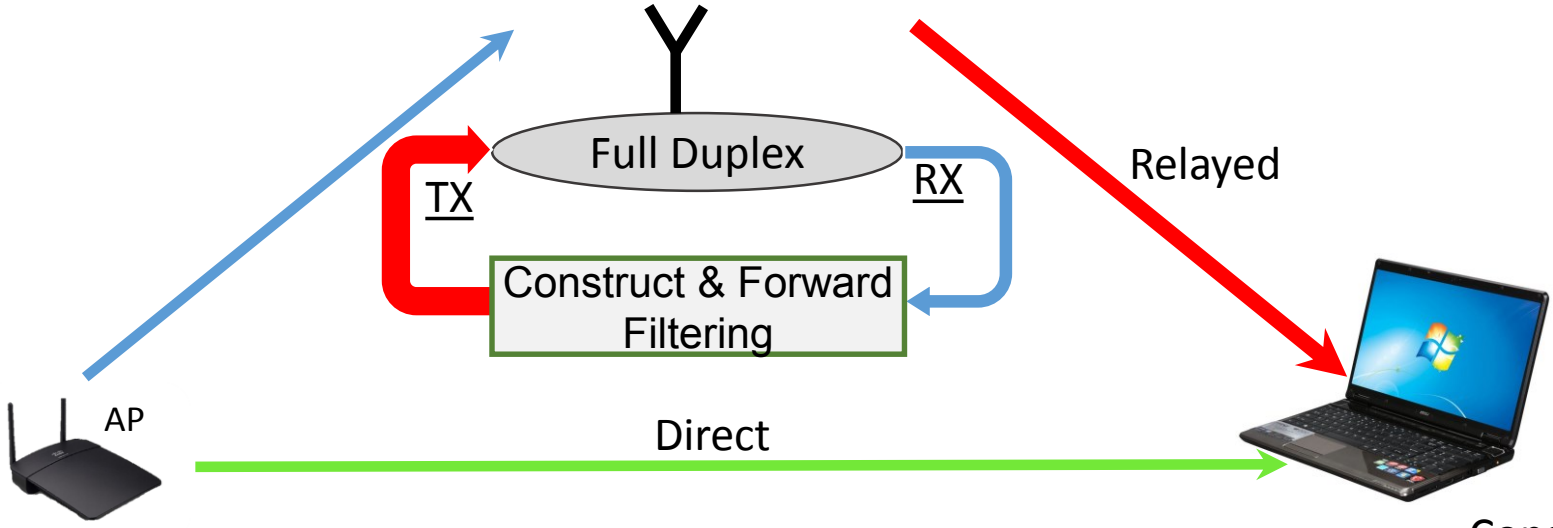


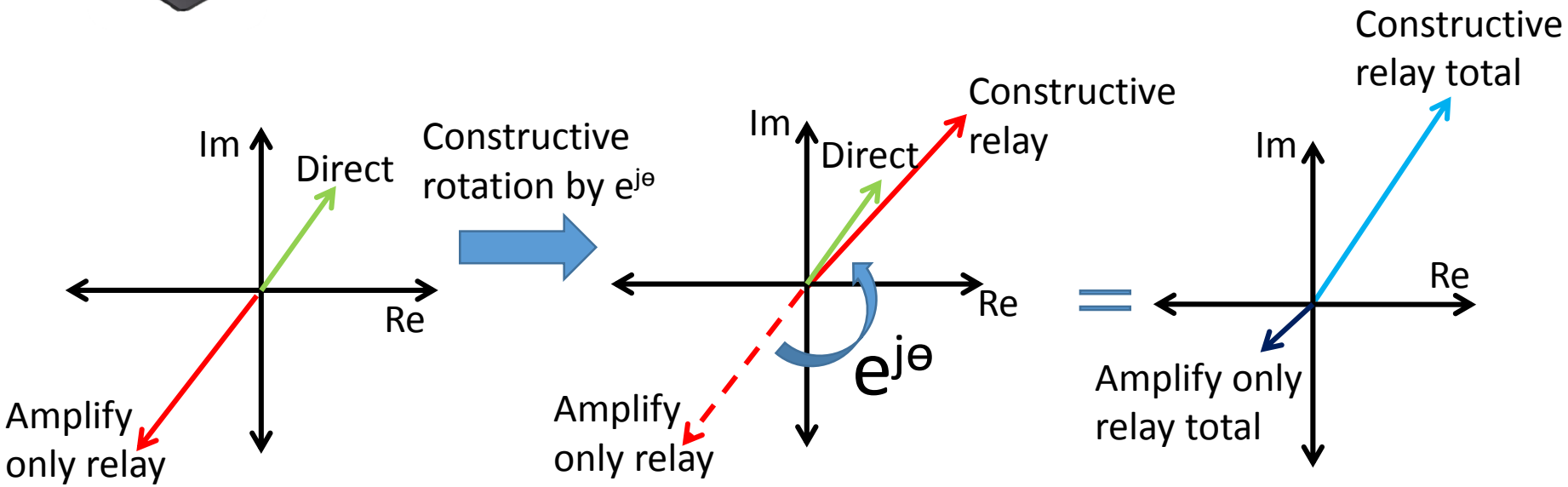




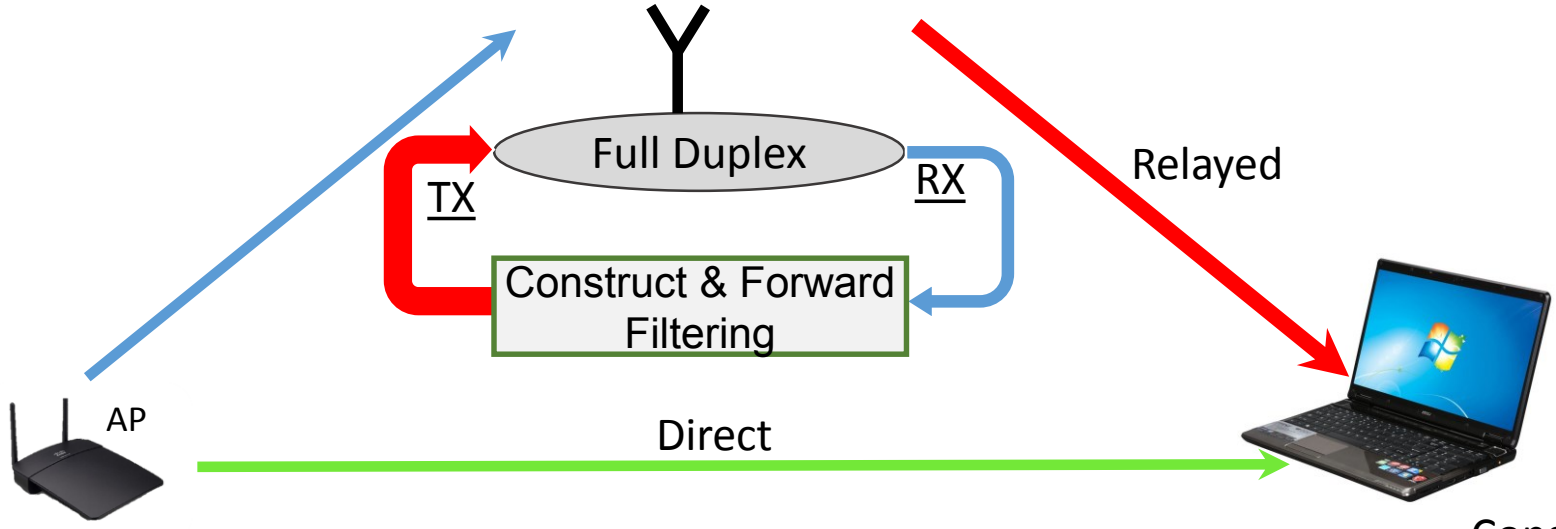


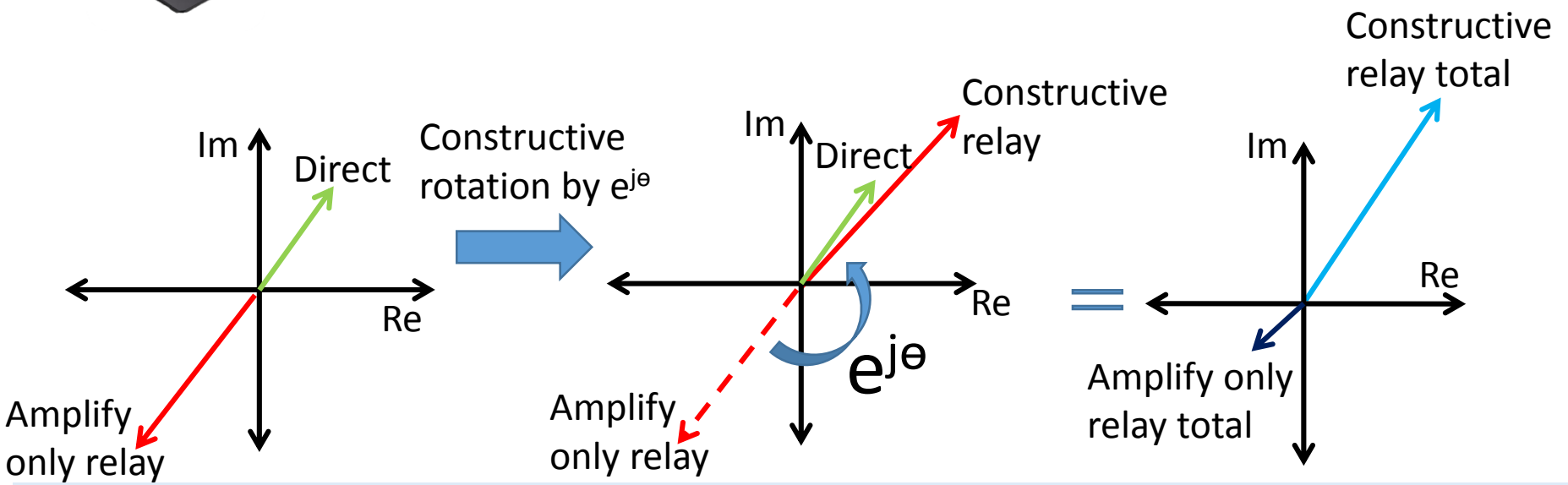
Constructive rotation $e^{j\theta}$





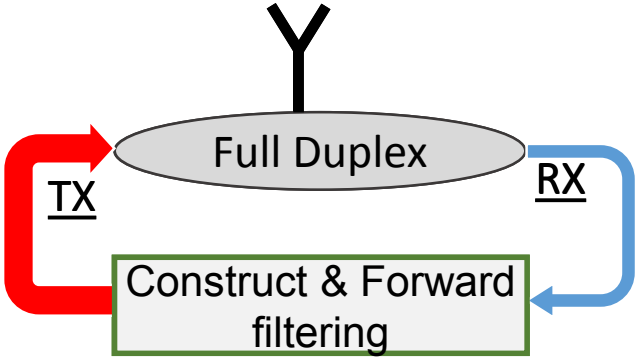
Constructive rotation $e^{j\theta}$

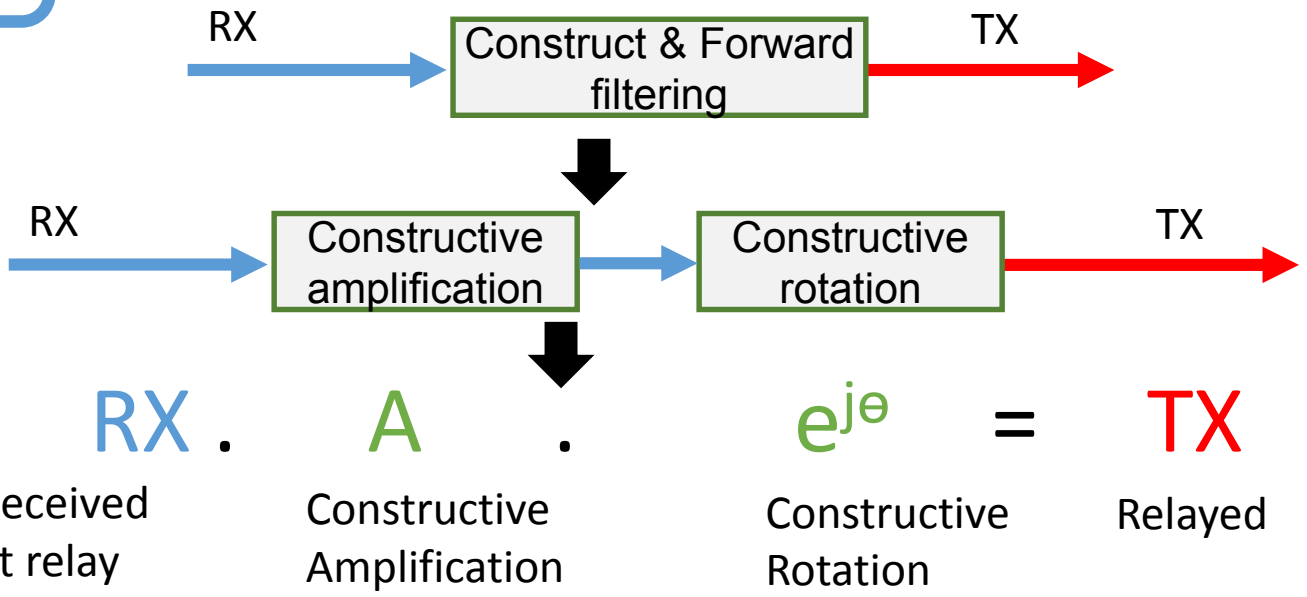




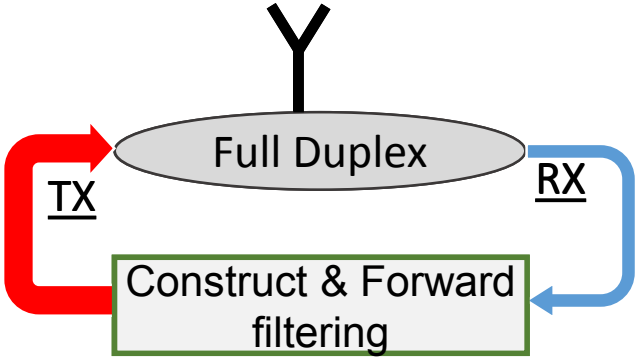
Constructive rotation $e^{j\theta}$ should be as close as possible to the phase difference between the direct and the relay path's channels

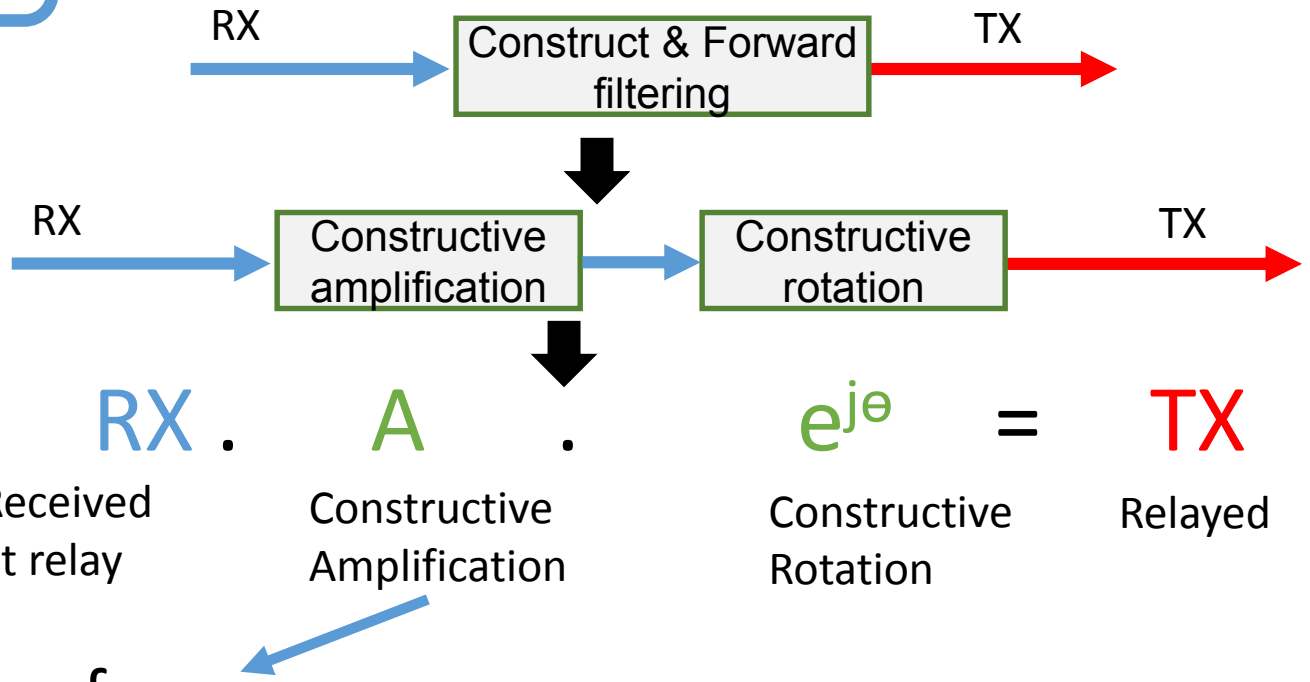
Summary: Construct and Forward filter





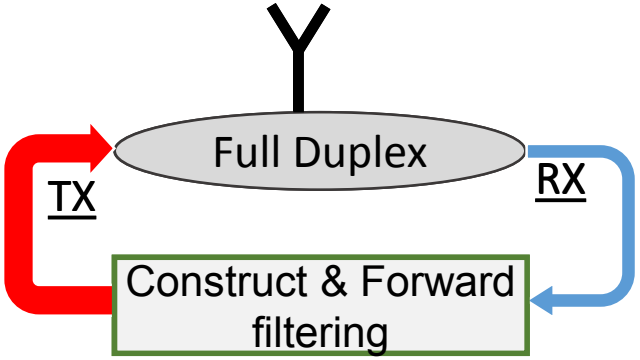
Summary: Construct and Forward filter

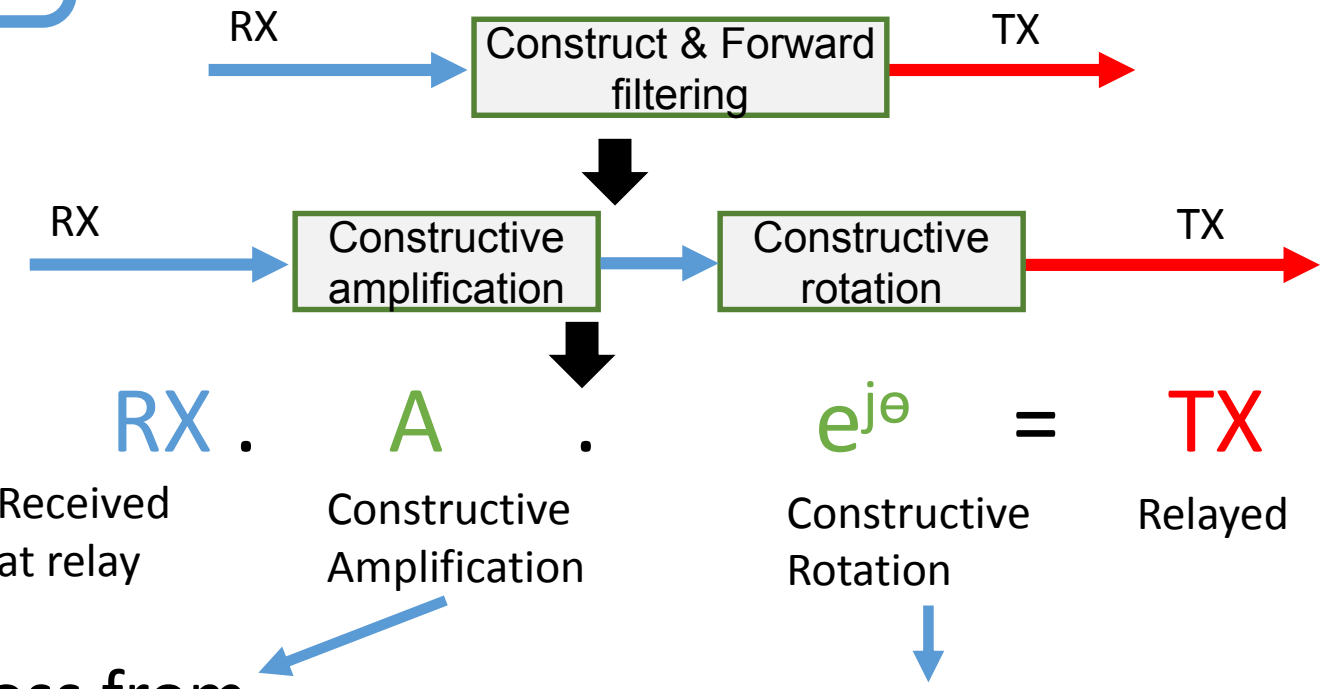




Propagation loss from relay to destination

Summary: Construct and Forward filter





Propagation loss from relay to destination

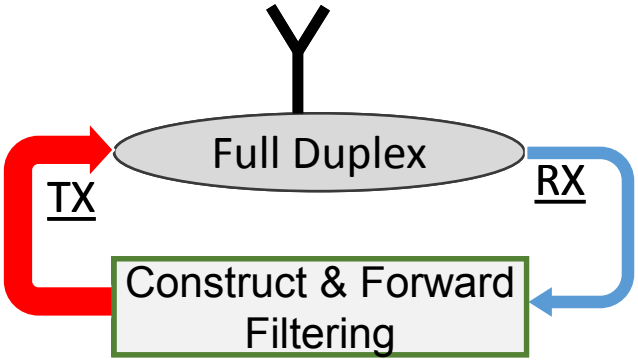
Align the phases of the relay path and direct path at the destination

High latency leads to inter-symbol interference

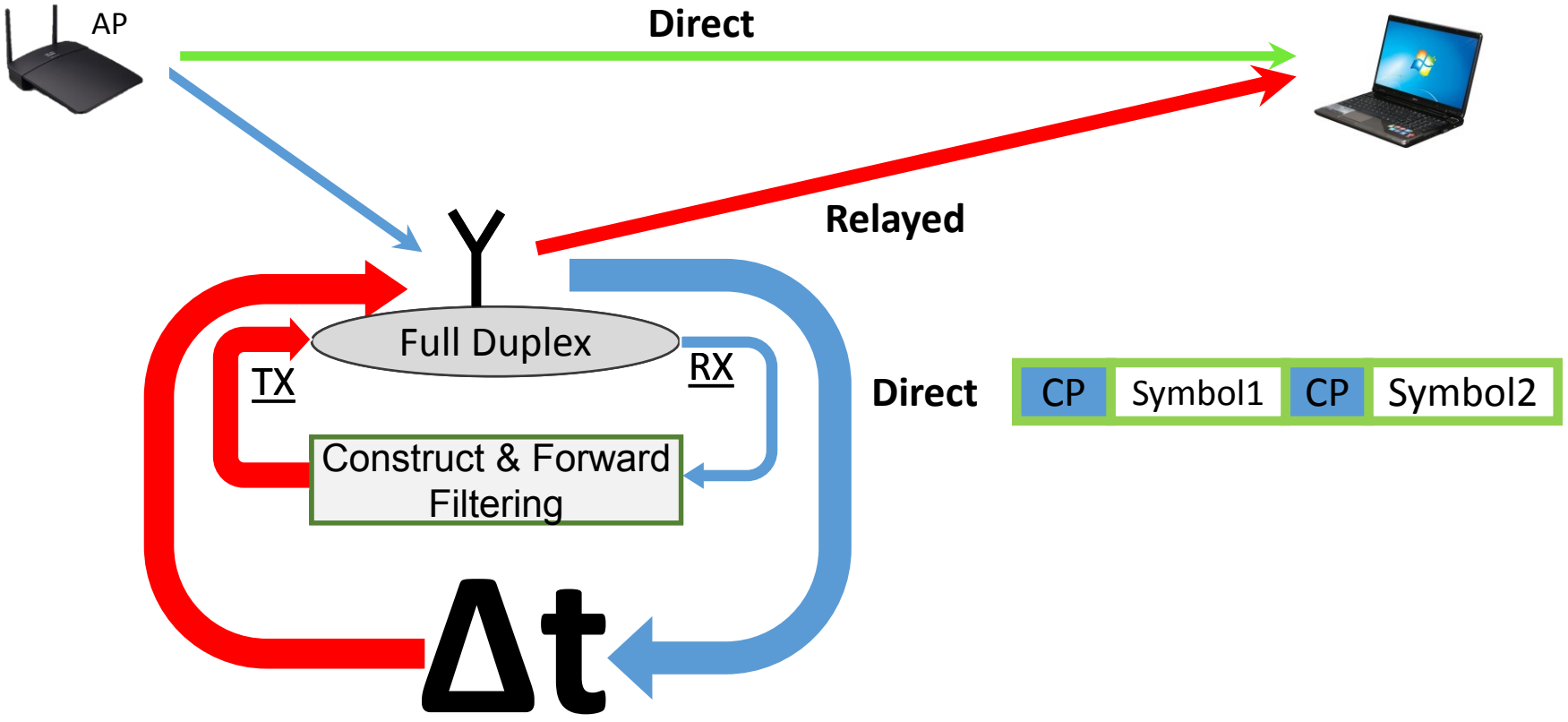
High latency leads to inter-symbol interference

High latency leads to inter-symbol interference

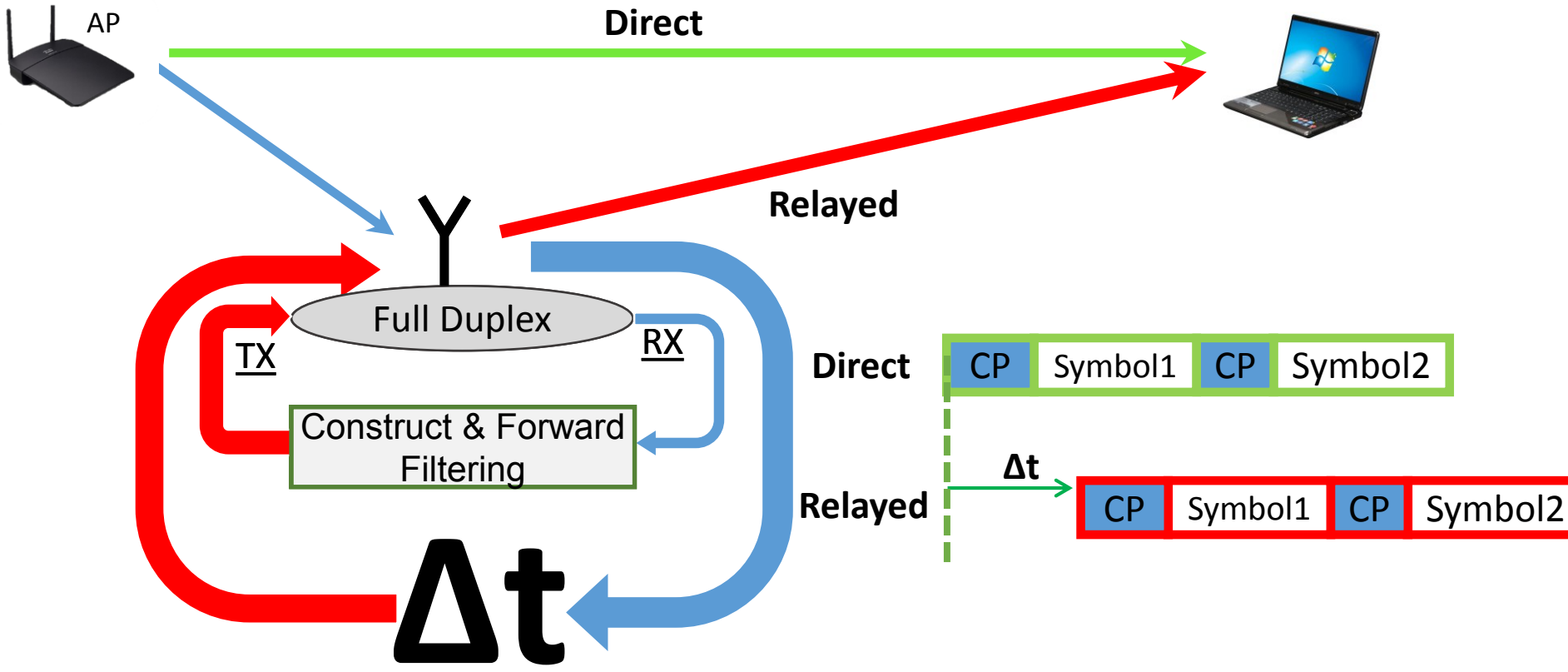
High latency leads to inter-symbol interference



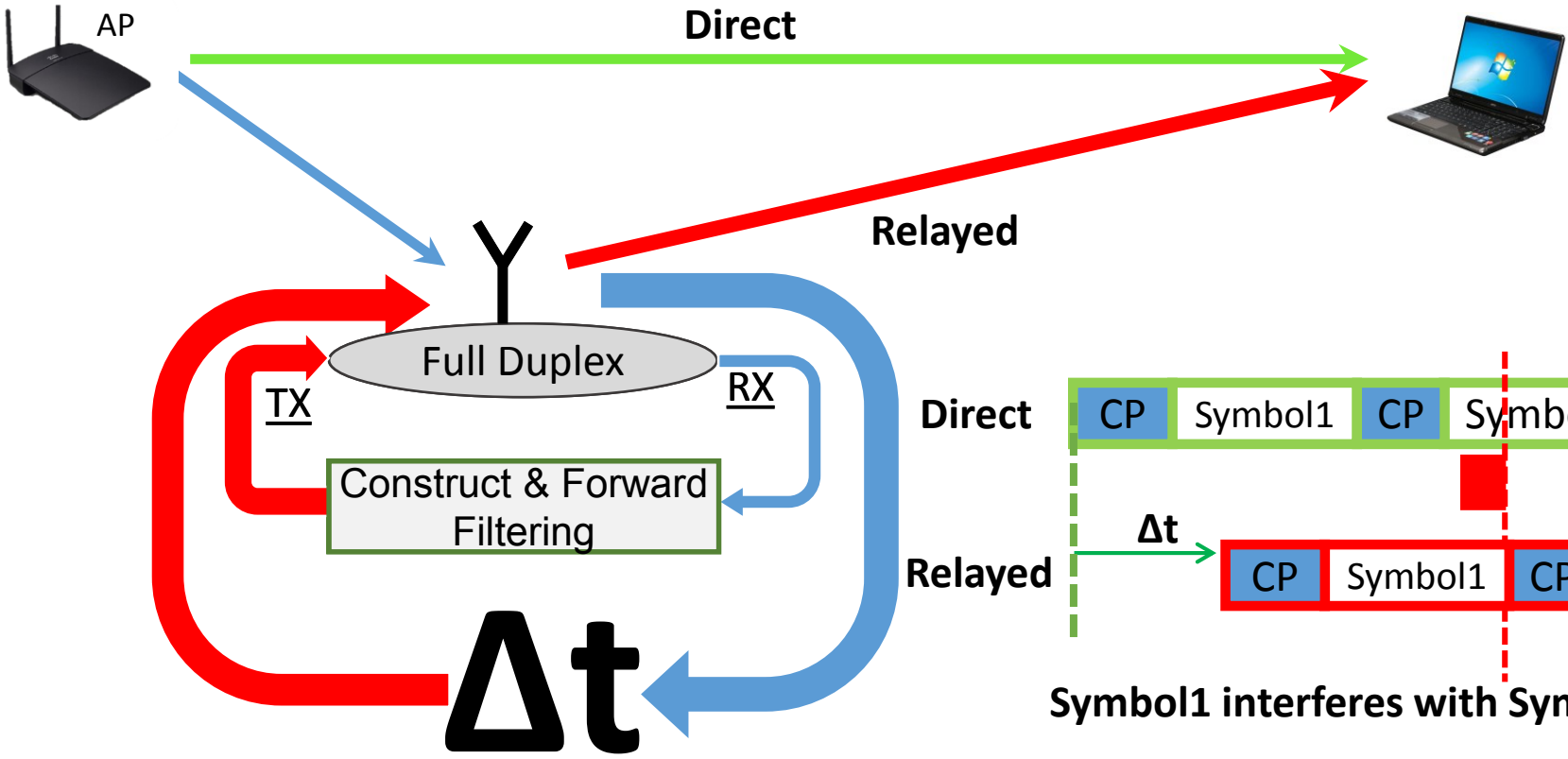
High latency leads to inter-symbol interference



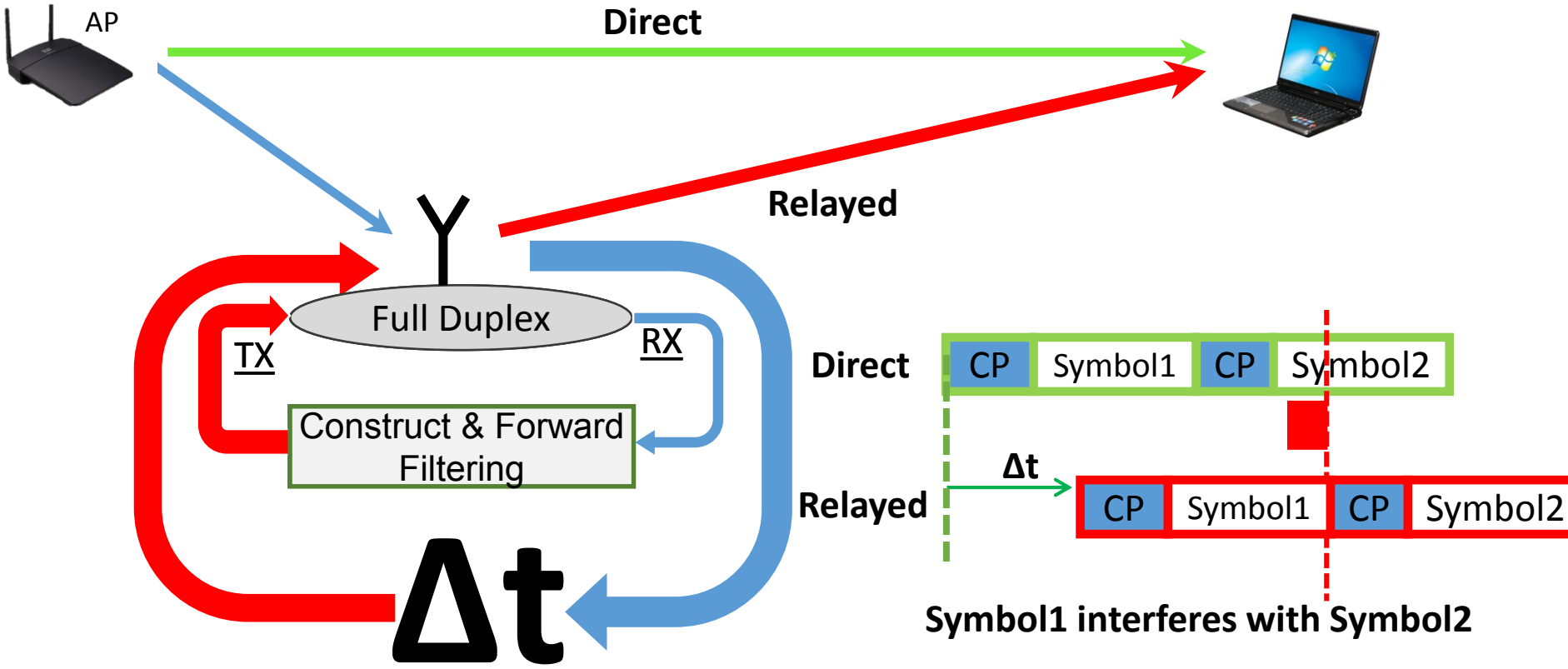
High latency leads to inter-symbol interference



High latency leads to inter-symbol interference

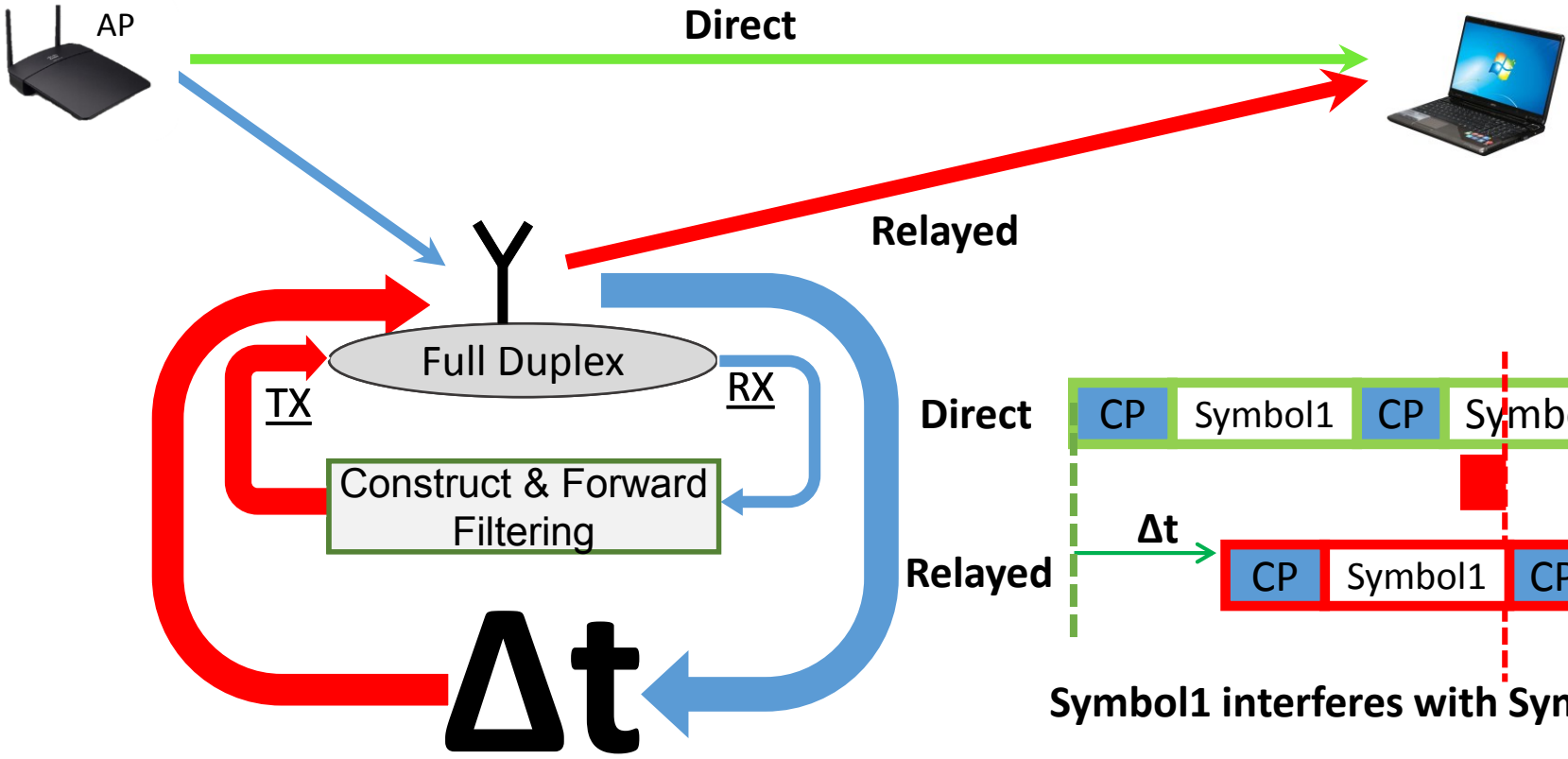


High latency leads to inter-symbol interference

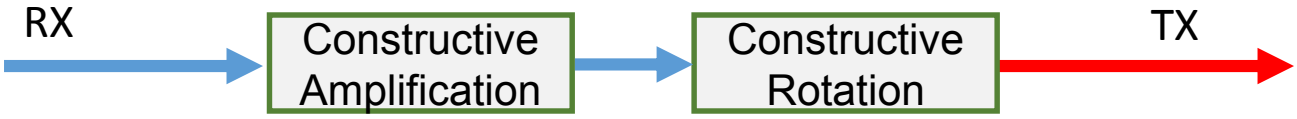


Minimize the latency of Construct & Forward filter to avoid inter symbol interference

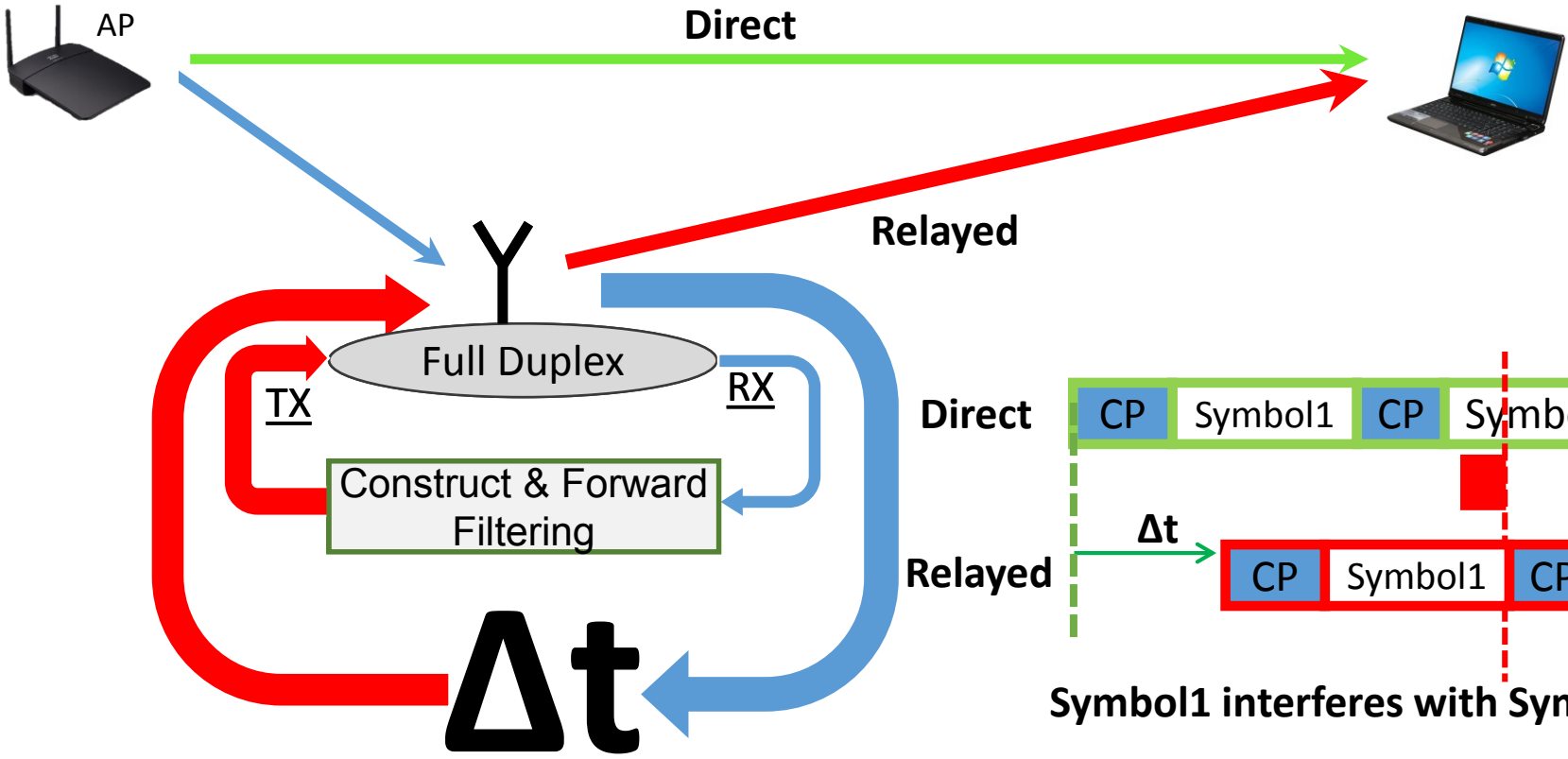
High latency leads to inter-symbol interference



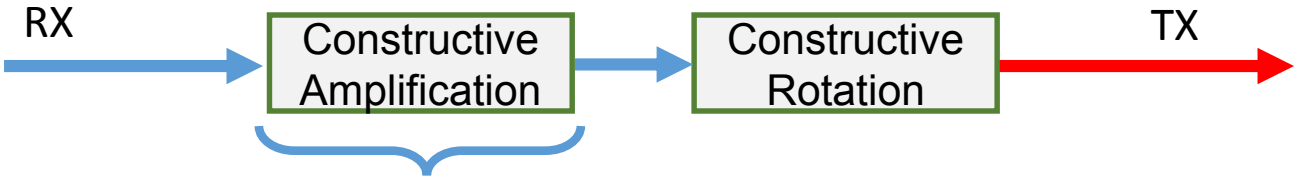
Minimize the latency of Construct & Forward filter to avoid inter symbol interference



High latency leads to inter-symbol interference

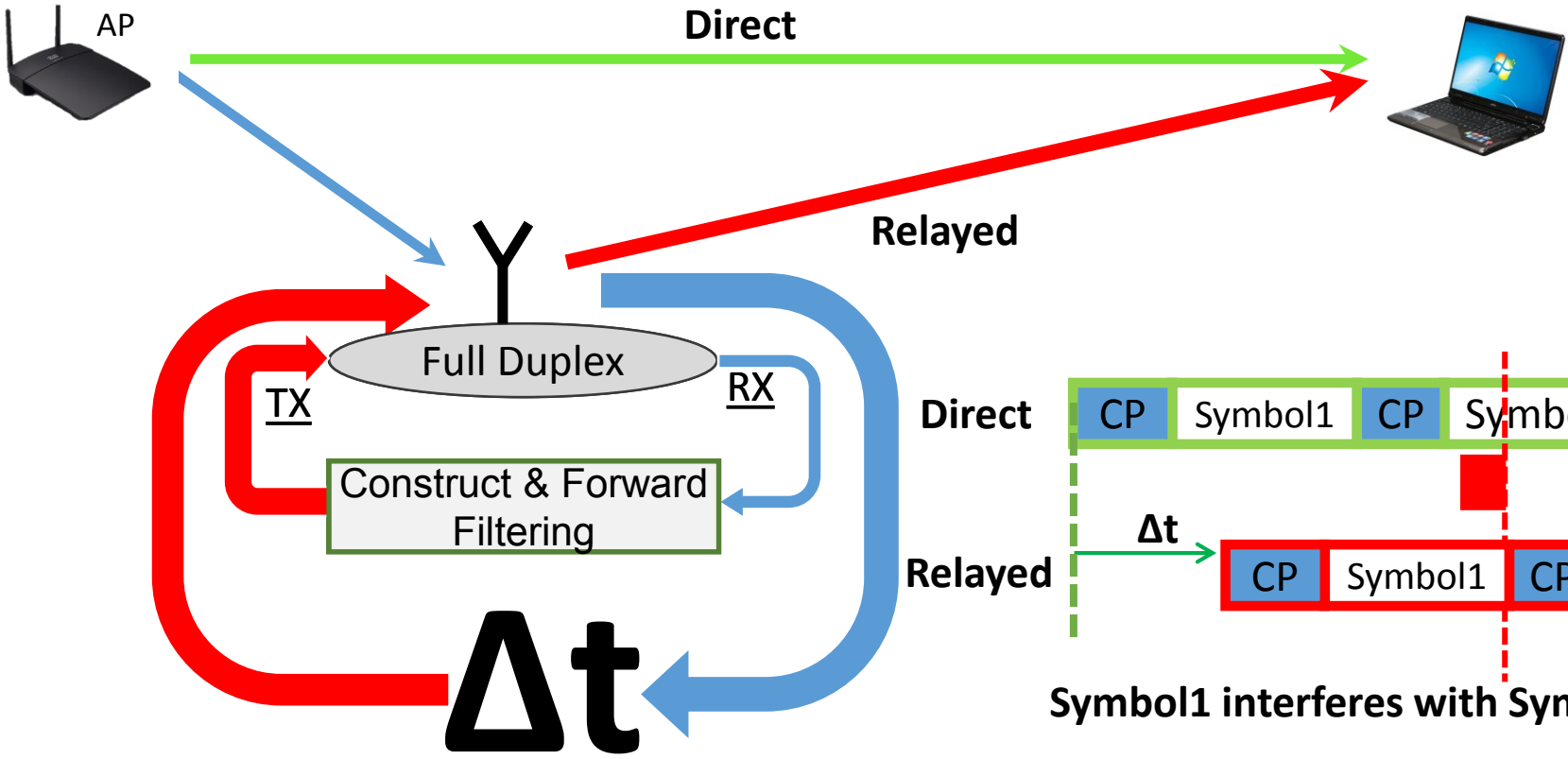


Minimize the latency of Construct & Forward filter to avoid inter symbol interference

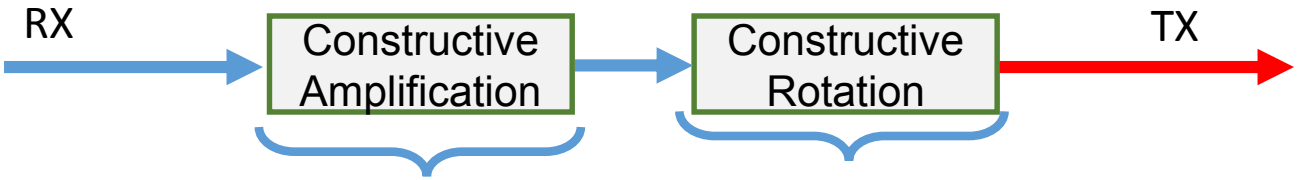


Negligible Latency

High latency leads to inter-symbol interference



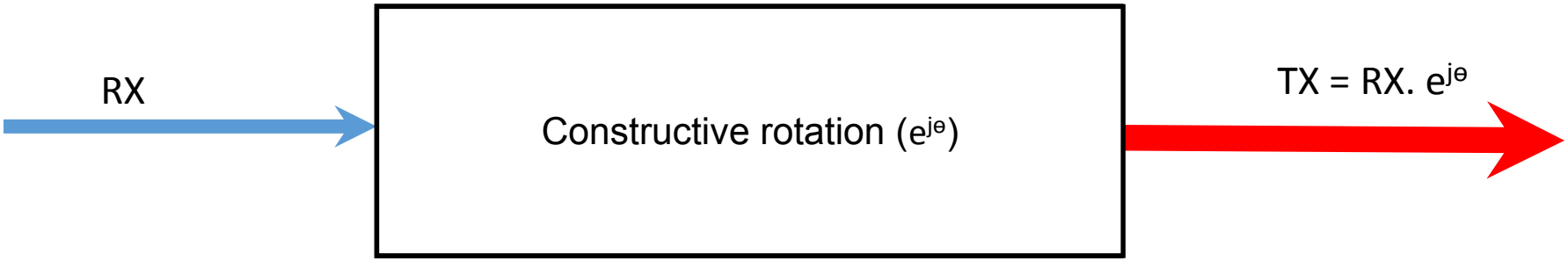
Minimize the latency of Construct & Forward filter to avoid inter symbol interference



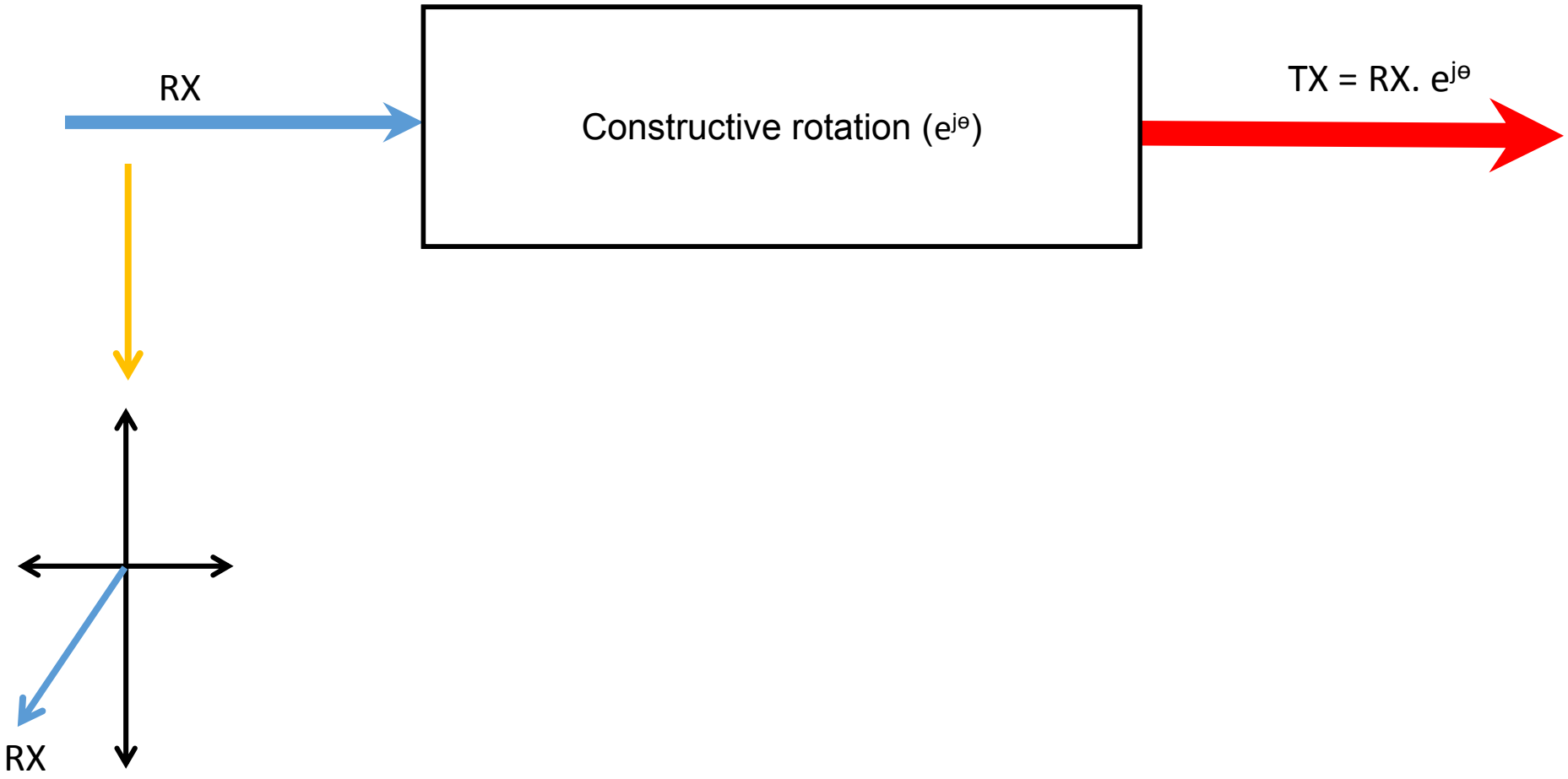
Negligible Latency

How do we achieve this block with minimum latency?

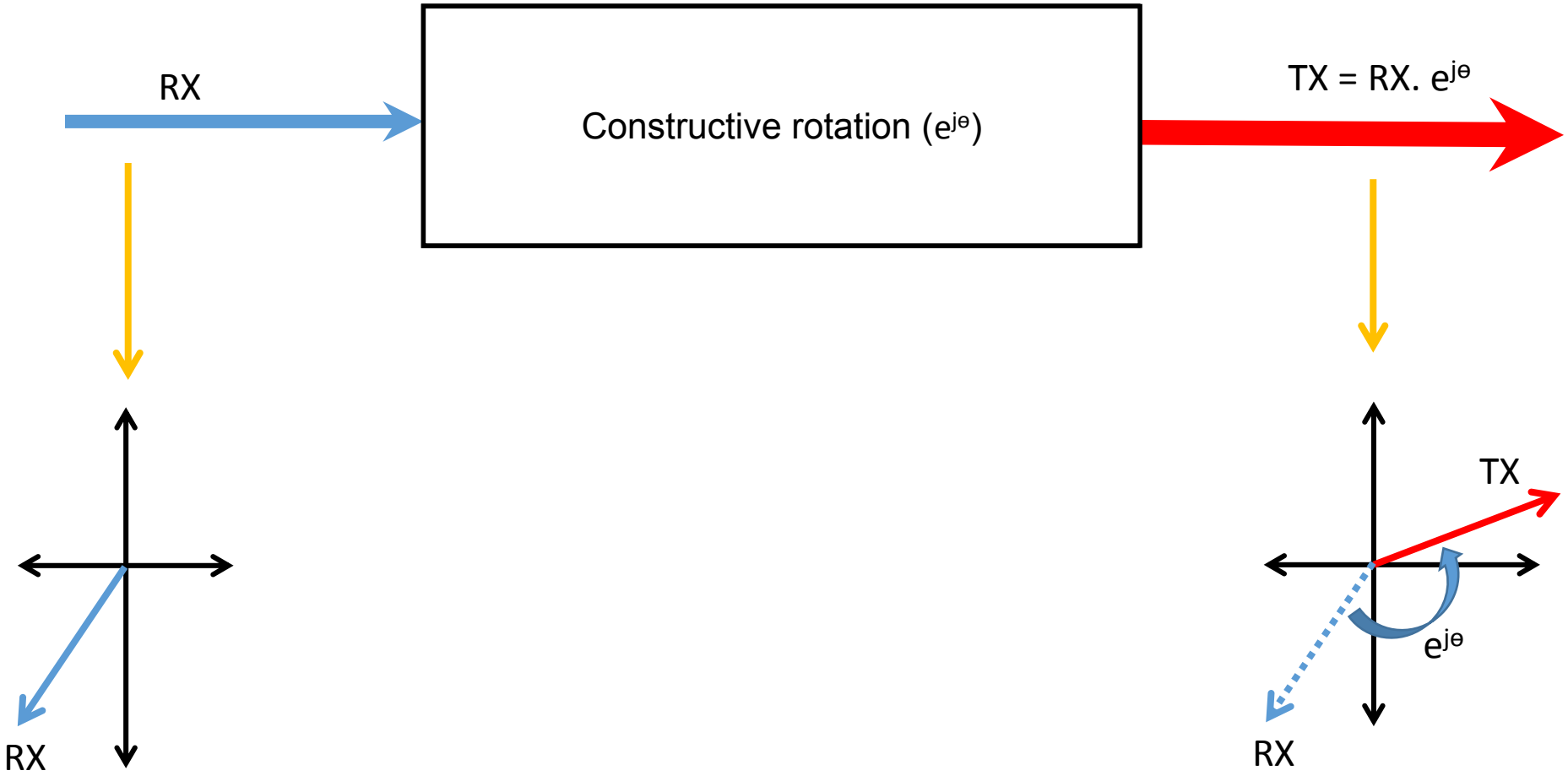
Low latency constructive rotation filter



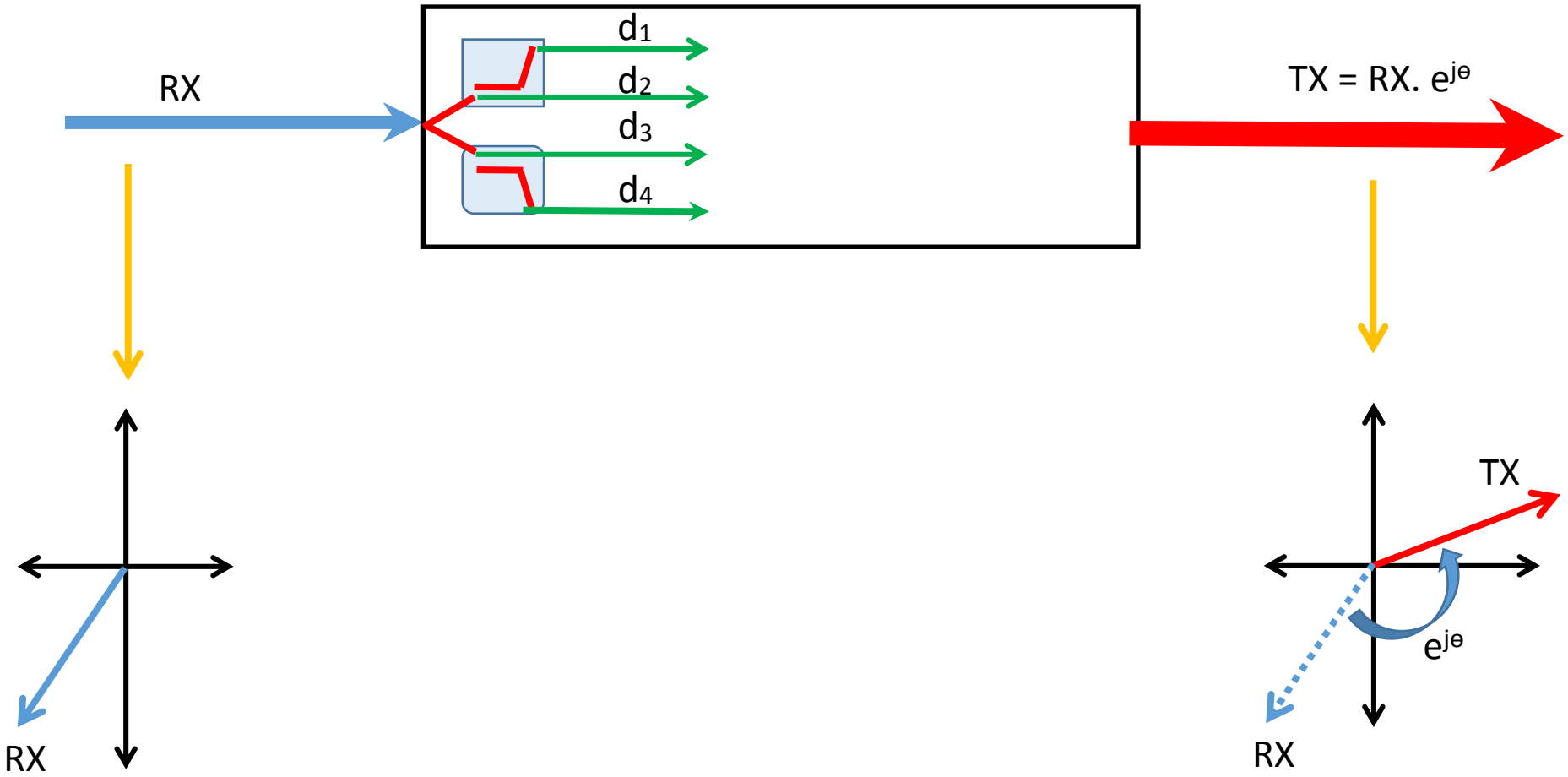
Low latency constructive rotation filter



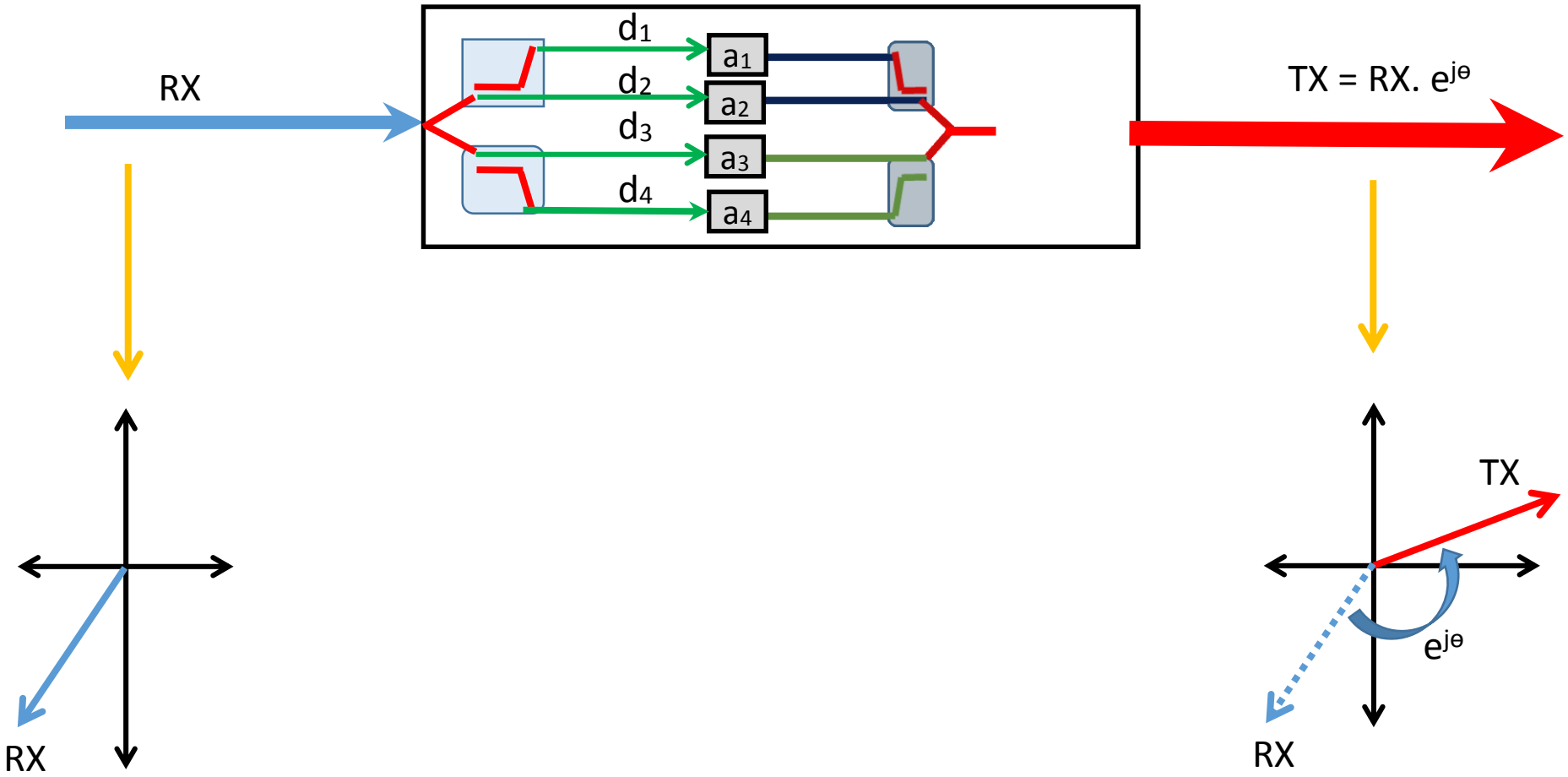
Low latency constructive rotation filter



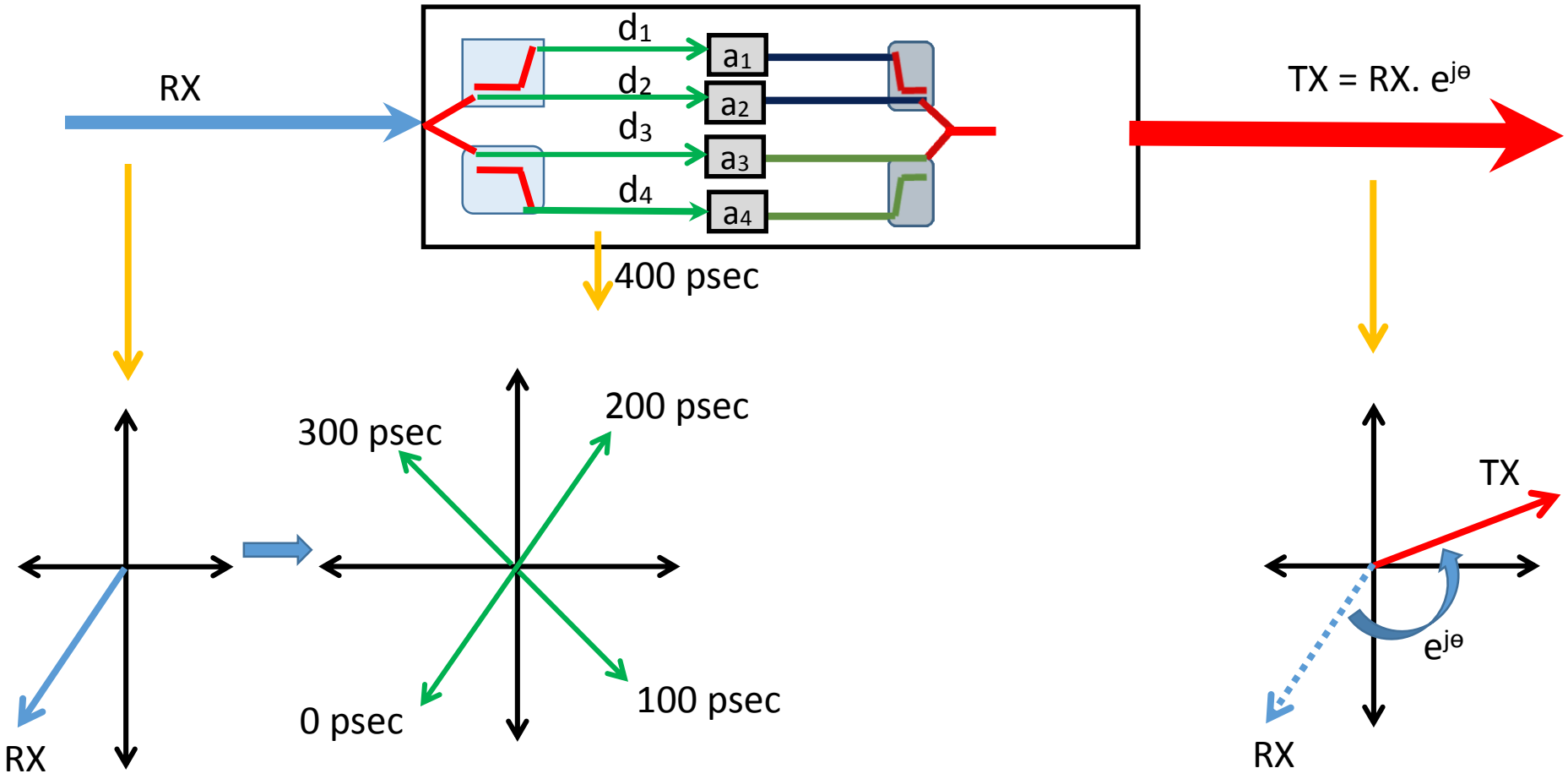
Low latency constructive rotation filter



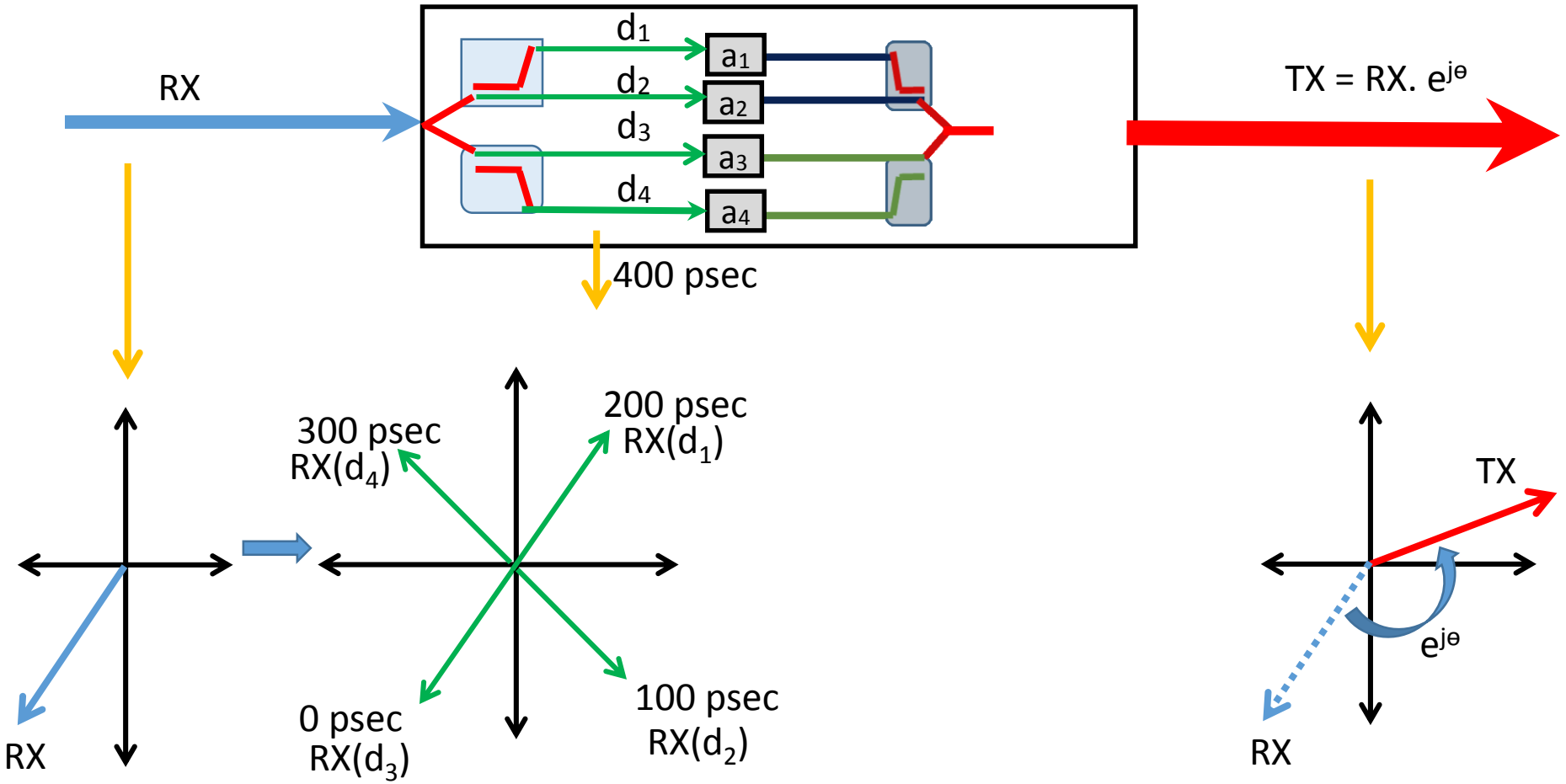
Low latency constructive rotation filter



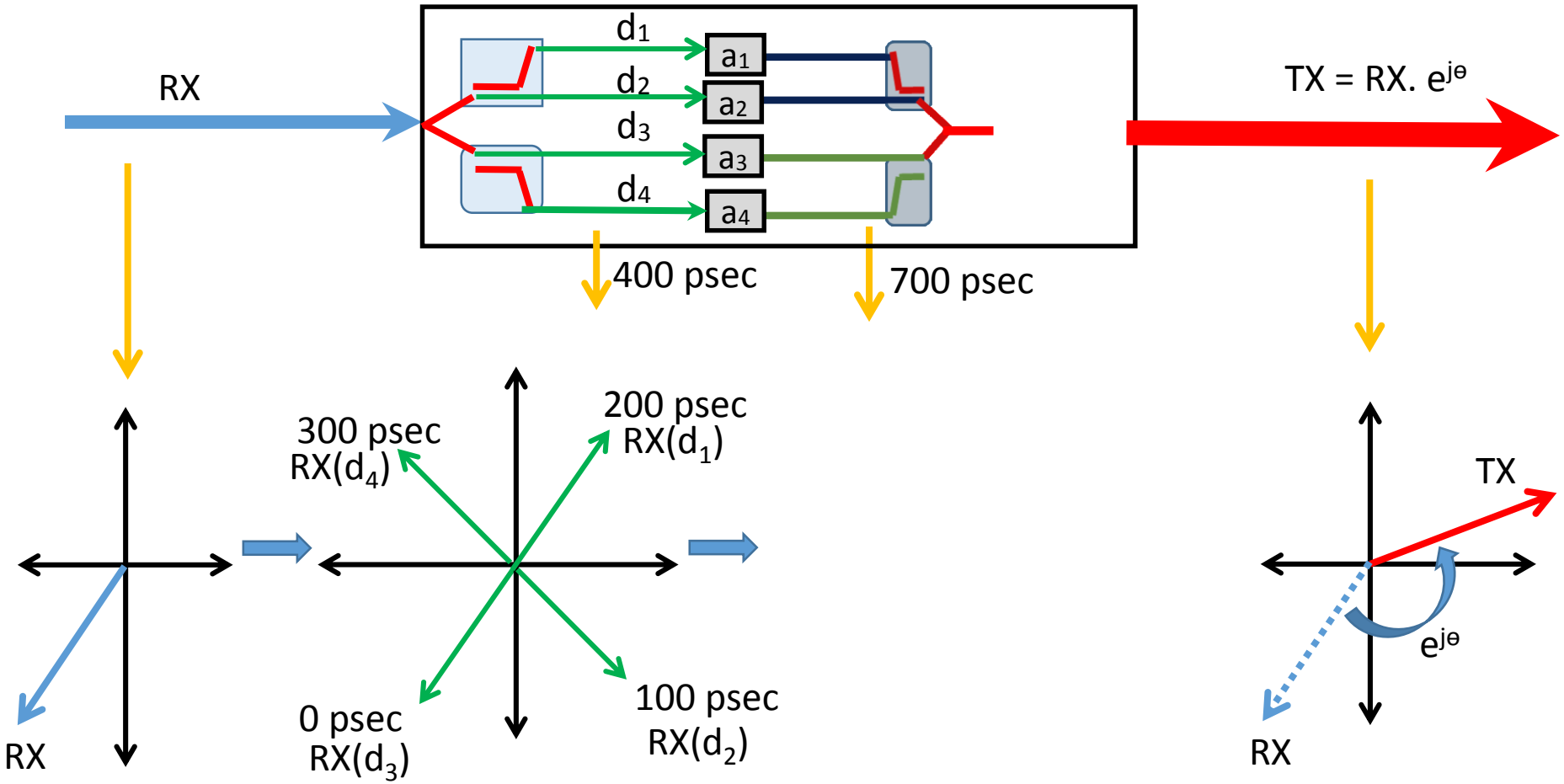
Low latency constructive rotation filter



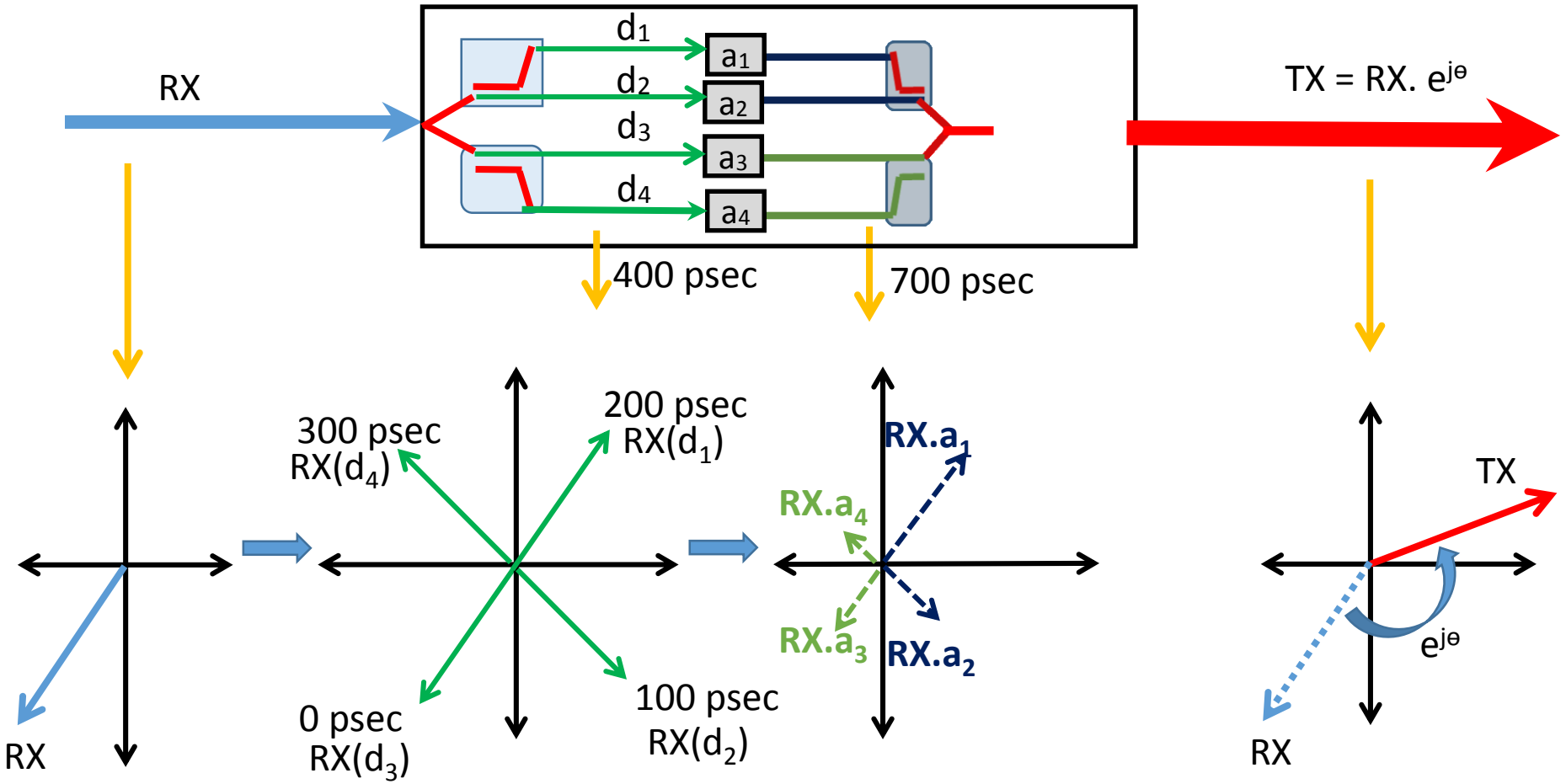
Low latency constructive rotation filter



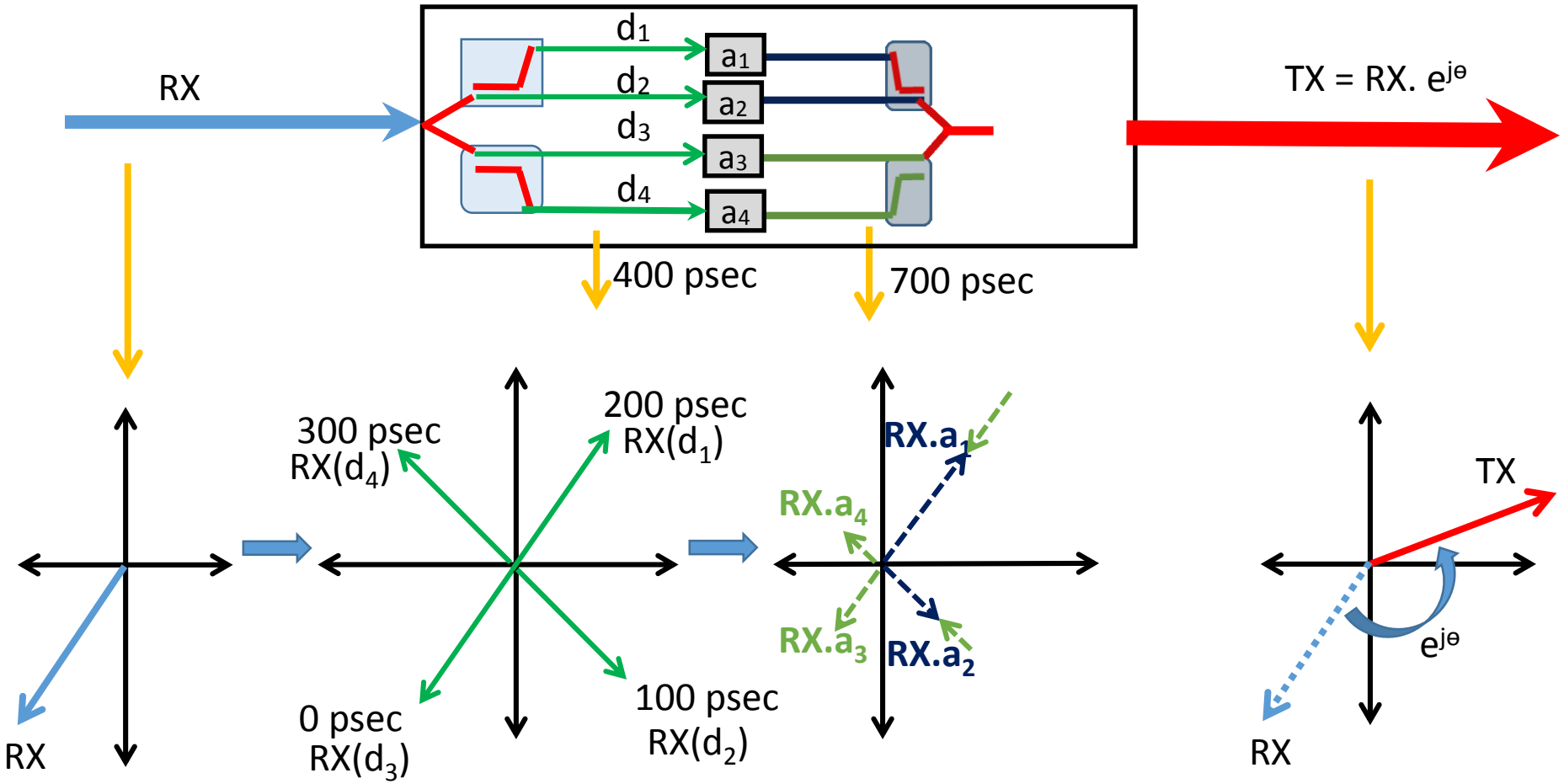
Low latency constructive rotation filter



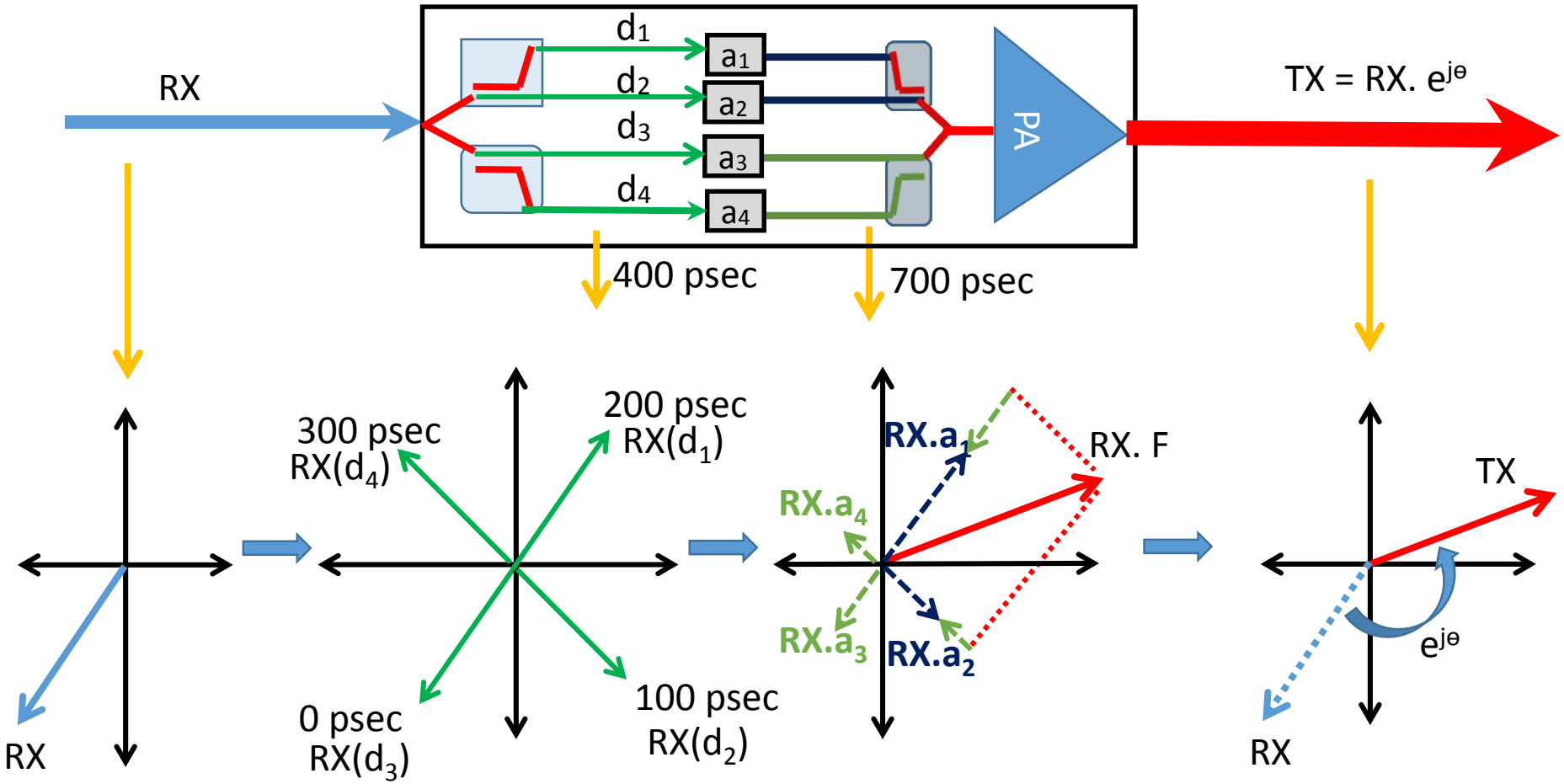
Low latency constructive rotation filter



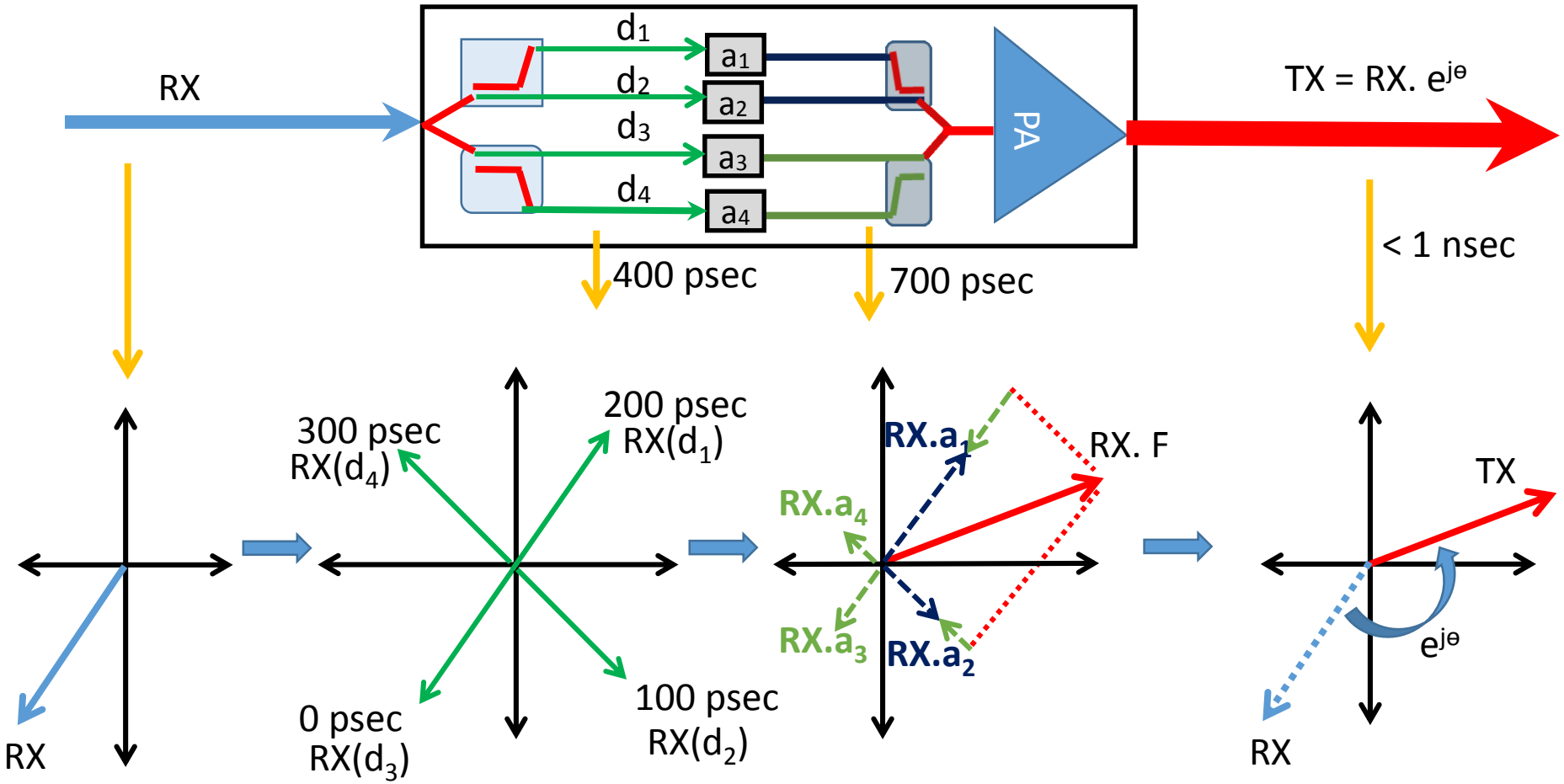
Low latency constructive rotation filter



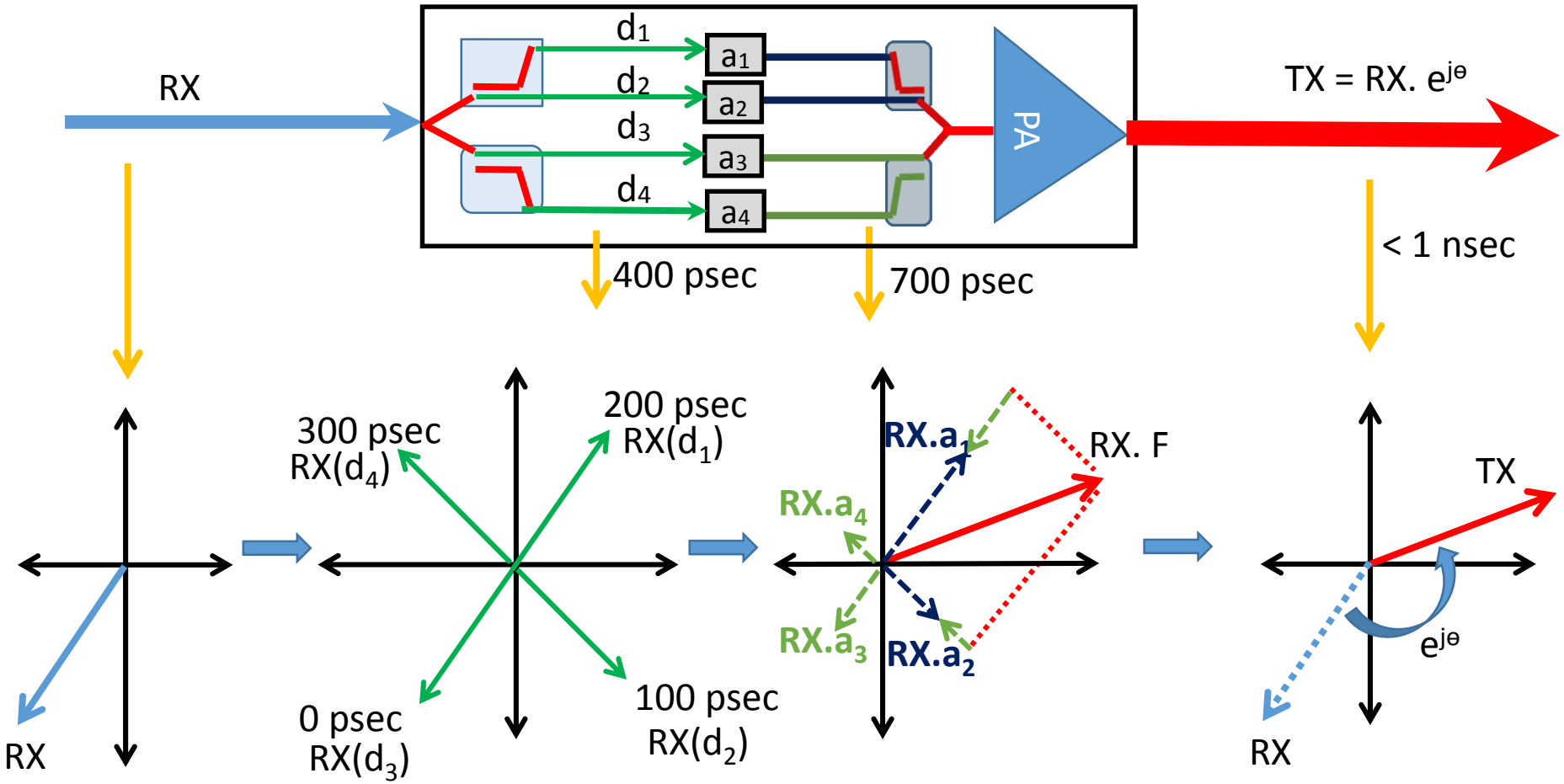
Low latency constructive rotation filter



Low latency constructive rotation filter

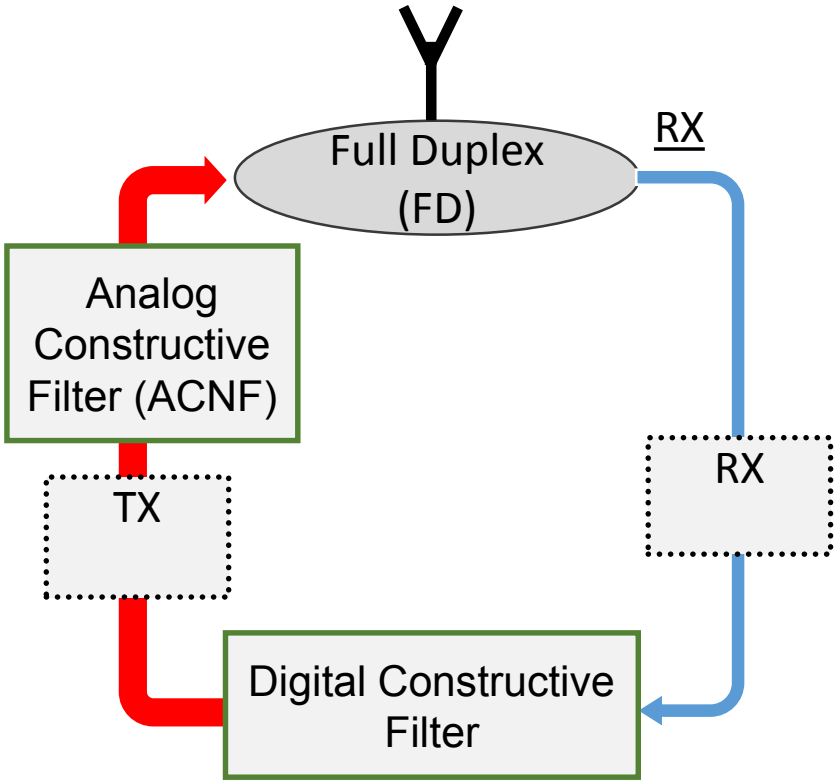


Low latency constructive rotation filter



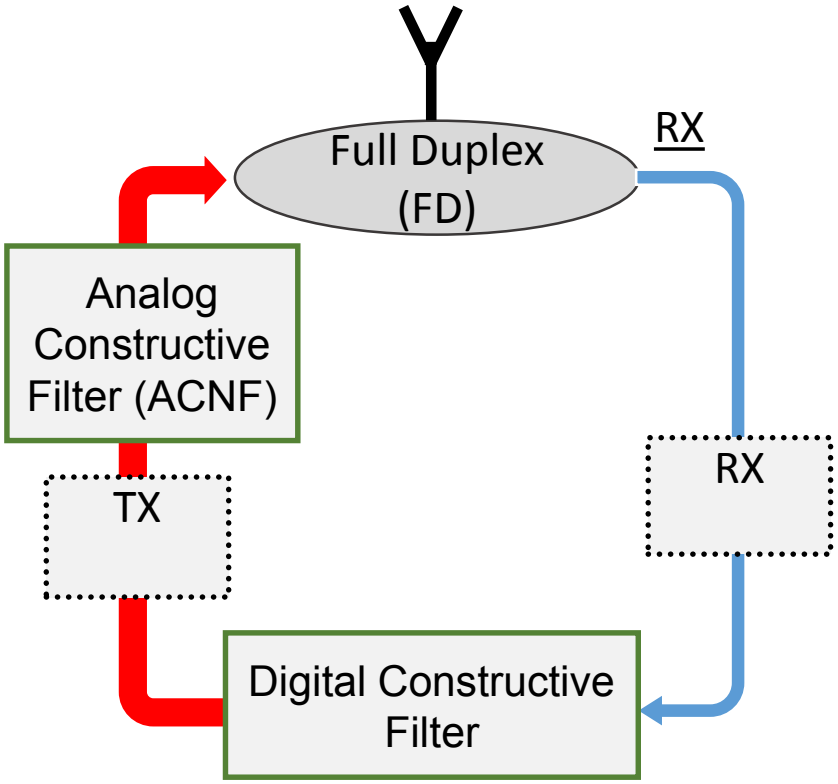
Filtering in analog achieves constructive rotation within a nanosecond

Implementation of FastForward

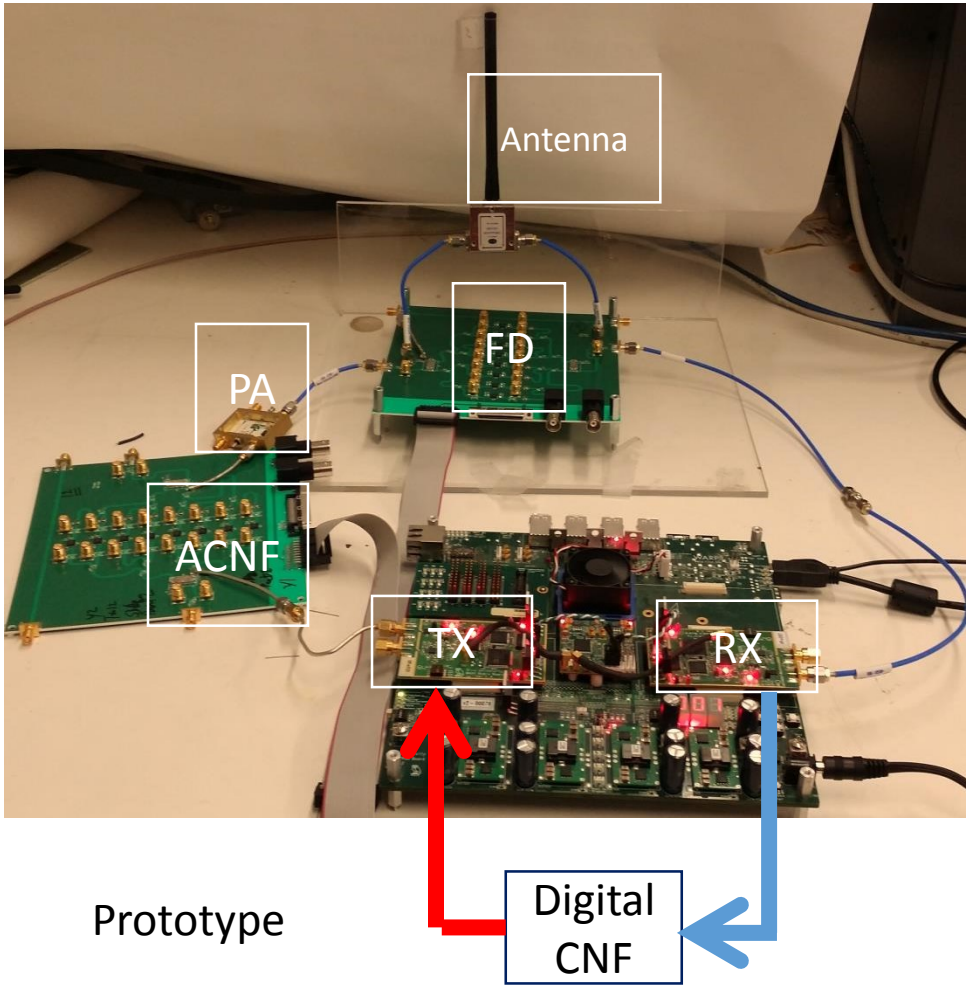


Block Diagram

Implementation of FastForward



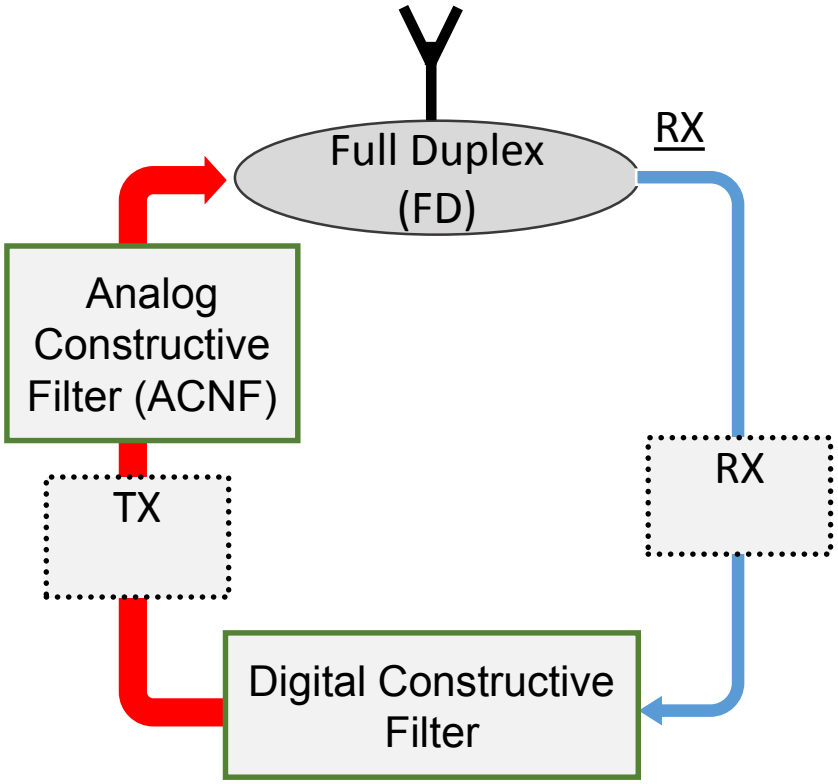
Block Diagram



Prototype

Implementation of FastForward

- Built using WARP SDR platform, designed for 802.11



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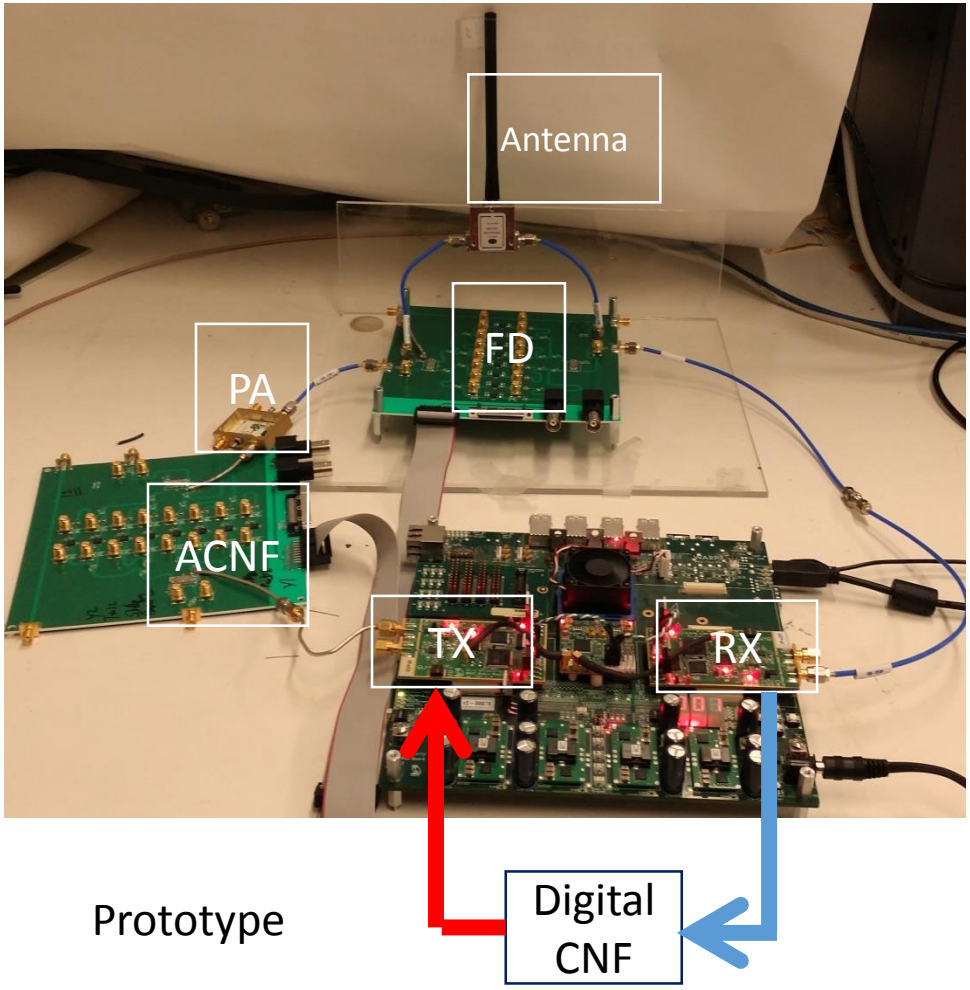

Prototype

Implementation of FastForward

- Built using WARP SDR platform, designed for 802.11
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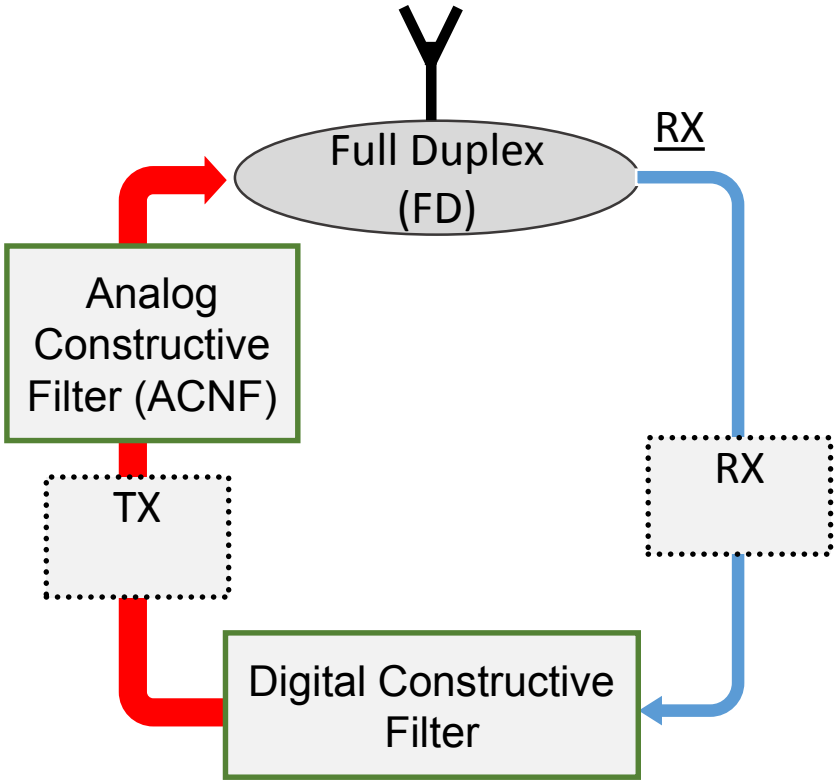
- BW 20MHz, 20dBm TX power



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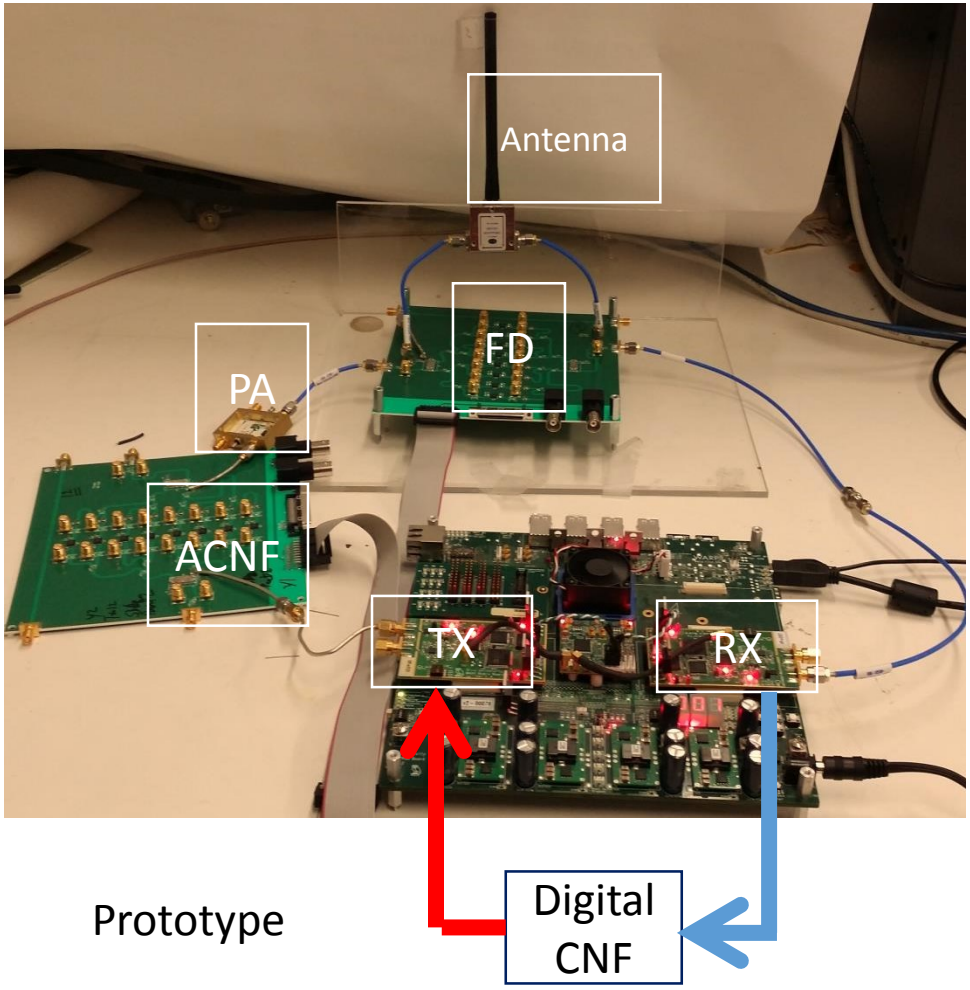

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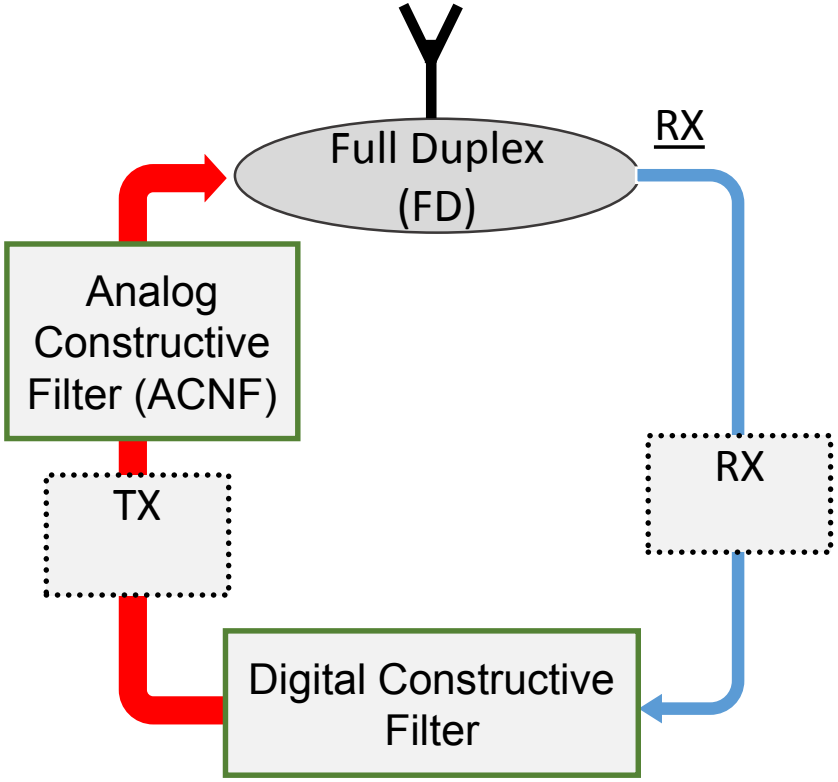
- **Built 2x2 MIMO FF Prototype**



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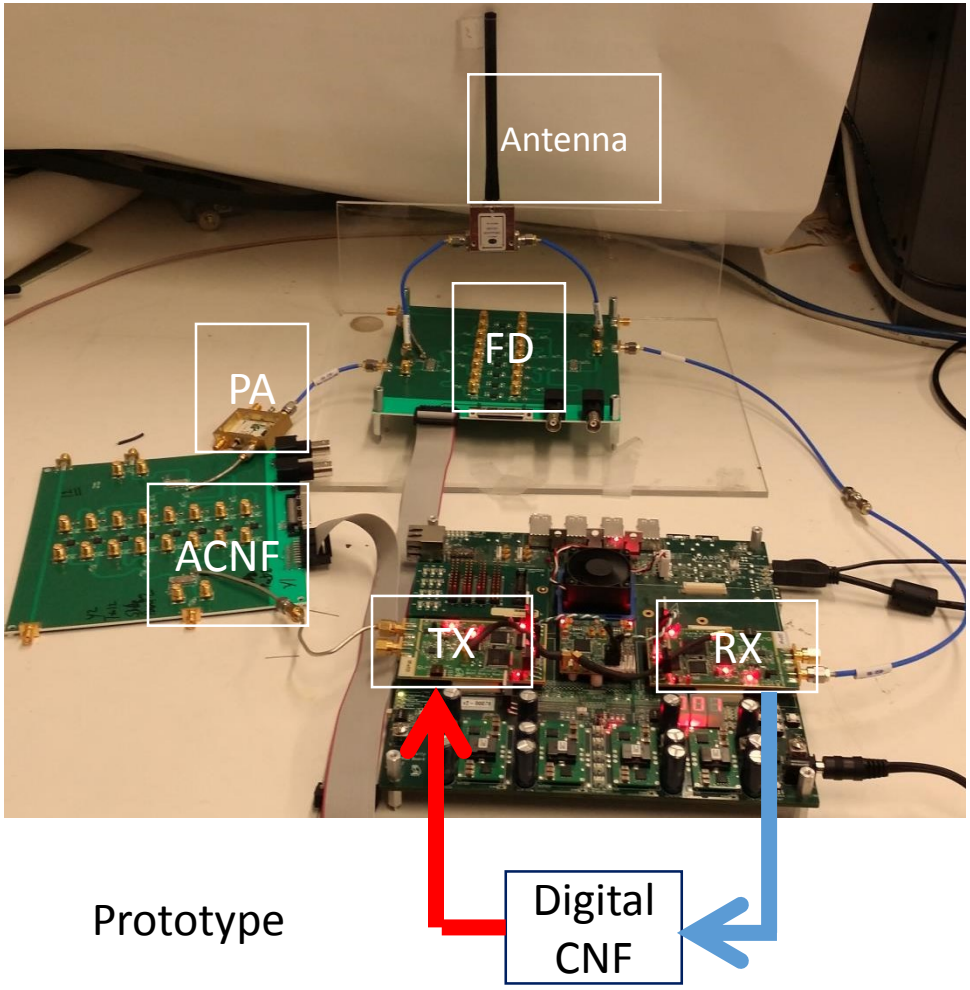

Prototype

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

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$$\text{Relative Gain} = \frac{\textbf{Bitrate of any approach}}{\textbf{Bitrate of AP + HD mesh router}}$$

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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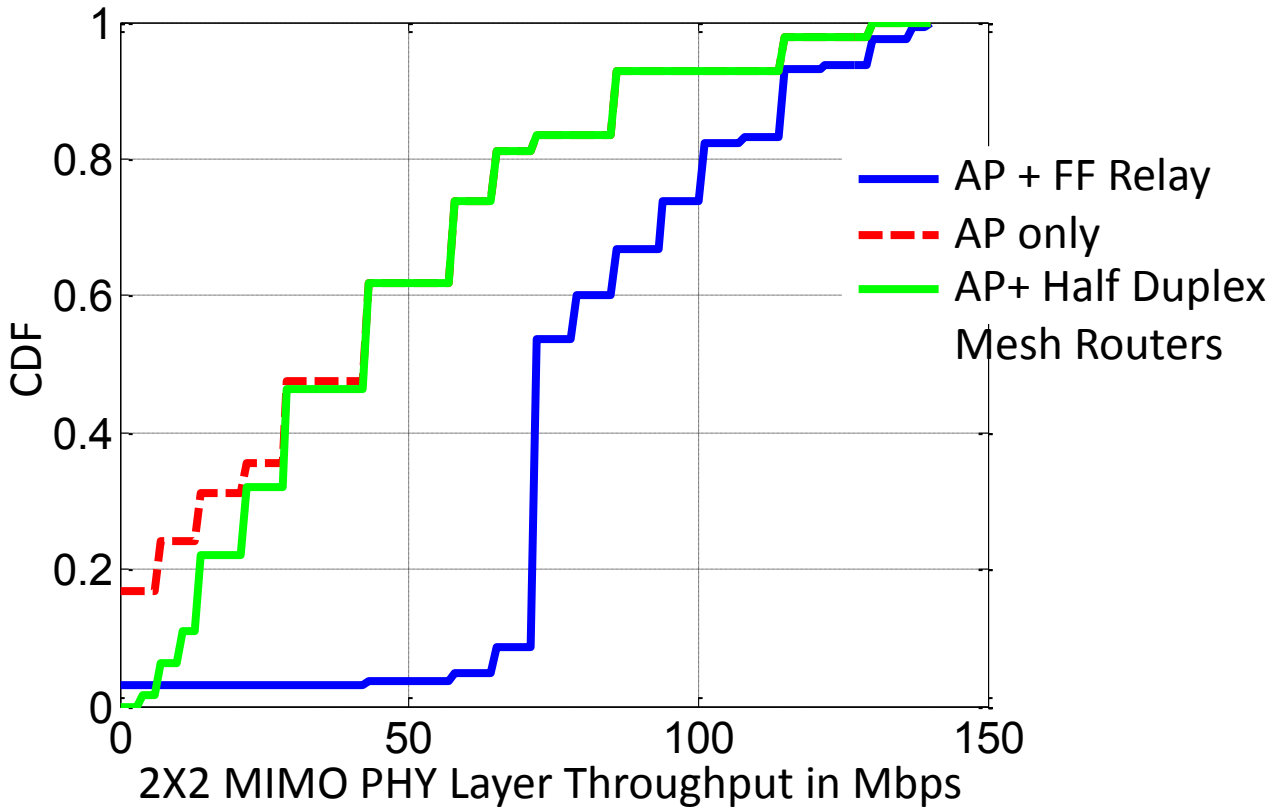

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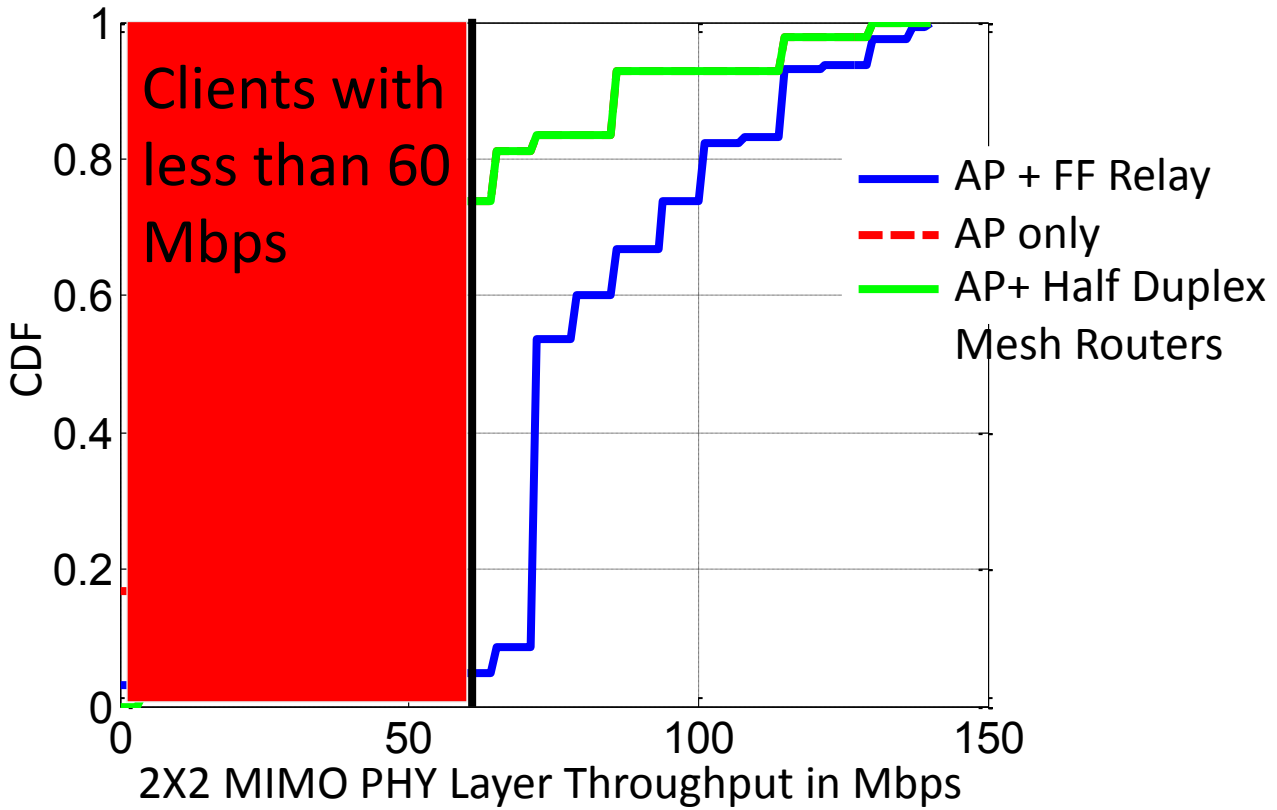

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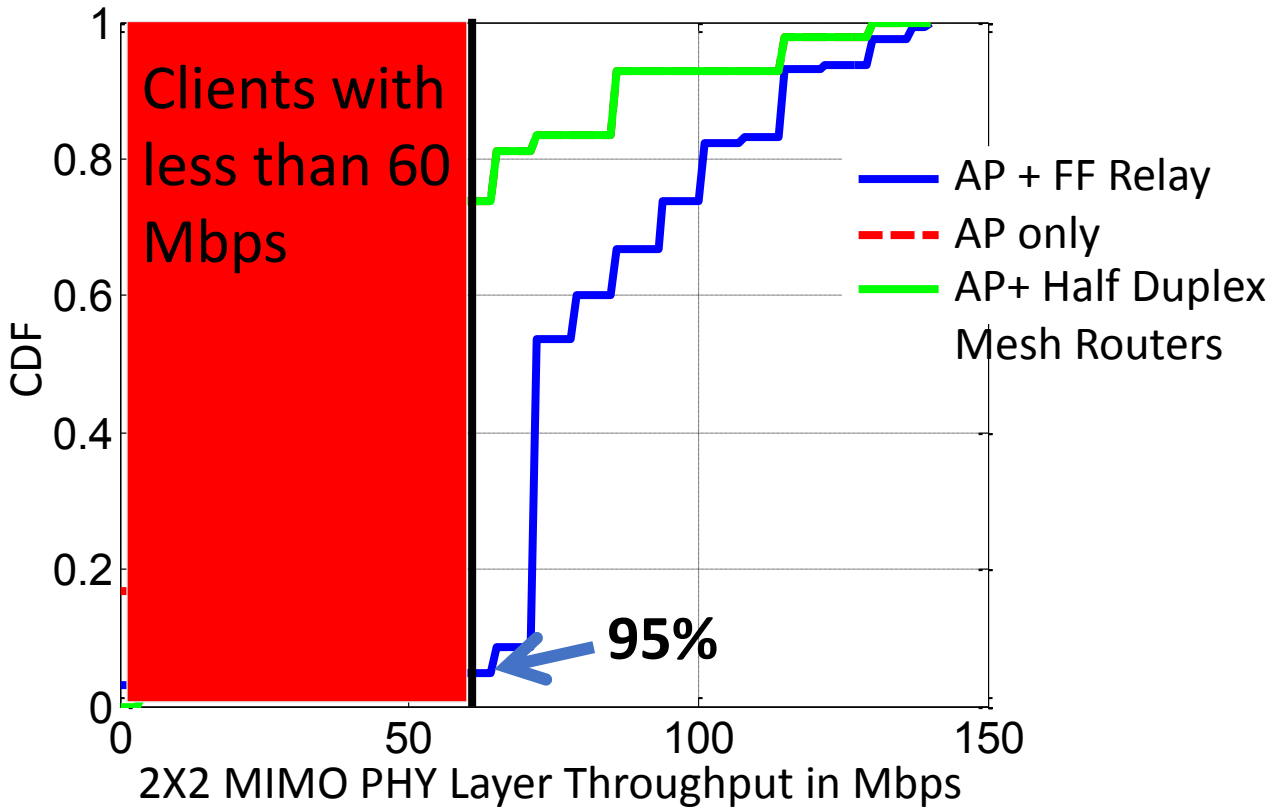

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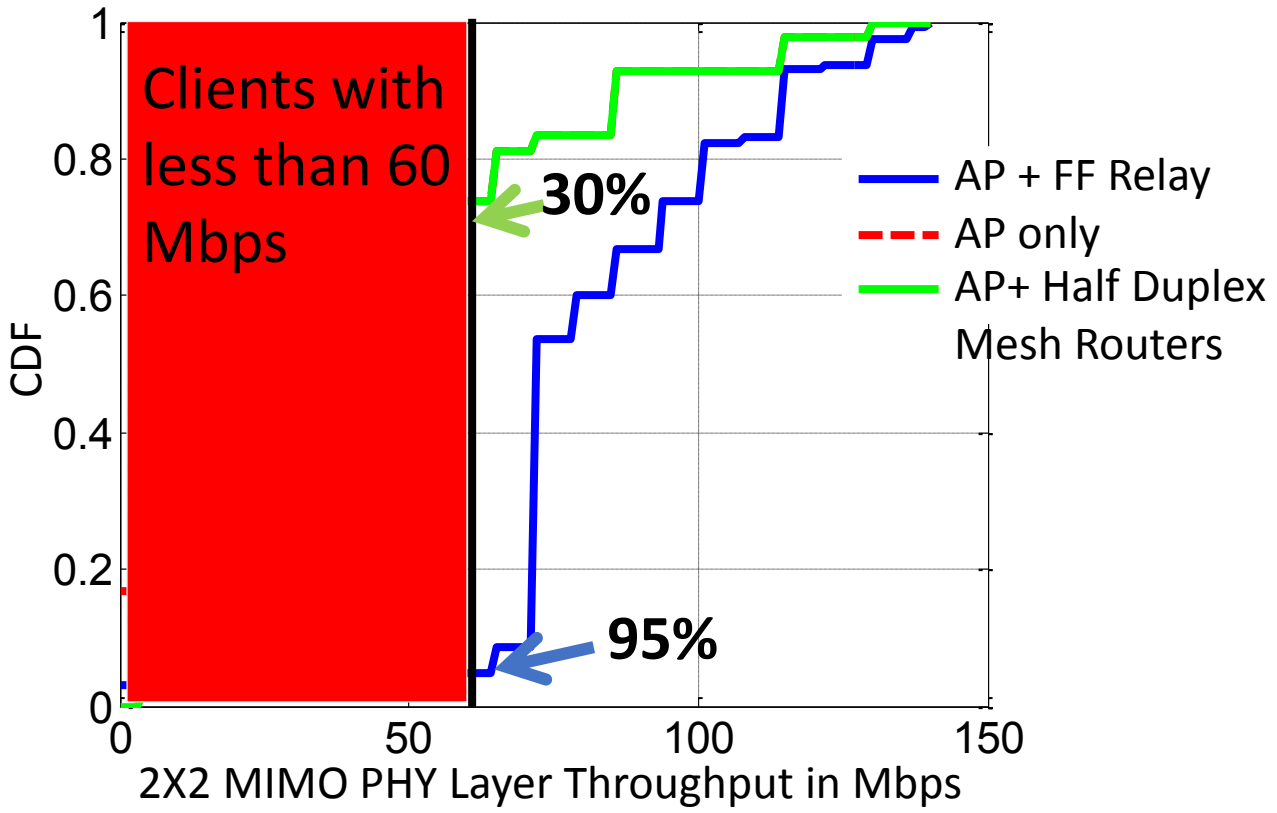


AP+ FF: 95% of locations get at least 60Mbps

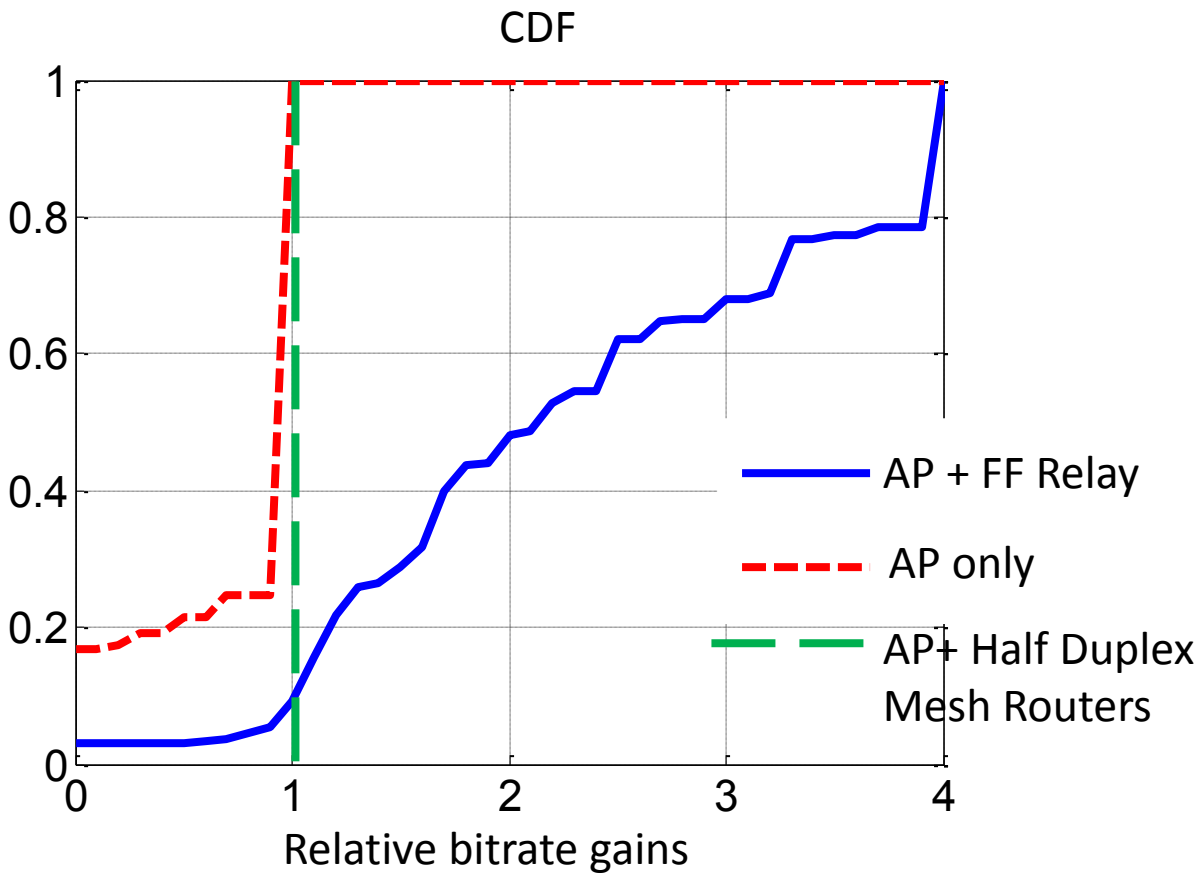
AP + Mesh Router: Only 30% of locations get at least 60Mbps

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



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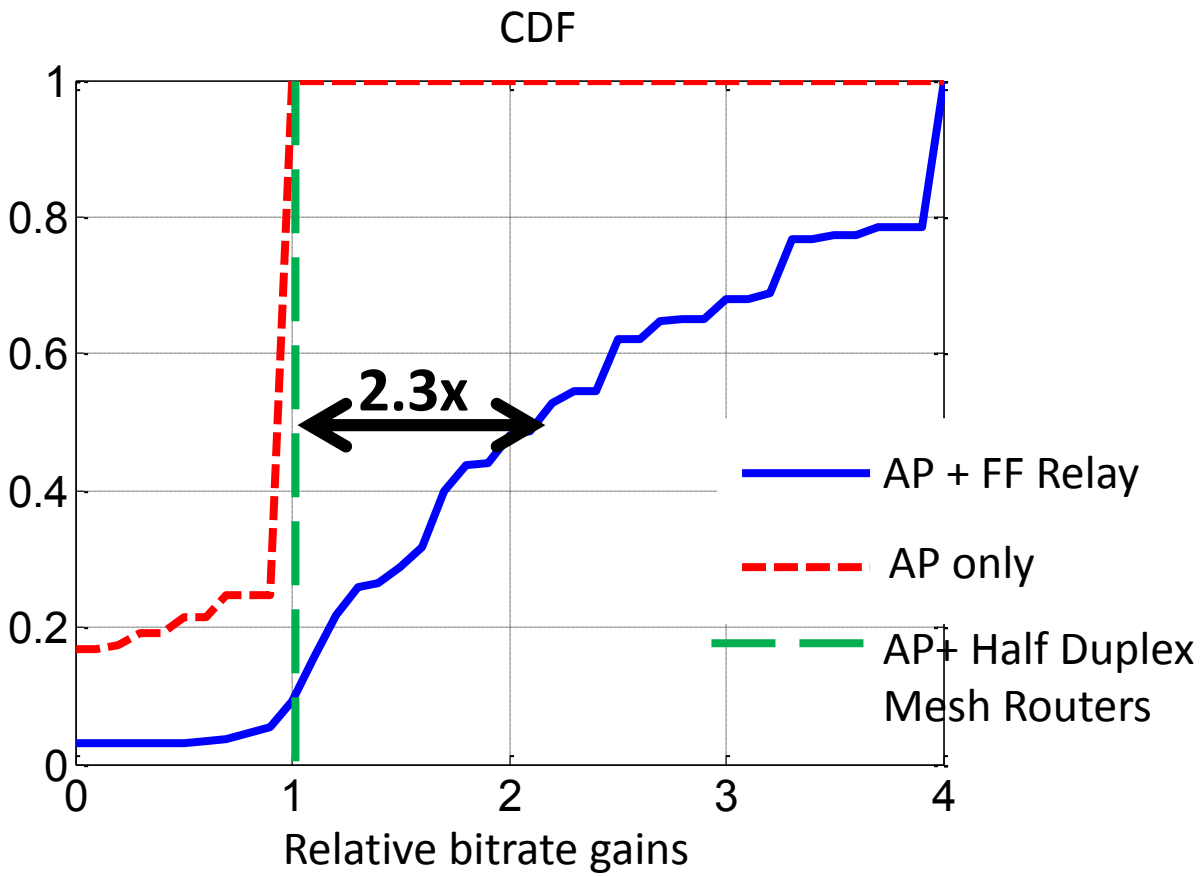

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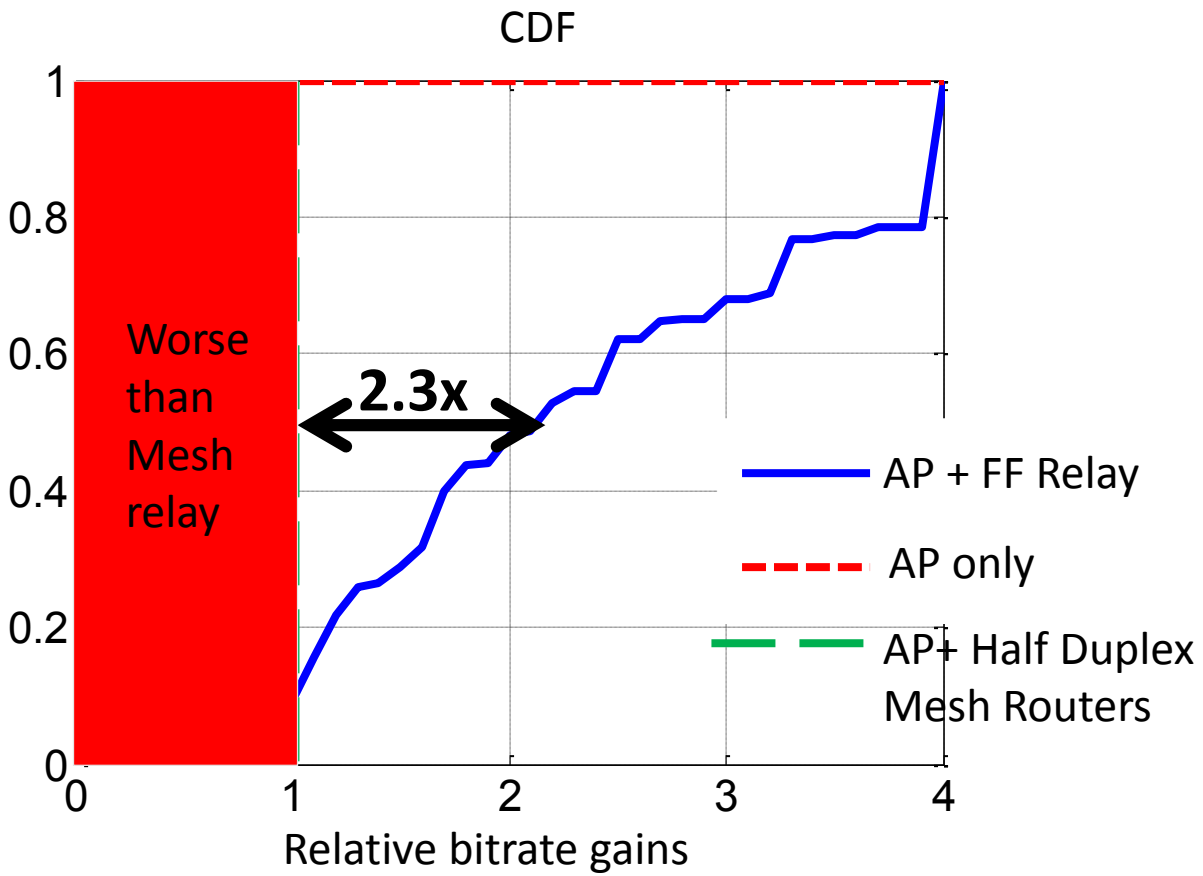

Our design achieves the 2.3x times the half duplex Mesh router

To Conclude

Forward signals, not packets!