ECE/CS 707
Mobile and Wireless Networking

Introduction to MIMO

Prof. Xinyu Zhang

Dept. of Electrical and Computer Engineering

University of Wisconsin-Madison

Today's agenda

- Overview of MIMO communications
- Single-user MIMO
- Multi-user MIMO
- Network MIMO

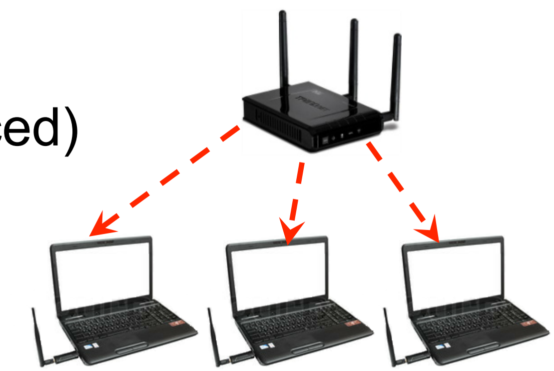
MIMO: an Overview

- MIMO (Multiple-Input Multiple-Output)
  - Transmitter/receiver can have multiple antennas
  - A modern wireless communication technology
    - Theory: late 1980’s
    - Standards and products: after 2000’s
    - Now: core feature in WLAN (802.11 WiFi) and cellular (3G LTE, WiMax)
  - Two benefits, simply put
    - Improve link SINR
    - Improve link concurrency

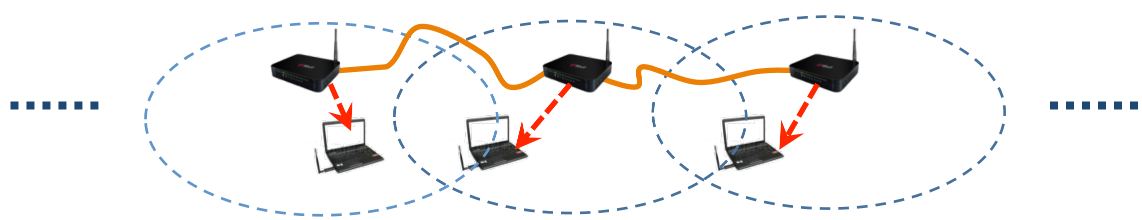
MIMO: an Overview

- MIMO network architectures
  - Single-user MIMO (in 802.11n-2009, LTE)
    - One TX, one RX. Either TX or RX or both can have multiple antennas

  - Multi-user MIMO (in 802.11ac-2014, LTE-Advanced)
    - One TX, multiple RX. Parallel transmissions.

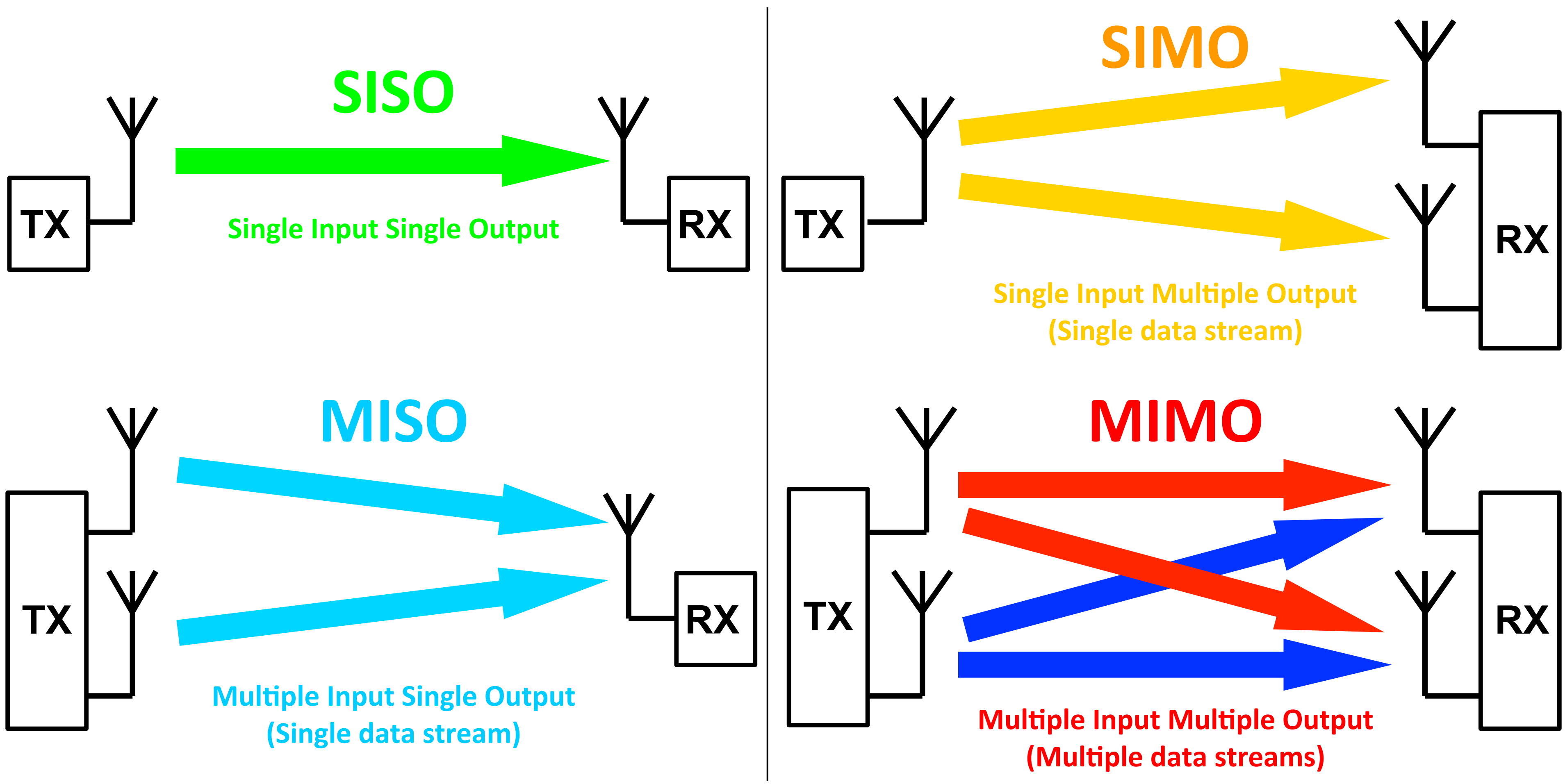


  - Network MIMO (expected in near-future)
    - Multiple TX, multiple RX. Parallel transmissions.

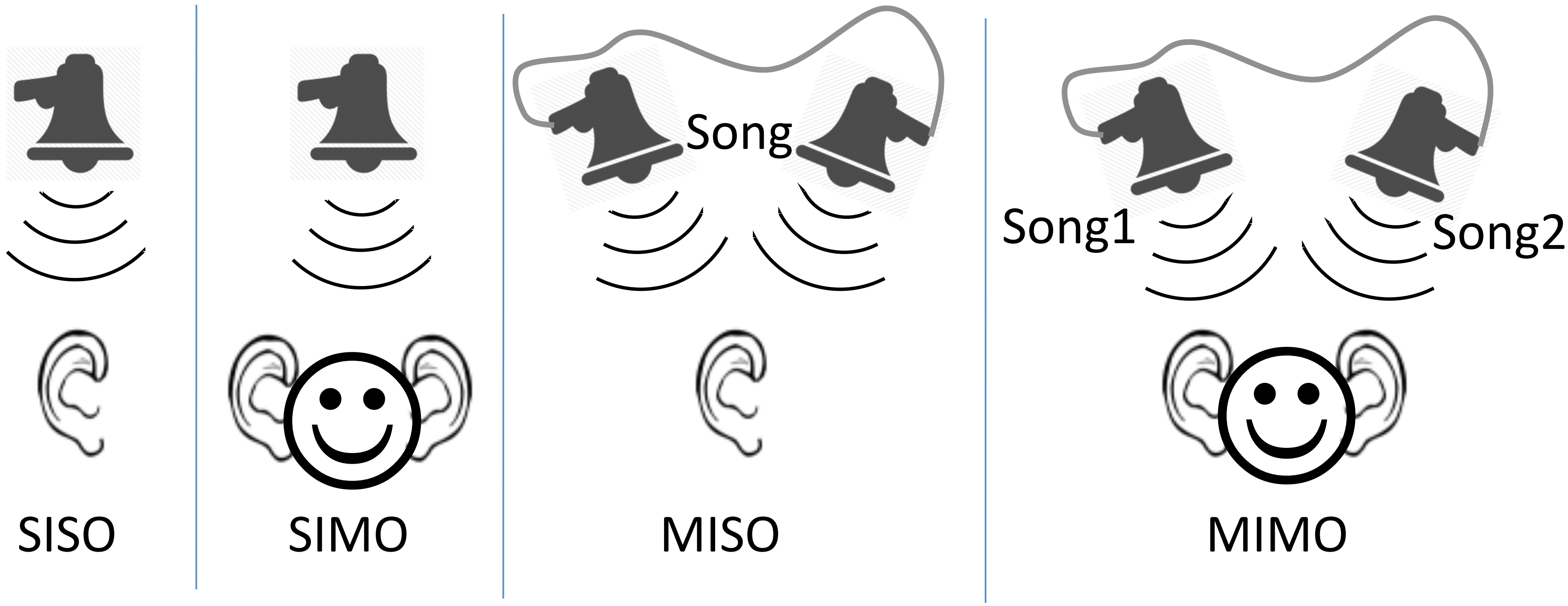


Single-user MIMO

- Basic communication modes



MIMO benefits: an audio metaphor

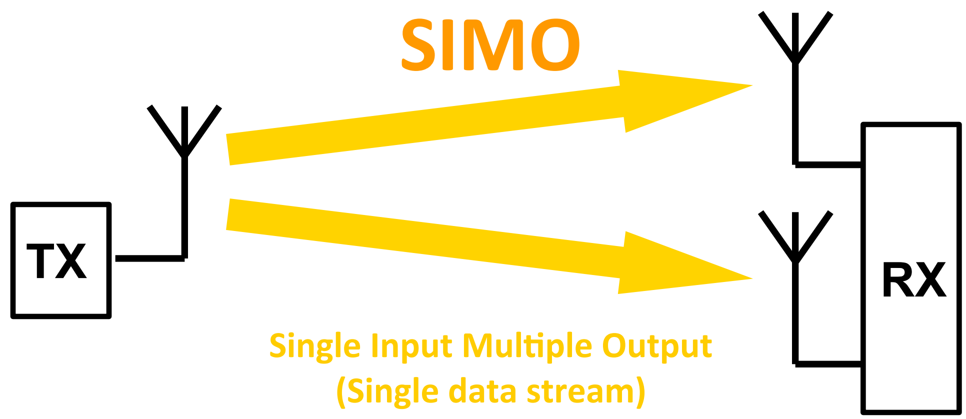


Single-user MIMO benefits: capacity gains

- Diversity gain
  - Receiver diversity
  - Transmit diversity
- Multiplexing gain
  - Spatial multiplexing

Receiver diversity

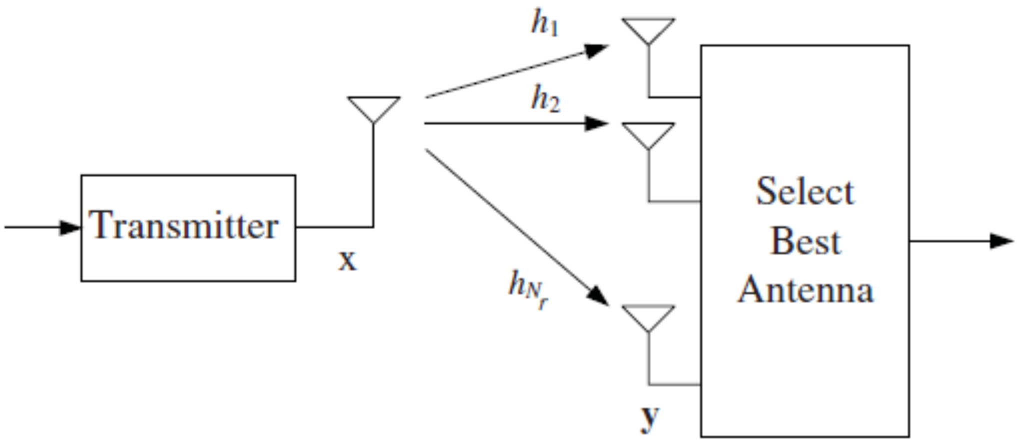
- Receiver coherently combines signals received by multiple antennas



- Asymptotic gain: Increasing SNR proportionally to Nr (#of receive antennas)
  * Intuition: received signal power adds up

- What's the capacity gain?
  * Logarithmically, according to Shannon's equation: C=B log(1+SNR)
  * When SNR is low, $\log(1+SNR) \approx SNR$, so gain is almost linear w.r.t. Nr

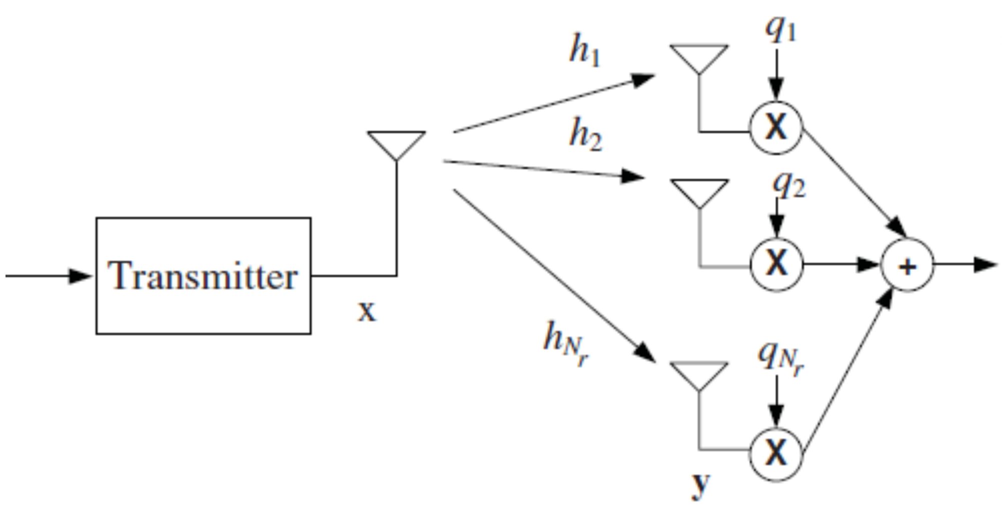
Implementing receiver diversity



* Selection combining

  Improves SNR to

$$avgSNR \cdot (1 + \frac{1}{2} + \ldots + \frac{1}{N_r})$$

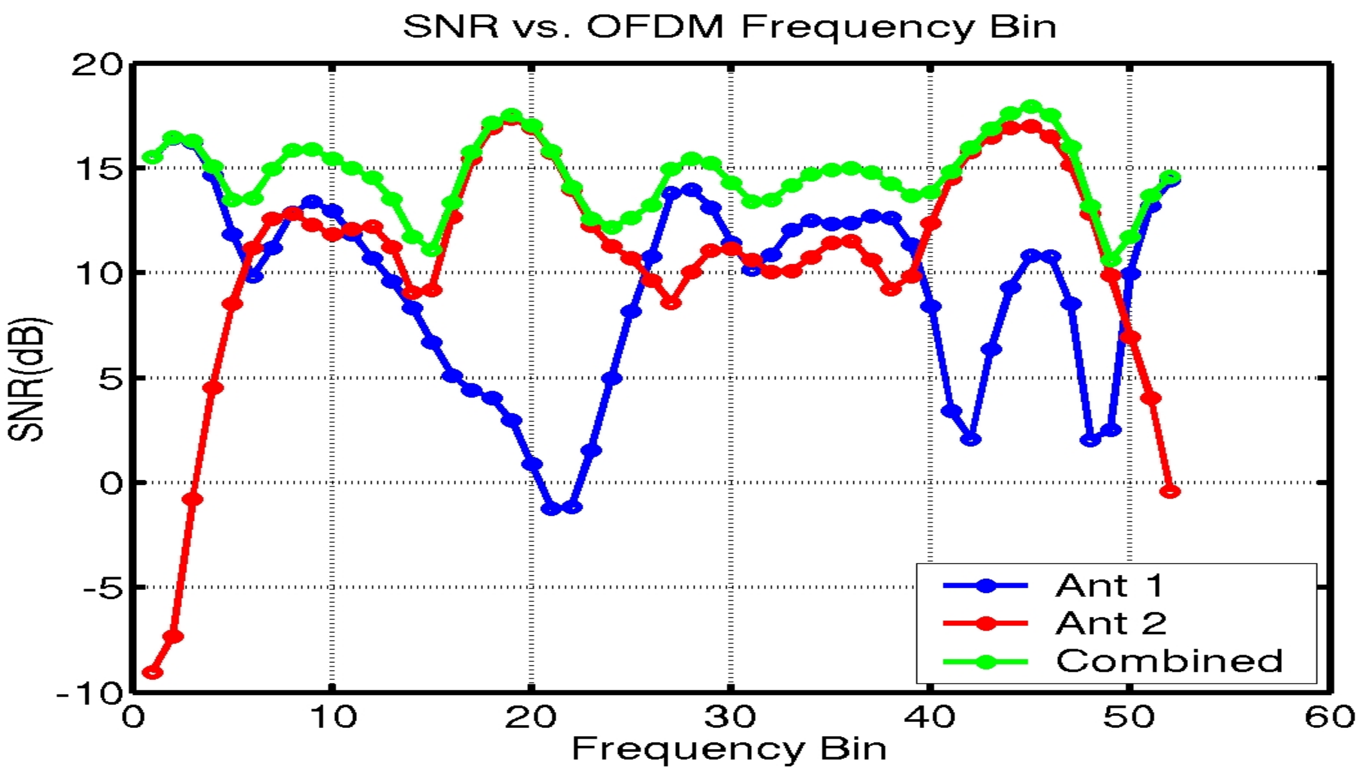


* Maximum Ratio combining

  Improves SNR to

$$\sum_{i=1}^{N_r} SNR_i$$

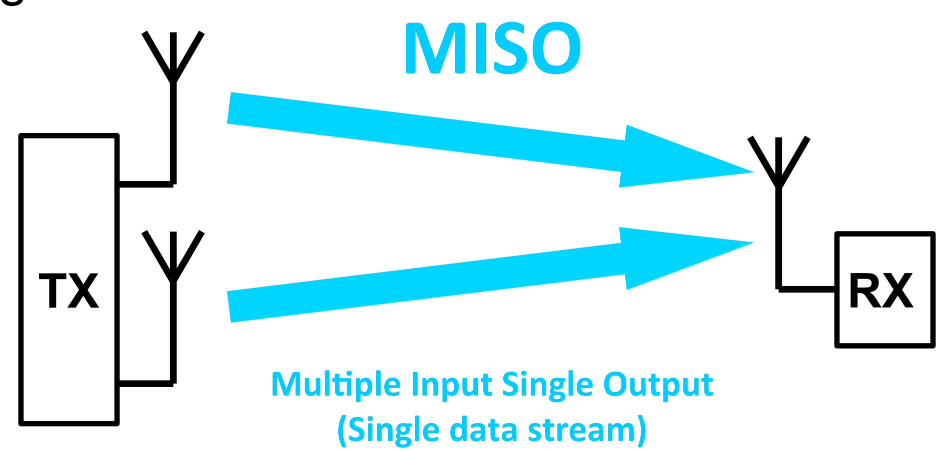
Mitigating fading with receiver diversity



- Multiple receive antennas allow compensation of by non-notches in the other

Transmitter diversity

- Transmitter sends multiple versions of the same signal, through multiple antennas



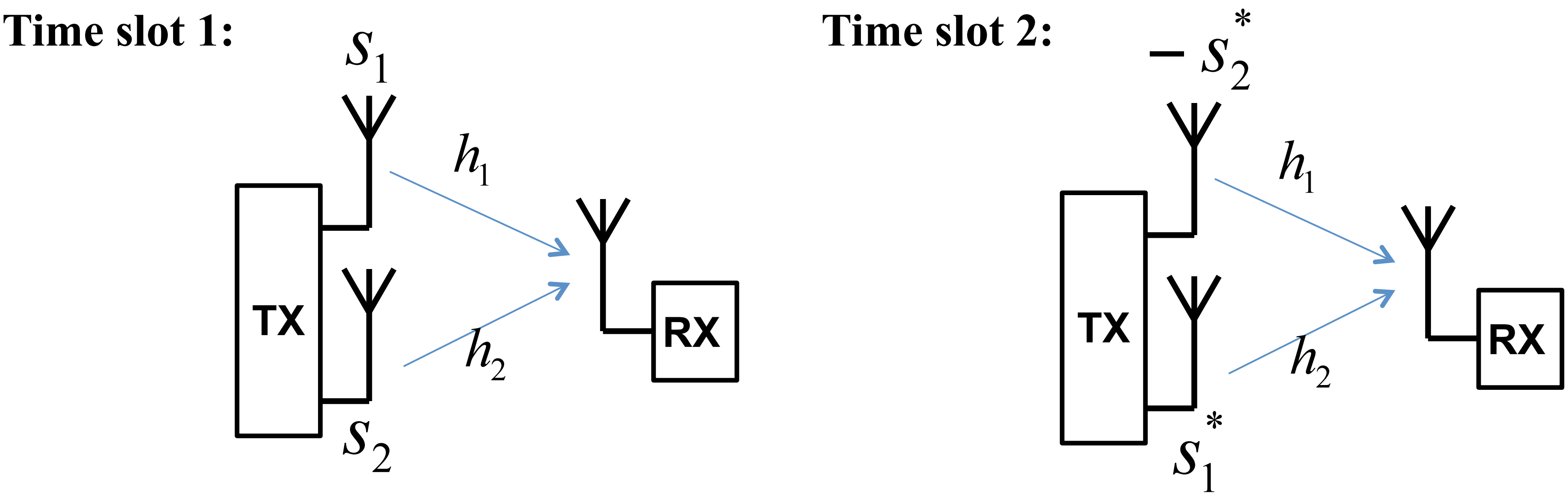
- Two modes of transmit diversity
  - Open-loop transmit diversity
  - Closed-loop transmit diversity

Open-loop transmit diversity

- Principle
  - Send redundant versions of the same signal (symbol), over multiple time slots, and through multiple antennas
  - Encode the symbols differently for different time slots and TX antennas
    - Space-Time Block Code (STBC)

Open-loop transmit diversity

- Example: 2 TX antenna STBC
  - Send two data symbols, s_1 and s_2



  - Received signals:

$$r(t_1) = h_1 s_1 + h_2 s_2$$

$$r(t_2) = -h_1 s_2^* + h_2 s_1^*$$

Open-loop transmit diversity

- Example: 2 TX antenna STBC
  - Diversity combining

$$y_1 = h_1^* r(t_1) + h_2 r(t_2) = (|h_1|^2 + |h_2|^2) s_1$$

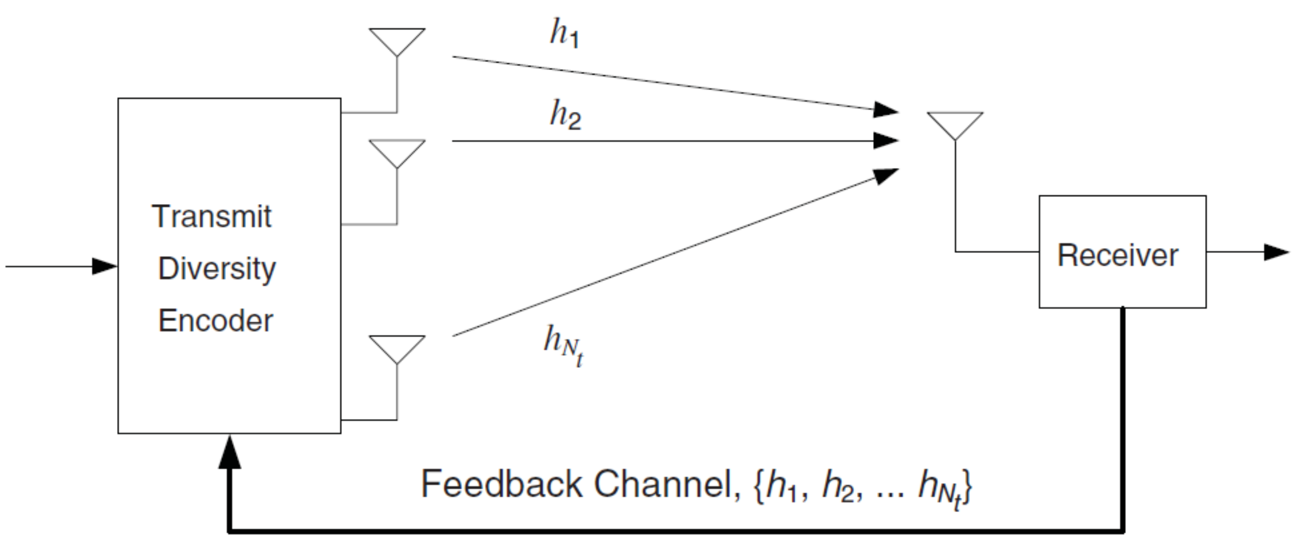
  - i.e., signal power is boosted from $|h_1|^2$ to $|h_1|^2 + |h_2|^2$
  - Open-loop transmit diversity gain:

    In general, open-loop transmit diversity increases SNR **linearly** with the number of transmit antennas

  - What's the capacity gain?

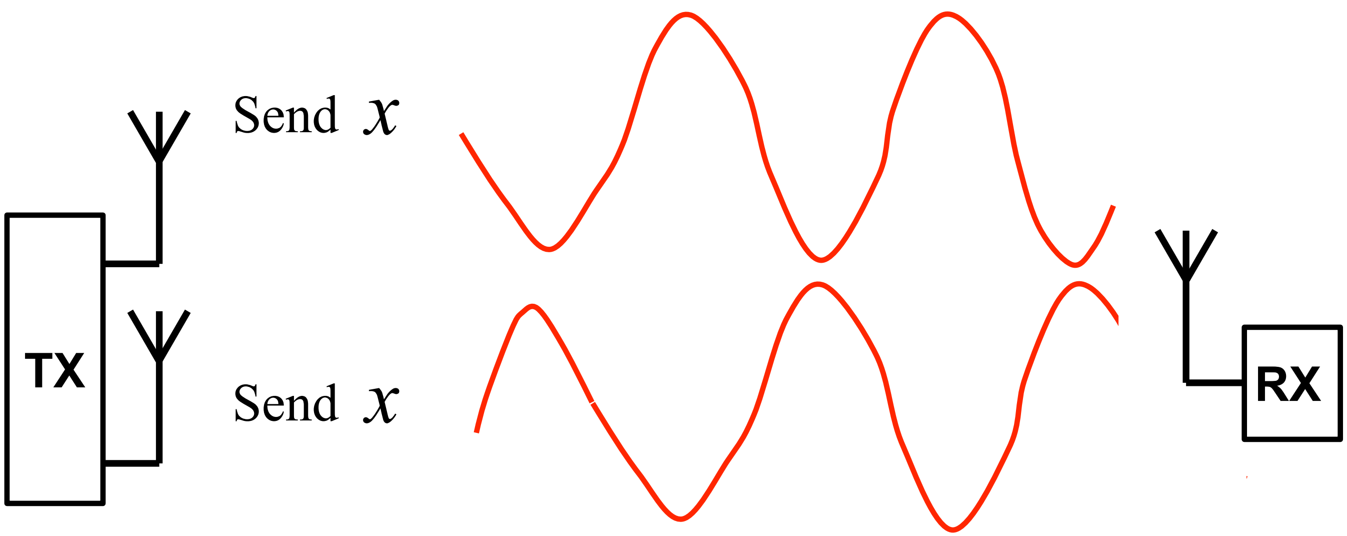
Closed-loop transmit diversity

- Principle
  - Send redundant versions of the same signal (symbol), over the same time slot
  - Encode the symbols differently for different TX antennas
    - i.e., weight the symbols on different antennas, following a precoding algorithm
    - Precoding design requires feedback of channel state information (CSI)



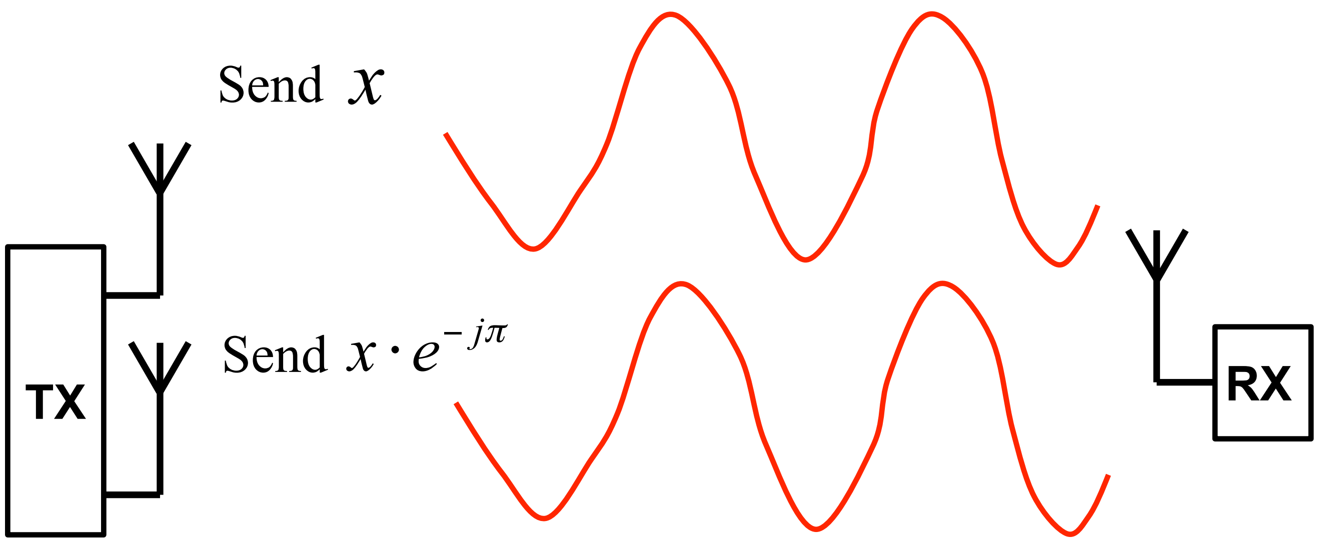
Closed-loop transmit diversity

- Why precoding?
  - Signals from different antennas need to sync (align) their phases
  - But the different channels (between TXantennas and RXantenna) distort signals differently, causing phase offset
    - e.g., both TX antennas sends $x = e^{j2\pi f t}$; RX may receive $e^{j2\pi f t}$ one TX antenna, but $e^{j(2\pi f t+\pi)}$ from the other, which weaken each other!



Closed-loop transmit diversity

- How does precoding help?
  - Precoding: TX compensates the phase offset, and aligns the phases of signals going through different channels



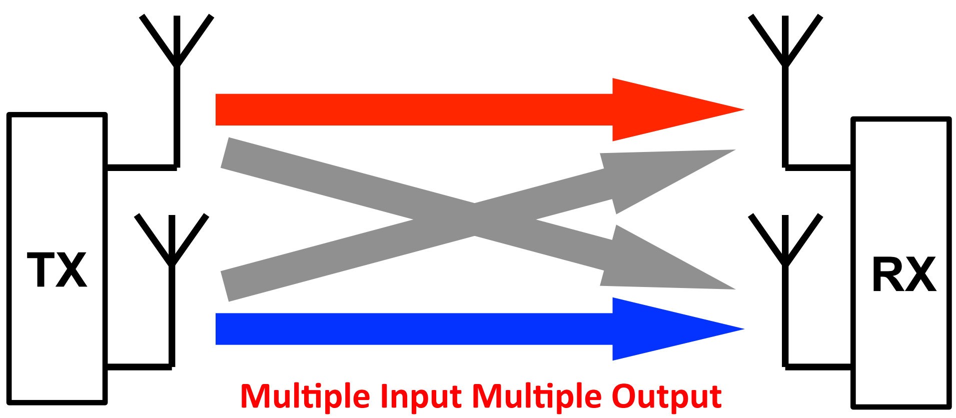
  - Why CSI feedback is needed for precoding?
    - TX must know the phase offset, in order to perform compensation

Closed-loop transmit diversity

- Asymptotic gain from closed-loop transmit diversity
  - Signal level combining, also called transmit beamforming
    - Suppose we have 2 transmit antennas, then instead of x, we receive: x+x=2x, received power becomes $4|x|^2$, SNR increases to 4 times!
    - More generally, with N_t TX antennas, SNR increases to N_t^2
    - What's the capacity gain?

Spatial multiplexing

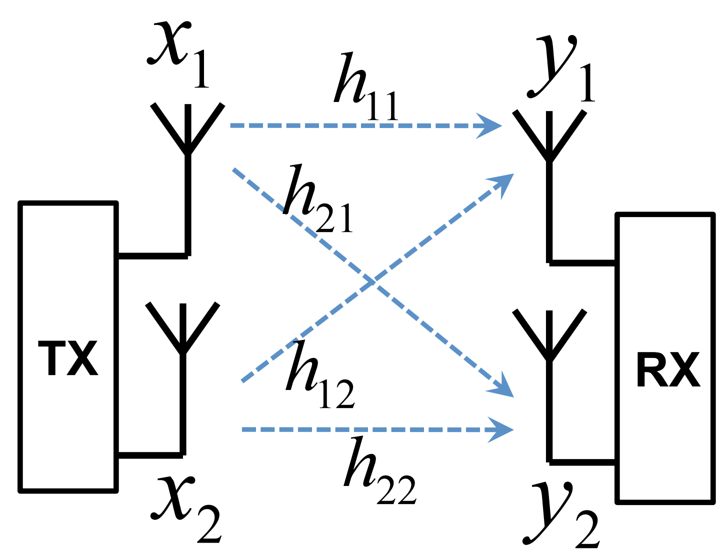
- Spatial multiplexing concept
  - Form multiple independent links (on the same spectrum band) between TX and RX, and send data in parallel through them
  - Unfortunately, there is cross-talk between antennas
  - Cross-talk must be removed by digital signal processing algorithms



Multiple Input Multiple Output
(Multiple data streams)

Spatial multiplexing: signal processing

- Example 2x2 MIMO spatial multiplexing
  - Data to be sent over two TX antennas: x_1, x_2
  - Data received on two RX antennas:



$$y_1 = h_{11}x_1 + h_{12}x_2$$
$$y_2 = h_{21}x_1 + h_{22}x_2$$

* Channel distortions: h_{**} can be estimated by the receiver
* Only two unknowns: x_1, x_2, easily obtained by solving the equations!

Spatial multiplexing gain

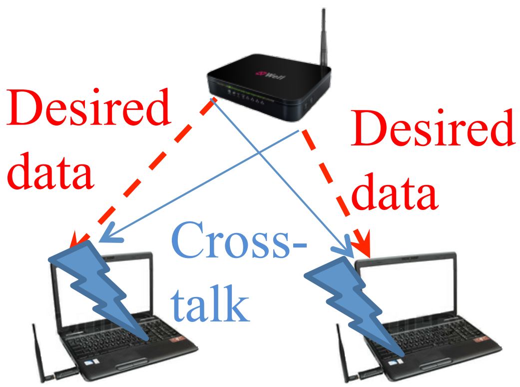
- Asymptotic gain
  - In general, capacity gain from spatial multiplexing scales linearly with

$$\min(N_t, N_r)$$

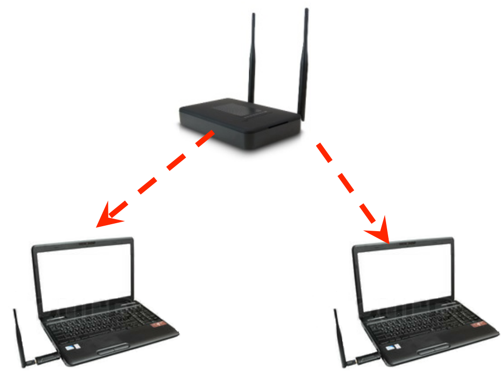
- In practice
  - Spatial multiplexing gain also depends on channel "condition"
    - If the channels between different antennas are *correlated*, e.g., h_{**} are all the same, then you can't solve the equations. Spatial multiplexing becomes infeasible!
    - Channel condition can be profiled using "condition number" (see reference)
  - Practical wireless devices' multiple antennas are separated sufficiently far (further than half-wavelength), so the channel is usually uncorrelated

Multi-user MIMO

- Concept of Multi-User MIMO (MU-MIMO)
  - Single-antenna network



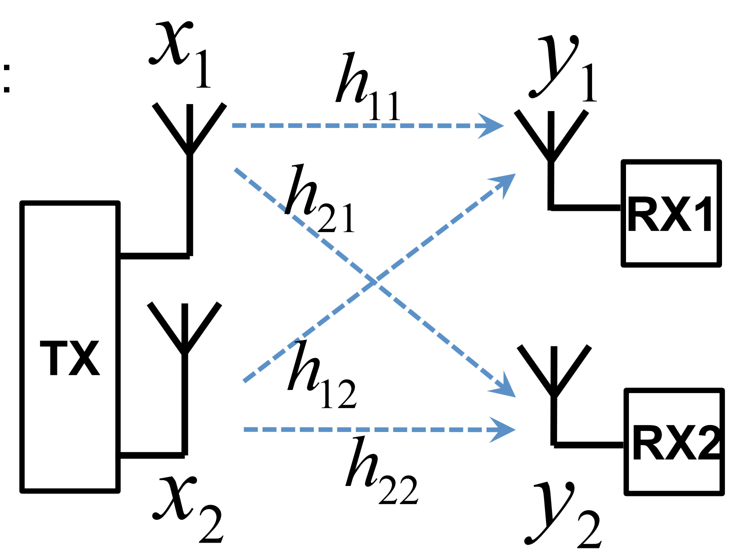
  - Multi-user MIMO



  - MU-MIMO enables multiple streams of data to be sent to different users in parallel, without cross-talk interference

Multi-user MIMO: how does it work?

- MU-MIMO differs from traditional MIMO
  - Data to be sent over two TX antennas: x_1, x_2
  - Data received on two RX nodes:



$$y_1 = h_{11}x_1 + h_{12}x_2$$
$$y_2 = h_{21}x_1 + h_{22}x_2$$

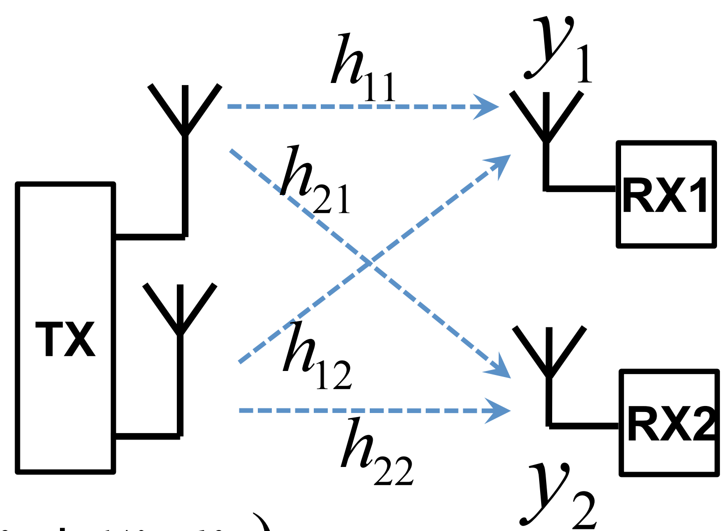
  - Each RX only has one equation, but two variables; no way to solve it directly
    * x2 causes cross-talk interference to x1, and vice versa

Multi-user MIMO: how does it work?

- How to remove cross-talk?
  - Send a weighted mix of x1 and x2

    TX antenna1 sends: $w_{11}x_1 + w_{12}x_2$

    TX antenna2 sends: $w_{21}x_1 + w_{22}x_2$



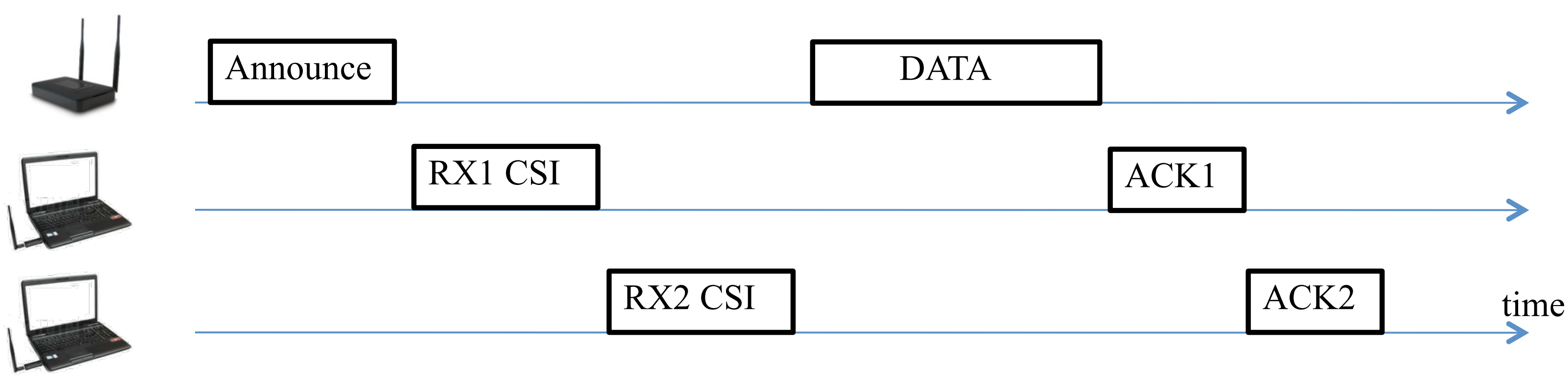
  - Data received on RX1:

$$y_1 = h_{11}(w_{11}x_1 + w_{12}x_2) + h_{12}(w_{21}x_1 + w_{22}x_2)$$
$$= (h_{11}w_{11} + h_{12}w_{21})x_1 + (h_{11}w_{12} + h_{12}w_{22})x_2$$

  - RX1 only wants x1, so ideally, we should have $(h_{11}w_{12} + h_{12}w_{22}) = 0$

Multi-user MIMO: how does it work?

- MU-MIMO precoding
  - TX can obtain h_{11}, h_{12} from RXs' feedback, so it can tune w_{12}, w_{22} to satisfy $(h_{11}w_{12} + h_{12}w_{22}) = 0$
    * This cancels the cross-talk interference from x2 to x1
    * Similarly, we can cancel that from x1 to x2
    * This is called Zero-Forcing Beamforming (ZFBF)
- How does TX obtain channel state information h_{**}
    * Simplest approach in 802.11ac: CSI feedback scheduling

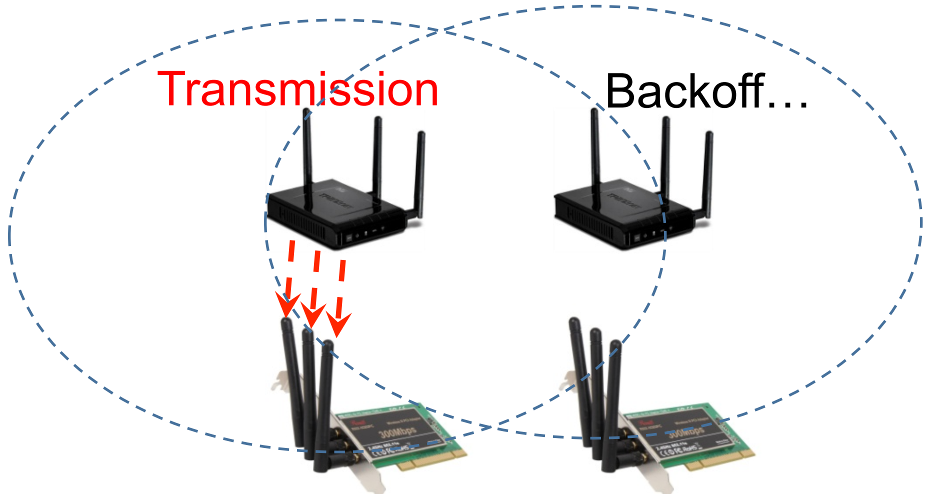


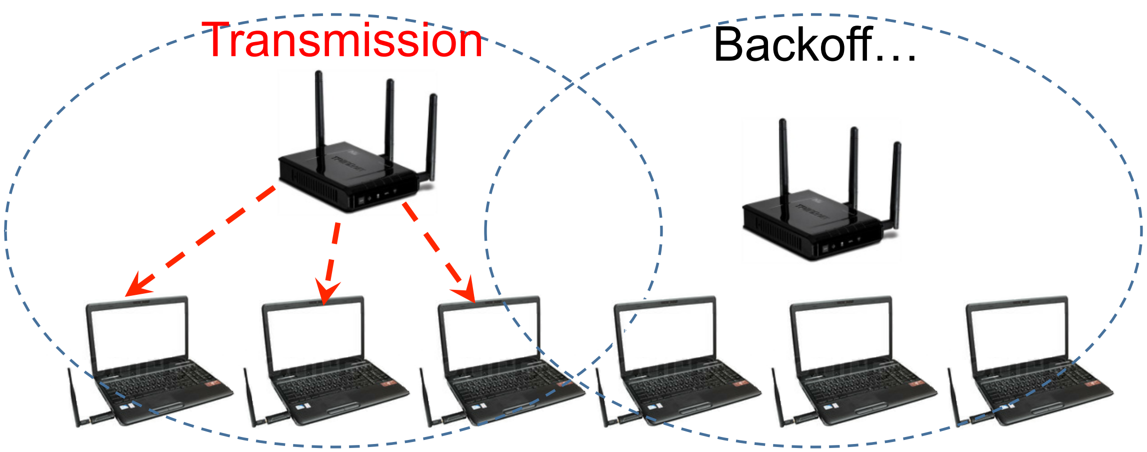
MU-MIMO capacity gain

- Asymptotic capacity gain
  - If the transmitter has N_t antennas, then it can send N_t streams of data simultaneously to N_t users, increasing capacity to N_t times compared with single-antenna transmitter
- Limitation
  - MU-MIMO is essentially a form of spatial multiplexing
  - So the channel must be well-conditioned

MIMO limitation in large networks

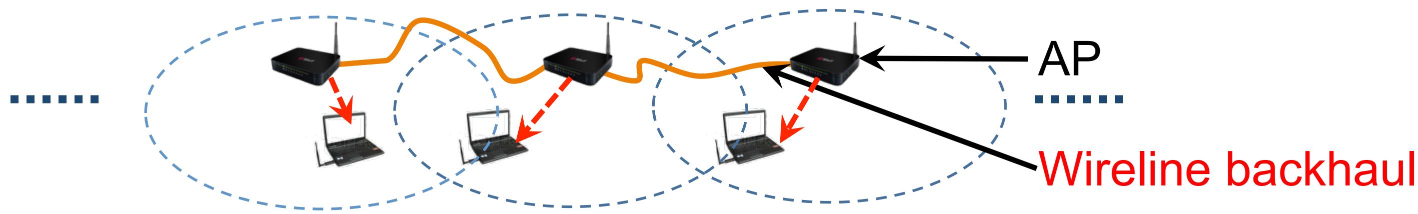
- Limitations of existing MIMO architectures
  - Only one transmitter at a time
  - Simultaneous transmission from different transmitters causes collision!
  - So network capacity doesn't scale with transmitter density





Network MIMO

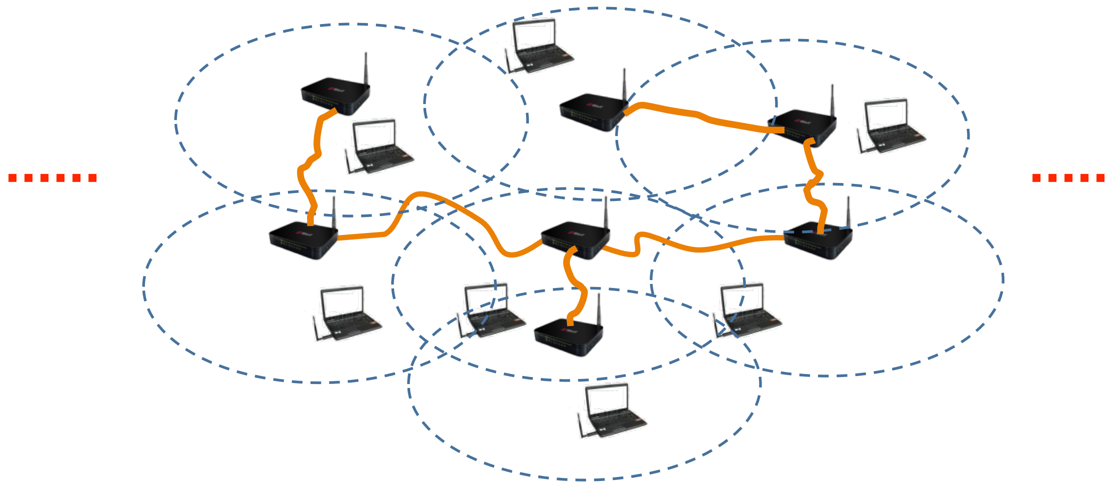
- A **giant-MIMO** comprised of many APs



  - APs are tightly synchronized and share data
  - Mutual interference can be cancelled
  - Asymptotic gain: Network capacity scales **linearly** with the number of APs, theoretically

Network MIMO in large networks

- Is network MIMO practical?



- A super-giant-MIMO solution?

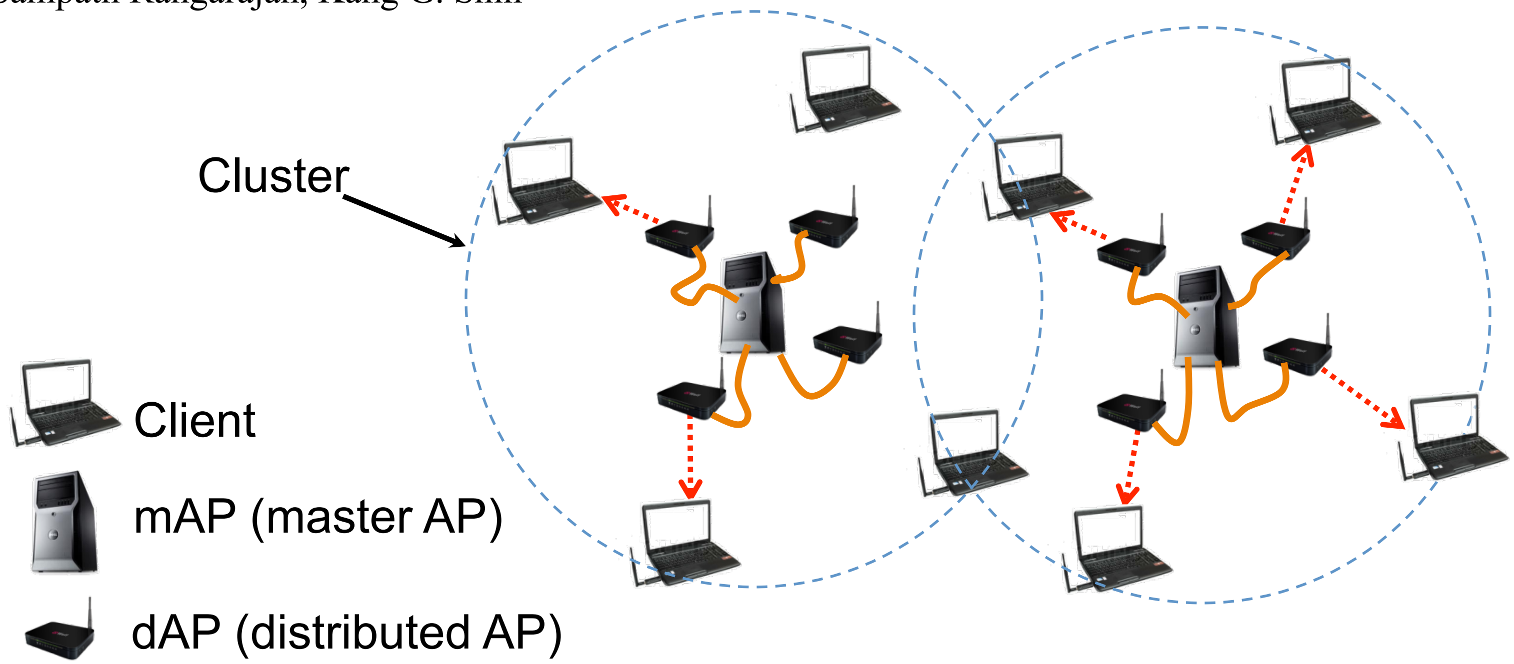
APs need:

* Full synchronization: carrier phase, frequency, sampling-clock
* Full data sharing: large volumes of data and CSI exchange

Infeasible!

NEMOx: making network MIMO scalable

"NEMOx: Scalable Network MIMO for Wireless Networks ",
ACM MobiCom'13, by Xinyu Zhang, Karthikeyan Sundaresan, Mohammad A. (Amir) Khojastepour, Sampath Rangarajan, Kang G. Shin



- A **hierarchical architecture** to realize scalable network MIMO
  - **Intra-cluster:** dAPs within each cluster can TX concurrently
  - **Inter-cluster:** neighboring clusters contend for channel access
  - **Capacity can scale with #of dAPs within each cluster, and with #of clusters** (capacity ≈ 6 in this case)

Summary

- Take-home message:
  (1) What are the various modes of operations in MIMO?
  (2) How does each MIMO mode scale link/network capacity?
- References:
  - Book1: Fundamentals of LTE
  - Book2: Fundamentals of Wireless Communications