Many-to-Many Beam Alignment in Millimeter Wave Networks

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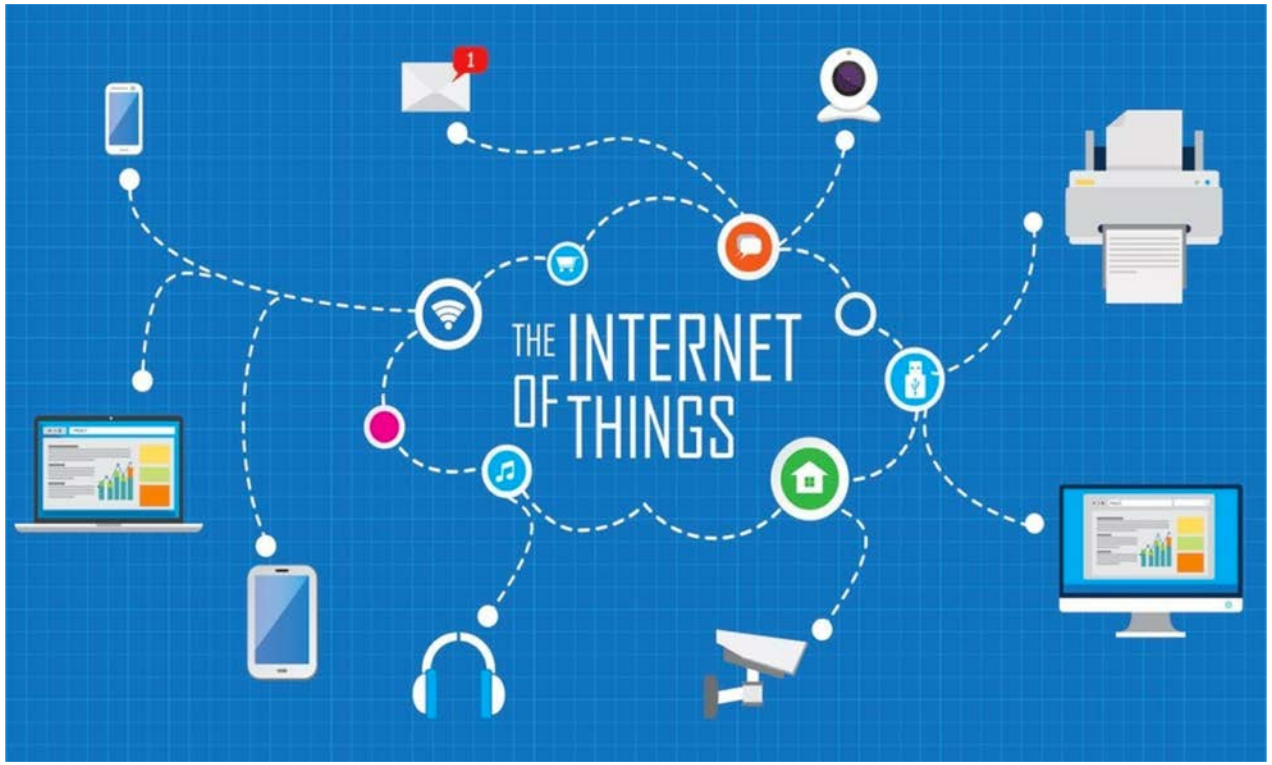
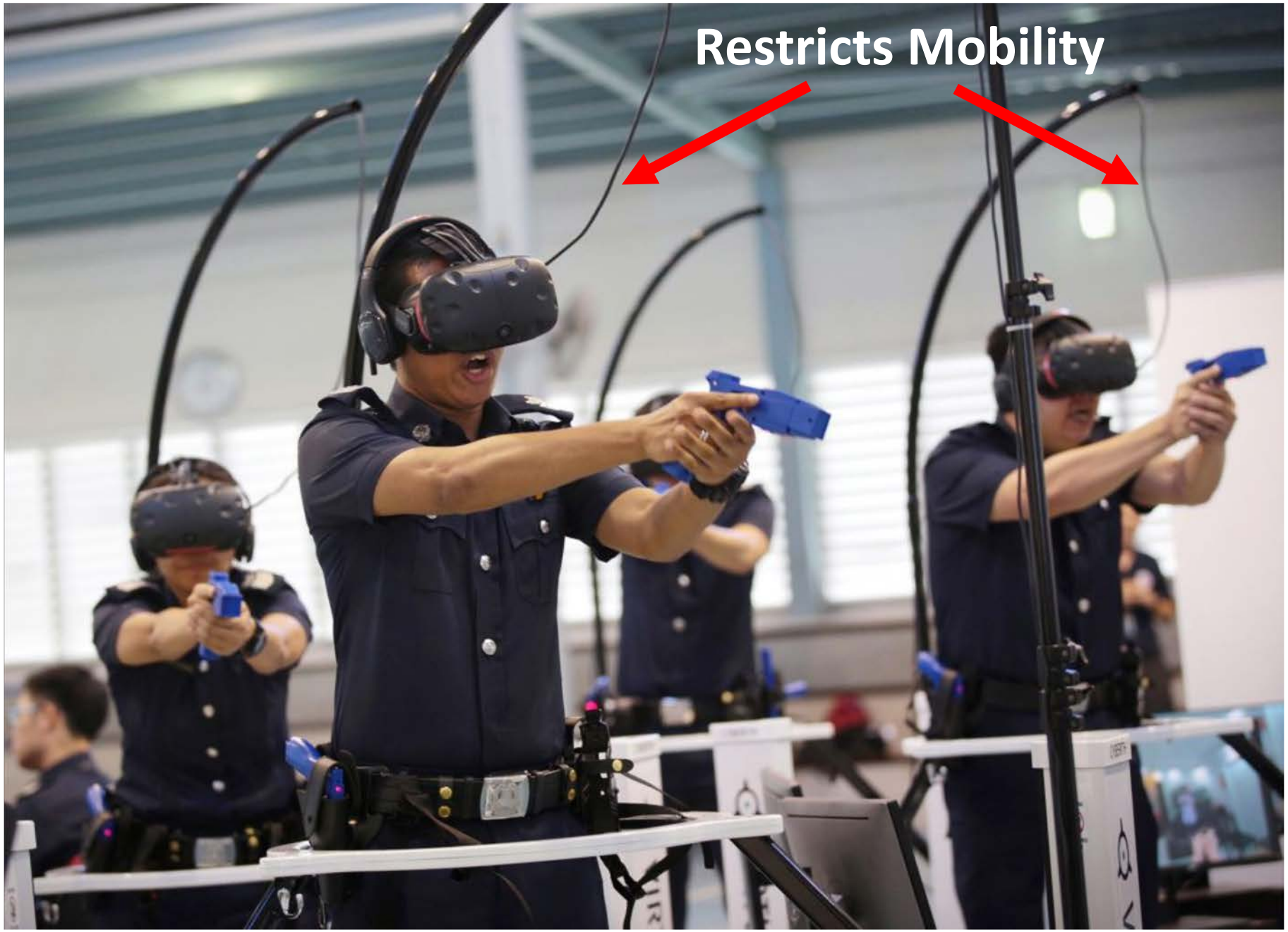
Bandwidth requirement of wireless applications is growing



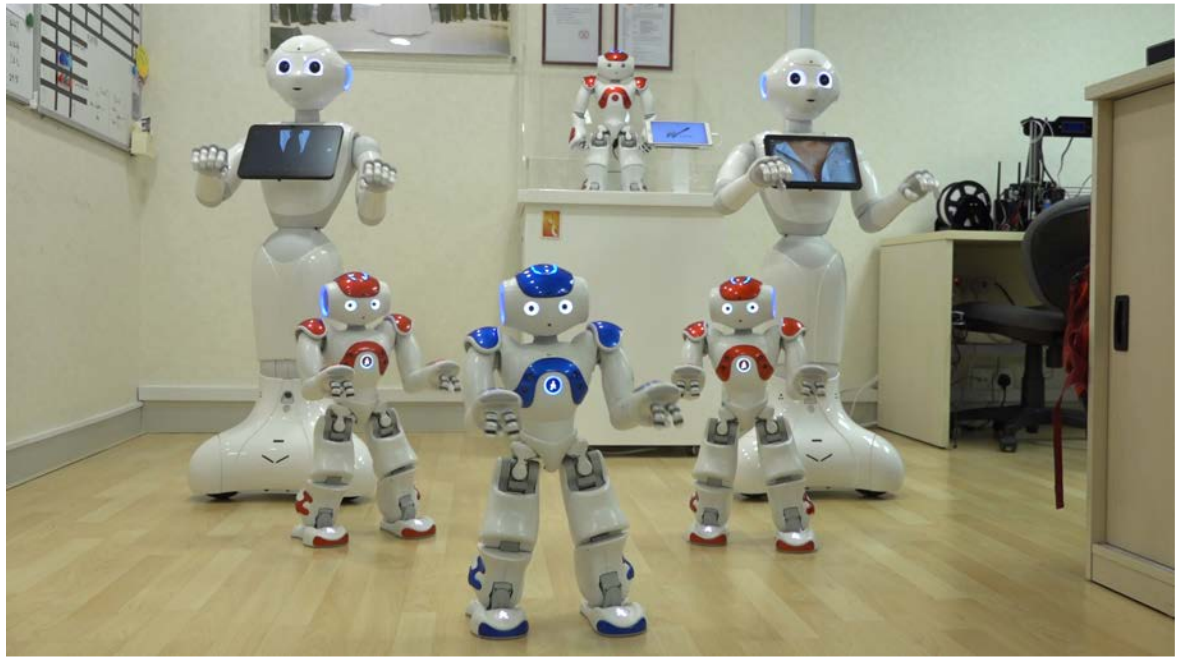
VR and AR



VR and AR

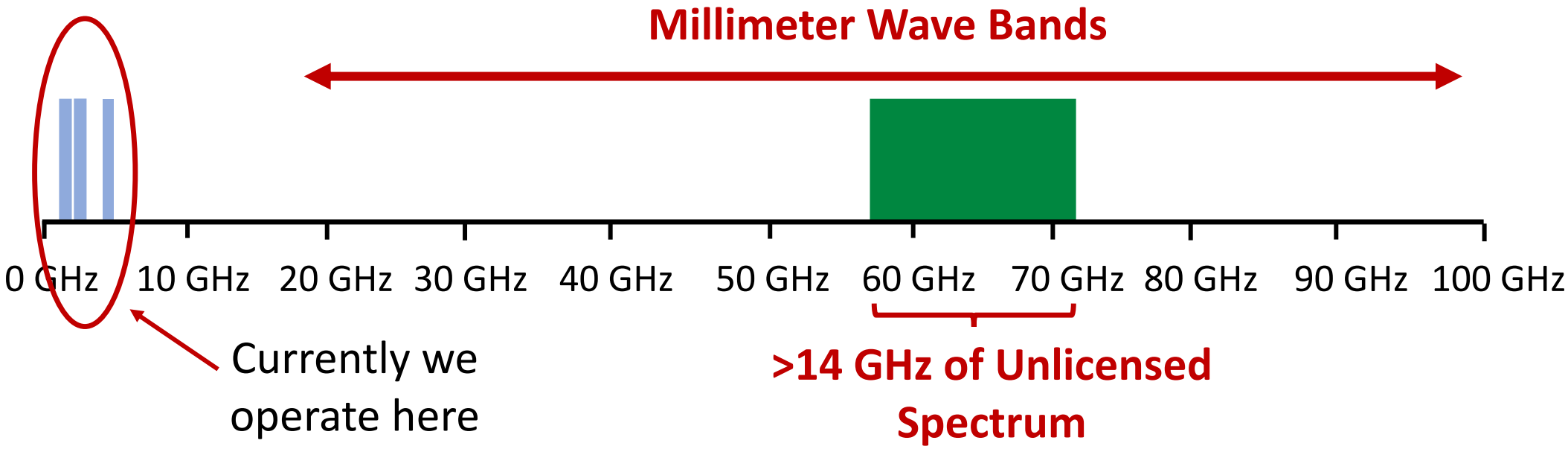
VR and AR

Robotic Automation and Collaboration Tasks



Millimeter Wave Technology

Huge bandwidth available at millimeter wave frequencies



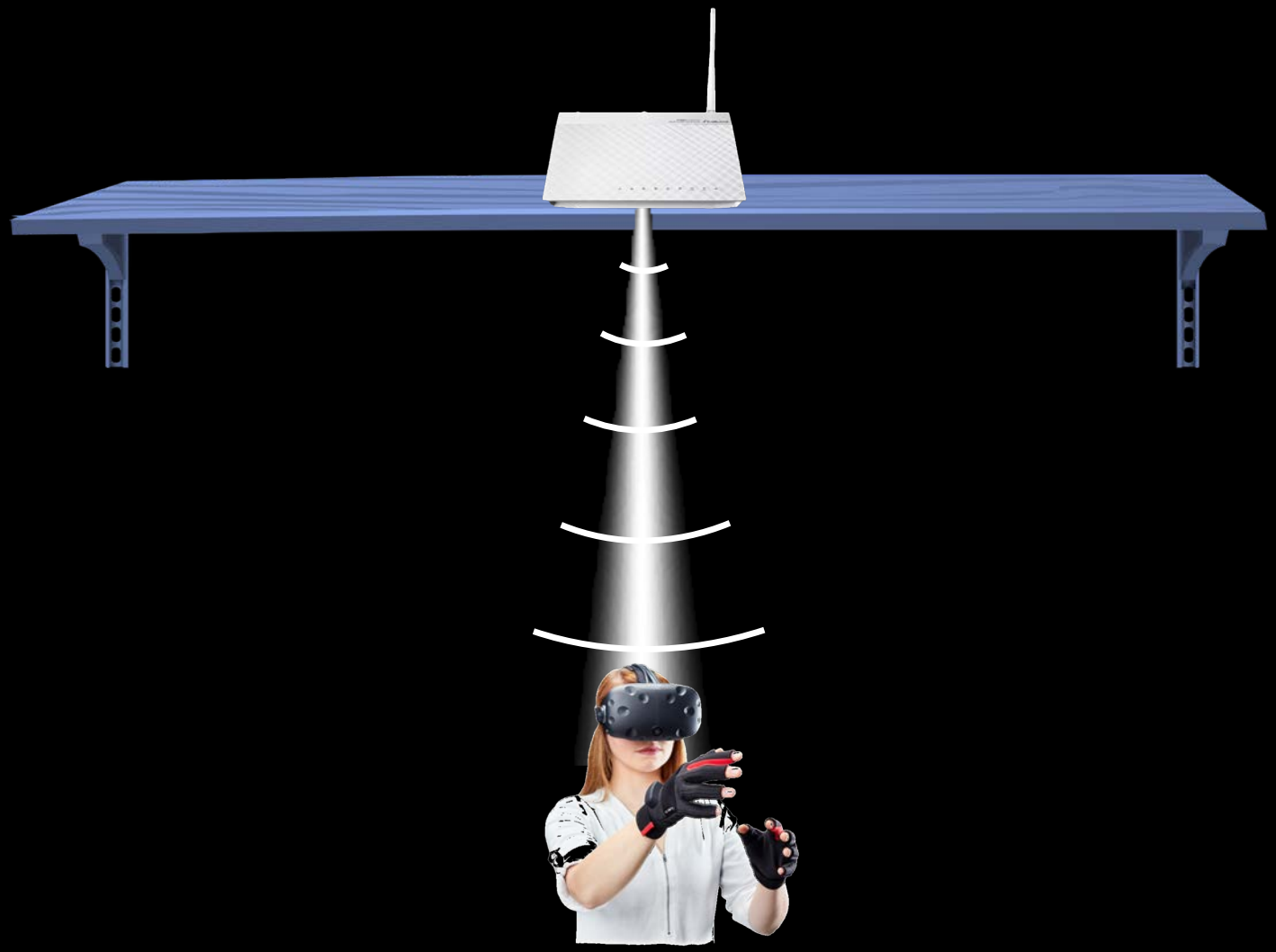
Millimeter Wave can support data rates of multi-Gbps

How to scale mmWave networks while maintaining multi-Gbps throughput per user?

Today's Networks : Broadcast

mmWave changes how wireless systems operate

mmWave: Narrow-beam Antennas



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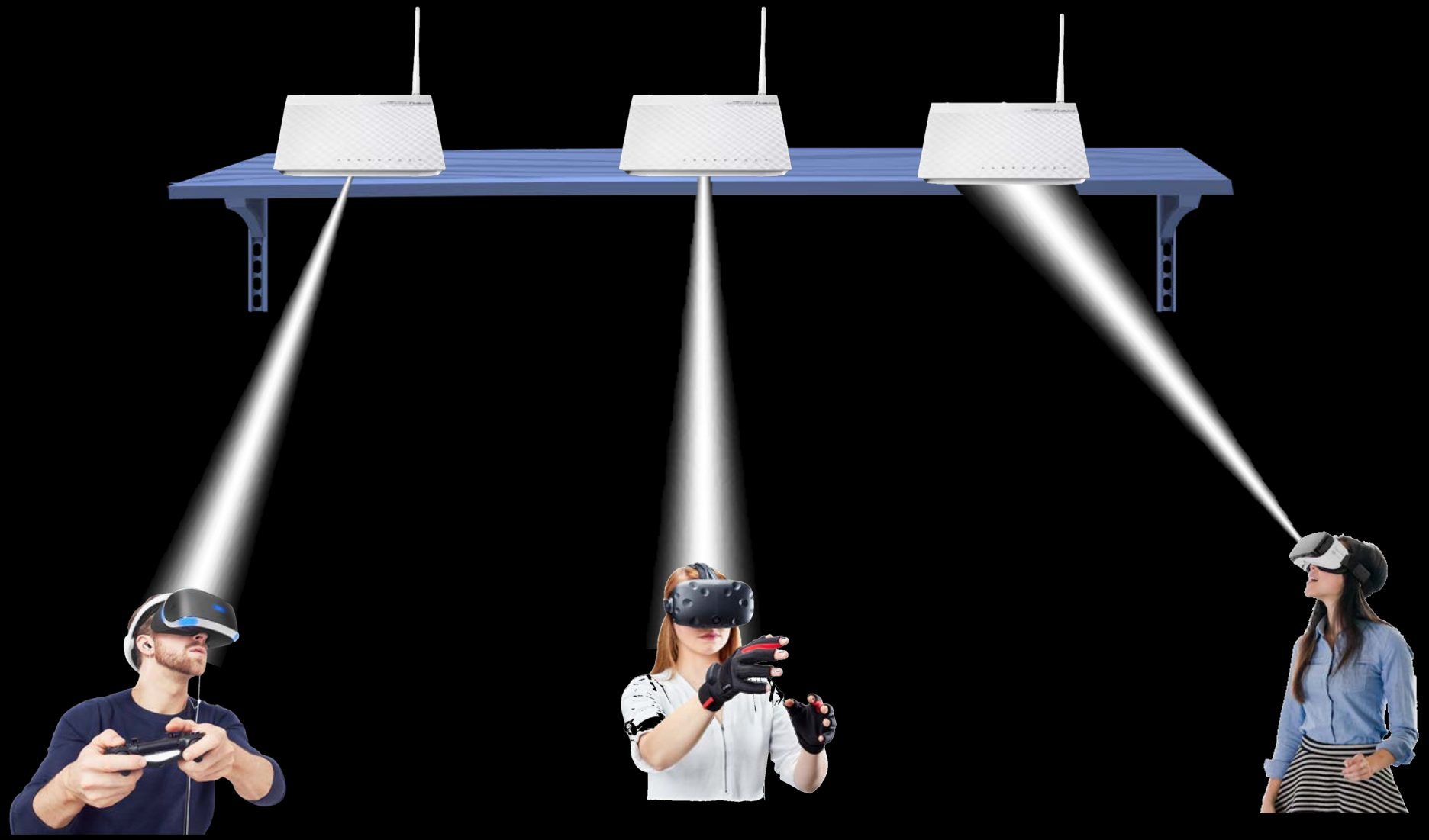
mmWave: Narrow-beam Antennas



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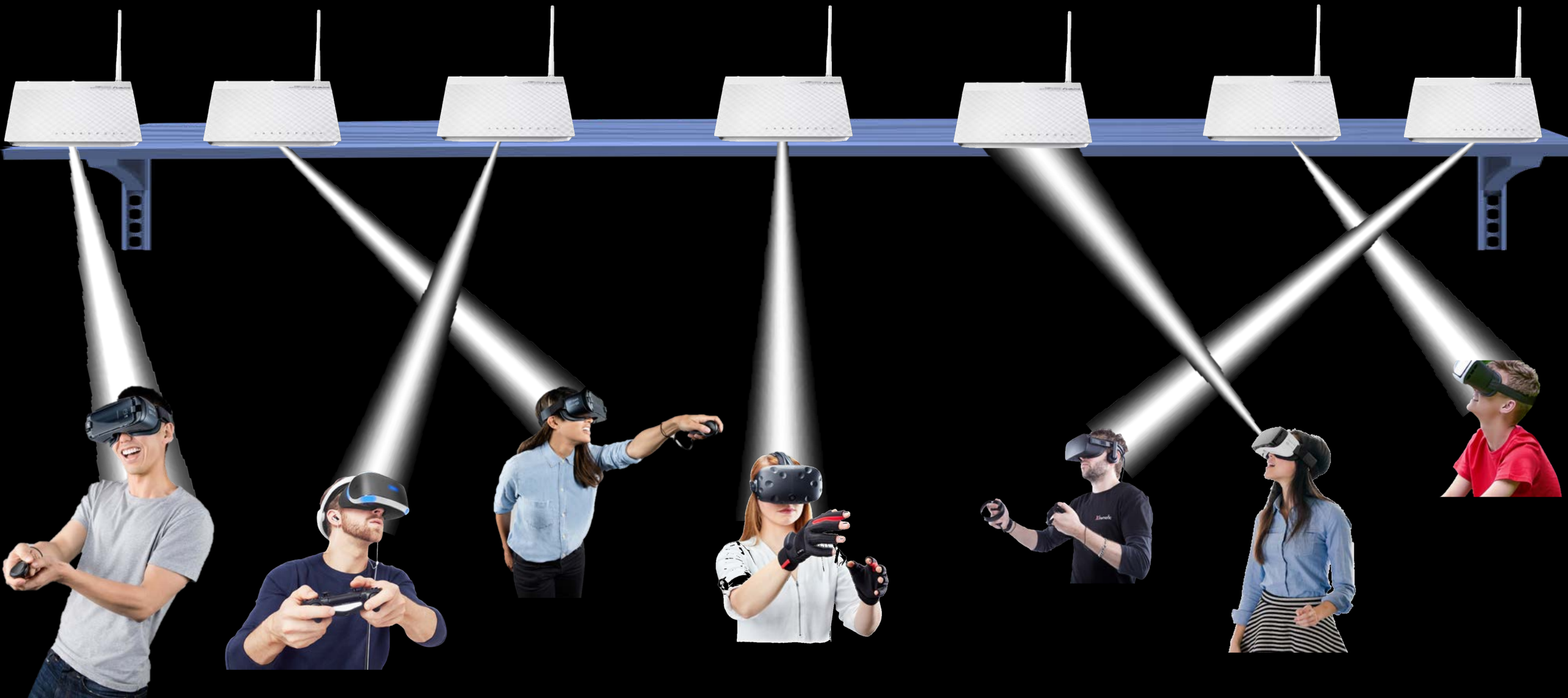


Past work focuses on quickly finding best alignment for a single communication link

[NSDI'17, SIGCOMM'18, INFOCOM'15, SIGMETRICS'15]

Multi-Link Beam Alignment is challenging!

Client 1

Collision

Client 2

Carrier Sense does not work in directional networks

[MOBICOM'02, SIGCOMM'09]

AP1

AP2

We cannot align the beams of each AP and client independent of other APs and clients in the network

BounceNet

A **many-to-many beam alignment** protocol that can enable many links to operate in parallel in confined spaces without interfering.

Many-to-Many Beam Alignment

What is the best alignment of beams that densely packs as many links as possible?

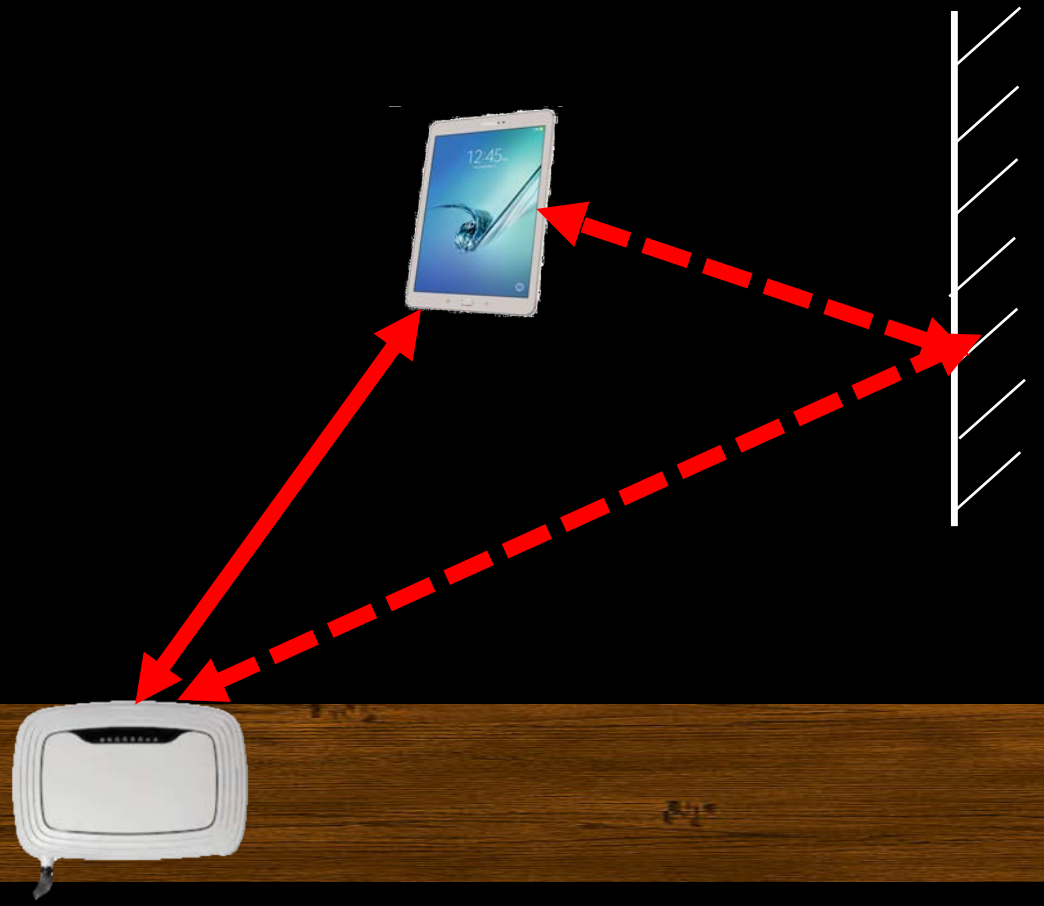
Many-to-Many Beam Alignment

What is the best alignment of beams that densely packs as many links as possible?

Leverage sparsity in the mmWave channel!

Millimeter Wave Channels are sparse

There are only a few number of paths between any TX and RX



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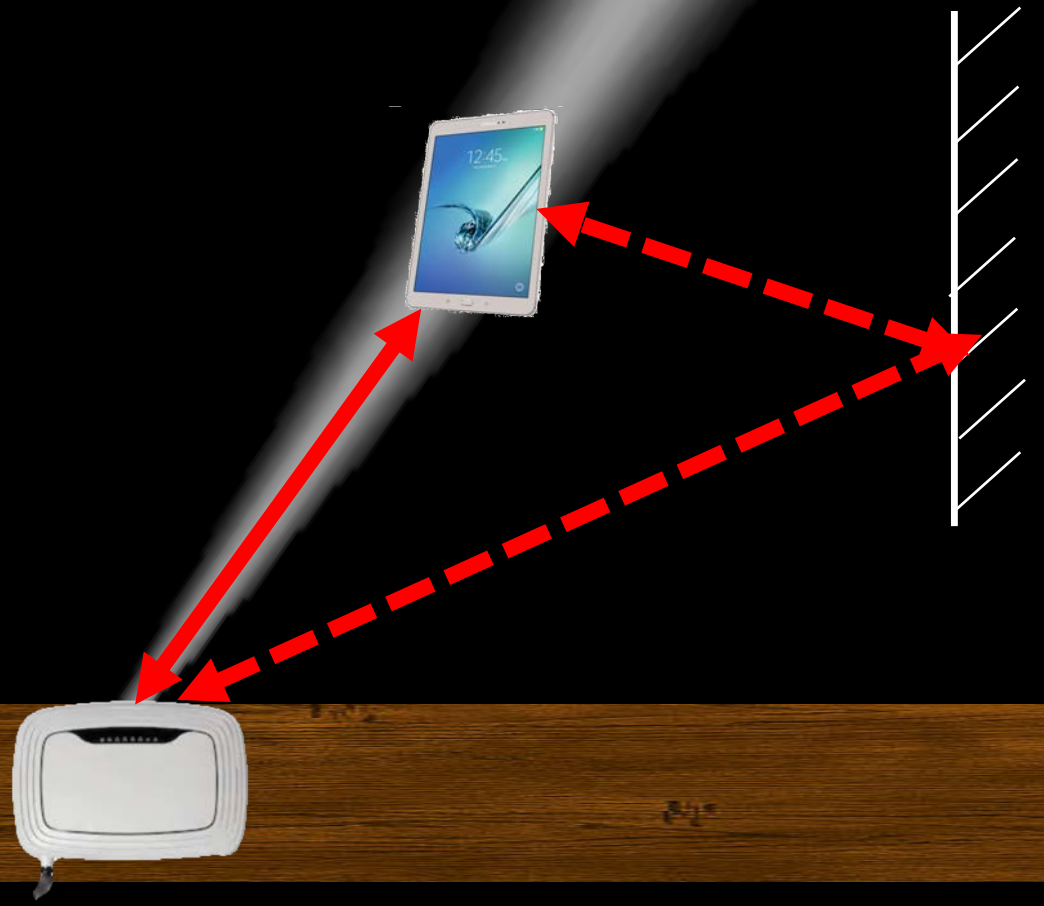

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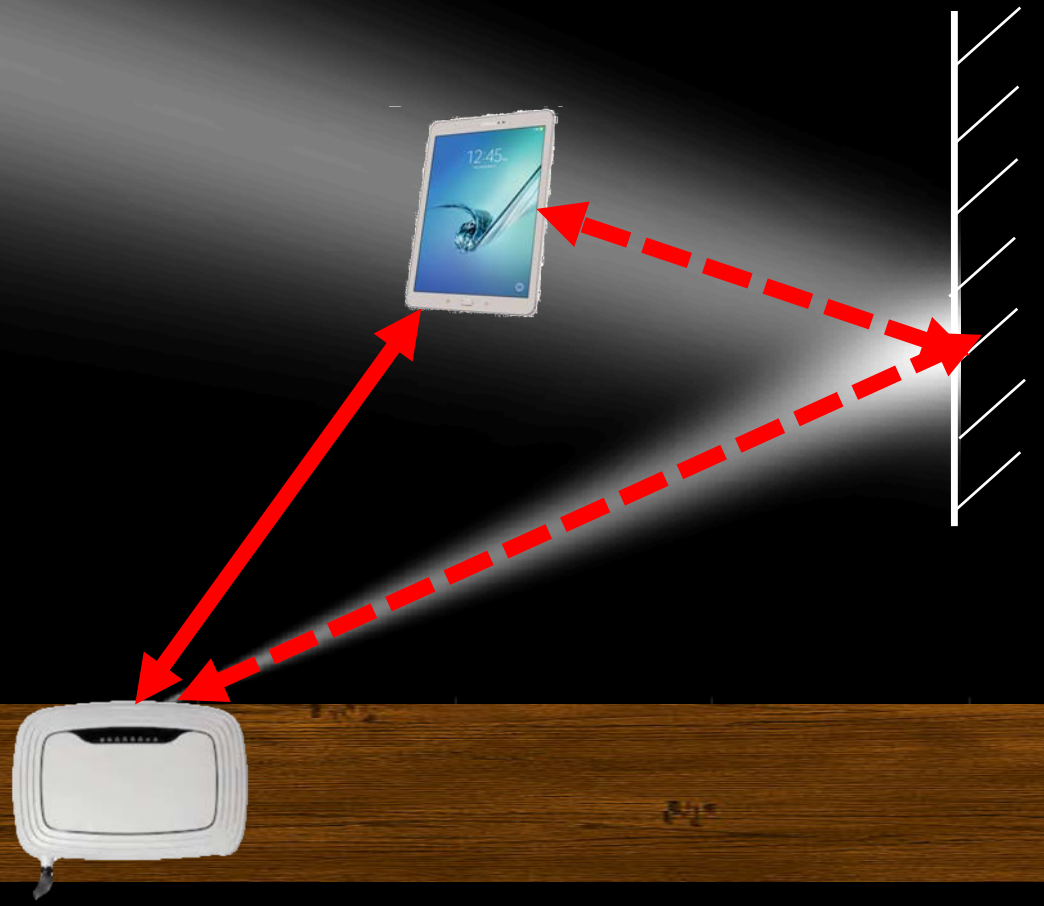
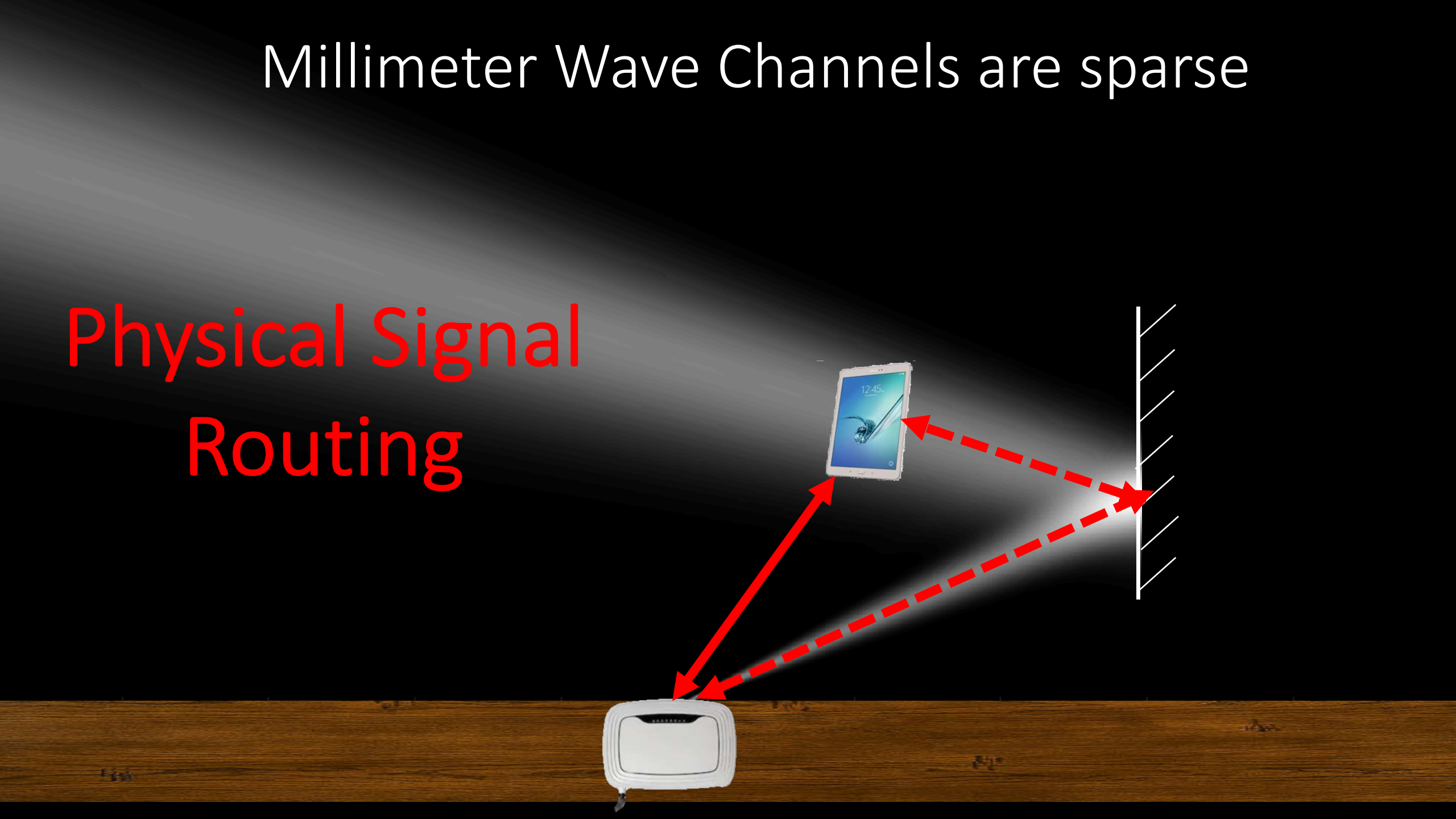


Millimeter Wave Channels are sparse

Physical Signal Routing




Collision
Cannot Transmit at the same time


Can both Transmit at the same time

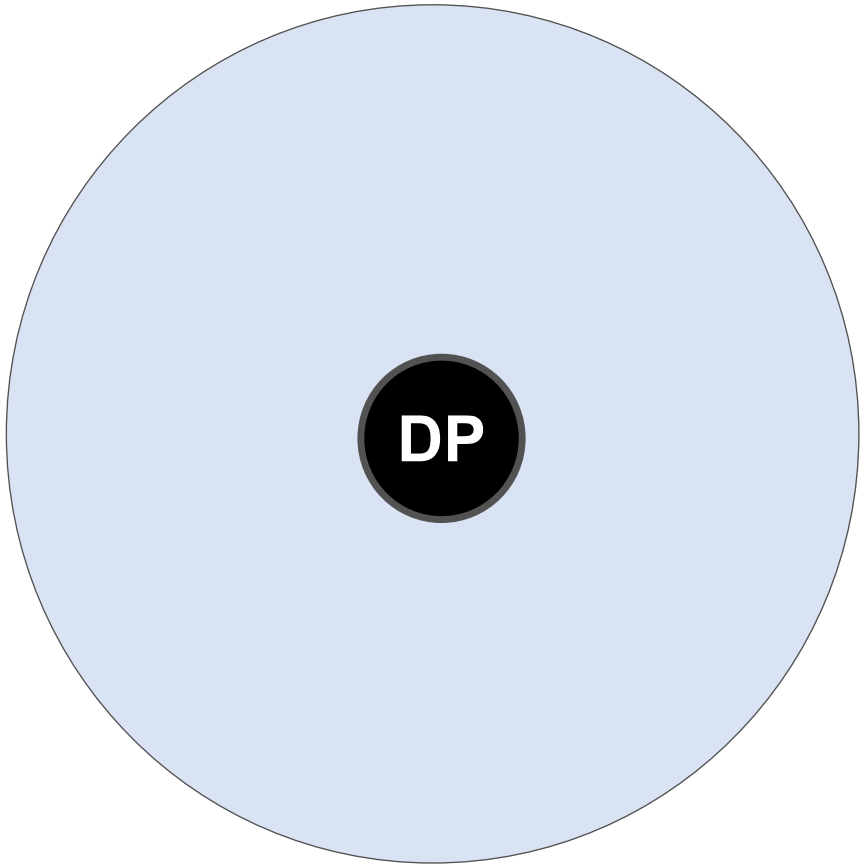
Physical Signal Routing enables more efficient beam alignment

Can both Transmit at the same time

Many-to-Many Beam Alignment

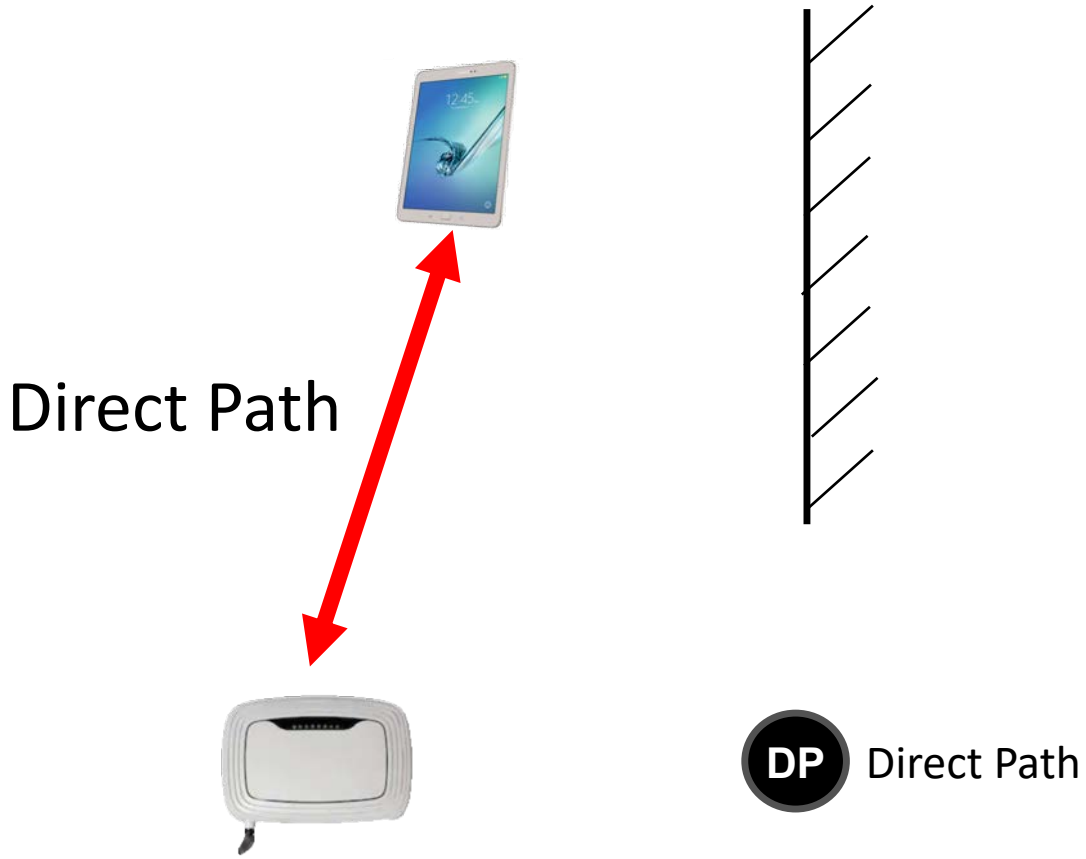
Conflict Graphs

AP-Client Pair 1



Super Node

AP-Client Pair 1



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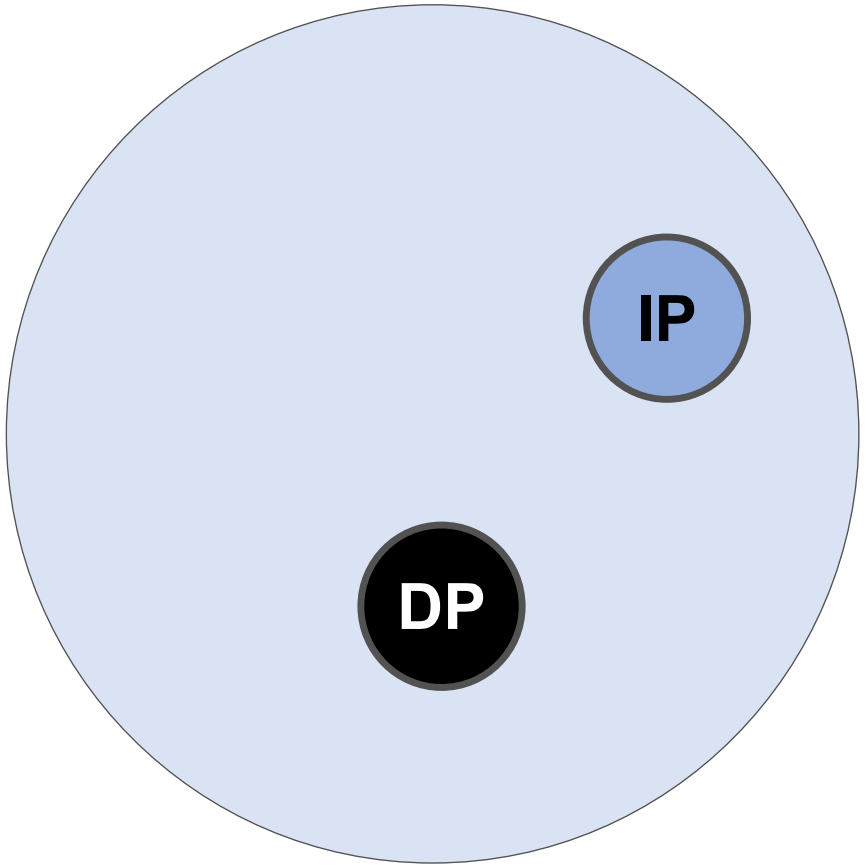

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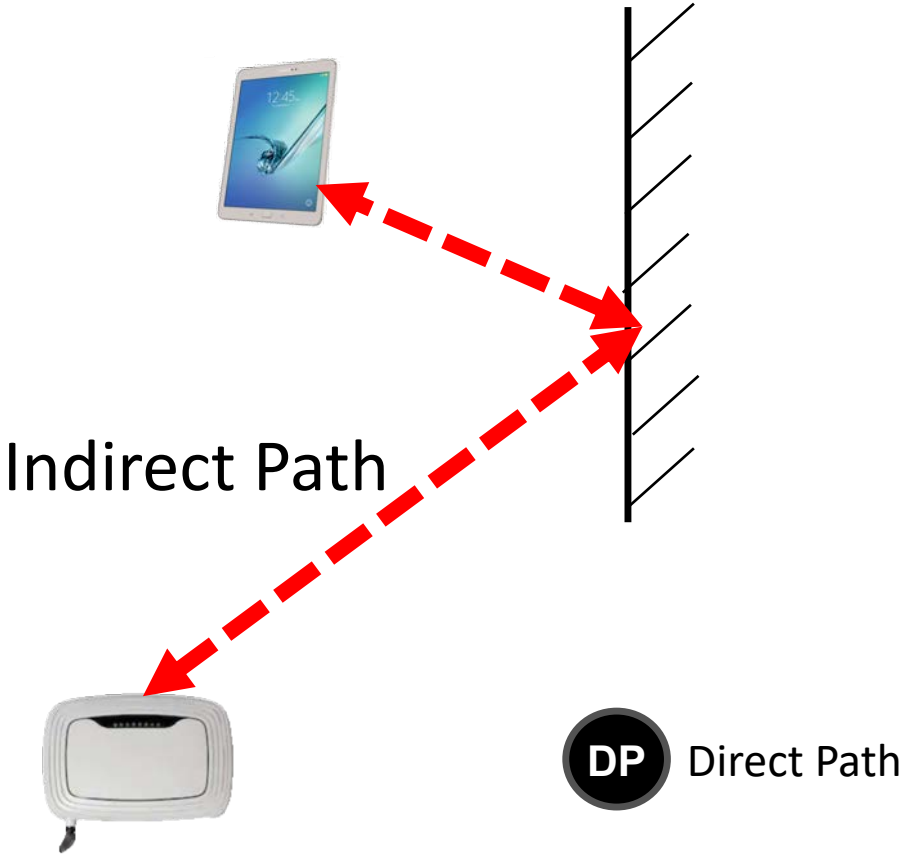

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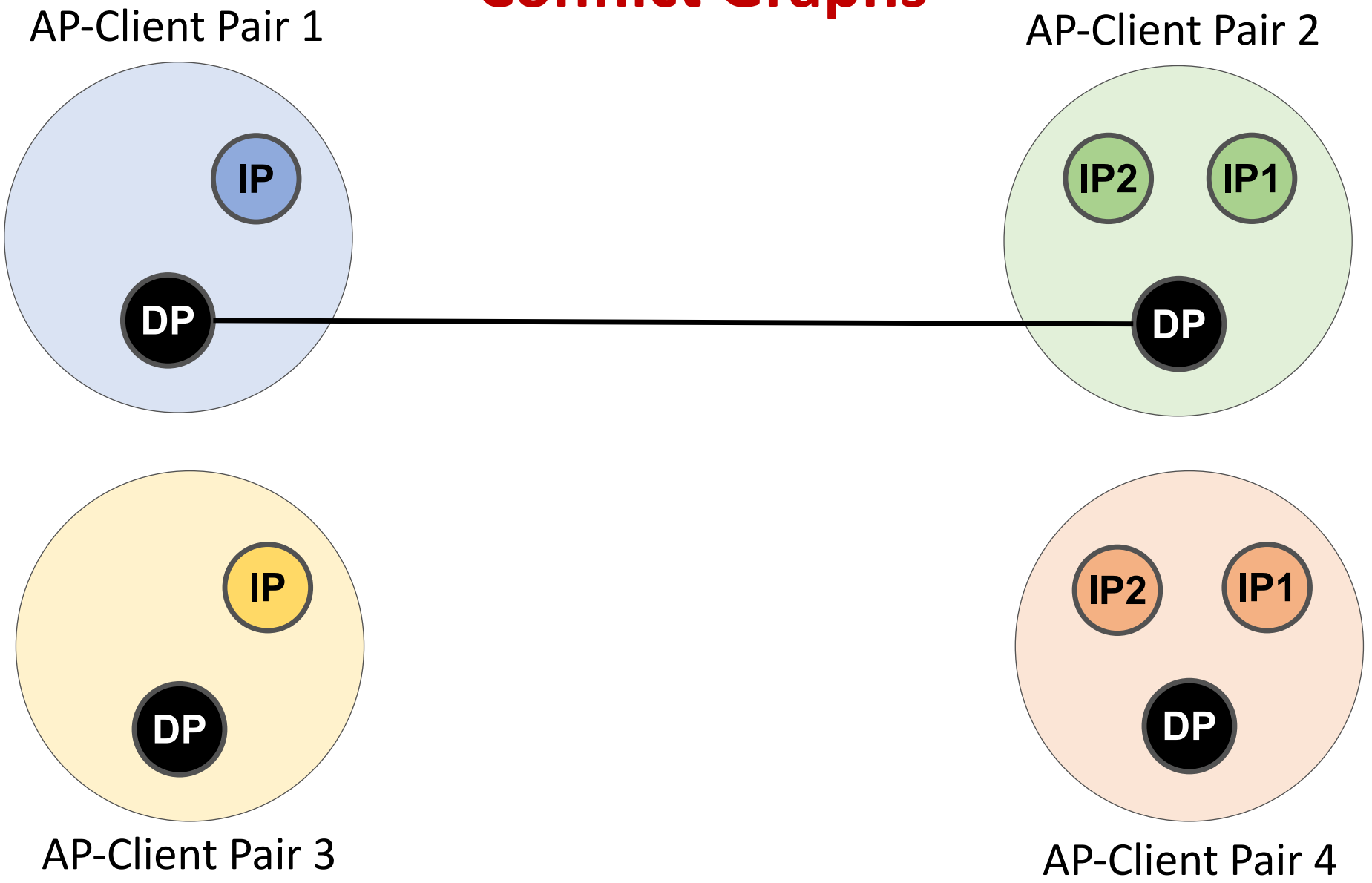

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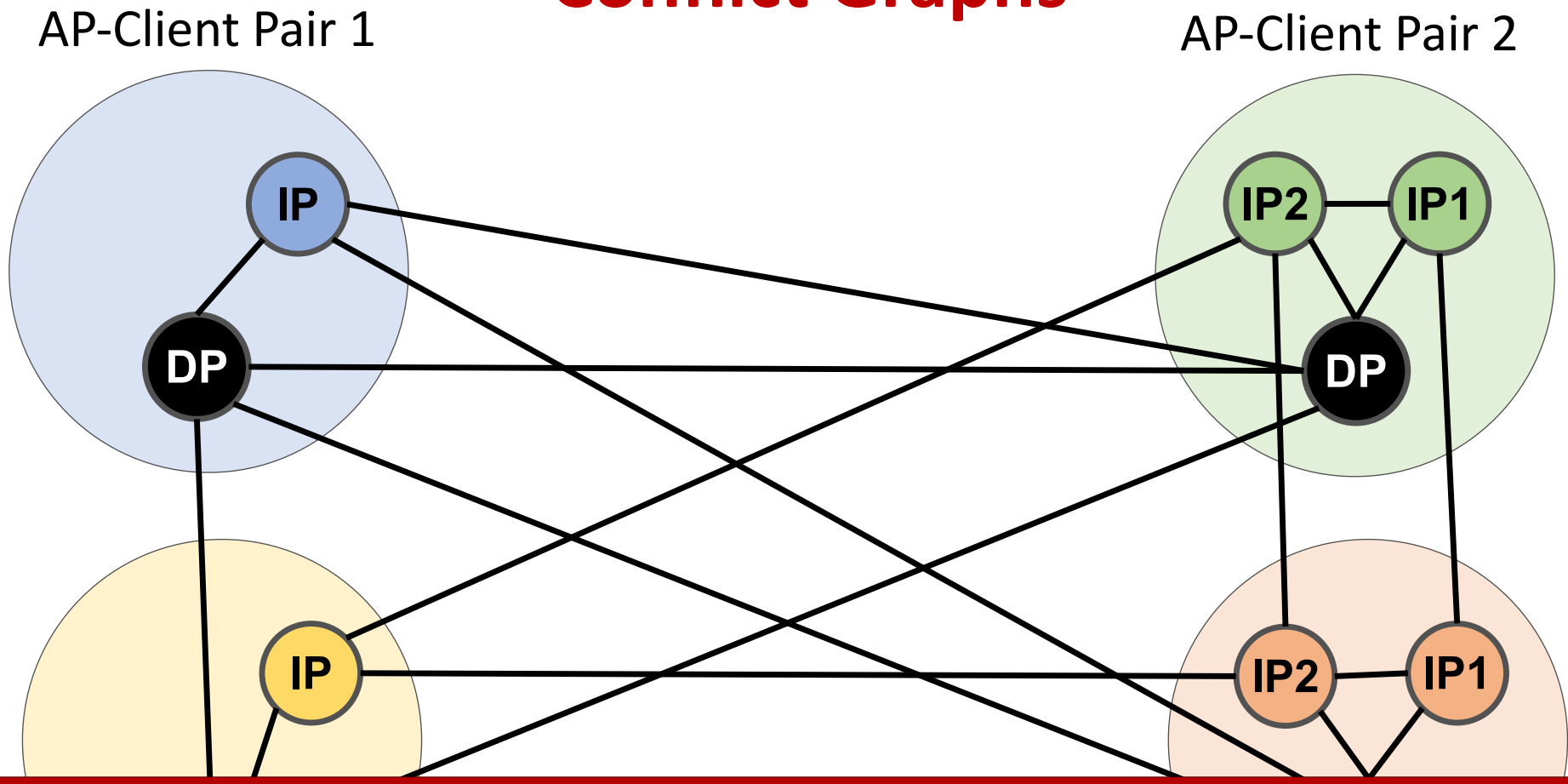
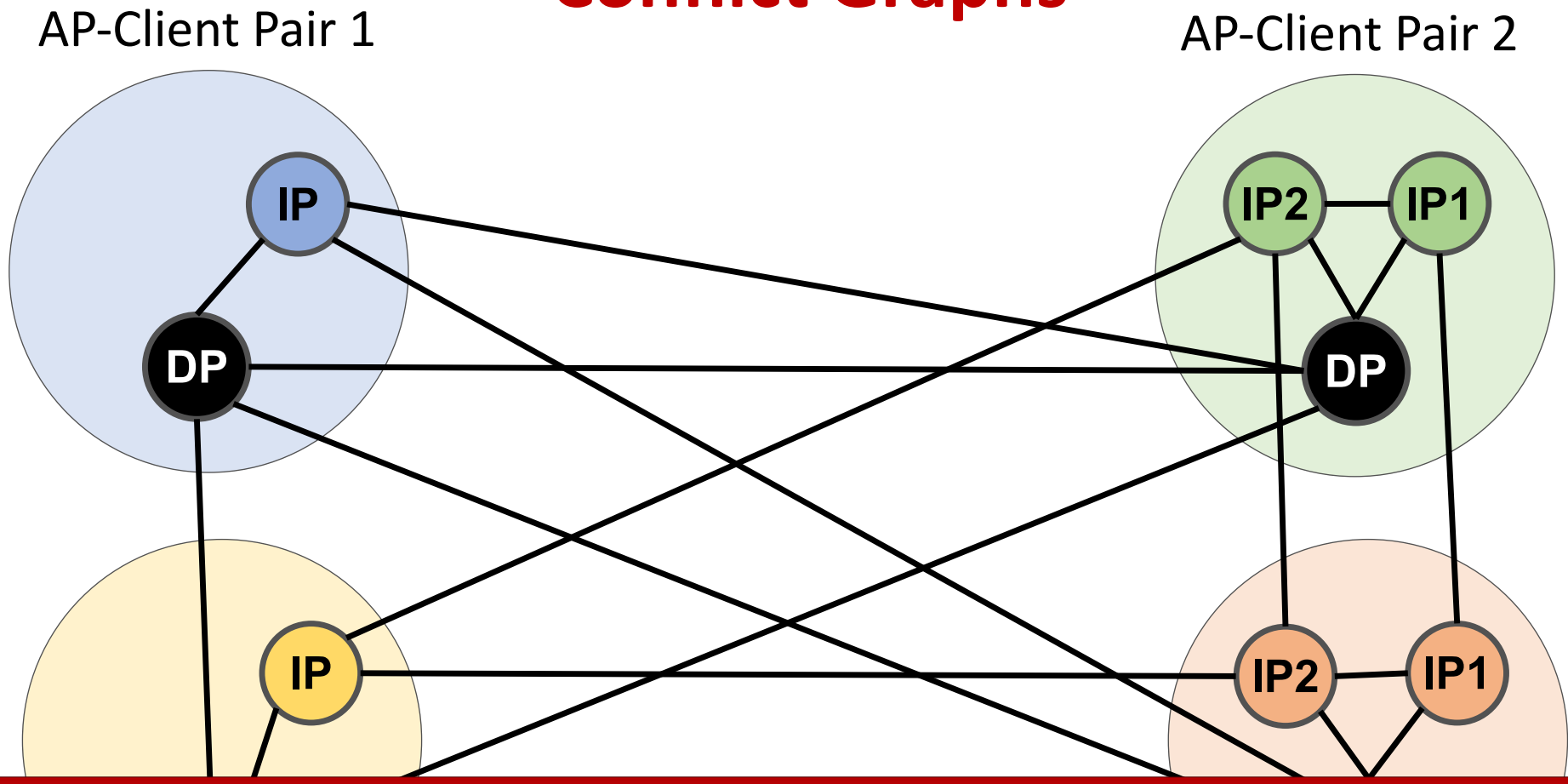


Maximum Weighted Independent Set

Many-to-Many Beam Alignment

Conflict Graphs



Maximum Weighted Independent Set → NP-Hard

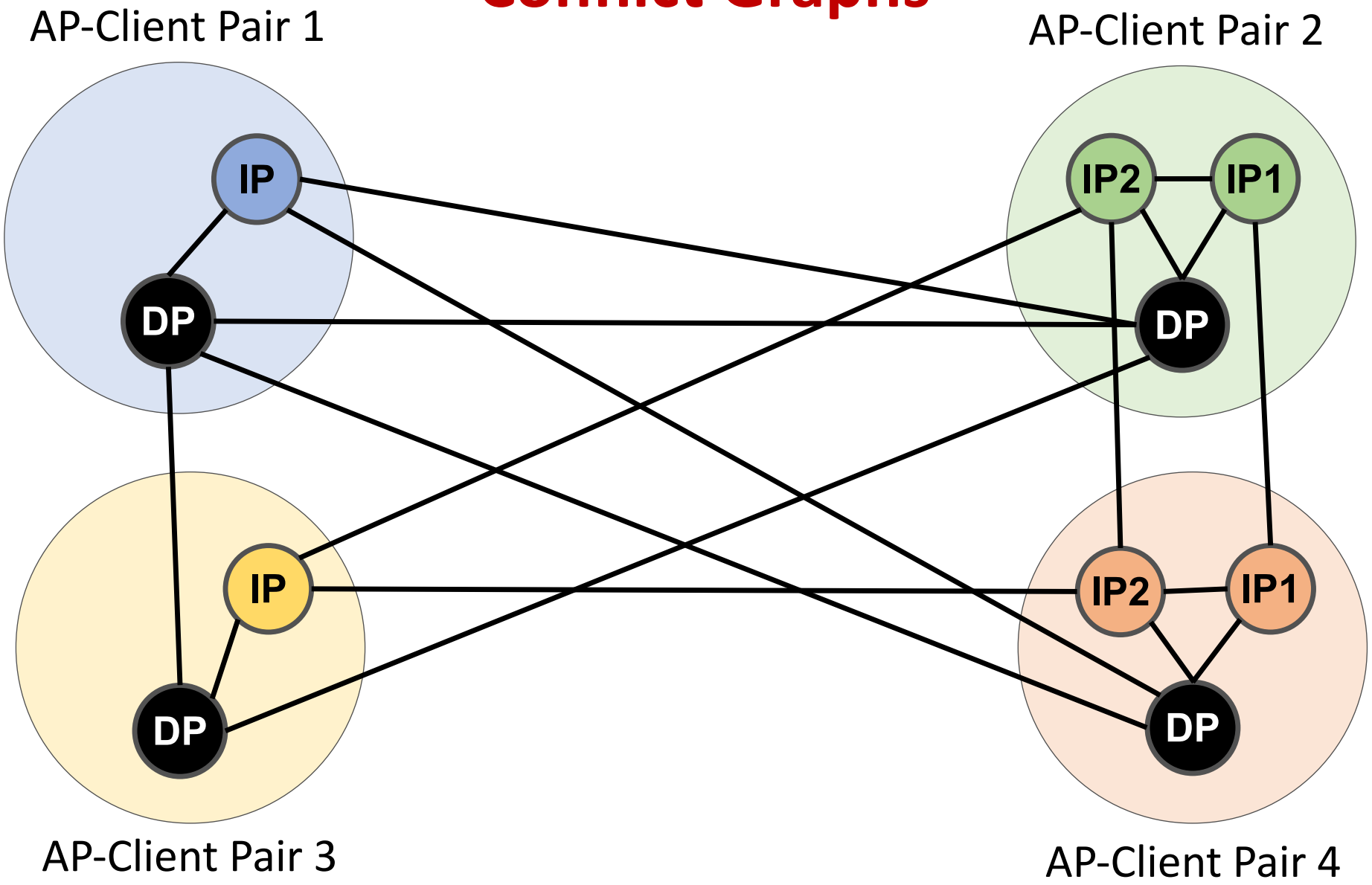
Many-to-Many Beam Alignment

Key Idea

- Direct paths are highest data rate paths
  → Prioritize routing along direct path
- Decouple routing along direct and indirect paths

Many-to-Many Beam Alignment

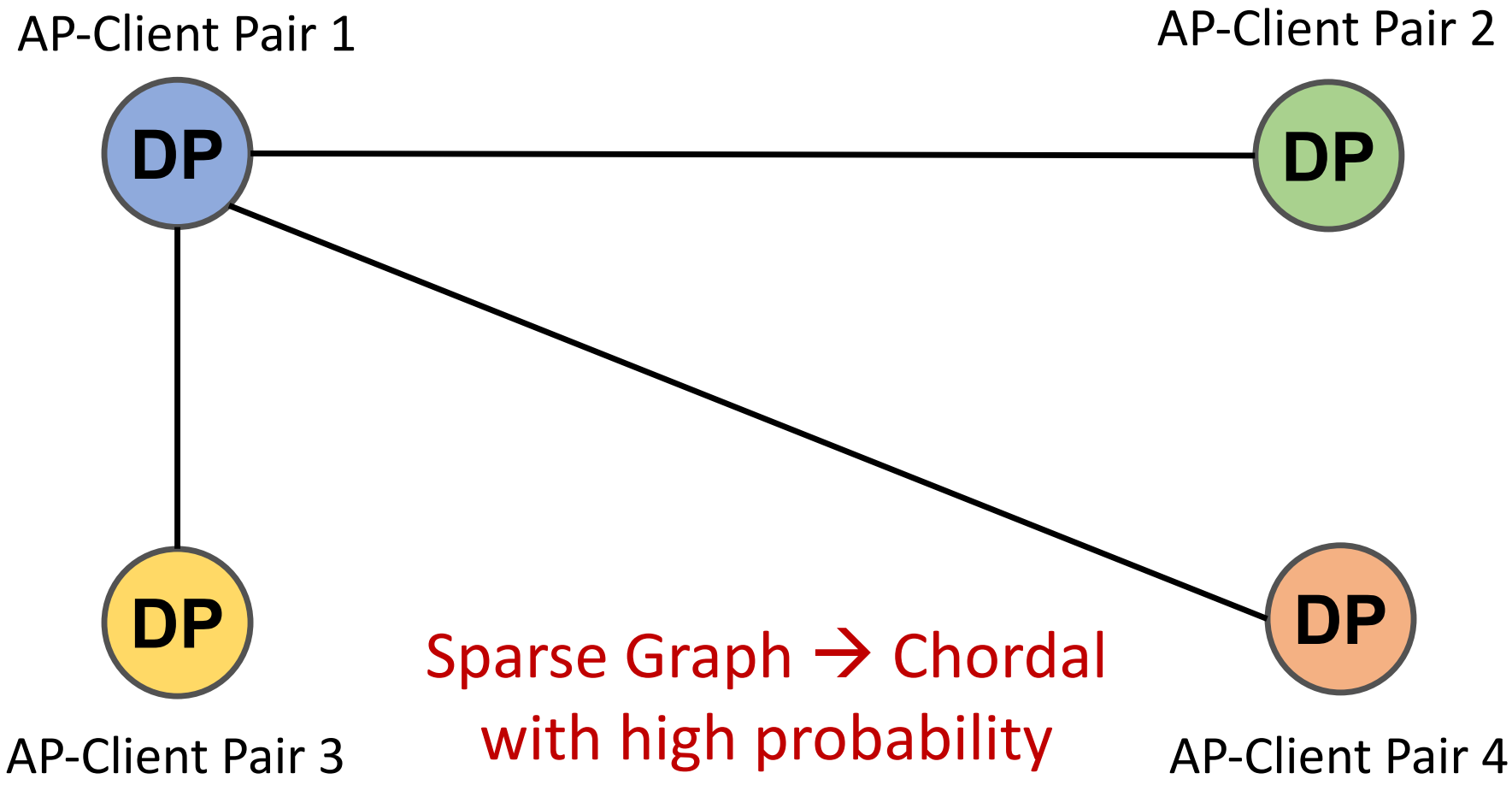
Conflict Graphs



Many-to-Many Beam Alignment

Conflict Graphs

Direct Path Conflict Graphs



Many-to-Many Beam Alignment

Fairness among links

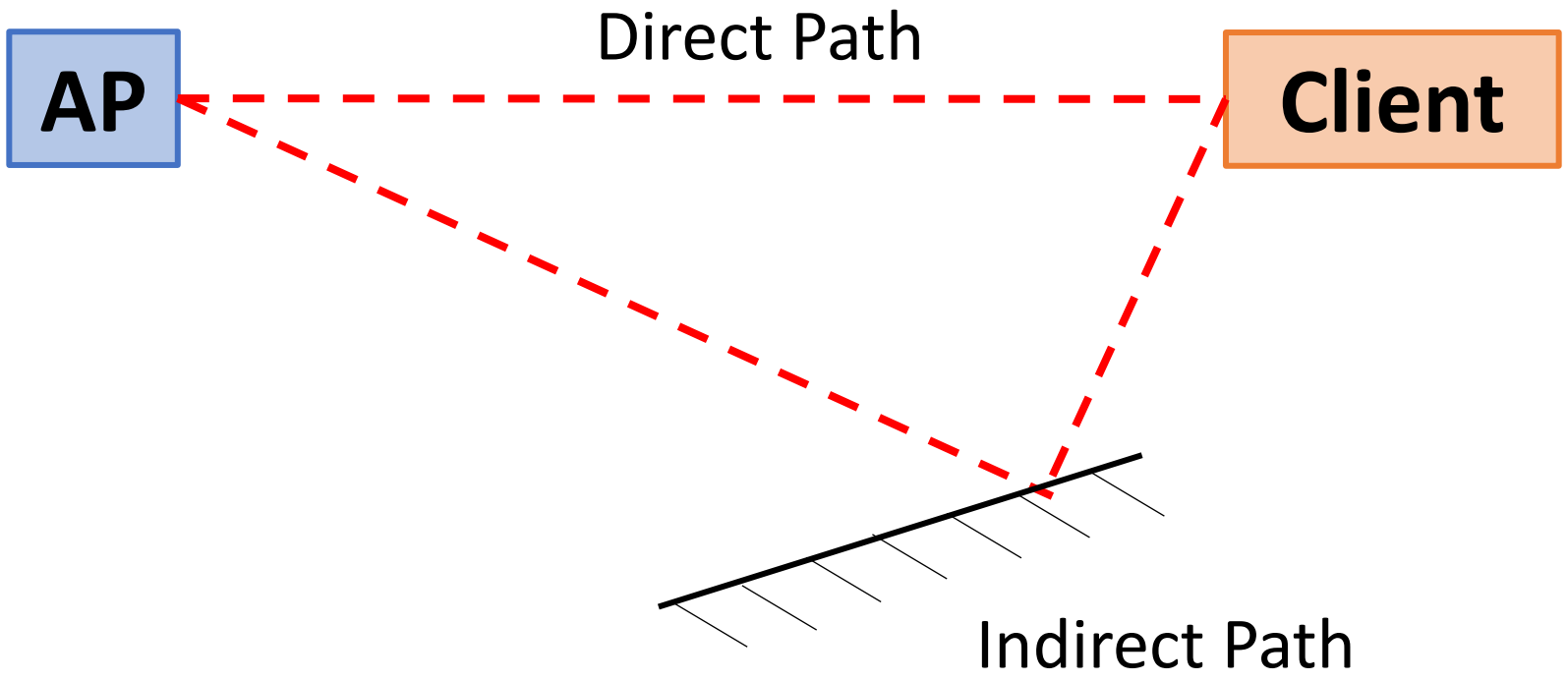
Create Multiple Many-to-Many Alignments

1. Maximize number of nodes that transmit simultaneously
2. Ensure each client its fair share on highest data rate path

Many-to-Many Beam Alignment

How to quickly learn the paths and interference patterns to adapt the alignment?

Learn paths between nodes



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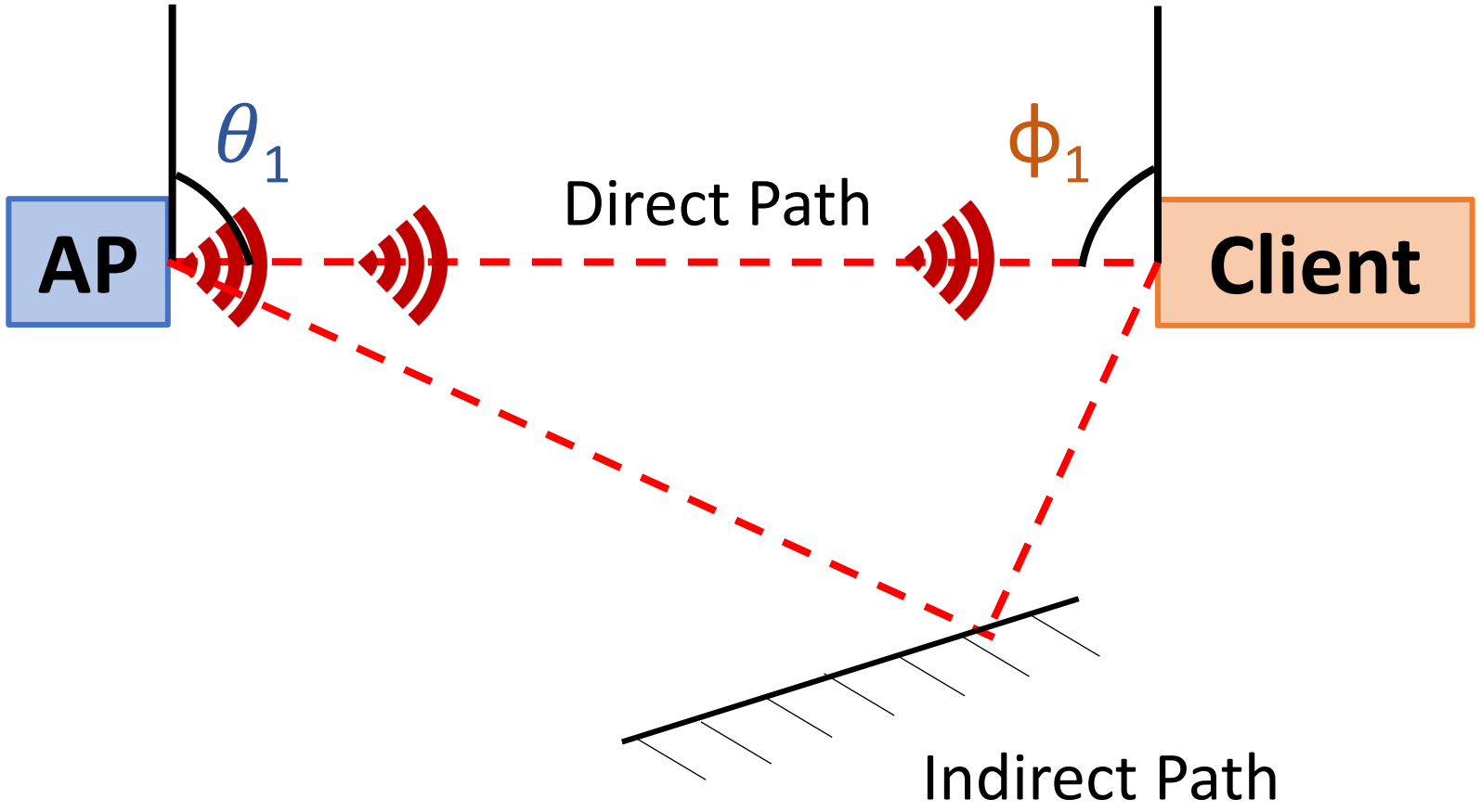

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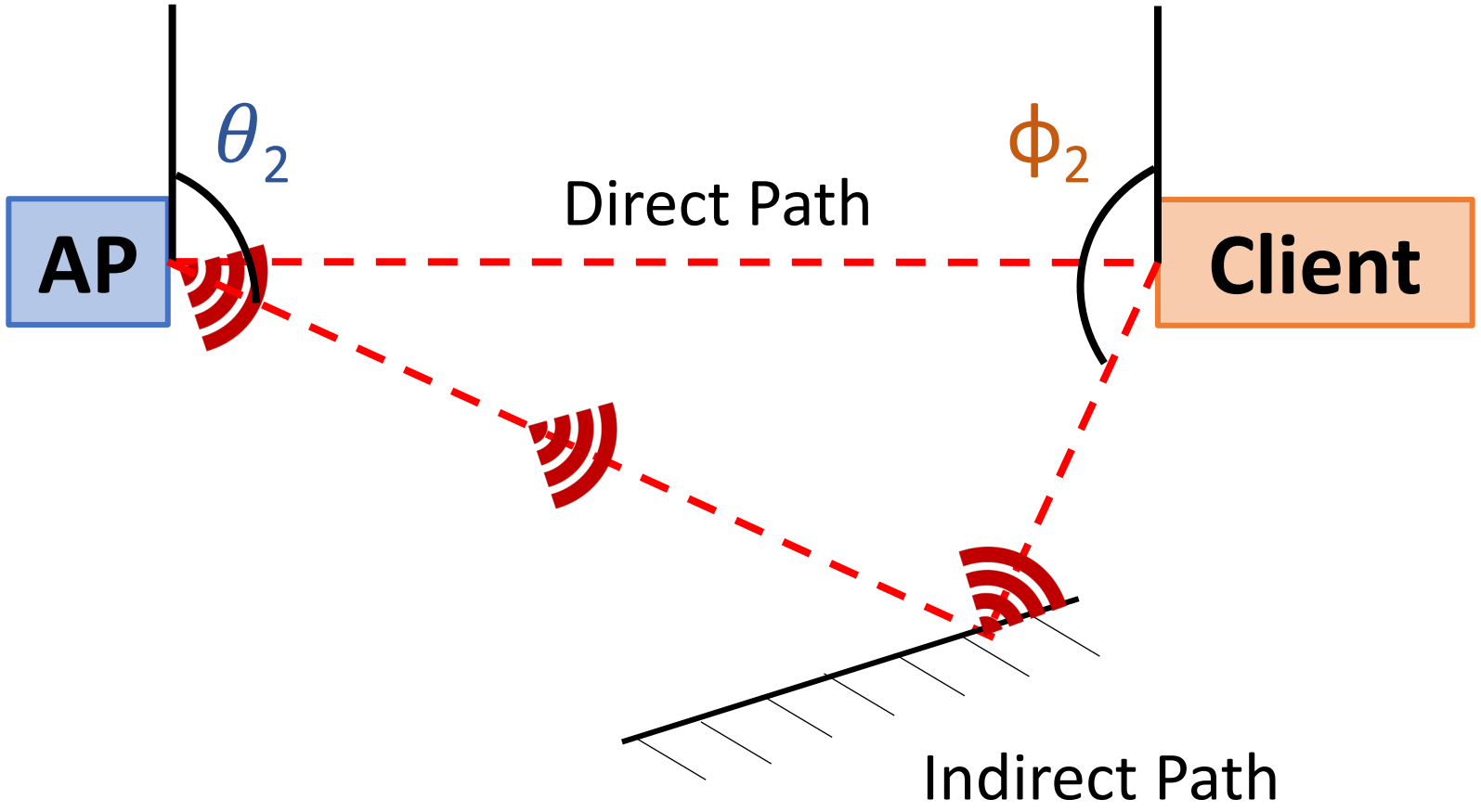

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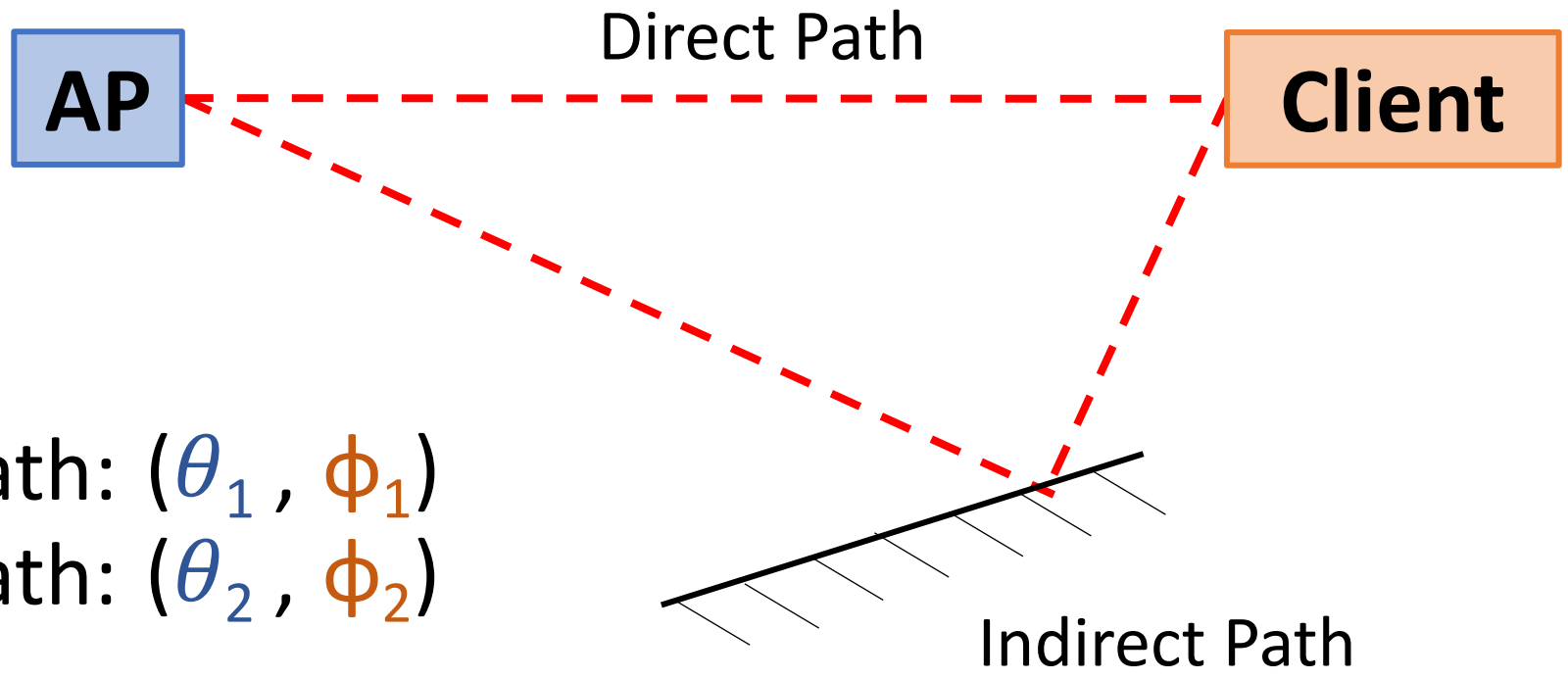
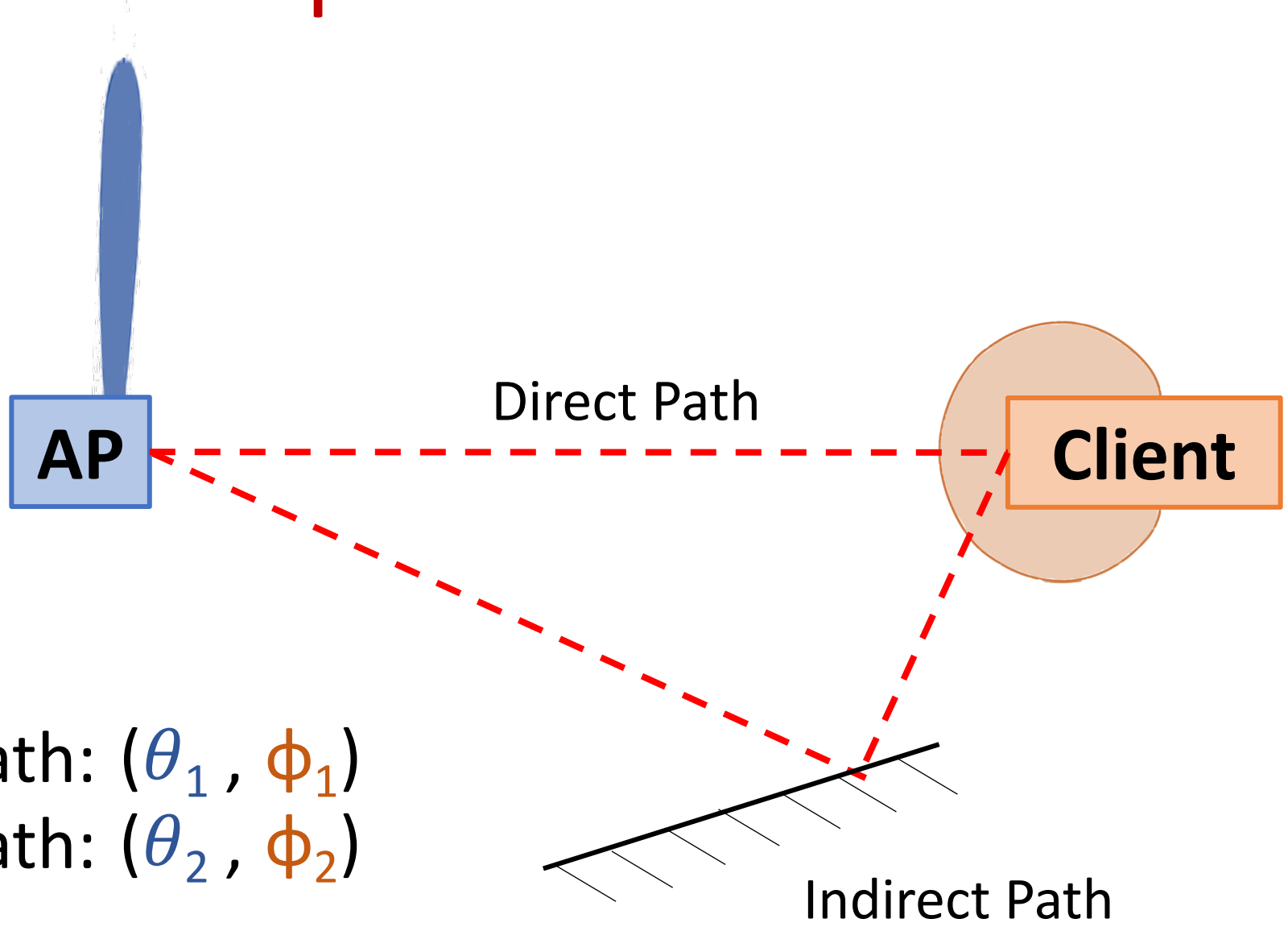


Direct Path: (θ_1, ϕ_1)

Indirect Path: (θ_2, ϕ_2)

Learn paths between nodes



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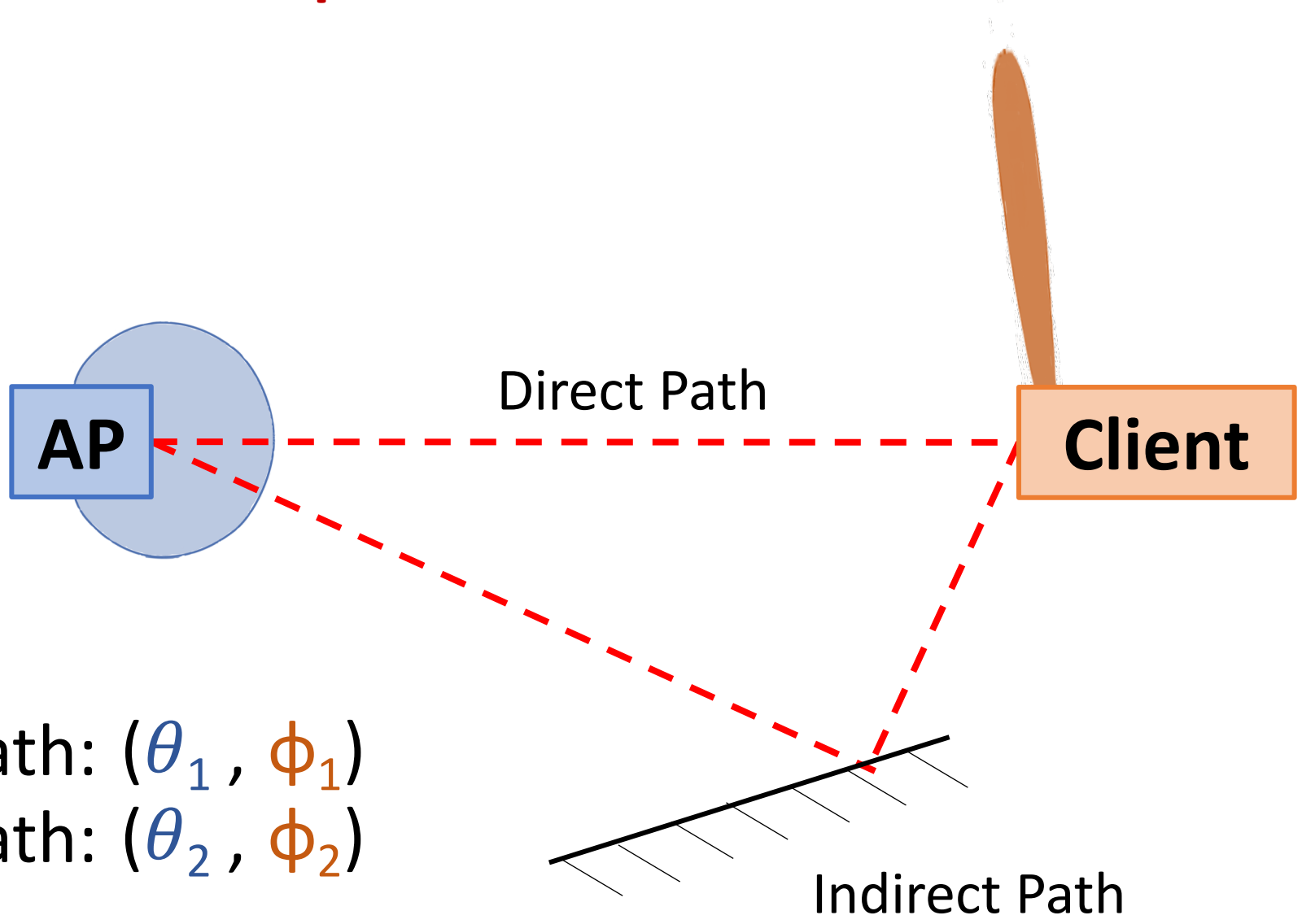

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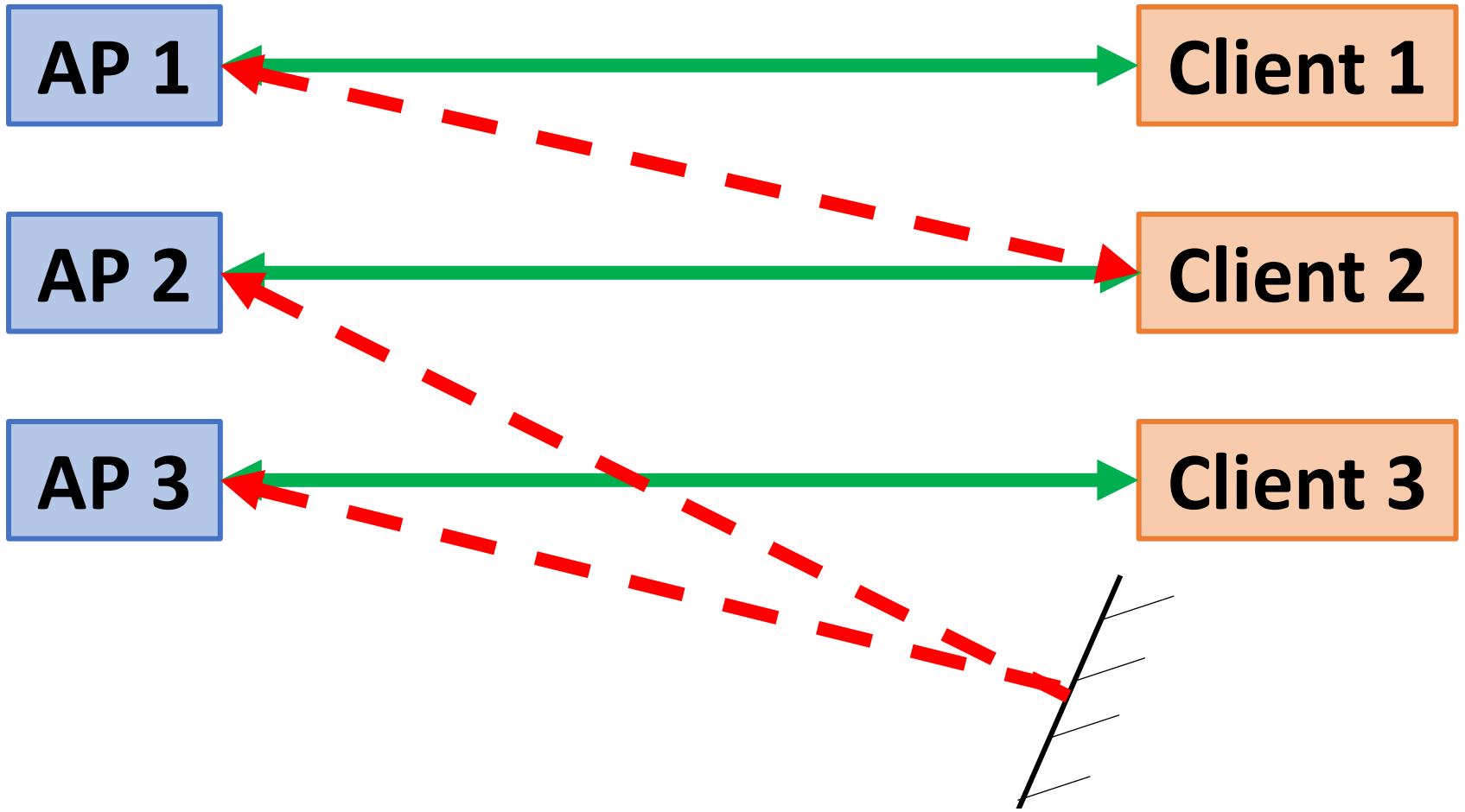


Learn paths between nodes

Learn paths between nodes

AP 1

AP 2

AP 3

AP N

Client 1

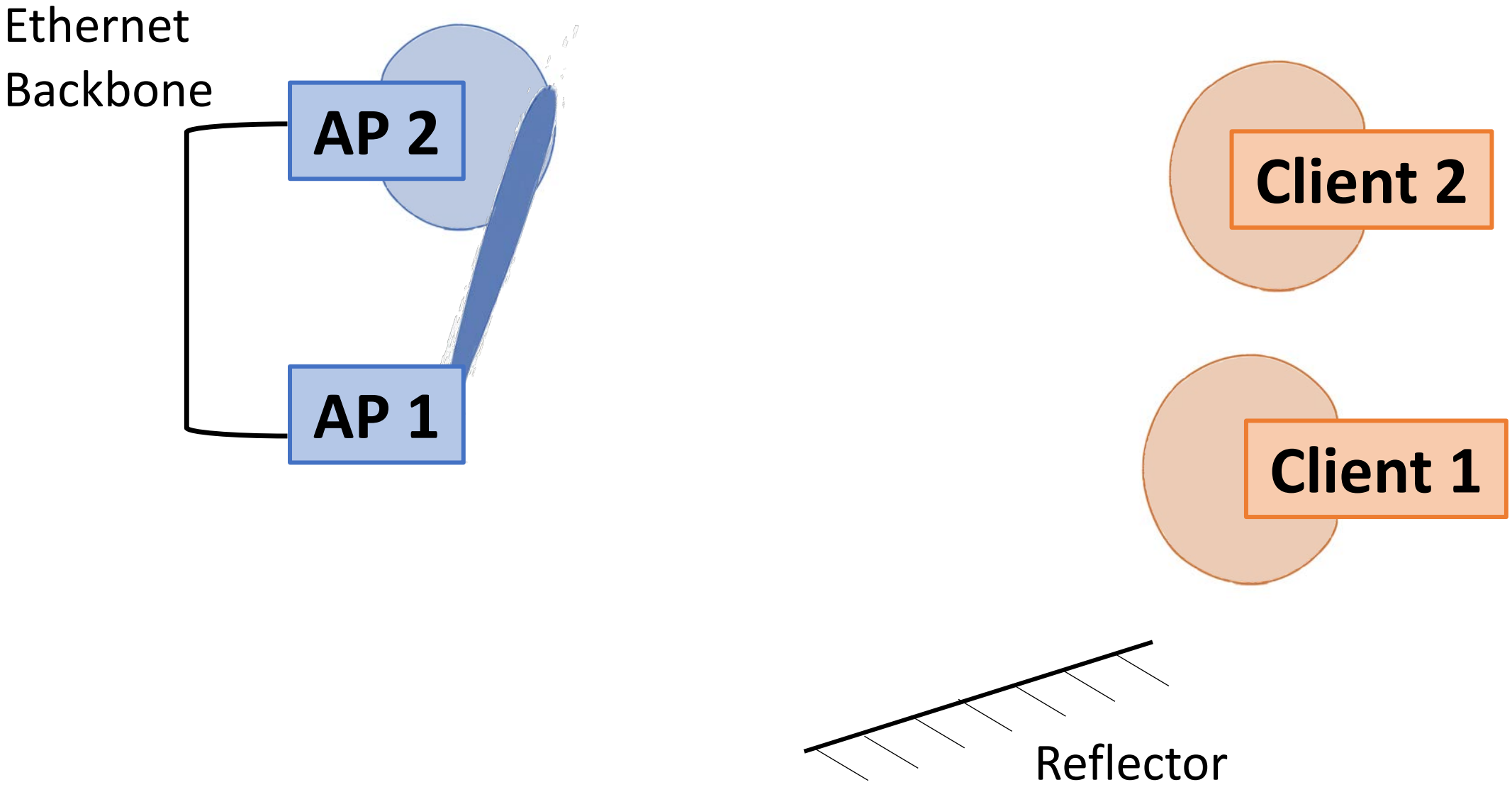
Client 2

Client 3

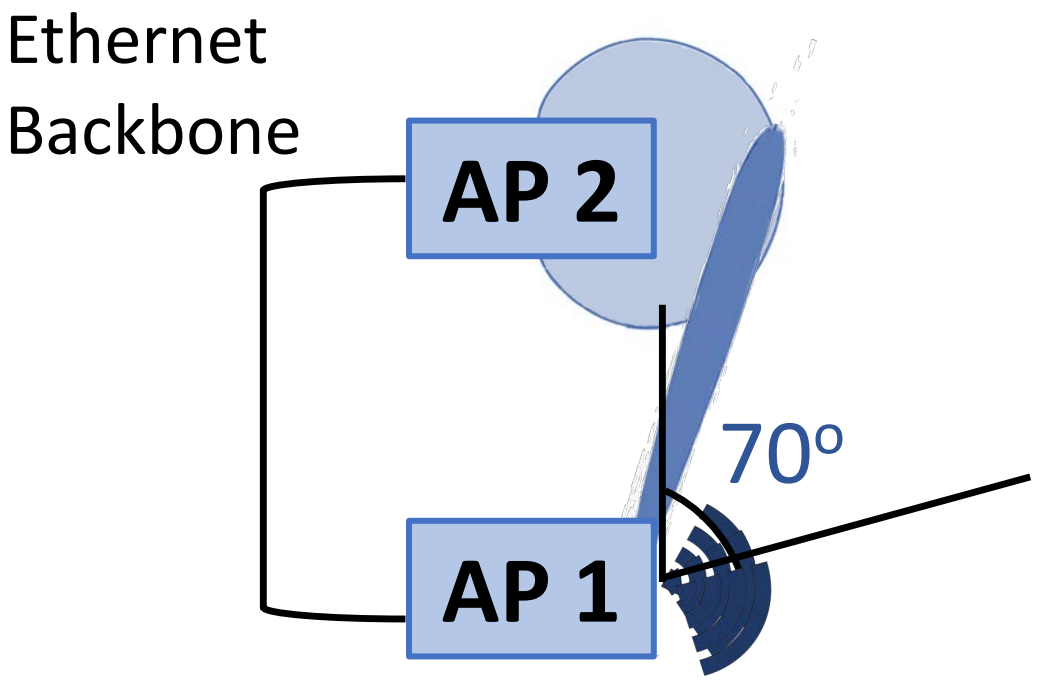
Client N

Overhead scales as $O(N^2)$ for N links

Learn paths between nodes



Learn paths between node

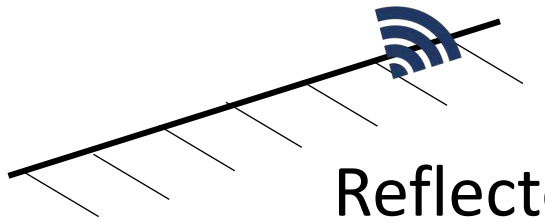


AP1 can align towards me along 70 degree

Clien

AP1 can align towards me along 130 degree

Client 1



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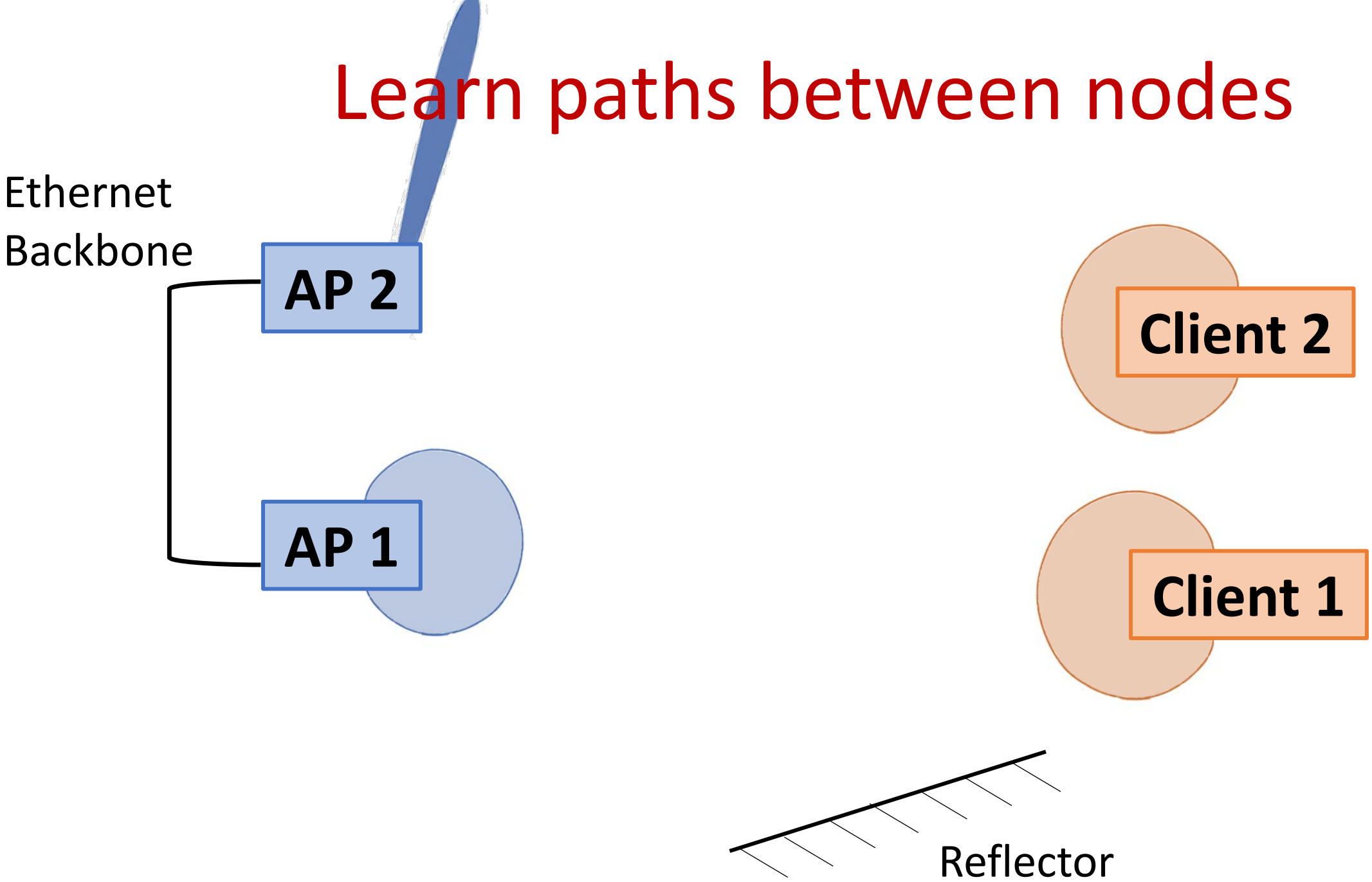

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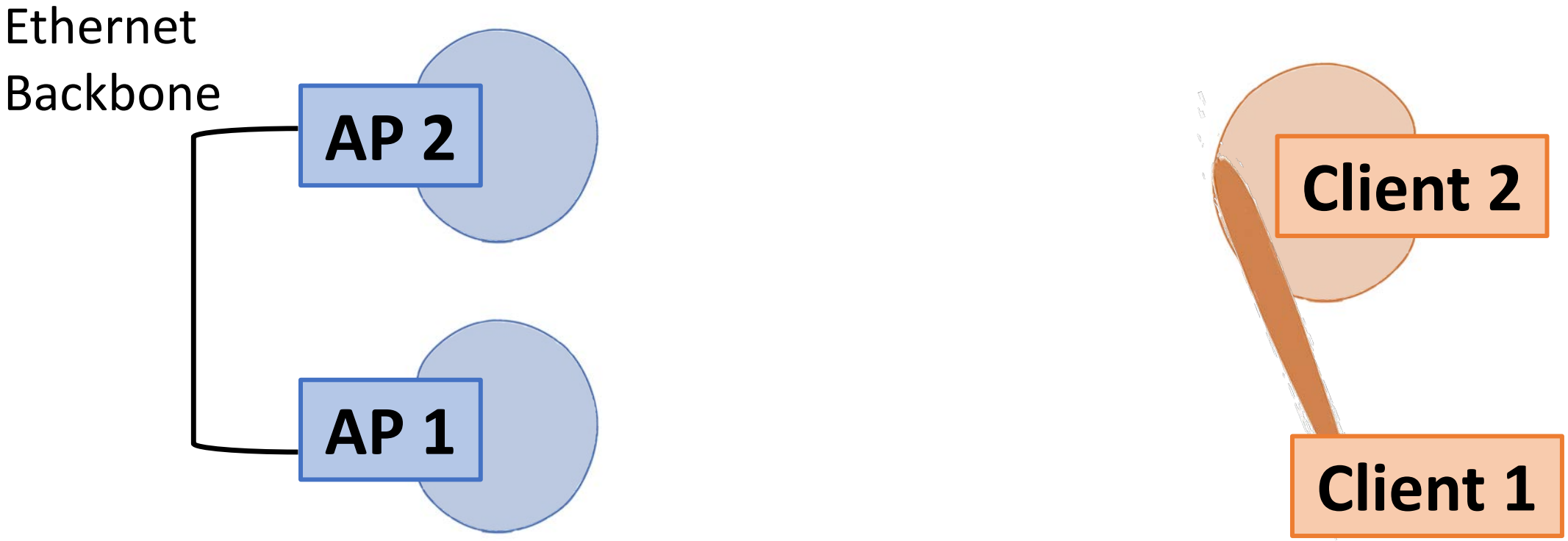

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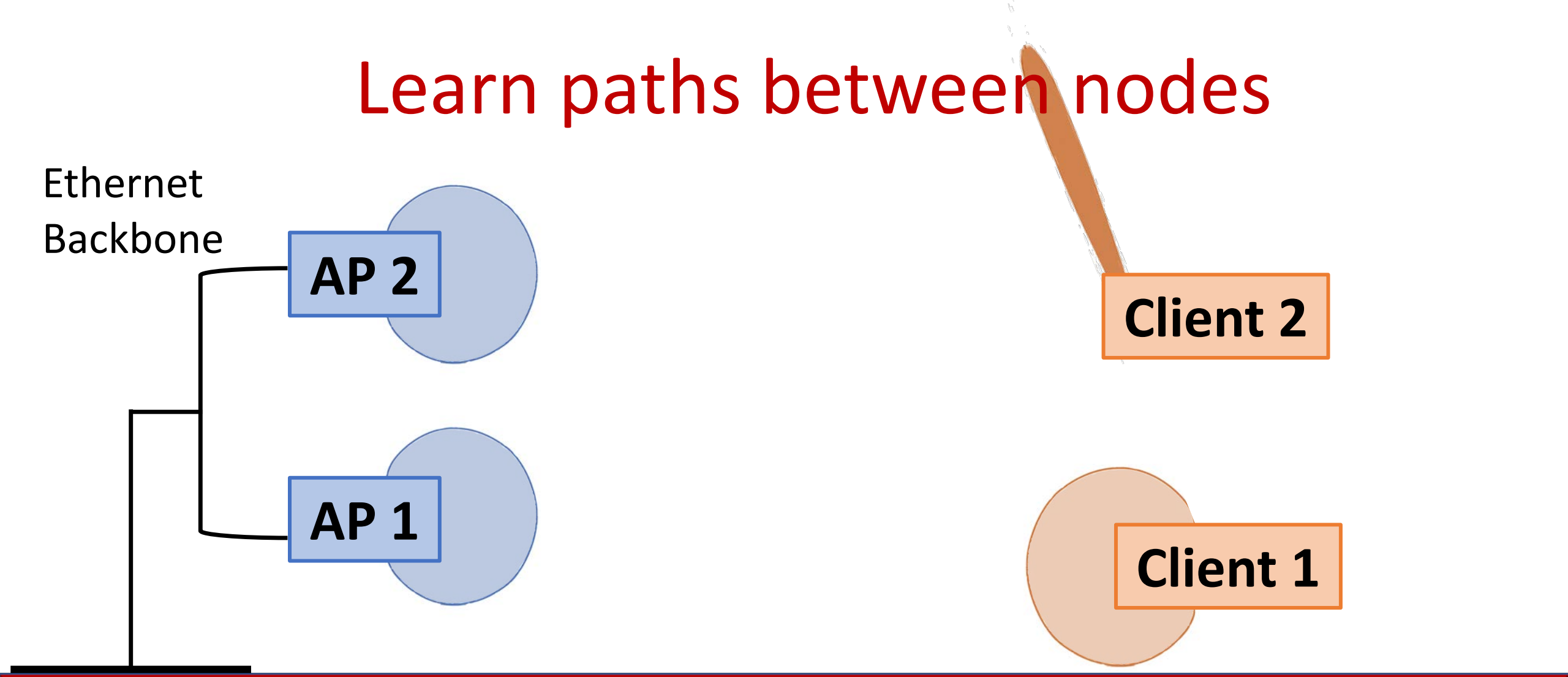
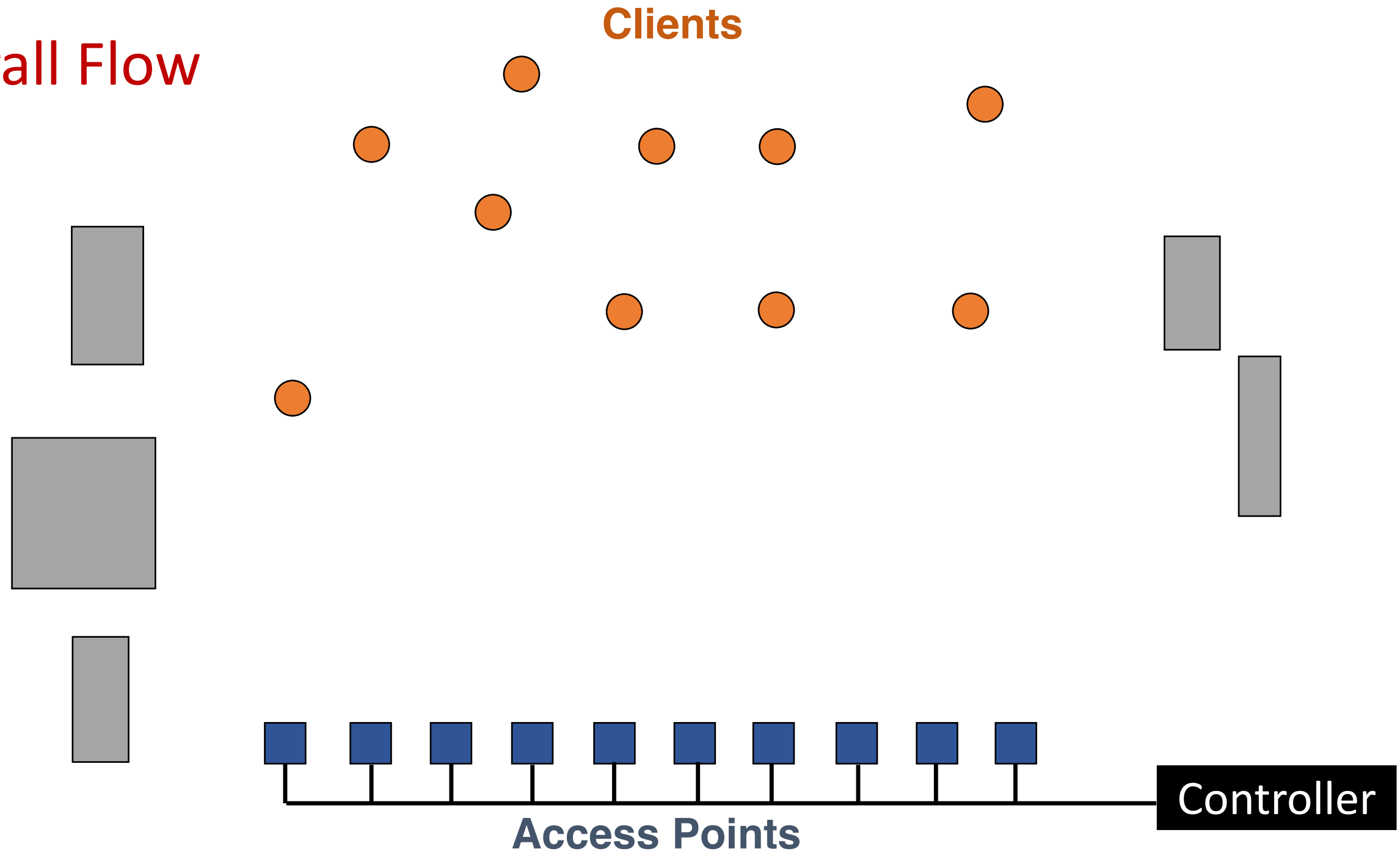


Require only O(N) scans to find all paths between every pair of nodes

Overall Flow



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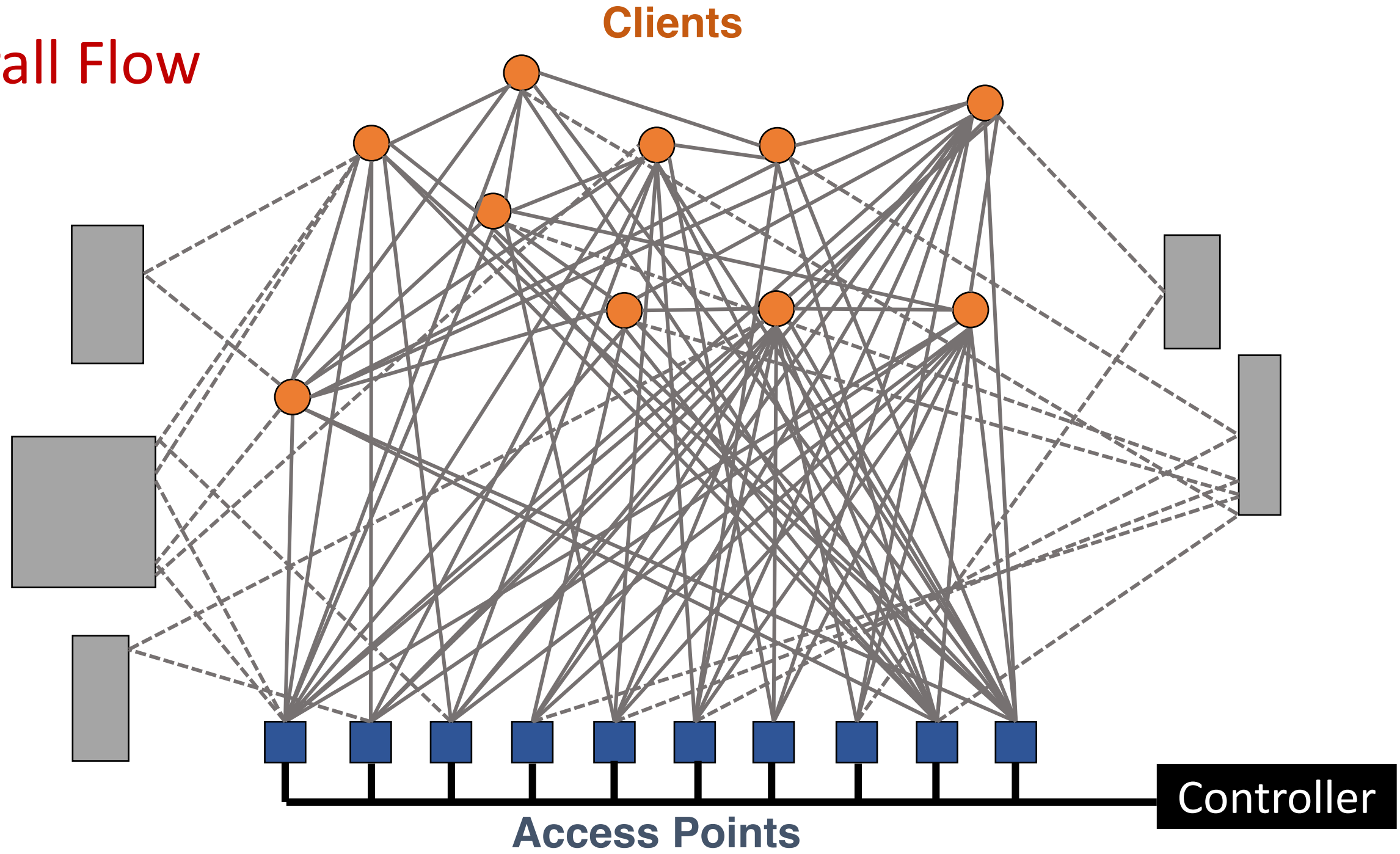
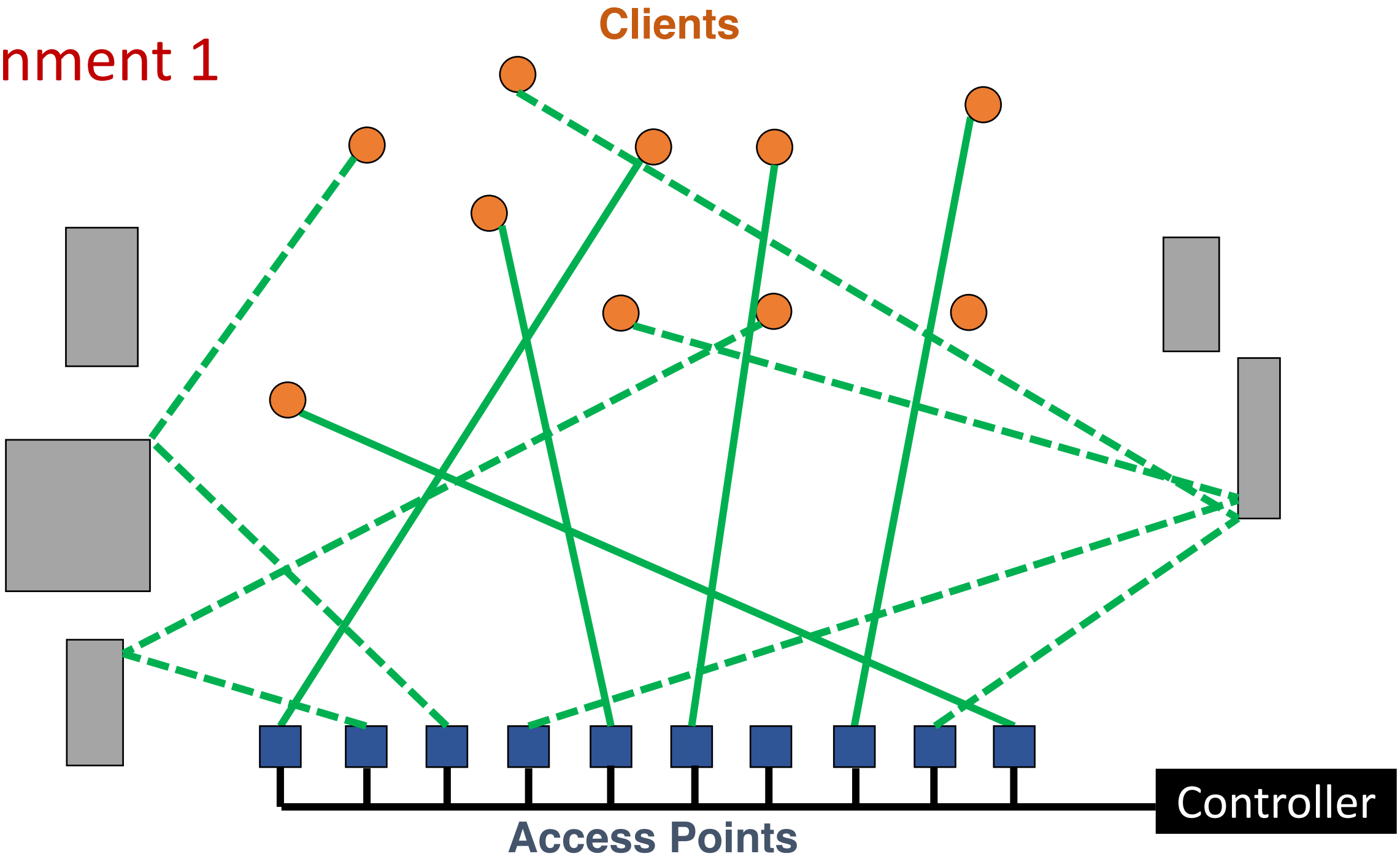
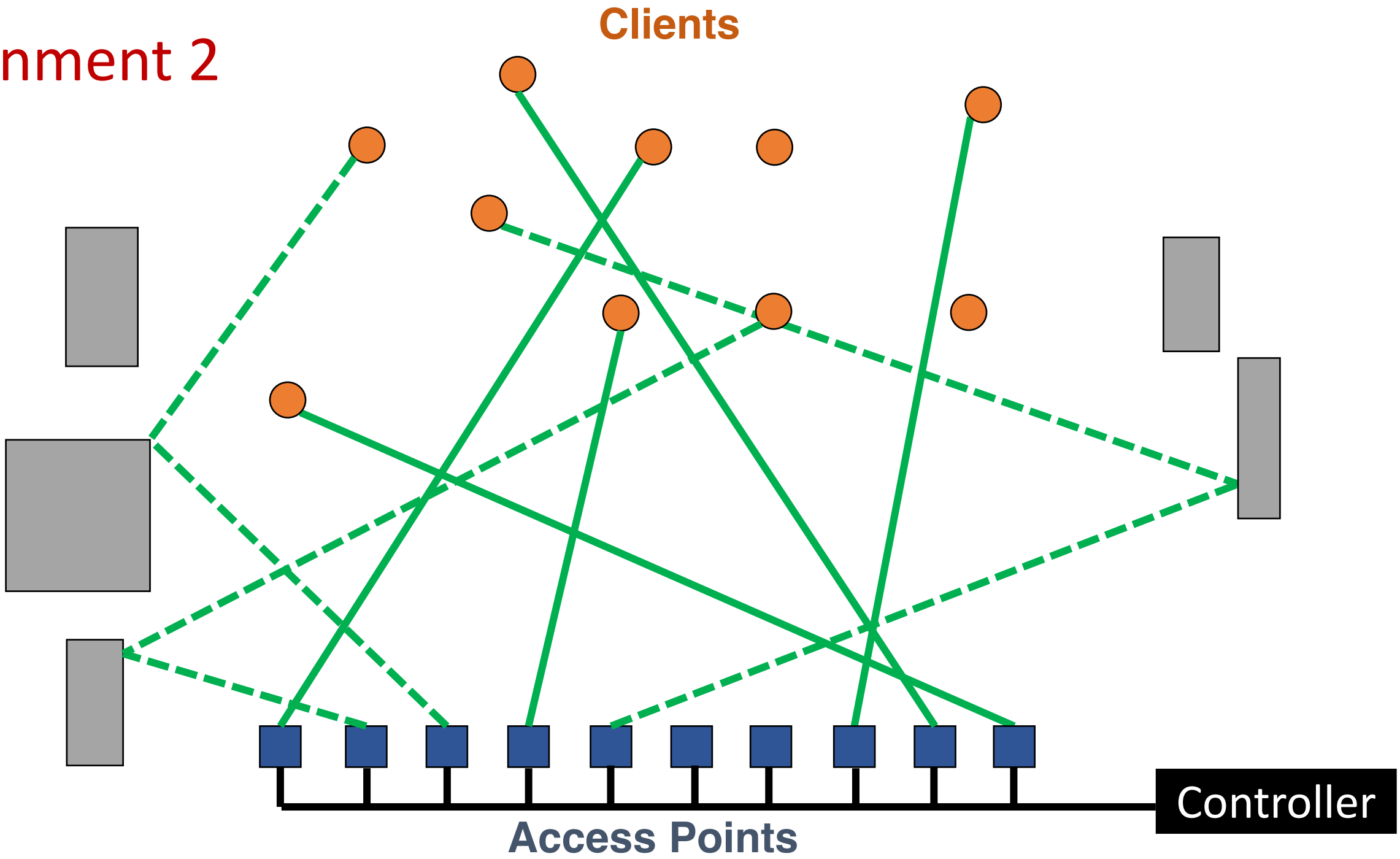


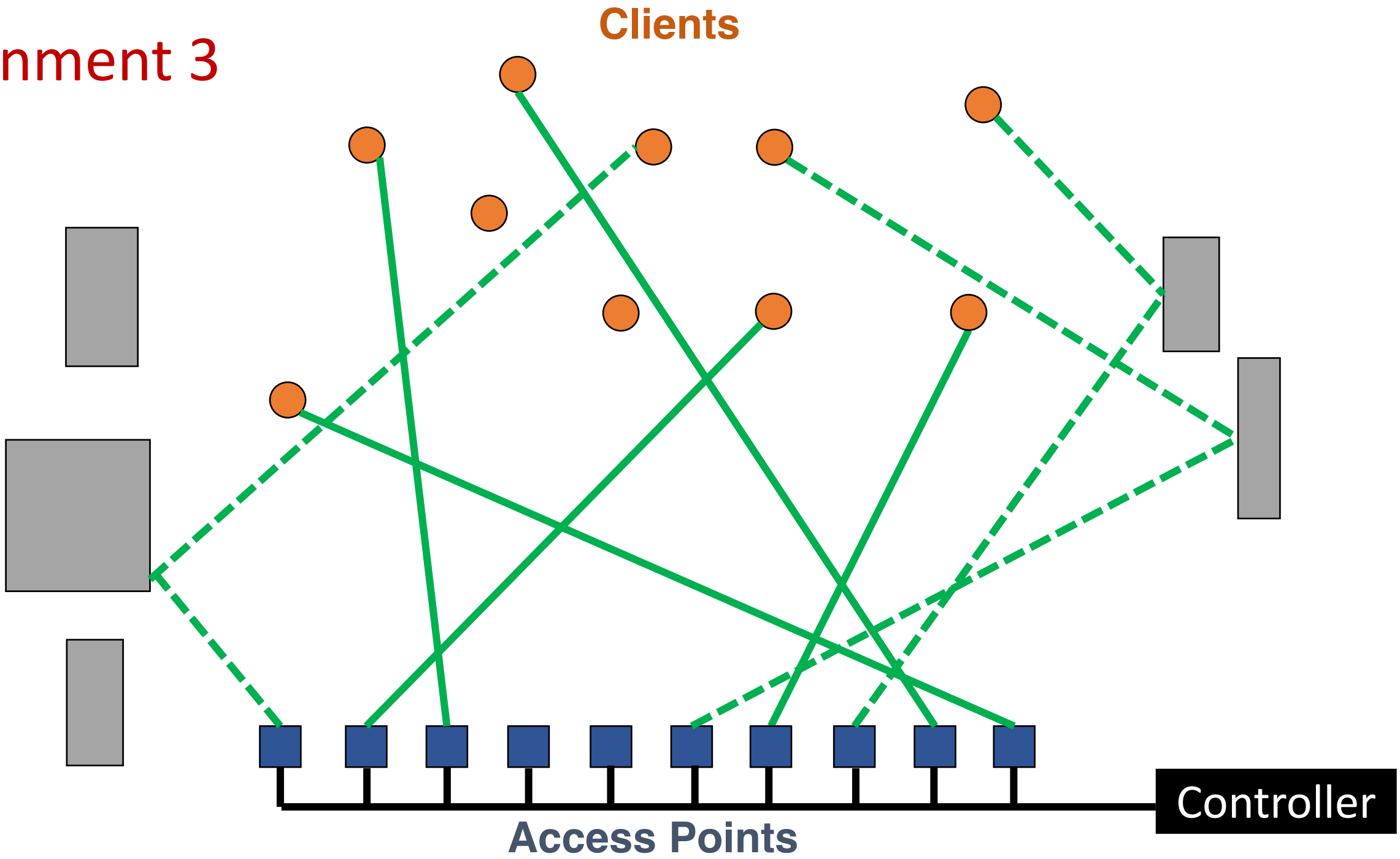
Alignment 1



Alignment 2



Alignment 3



Many-to-Many Beam Alignment

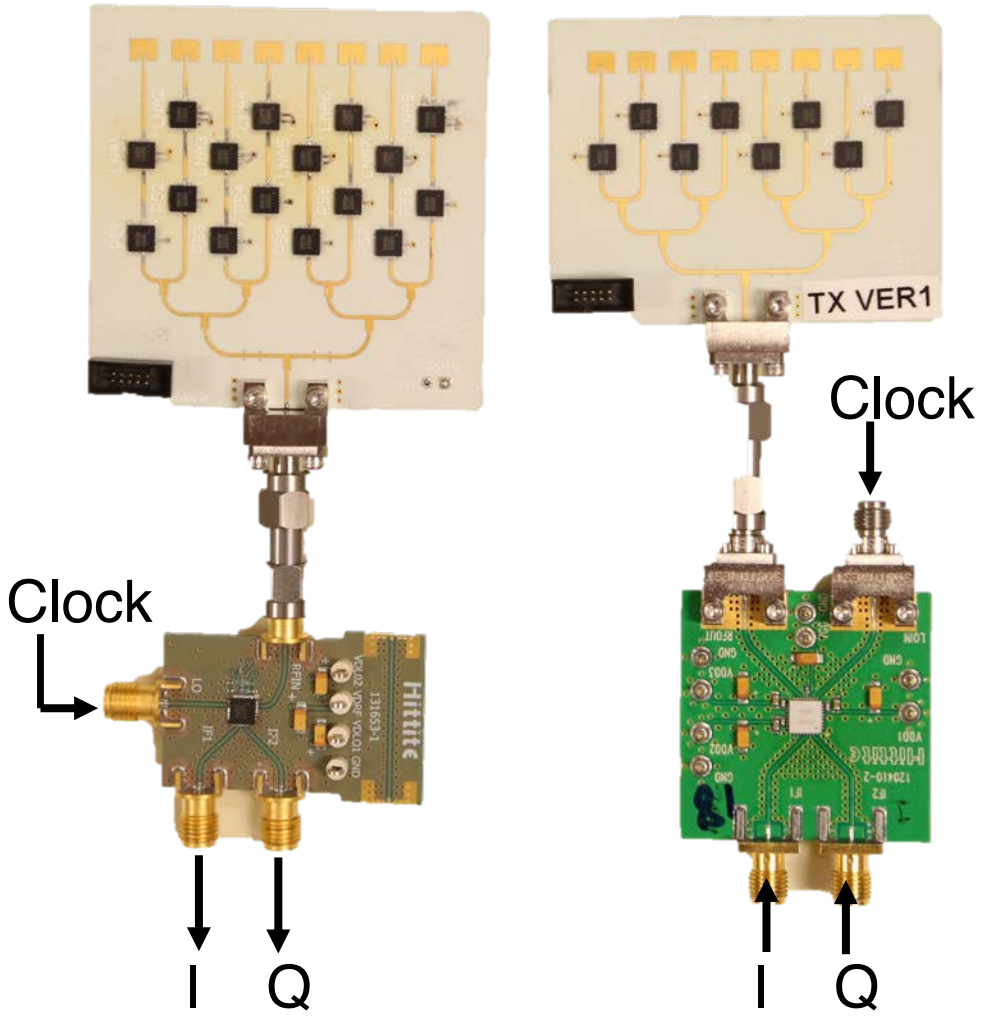
1. How to quickly learn the paths and interference patterns to adapt the alignment?

2. What is the best alignment of beams that densely packs as many links as possible?

BounceNet Evaluation

(a) 60 GHz Radios

(c) 12º and 3º Antennas



(b) 24 GHz radios with phased arrays

BounceNet Evaluation






Evaluation Methodology

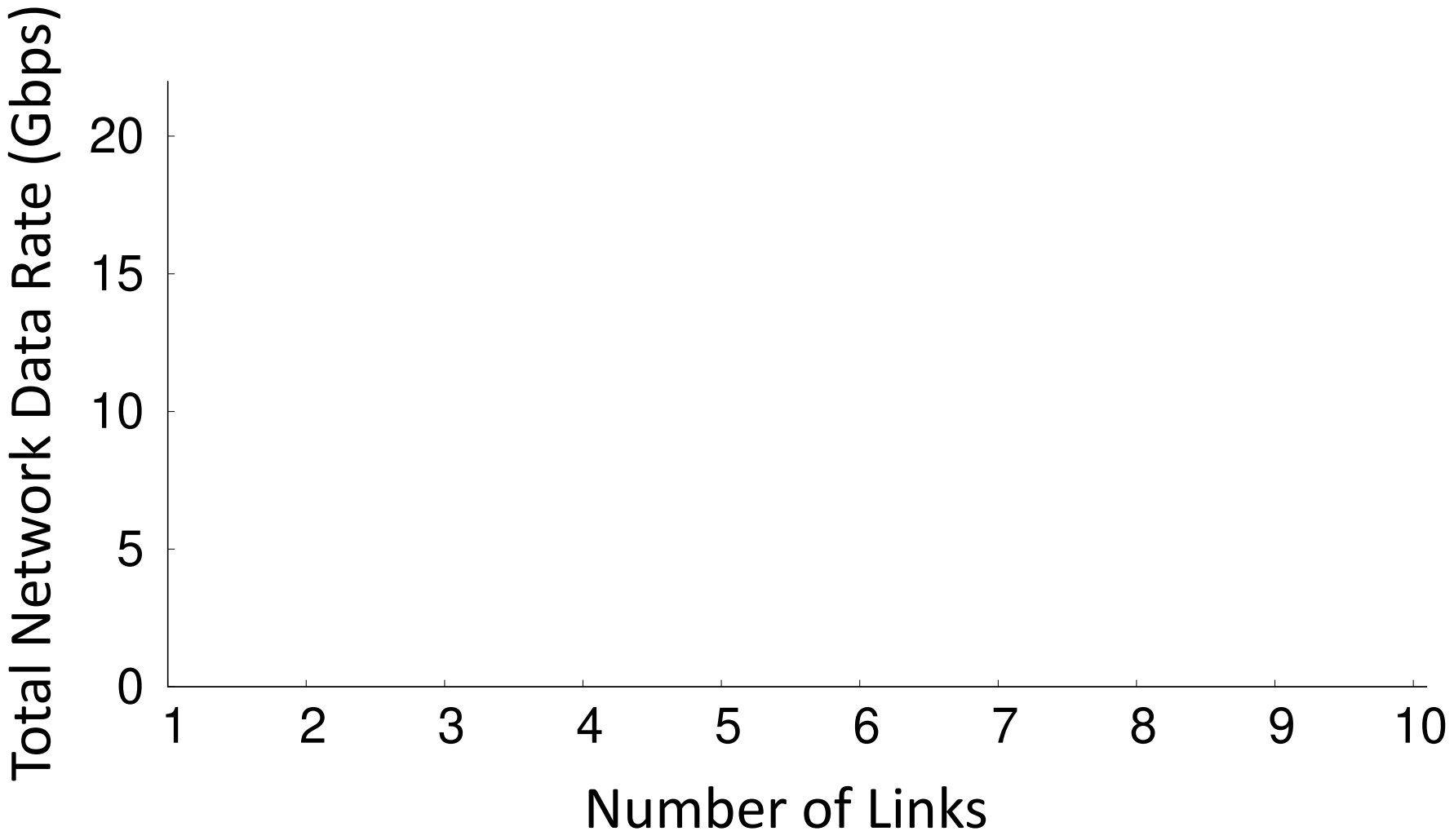
Compare Schemes

1. 802.11ad Standard

2. Baseline: Independent Alignment with Carrier Sense

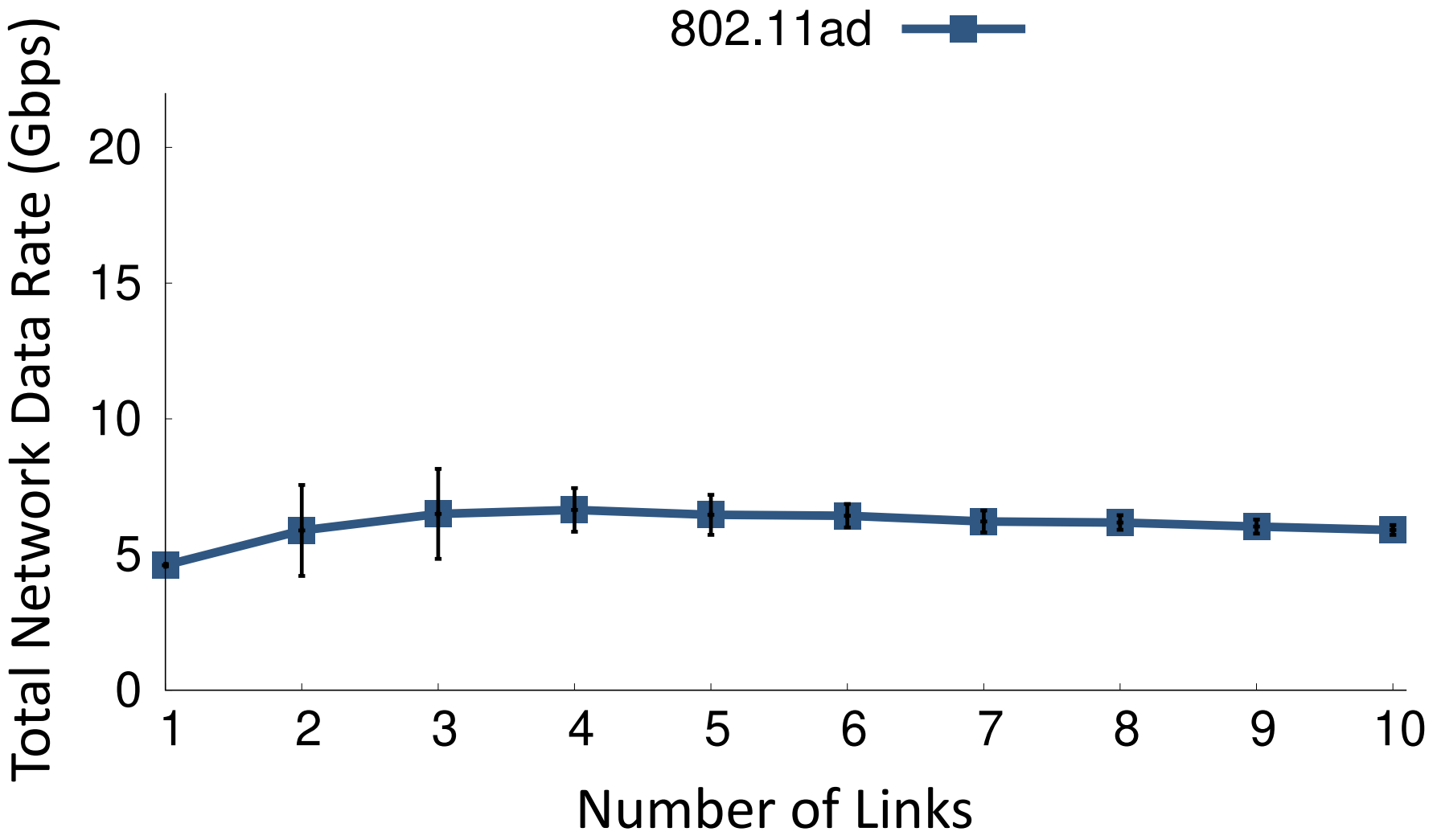
Total Network Data Rate

Phased Array



Total Network Data Rate

Phased Array



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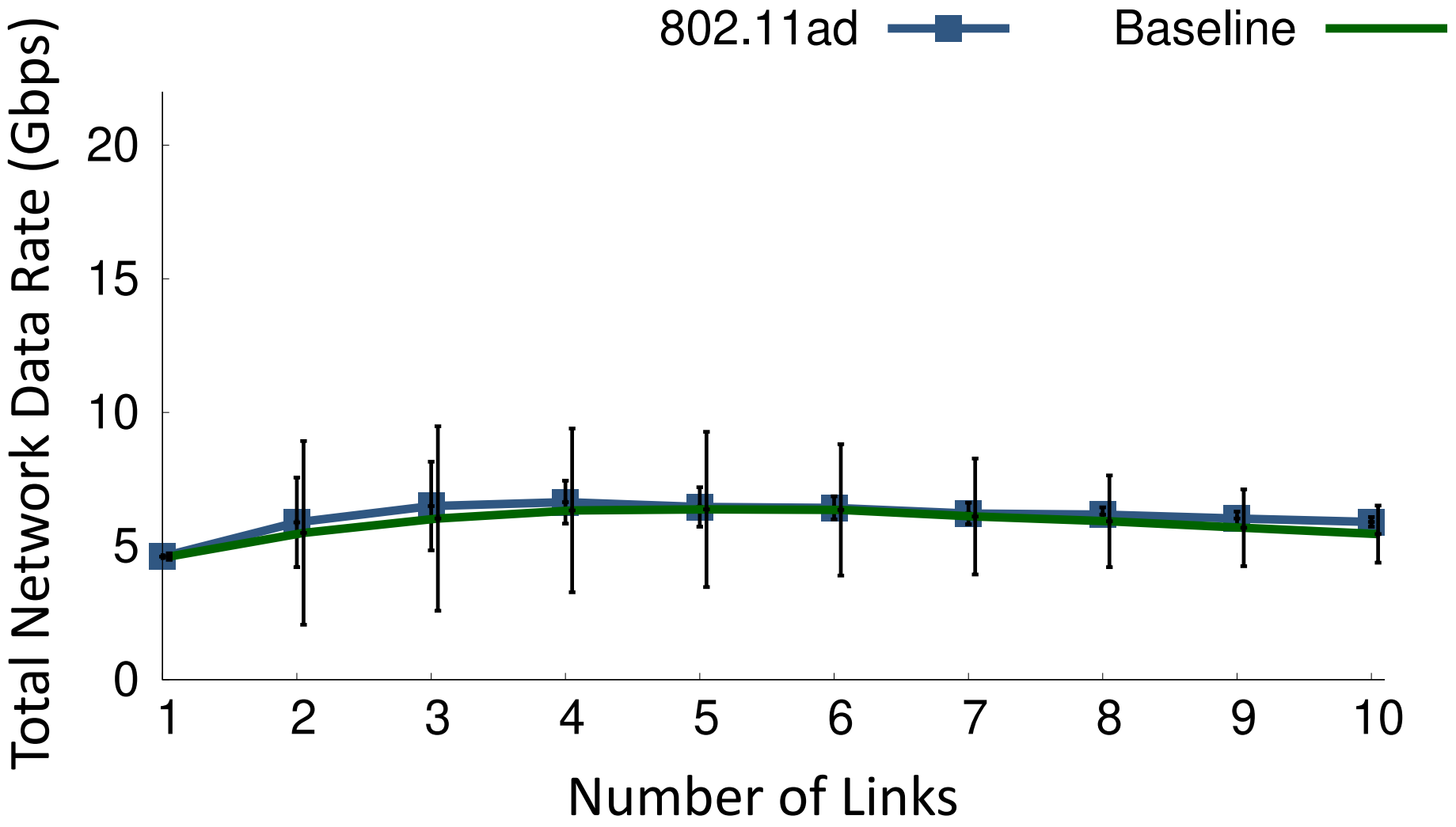

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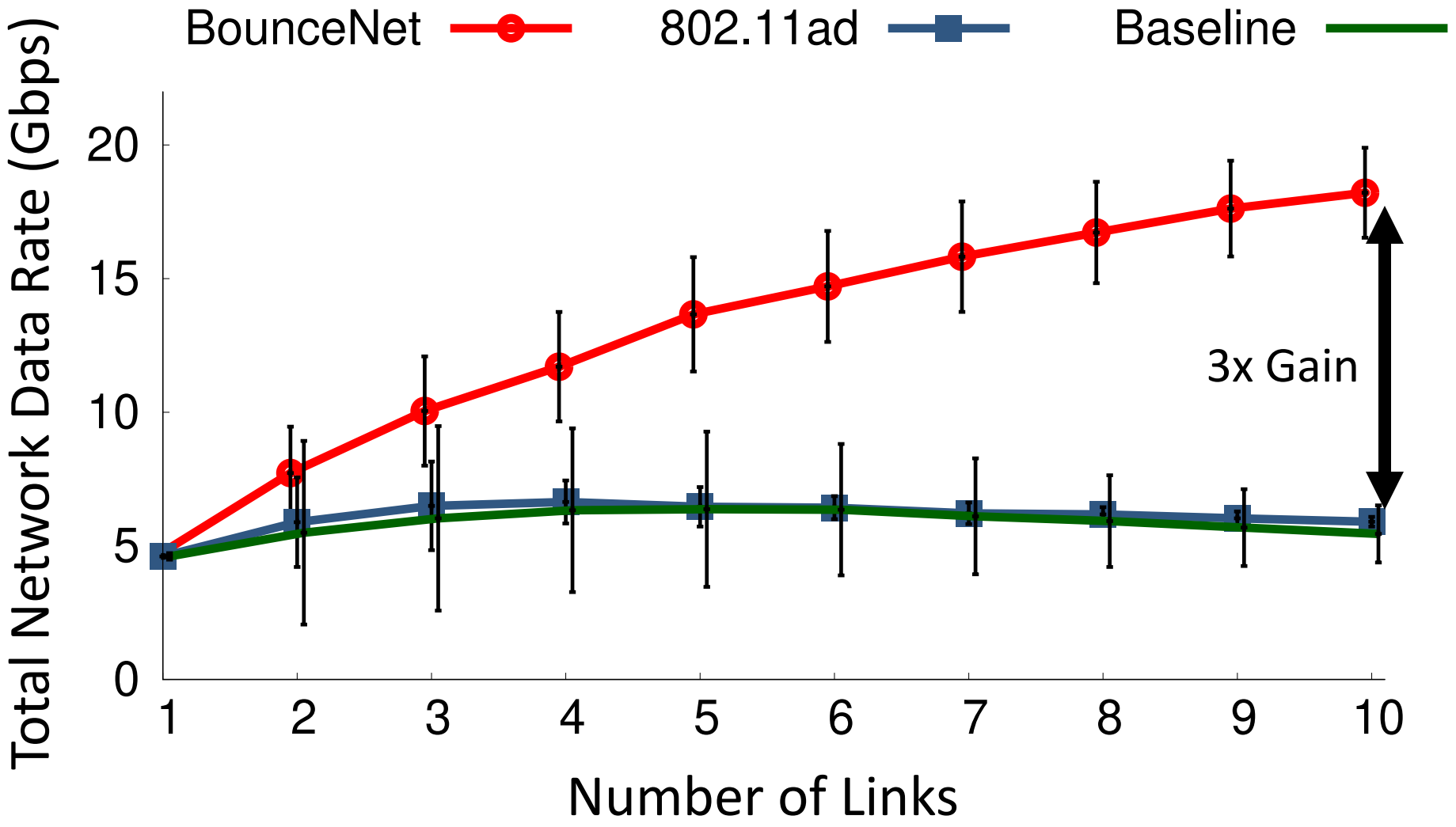
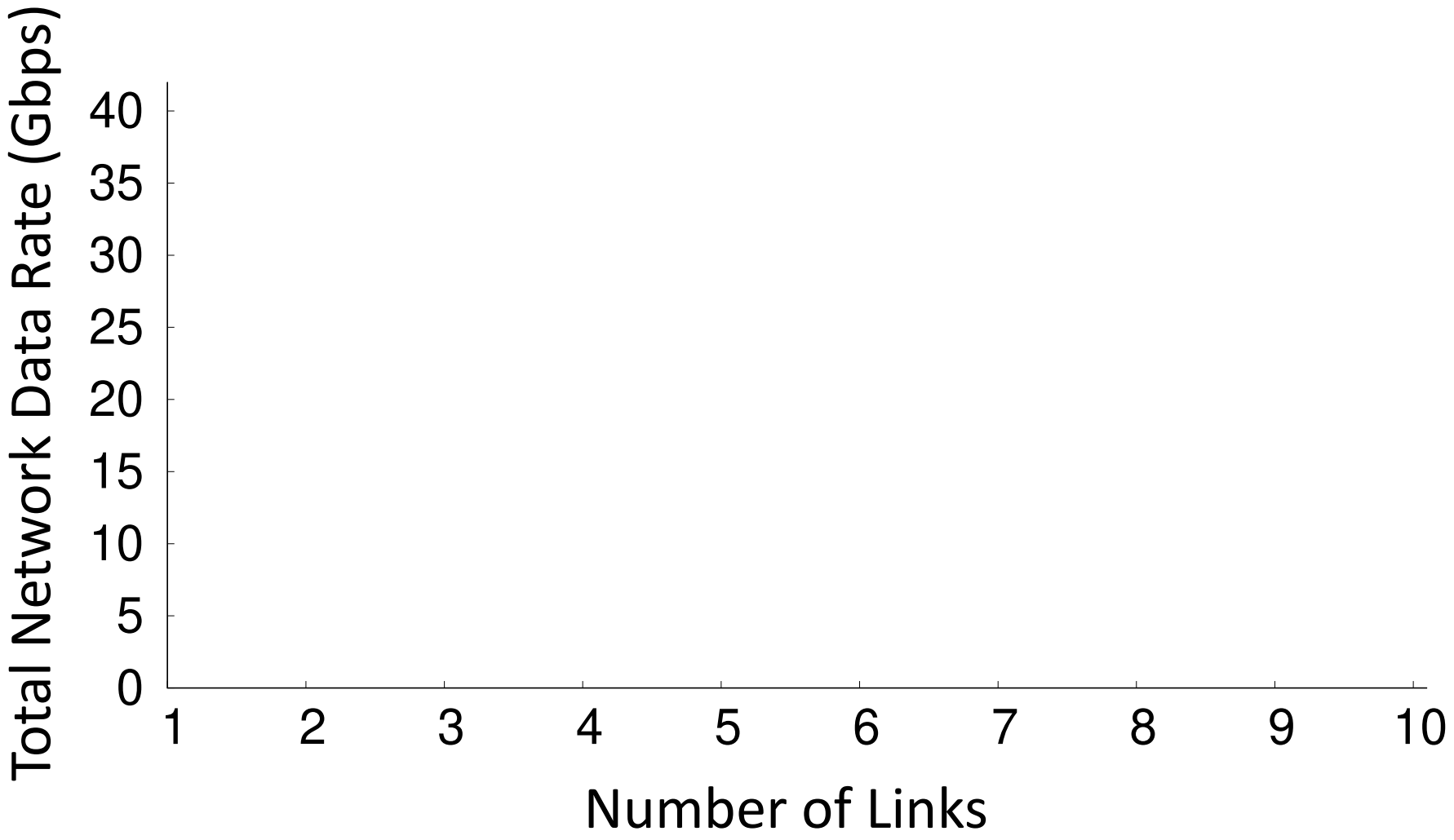
Phased Array



Total Network Data Rate

3 Degree



Total Network Data Rate

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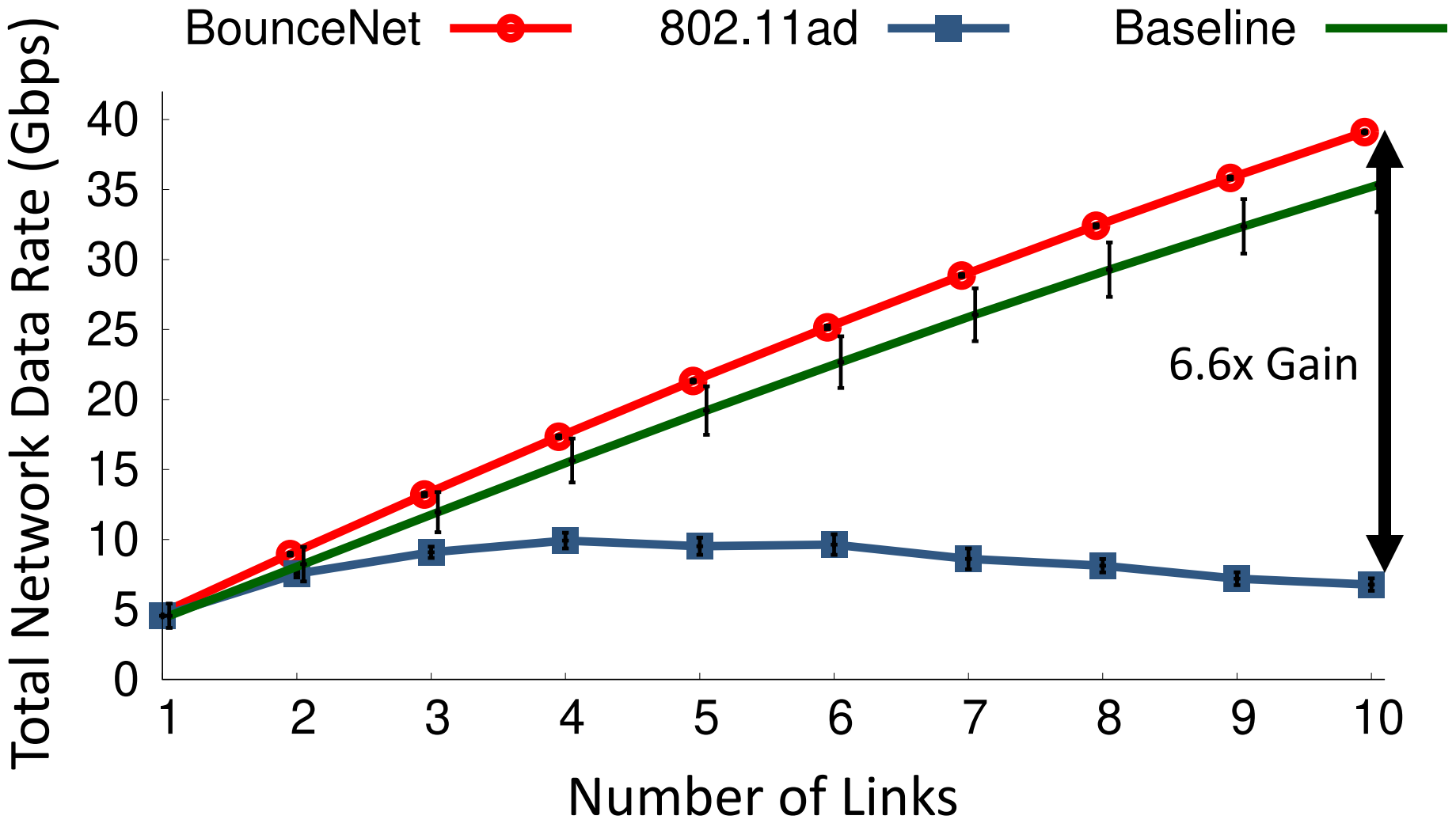

Data Rate of Worst Case Client

	Baseline	BounceNet	Gain
3 Degree			
12 Degree			
Phased Array			

BounceNet scales network throughput and ensures fairness, outperforming compare schemes

To conclude

1. BounceNet enables many-to-many beam alignment by exploiting dense spatial reuse

2. mmWave opens up a new paradigm and requires rethinking of wireless network design