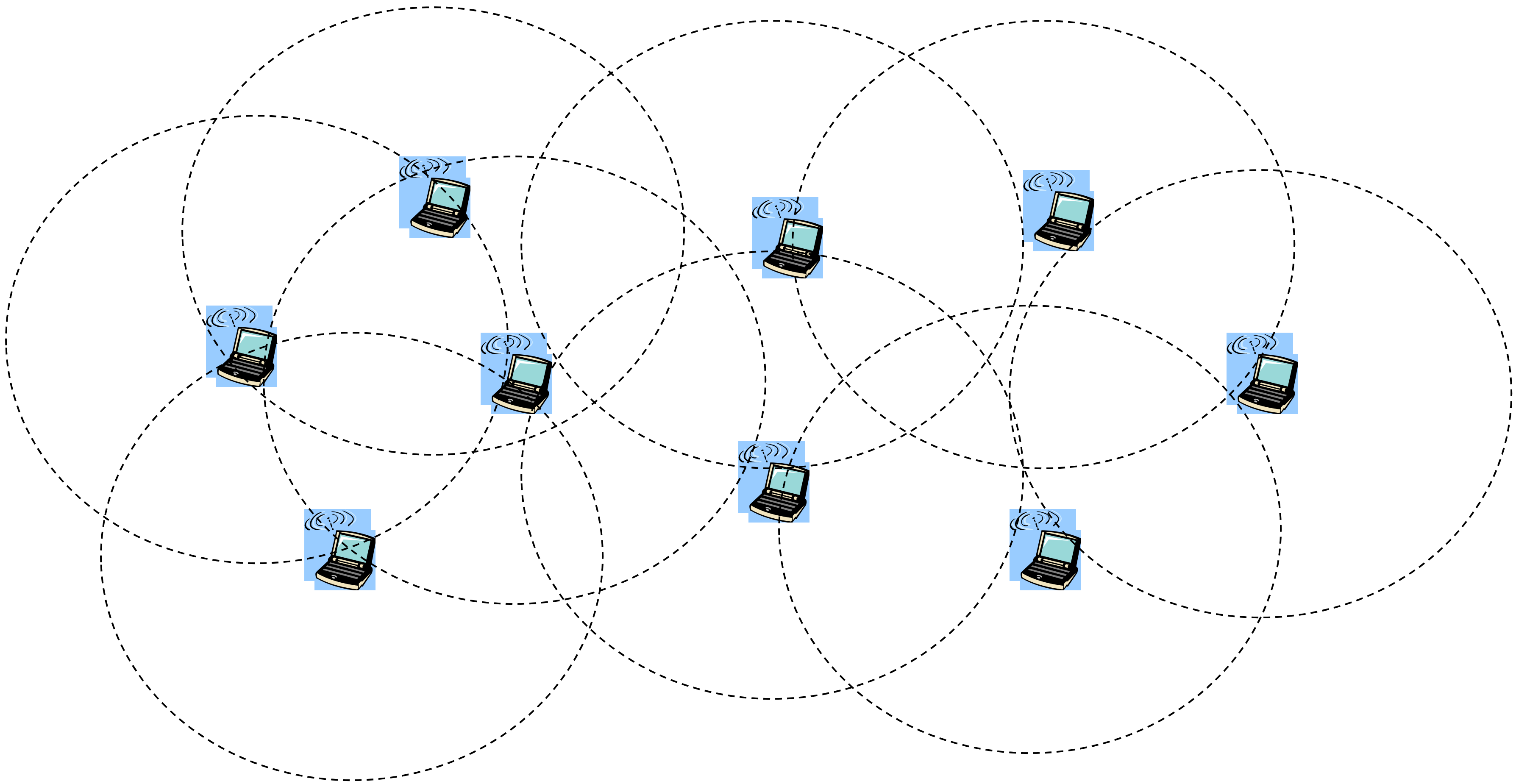
Lecture 5. Multiple Access

- Overview of Multiple Access
- Centralized MAC
- Distributed MAC
- Case Study: WiFi

What is Multiple Access?



- Broadcast channel
- How to share the channel? Multiple Access

Ideal MAC

- Sum rate (system throughput) $\sum_{k=1}^{K} R_k$ — High throughput
- Rate of each single user R_k — Fairness
- Complexity — Low complexity
- ……

- Resource Allocation
  - Given the resources (time, frequency, antennas, power, …), how to maximize the system objective (sum rate, average user rate, …)?

A central controller is required to perform the optimal resource allocation.

- Protocol Design
  - What is the simplest way to determine how nodes share the channel?

Minimum system control, fully distributed

Centralized MAC vs. Distributed MAC

Centralized MAC	Distributed MAC
• Resource allocation	• Resource competition
• Joint processing of users' information	• No joint transmission/detection (A "collision" occurs if more than one user transmits. None of them can succeed.)
• Multiuser information theory – Perfect system guidance and performance evaluation – Bursty arrival is not taken into consideration	• Random access theory – Simple, scalable – No unified framework
• CDMA, OFDMA and Scheduling	• Aloha and CSMA

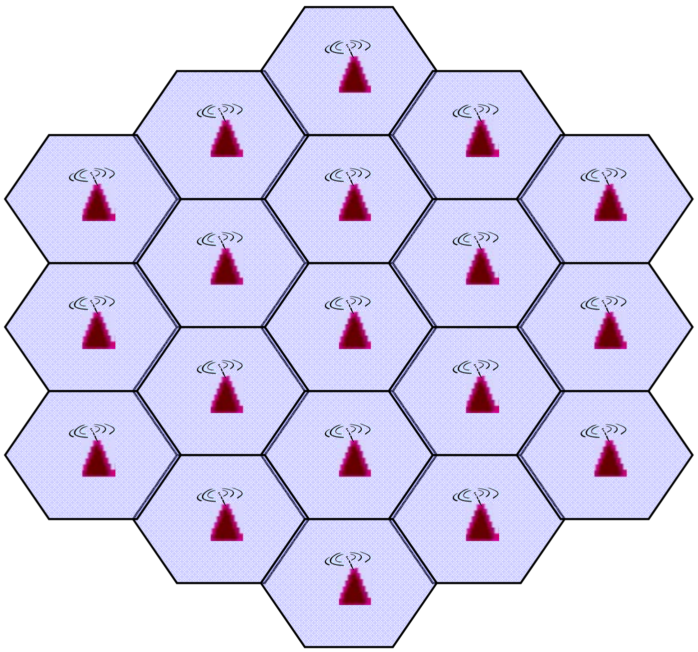
Centralized MAC I: MAC of Wideband Cellular Networks

- CDMA
- OFDMA
- Scheduling

A little bit of History

- 1st Generation: AMPS, TACS, NMT
- 2nd Generation: GSM, IS-136, IS-95
  - 2.5G: GPRS, EDGE
- 3rd Generation: WCDMA, CDMA2000, TD-SCDMA
- 4th Generation: WiMAX, LTE, LTE Advanced

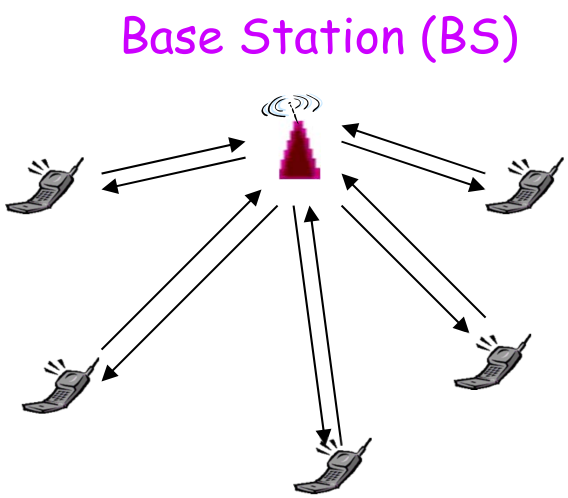
Cellular Networks



- Intra-cell: How to allocate resources to different users inside the cell?
  - FDMA, TDMA, CDMA, OFDMA, SDMA, …
- Inter-cell: How to overcome the interference outside the cell?
  - *Avoid - Average out - Cancel*
- How to manage cells?
  - *Cell planning - Cell cooperation*

• *Voice and data service*	⟹	• *Provide distinct QoS*
• *Expensive spectrum*	⟹	• *Improve spectral efficiency*
• *Large-scale network*	⟹	• *Decompose the network*

Uplink vs. Downlink

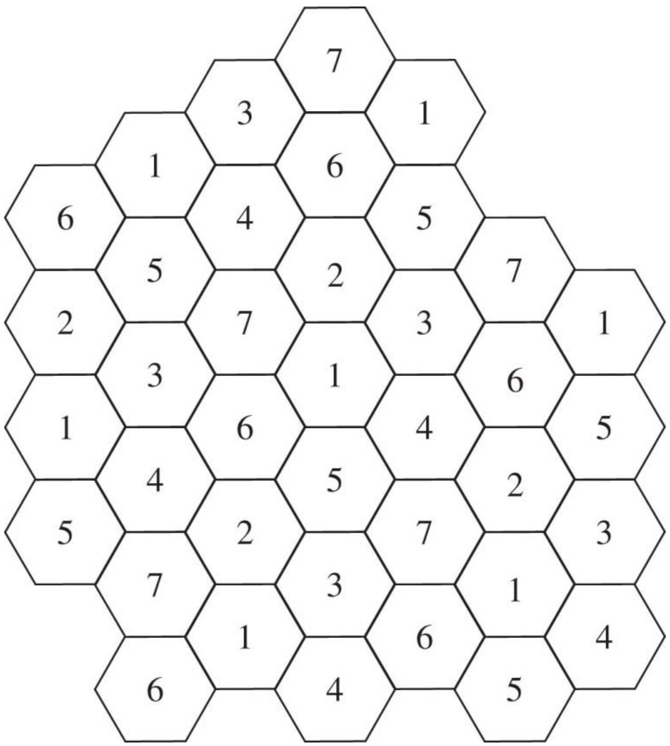


BS→user: downlink

user→BS: uplink

- Synchronization
  - Easier in downlink because all the signals originate from the same transmitter (BS)
- Power control
  - More crucial for uplink because the receive signals experience distinct channels
- Channel measurement
  - Easier in downlink because BS can send a strong pilot signal
- Data rate requirement
  - Higher in downlink (for data service)
- Duplexing: How to allocate resources between uplink and downlink
  - Time Division Duplex (TDD) or Frequency Division Duplex (FDD)

Narrowband Cellular Network (e.g. GSM)



- Intra-cell: TDMA
  - Users are allocated different time slots.
- Inter-cell: Avoid the interference
  - Frequency reuse factor: 1/7
- Complicated cell planning
- Hard handoff

✓ No intra- or inter-cell interference

✓ Inefficient use of resources

Wideband Cellular Network

- Universal frequency reuse
  - Share the bandwidth
- Cell cooperation
  - Soft handoff
- Flexible resource allocation
  - Allocate on-demand
  - Exploit the channel condition

Examples:

- CDMA (e.g. IS-95, WCDMA, CDMA2000, TD-SCDMA)
- OFDMA (e.g. Flash-OFDM, WiMAX, LTE)
- Channel-aware Scheduling (e.g. CDMA 1xEVDO, HSDPA)

Wideband Cellular (1): CDMA

- Intra-cell: CDMA
  - Users are allocated different PN sequences.
- Inter-cell: average out the interference
  - Fluctuations of aggregate interference in adjacent cells are reduced when there are many users in the network.

✓ Decompose the network problem into a set of independent point-to-point links, while each link sees both interference (regardless of intra-cell or inter-cell) and background thermal noise.

  ✓ Simple transceiver design

  ✓ Soft capacity

CDMA Uplink vs. Downlink

Uplink (users-BS)	Downlink (BS-users)
• Near-far effect (power control is crucial)	• No near-far problem
• Intra-cell interference (chip-level synchronization is required to keep users orthogonal)	• Much smaller intra-cell interference
• Interference averaging	• Less interference averaging due to few base stations
• Non-coherent demodulation	• Coherent demodulation (strong pilot)
• Multiuser detector is affordable	• Rake receiver

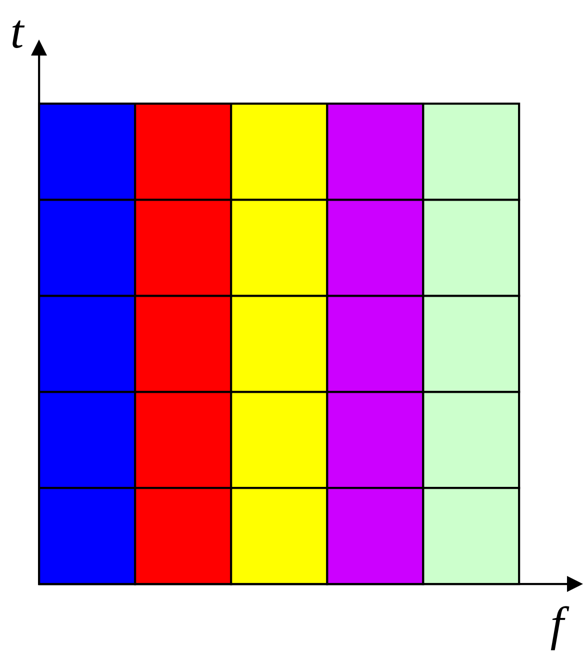
Wideband Cellular (2): OFDMA

- Intra-cell: OFDMA
  - Users are allocated different subcarriers using OFDM.
  - No intra-cell interference.
- Inter-cell: average out the interference
  - Hopping

✓ Flexible resource allocation
  - ✓ Abundant frequency and time units
  - ✓ Various allocation strategies

Hopping Pattern

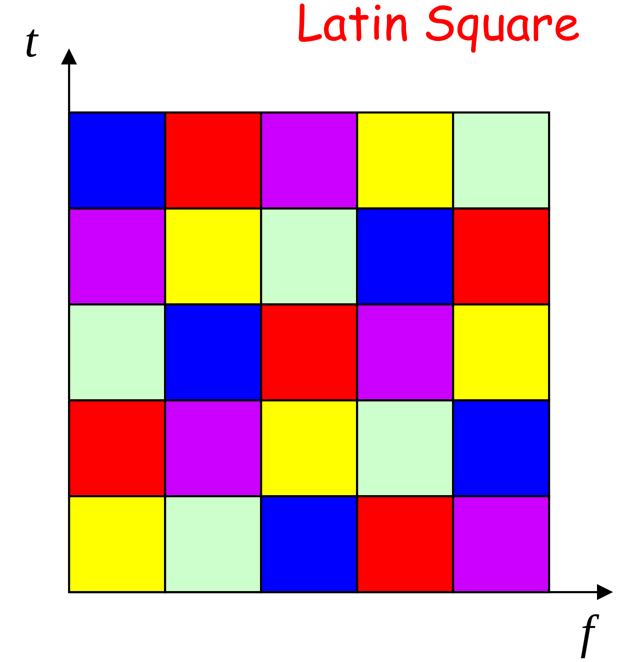
Resources: 5 by 5 time-frequency units. To be allocated to 5 users.



• Users should be spread out.

• fair allocation

Latin Square



No interference averaging.
Similar to a narrowband system.

Each user sees interference from many users instead of a single strong user.

CDMA vs. OFDMA

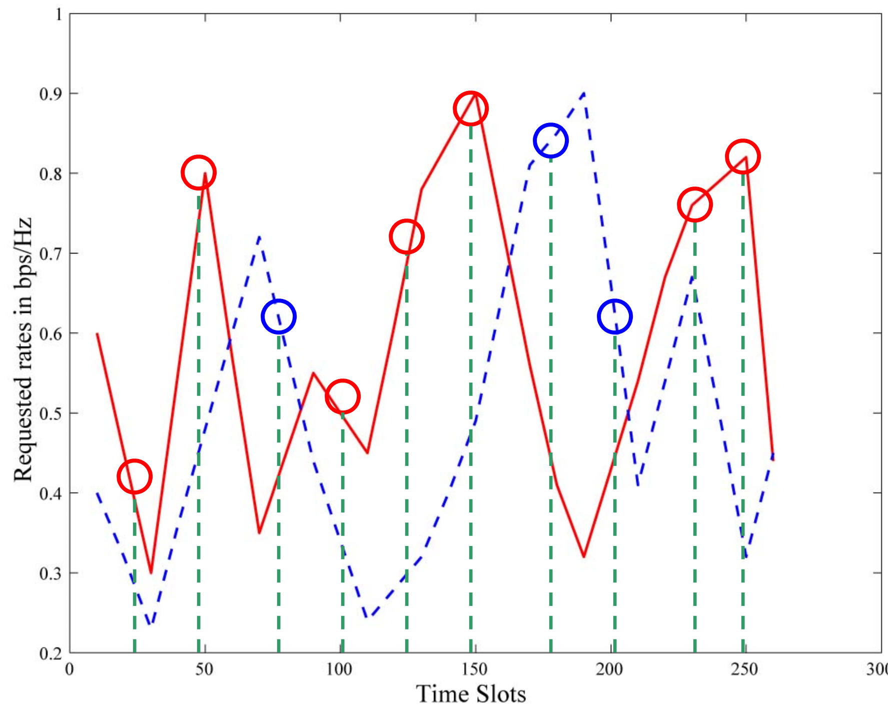
CDMA	OFDMA
• Universal frequency reuse	• Universal frequency reuse
• Inter-cell interference averaged	• Inter-cell interference averaged
• Significant intra-cell interference	• No intra-cell interference
• Tight power control – "expensive" for users who only transmit infrequently – incur delay	• Timing and frequency synchronization
• Fewer degrees of freedom	• Adaptive resource allocation
• Medium PAPR	• High PAPR

(Peak-to-Average Power Ratio)

Wideband Cellular (3): Channel-aware Scheduling

- Intra-cell: channel-aware scheduling
  - Users are allocated different time slots according to their channel conditions: select the best user at each time slot.
  - No intra-cell interference.

- Inter-cell: opportunistically avoid the interference

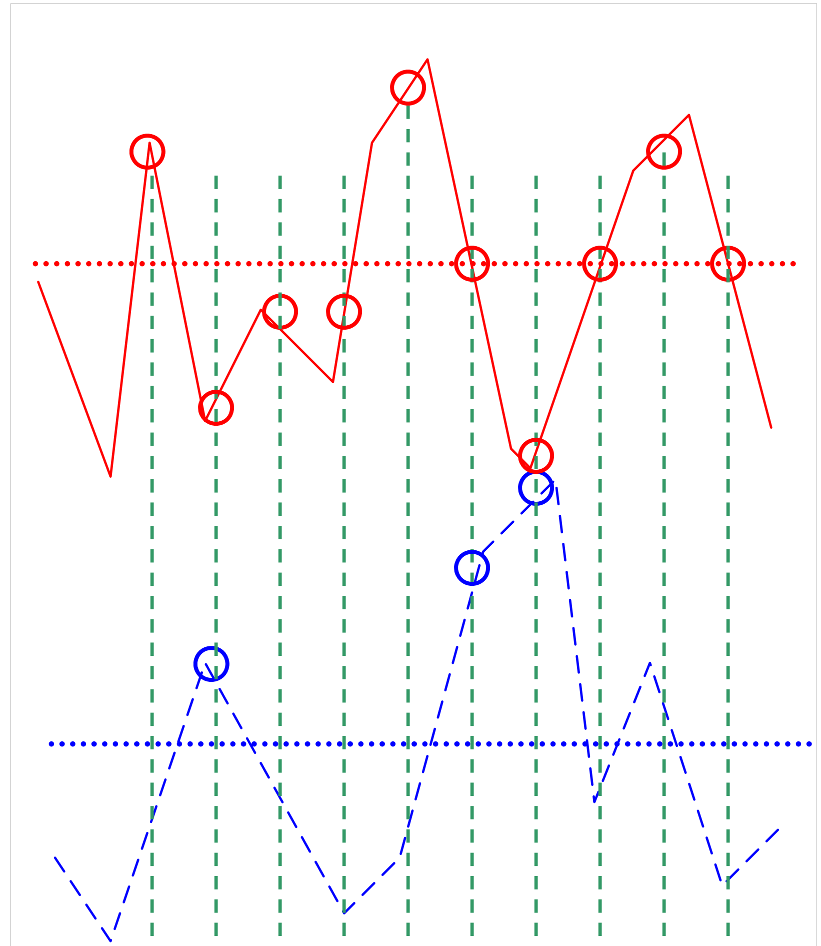


CDMA vs. Channel-aware Scheduling

CDMA	Channel-aware Scheduling
• Average out channel fluctuations	• Exploit channel fluctuations
• Track slow fluctuations	• Track as many fluctuations as possible
• Power control	• Rate control
• Average out inter-cell interference	• Opportunistically avoid inter-cell interference
• Support tight delay	• Need some laxity

More about Channel-aware Scheduling

- Fairness
  - Hit the “peak”
- Channel measurement and feedback
  - Fast channel tracking
- Channel fluctuations
  - Too fast
  - Too slow



“Opportunistic Beamforming”
Introducing randomness

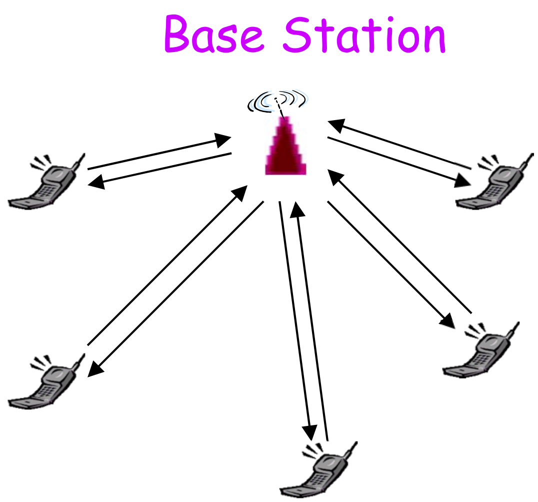
Summary I: MAC of Wideband Cellular Networks

	CDMA	OFDMA	Channel-aware Scheduling
Intra-cell Resources	PN Sequences	Subcarriers & Time slots	Time slots
Intra-cell Interference	Significant	None	None
Control at BS	Tight Power Control	Timing & Frequency Synchronization	Rate Control Track as many fluctuations as possible
	Track slow fluctuations		
Delay Requirement	Can Support Tight Delay		Need some laxity

Centralized MAC II: Multiuser Capacity

- Multiuser Capacity of AWGN Channels
- Multiuser Capacity of Fading Channels

Uplink vs. Downlink Channel Model



- user→BS: uplink

$$y[m]=\sum_{k=1}^{K}h_k[m]x_k[m]+z[m]$$

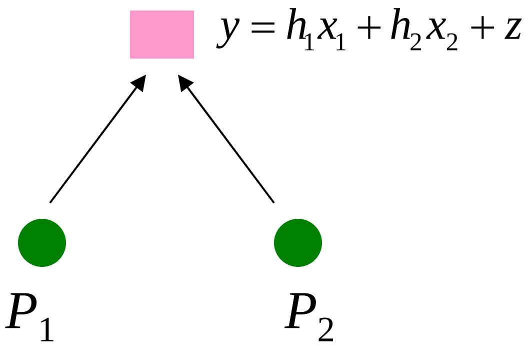
- BS→user: downlink

$$y_k[m]=h_k[m]x[m]+z_k[m],\quad k=1,\dots,K$$

Multiuser Capacity of AWGN Channels

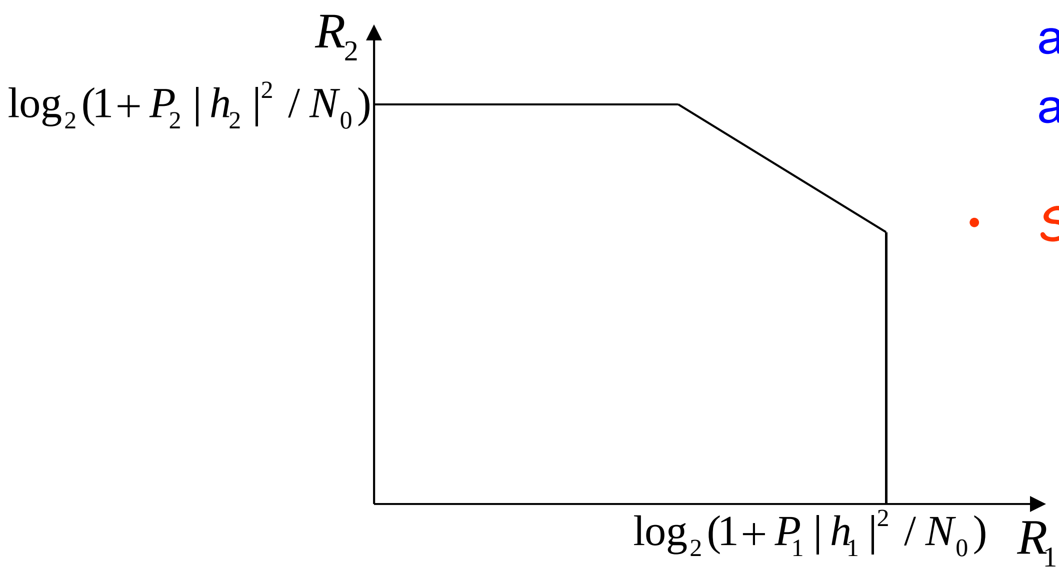
- Uplink Capacity
- Downlink Capacity

Capacity of Uplink AWGN Channel



$$R_1 \le \log_2(1 + P_1 |h_1|^2 / N_0) \qquad R_2 \le \log_2(1 + P_2 |h_2|^2 / N_0)$$

$$R_1 + R_2 \le \log_2(1 + (P_1 |h_1|^2 + P_2 |h_2|^2) / N_0)$$



- Capacity Region: set of pairs (R1, R2) at which users 1 and 2 can reliably and simultaneously communicate.
- Sum Capacity: the maximum total rate

$$C_{sum} = \max_{(R_1, R_2) \in \mathcal{C}} R_1 + R_2$$

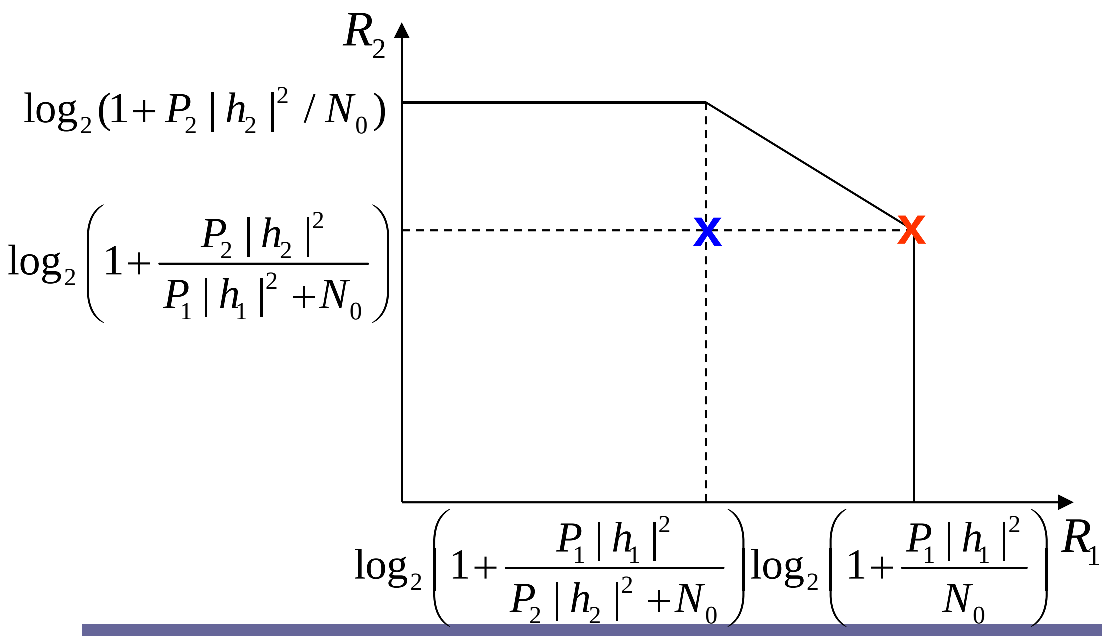
$$= \log_2\left(1 + \frac{P_1 |h_1|^2 + P_2 |h_2|^2}{N_0}\right)$$

To Achieve Uplink Capacity I: Non-orthogonal Access

- Always treat the other user's signal as noise during detection

$$R_1 = \log_2(1 + P_1|h_1|^2 / (P_2|h_2|^2 + N_0)) \qquad R_2 = \log_2(1 + P_2|h_2|^2 / (P_1|h_1|^2 + N_0))$$

- Successive Interference Cancellation (SIC)
  - ✓ Decode the data of user 2, treating user 1's signal as Gaussian noise;



  - ✓ Reconstruct user 2's signal and subtract it from the aggregate received signal. Decode the data of user 1.

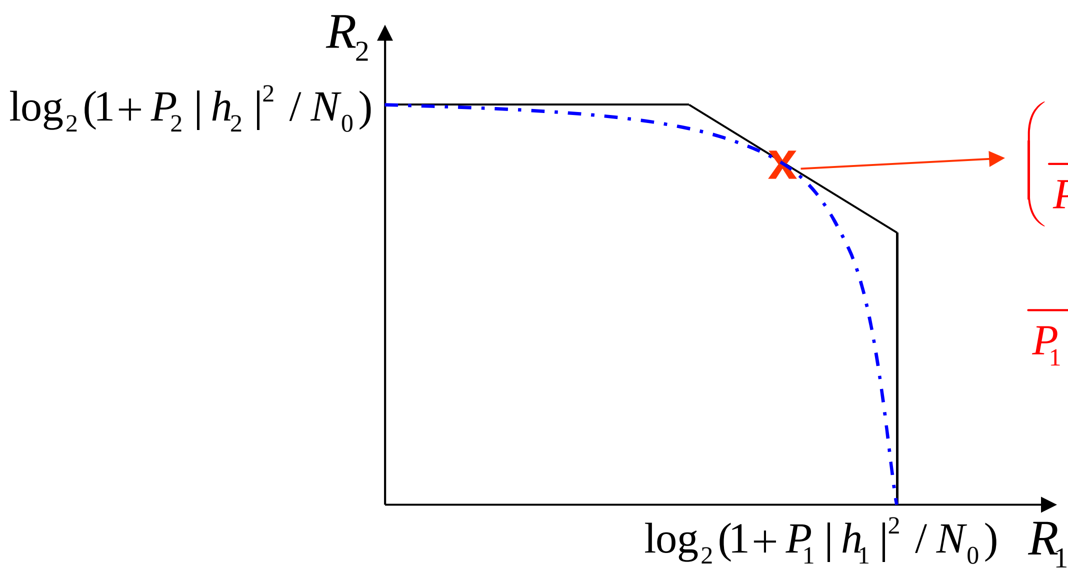
$$R_1 = \log_2\left(1+\frac{P_1|h_1|^2}{N_0}\right)$$

$$R_2 = \log_2\left(1+\frac{P_2|h_2|^2}{P_1|h_1|^2+N_0}\right)$$

To Achieve Uplink Capacity II: Orthogonal Access

- Suppose a fraction of α of the bandwidth is allocated to user 1 and the rest is allocated to user 2.

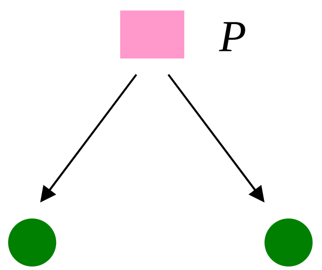
$$R_1 = \alpha \log_2\left(1+\frac{P_1|h_1|^2}{\alpha N_0}\right) \qquad R_2 = (1-\alpha)\log_2\left(1+\frac{P_2|h_2|^2}{(1-\alpha)N_0}\right)$$



$$\left(\frac{P_1|h_1|^2}{P_1|h_1|^2+P_2|h_2|^2}\log_2\left(1+\frac{P_1|h_1|^2+P_2|h_2|^2}{N_0}\right),\ \frac{P_2|h_2|^2}{P_1|h_1|^2+P_2|h_2|^2}\log_2\left(1+\frac{P_1|h_1|^2+P_2|h_2|^2}{N_0}\right)\right)$$

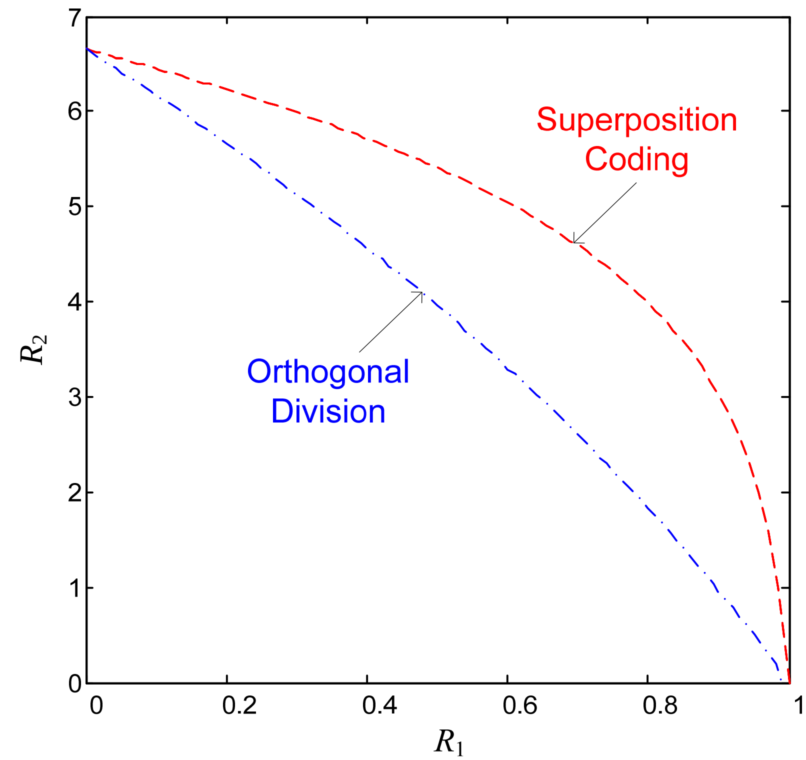
Optimal when $\alpha = \dfrac{P_1|h_1|^2}{P_1|h_1|^2+P_2|h_2|^2}$

Capacity of Downlink AWGN Channel



$y_1 = h_1 x + z_1$ $\qquad$ $y_2 = h_2 x + z_2$

$$R_k \le \log_2(1 + P\,|h_k|^2 / N_0), \quad k = 1, 2.$$



Suppose $|h_1| < |h_2|$.

- User 2 has a better channel than user 1.
- User 2 can decode any data that user 1 can successfully decode.

> - Superposition coding achieves the downlink AWGN capacity.
> - Orthogonal division is strictly inferior to superposition coding.

To Achieve Downlink Capacity

- Superposition Coding
  - ✓ The transmit signal is a linear superposition of the signals of two users.

  Total transmission power: $P = P_1 + P_2$

  Decode user 1's signal first, and then decode its own signal using SIC

User 1: Treat user 2's signal as noise

$$R_1 = \log_2\left(1 + \frac{P_1 |h_1|^2}{P_2 |h_1|^2 + N_0}\right)$$

User 2: Perform SIC

$$R_2 = \log_2\left(1 + \frac{P_2 |h_2|^2}{N_0}\right)$$

- Orthogonal Division
  - ✓ a fraction of α of the bandwidth is allocated to user 1 and the rest is allocated to user 2. $P = P_1 + P_2$

$$R_1 = \alpha \log_2\left(1 + \frac{P_1 |h_1|^2}{\alpha N_0}\right) \qquad R_2 = (1-\alpha)\log_2\left(1 + \frac{P_2 |h_2|^2}{(1-\alpha) N_0}\right)$$

K-User Capacity

- Capacity Region

Uplink

$$R_k \le \log_2\left(1+\frac{P_k|h_k|^2}{N_0}\right),\quad k=1,..,K.$$

$$\sum_{k\in\mathcal{S}} R_k \le \log_2\left(1+\frac{\sum_{k\in\mathcal{S}} P_k|h_k|^2}{N_0}\right),\ \mathcal{S}\subset\{1,\ldots,K\}$$

✓ SIC

$$R_1 \le \log_2\left(1+\frac{P_1|h_1|^2}{\sum_{k=2}^{K} P_k|h_k|^2+N_0}\right),$$

……

$$R_K \le \log_2\left(1+\frac{P_K|h_K|^2}{N_0}\right).$$

✓ Orthogonal Access

$$R_k \le \alpha_k\log_2\left(1+\frac{P_k|h_k|^2}{\alpha_k N_0}\right),$$

$$\sum_{k=1}^{K}\alpha_k=1.$$

Downlink $\left(|h_1|^2\le|h_2|^2\le\cdots\le|h_K|^2\right)$

$$R_1 \le \log_2\left(1+\frac{P_1|h_1|^2}{|h_1|^2\sum_{k=2}^{K}P_k+N_0}\right),$$

……

$$R_K \le \log_2\left(1+\frac{P_K|h_K|^2}{N_0}\right),\quad \sum_{k=1}^{K}P_k=P.$$

✓ Superposition Coding

$$R_1 \le \log_2\left(1+\frac{P_1|h_1|^2}{|h_1|^2\sum_{k=2}^{K}P_k+N_0}\right),$$

……

$$R_K \le \log_2\left(1+\frac{P_K|h_K|^2}{N_0}\right),\quad \sum_{k=1}^{K}P_k=P.$$

✓ Orthogonal Division

$$R_k \le \alpha_k\log_2\left(1+\frac{P_k|h_k|^2}{\alpha_k N_0}\right),$$

$$\sum_{k=1}^{K}P_k=P,\sum_{k=1}^{K}\alpha_k=1.$$

K-User Capacity

- Sum Capacity $C_{sum} = \max_{R_1 \ldots R_K} \sum_{k=1}^{K} R_k$

Uplink

$$C_{sum}^{U} = \log_2\left(1 + \frac{\sum_{k=1}^{K} P_k |h_k|^2}{N_0}\right)$$

To achieve the sum capacity:

- ✓ SIC
- ✓ Orthogonal Access with

$$\alpha_k = \frac{P_k |h_k|^2}{\sum_{j=1}^{K} P_j |h_j|^2}, \quad k = 1, \ldots, K.$$

Downlink

With $|h_1|^2 \le |h_2|^2 \le \cdots \le |h_K|^2$:

$$C_{sum}^{D} = \log_2\left(1 + \frac{P |h_K|^2}{N_0}\right)$$

To achieve the sum capacity:

Allocate all the transmission power to the strongest user!

Multiuser Capacity of Fading Channels

- Ergodic Uplink Sum Capacity without CSIT
- Ergodic Uplink Sum Capacity with CSIT

Ergodic Uplink Sum Capacity of without CSIT

- Single-user: $C = \mathrm{E}_h[\log_2(1+|h|^2 P/N_0)]$

- K-user:

$$C_{sum} = \mathrm{E}_h\left[\log_2\left(1+\frac{\sum_{k=1}^{K}|h_k|^2 P_k}{N_0}\right)\right]$$

$$\leq \log_2\left(1+\frac{\sum_{k=1}^{K}\mathrm{E}_h|h_k|^2 P_k}{N_0}\right) = \log_2\left(1+\frac{\sum_{k=1}^{K}P_k}{N_0}\right)$$

Fading always hurts if no CSI is available at the transmitter side!

Ergodic Uplink Sum Capacity with CSIT

- Single-user:

$$\max_{P_1,\dots,P_L} \frac{1}{L}\sum_{l=1}^{L}\log_2\left(1+\frac{P_l|h_l|^2}{N_0}\right)$$

Subject to: $\frac{1}{L}\sum_{l=1}^{L}P_l = P.$

$\Rightarrow$ $$P_l^{optimal} = \left(\mu - \frac{N_0}{|h_l|^2}\right)^+$$

Waterfilling power allocation

- K-user:

$$\max_{P_{k,l}:k=1,\dots,K,l=1,\dots,L} \frac{1}{L}\sum_{l=1}^{L}\log_2\left(1+\frac{\sum_{k=1}^{K}P_{k,l}|h_{k,l}|^2}{N_0}\right)$$

Subject to: $\frac{1}{L}\sum_{l=1}^{L}P_{k,l} = P, \quad k=1,\dots,K.$

$\Rightarrow$ $$P_{k,l}^{optimal} = \begin{cases}\left(\mu - \frac{N_0}{|h_{k,l}|^2}\right)^+ & \text{if } |h_{k,l}| = \max_{i=1,\dots,K}|h_{i,l}| \\ 0 & \text{otherwise}\end{cases}$$

Ergodic Uplink Sum Capacity with CSIT

- Single-user:

$$C = \mathrm{E}_h\left[\log_2\left(1+\frac{P^*(h)|h|^2}{N_0}\right)\right]$$

$$P^*(h) = \left(\mu - \frac{N_0}{|h|^2}\right)^+ \quad \text{where } \mu \text{ satisfies } \mathrm{E}_h[P^*(h)] = P$$

- K-user:

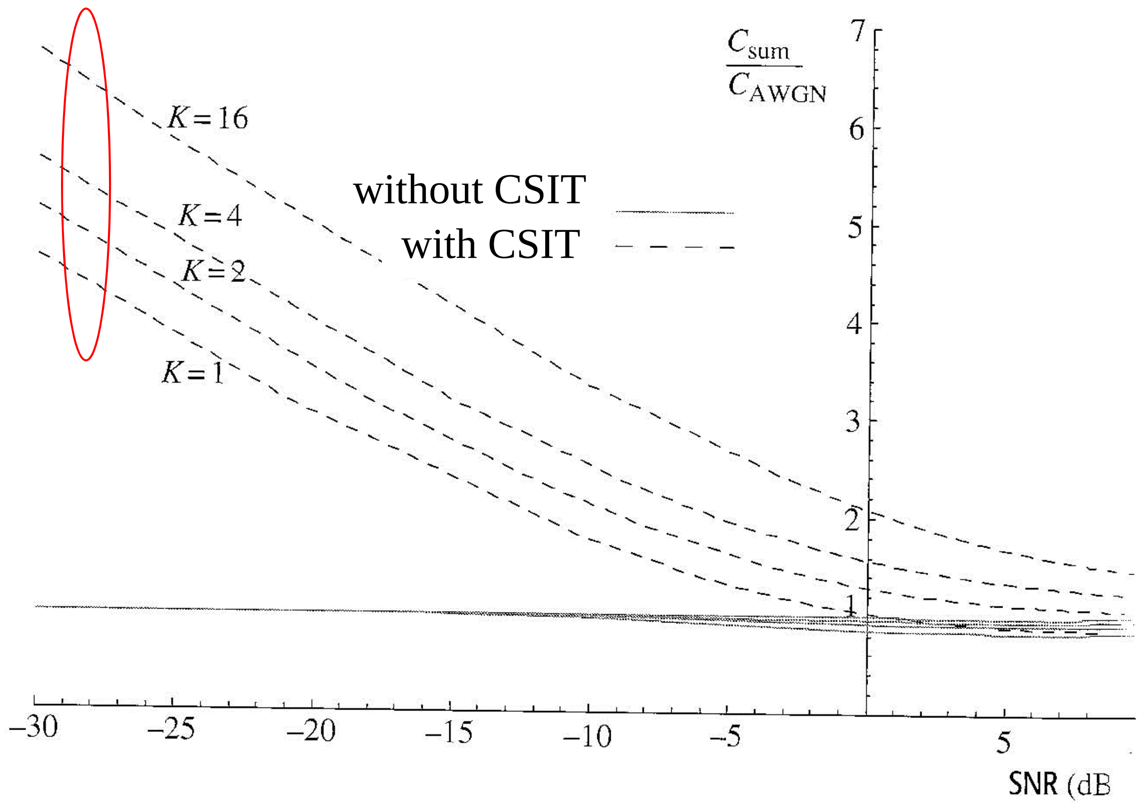
$$C_{sum} = \mathrm{E}_{\mathbf{h}}\left[\log_2\left(1+\frac{P_k^*(\mathbf{h})|h_k|^2}{N_0}\right)\right] \qquad \mathbf{h} = [h_1, h_2, \ldots, h_K]$$

$$P_k^*(\mathbf{h}) = \begin{cases} \left(\mu - \frac{N_0}{|h_k|^2}\right)^+ & \text{if } |h_k| = \max_{i=1,\ldots,K}|h_i| \\ 0 & \text{otherwise} \end{cases} \quad \text{where } \mu \text{ satisfies } \sum_{k=1}^{K}\mathrm{E}_{\mathbf{h}}[P_k^*(\mathbf{h})] = KP$$

Select the user with the best channel condition!

Multiuser Diversity

The more users, the higher capacity benefits!



Multiuser Diversity: when there are many users that fade independently, at any time there is a high probability that one of the users will have a strong channel.

Summary II: Multiuser Capacity

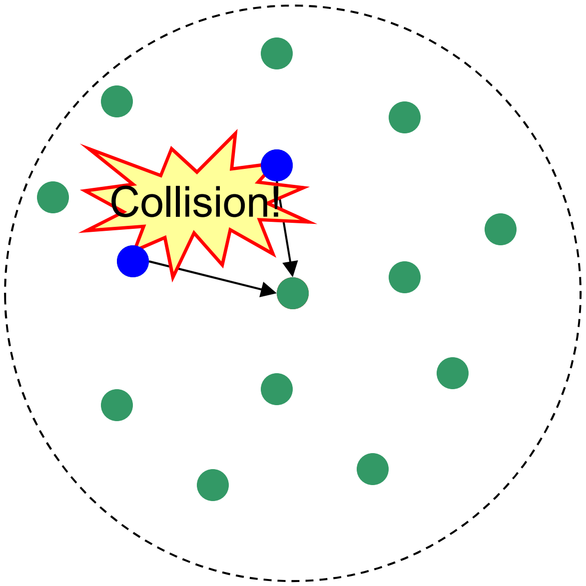
- AWGN channel
  - To achieve uplink capacity: SIC
  - To achieve downlink capacity: superposition coding
- Fading channel
  - Without CSIT: always inferior to AWGN
  - With CSIT: better than AWGN with optimal power allocation

Distributed MAC

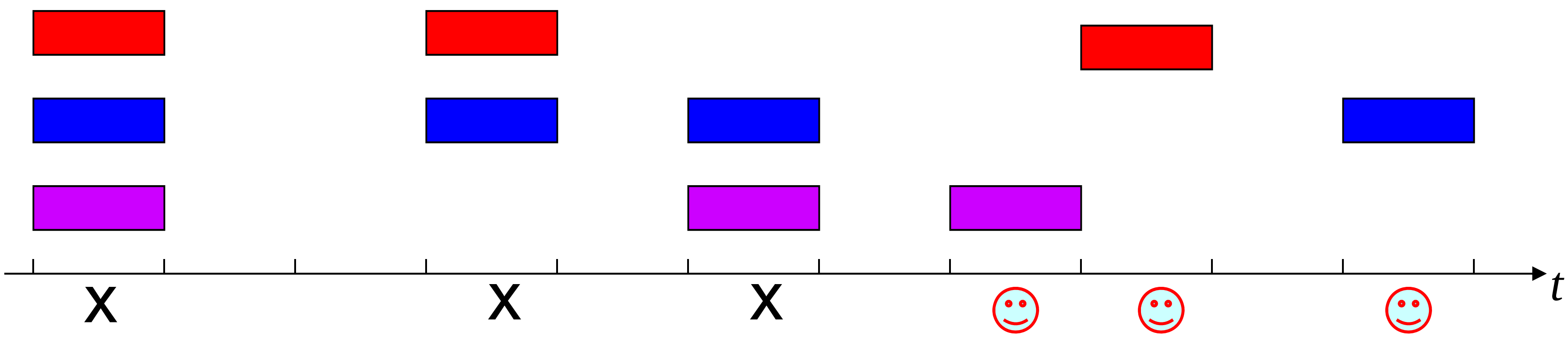
- Aloha
- CSMA

Random Access

- Each node determines whether to access the channel independently.
- Collision
  - The receiver cannot properly detect the signal if more than one node transmit simultaneously.
- Resolving collisions: Backoff
  - Retransmit with a certain probability; or
  - Choose a random value and countdown. Retransmit when the counter is zero.



Random Access I: Aloha



- Slotted Aloha
  - Transmit if there is a new packet;
  - Backoff if there is a collision:
    - Retransmit with a constant probability q; or
    - Choose a value from {0, 1, …, $\lfloor 1/q \rfloor$} and count down. Retransmit when the counter is zero.

Network Throughput of Slotted ALOHA

- Network Throughput: The percentage of time that the network produces an effective output.
  - What is the maximum network throughput of slotted Aloha?

    n: the number of nodes G: the attempt rate

    ✓ G/n is the attempt rate per node, which is also the probability that a node has an attempt for given time.

    ✓ The probability of successful transmission p is the probability that there is only one attempt among n nodes for given time.

    $$p = n \cdot \frac{G}{n} \cdot \left(1 - \frac{G}{n}\right)^{n-1} \approx Ge^{-G} \quad \text{with a large } n$$

    ✓ The network has an effective output if there is a successful transmission. Network throughput $S = p \approx Ge^{-G}$

The maximum network throughput of slotted Aloha is e^{-1}, achieved when $G=1$.

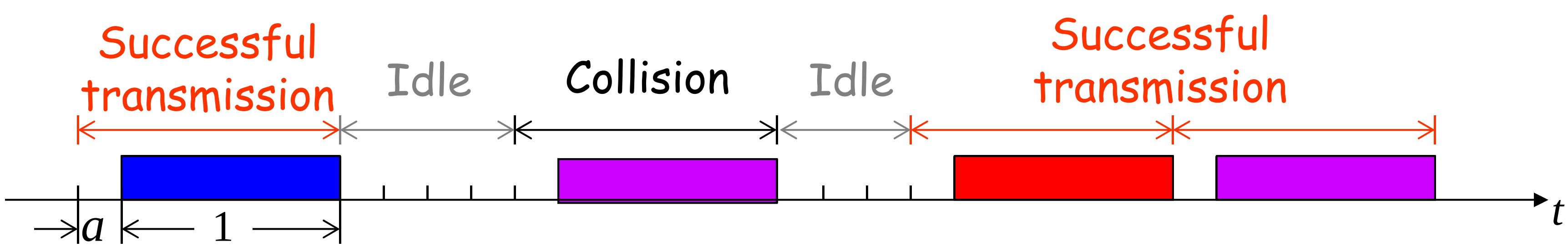
Random Access II: Carrier Sense Multiple Access (CSMA)

CSMA: listen before transmit

- If channel sensed idle, transmit entire frame
- If channel sensed busy, defer transmission

✓ Can collisions be completely avoided in this way? No.

✓ What is the maximum network throughput? 1.



More about CSMA

- The network throughput of CSMA increases as the propagation delay a decreases.
  - CSMA has a much higher throughput than Aloha if a is small enough.
- CSMA/CD (Collision Detection) vs. CSMA/CA (Collision Avoidance)
  - The collision can be detected only if the node is full-duplex (i.e., be able to receive signals via transmission)

Ethernet: CSMA/CD + Binary Exponential Backoff

WiFi: CSMA/CA + Binary Exponential Backoff

Summary III: Distributed MAC

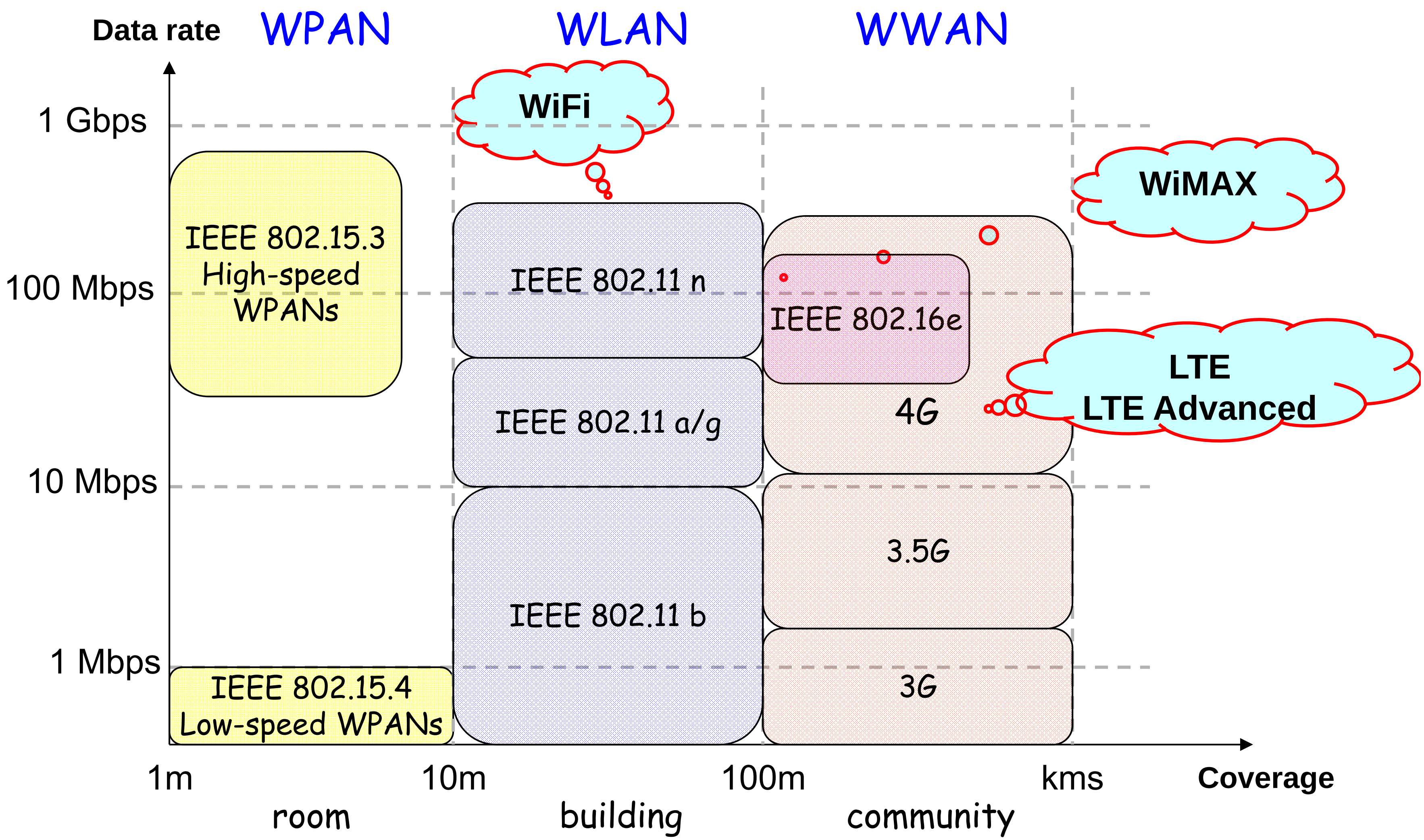
- No central controller
- Resource competition

- Aloha: transmit if there is a request, back off if a collision occurs
  - Maximum network throughput e^{-1}

- CSMA: Listen before transmit
  - Reduce the propagation delay a to improve the network throughput.
  - The maximum network throughput approaches 1 as a goes to zero.

Case Study: WiFi

Wireless Networks



WiFi and IEEE 802.11

- WiFi
  - a class of WLAN devices based on the IEEE 802.11 standards.

- IEEE 802.11
  - a set of standards carrying out WLAN computer communication in the 2.4, 3.6 and 5 GHz frequency bands. They are implemented by the IEEE LAN/MAN Standards Committee (IEEE 802).

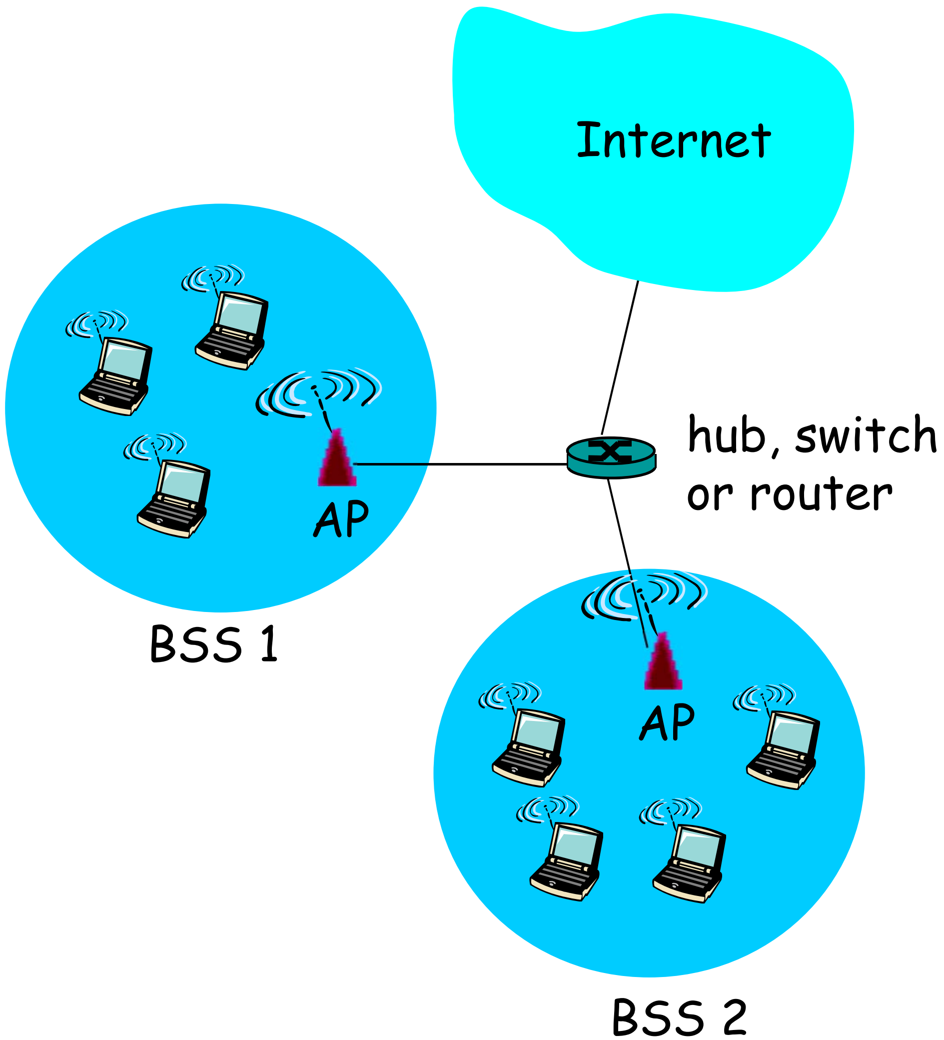
IEEE 802.11 Standards

- 802.11a
  - 5 GHz
  - up to 54 Mbps
  - OFDM in physical layer
- 802.11b
  - 2.4 GHz unlicensed spectrum
  - up to 11 Mbps
  - DSSS in physical layer
- 802.11g
  - 2.4 GHz
  - up to 54 Mbps
  - OFDM in physical layer

> - all use CSMA/CA for multiple access
> - all have access-point-based and ad-hoc network versions

- 802.11n
  - 2.4 GHz
  - up to 200 Mbps
  - OFDM, Multiple antennas (4)
- 802.11ac
  - 5 GHz
  - up to 900 Mbps
  - OFDM, Multiple antennas (8)

LAN Architecture



AP: Access Point

BSS: Basic Service Set

Channels and Association

- 802.11b: 2.4GHz-2.485GHz spectrum divided into 11 channels at different frequencies
  - AP admin chooses frequency for AP
  - interference possible: channel can be same as that chosen by neighboring AP!
- Wireless Station: must *associate* with an AP
  - scans channels, listening for *beacon frames* containing AP's name (SSID) and MAC address
  - selects AP to associate with
  - typically run DHCP to get IP address in AP's subnet

MAC Protocol: CSMA/CA + Binary Exponential Backoff

Transmitter (Wireless Station)

if sense channel idle (idle for a period of time equal to DIFS), then transmit the entire frame.

* else, choose a random backoff value and count down whenever the channel is sensed idle. Transmit the entire frame when the counter reaches zero.

Collision Avoidance

Receiver (Access Point)

- if frame received OK, then return ACK

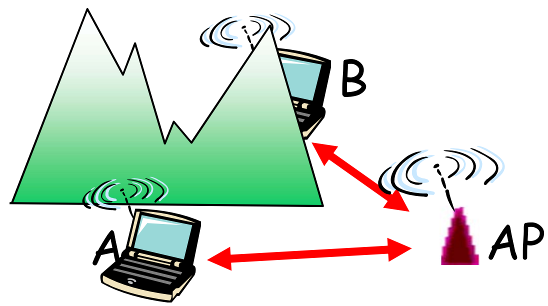
Transmitter (Wireless Station)

if ACK, then repeat step * if it has another frame to transmit.

else, choose a random backoff value from (0, w-1), w is initialized at CW_{min} and doubled after each unsuccessful transmission. Count down whenever the channel is sensed idle. Transmit the entire frame when the counter reaches zero.

Binary Exponential Backoff

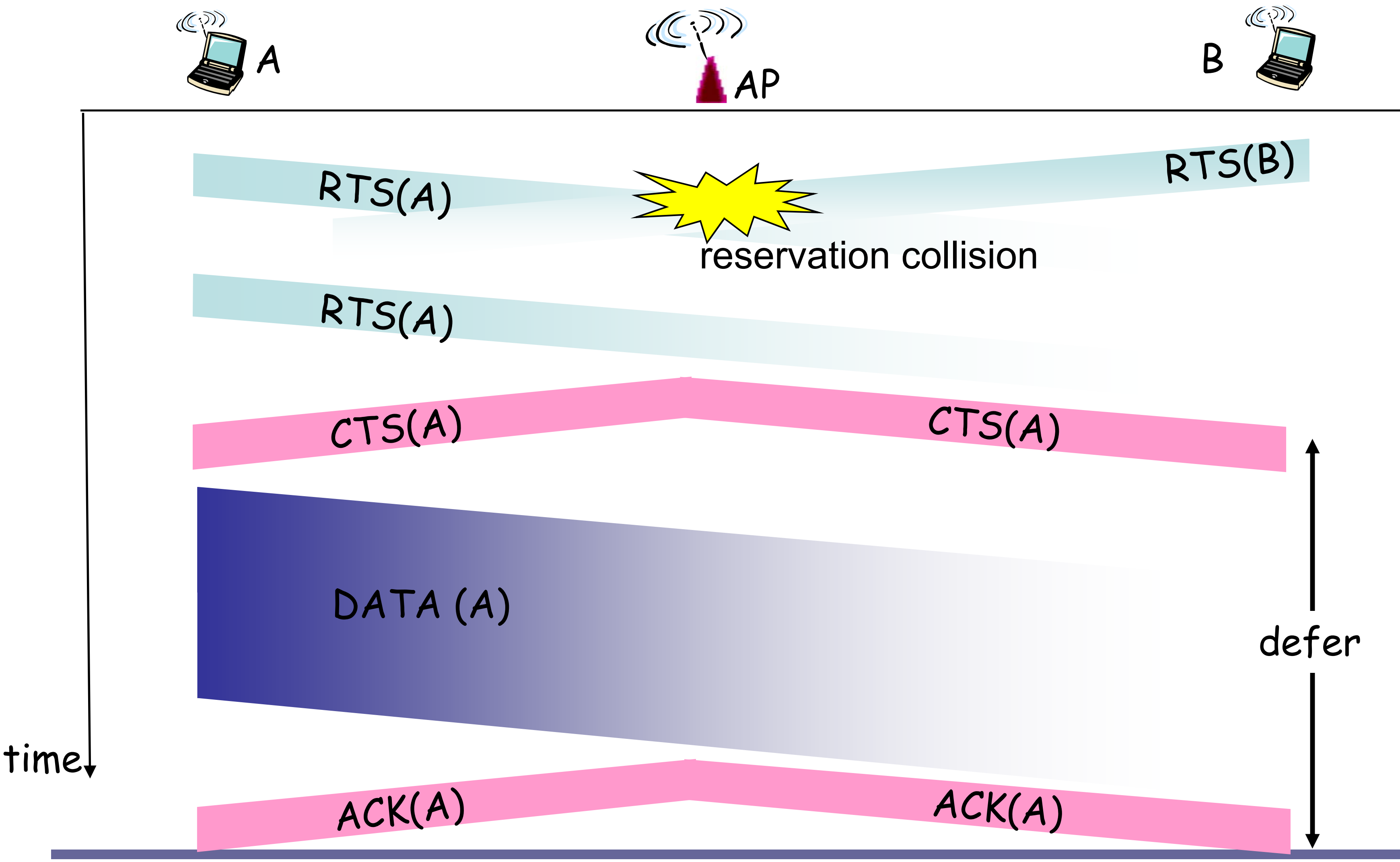
Hidden Terminal Problem



- Node A and AP hear each other
- Node B and AP hear each other
- Node A and Node B cannot hear each other

A and B are unaware of each other's transmission

RTS-CTS Exchange



To Solve the Hidden Terminal Problem: RTS-CTS

- Sender transmits *small* request-to-send (RTS) packets to AP
  - RTSs may still collide with each other (but they're short)
- AP broadcasts clear-to-send (CTS) in response to RTS
- CTS heard by all nodes
  - sender transmits data frame
  - other stations defer transmissions

Avoid data frame collisions by using small reservation packets!

Summary

- Low cost, short-distance transmission
  - Free spectrum
  - High data rate
- Limited network control
  - Distributed MAC
  - Simple coordination among APs
- IP-based network architecture