Wireless Communication Systems
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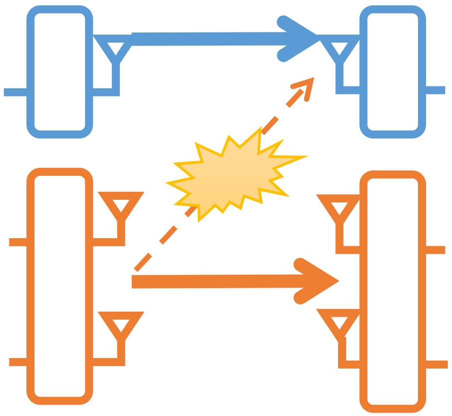
Lecture 5: Multi-User MIMO (MU-MIMO)

Instructor: Kate Ching-Ju Lin (林靖茹)

Agenda

- Interference Nulling
- Zero-forcing Beamforming (802.11ac)
- Interference Alignment
- Network MIMO

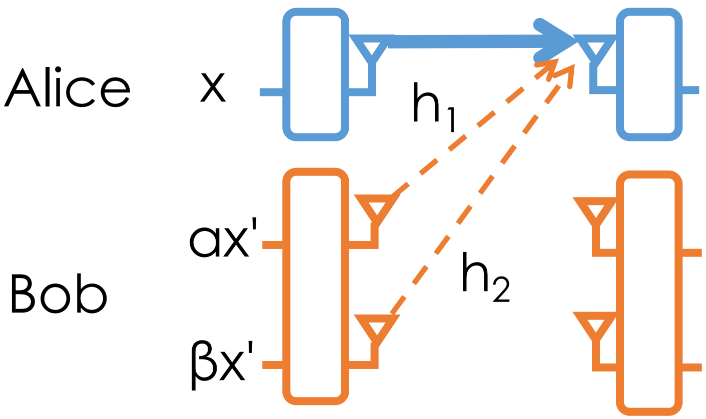
Cross-Link Interference



- Problem:
  - Any two nearby links cannot transmit simultaneously on the same frequency
- Solution:
  - A transmitter with multiple antennas can ***actively*** cancel its interfering signals at nearby receiver(s)

Interference Nulling

Nulling: make $(h_1 \alpha + h_2 \beta) = 0$
$\rightarrow$ **$\alpha = -(h_2/h_1)\beta$**



$y = hx + (h_1\alpha + h_2\beta)x'$

$y' = h'x + (h_{1a}\alpha + h_{1b}\beta)x'$

$y'' = h''x + (h_{2a}\alpha + h_{2b}\beta)x'$

$\downarrow$

$\neq 0$

- Signals cancel each other at Alice's receiver
- Signals don't cancel each other at Bob's receiver
  - Because channels are different
  - Bob's receiver can remove Alice's interference via ZF decoding

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802.11ac

Cannot leverage multiplexing gains if clients only have a single antenna

- From 802.11a/b/g, to 802.11n, to 802.11ac
  - AP can be more and more powerful → supporting multiple antennas
  - But, how about mobile devices? → usually light-weight and small size → limited number of antennas

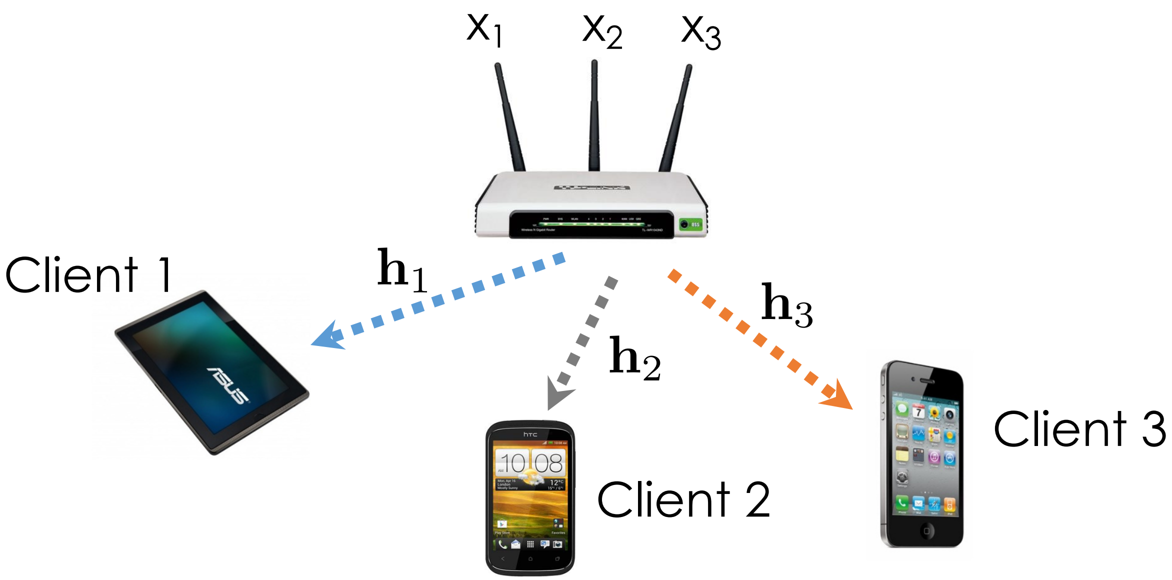
802.11ac

- 802.11ac adopts multiuser MIMO (MU-MIMO)
  - Involve multiple clients in concurrent transmissions
  - Extract the multiplexing gain
  - Maximal number of clients (streams) = number of antennas at the AP
  - Only support downlink MU-MIMO now

Cross-Stream Interference

- Say the AP send x_1, x_2 and x_3 to client 1, 2 and 3, respectively
  - If the AP simply uses each antenna to send one stream,
  - Each client receives the combined signal of x_1, x_2 and x_3
  - x_2 and x_3 are cross-stream interference for client 1

Channel Model



$$\mathbf{h}_1 = [h_{11} \ h_{12} \ h_{13}]^T$$
$$\mathbf{h}_2 = [h_{21} \ h_{22} \ h_{23}]^T$$
$$\mathbf{h}_3 = [h_{31} \ h_{32} \ h_{33}]^T$$

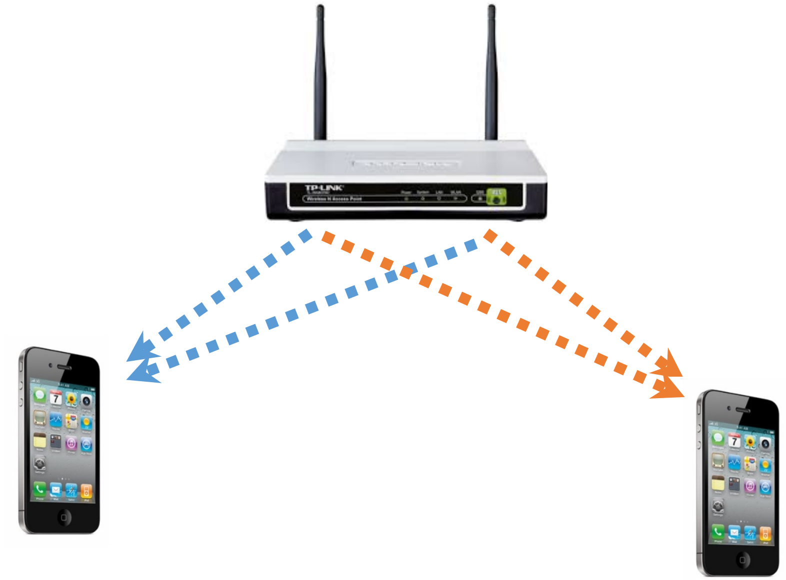
Interference

$$y_1 = h_{11}x_1 + (h_{12}x_2 + h_{13}x_3) + n_1$$
$$y_2 = h_{22}x_2 + (h_{21}x_1 + h_{23}x_3) + n_2$$
$$y_3 = h_{33}x_3 + (h_{31}x_1 + h_{32}x_2) + n_3$$

How to Remove Cross-Stream Interference?

- **Zero-Forcing Beamforming (ZFBF)**
  - Also called zero-forcing precoding or null-steering
  - Linear precoder that maximizes the output SNR
- The AP uses its antennas to actively cancel the interfering streams at a particular client
  - In the previous example, the AP
    cancel x_2 and x_3 at client 1
    cancel x_1 and x_3 at client 2
    cancel x_1 and x_2 at client 3
  - Steer a beam toward to its intended receiver
- How to suppress all the interference using the limited number of antennas?

QUIZ

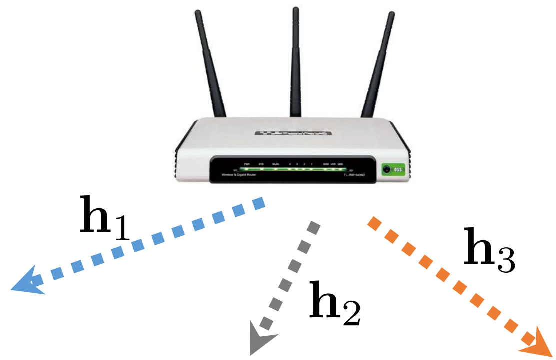


Zero-Forcing Beamforming (ZFBF)

$[w_{11} \;\; w_{12} \;\; w_{13}] * x_1$

$[w_{21} \;\; w_{22} \;\; w_{23}] * x_2$

$[w_{31} \;\; w_{32} \;\; w_{33}] * x_3$



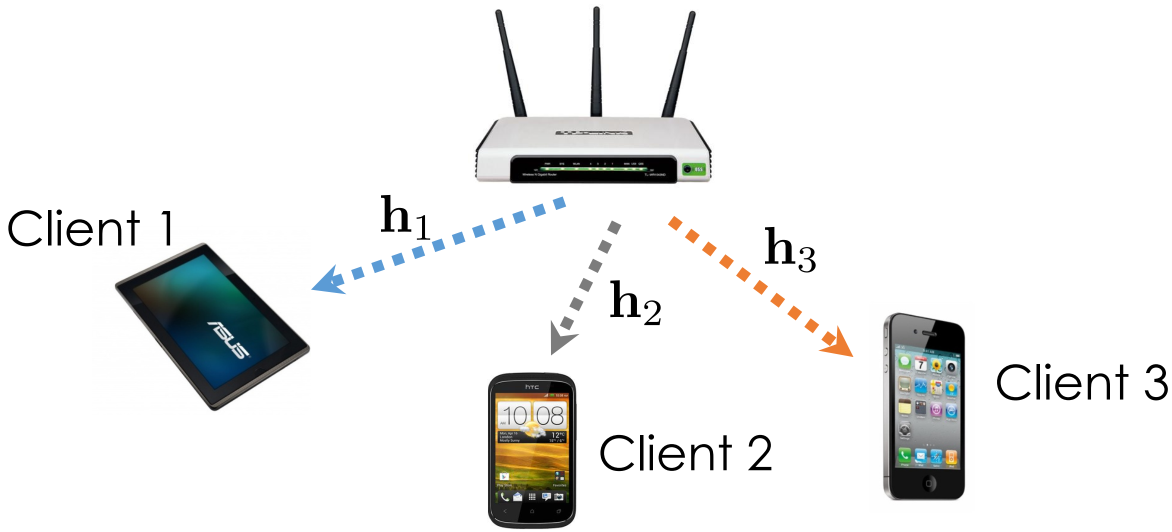
- Use all the antennas to send every stream
- Each stream *i* is precoded using ZFBF weight vector $w_i = [w_{i1} \; w_{i2} \; \ldots \; w_{iN}]$
- The precoded signal $w_{ij}x_i$ is sent by the *j*-th antenna
- The *j*-th antenna transmit the summation of all the precoded signal $(w_{1j}x_1 + w_{2j}x_2 + \ldots + w_{Nj}x_N)$

Zero-Forcing Beamforming (ZFBF)

$[w_{11} \;\; w_{12} \;\; w_{13}] * x_1 * \sqrt{P_1}$

$[w_{21} \;\; w_{22} \;\; w_{23}] * x_2 * \sqrt{P_2}$

$[w_{31} \;\; w_{32} \;\; w_{33}] * x_3 * \sqrt{P_3}$



$$y_i = \sqrt{P}_i \mathbf{h}_i \mathbf{w}_i x_i + \underbrace{\sum_{j \neq i} \sqrt{P}_j \mathbf{h}_i \mathbf{w}_j x_j}_{\text{Interference}} + n_i$$

→ Null the interference:

$$\sqrt{P}_j \mathbf{h}_i \mathbf{w}_j = 0, \forall j \neq i$$

Matrix: $\mathbf{y} = \mathbf{H}\mathbf{W}\sqrt{\mathbf{P}}\mathbf{x} + \mathbf{n}$ →

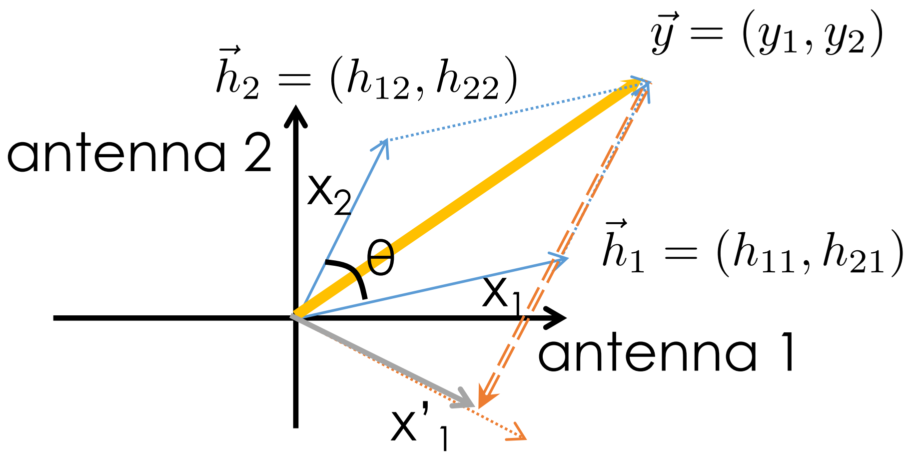
Let **W** be the **pseudo inverse** of **H**

$$\mathbf{W} = \mathbf{H}^{\dagger} = \mathbf{H}^{*}(\mathbf{H}\mathbf{H}^{*})^{-1}$$

Then, $\mathbf{y} = \sqrt{\mathbf{P}}\mathbf{x} + \mathbf{n}'$

SNR of ZFBF

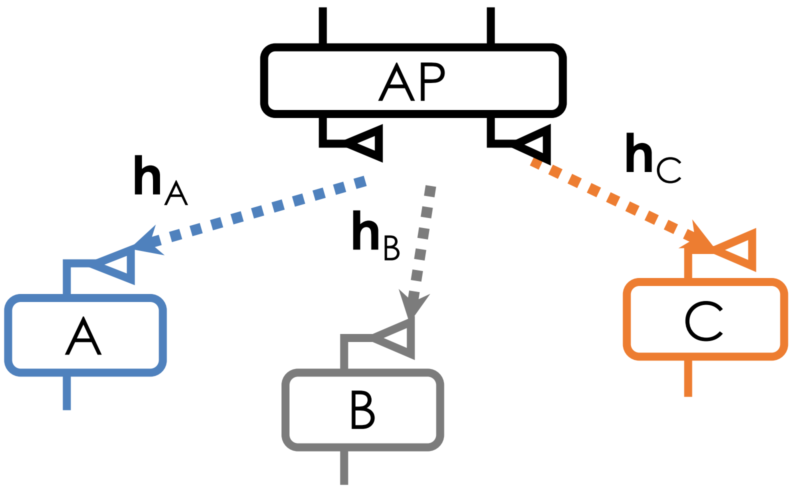
- ZFBF is essentially equivalent to ZF, but just performed by the transmitter



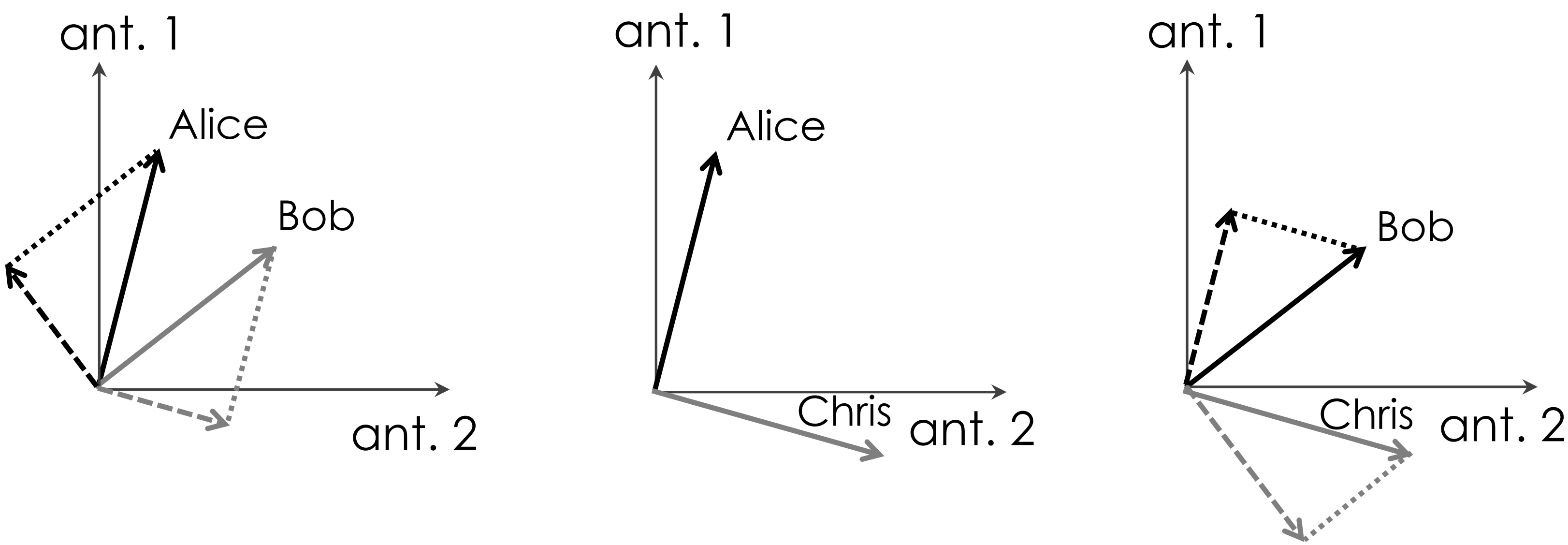
$$|x_1'| = |x_1|\cos(90 - \theta) = |x_1|\sin(\theta)$$

- The achievable SNR is determined by the channel correlation among concurrent clients

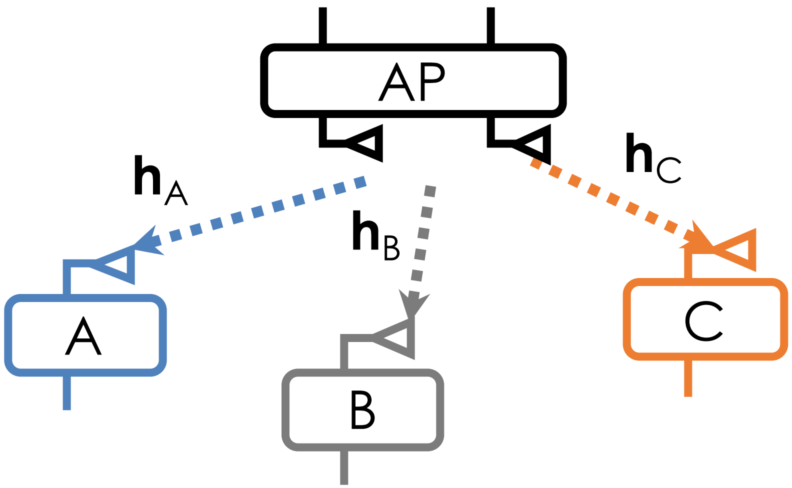
MU-MIMO Bit-Rate Selection



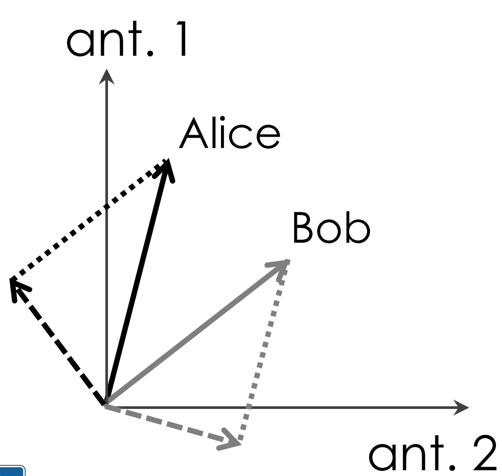
Select a proper rate based on SNR_{ZFBF}

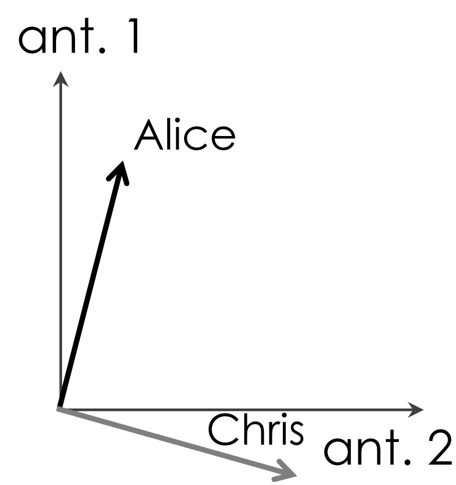


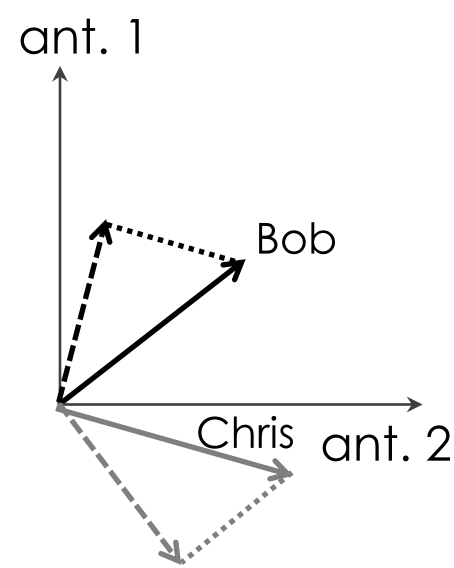
MU-MIMO User Selection



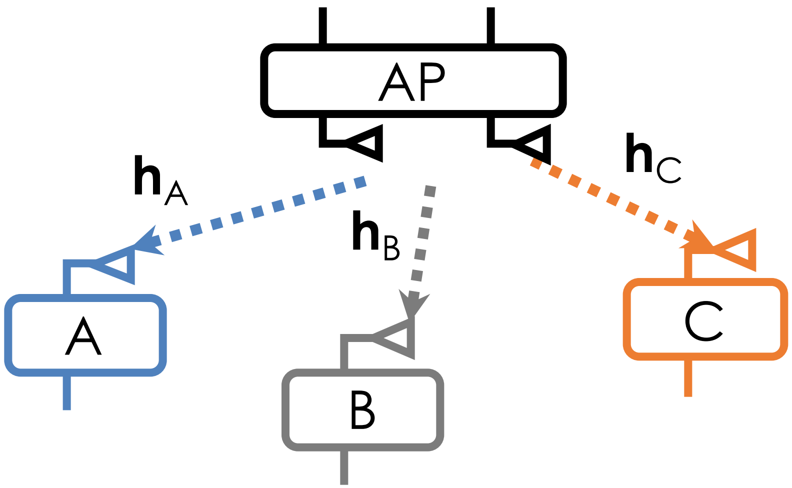
Grouping different subsets of clients as concurrent receivers results in different sum-rates
→ **Need proper user selection**







MU-MIMO User Selection



Grouping different subsets of clients as concurrent receivers results in different sum-rates
→ **Need proper user selection**

- Exhaustive search:
  - Calculate the sum-rate for each of $\binom{N}{k}$ groups
  - Pick the one with the maximal sum-rate
- Greedy:
  - sequentially add a user producing the maximal rate after projecting on the subspace of the users that have been selected

MU-MIMO Power Allocation

- Achievable sum-rate for a set of user S

$$R = \max_{p_i} \sum_{i \in \mathcal{S}} \log(1 + p_i |\mathbf{h}_i \mathbf{w}_i|^2)$$

subject to

$$\sum_{i \in \mathcal{S}} \|\mathbf{w}_i\|^2 p_i \leq P_{\max}$$

Power allocated to user *i*

MU-MIMO Power Allocation

$$R = \max_{p_i} \sum_{i \in \mathcal{S}} \log(1 + p_i |\mathbf{h}_i \mathbf{w}_i|^2) \quad \text{s.t.} \quad \sum_{i \in \mathcal{S}} \|\mathbf{w}_i\|^2 p_i \leq P_{\max}$$

- Optimal power allocation: Waterfilling

$$p_i = \left(\frac{\mu}{\|\mathbf{w}_i\|^2} - 1 \right)^+,$$

where

$$(x)^+ = \max\{x, 0\}$$

μ is the water level satisfying $\sum_{i \in \mathcal{S}} (\mu - \|\mathbf{w}_i\|^2)^+ = P$

[1] Yoo et.al. "On the optimality of multiantenna broadcast scheduling using zero-forcing beamforming," IEEE JSAC, 24(3):528–541, March 2006.
[2] Huang et.al., "User Selection for Multiuser MIMO Downlink With Zero-Forcing Beamforming," in IEEE TVT, vol. 62, no. 7, pp. 3084-3097, Sept. 2013.

Waterfilling Power Allocation

power allocated to user *i*: $p_i = \left(\frac{\mu}{\|\mathbf{w}_i\|^2} - 1 \right)^+$

water level μ such that

$$\sum_{i \in \mathcal{S}} (\mu - \|\mathbf{w}_i\|^2)^+ = P$$

$\|\mathbf{w}_i\|^2$

- Good channels get more power than poor channels
- **Fairness** is a concern

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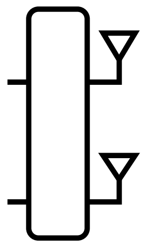
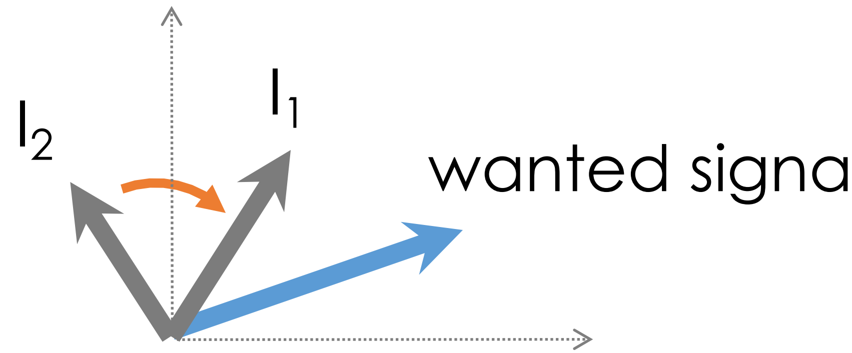
Interference Alignment





N-antenna node can only decode N signals

If I_1 and I_2 are aligned,

→ appear as one interferer

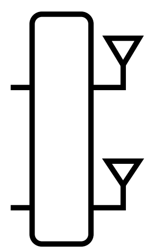
→ 2-antenna receiver can decode the wanted signal x and the combined interference (I_1+I_2)

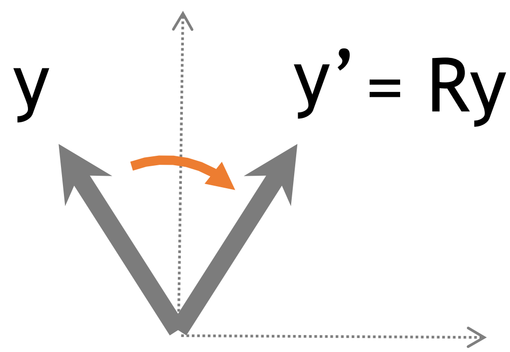
→ No need to decode I_1 and I_2 since the Rx does not care

Rotate Signal

- A multi-antenna transmitter can rotate the received signal

2-antenna receiver

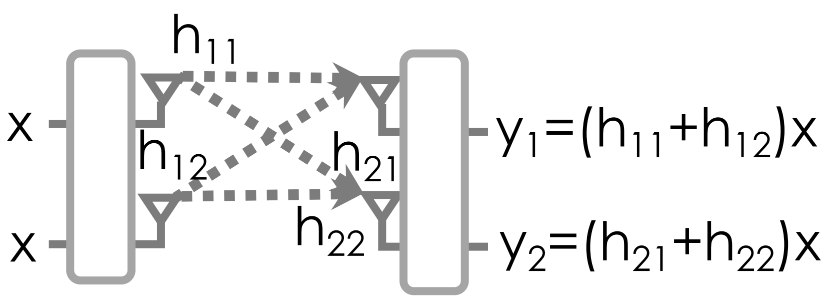


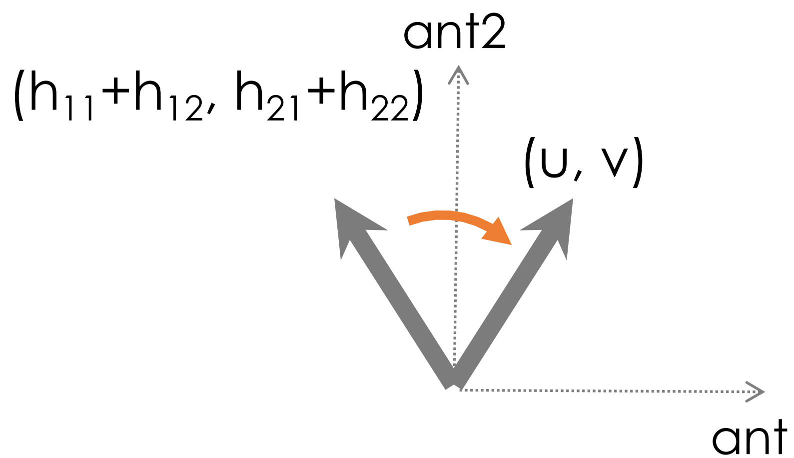


- To rotate received signal y to $y' = Ry$, the transmitter precodes the transmitted signal by multiplying it with the rotation matrix R

Rotate Signal (2x2 Example)

- Say an interfering transmitter wants to align its signal at the interfered receiver along the direction (u,v)
- The interferer precodes its signal x with a weight vector (w_1, w_2)





Rotate Signal (2x2 Example)

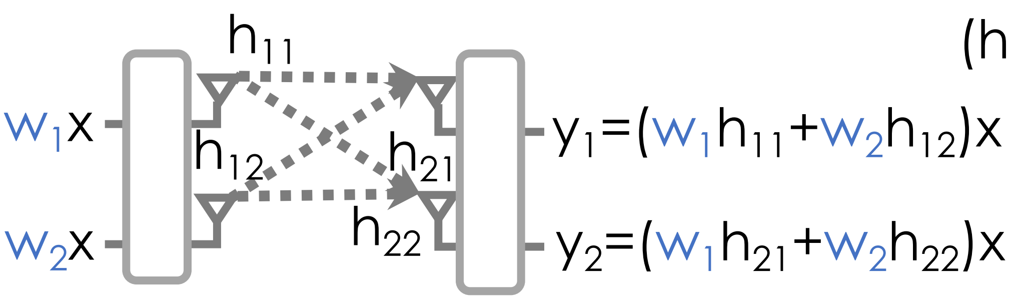
- Find (w_1, w_2) such that
  - $(w_1h_{11}+w_2h_{12}, w_1h_{21}+w_2h_{22}) \mathbin{/\!/} (u, v)$

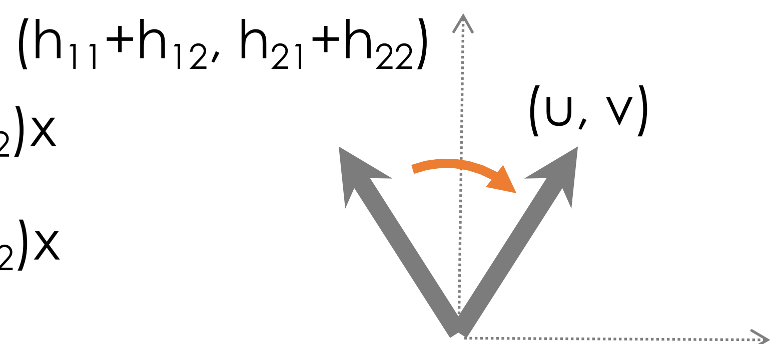
$$(1)\quad \frac{w_1 h_{11} + w_2 h_{12}}{w_1 h_{21} + w_2 h_{22}} = \frac{u}{v}$$

Alignment

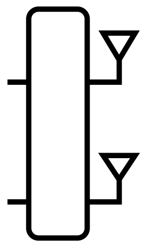
$$(2)\quad \sqrt{w_1^2 + w_2^2} = 1$$

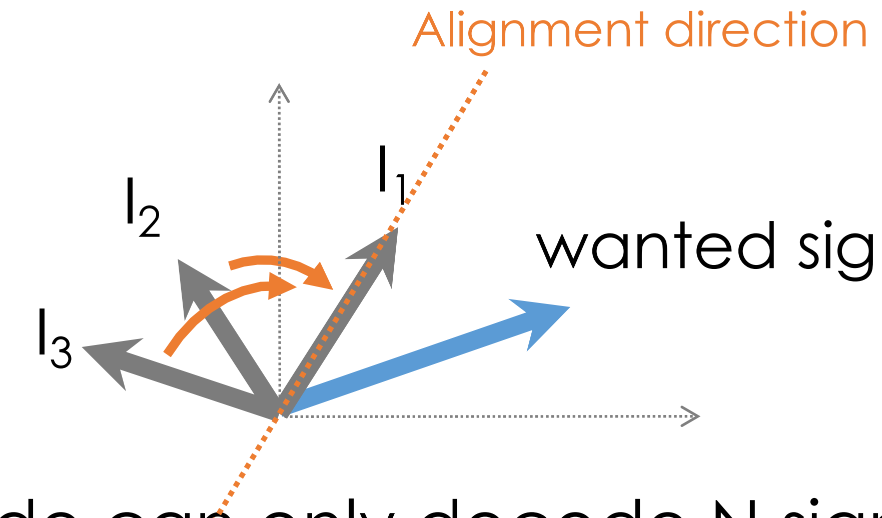
Power constraint





Interference Alignment





<u>N-antenna node can only decode N signals</u>

How to align interfering signals?

→ Find the direction of any interference (e.g., I_1)

→ All the remaining interferers (e.g., I_1 and I_2) rotate their signals to that direction

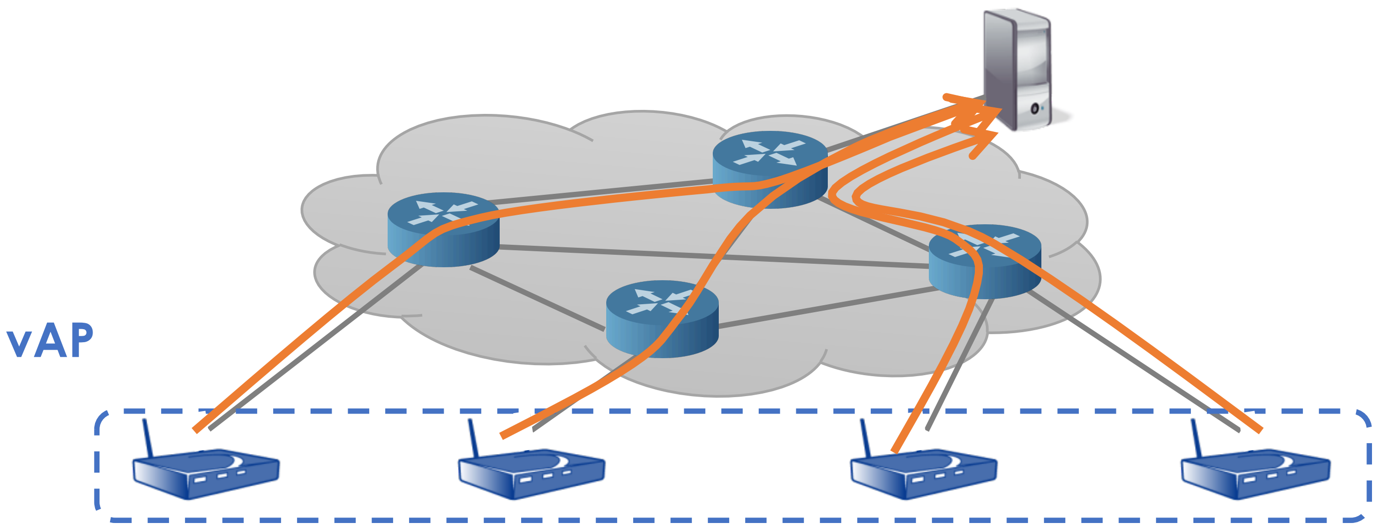
Agenda

- Interference Nulling
- Zero-forcing Beamforming (802.11ac)
- Interference Alignment
- Network MIMO

Network MIMO

- Also known as virtual MIMO, cooperative MIMO, distributed MIMO
- Why we need network MIMO?
  - Maximal number of concurrent packets is limited by the number of antennas per AP
  - It is hard to equip with a large number of antennas in a single AP
- How to build a network MIMO node?

Network MIMO



- Combine multiple APs as a giant virtual AP
- Distributed antennas are connected via backhual wired network
- Process signals by one or multiple backend servers

Open Issues of Network MIMO

- Salability
- Latency
- Synchronization

Scalability

- Forwarding raw complex signals through the Ethernet requires an extremely large backhual bandwidth
  - Ethernet capacity might now become a bottleneck
- Complexity of precoding/decoding a large scale of streams is fairly high
  - A single server can only support a limited number of concurrent packets
  - Software-based precoding/decoding at the servers is less efficient than hardware-based processing at APs

Latency

- Servers need to collect the received signals from distributed antennas
- The latency between antennas and servers might be longer than symbol duration
  - For example, the symbol duration of 802.11n is only 4 microseconds (us)
- A packet might not be able to be acknowledged immediately after data transmission
  - The MAC protocol might need to be re-designed

Synchronization

- MIMO transmissions require all the antennas to be tightly synchronized
  - Otherwise, a small frequency offset could destroy all the concurrent packets
- Potential Solutions
  - Connect all the APs to an external clock → scalability would be an issue
  - Each AP learn the frequency offset based on a reference clock and calibrate the offset → hard to achieve a granularity acceptable for network MIMO

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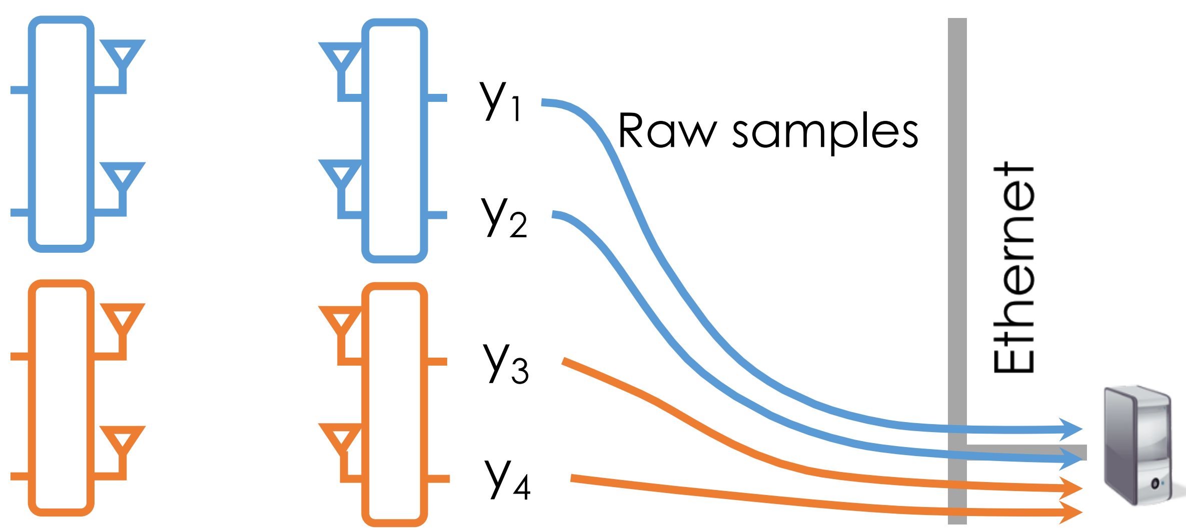
Lecture 5: Multi-User MIMO (MU-MIMO)

Interference Alignment and Cancellation (SIGCOMM'09)

Lecturer: Kate Ching-Ju Lin (林靖茹)

Naïve Cooperative MIMO

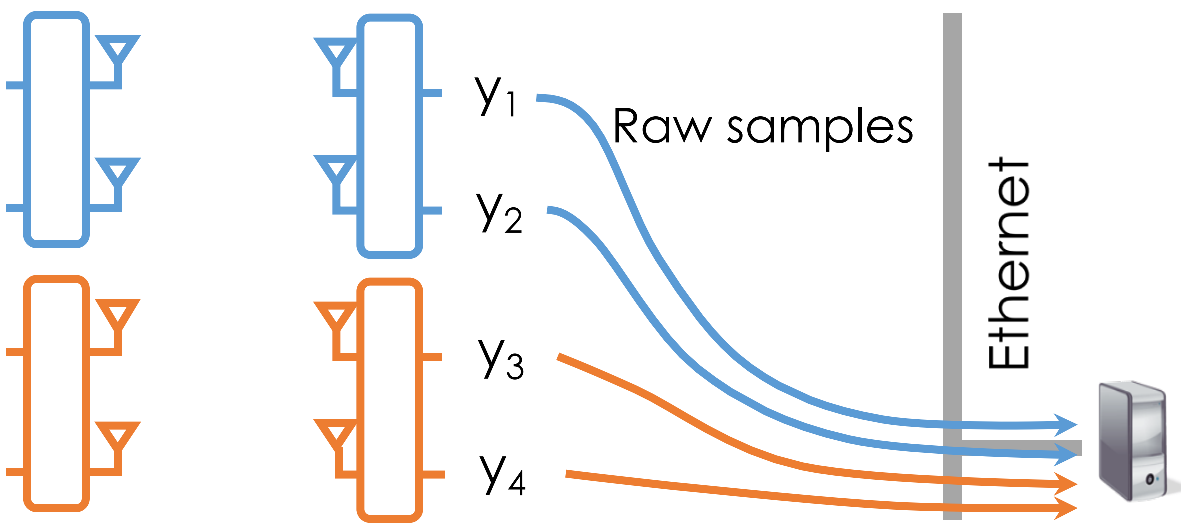
- Say we combine two 2-antnena APs as a 4–antenna virtual AP
- Naïve solution:
  - Connect the two APs to a server via Ethernet
  - Each physical AP sends every received raw signal (complex values) to the server over Ethernet



Naïve Cooperative MIMO

Impractical overhead:
For example, a 3 or 4-antenna system needs 10's of Gb/s

- Naïve solution:
  - Connect the two APs to a server via Ethernet
  - Each physical AP sends every received raw signal (complex values) to the server over Ethernet



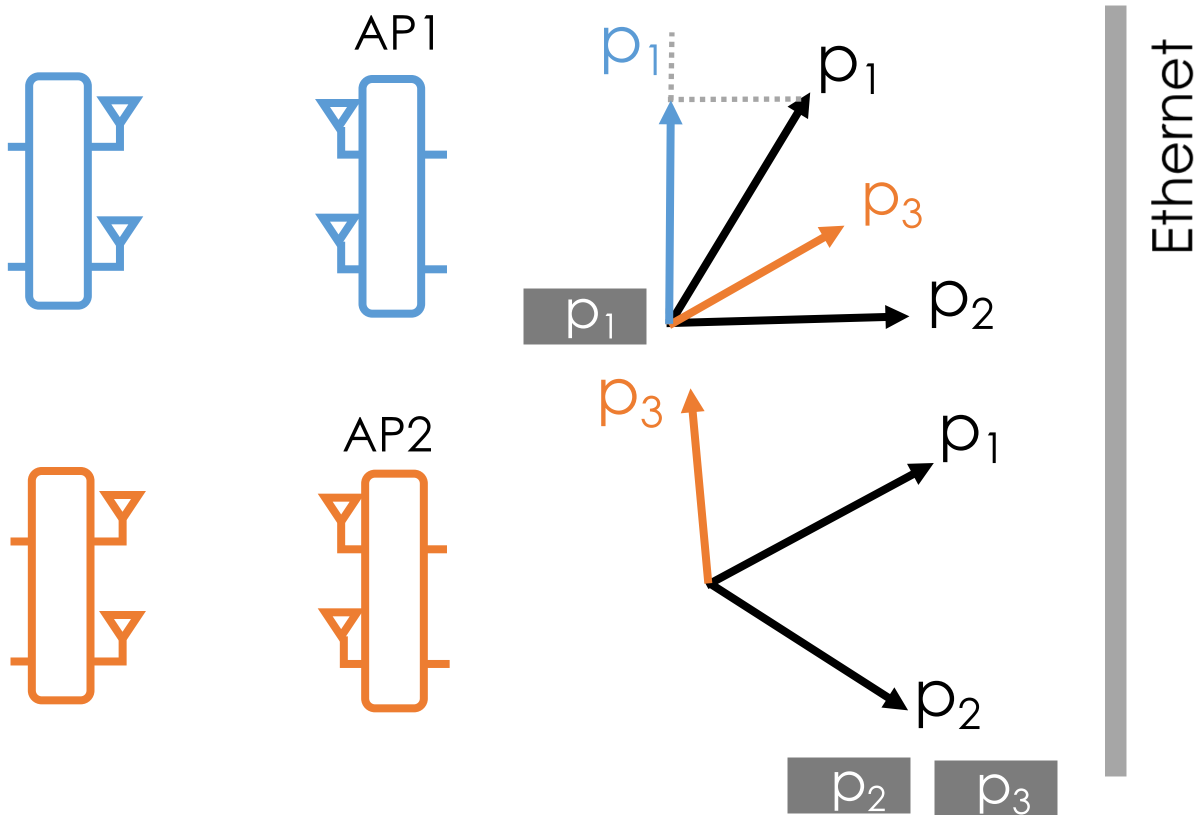
How to Minimize Ethernet Overhead?

- High-level idea:
  1. Decode some packets in certain AP
  2. Forward the decoded packets through the Ethernet to other APs
  3. Other APs decode the remaining packets
  4. Repeat 1-3 until all packets are recovered

How to Minimize Ethernet Overhead?

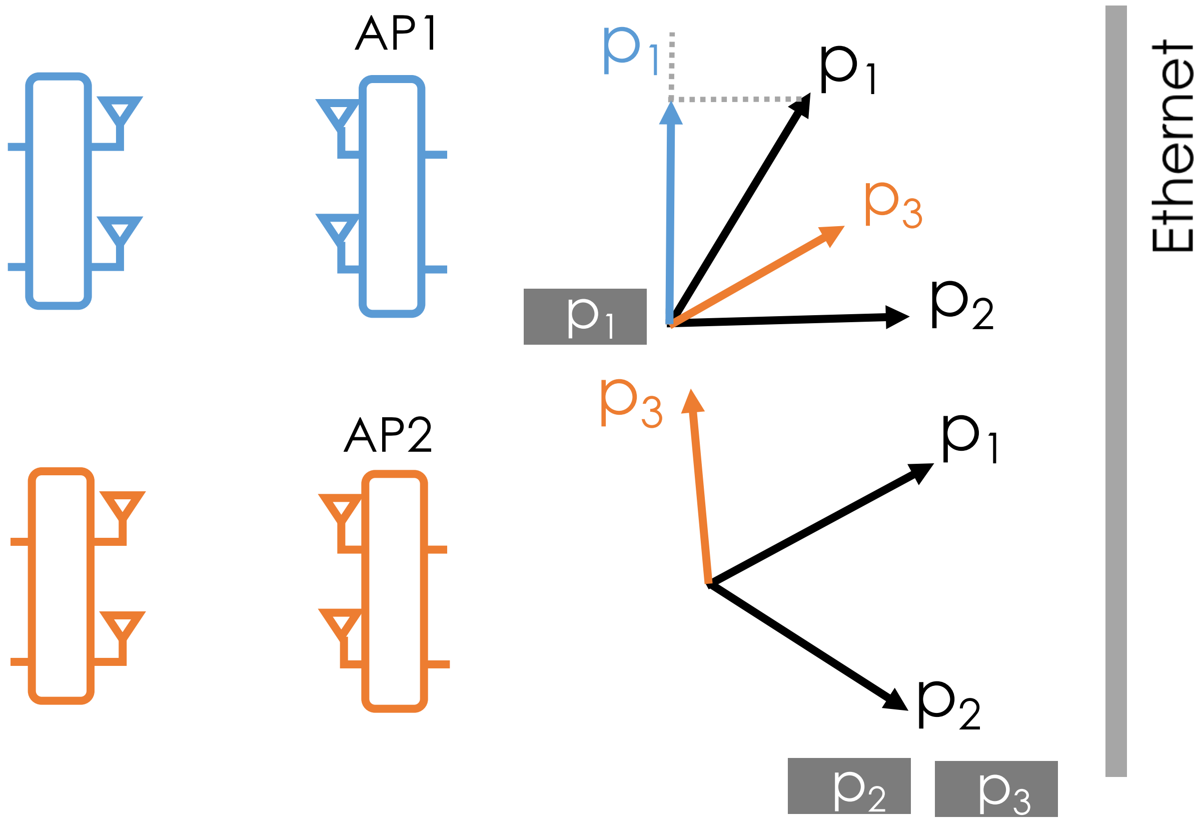
- Advantage:
  - The size of data packets is much smaller than the size of raw samples → minimize overhead
- Challenge:
  - In theory, an N-antenna AP cannot recover M concurrent transmissions if M>N
  - How can an N-antenna AP recover its packet from M concurrent transmissions (M>N)?
    → **Interference Alignment and Cancellation**

Interference Alignment and Cancellation



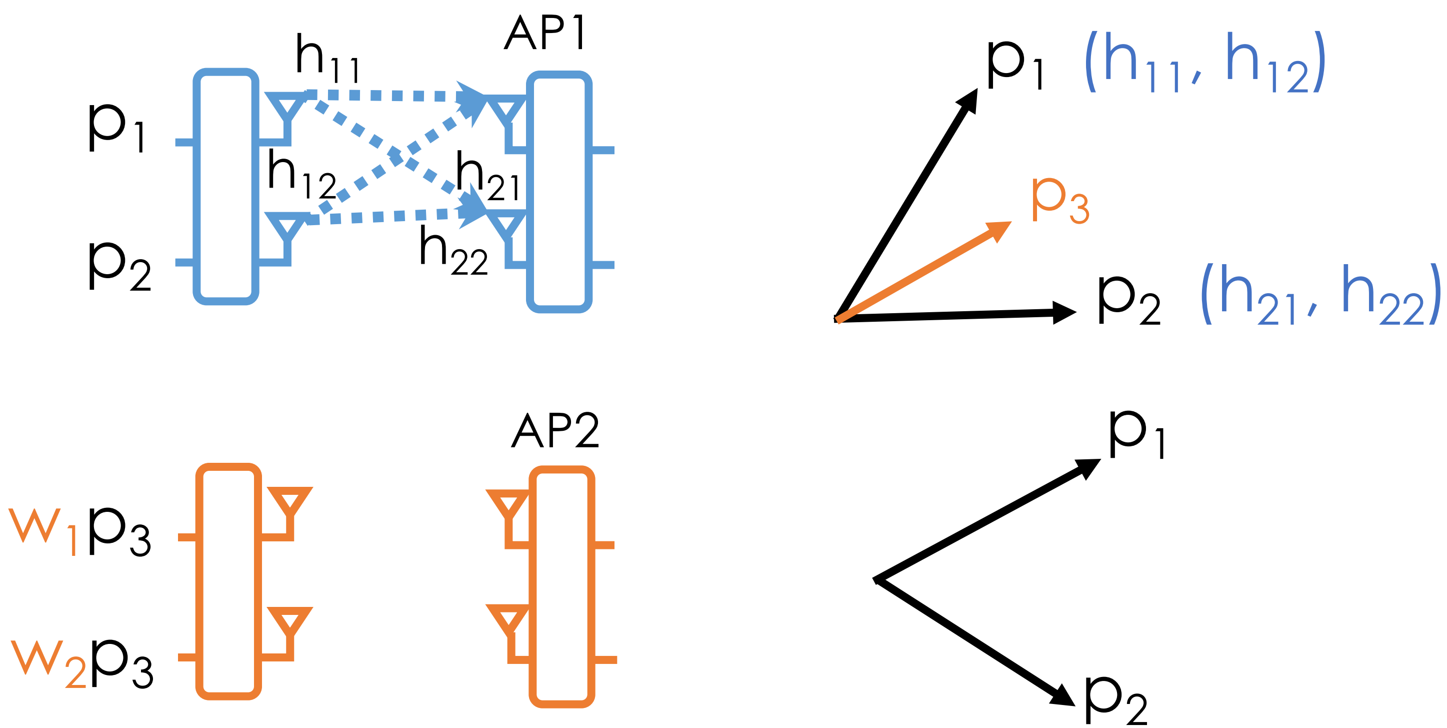
- Align p_3 with p_2 at AP1
- AP1 broadcasts p_1 on Ethernet
- AP2 subtracts/cancels $p_1 \rightarrow$ decodes p_2, p_3

Interference Alignment and Cancellation



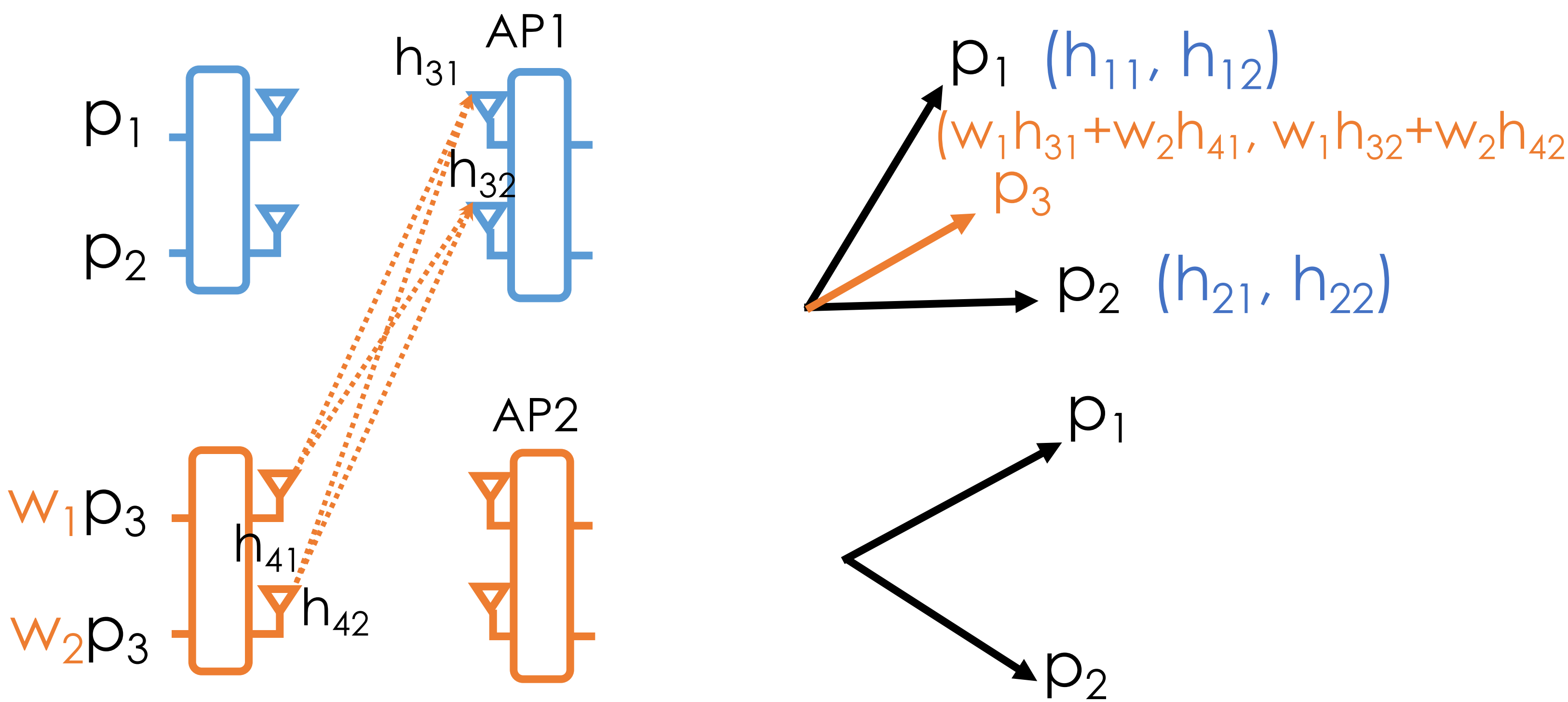
Only forward **1 data packet** through the Ethernet!

How to Align?



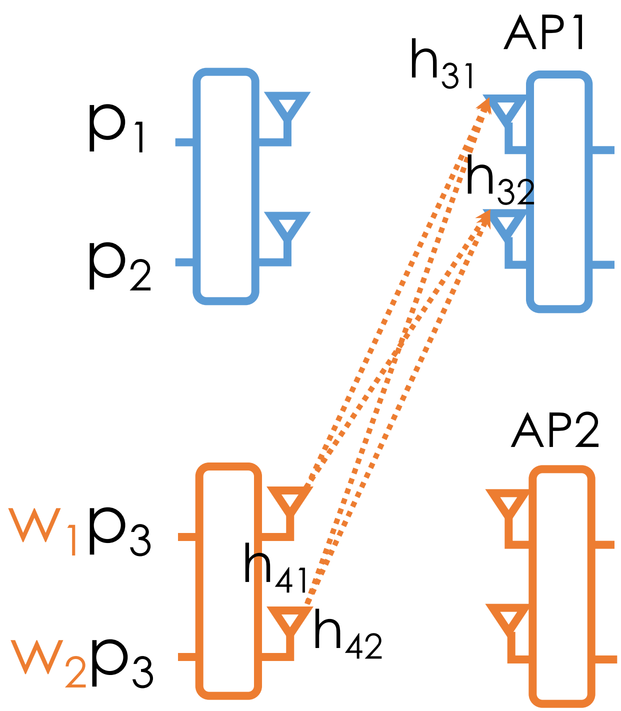
1. Learn the direction we need to align
   – Client 2 aligns p_3 along (h_{21}, h_{22}) at AP1

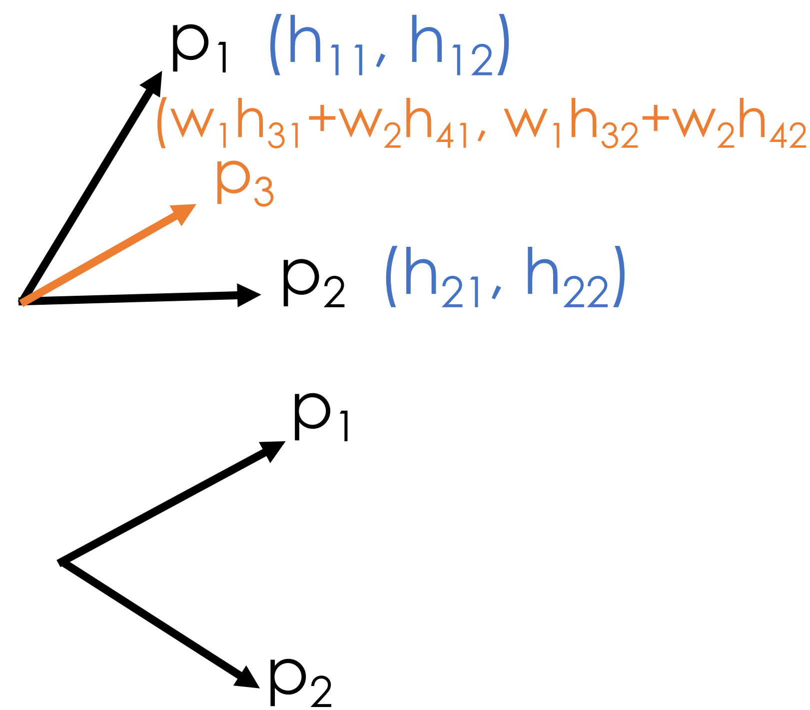
How to Align?



2. Precode p_3 by (w_1, w_2)
3. AP2 receives p_3 along the direction $(w_1 h_{31}+w_2 h_{41}, w_1 h_{32}+w_2 h_{42})$

How to Align?





4. Since AP1 tries to decode p_1, we align the interference p_3 along the direction of p_2

→ Let $(w_1h_{31}+w_2h_{41})/(w_1h_{32}+w_2h_{42})=h_{21}/h_{22}$

Infinite number of solution?

No! **power constraint** $w_1{}^2+w_2{}^2=P_{max}$

How to Remove Interference?

- For example, how can AP2 remove the interference from p_1?
- Cannot just subtract the bits of p_1 from the received packet
  - Should subtract interference signals as received by AP2
- How? → Similar to SIC
  - AP2 re-modulates p_1's bits
  - AP2 estimate the channel from client 1 to AP2 and apply the learned channel on the re-modulated signals of p_1
  - Subtract it from the received signal y

How to Generalize to M-Antenna MIMO?

Theorem

In a M- antenna MIMO system, IAC delivers

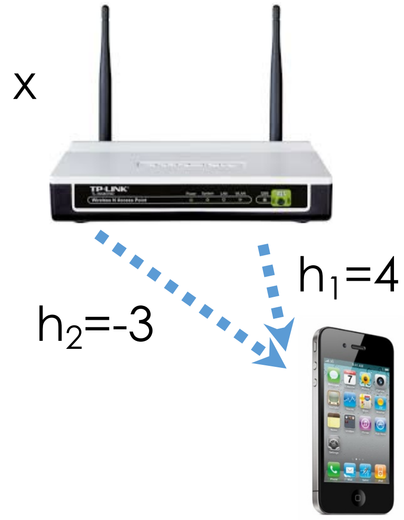
- *2M concurrent packets on uplink*
- *max{2M-2, 3M/2} concurrent packets on downlink*

e.g., M=2 antennas { 4 packets on uplink
3 packets on downlink

See the paper for the details!

Quiz

- Consider a 2x1 system



- How can the AP (Tx) send a symbol x without being heard by the smartphone?