Wireless Communication Systems
@CS.NCTU

Lecture 6: Multi-User MIMO (MU-MIMO)

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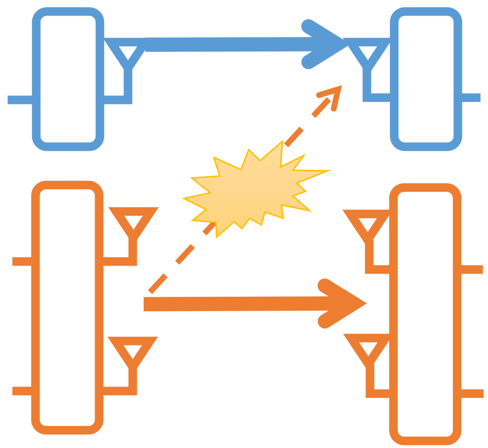
Agenda

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

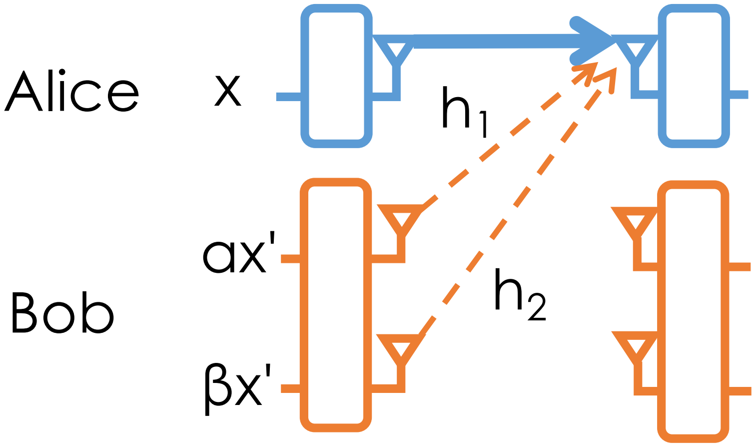
Cross-Link Interference



- 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 $(h_1\alpha+h_2\beta)=0$
$\rightarrow \alpha = -(h_2/h_1)\beta$



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

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

$y'' = h''x + \underbrace{(h_{2a}\alpha+h_{2b}\beta)}_{\neq 0}x'$

- 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

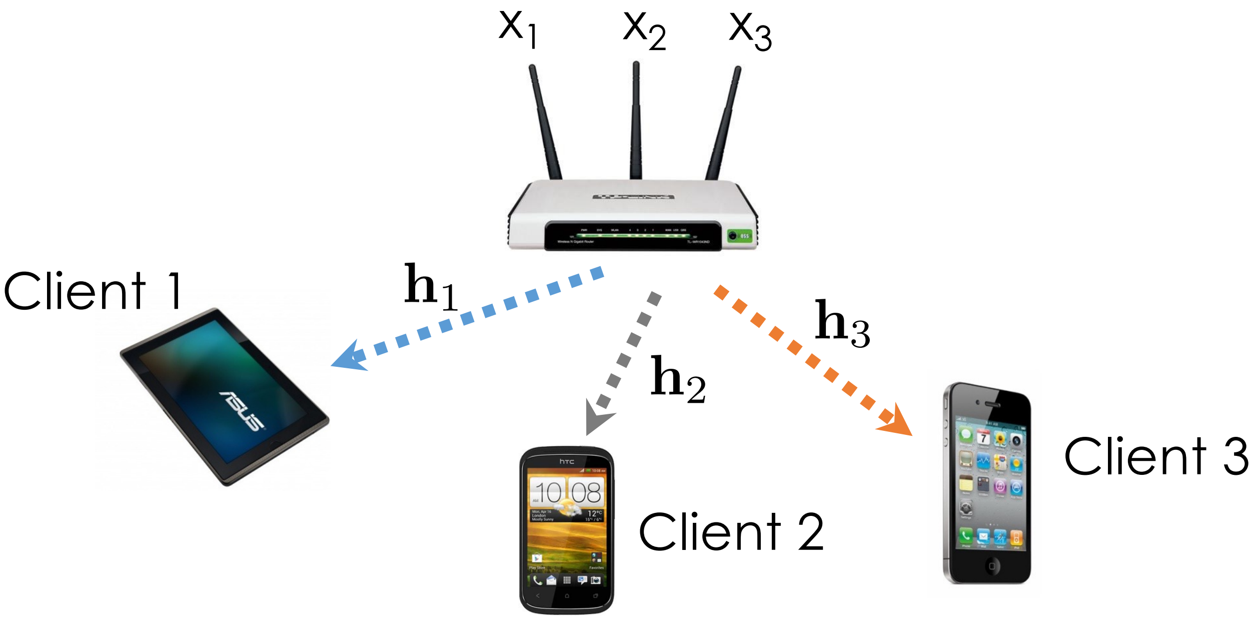
802.11ac

- 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



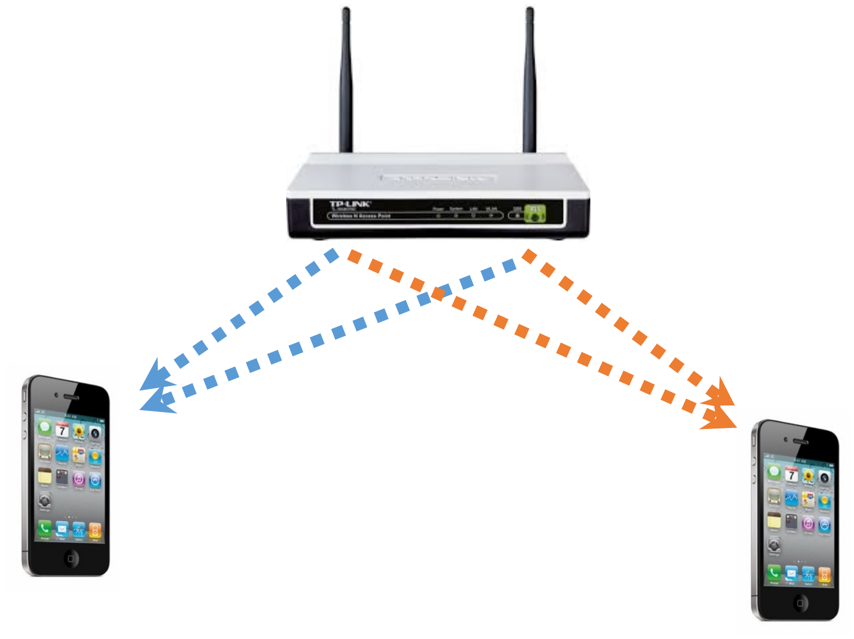
$$\mathbf{h}_1 = [h_{11}\ h_{12}\ h_{13}]^T$$
$$\mathbf{h}_2 = [h_{21}\ h_{22}\ h_{23}]^T$$
$$\mathbf{h}_3 = [h_{31}\ h_{32}\ h_{33}]^T$$

Interference

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

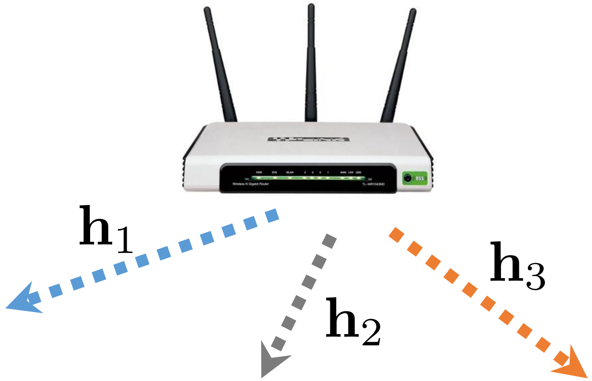
How to Remove Cross-Stream Interference?

- **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?


TP-LINK

Zero-Forcing Beamforming (ZFBF)

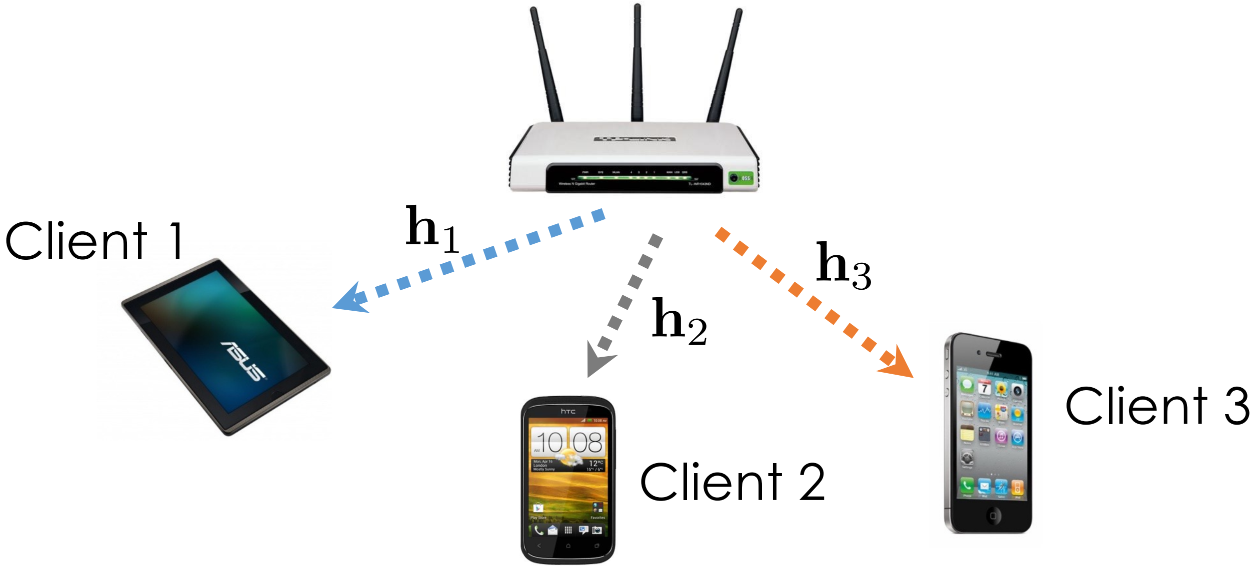
$$[w_{11}\ \ w_{12}\ \ w_{13}] * x_1$$
$$[w_{21}\ \ w_{22}\ \ w_{23}] * x_2$$
$$[w_{31}\ \ w_{32}\ \ w_{33}] * x_3$$



- 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)

$[w_{11}\ \ w_{12}\ \ w_{13}] * x_1 * \sqrt{P_1}$
$[w_{21}\ \ w_{22}\ \ w_{23}] * x_2 * \sqrt{P_2}$
$[w_{31}\ \ w_{32}\ \ w_{33}] * x_3 * \sqrt{P_3}$



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

Null the interference:

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

Matrix: $\mathbf{y} = \mathbf{HW}\sqrt{\mathbf{P}}\mathbf{x} + \mathbf{n} \rightarrow$

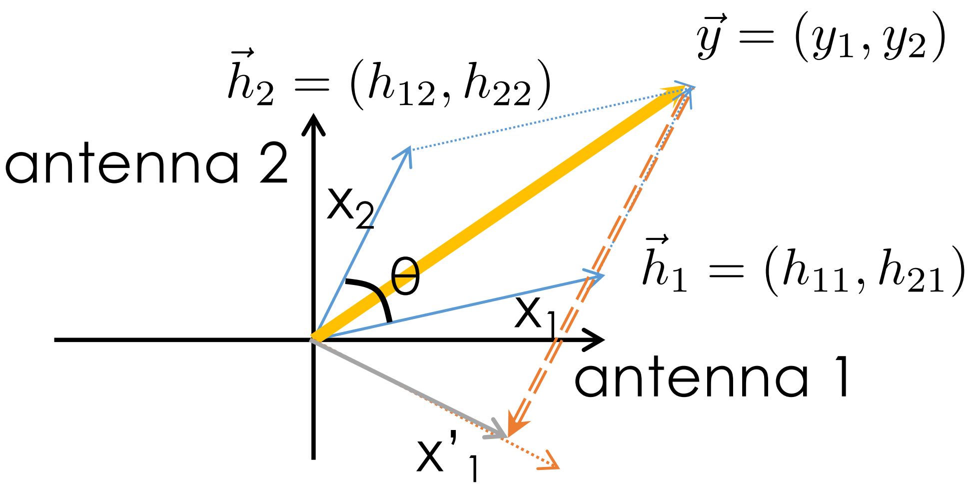
Let **W** be the **pseudo inverse** of **H**

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

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

SNR of ZFBF

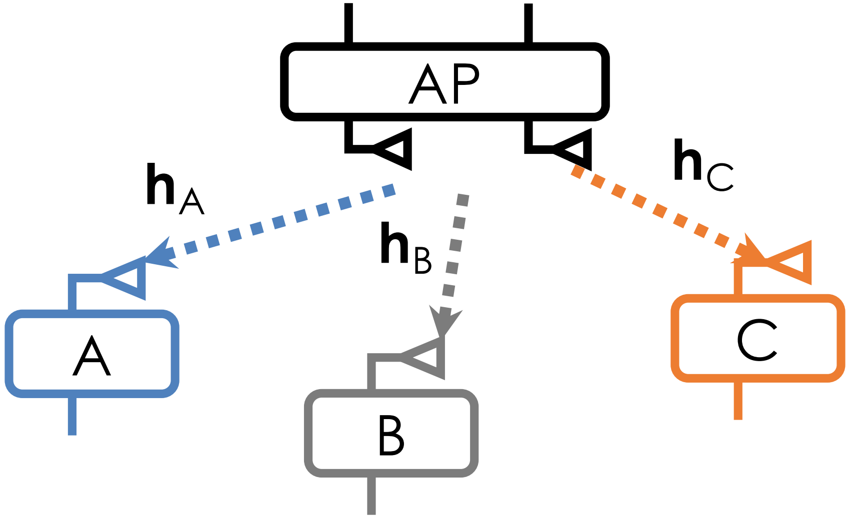
- ZFBF is essentially equivalent to ZF, but just performed by the transmitter



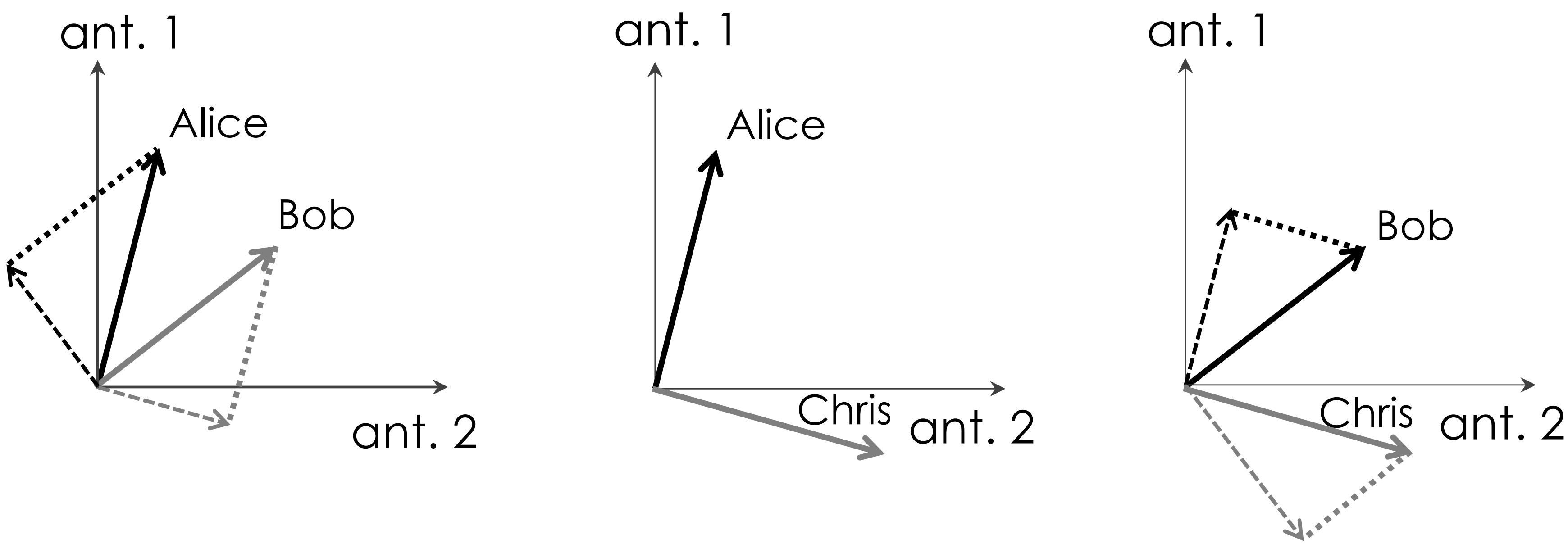
$$|x_1'| = |x_1| \cos(90 - \theta) = |x_1| \sin(\theta)$$

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

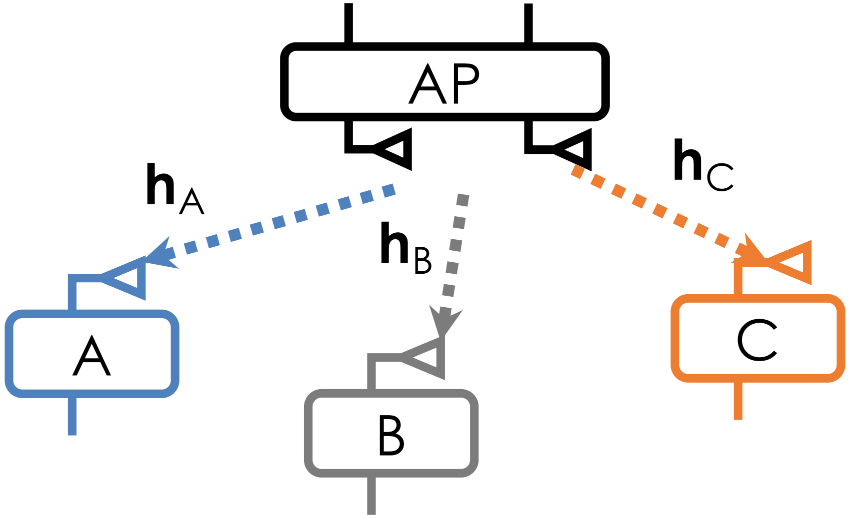
MU-MIMO Bit-Rate Selection



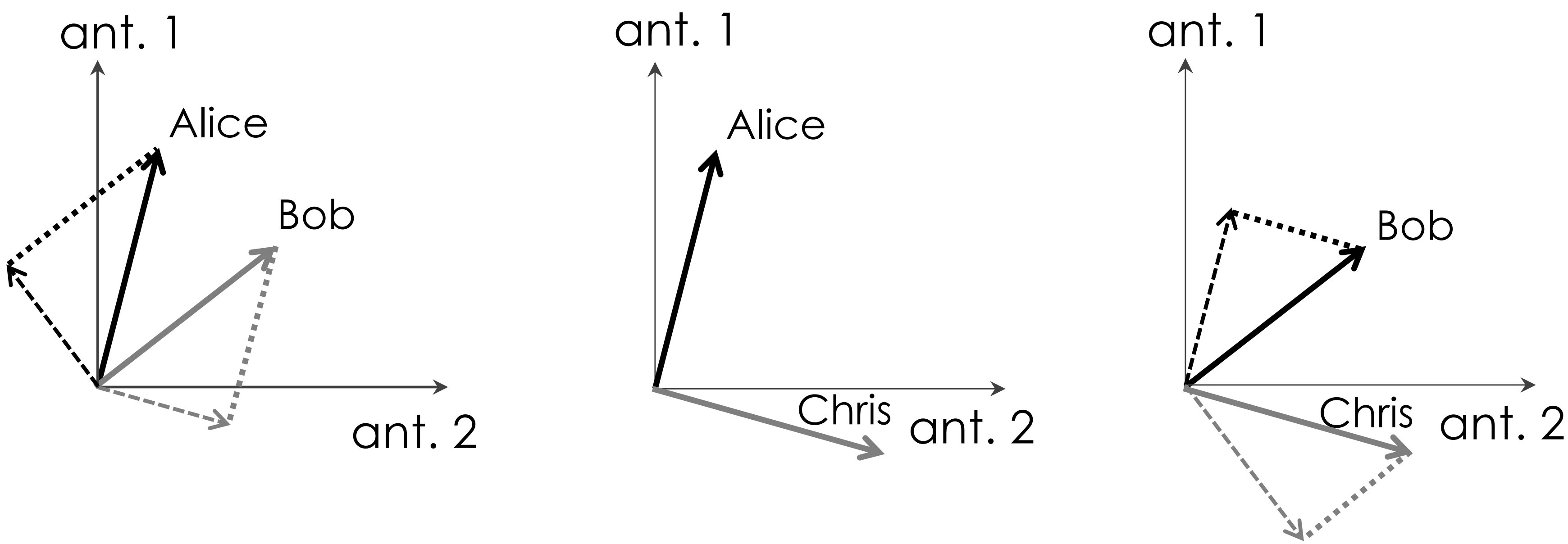
Select a proper rate based on SNR_{ZFBF}



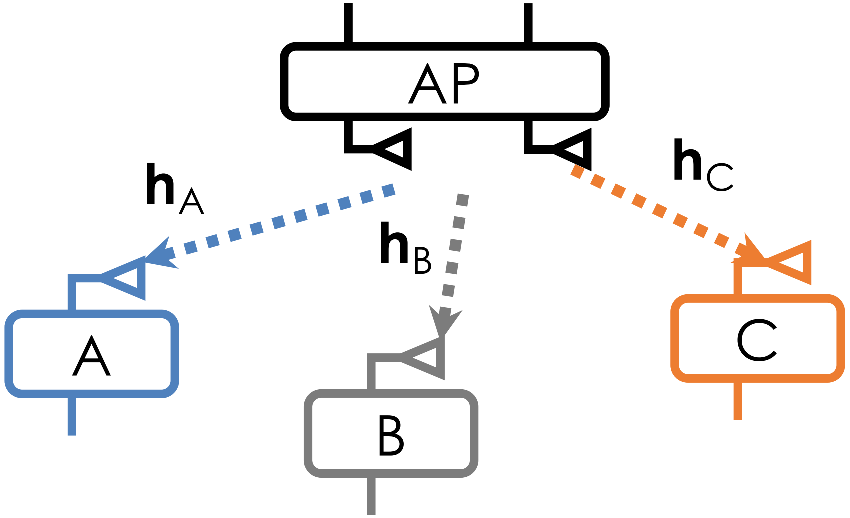
MU-MIMO User Selection



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 $\mathcal{S}$

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

subject to

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

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: Water filling

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

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

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

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

- Unequal power allocation
- **Fairness** is a concern

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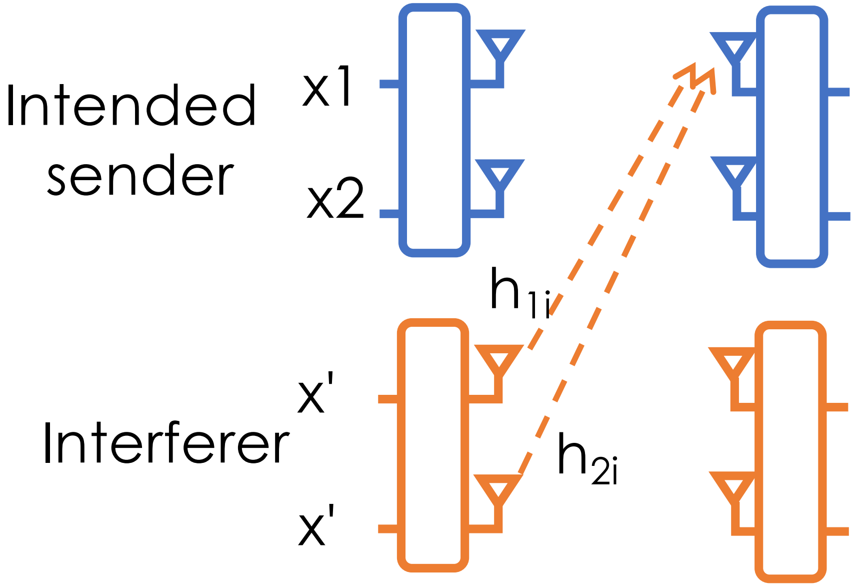
Interference Alignment Example



interference

$$y_1 = h_{11}x_1 + h_{12}x_2 + h_{1i}x'$$

$$y_2 = h_{21}x_1 + h_{22}x_2 + h_{2i}x'$$

x_1 can be decoded if x2 and x’ are **aligned**!

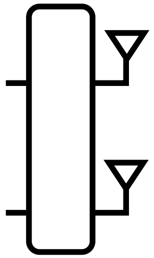
$$y_1 = h_{11}x_1 + h_{12}(x_2 + x')$$

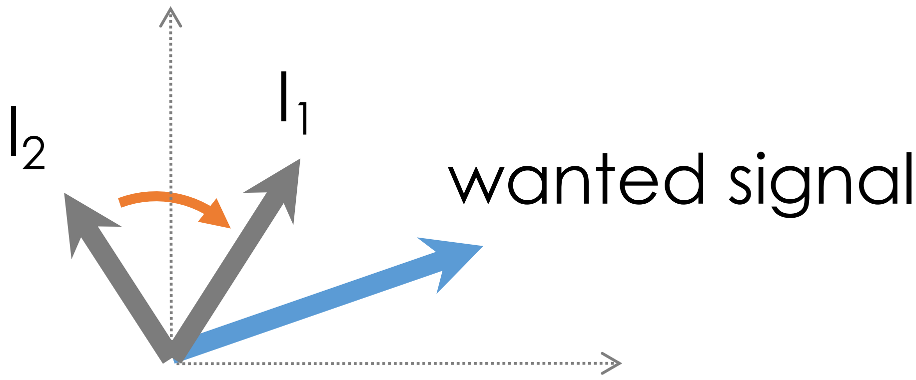
$$y_2 = h_{21}x_1 + h_{21}(x_2 + x')$$

though x_2 and x’ cannot be decoded!

Interference Alignment

2-antenna receiver





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

If I_1 and I_2 are aligned,

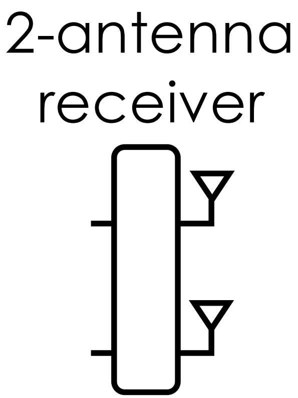
→ appear as one interferer

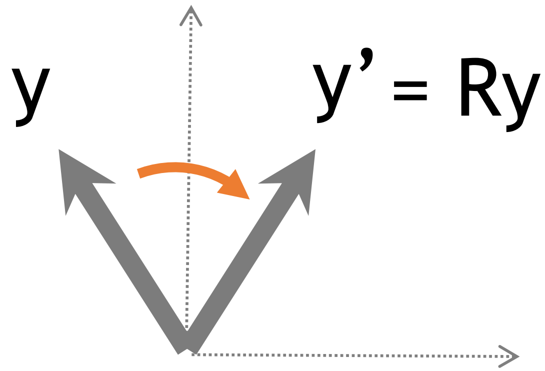
→ 2-antenna receiver can decode the wanted signal x and the combined interference (I_1+I_2)

→ 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

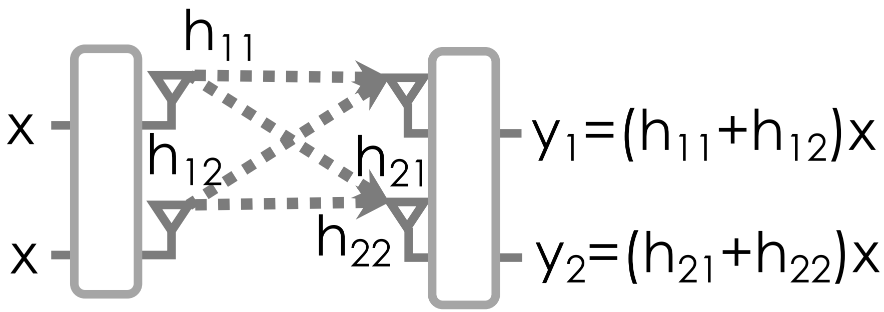


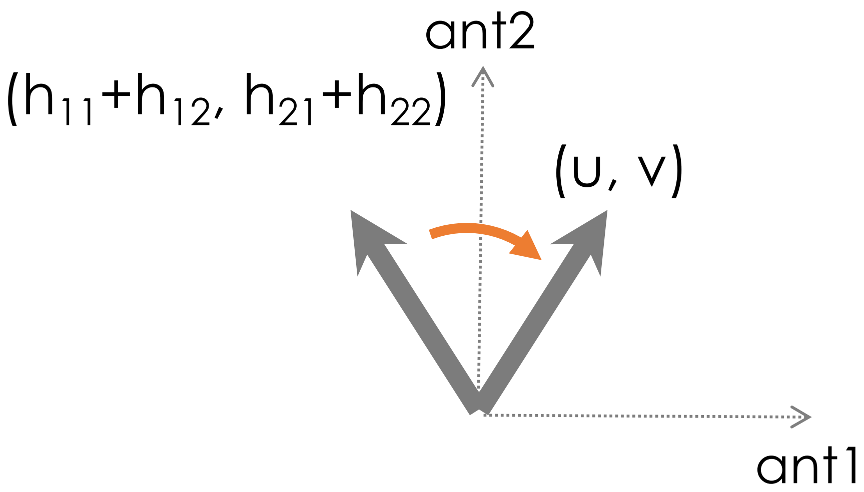


- To rotate received signal y to $y' = Ry$, the transmitter precodes the transmitted signal by multiplying it with the rotation matrix R

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)

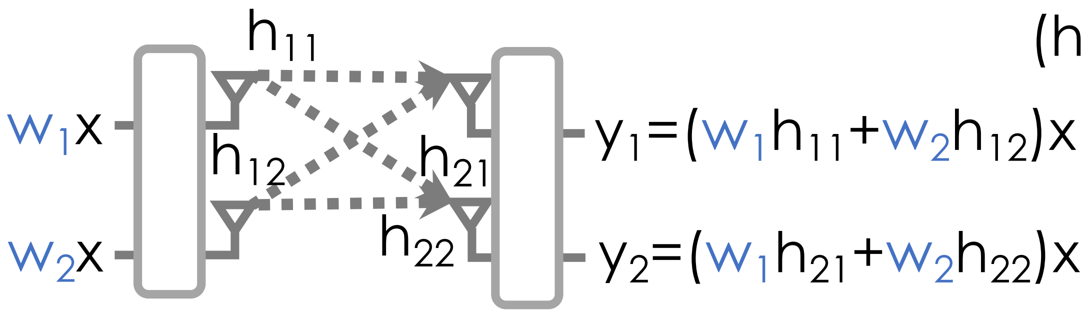
- Find (w_1, w_2) such that
  - $(w_1 h_{11} + w_2 h_{12},\ w_1 h_{21} + w_2 h_{22}) \parallel (u, v)$

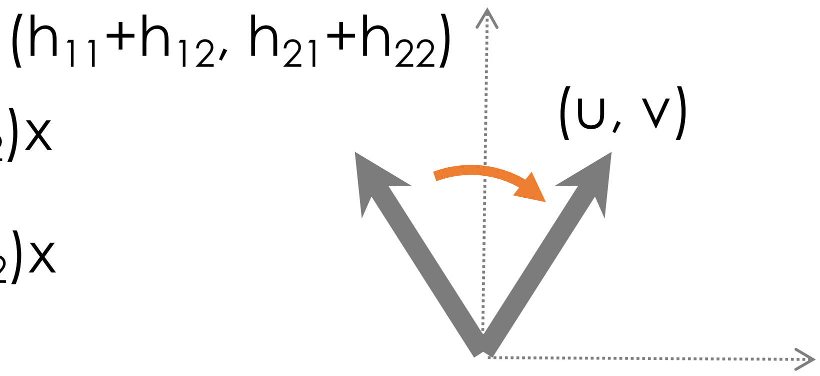
$$(1) \quad \frac{w_1 h_{11} + w_2 h_{12}}{w_1 h_{21} + w_2 h_{22}} = \frac{u}{v}$$

Alignment

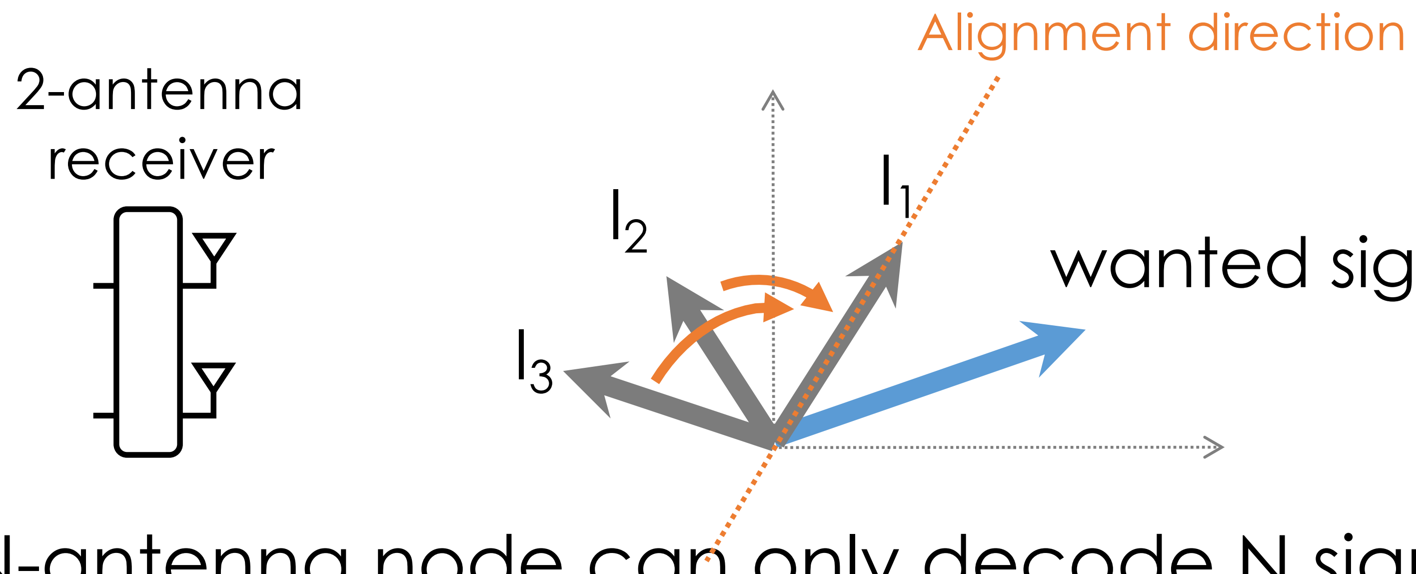
$$(2) \quad \sqrt{w_1^2 + w_2^2} = 1$$

Power constraint





Interference Alignment



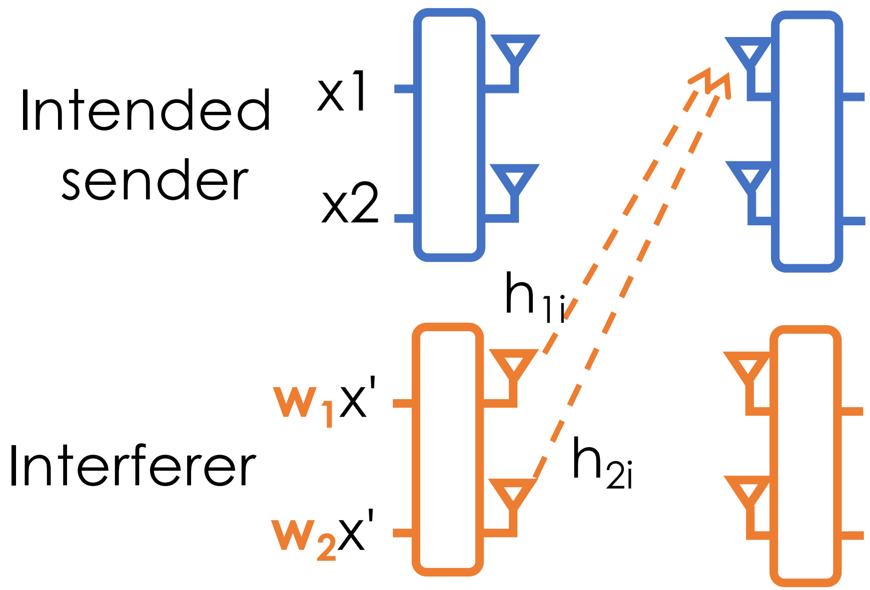
<u>N-antenna node can only decode N signals</u>

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

Interference Alignment Example



interference

$$y_1 = h_{11}x_1 + h_{12}x_2 + w_1 h_{1i} x'$$

$$y_2 = h_{21}x_1 + h_{22}x_2 + w_2 h_{2i} x'$$

Let $w_1 h_{1i} = h_{12}$
Let $w_2 h_{2i} = h_{22}$

x_1 can be decoded if x2 and x' are **aligned**!

$$y_1 = h_{11}x_1 + h_{12}(x_2 + x')$$

$$y_2 = h_{21}x_1 + h_{21}(x_2 + x')$$

though x_2 and x' cannot be decoded!

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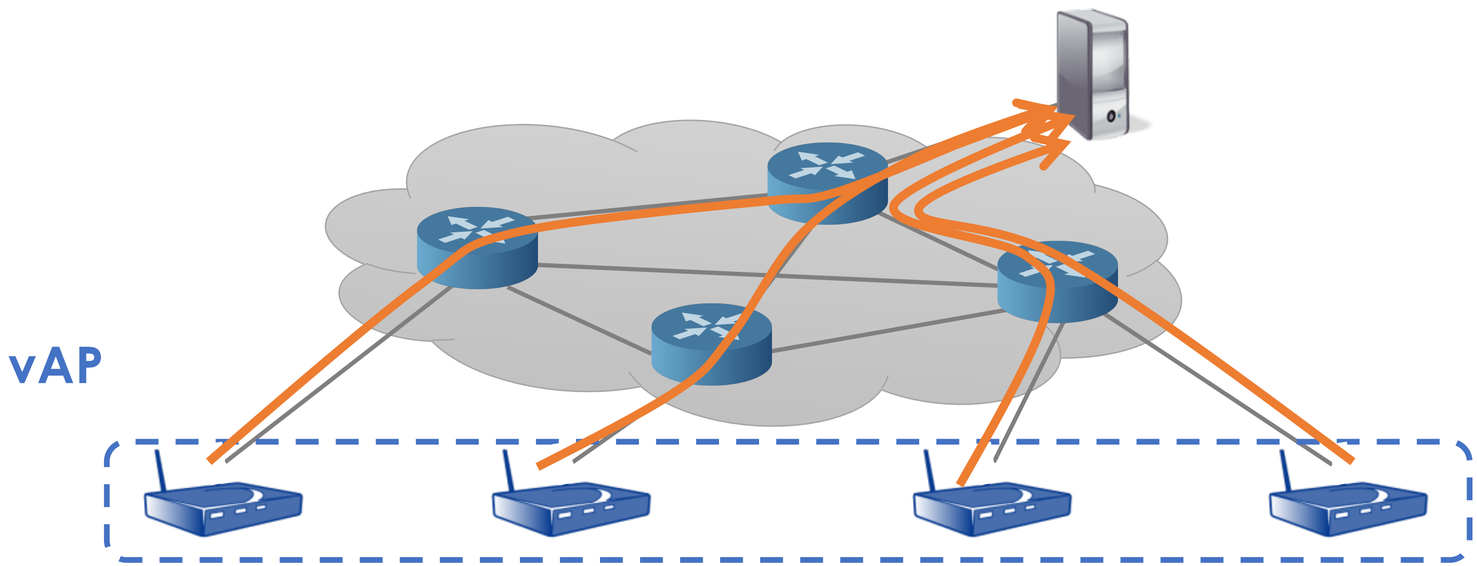
Network MIMO

- 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

- Scalability
- 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