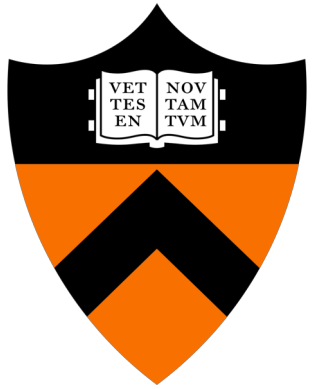
LAIA: Programming the Radio Environment with Large Arrays of Inexpensive Antennas

Speaker: Yaxiong Xie

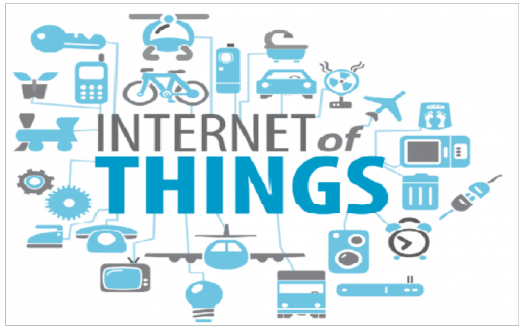
Zhuqi Li, Yaxiong Xie, Longfei Shangguan, Rotman Ivan Zelaya, Jeremy Gummeson, Wenjun Hu, Kyle Jamieson



Wireless communication

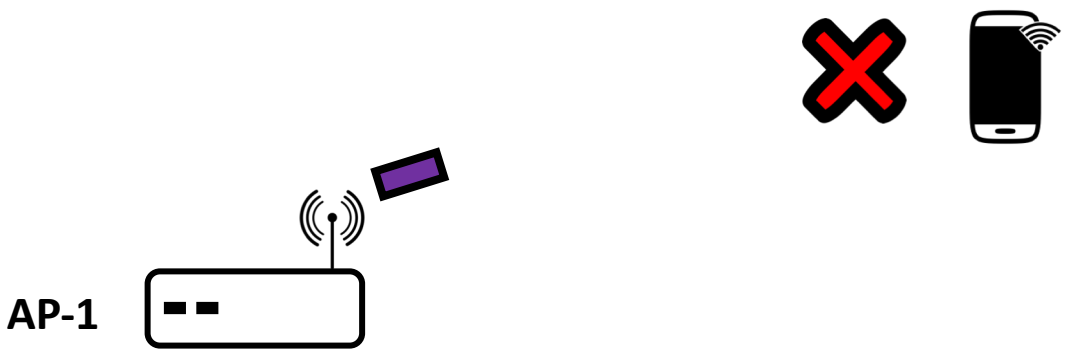
- We have witnessed the huge success of wireless communication

- Wireless communication still faces significant challenge
  - **High** throughput and **dense** deployment



Fundamental problem

- Wireless channel is unreliable and noisy



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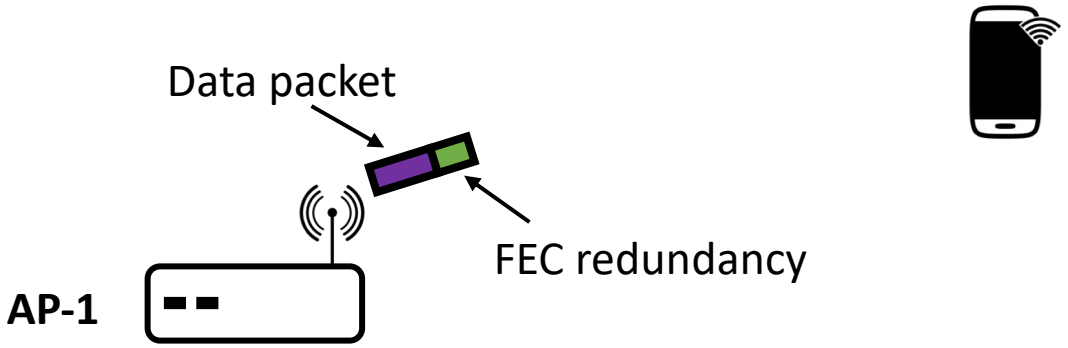

Previous solutions

➢ Channel coding: Spinal code, LDPC

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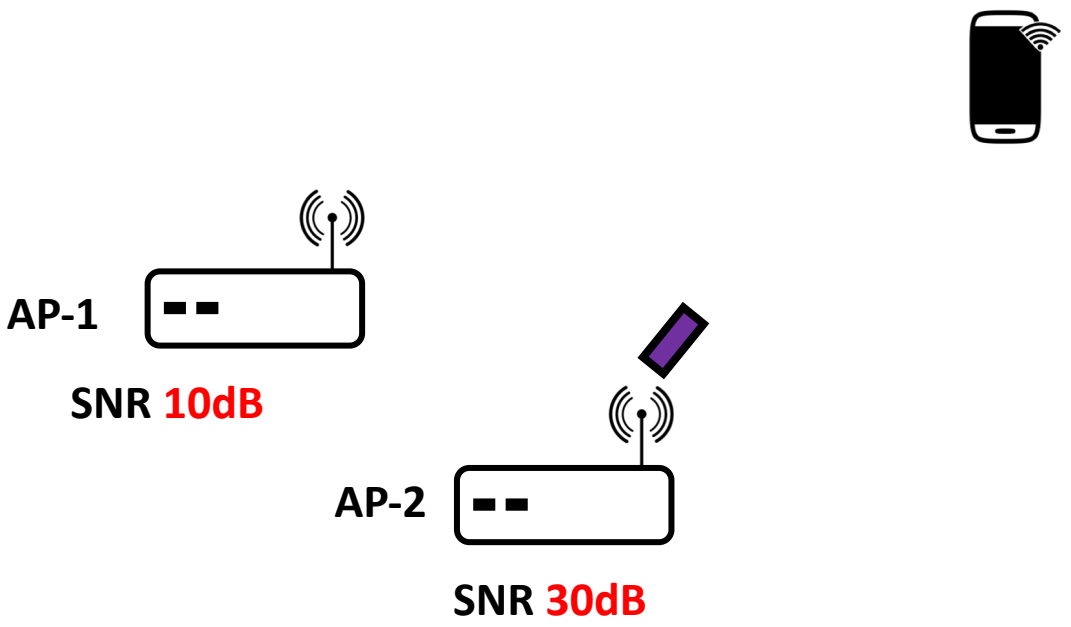

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- Leveraging diversity
  - Link diversity: MRD [Miu+05]

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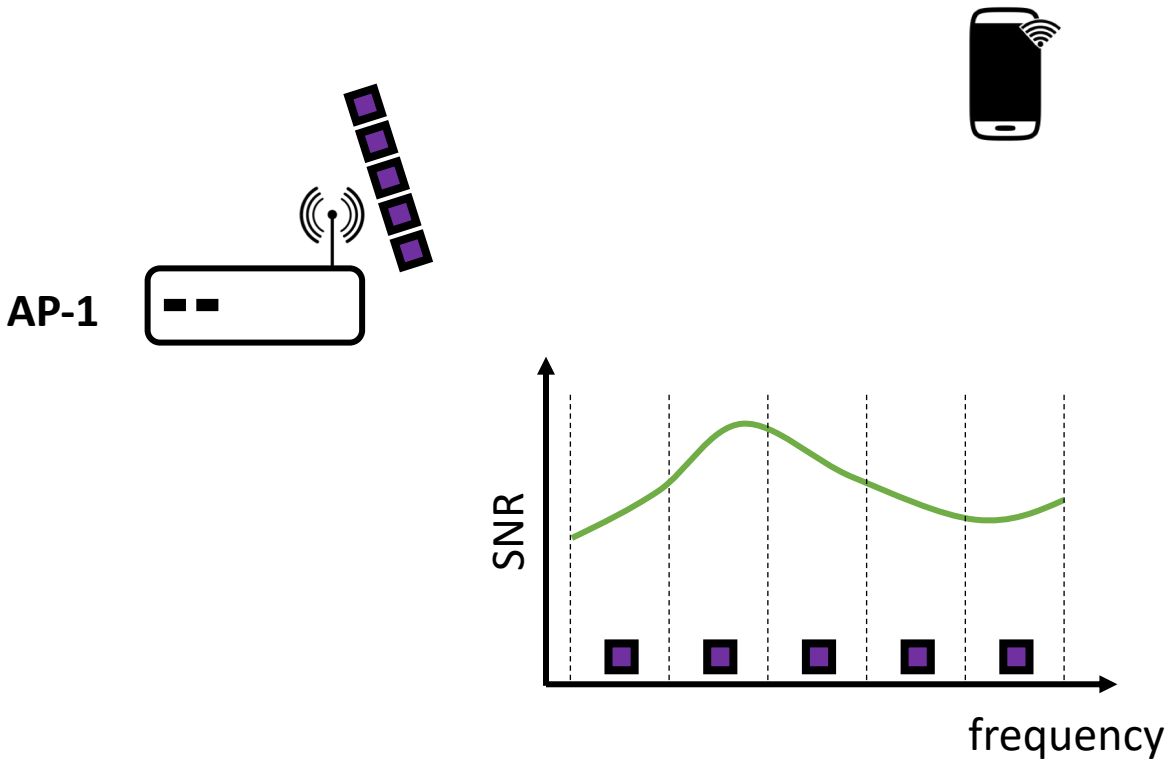

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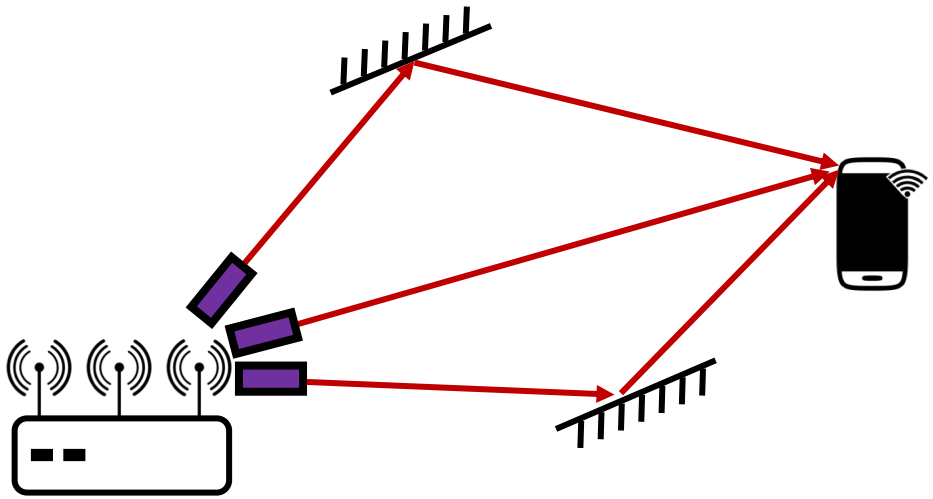

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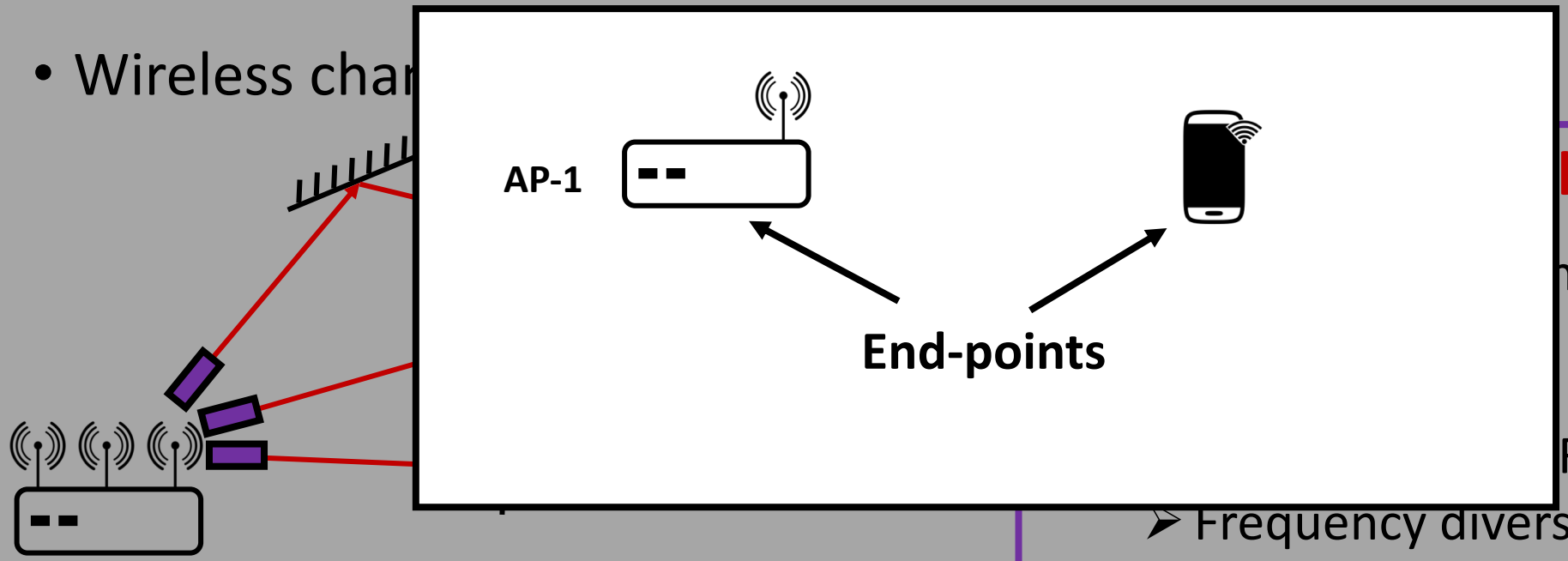

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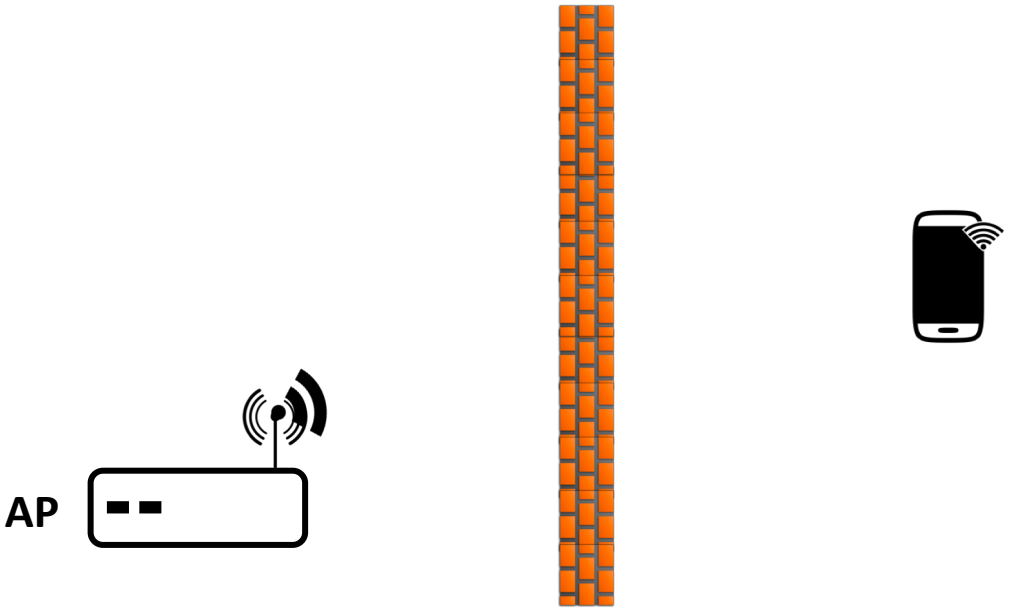
nal code, LDPC

RD

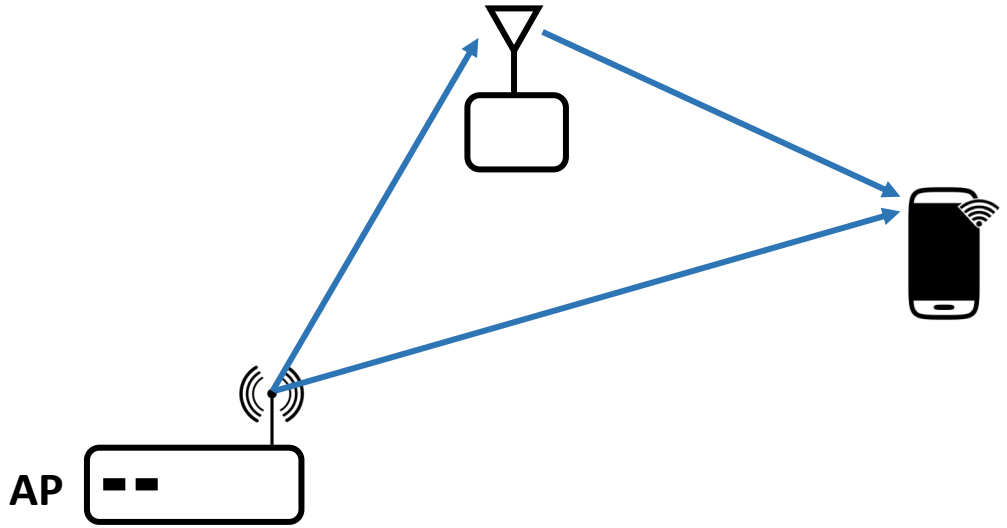
- Frequency diversity: OFDM
- Path diversity: MIMO

Previous work focuses on end-points!

Wouldn’t it be nice to change the channel itself?



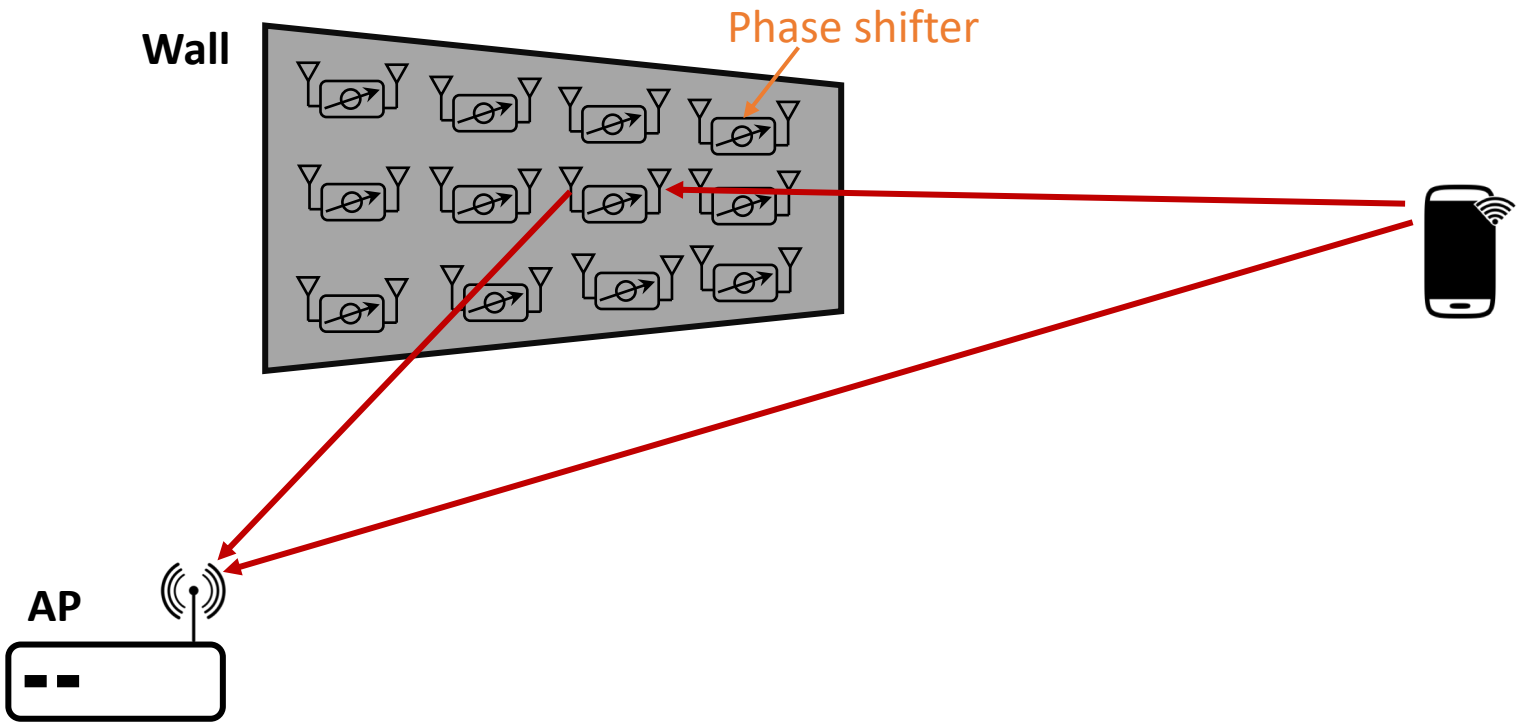
Not physically



Electronically and programmatically

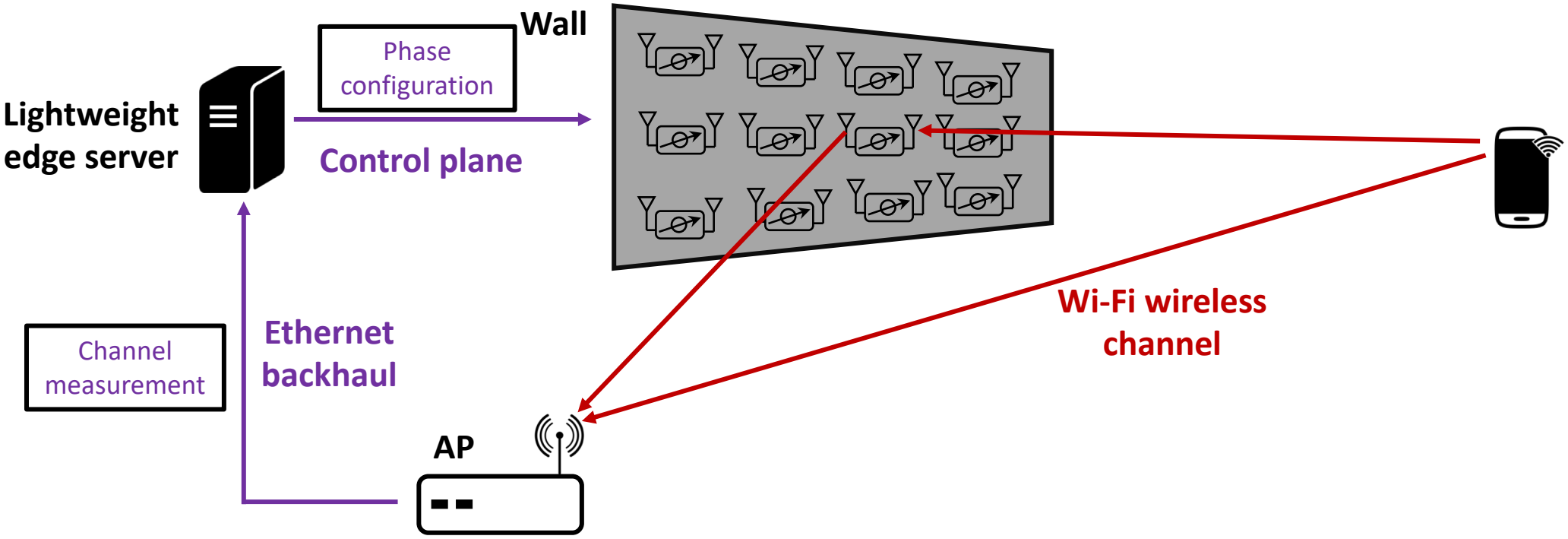
Large array of inexpensive antennas (LAIA)

- Many inexpensive, passive electronic elements
- One point in the design space



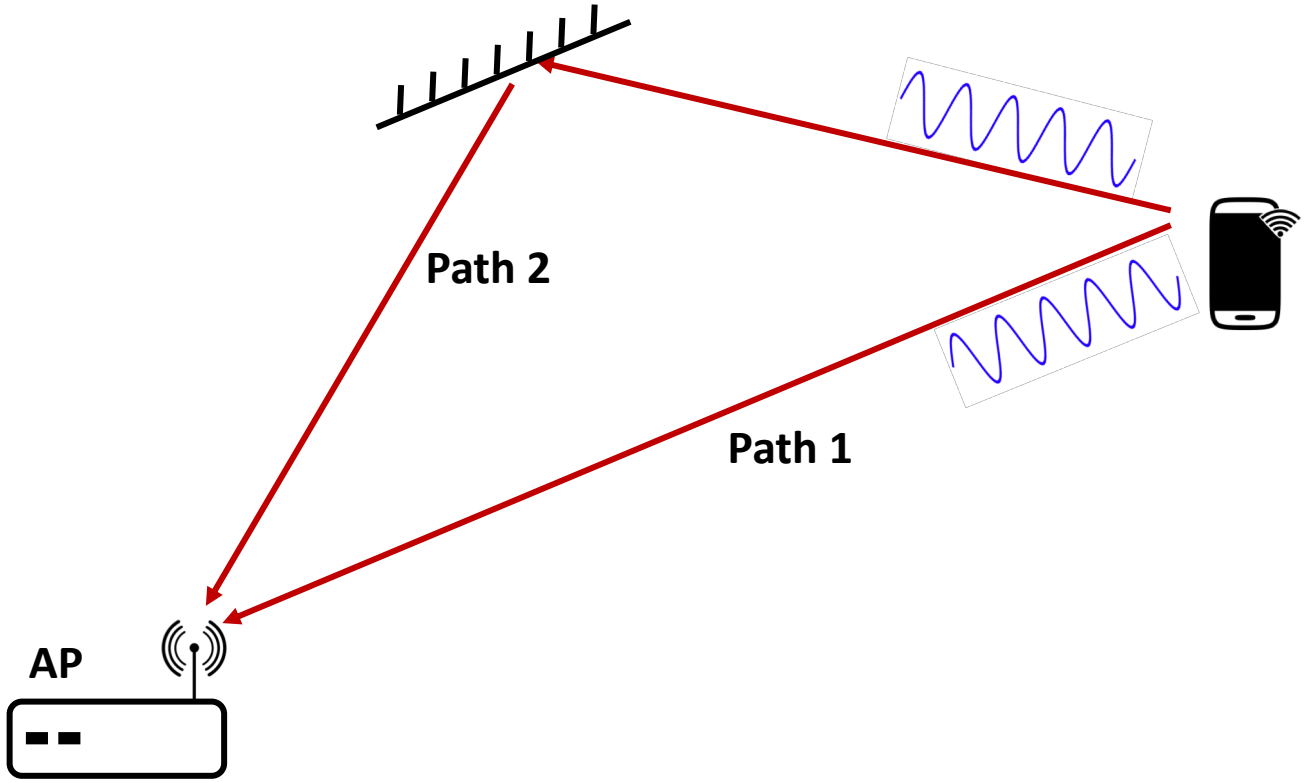
LAIA architecture

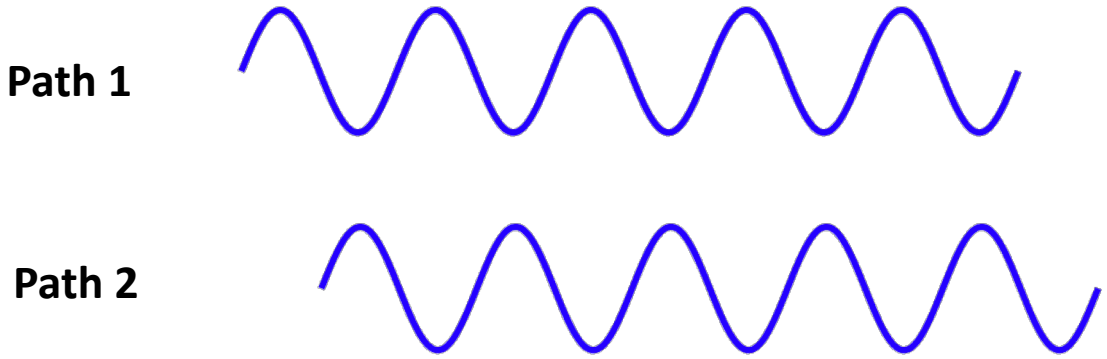
- Best phase configuration depends on the end-point channel measurements
- **Lightweight server** configures **phase shifter** setting of each element



How does LAIA program the wireless channel?

- Deconstructive superposition VS. constructive superposition





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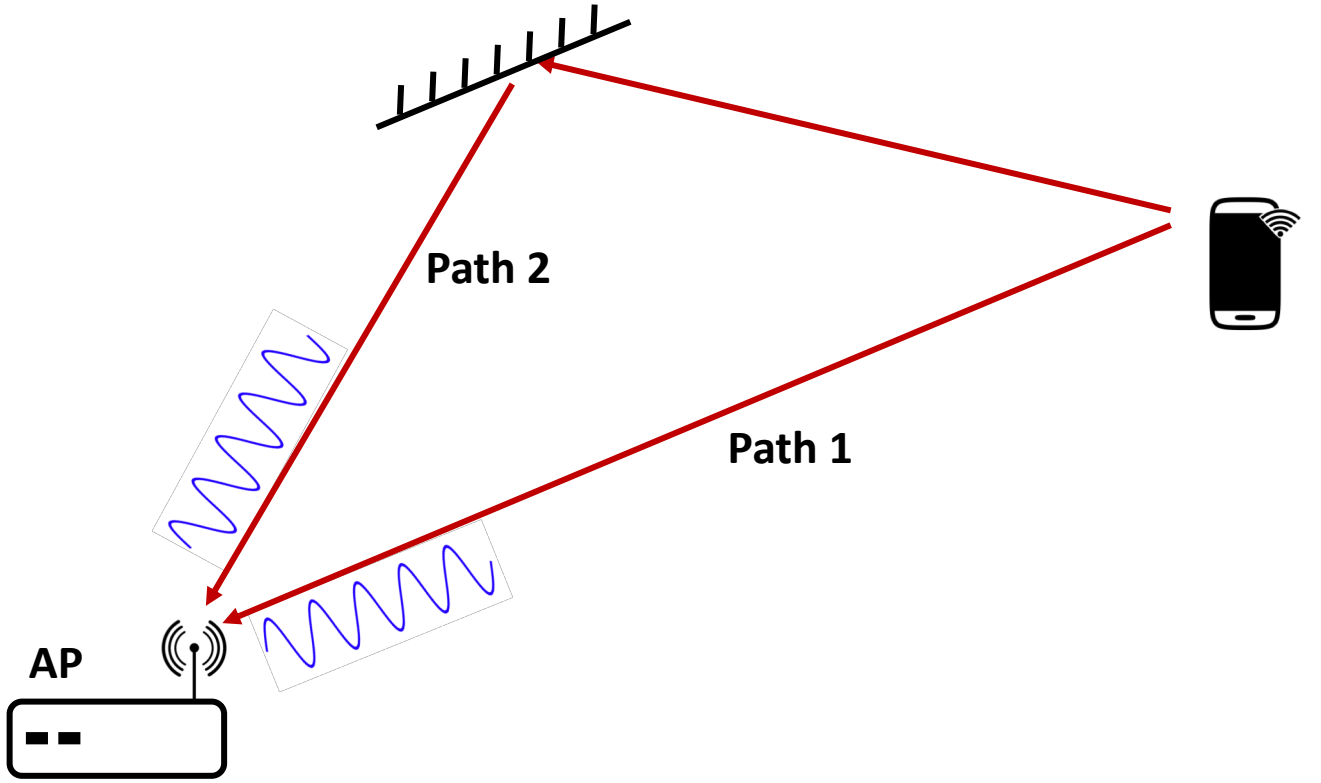

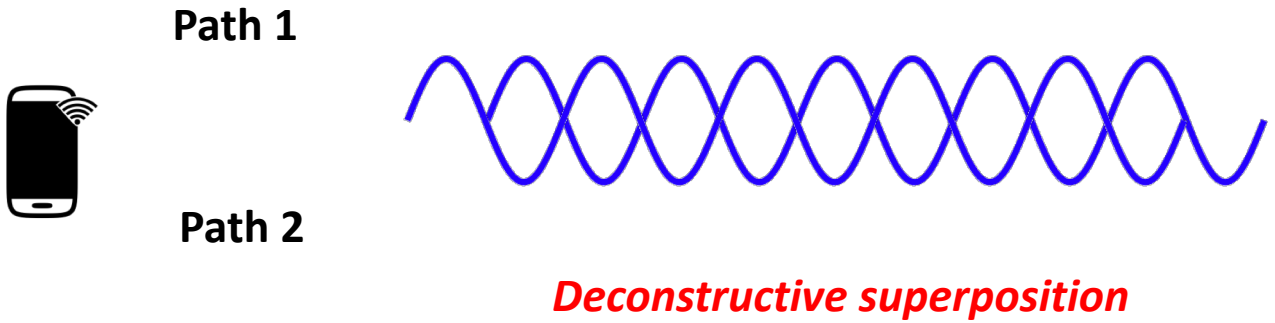

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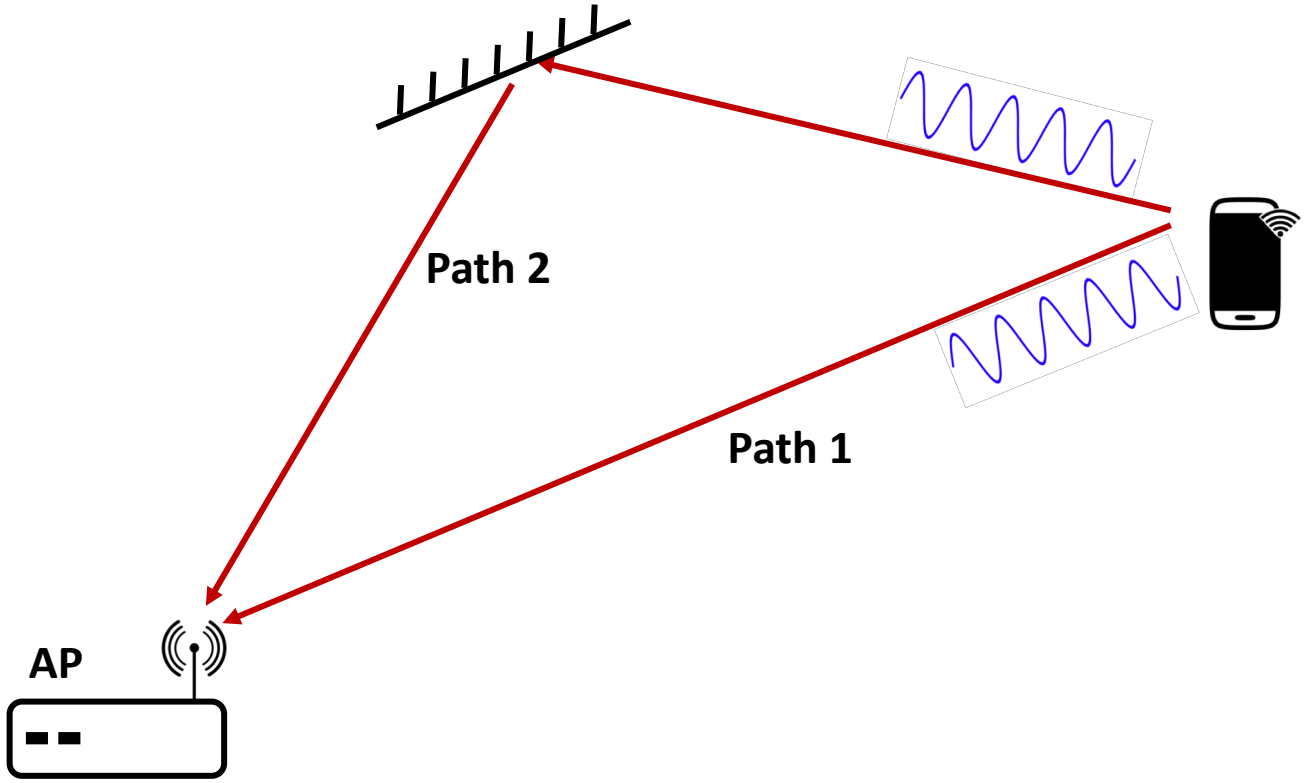

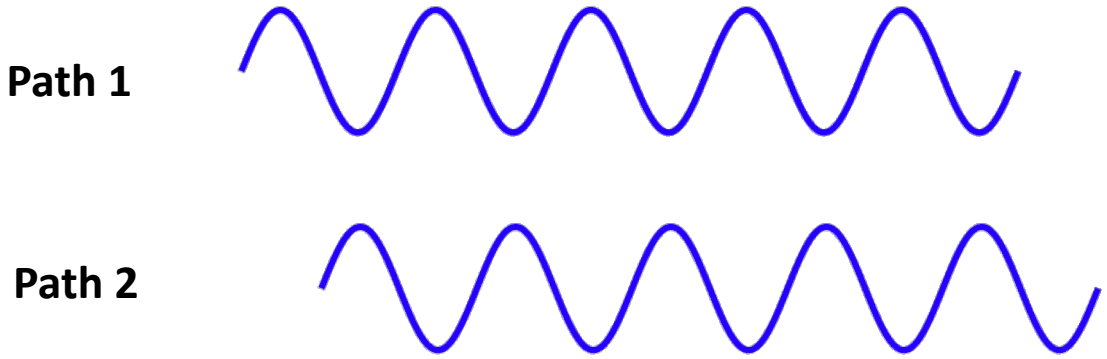

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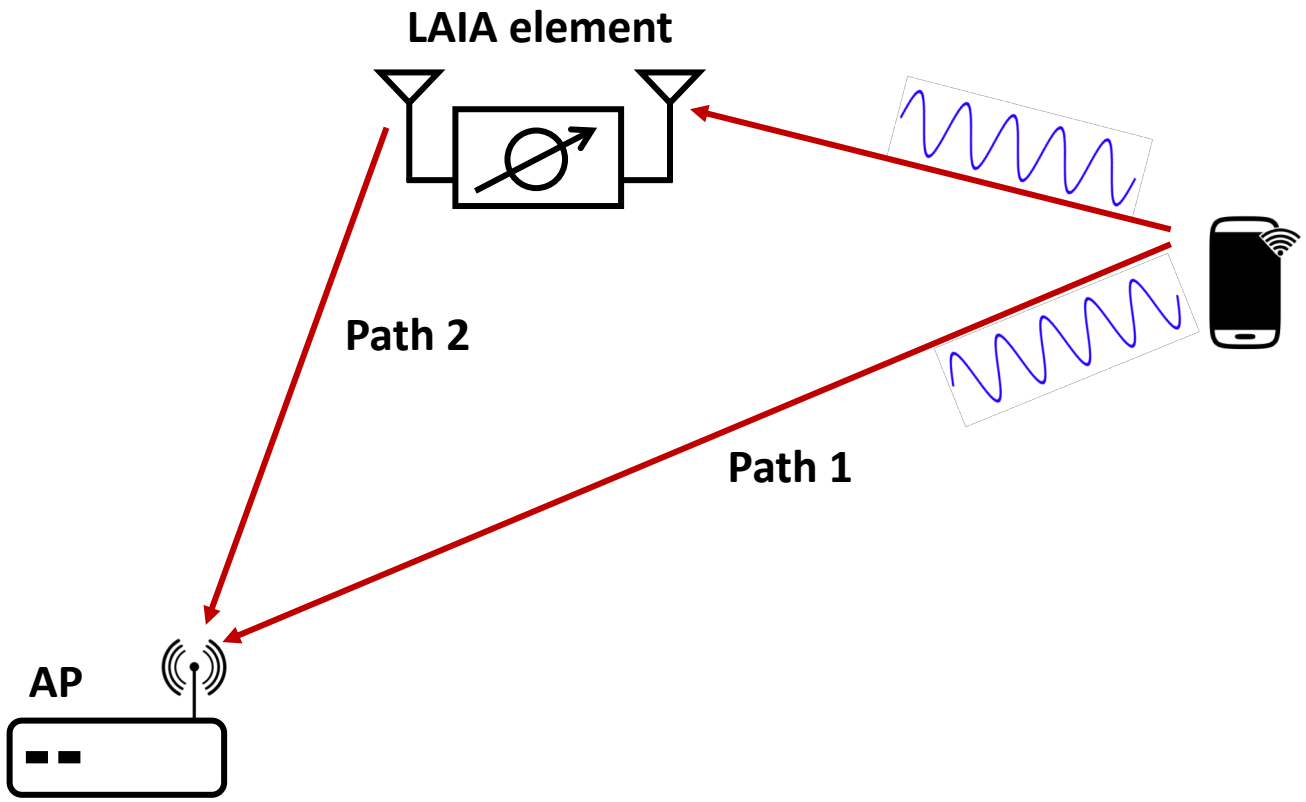

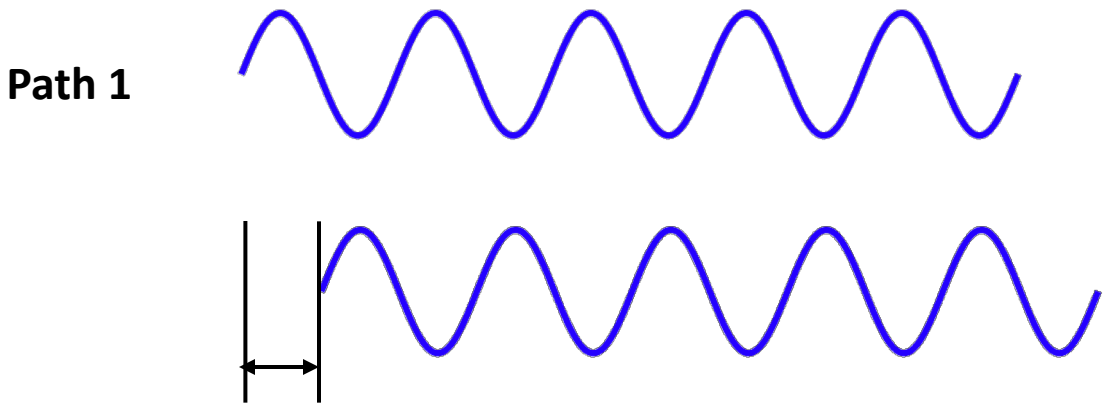

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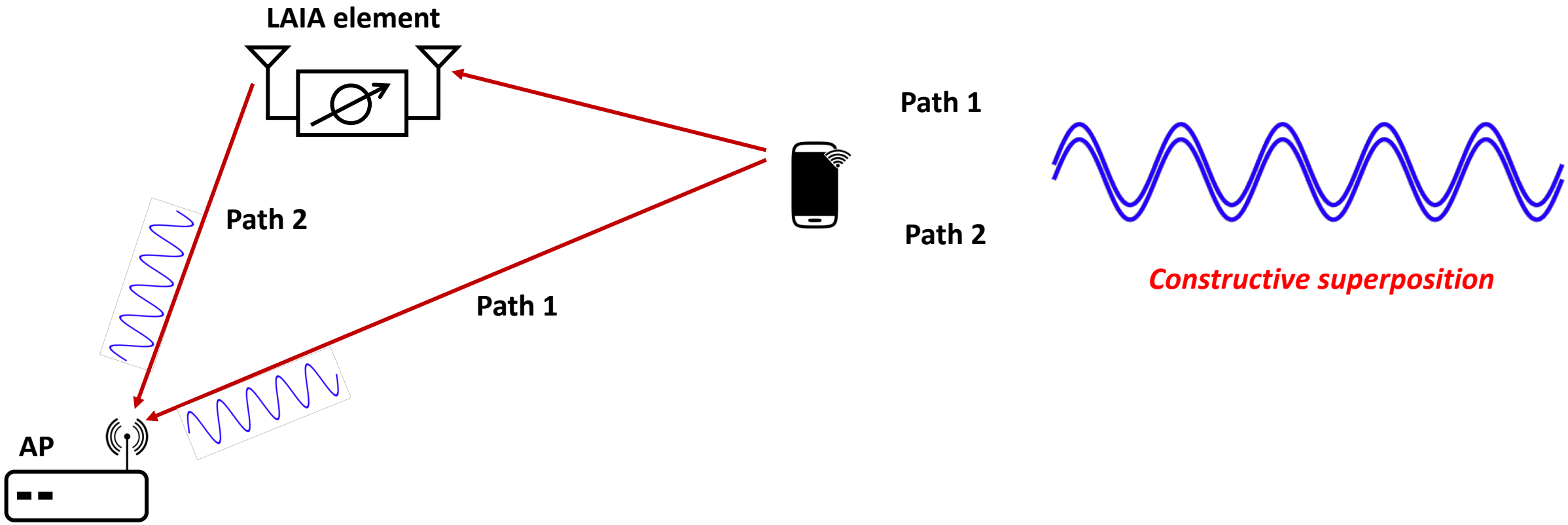

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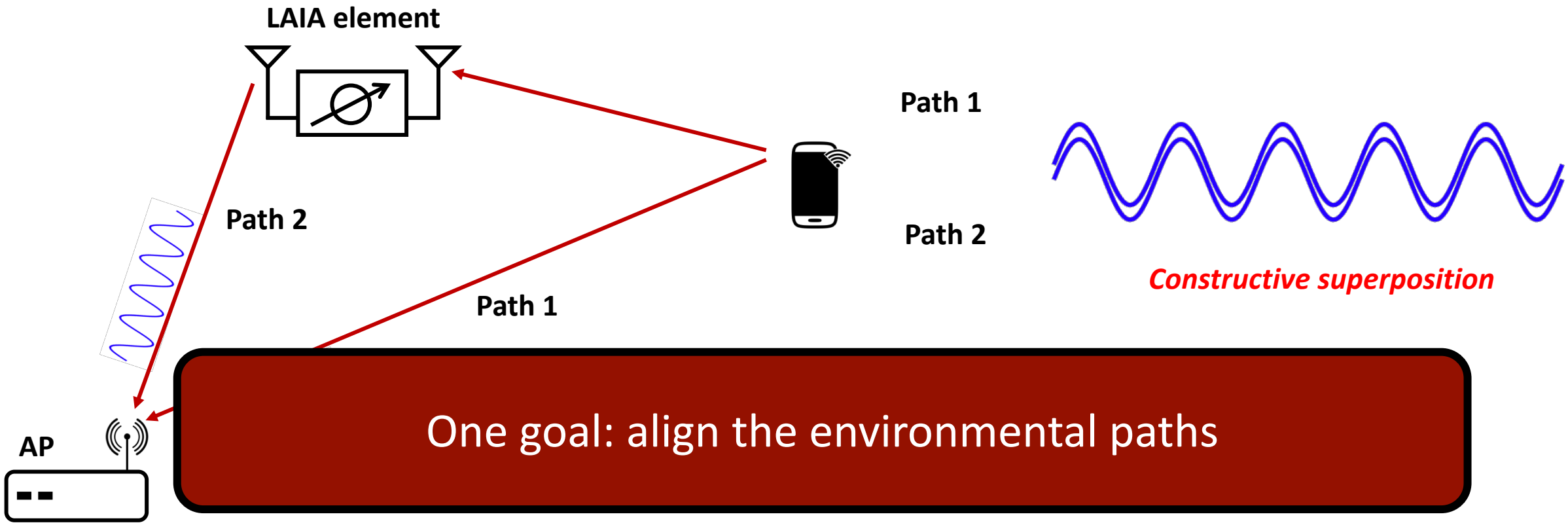
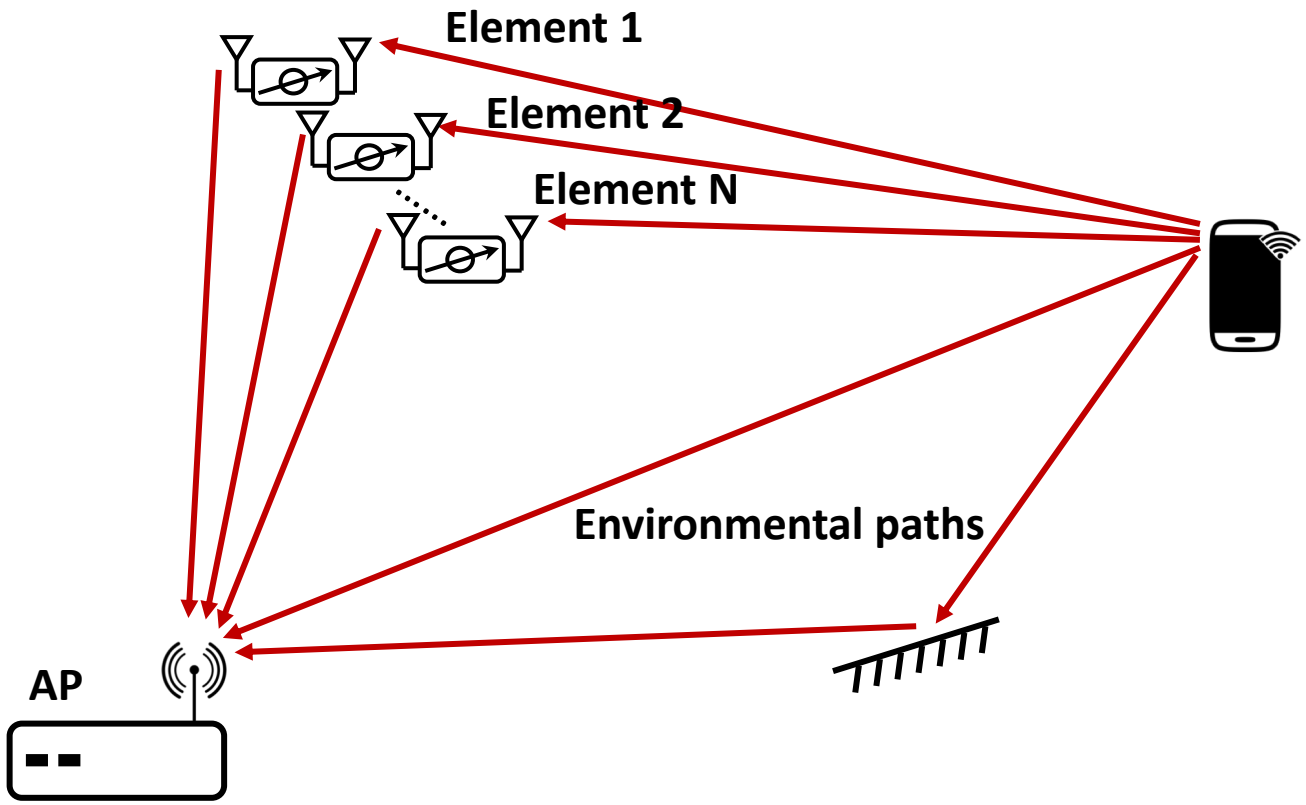
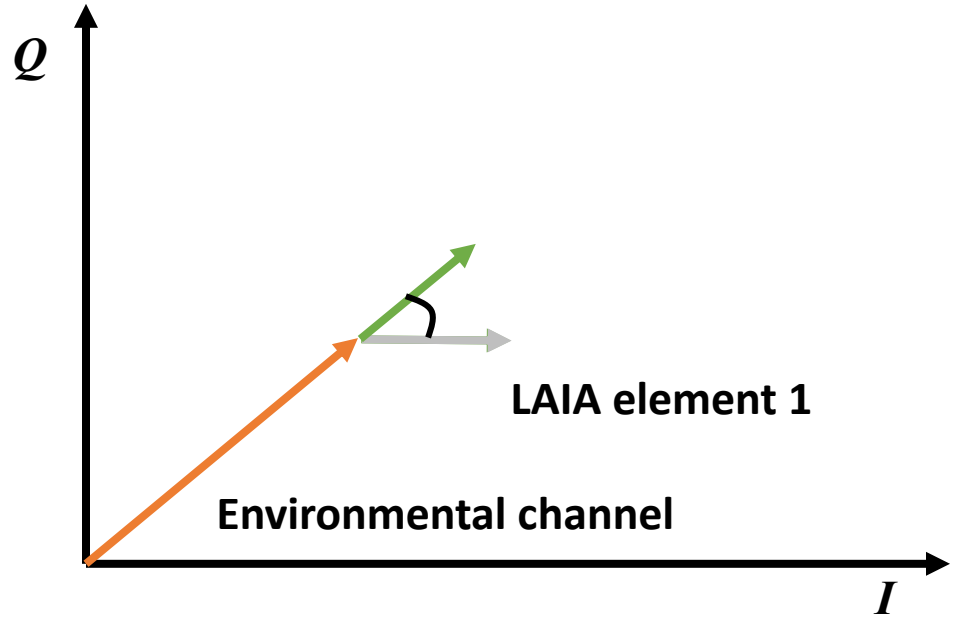


Align the LAIA path with environmental path





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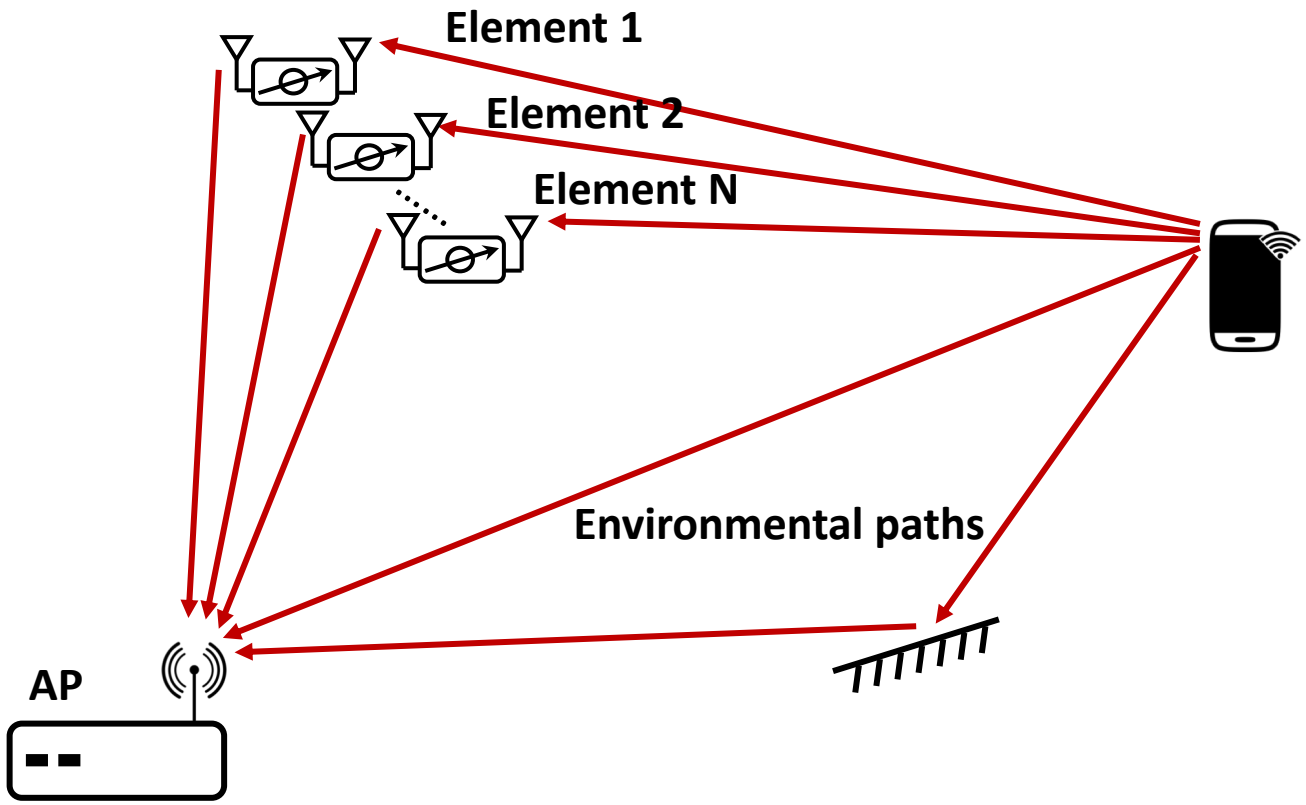
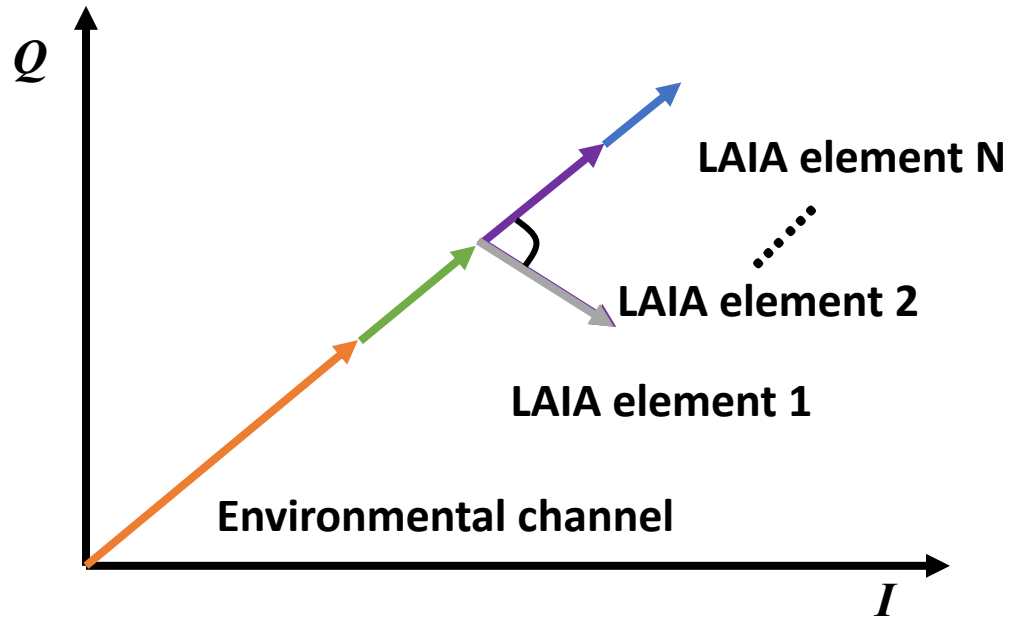
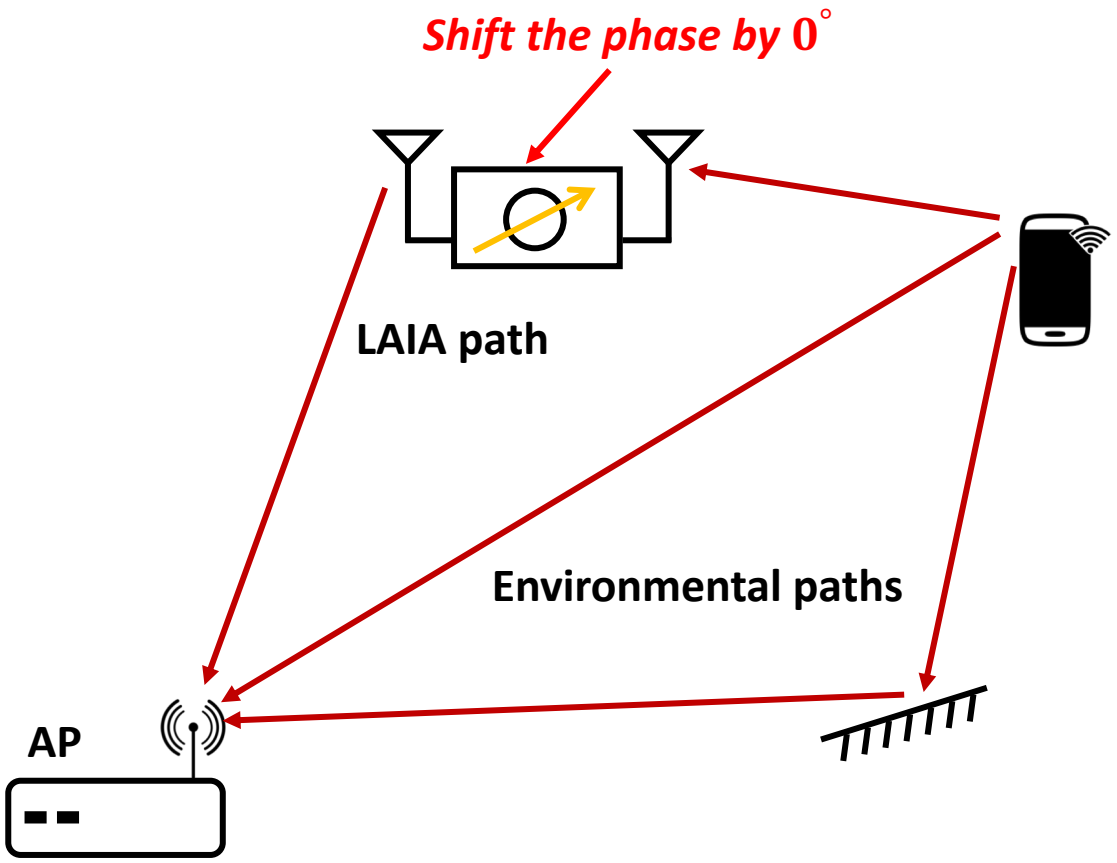


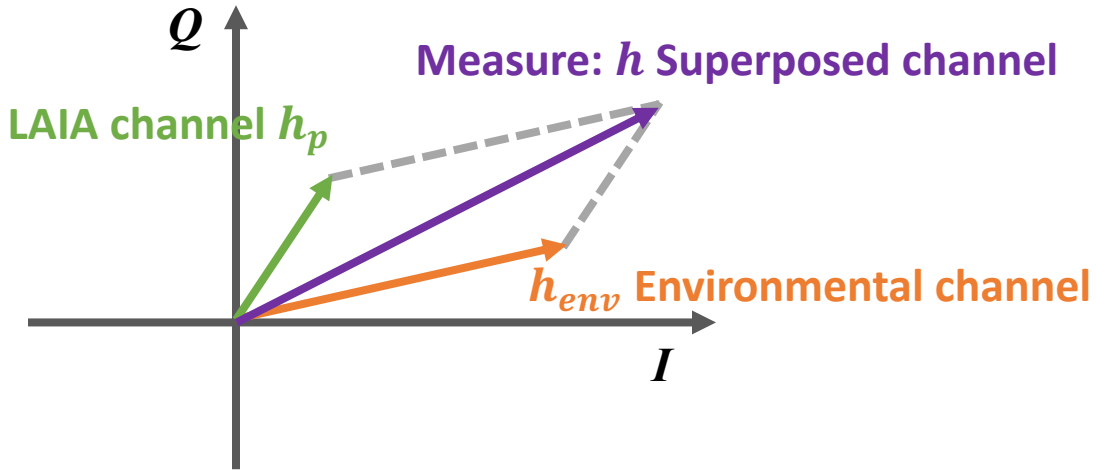


Challenges

- How to measure the effect of LAIA element channels?
- How to measure the effect of environmental channel?
  - The channel for environmental path and LAIA paths are superposed
- How to ***configure*** the phase of LAIA elements?
  - Searching the best phase combination for LAIA array is an exponentially complex problem.

Two-probe channel decomposition algorithm





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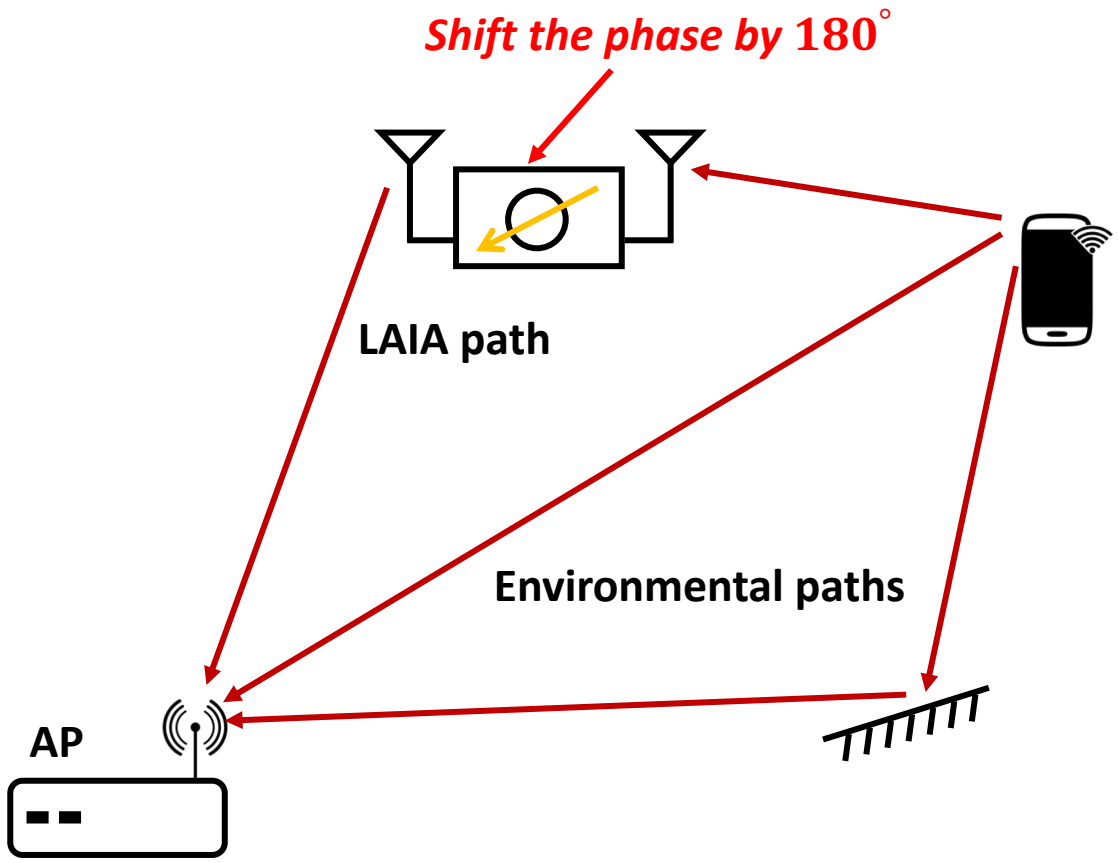

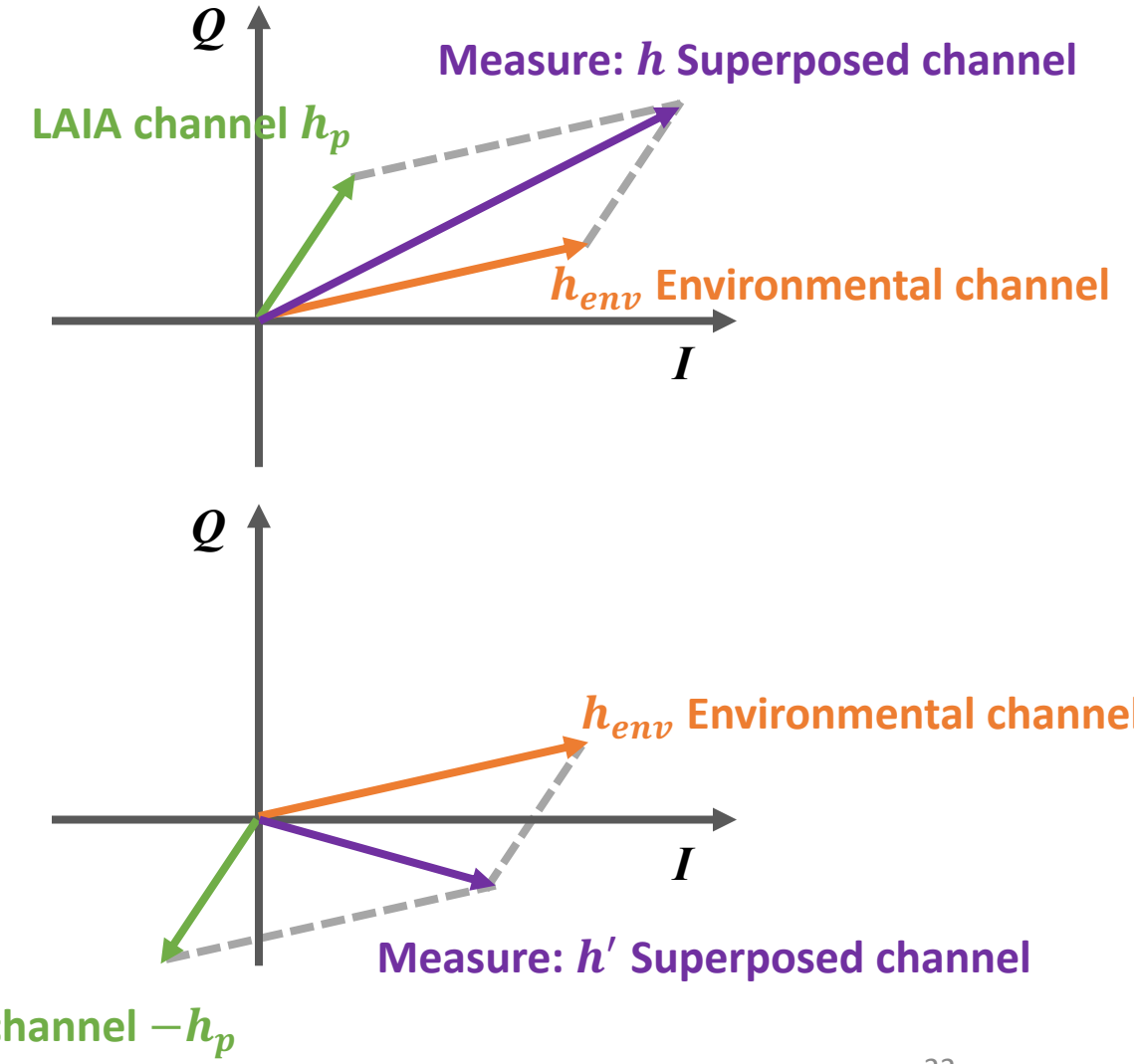

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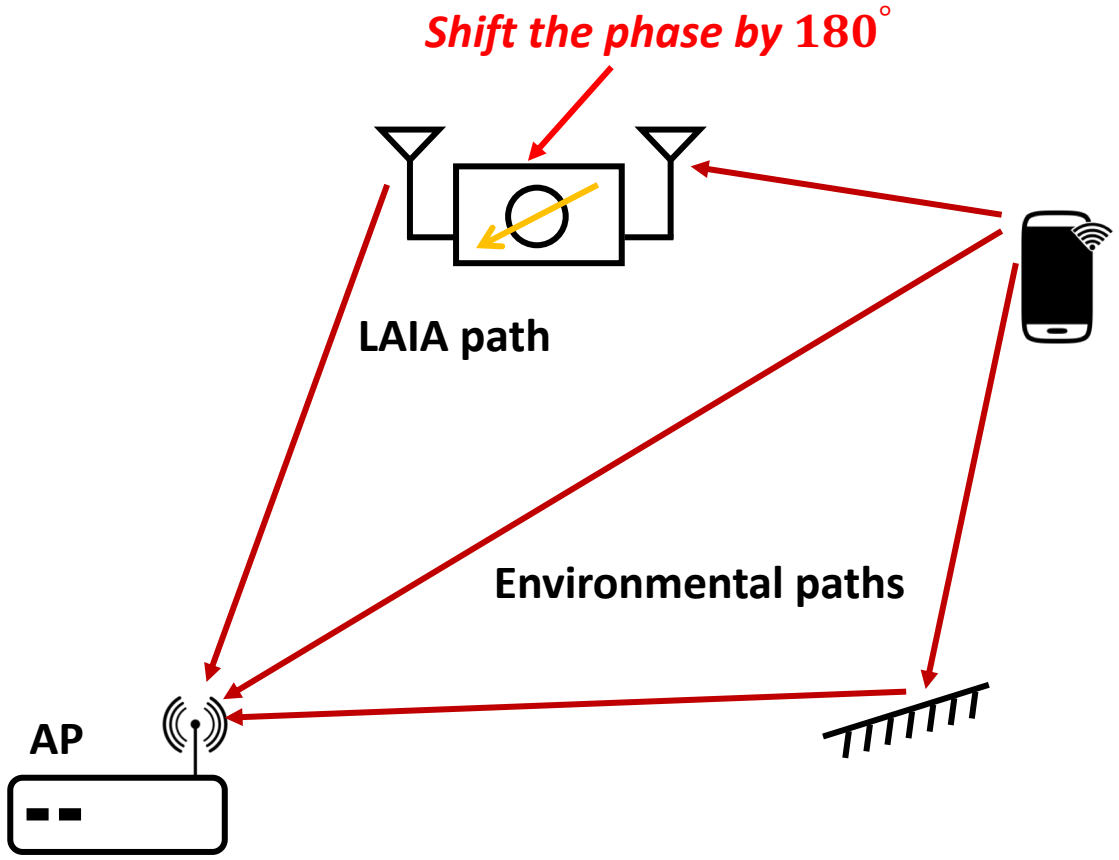
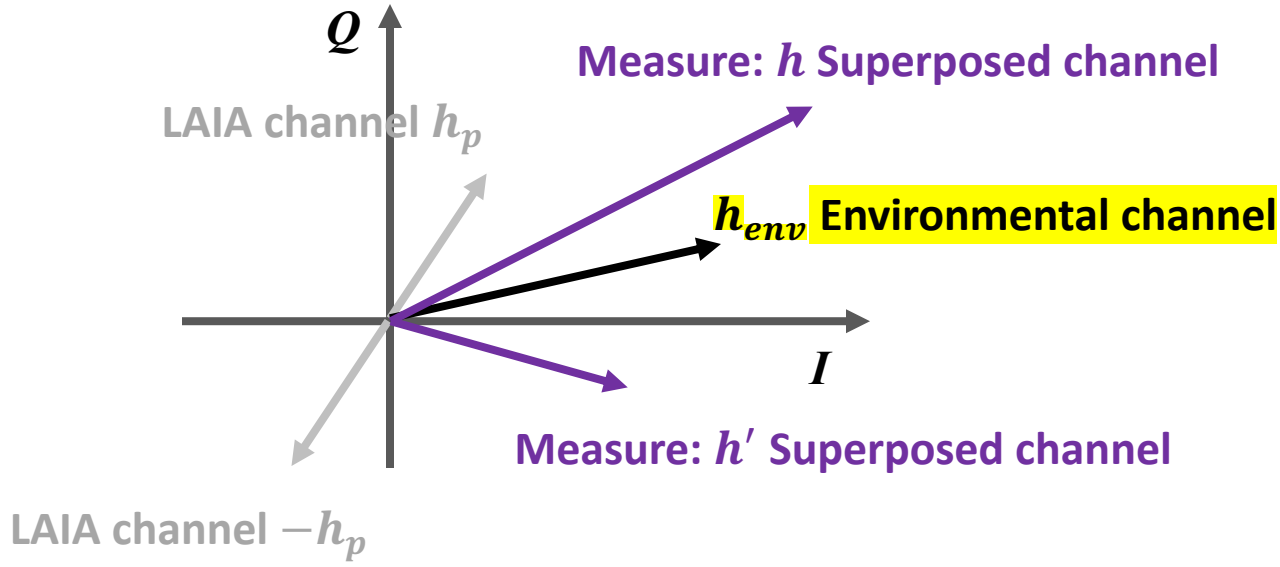
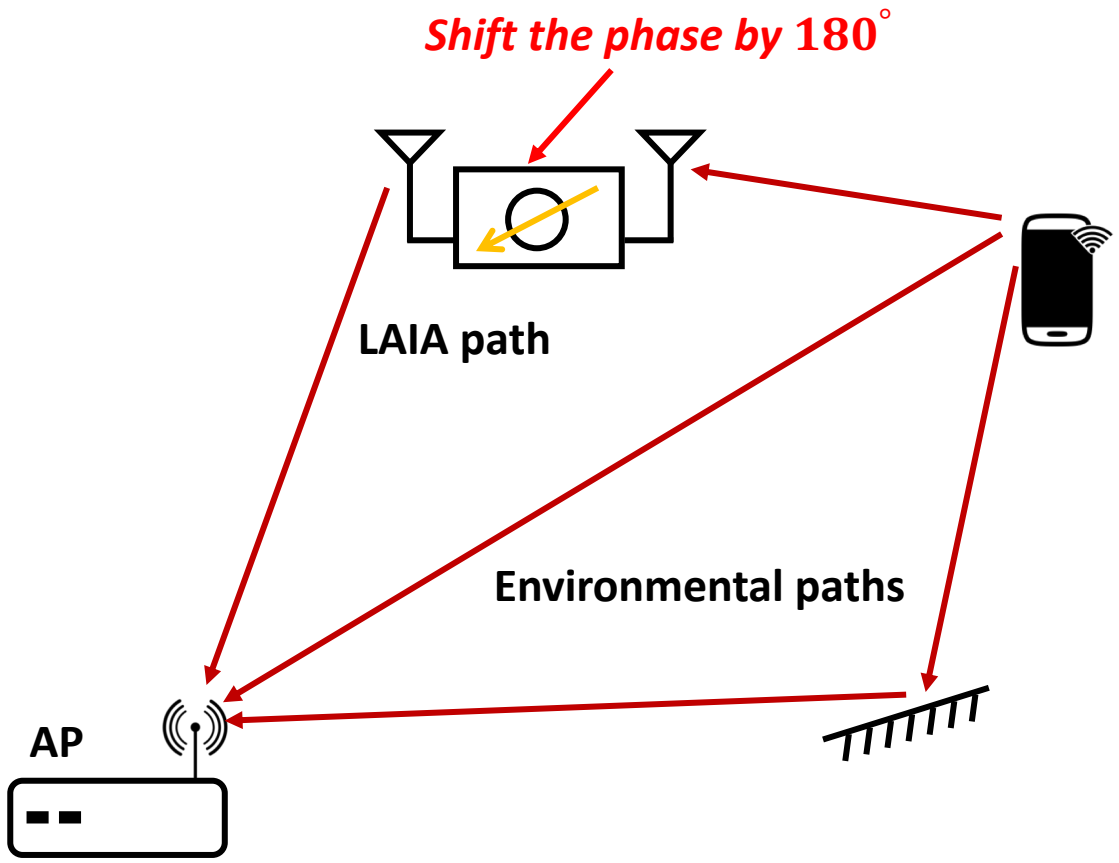
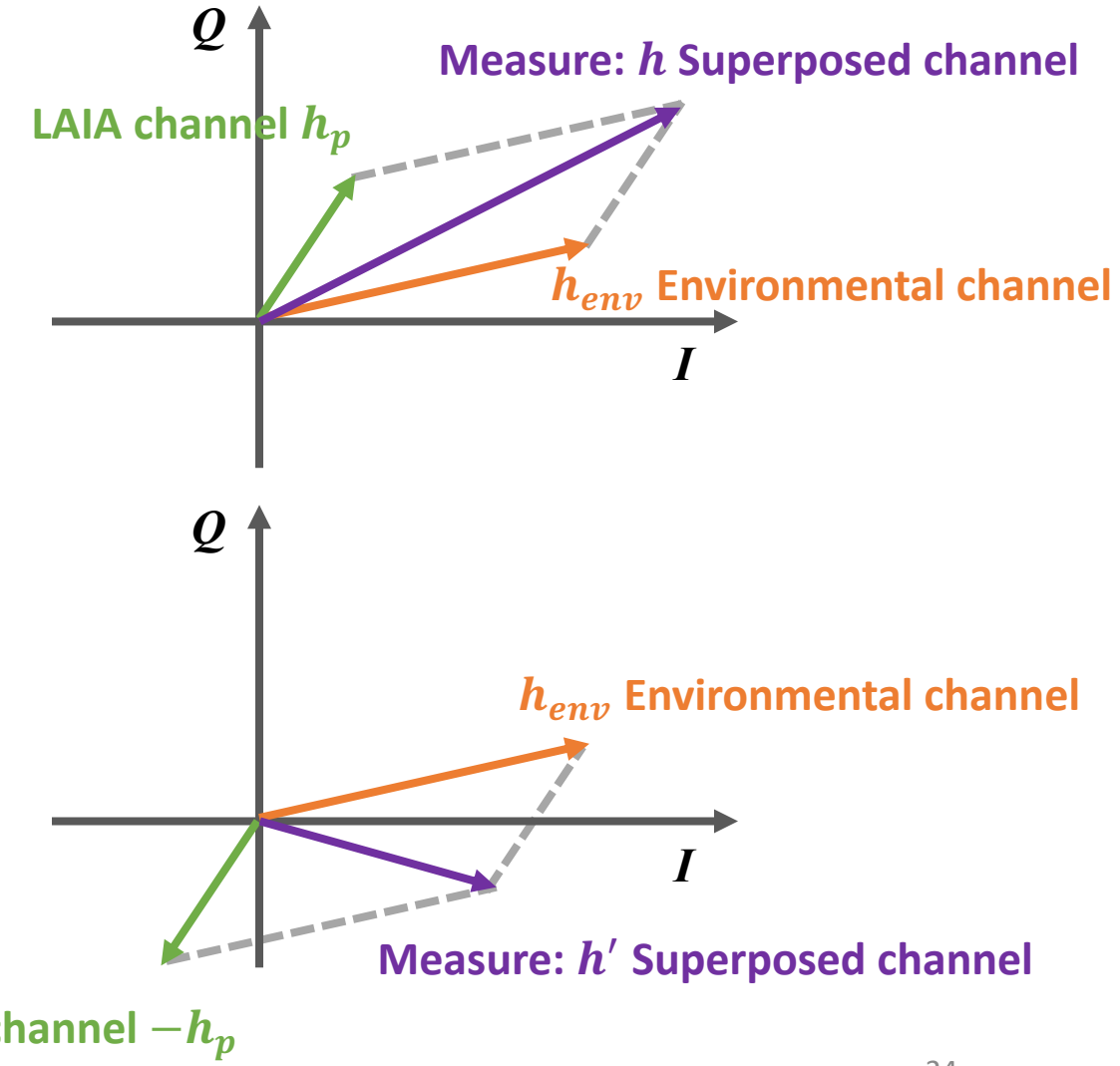




Environmental channel $h_{env} = \frac{h+h'}{2}$

Two-probe channel decomposition algorithm





Measure: h Superimposed channel

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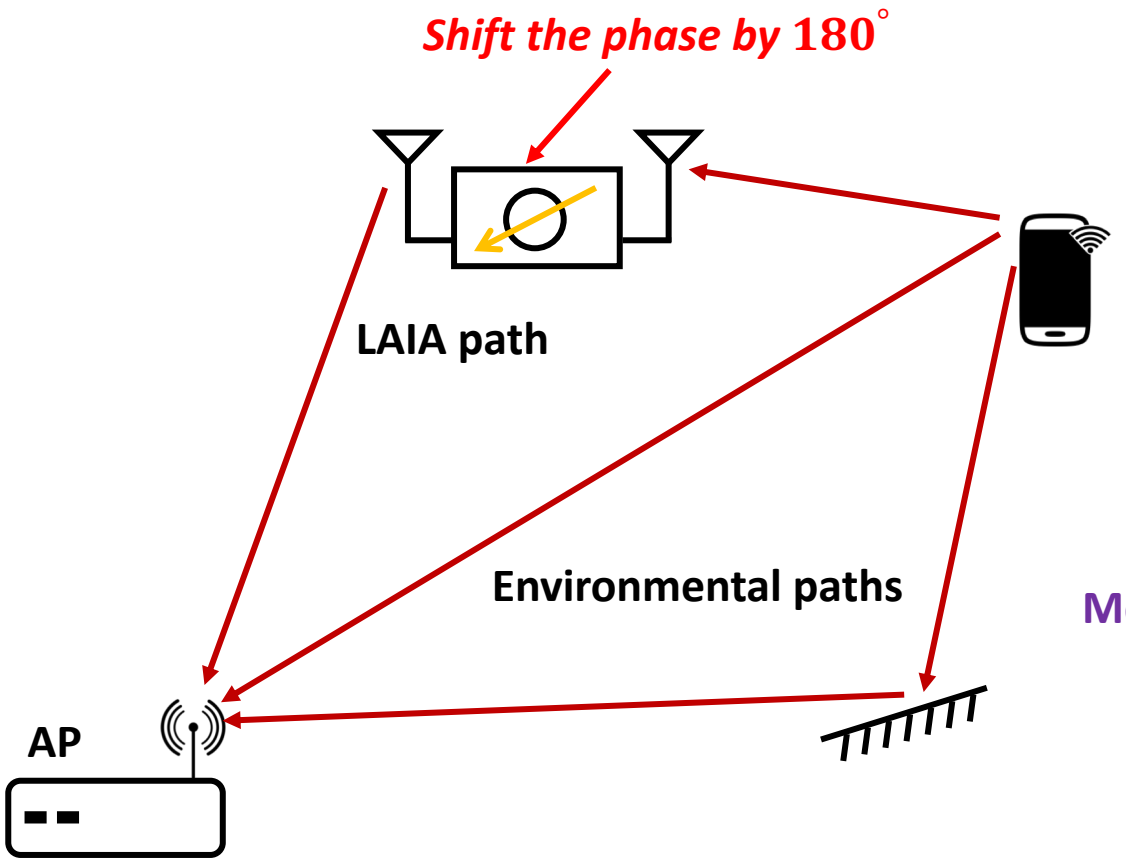

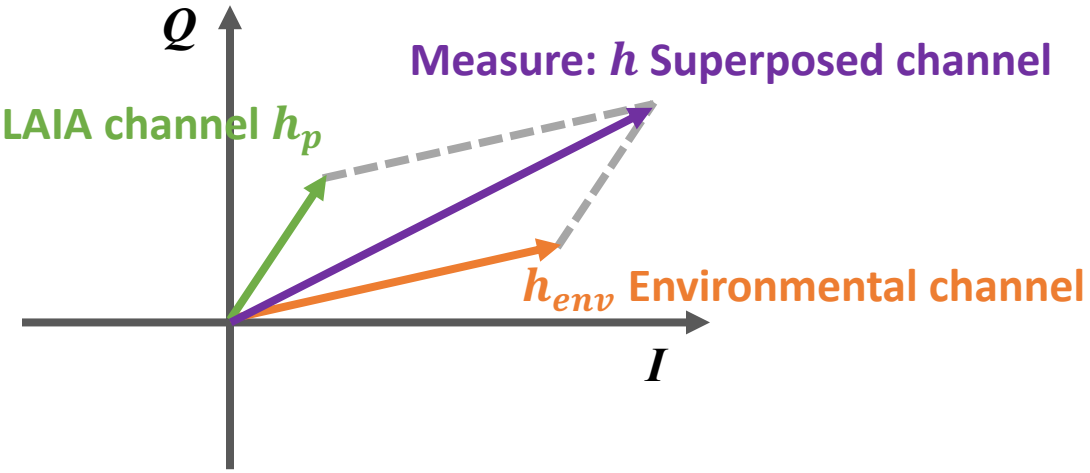

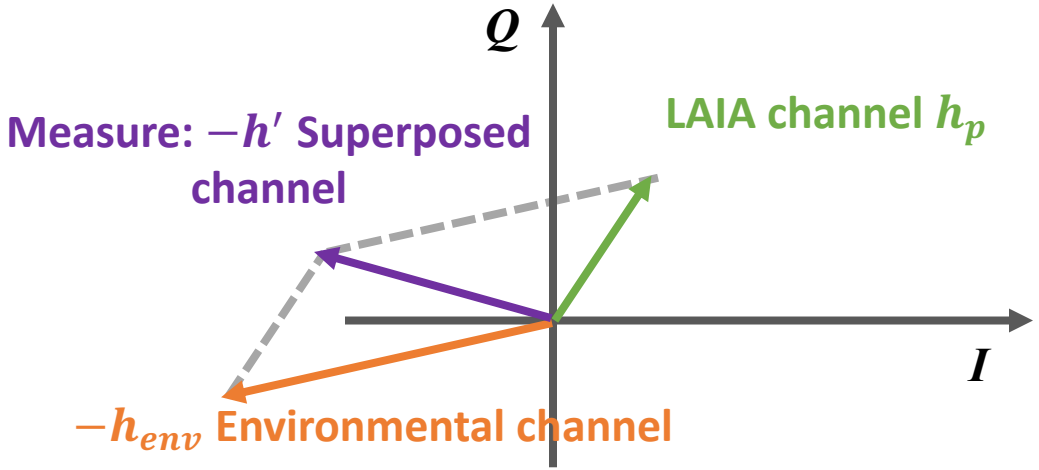

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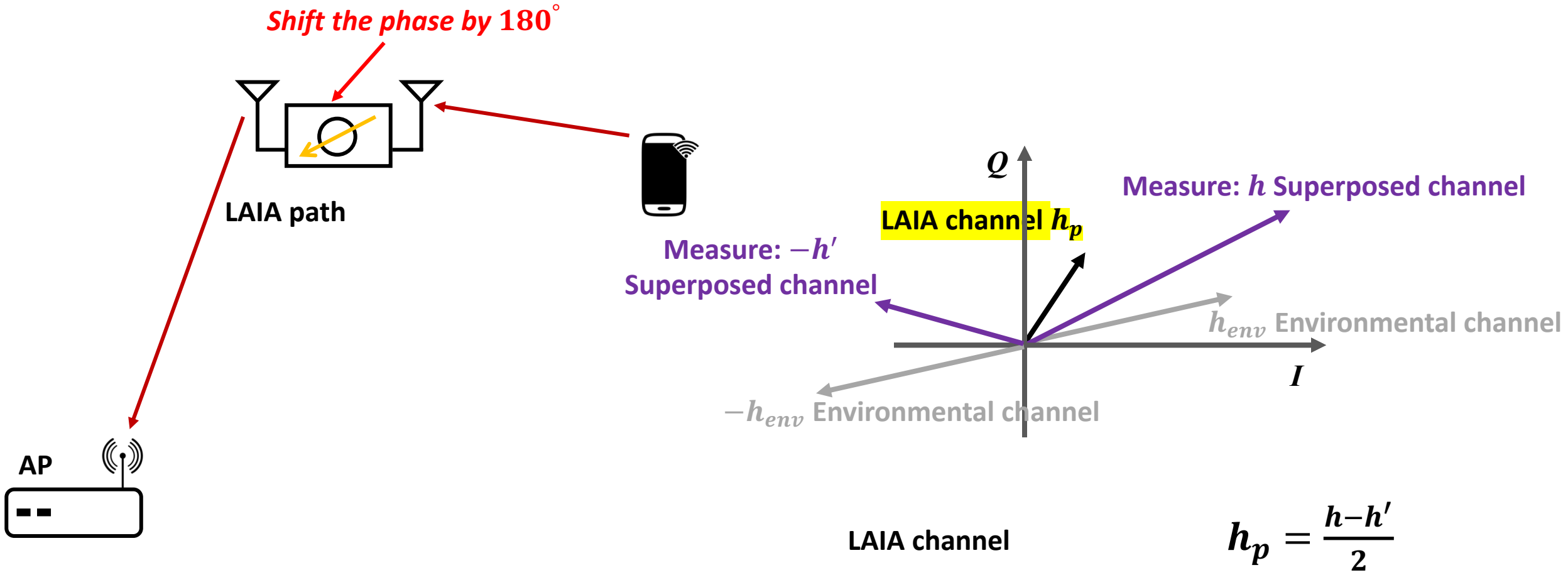

LAIA channel $h_p = \frac{h - h'}{2}$

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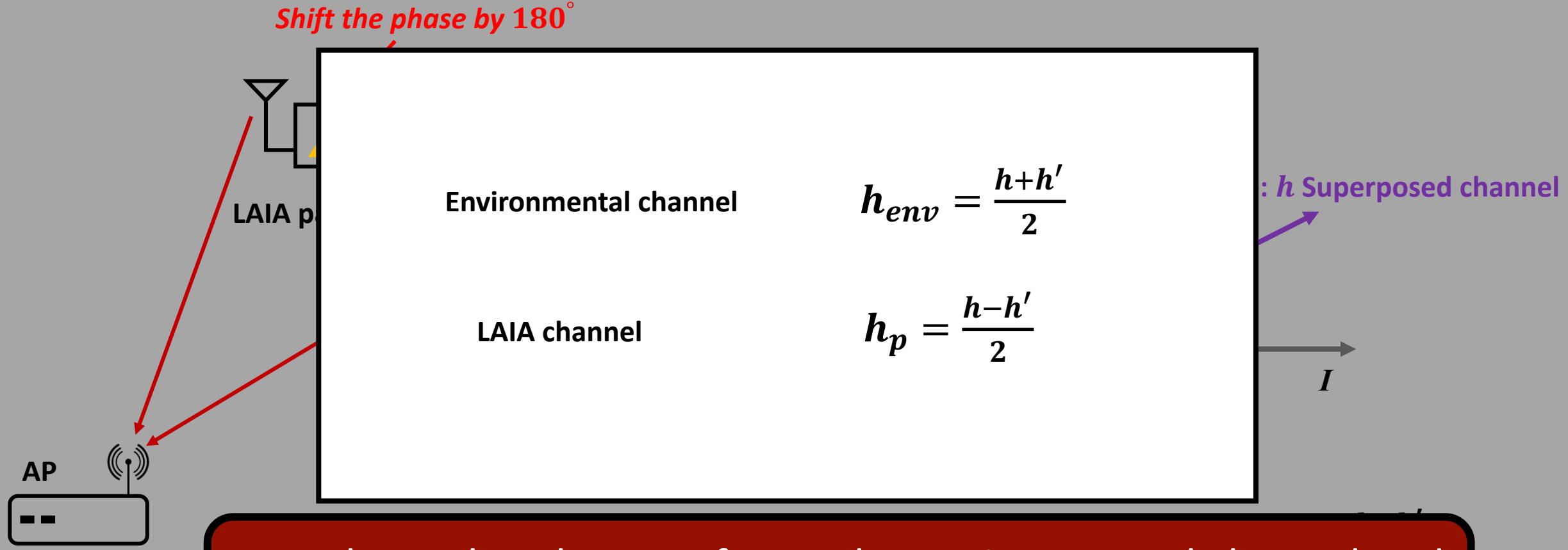
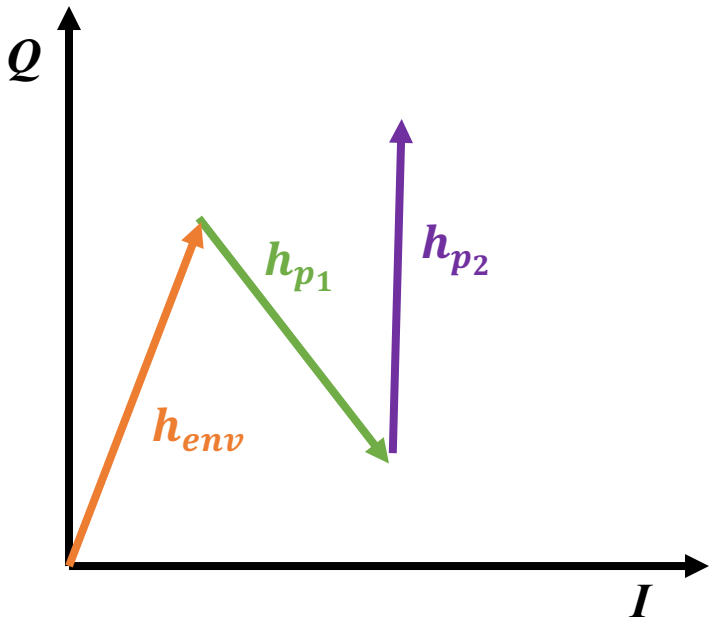


Two channel probes can factor the environmental channel and a LAIA element channel

Multi-element case: how to decompose?



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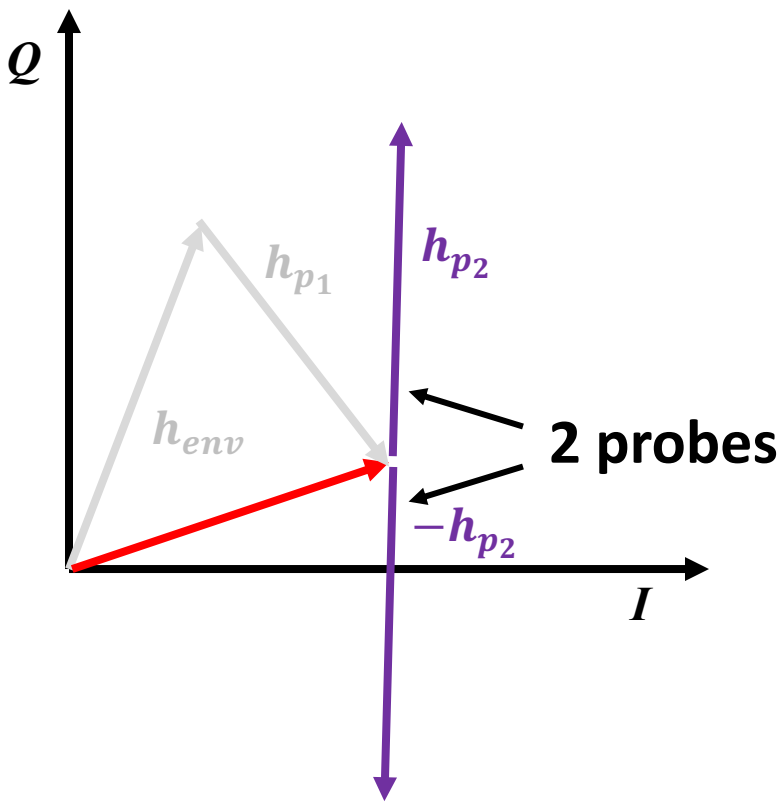

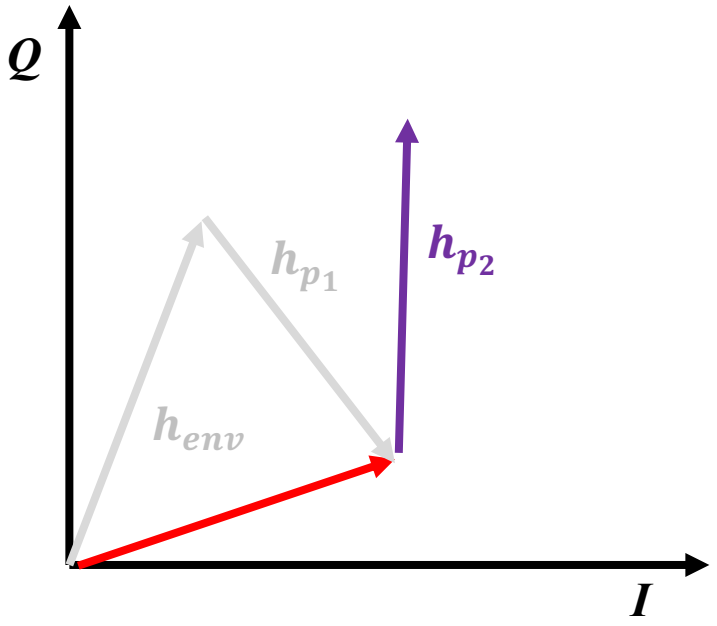

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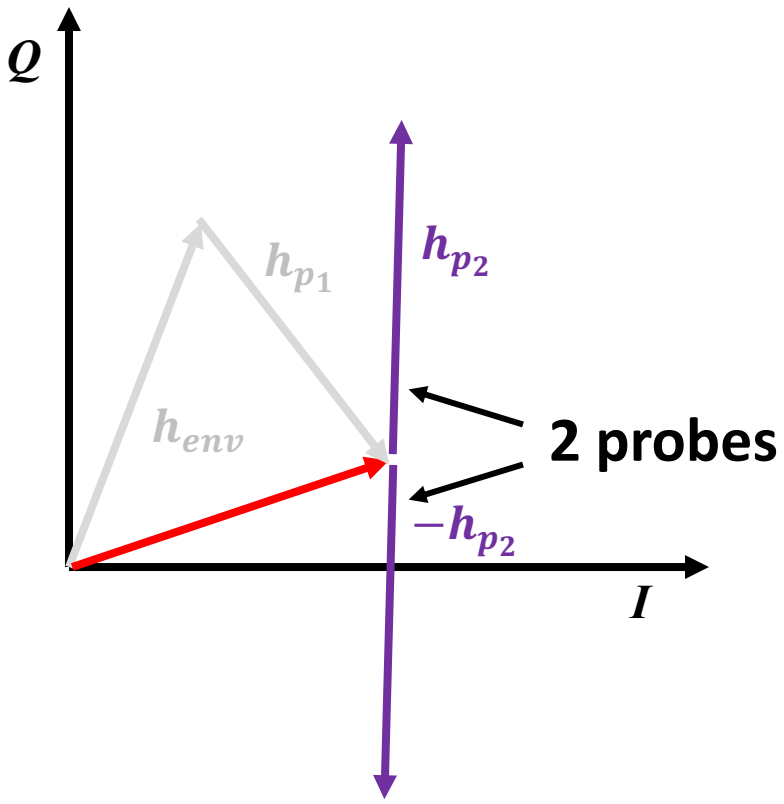

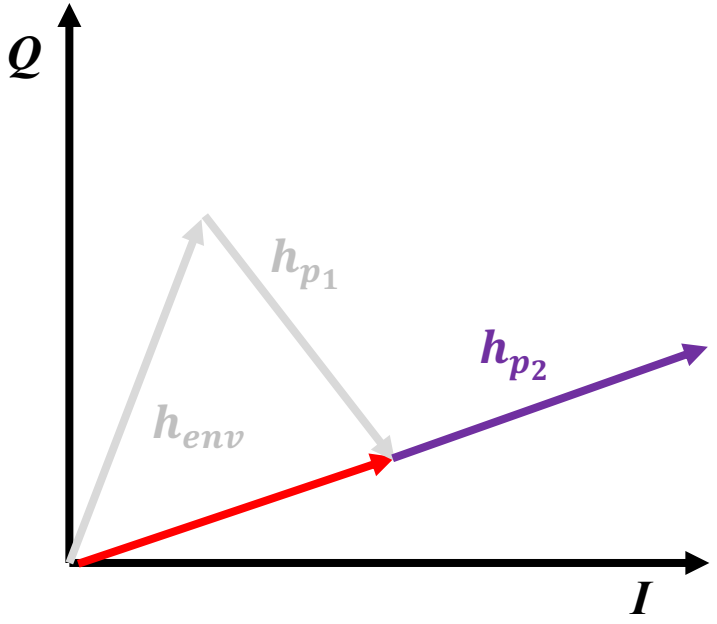

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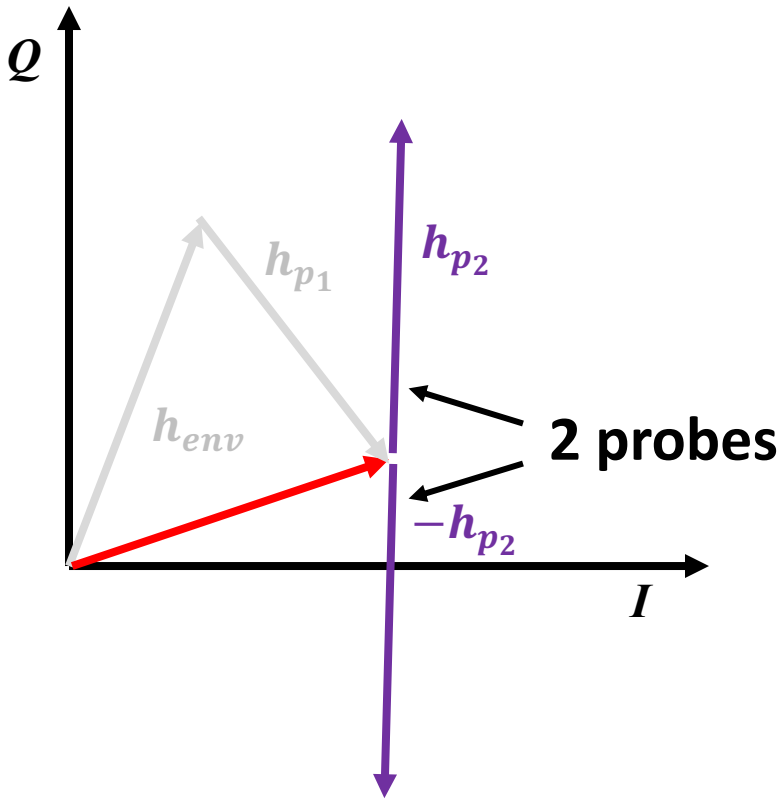

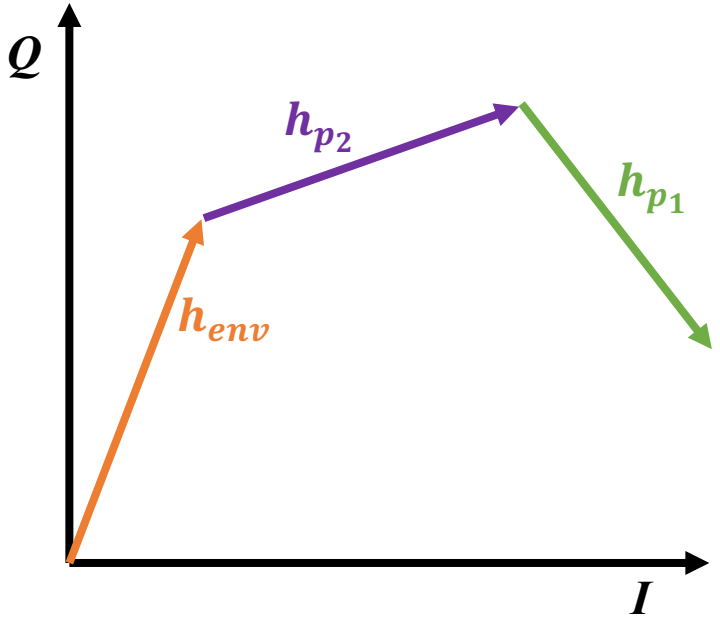

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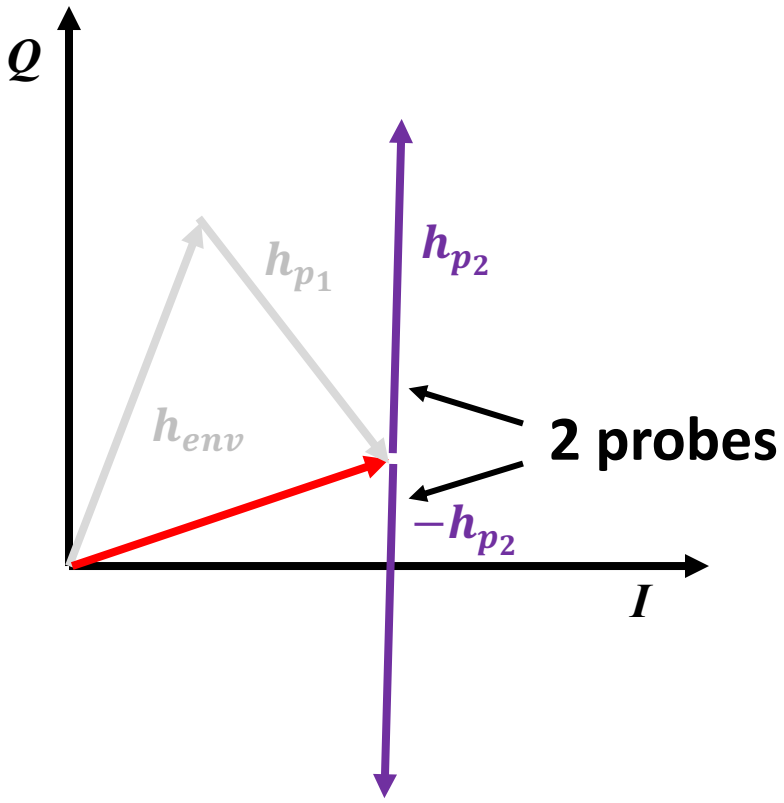

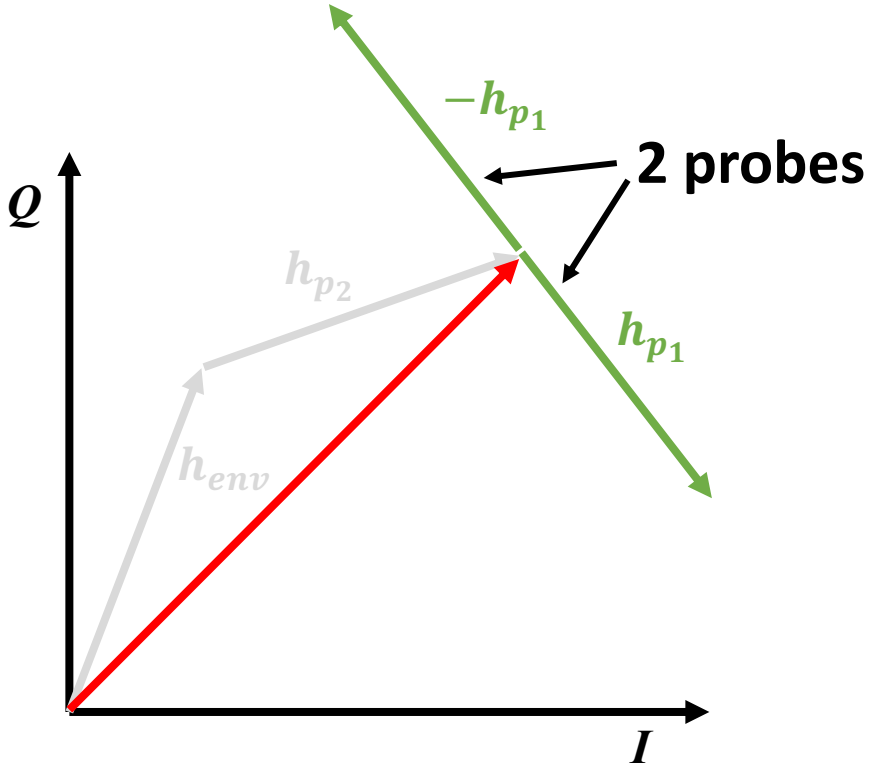

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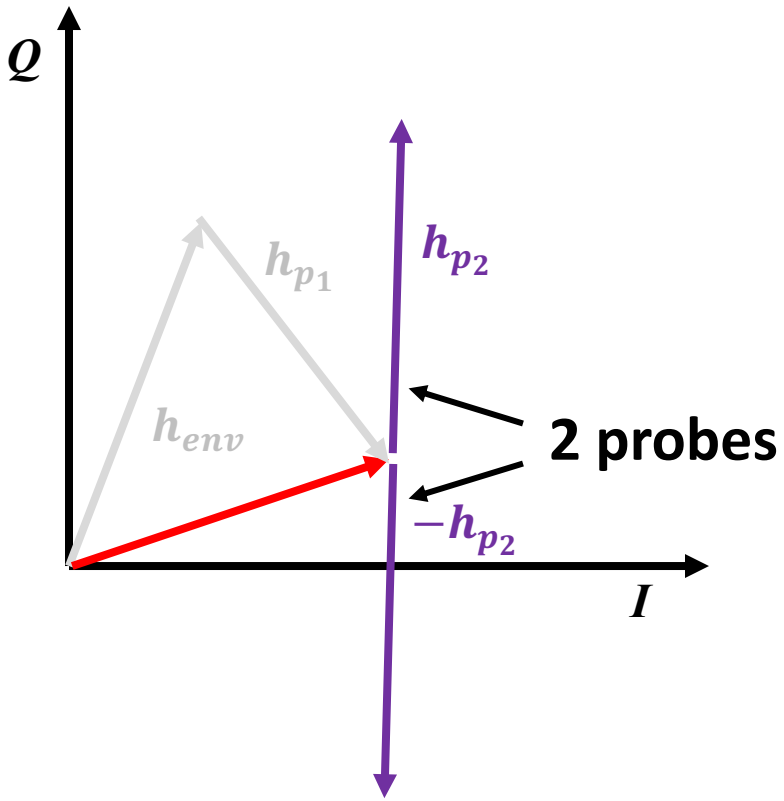

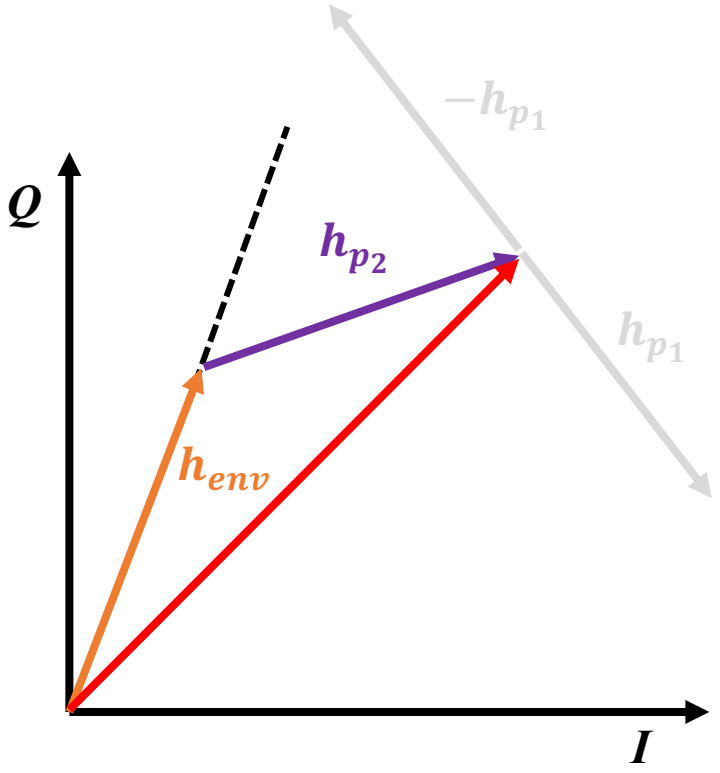

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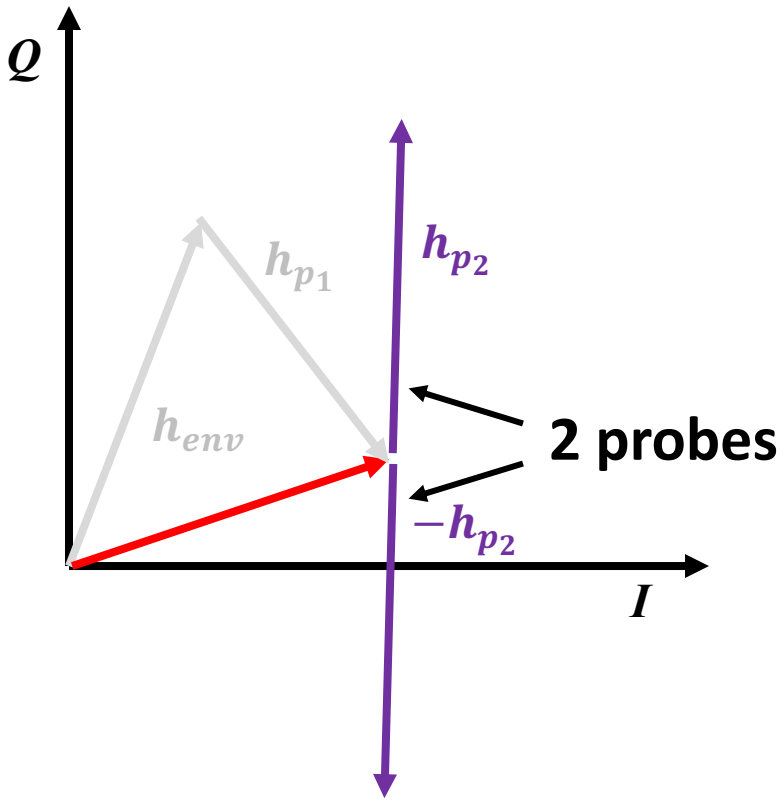
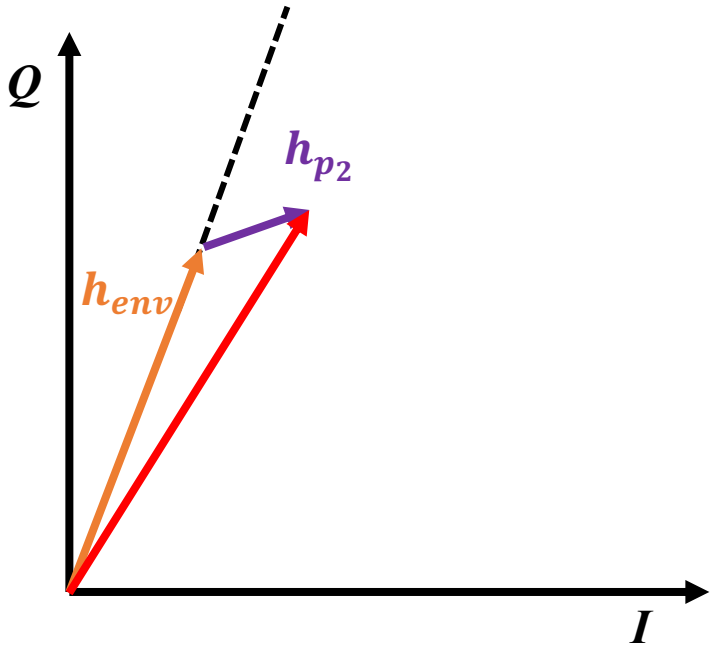
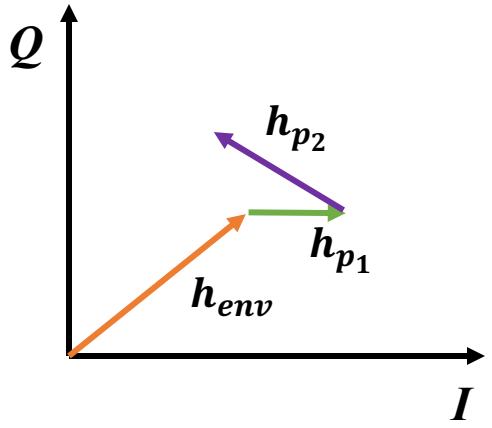




Channel alignment



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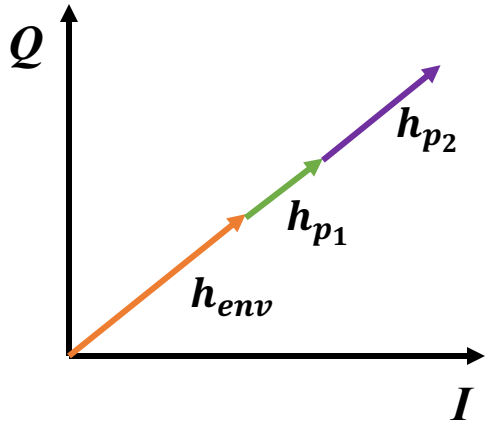
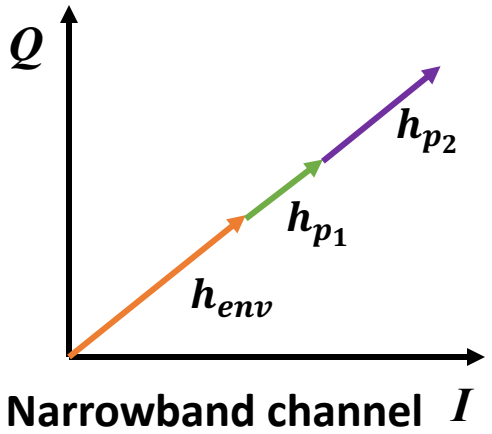
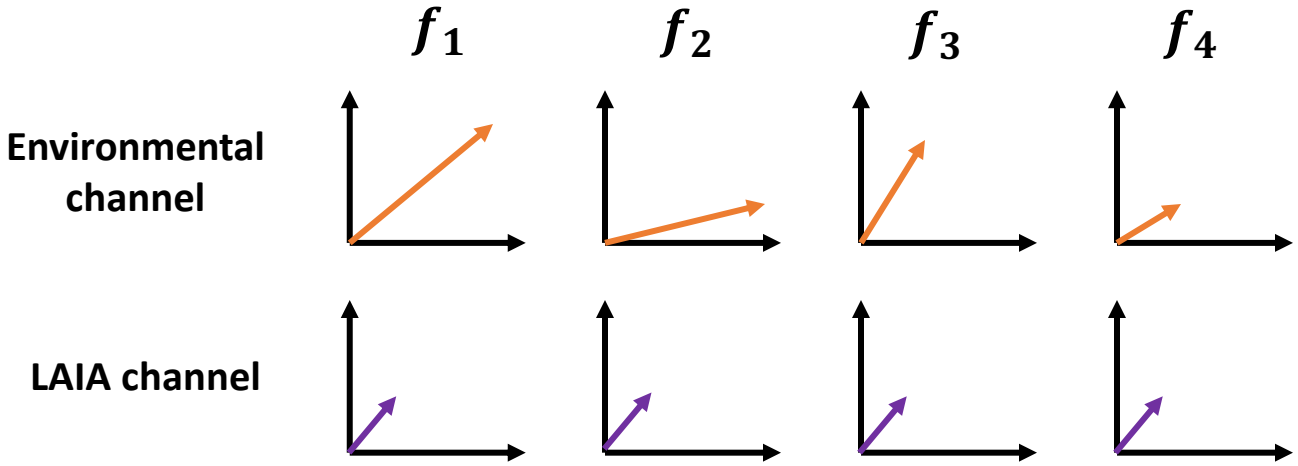


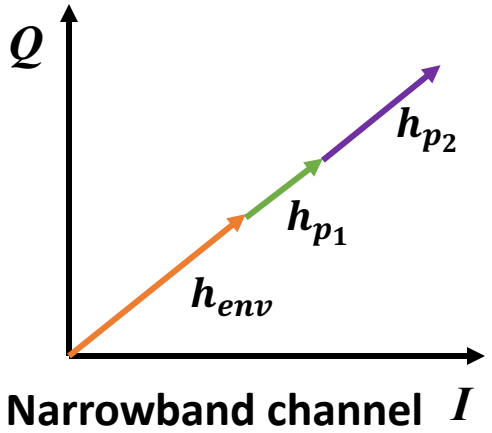
Channel alignment

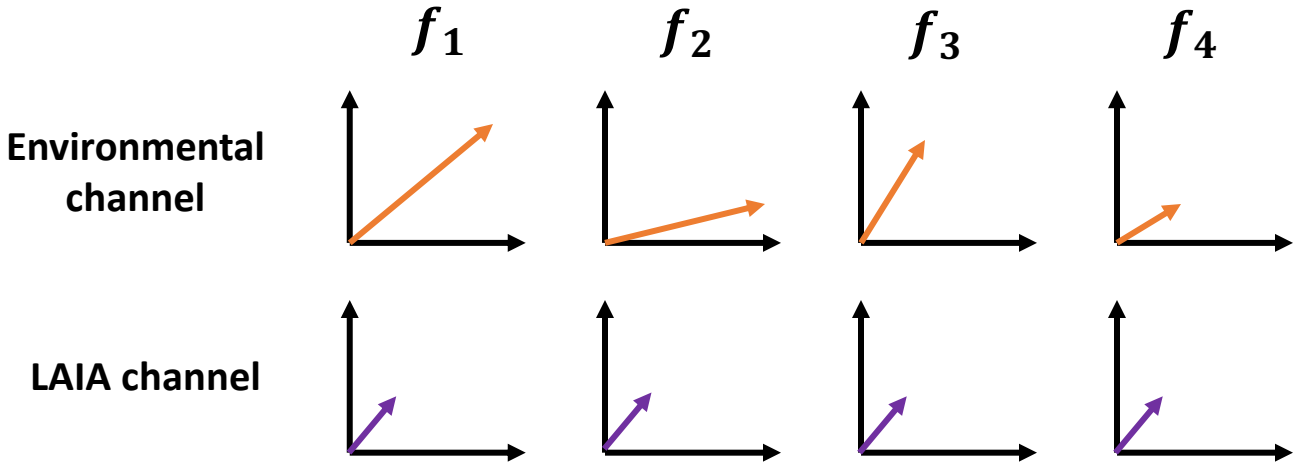




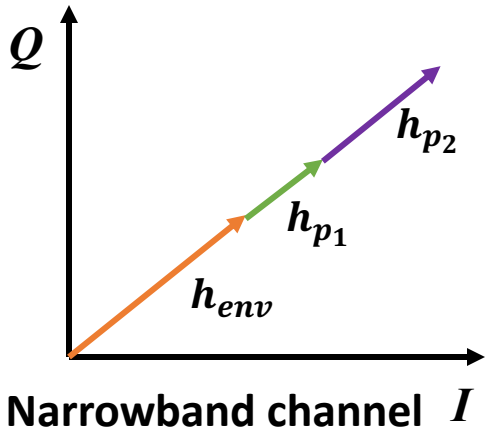
Phase shifter rotate the same amount of phase for channels of different frequencies!

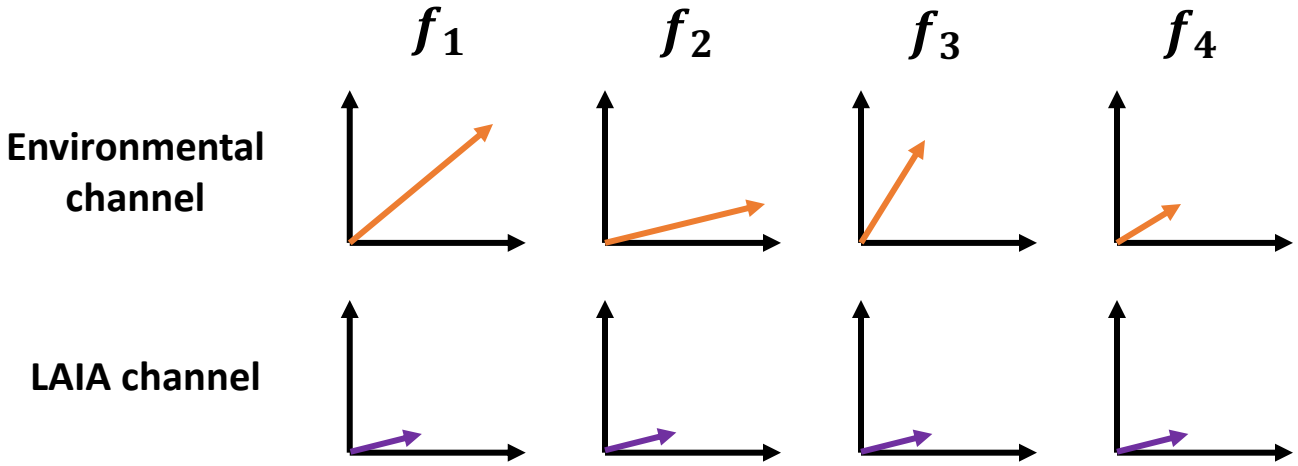
Channel alignment



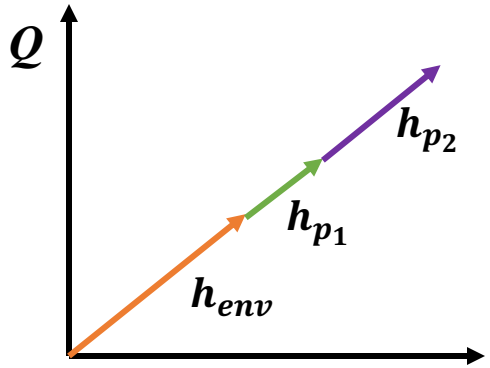


Channel alignment



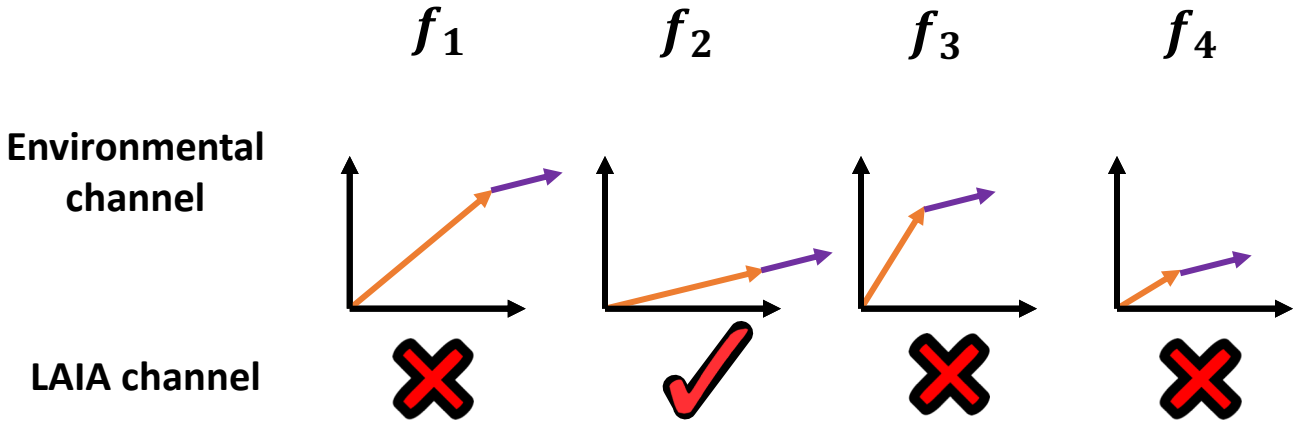


Channel alignment

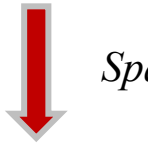


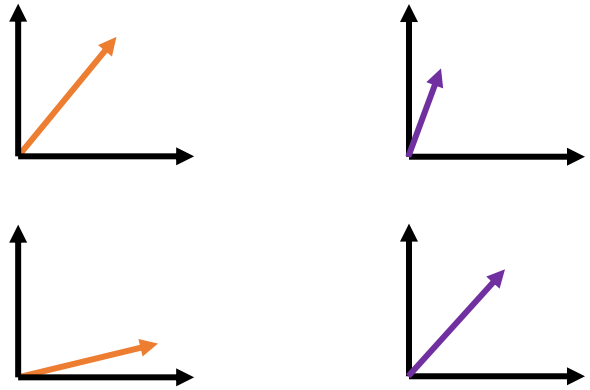
Narrowband channel

Frequency



Spatial





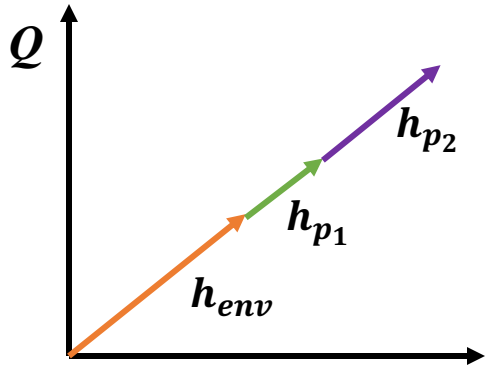
Antenna 1

Antenna 2

Environmental channel

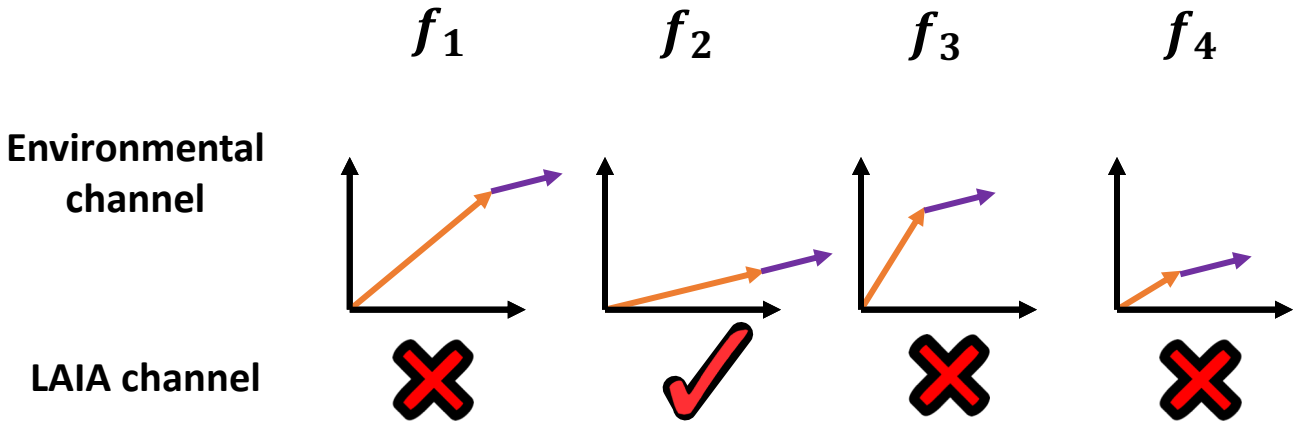
LAIA channel

Channel alignment

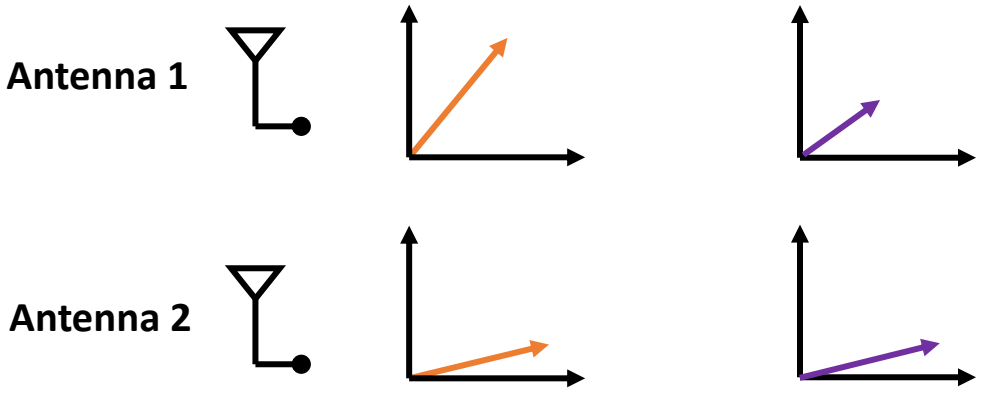


Narrowband channel

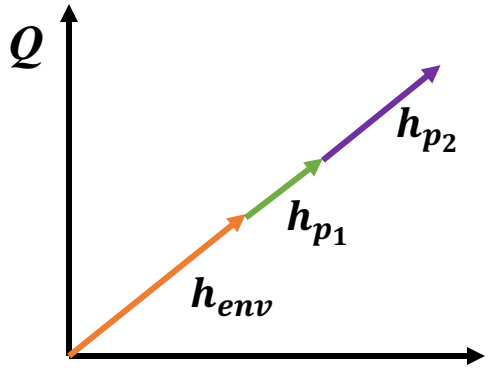
Frequency



Spatial

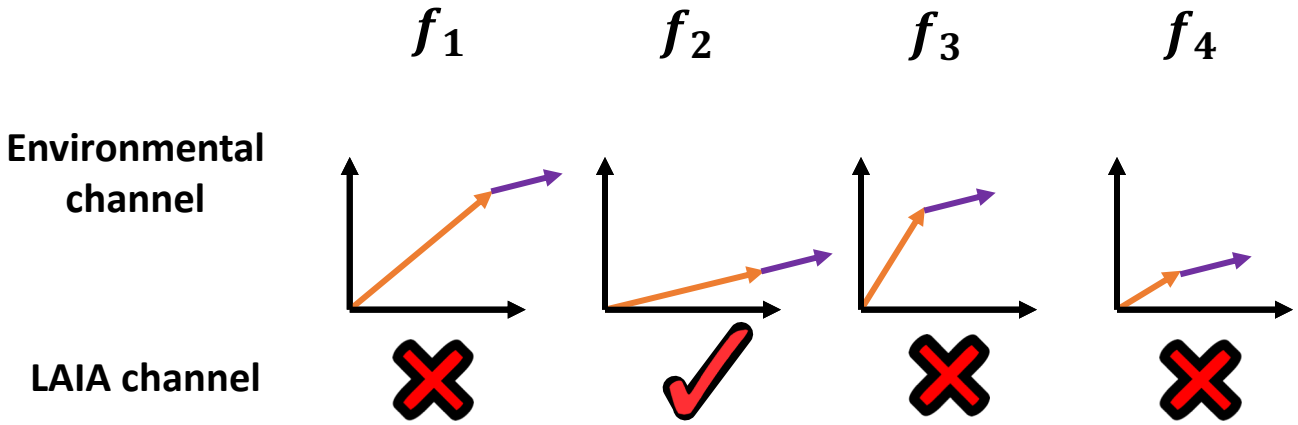


Channel alignment

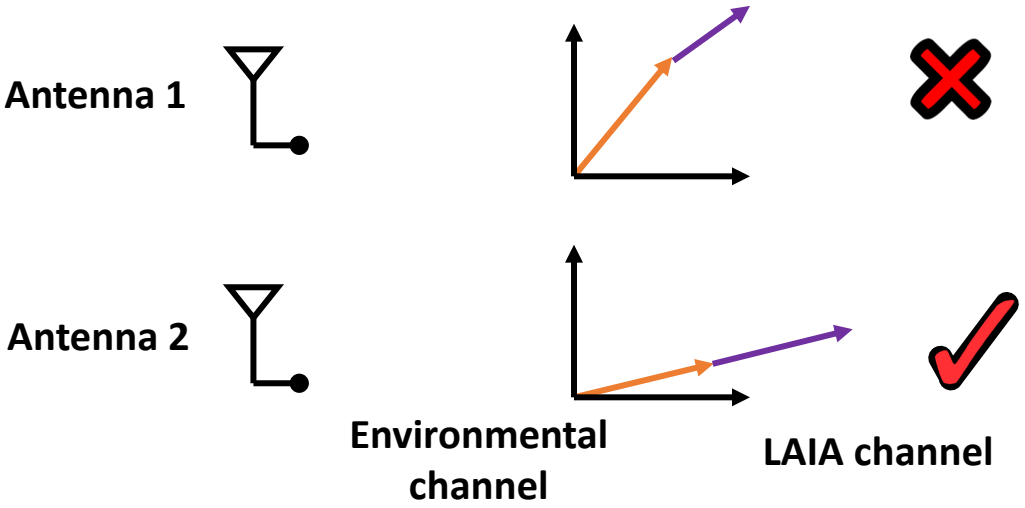


Narrowband channel

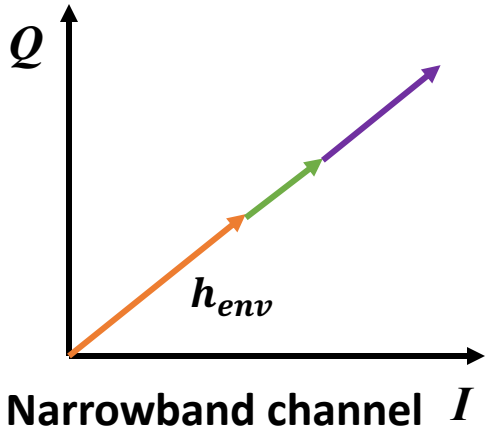
Frequency



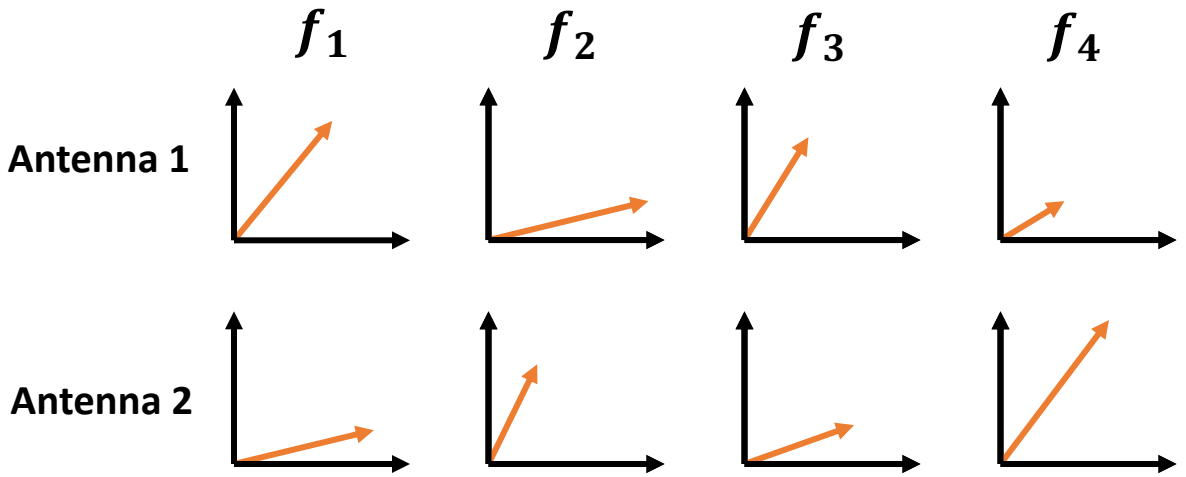
Spatial



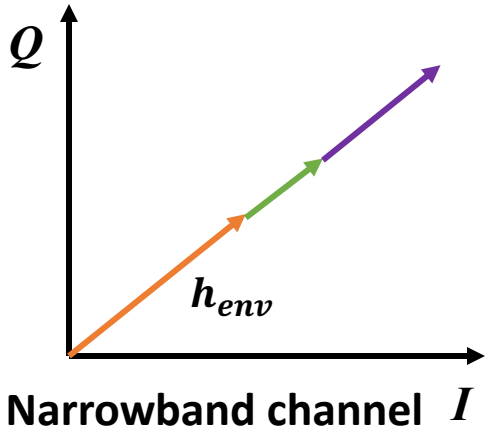
Channel alignment



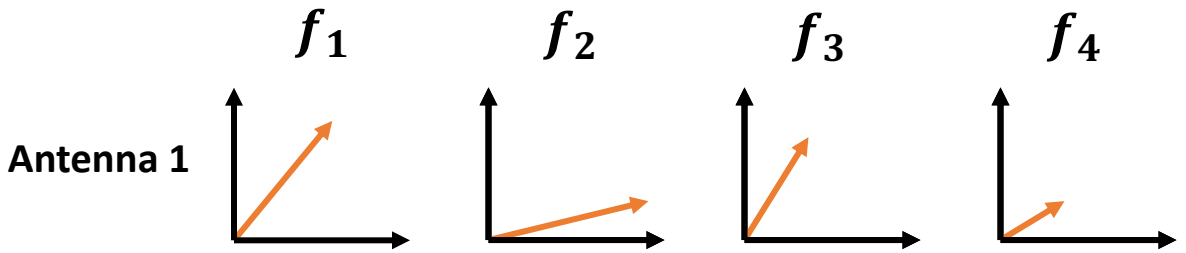
MIMO-OFDM channel



Channel alignment



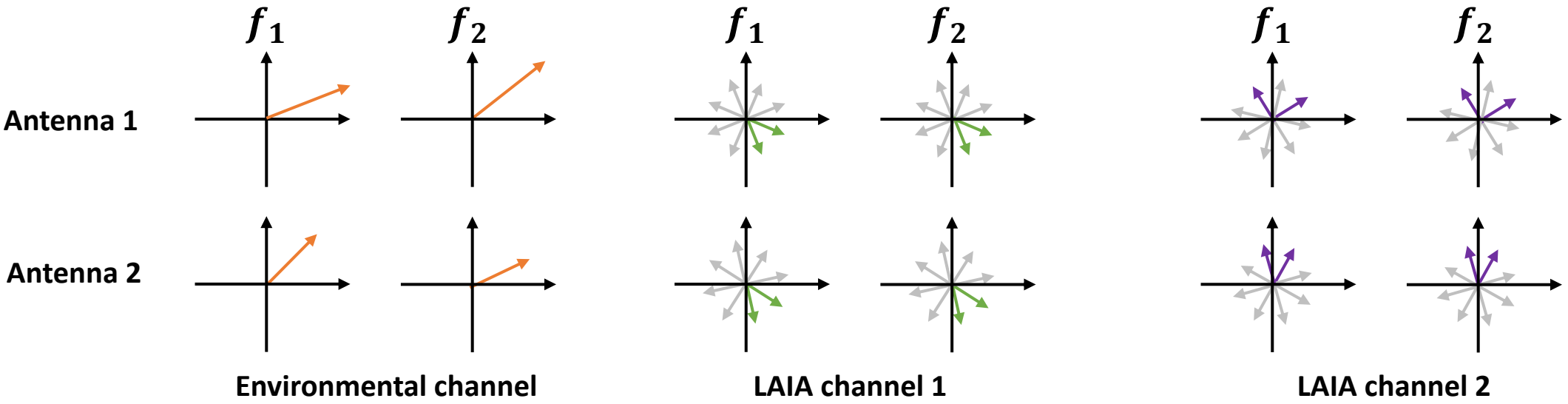
MIMO-OFDM channel



Problem: simultaneously align across multiple frequencies and antennas

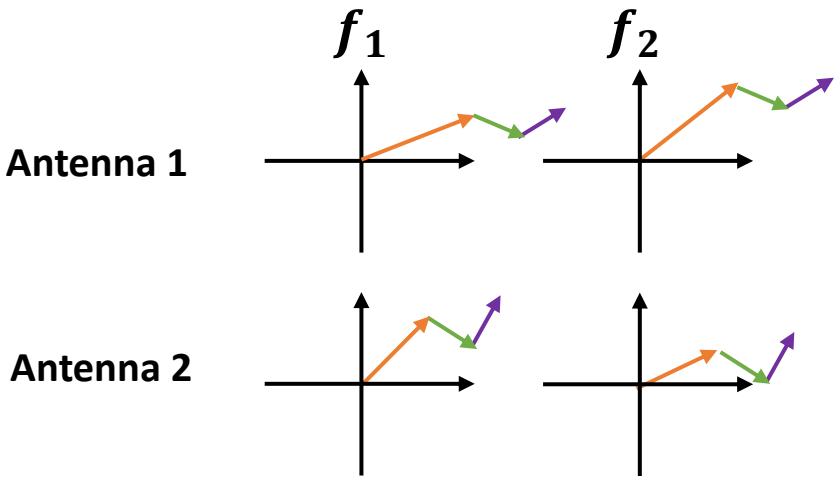
Strawman solution: exhaustive search

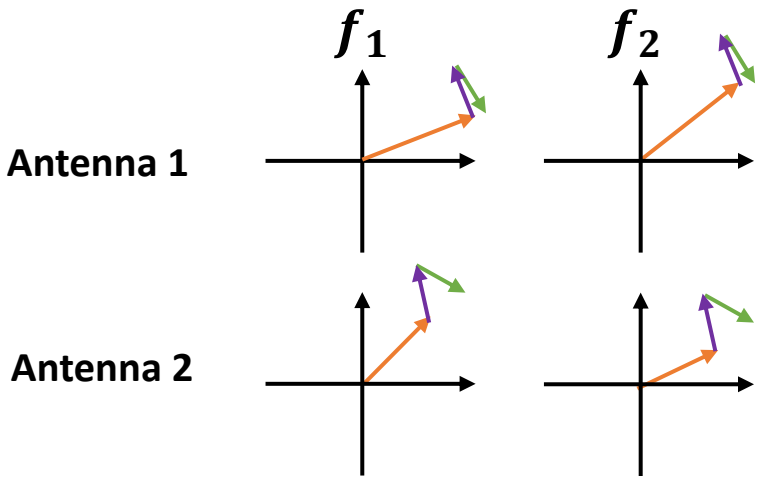
- ***Example***: 2-element LAIA array, MIMO wideband channel, 3-bit phase shifter (8 possible phase)



Strawman solution: exhaustive search

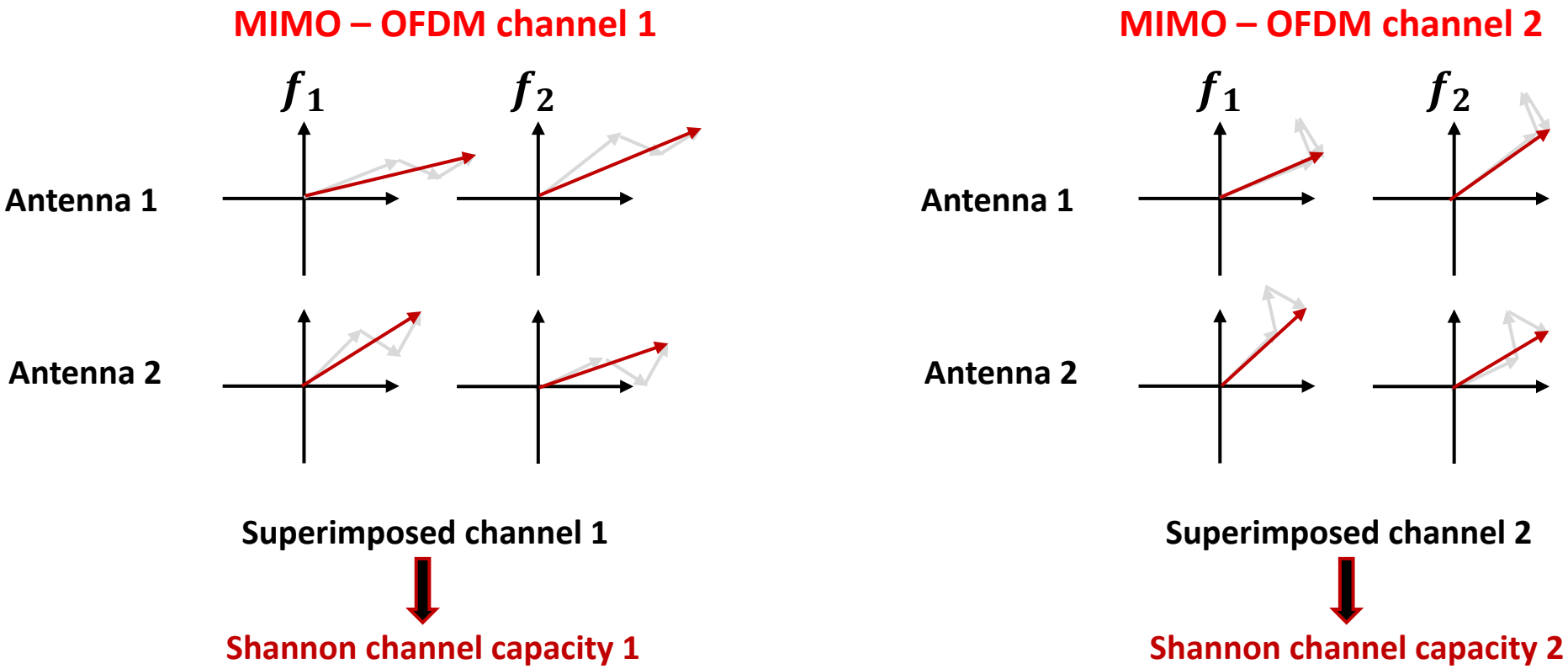
- ***Example***: 2-element LAIA array, MIMO wideband channel, 3-bit phase shifter (8 possible phase)





Strawman solution: exhaustive search

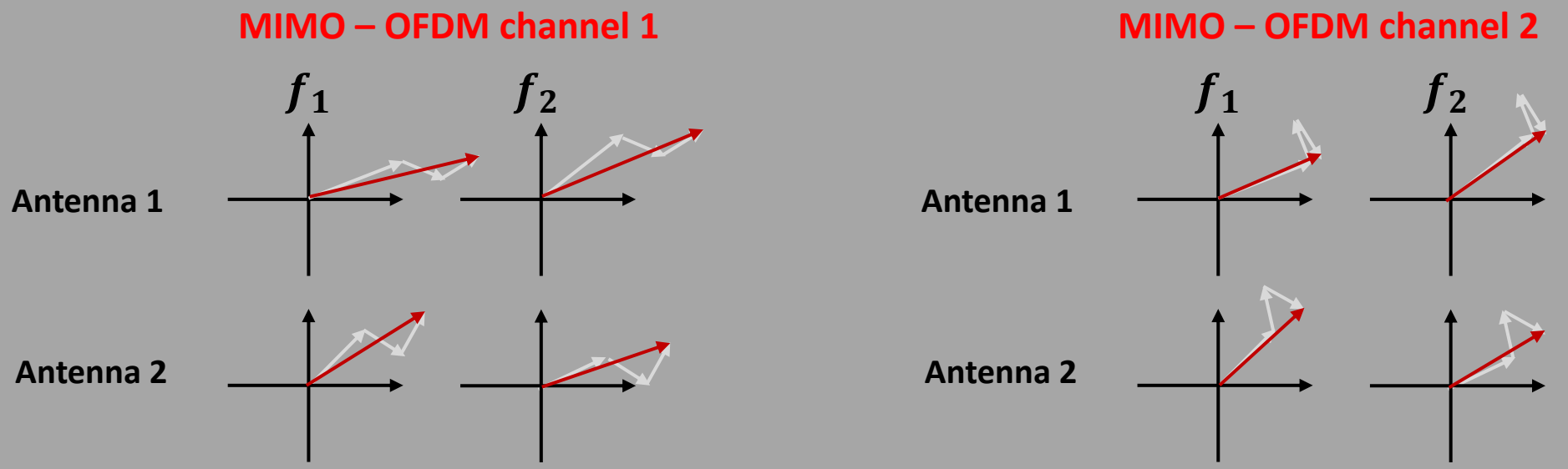
- ***Example***: 2-element LAIA array, MIMO wideband channel, 3-bit phase shifter (8 possible phase)



8^2 possible combinations

Strawman solution: exhaustive search

- ***Example***: 2-element LAIA array, MIMO wideband channel, 3-bit phase shifter (8 possible phase)

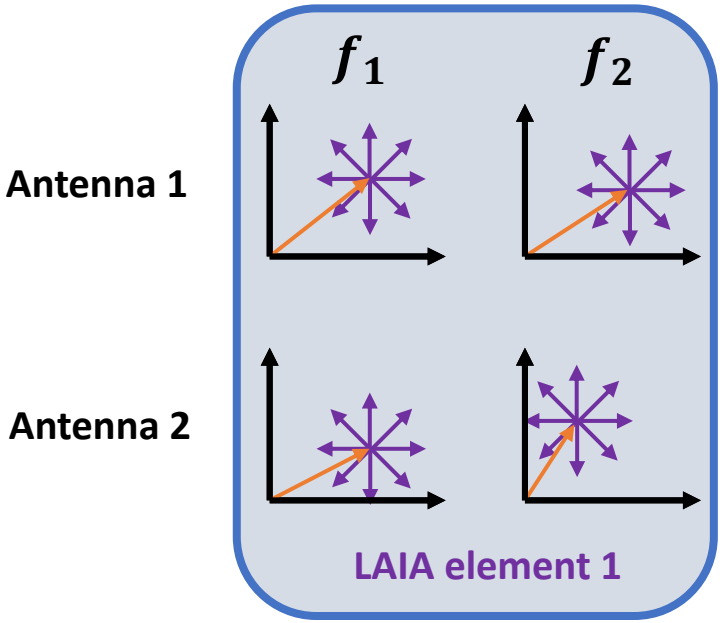


Search space is N^L where N is the number of phase shifts and L is the number of LAIA elements!

8 possible combinations

Our solution: iterative search

- ***Example***: 2-element LAIA array, MIMO wideband channel, 3-bit phase shifter (8 possible phase)

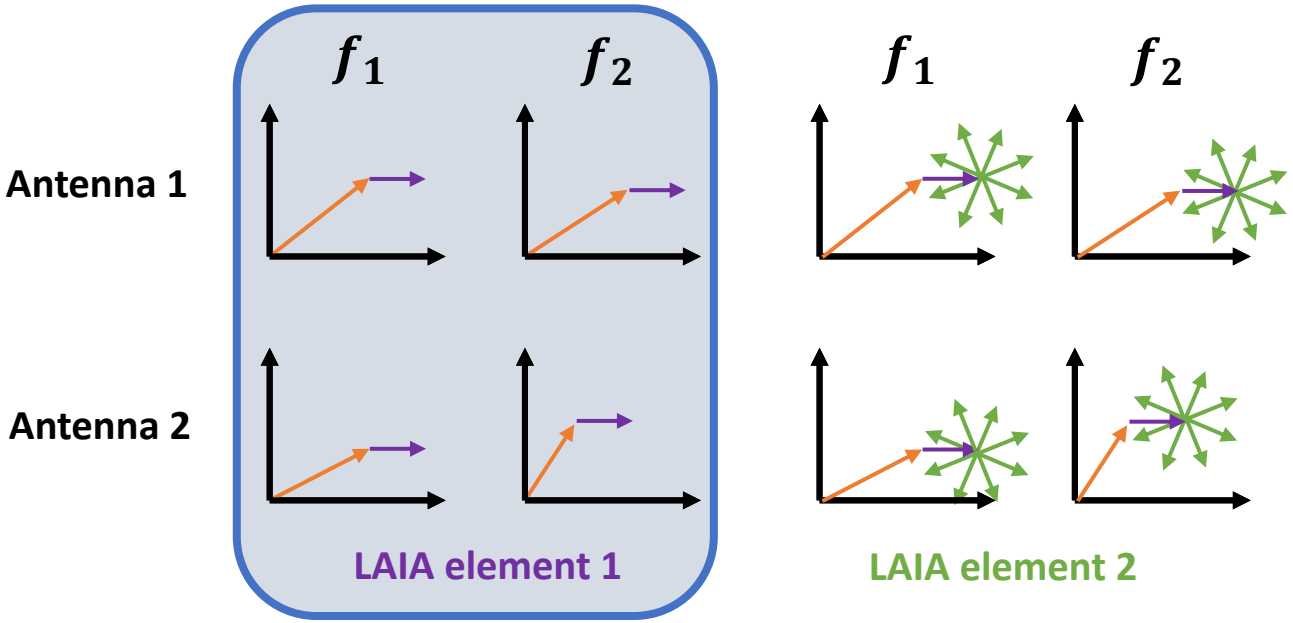


Channel capacity

$C_1(ele_1)$

Our solution: iterative search

- ***Example***: 2-element LAIA array, MIMO wideband channel, 3-bit phase shifter (8 possible phase)



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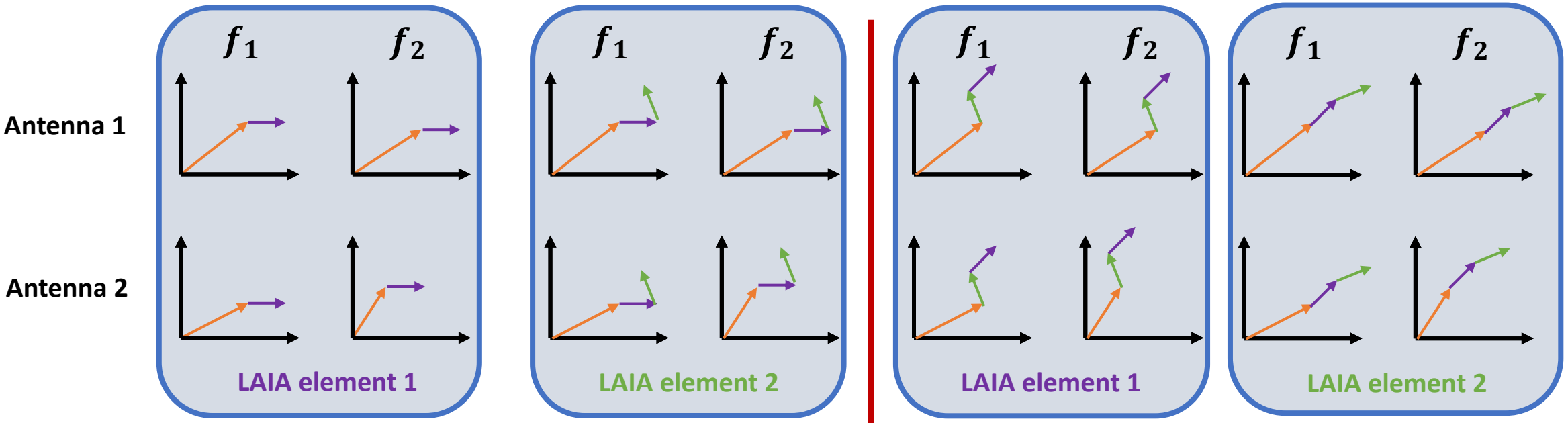
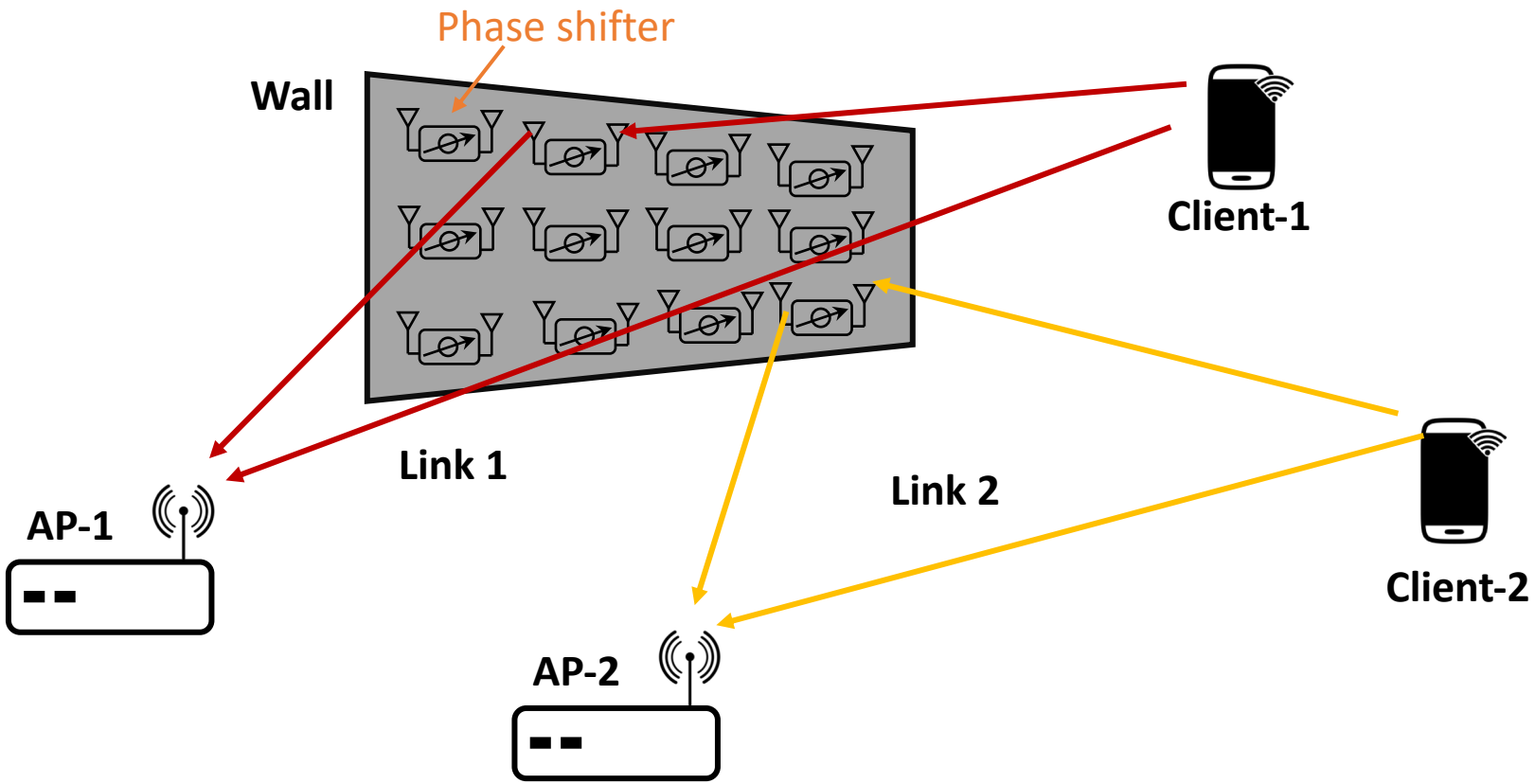
- ***Example***: 2-element LAIA array, MIMO wideband channel, 3-bit phase shifter (8 possible phase)



Multiple links

- Multiple links share the wireless medium via CSMA
- LAIA elements must be configured before working



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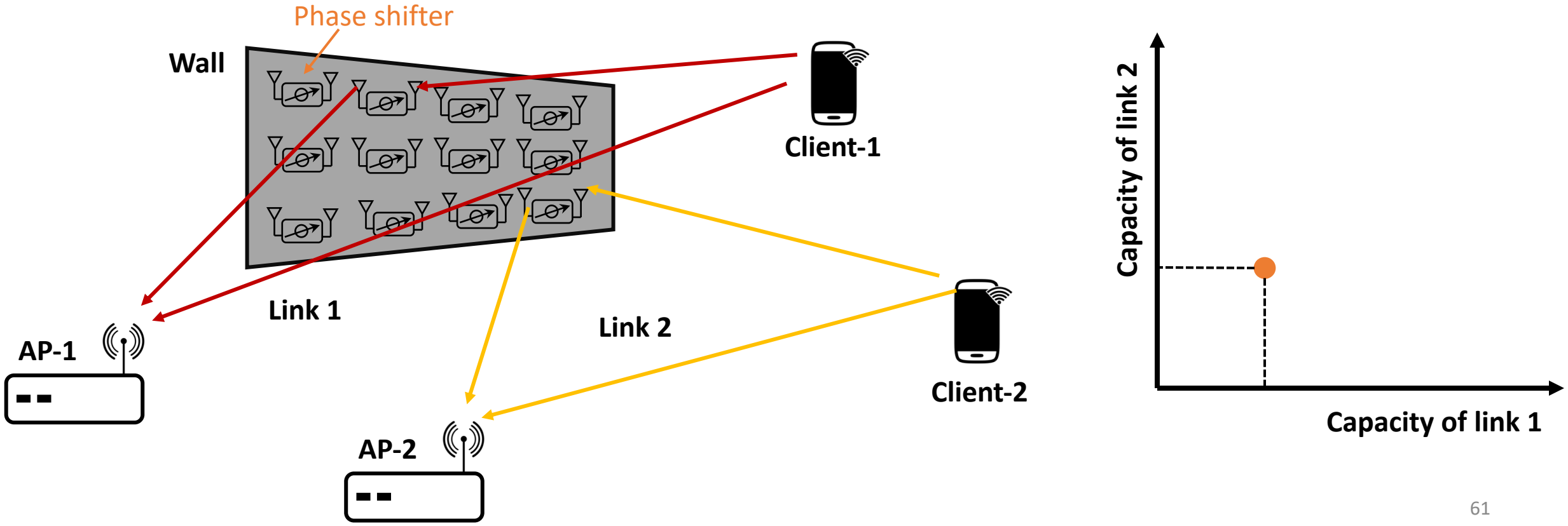

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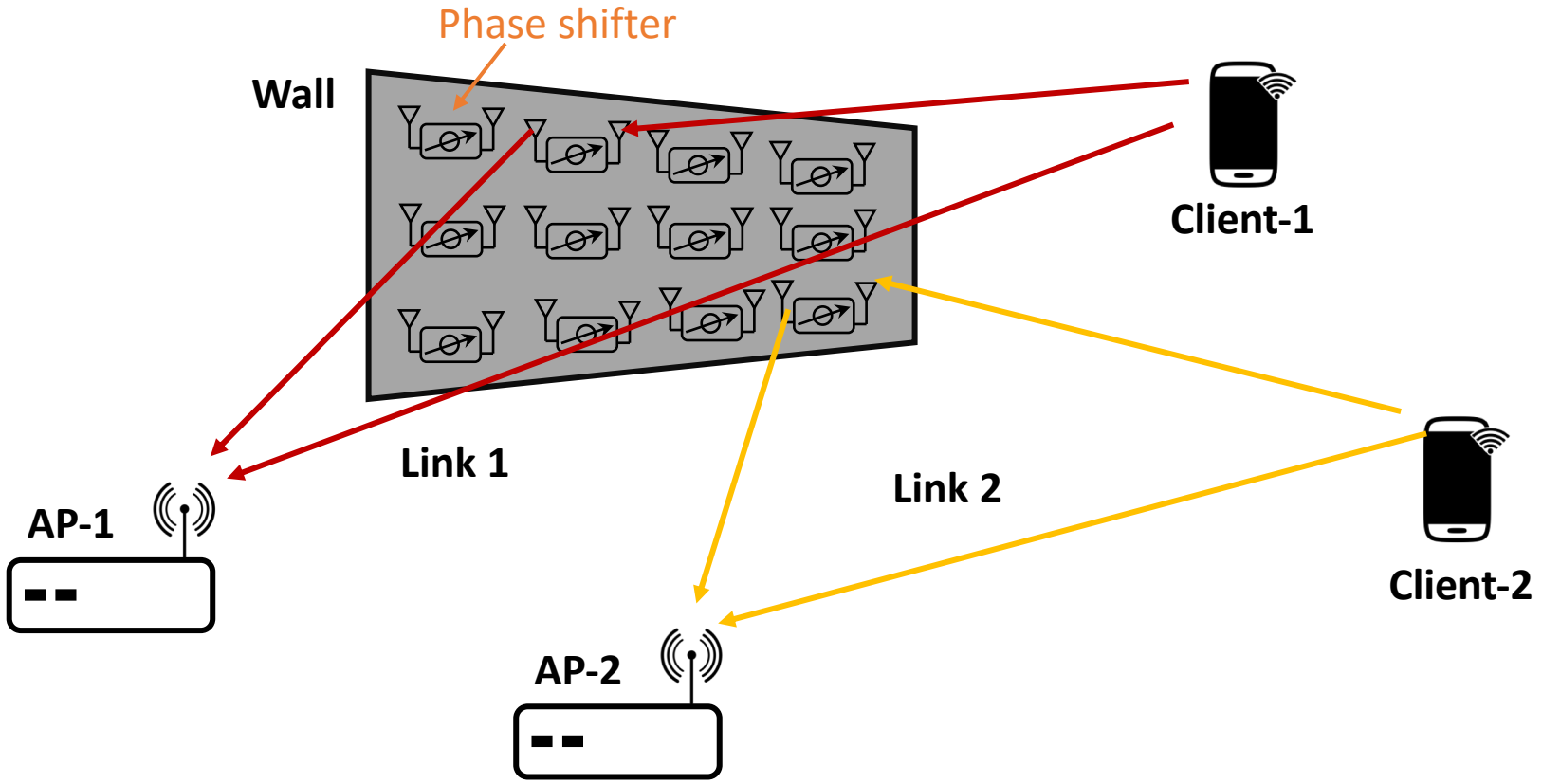

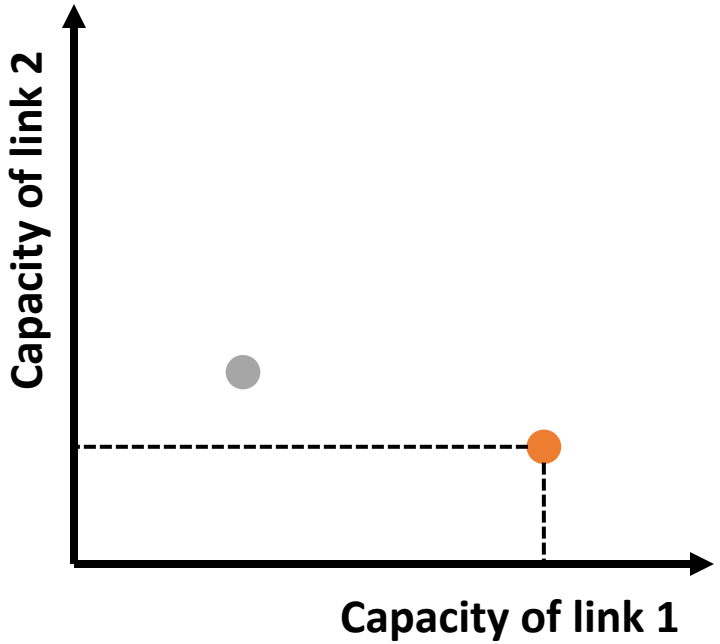

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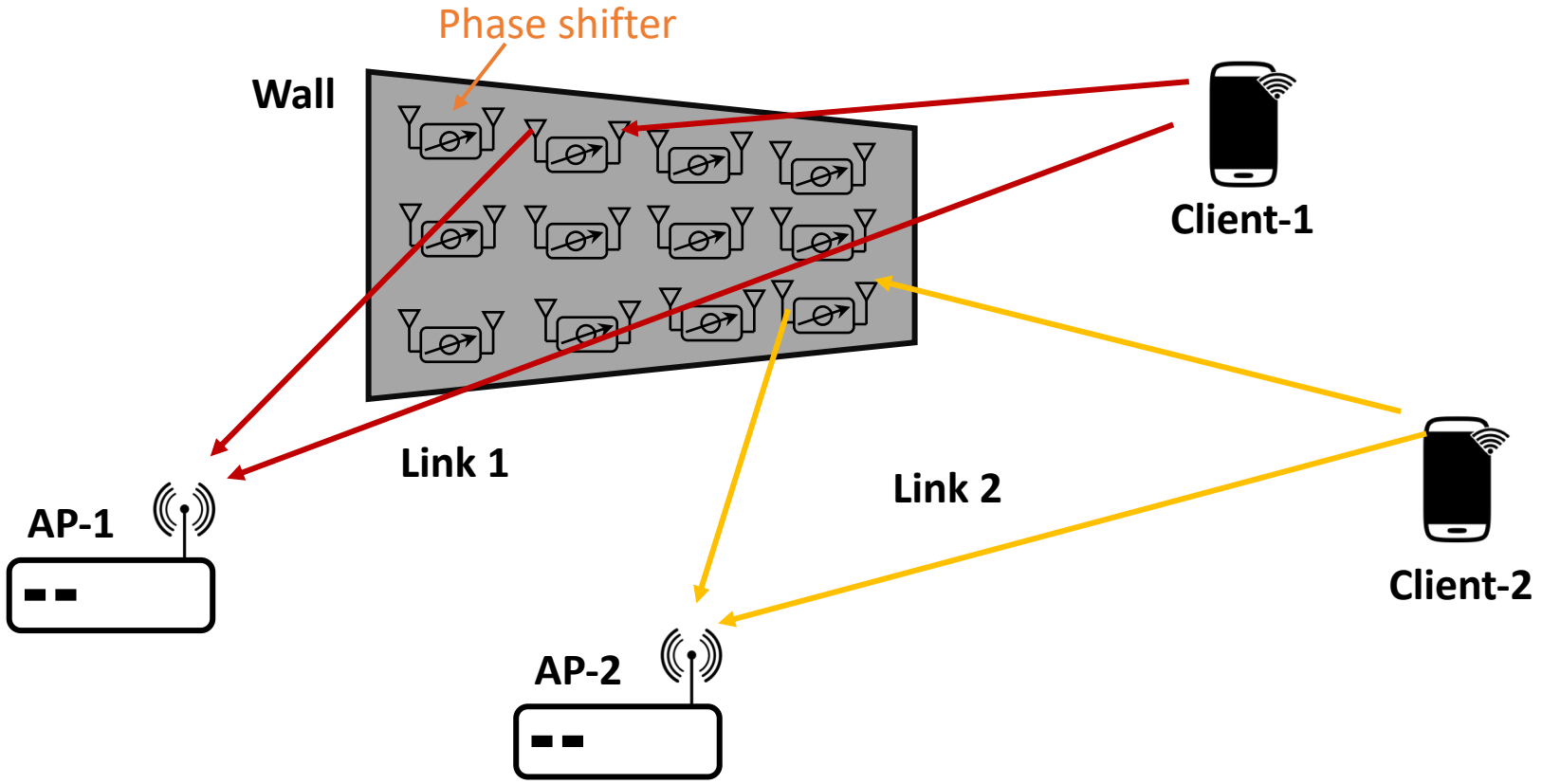

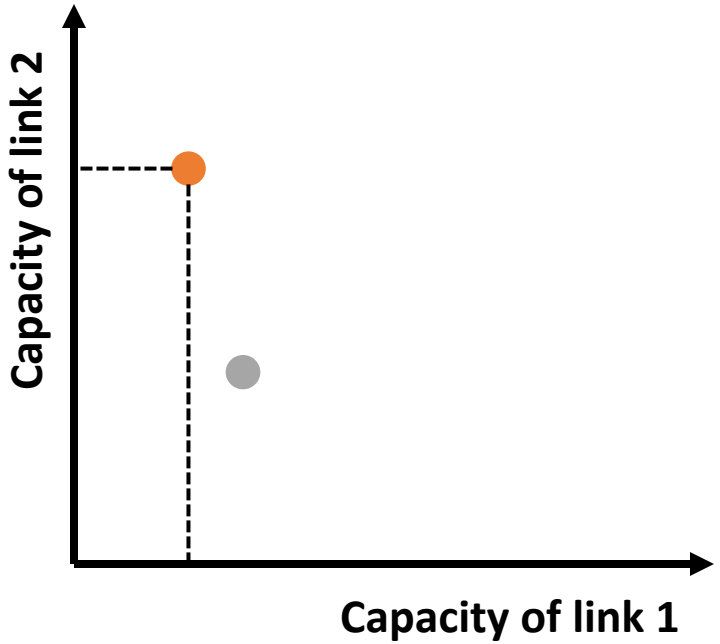

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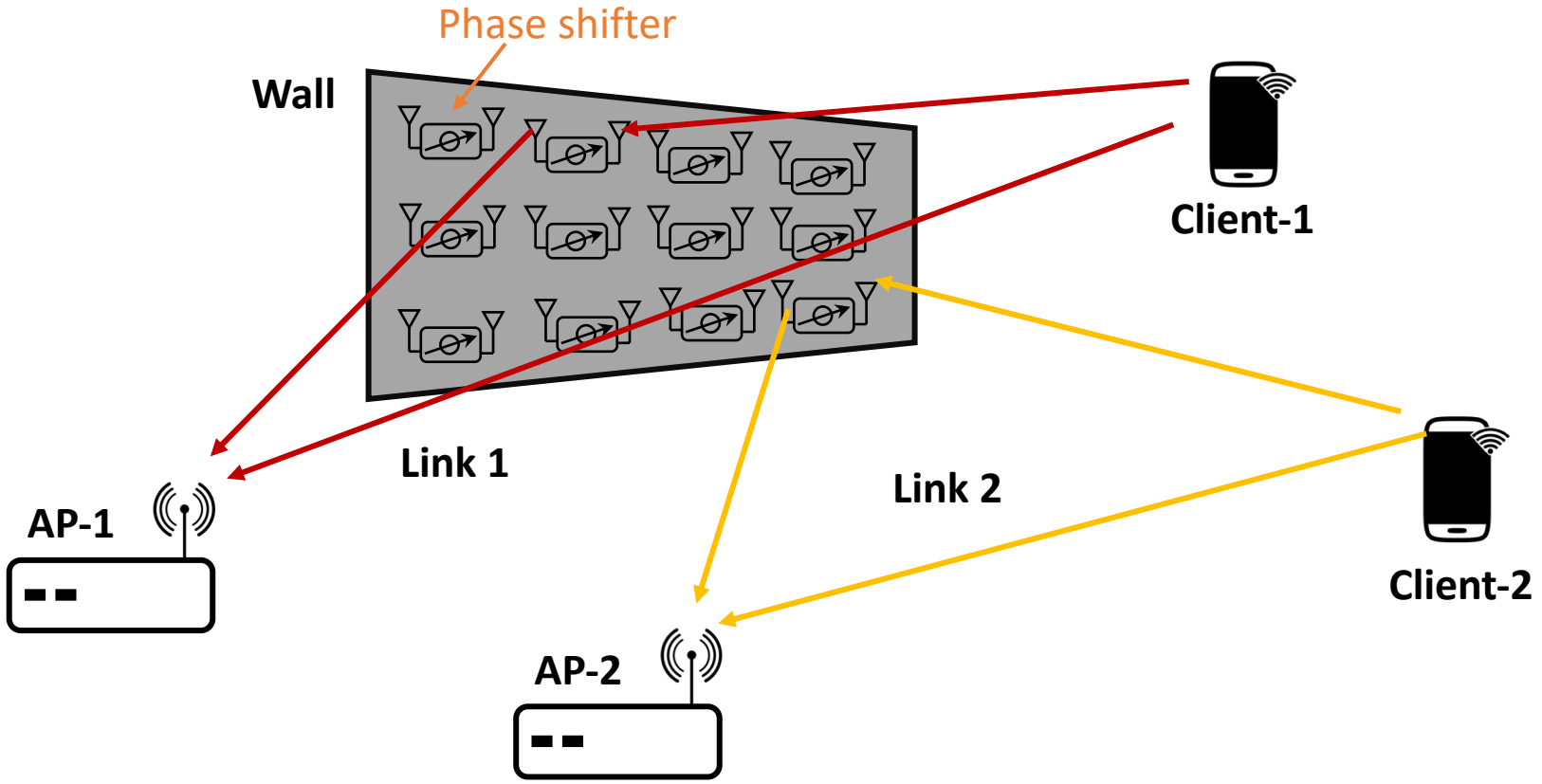

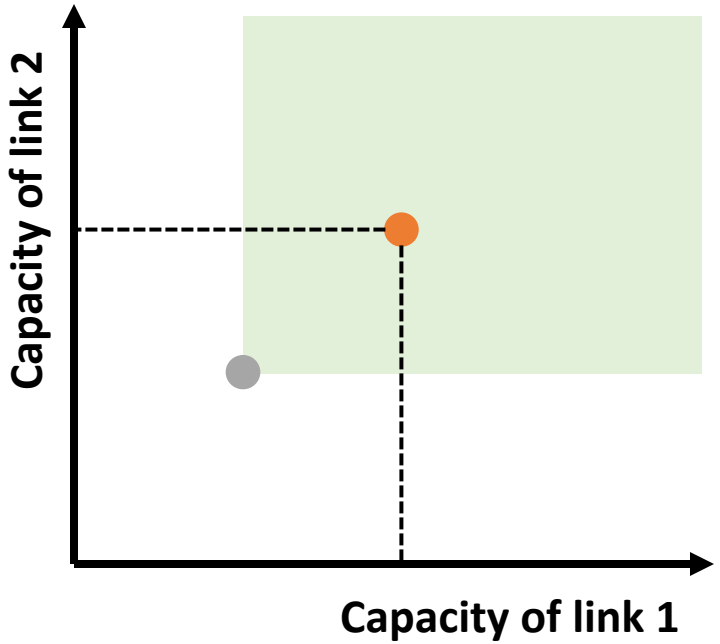

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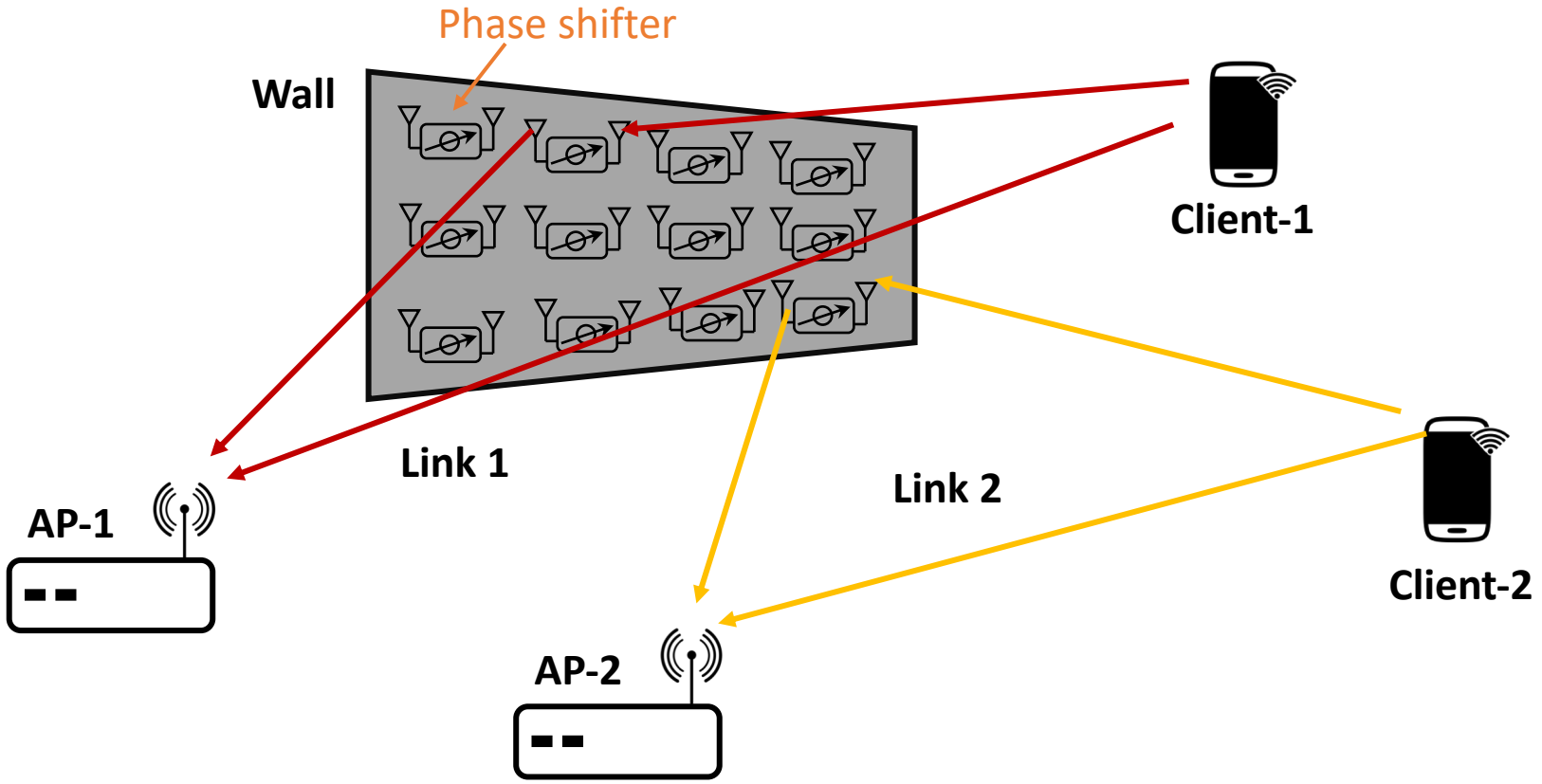

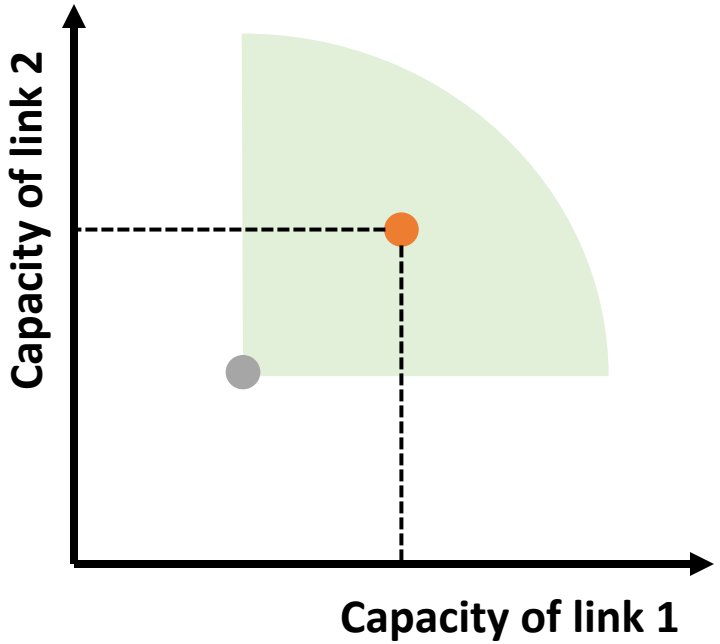

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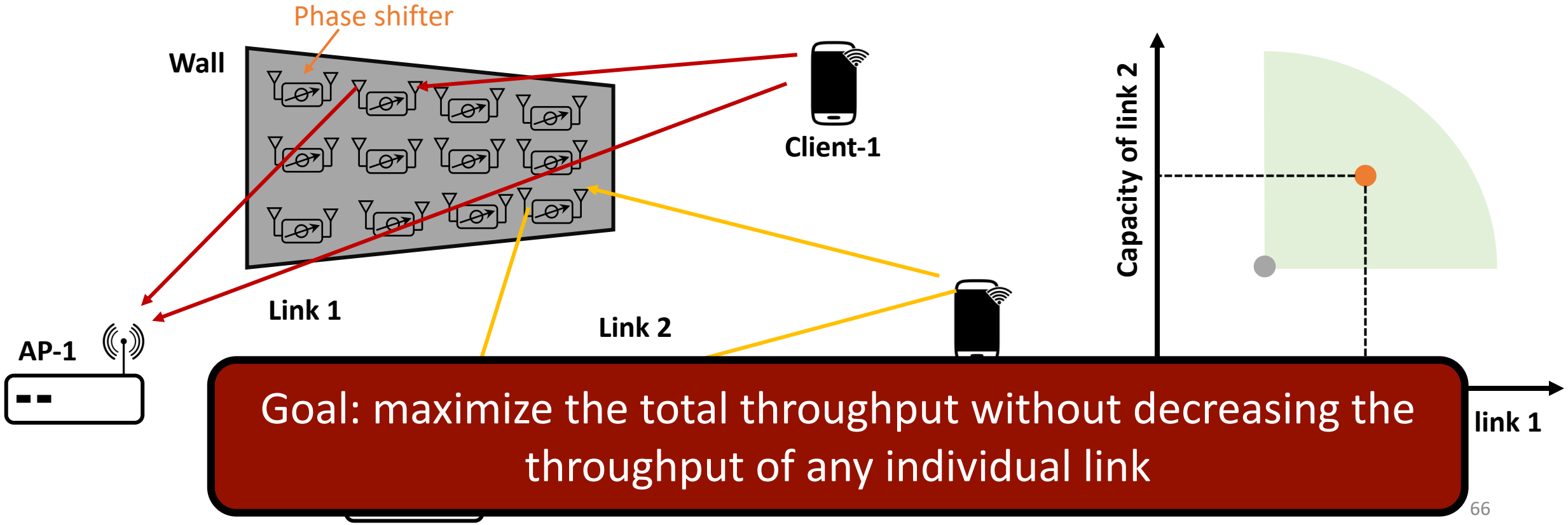


Multiple links

Optimization problem

Objective function: $\max_{\Theta} C_1(\Theta) + C_2(\Theta)$

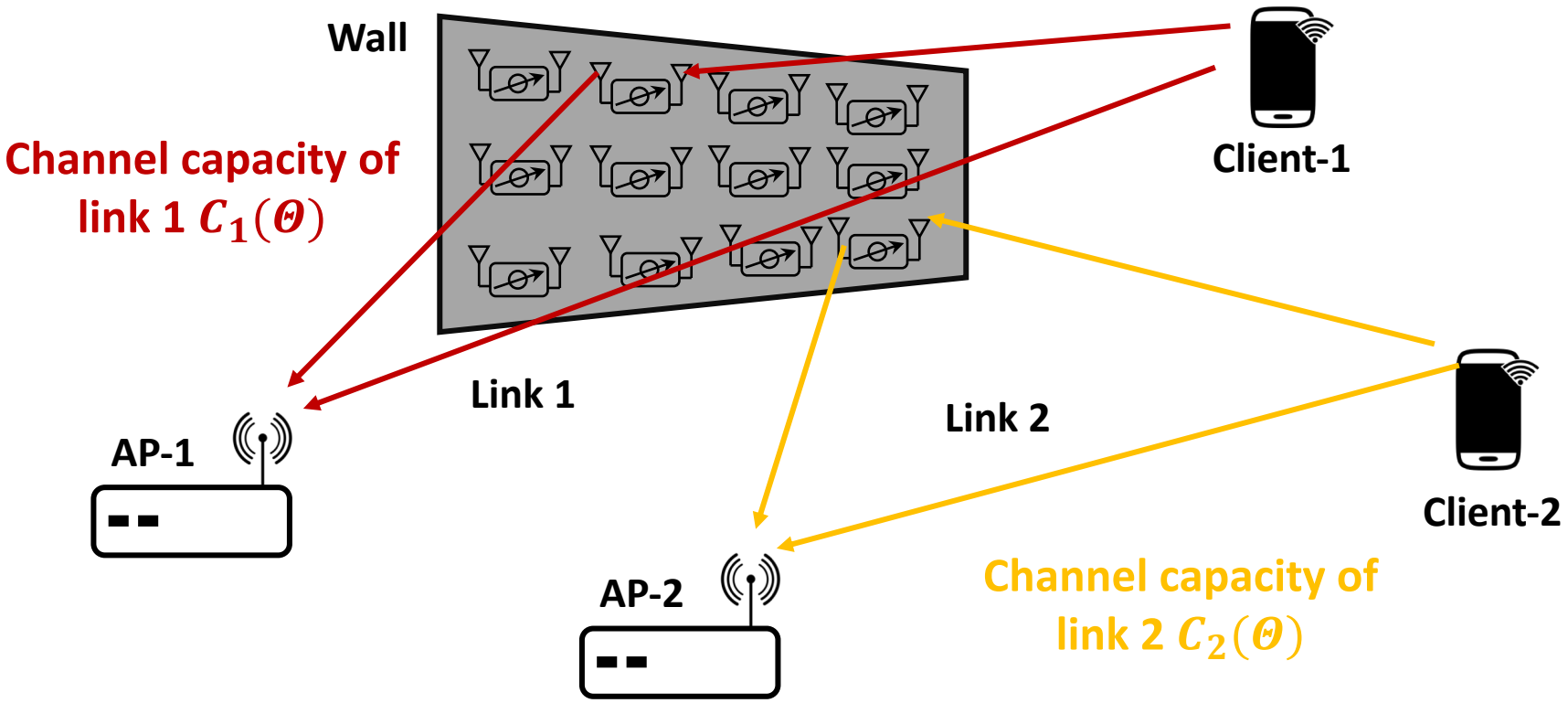
Subject to: $C_1(\Theta) > C_1(off)$

$C_2(\Theta) > C_2(off)$

where $C_1(off)$ and $C_1(off)$ is the channel capacities of link 1 and 2 when all LAIA elements are turned off.

Phase configuration of all LAIA elements

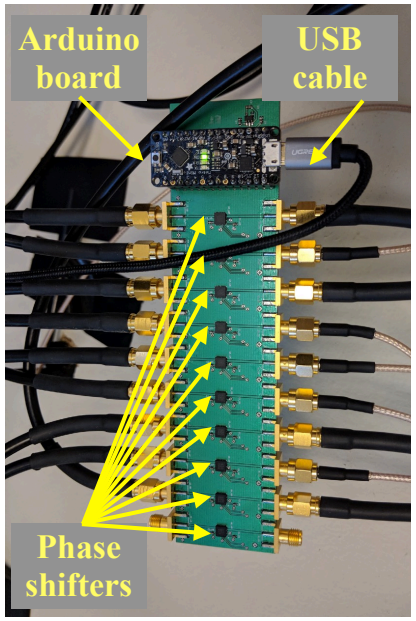
$$\Theta = [\theta_1, \theta_2, \dots, \theta_L]$$



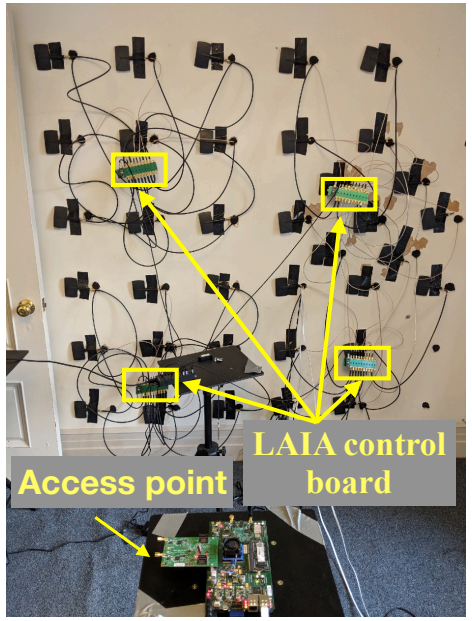
Implementation and deployment

- 36 LAIA elements are implemented in Princeton IoT house
- 4-bit phase shifters (16 phase shifts)

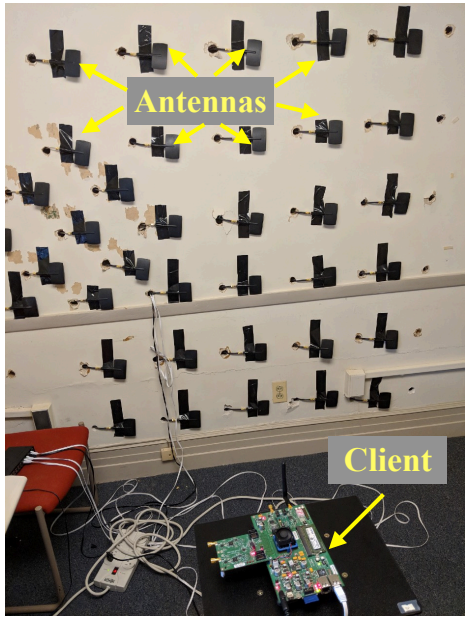
Princeton IoT house



(a) Control board



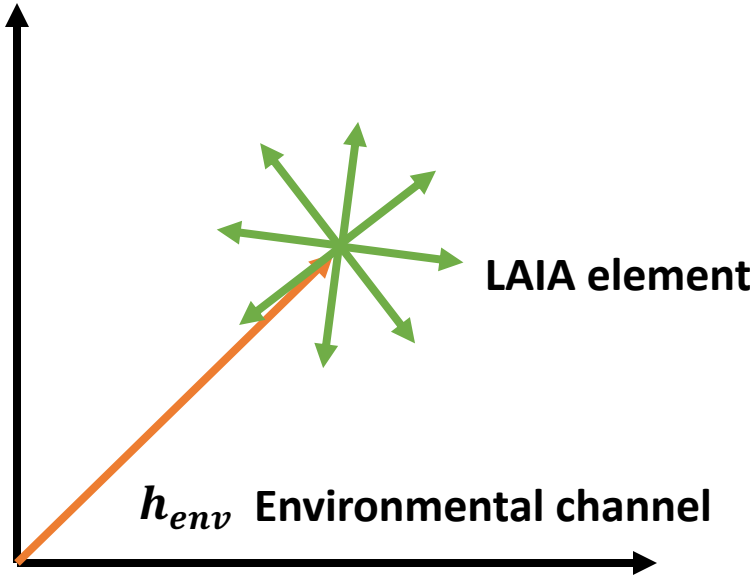
(b) AP side



(c) Client side

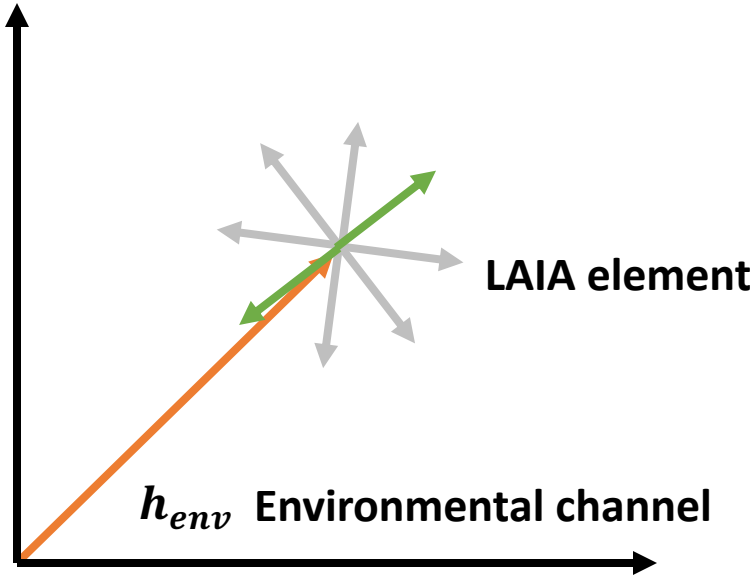
Micro-benchmark: controllability

- **Definition**: subcarrier controllability



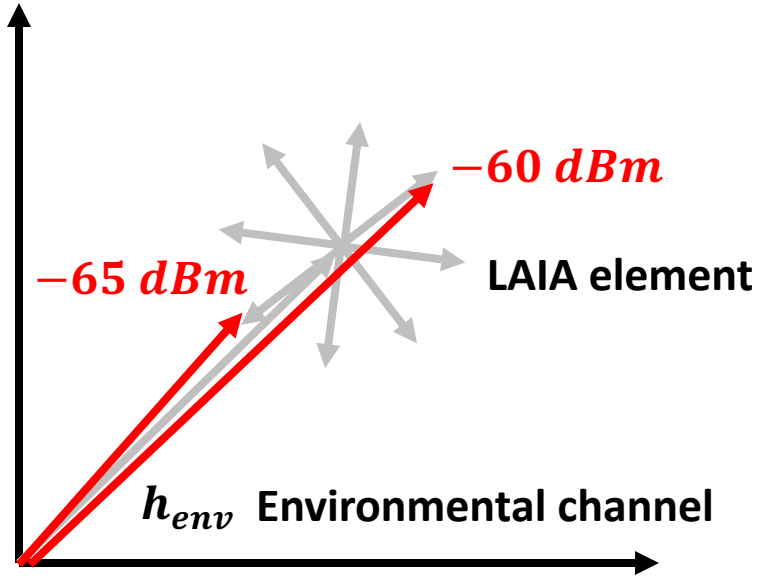
Micro-benchmark: controllability

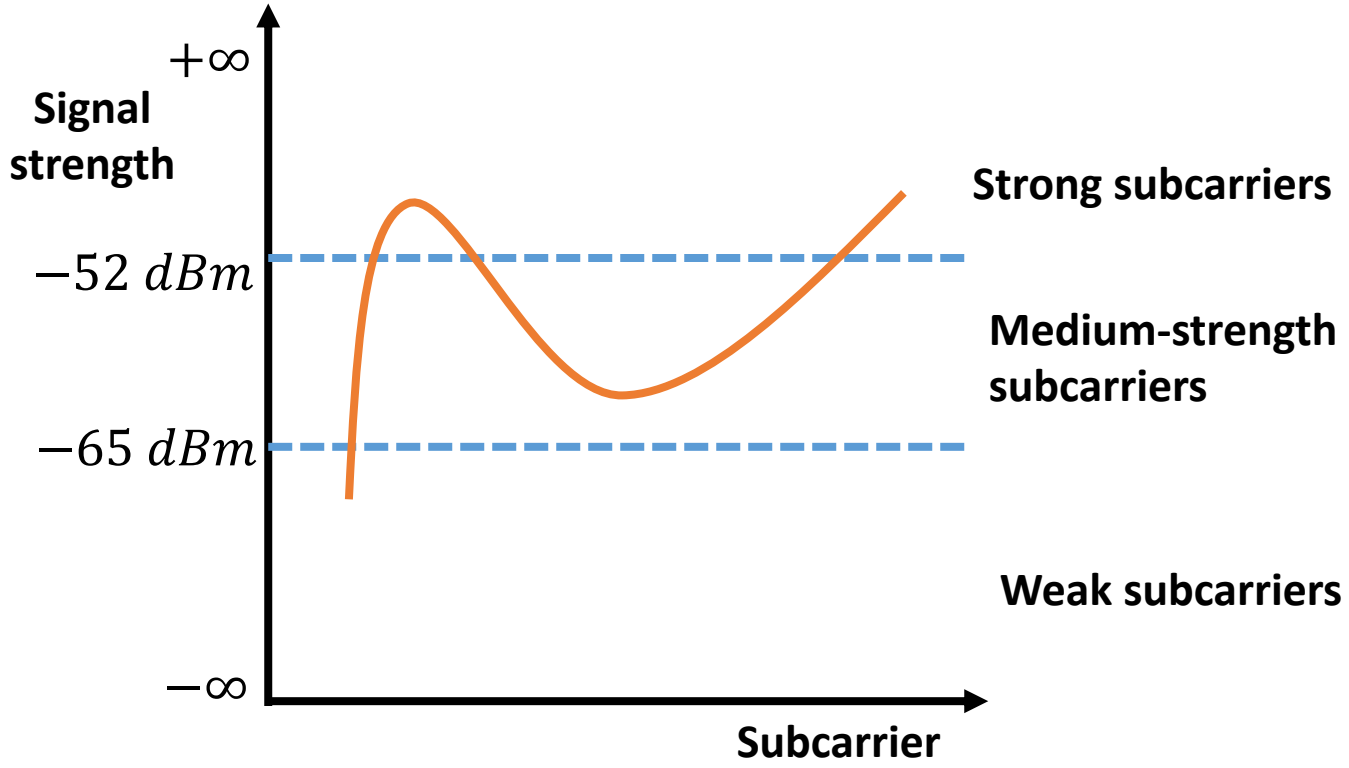
- **Definition**: subcarrier controllability



Micro-benchmark: controllability

- **Definition**: subcarrier controllability

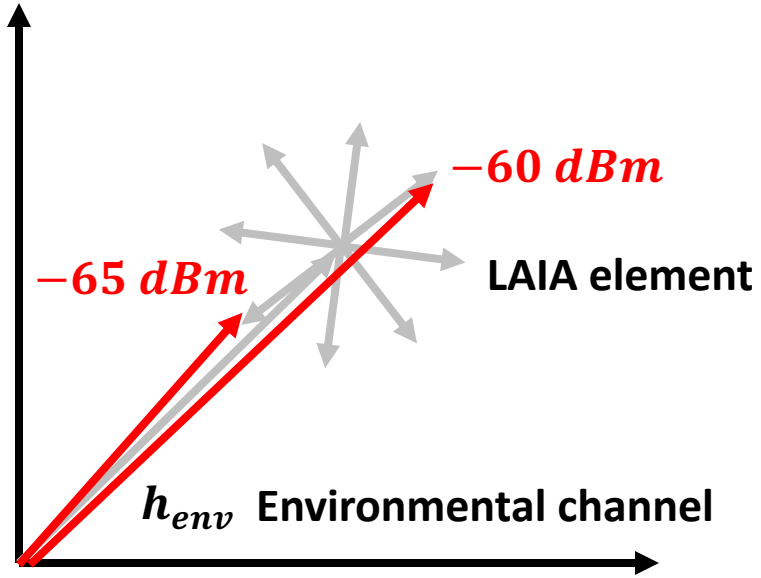


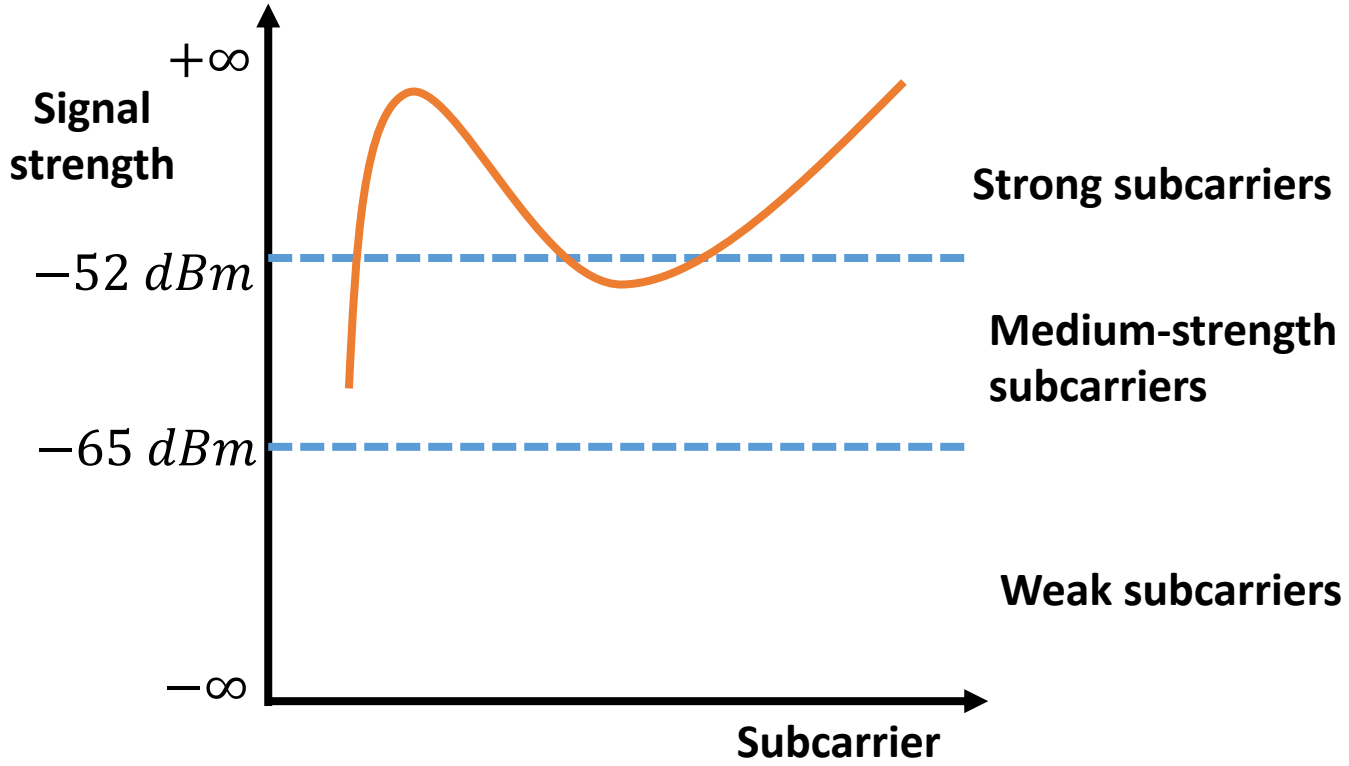


Subcarrier controllability $5\ dBm$

Micro-benchmark: controllability

- **Definition**: subcarrier controllability

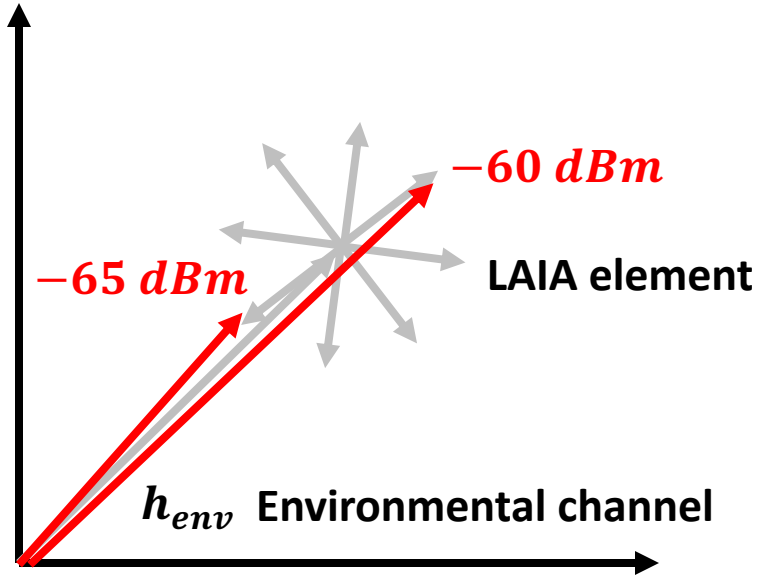


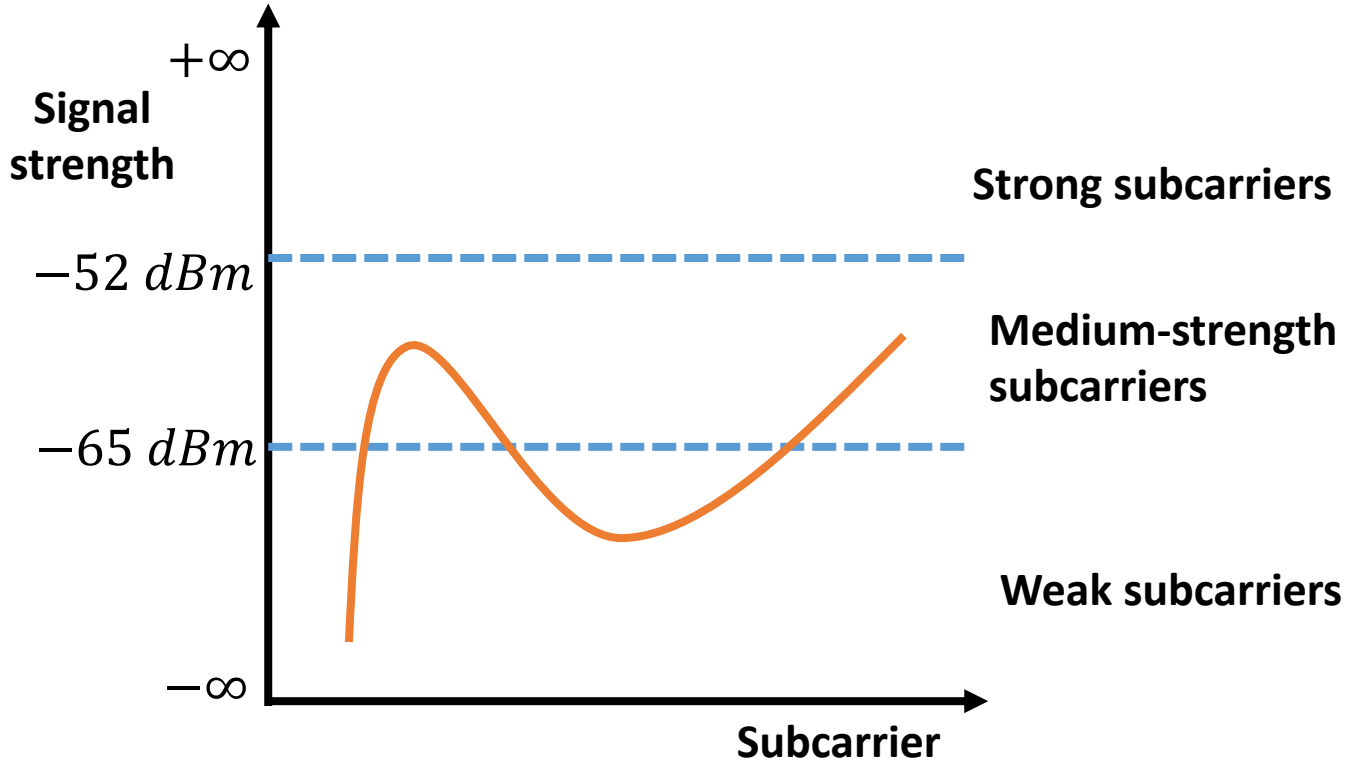


Subcarrier controllability $5\ dBm$

Micro-benchmark: controllability

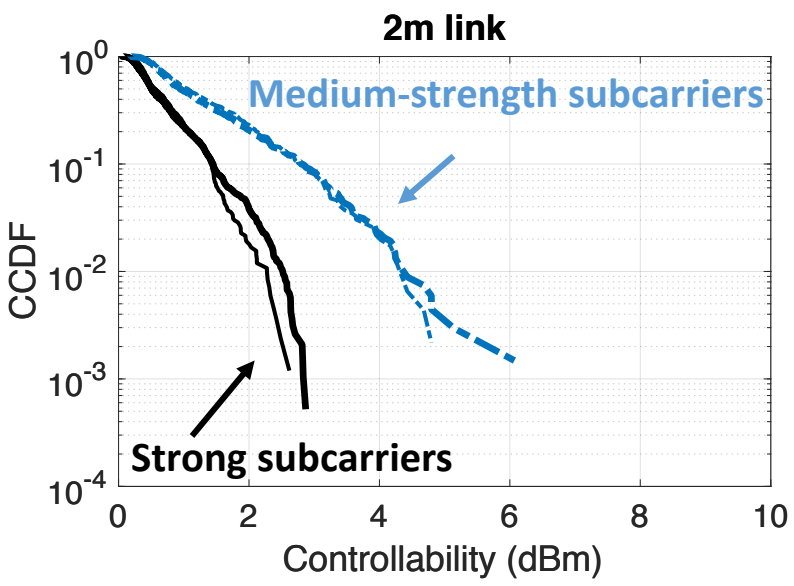
- **Definition**: subcarrier controllability

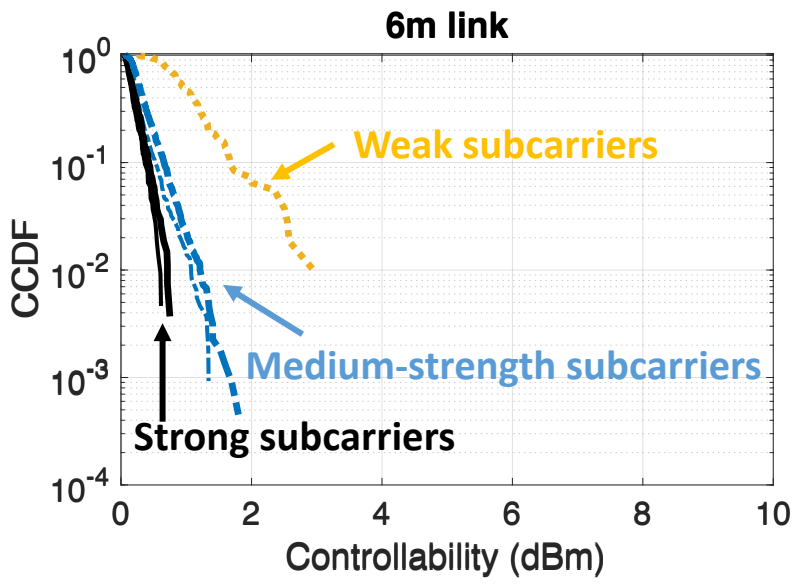


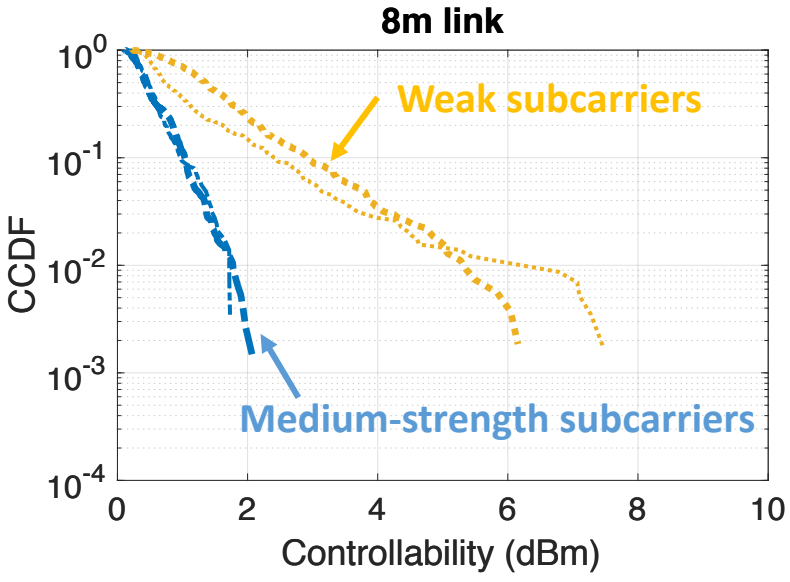


Subcarrier controllability $5\ dBm$

Micro-benchmark: controllability

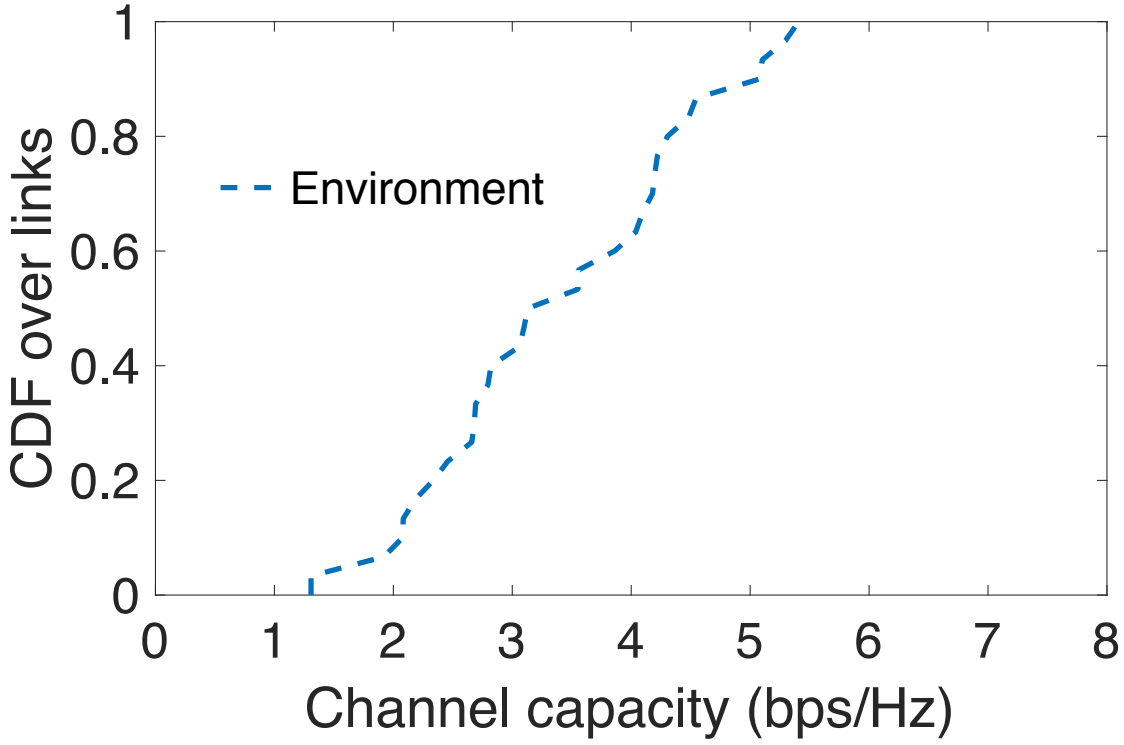




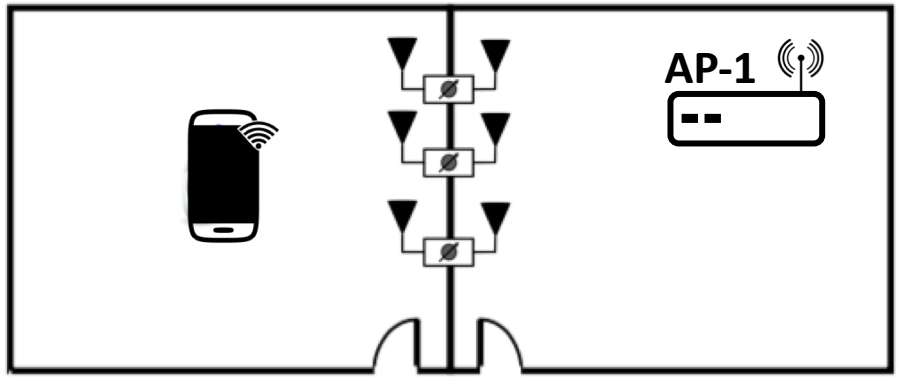


Greater controllability for weaker subcarriers

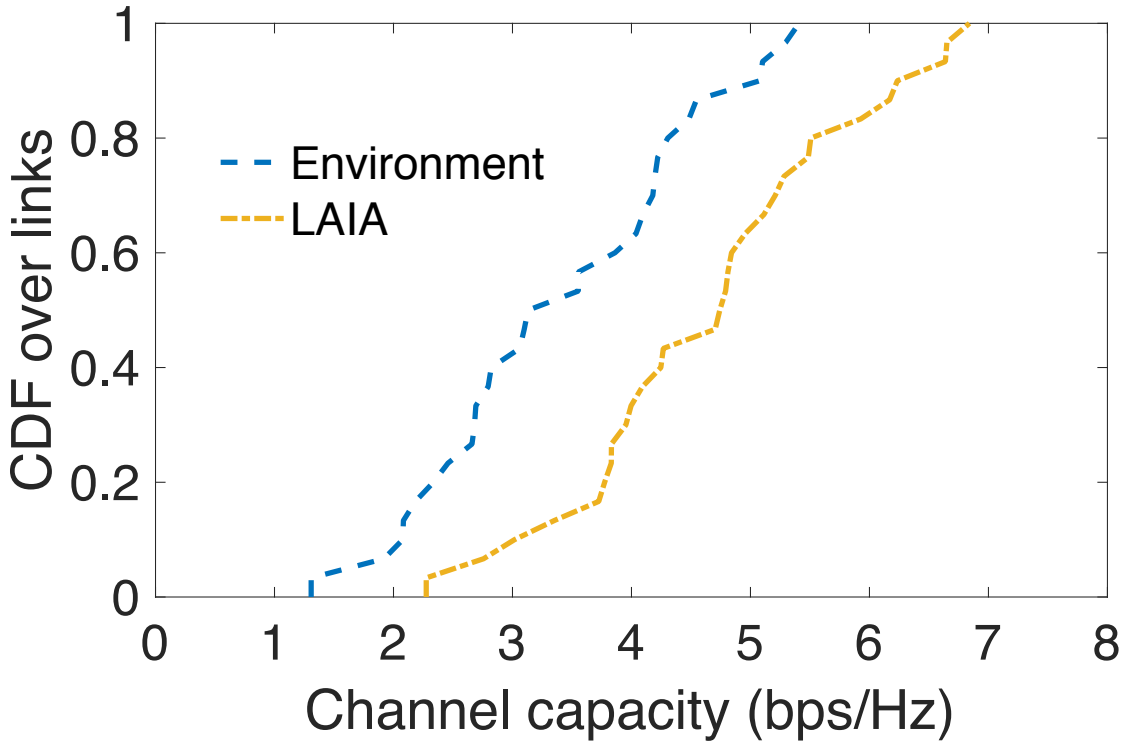
Baseline: Environmental SISO channel capacity



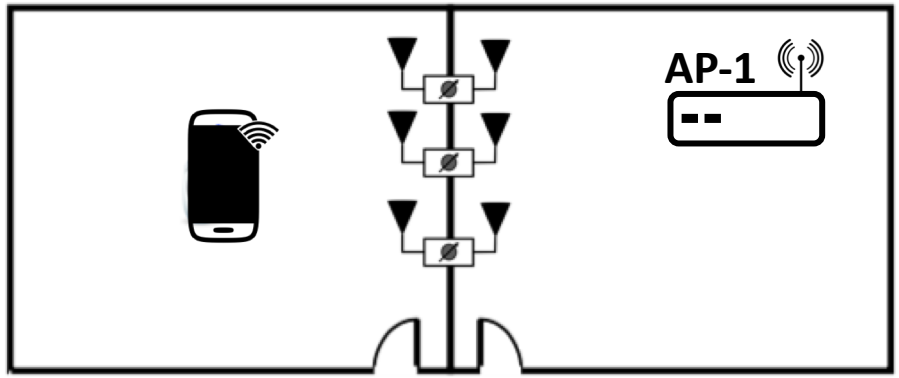
All LAIA elements are turned *OFF*



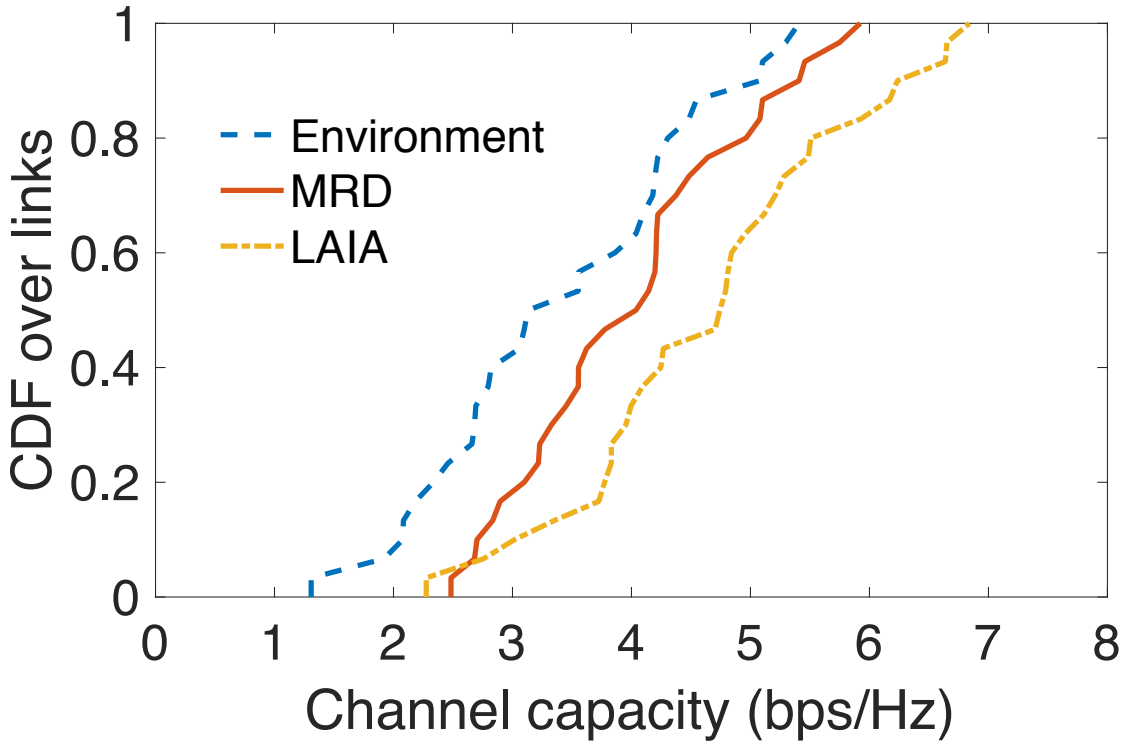
LAIA improves SISO channel capacity



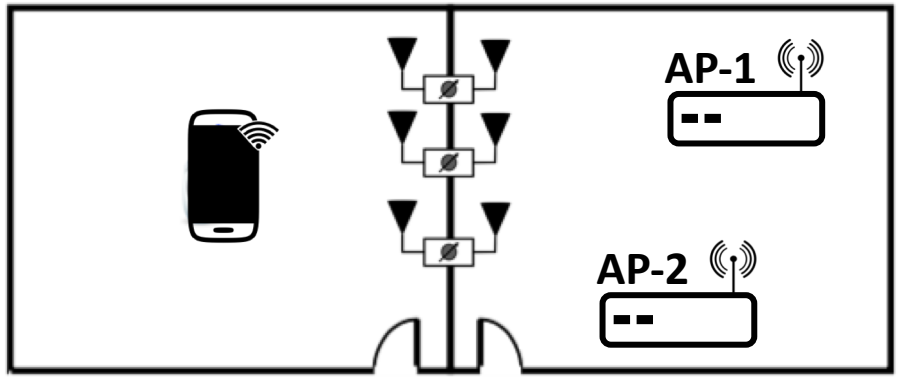
All LAIA elements are turned *ON*



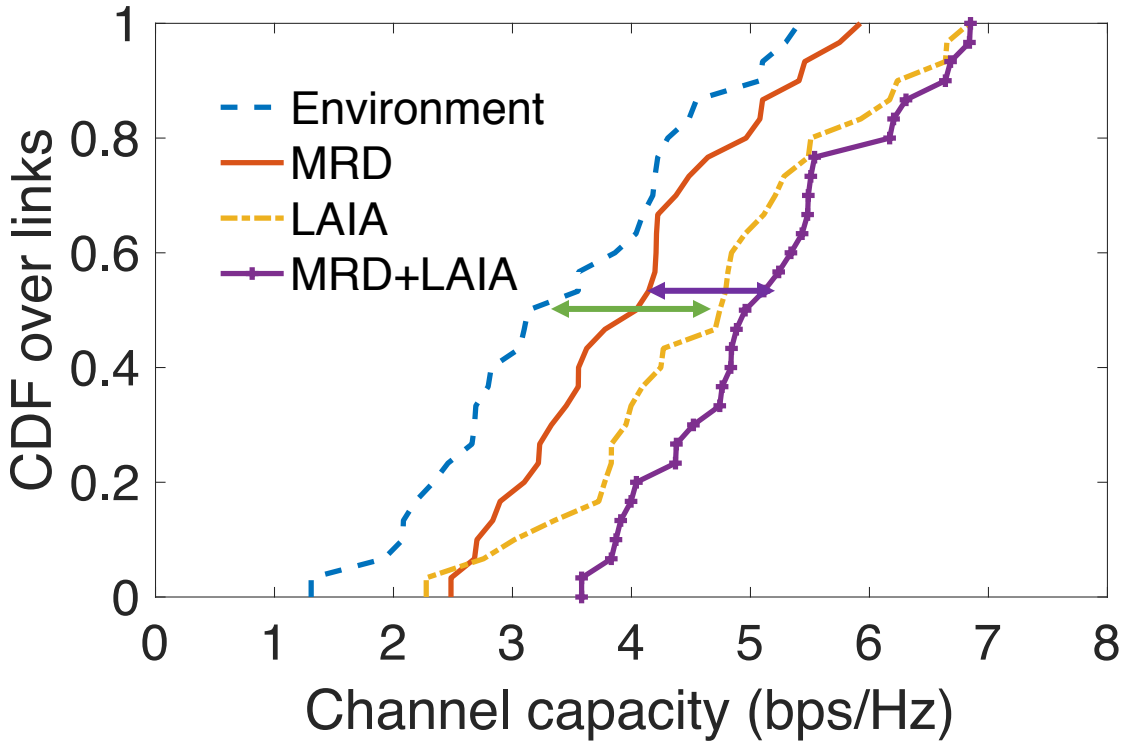
Link diversity also improves SISO channel capacity



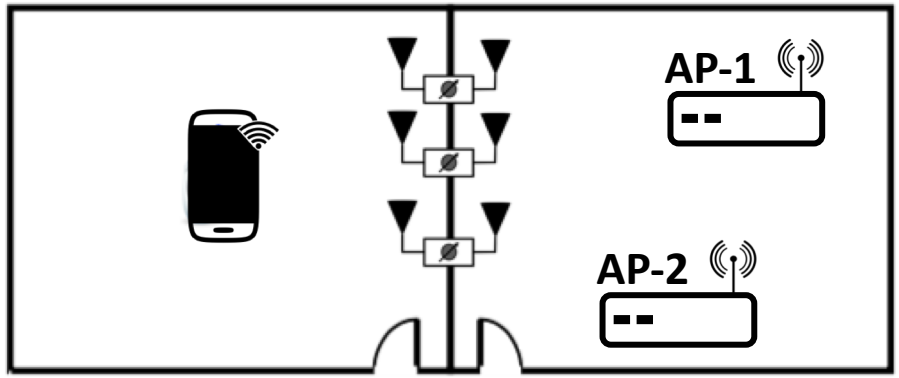
All LAIA elements are turned *OFF*



LAIA improves capacity with or without link diversity

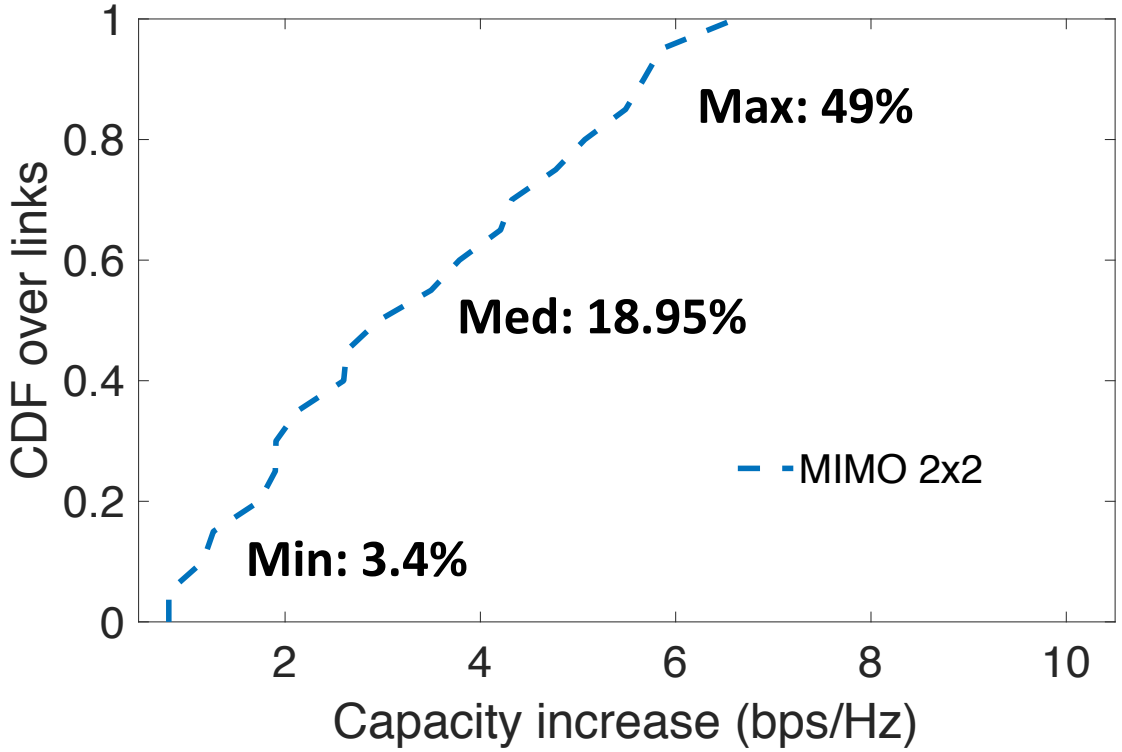


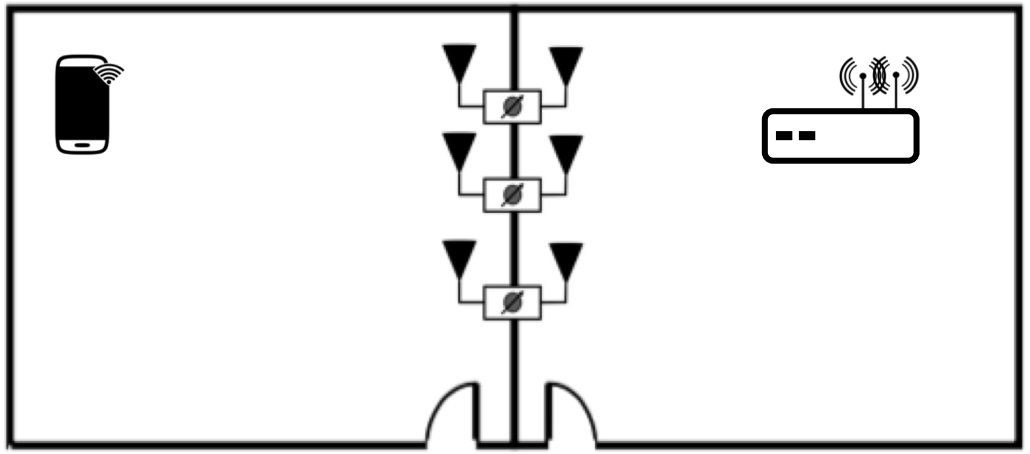
All LAIA elements are turned *ON*



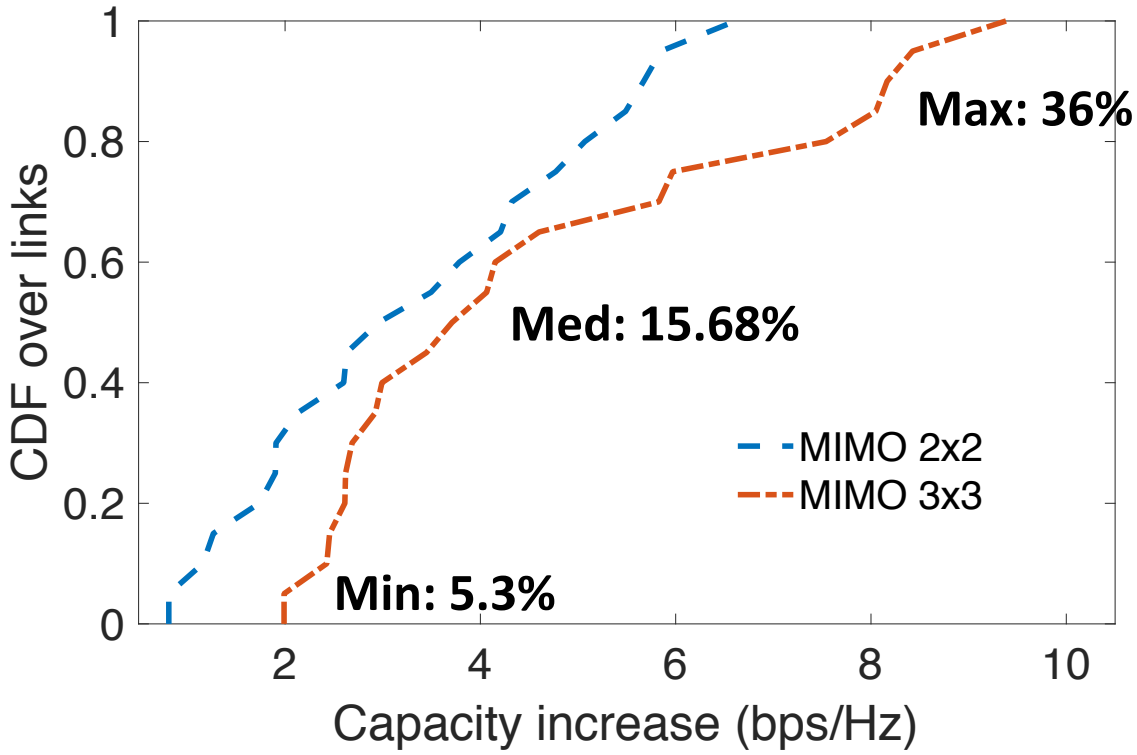
- LAIA provides a **51% channel capacity improvement** compared to the environment alone (**25% over MRD alone**)

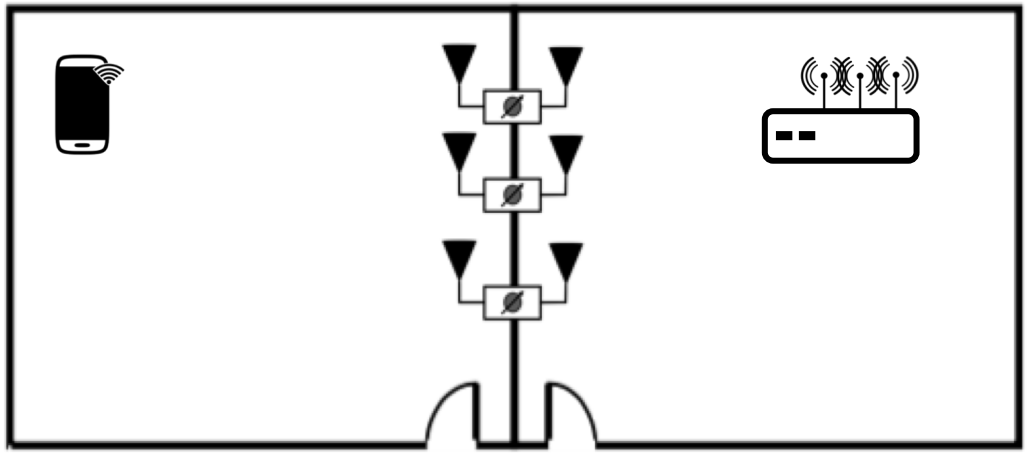
LAIA increases 2x2 MIMO channel capacity



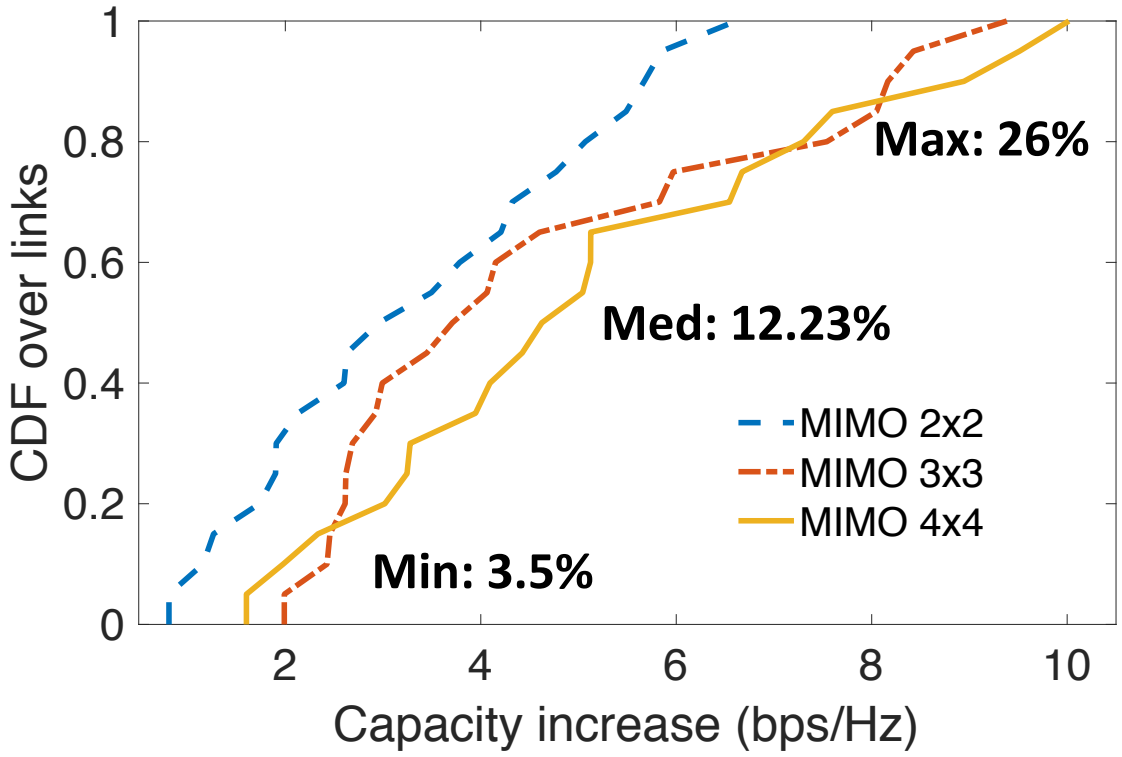


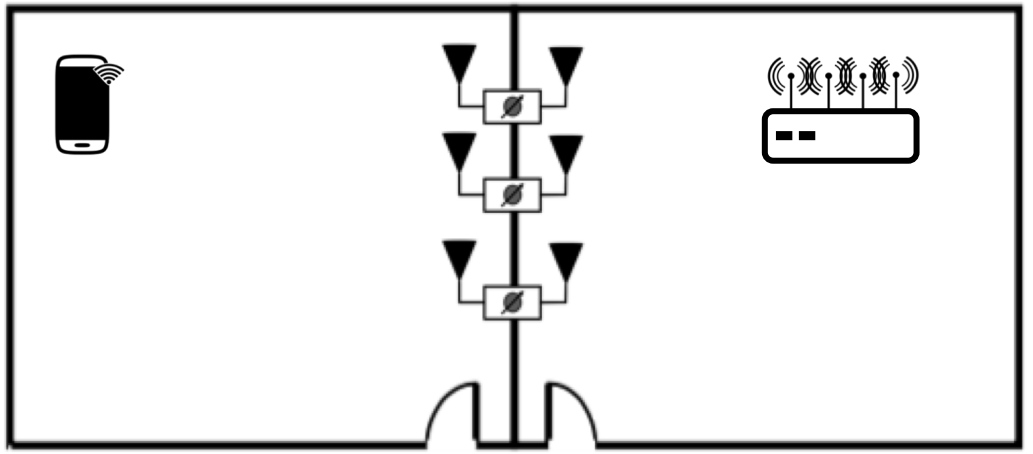
LAIA increases 3x3 MIMO channel capacity





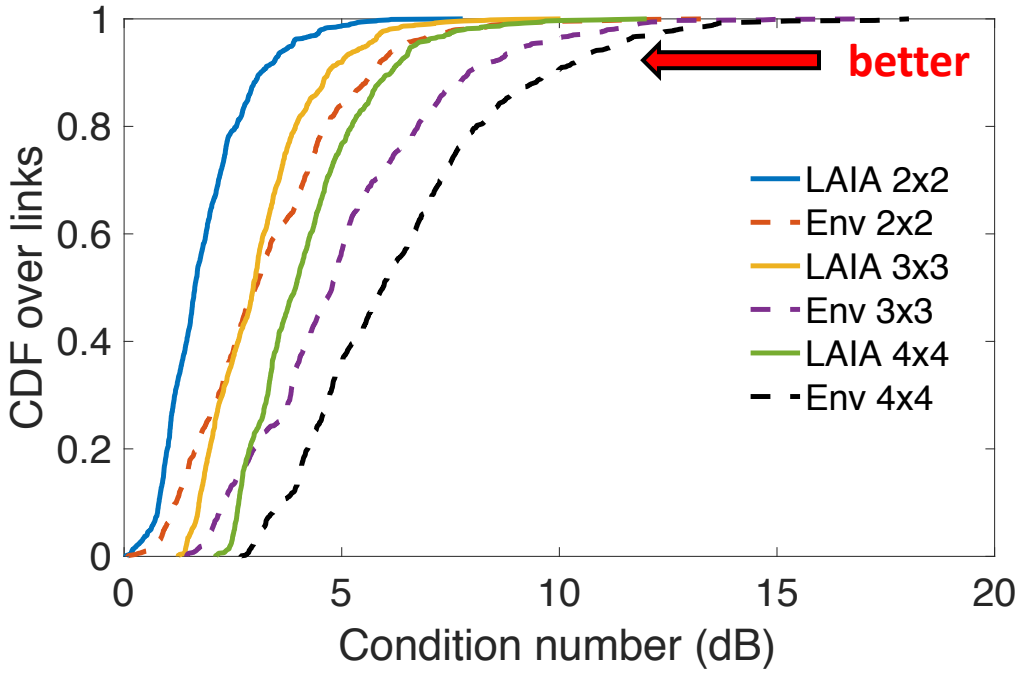
LAIA increases 4x4 MIMO channel capacity

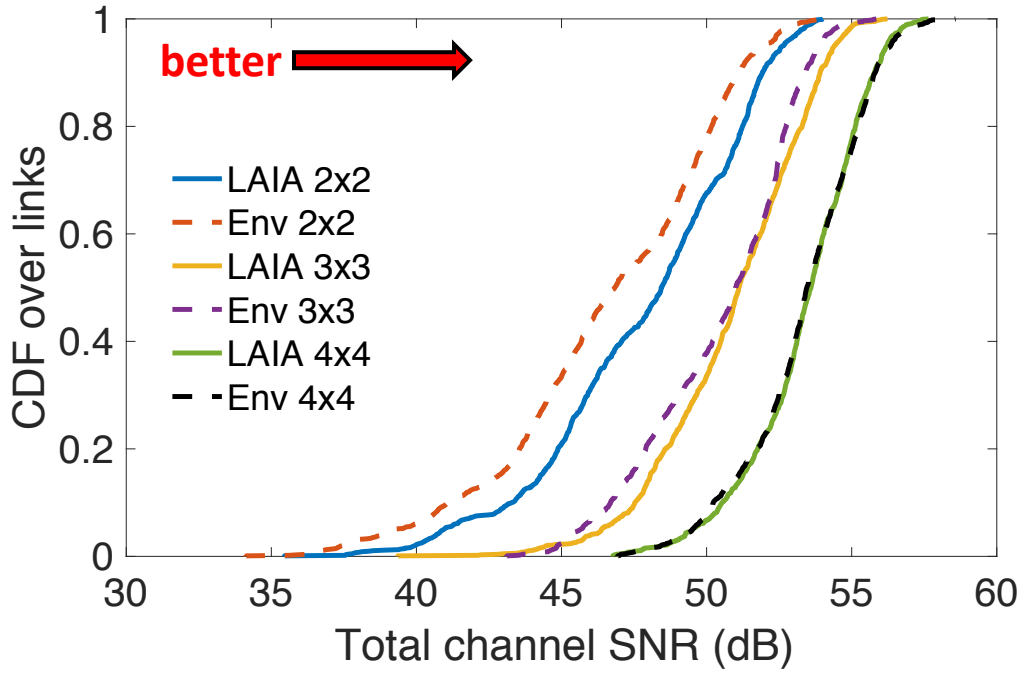




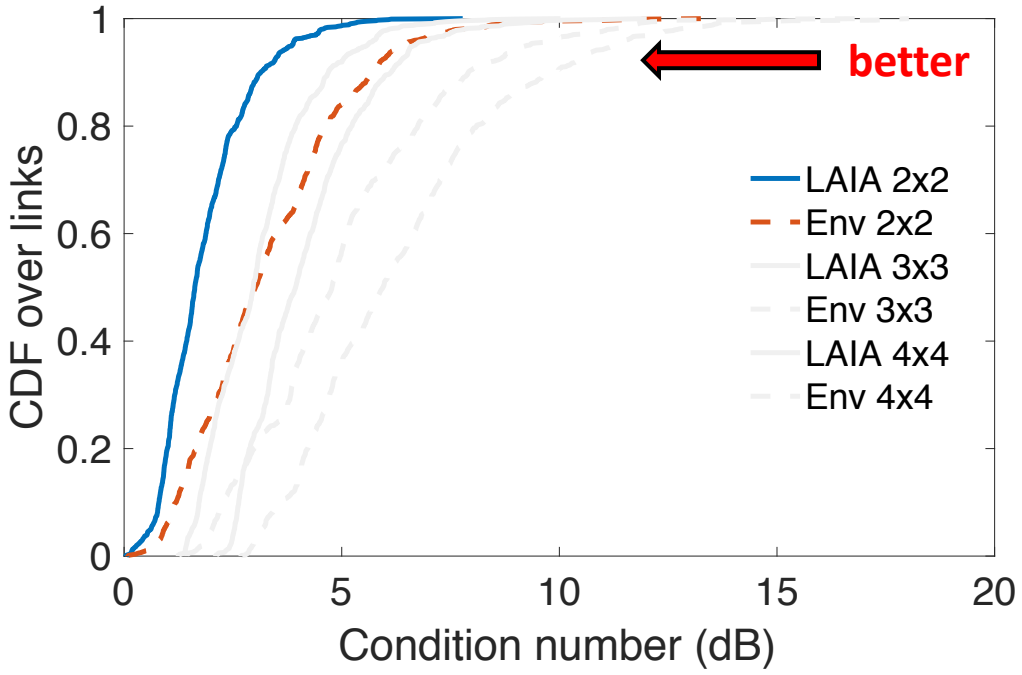
- Where the improvement comes from, total channel SNR or channel condition improvement?

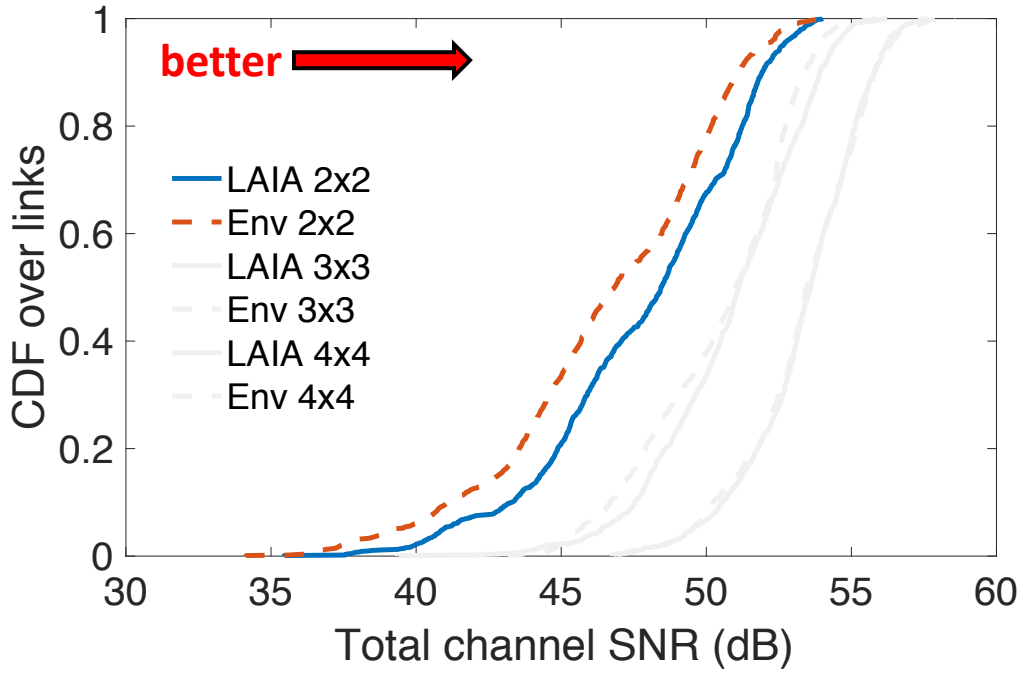
Why does LAIA help MIMO links?



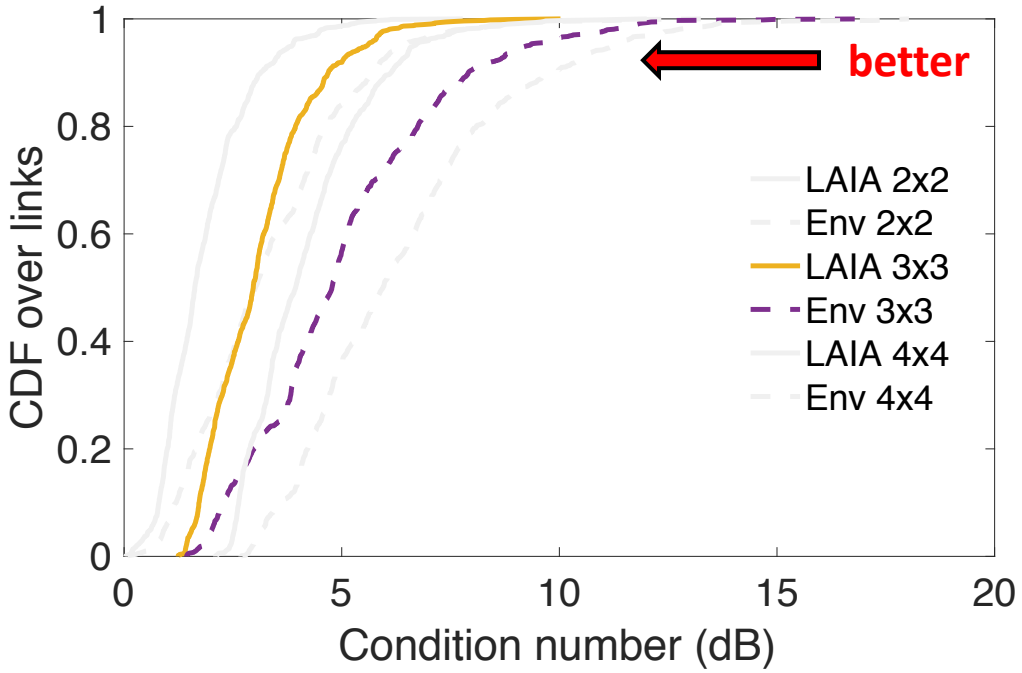


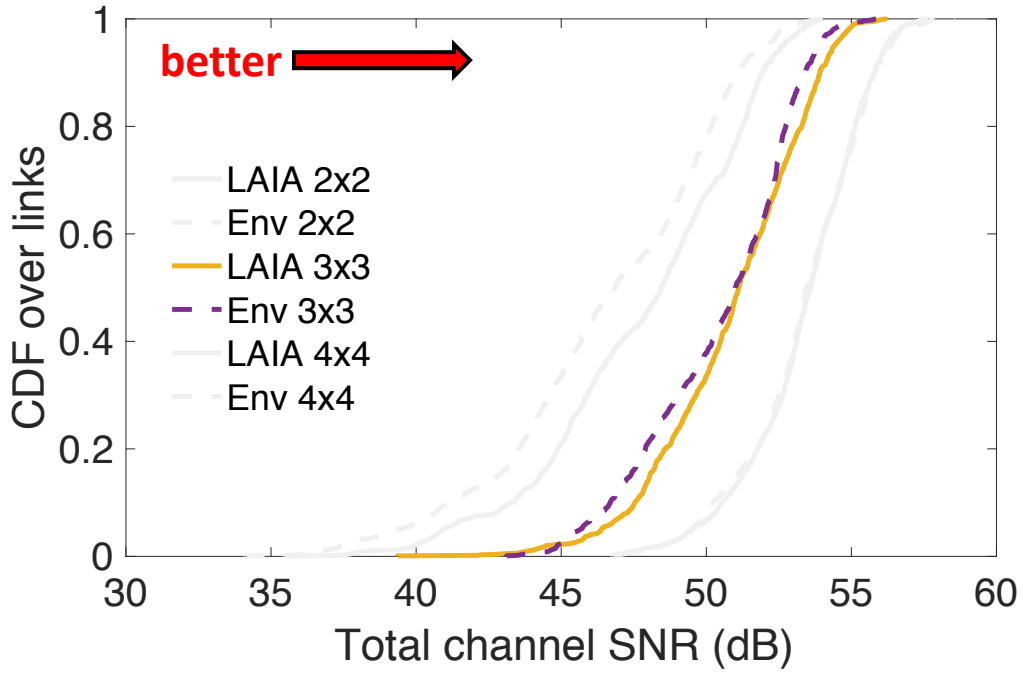
2x2: LAIA helps both channel conditioning and SNR



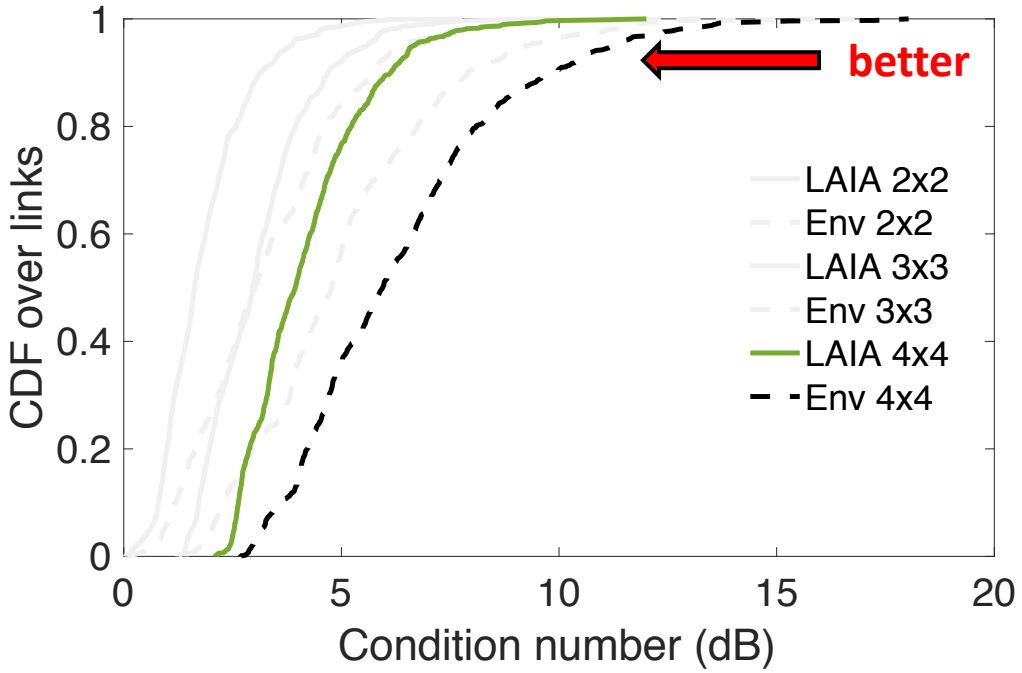


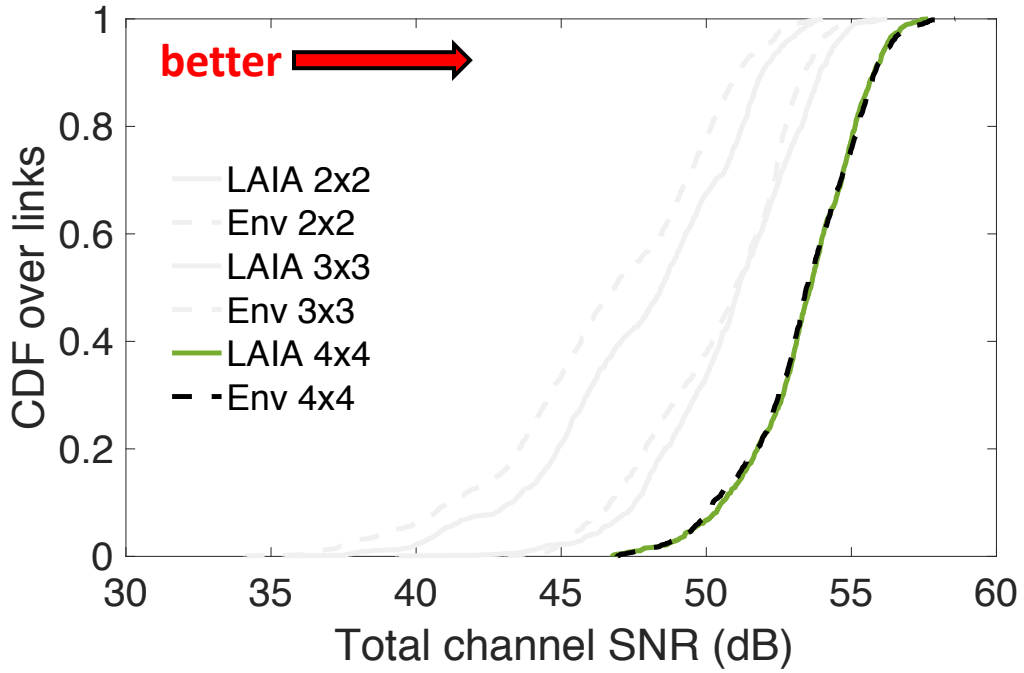
3x3: LAIA helps channel conditioning more than SNR





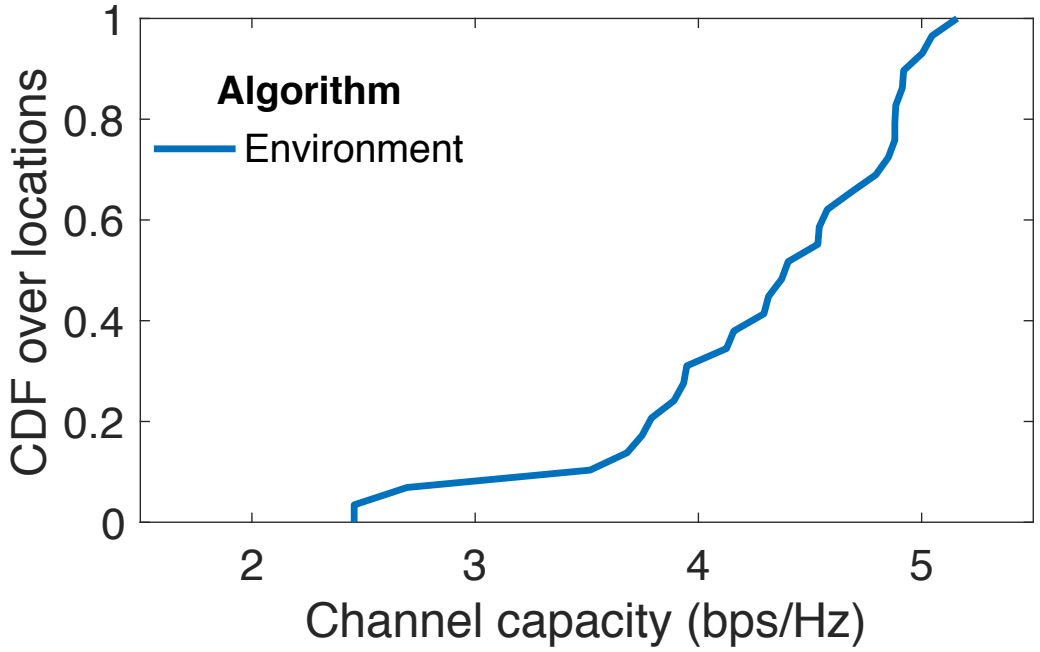
4x4: LAIA helps channel conditioning but not SNR



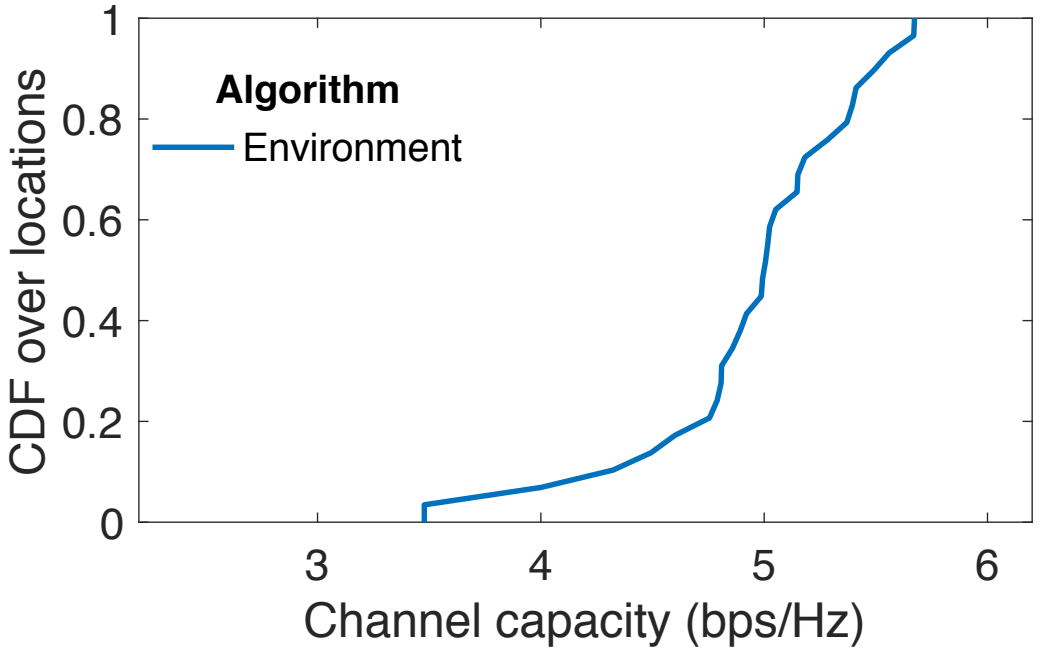


- Majority of the MIMO capacity gain is achieved by decreasing the condition number of the MIMO channel

The programmable environment may damage non-targeted links

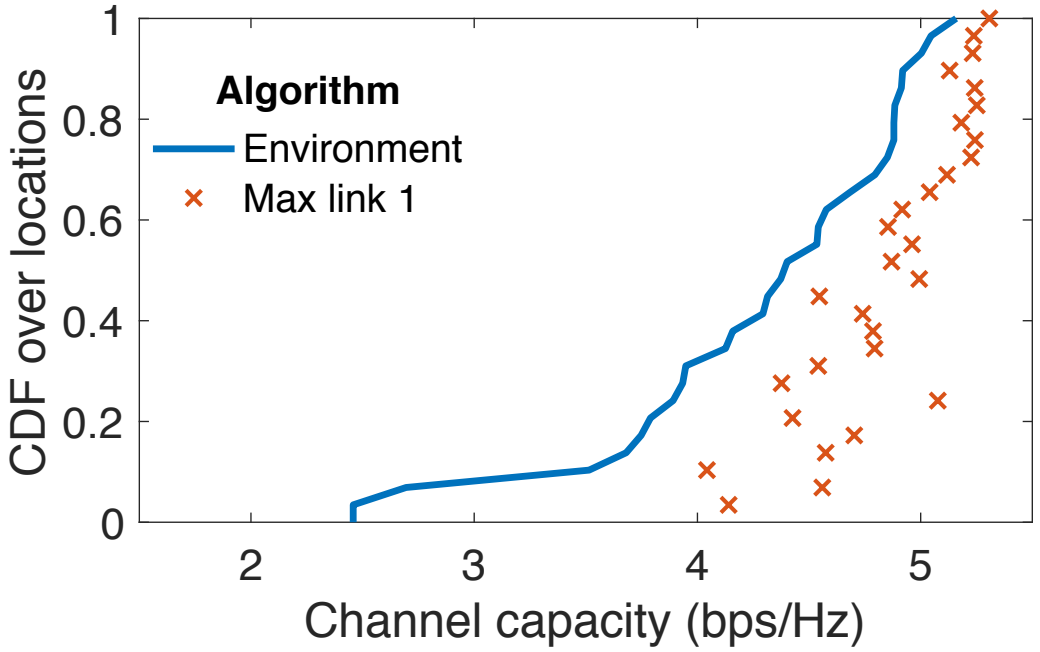


Capacity of Link 1

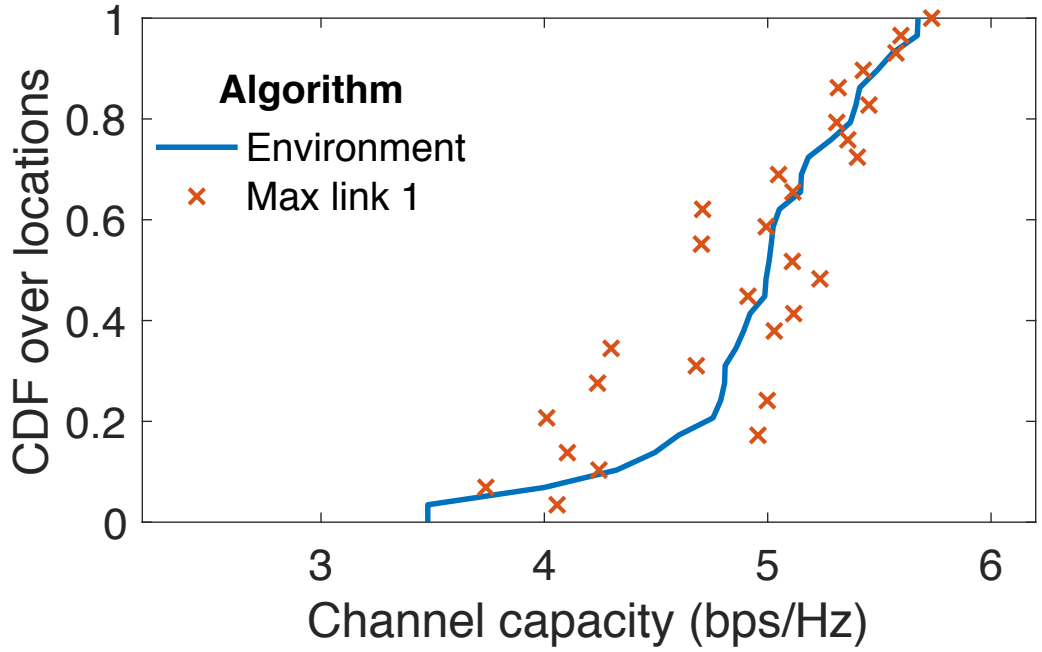


Capacity of Link 2

The programmable environment may damage non-targeted links

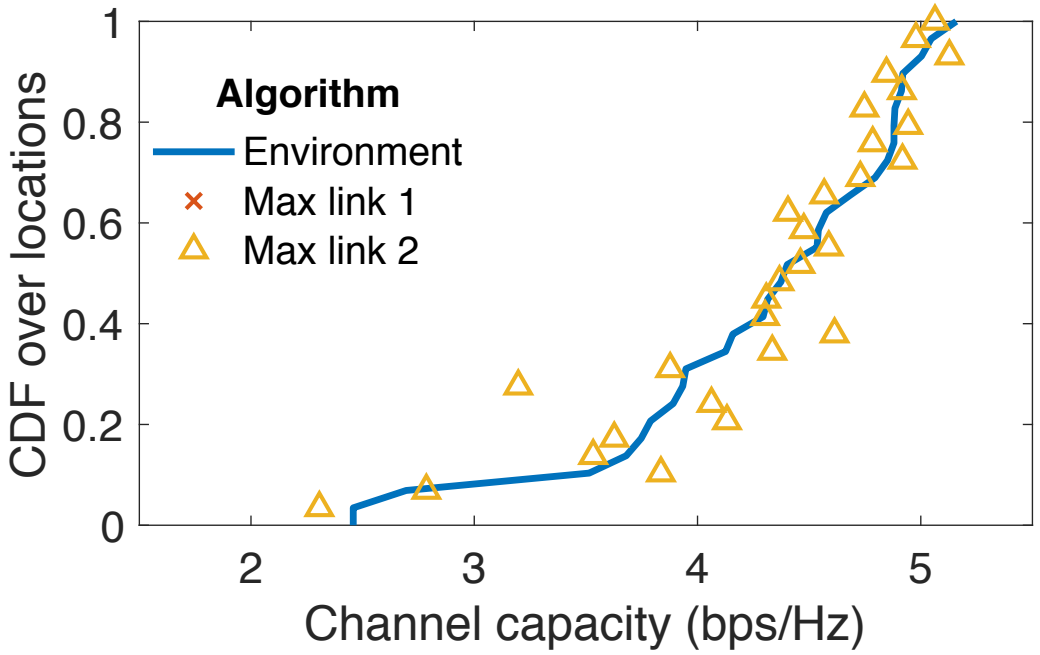


Capacity of Link 1

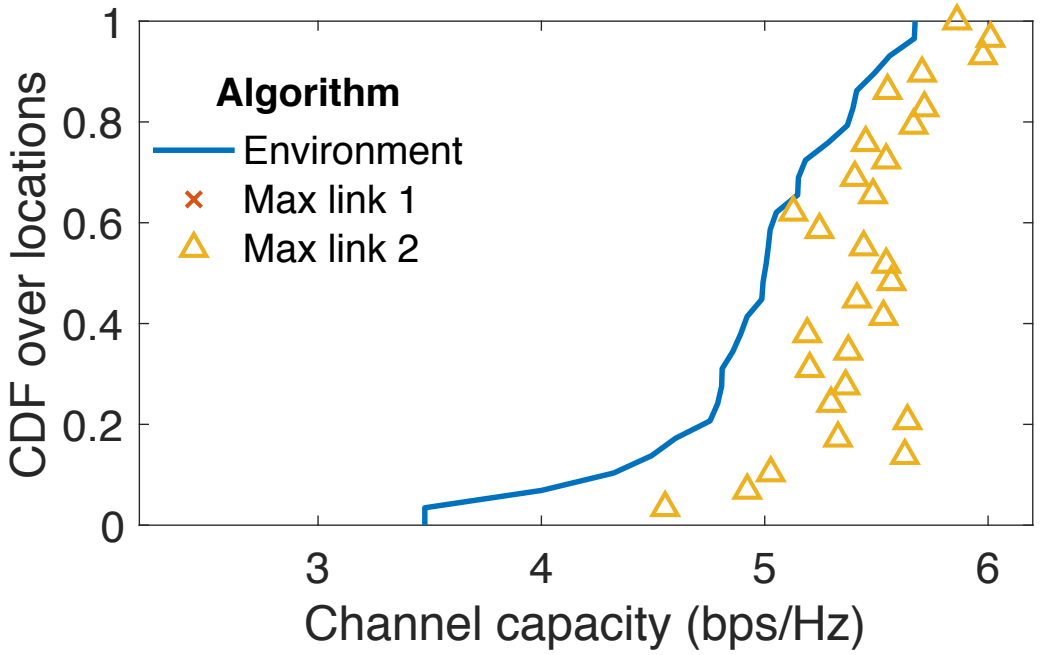


Capacity of Link 2

The programmable environment may damage non-targeted links

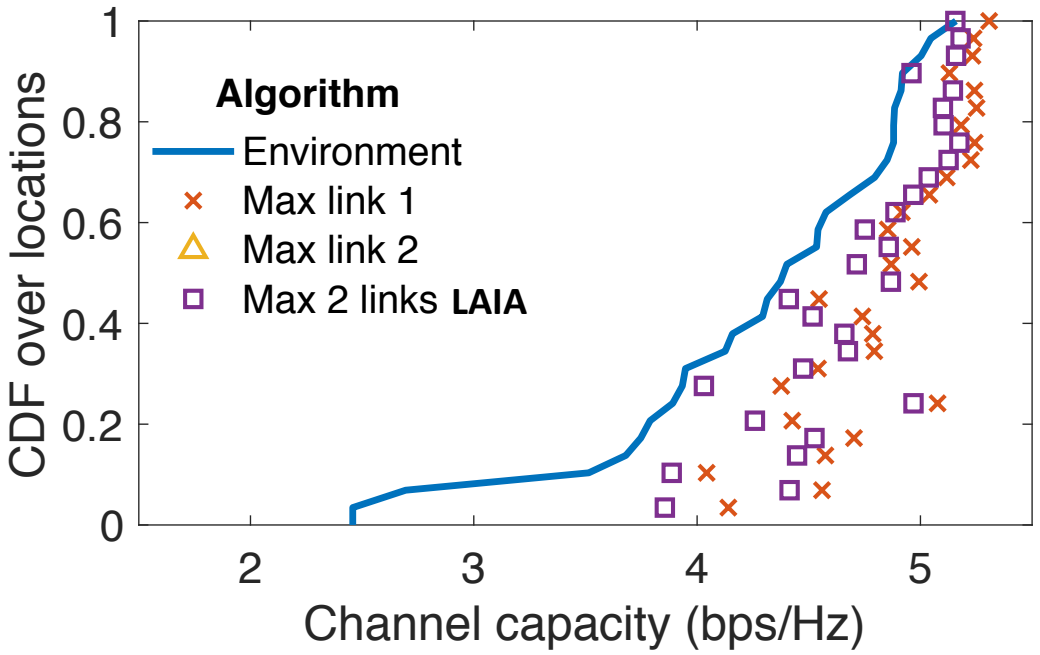


Capacity of Link 1

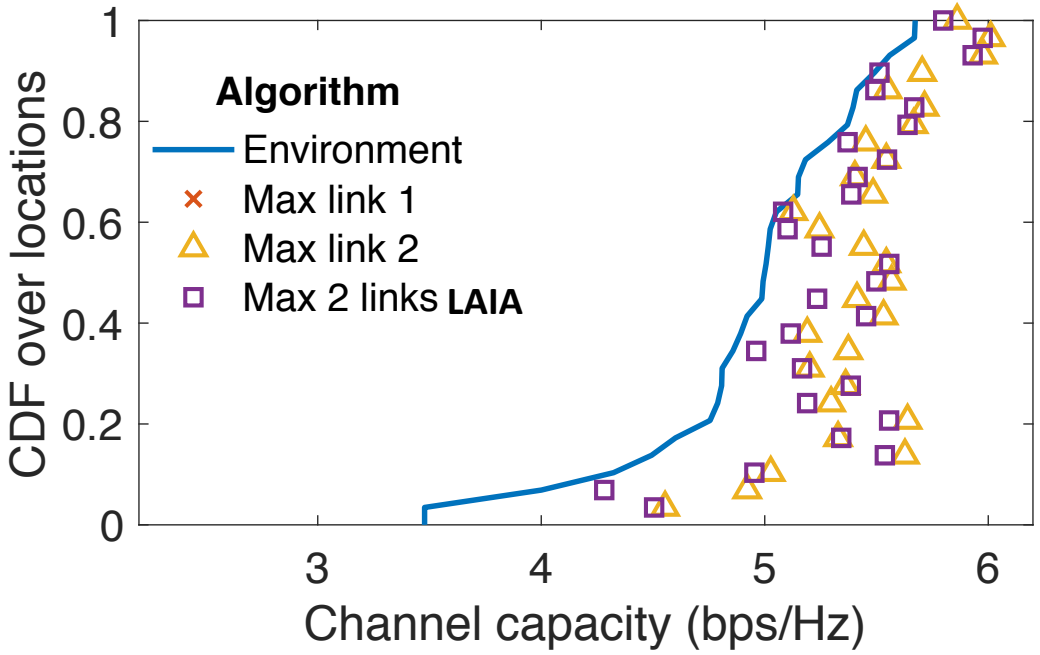


Capacity of Link 2

LAIA helps multiple links simultaneously

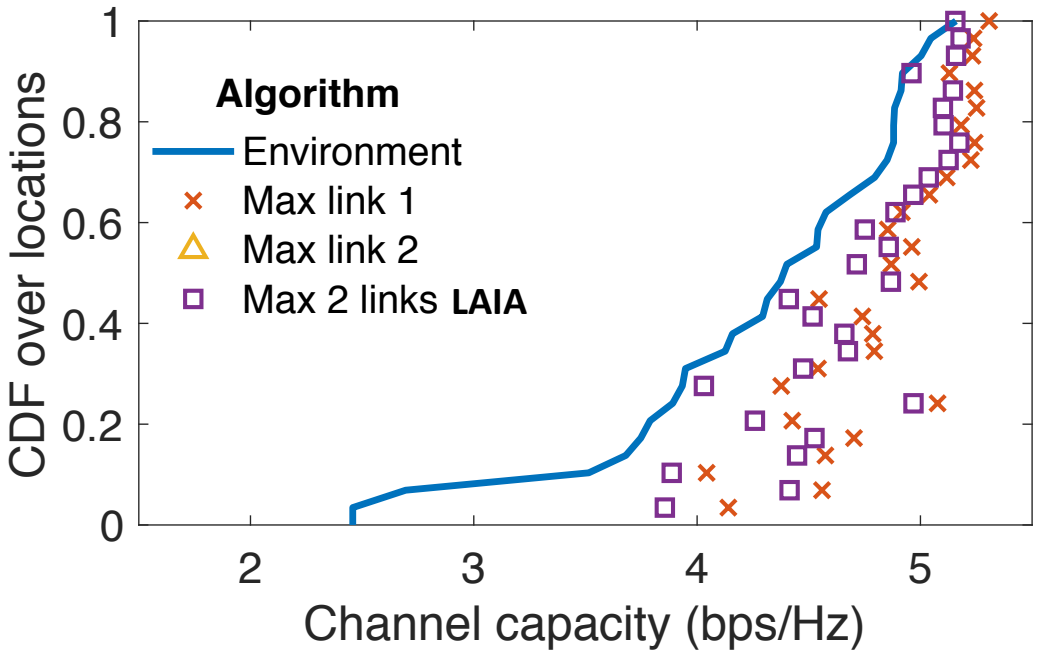


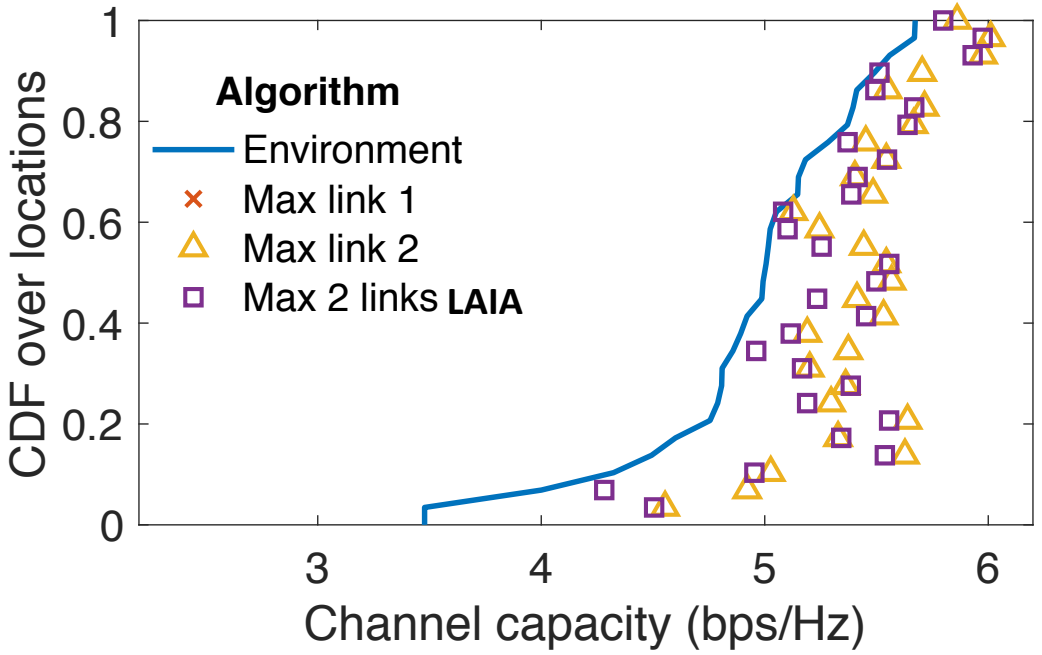
Capacity of Link 1



Capacity of Link 2

LAIA helps multiple links simultaneously





LAIA achieves performance close to a programmable environment targeting one link in isolation

Conclusion

- The first step towards programming the radio environment
  - A qualitatively different approach to the conventional strategy of optimizing the endpoints
- We implement a prototype that reconfigures the radio environment in real time
- Extensive evaluation demonstrating communications throughput enhancement that complement many other state of the art methods