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  
  - A central controller is required to perform the optimal resource allocation.
  - Given the resources (time, frequency, antennas, power, ...), how to maximize the system objective (sum rate, average user rate, ...)?

- Protocol Design  
  - Minimum system control, fully distributed
  - What is the simplest way to determine how nodes share the channel?
# Centralized MAC vs. Distributed MAC

<table>
<thead>
<tr>
<th>Centralized MAC</th>
<th>Distributed MAC</th>
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</thead>
<tbody>
<tr>
<td>• Resource allocation</td>
<td>• Resource competition</td>
</tr>
<tr>
<td>• Joint processing of users’ information</td>
<td>• No joint transmission/detection</td>
</tr>
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<td>(A “collision” occurs if more than one user transmits. None of them can succeed.)</td>
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<tr>
<td>• Multiuser information theory</td>
<td>• Random access theory</td>
</tr>
<tr>
<td>– Perfect system guidance and performance evaluation</td>
<td>– Simple, scalable</td>
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<td>– Bursty arrival is not taken into consideration</td>
<td>– No unified framework</td>
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<tr>
<td>• CDMA, OFDMA and Scheduling</td>
<td>• Aloha and CSMA</td>
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### Notes:
- **Centralized MAC**
  - Joint processing of users’ information
  - Multiuser information theory
    - Perfect system guidance and performance evaluation
    - Bursty arrival is not taken into consideration
  - CDMA, OFDMA and Scheduling

- **Distributed MAC**
  - Resource competition
  - No joint transmission/detection
  - Random access theory
    - Simple, scalable
    - No unified framework
Centralized MAC I: MAC of Wideband Cellular Networks

- CDMA
- OFDMA
- Scheduling
A little bit of History

- 1\textsuperscript{st} Generation: AMPS, TACS, NMT
- 2\textsuperscript{nd} Generation: GSM, IS-136, IS-95
  - 2.5G: GPRS, EDGE
- 3\textsuperscript{rd} Generation: WCDMA, CDMA2000, TD-SCDMA
- 4\textsuperscript{th} 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

- **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

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

No interference averaging. Similar to a narrowband system.

Each user sees interference from many users instead of a single strong user.
## CDMA vs. OFDMA

<table>
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<th>OFDMA</th>
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<tr>
<td>• Universal frequency reuse</td>
<td>• Universal frequency reuse</td>
</tr>
<tr>
<td>• Inter-cell interference averaged</td>
<td>• Inter-cell interference averaged</td>
</tr>
<tr>
<td>• Significant intra-cell interference</td>
<td>• No intra-cell interference</td>
</tr>
</tbody>
</table>
| • 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  
  (Peak-to-Average Power Ratio) | • High PAPR |
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

<table>
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<th>Channel-aware Scheduling</th>
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<tr>
<td>• Average out channel fluctuations</td>
<td>• Exploit channel fluctuations</td>
</tr>
<tr>
<td>• Track slow fluctuations</td>
<td>• Track as many fluctuations as possible</td>
</tr>
<tr>
<td>• Power control</td>
<td>• Rate control</td>
</tr>
<tr>
<td>• Average out inter-cell interference</td>
<td>• Opportunistically avoid inter-cell interference</td>
</tr>
<tr>
<td>• Support tight delay</td>
<td>• Need some laxity</td>
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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

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<tr>
<td><strong>Intra-cell Resources</strong></td>
<td>PN Sequences</td>
<td>Subcarriers &amp; Time slots</td>
<td>Time slots</td>
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<tr>
<td><strong>Intra-cell Interference</strong></td>
<td>Significant</td>
<td>None</td>
<td>None</td>
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<td><strong>Control at BS</strong></td>
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<td><strong>Delay Requirement</strong></td>
<td>Can Support Tight Delay</td>
<td>Need some laxity</td>
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- **CDMA** uses PN Sequences as its resource allocation mechanism.
- **OFDMA** uses Subcarriers & Time slots.
- **Channel-aware Scheduling** involves utilizing Time slots.
- **Intra-cell Interference** for CDMA is significant, while for OFDMA it is none.
- **Control at BS** for CDMA involves tight power control, while for OFDMA it involves tight frequency synchronization.
- **Delay Requirement** for CDMA can support tight delay, while for OFDMA it needs 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
  \[ y_k[m] = h_k[m] x[m] + z_k[m], \quad k = 1, \ldots, K \]
Multiuser Capacity of AWGN Channels

- Uplink Capacity
- Downlink Capacity
Capacity of Uplink AWGN Channel

\[ y = h_1 x_1 + h_2 x_2 + z \]

\[ R_1 \leq \log_2 \left( 1 + P_1 |h_1|^2 / N_0 \right) \quad R_2 \leq \log_2 \left( 1 + P_2 |h_2|^2 / N_0 \right) \]

\[ R_1 + R_2 \leq \log_2 \left( 1 + (P_1 |h_1|^2 + P_2 |h_2|^2) / N_0 \right) \]

- **Capacity Region**: set of pairs \((R_1, R_2)\) at which users 1 and 2 can reliably and simultaneously communicate.

- **Sum Capacity**: the maximum total rate

\[
C_{\text{sum}} = \max_{(R_1, R_2) \in C} R_1 + R_2 \\
= \log_2 \left( 1 + \frac{P_1 |h_1|^2 + P_2 |h_2|^2}{N_0} \right)
\]
To Achieve Uplink Capacity I: Non-orthogonal Access

- Always treat the other user’s signal as noise during detection
  \[ R_1 = \log_2 \left( 1 + P_1 |h_1|^2 / (P_2 |h_2|^2 + N_0) \right) \]
  \[ R_2 = \log_2 \left( 1 + P_2 |h_2|^2 / (P_1 |h_1|^2 + N_0) \right) \]

- 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 $\alpha$ of the bandwidth is allocated to user 1 and the rest is allocated to user 2.

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

Optimal when

\[
\alpha = \frac{P_1 |h_1|^2}{P_1 |h_1|^2 + P_2 |h_2|^2}
\]
Capacity of Downlink AWGN Channel

\[ y_1 = h_1 x + z_1 \quad y_2 = h_2 x + z_2 \]

\[ R_k \leq \log_2 (1 + P |h_k|^2 / N_0), \quad k = 1, 2. \]

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: \( P = P_1 + P_2 \)

  - 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 \( \alpha \) of the bandwidth is allocated to user 1 and the rest is allocated to user 2. \( P = P_1 + P_2 \)

  \[
  R_1 = \alpha \log_2 \left( 1 + \frac{P_1 |h_1|^2}{\alpha N_0} \right) \\
  R_2 = (1 - \alpha) \log_2 \left( 1 + \frac{P_2 |h_2|^2}{(1 - \alpha)N_0} \right)
  \]
K-User Capacity

- **Capacity Region**

  **Uplink**

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

  \[ \sum_{k \in S} R_k \leq \log_2 \left( 1 + \frac{\sum_{k \in S} P_k |h_k|^2}{N_0} \right), \quad S \subset \{1, \ldots, K\} \]

  ✔ **SIC**

  \[ R_i \leq \log_2 \left( 1 + \frac{P_1 |h_i|^2}{\sum_{k=2}^K P_k |h_k|^2 + N_0} \right), \quad \text{for } i = 1, \ldots, K\]

  \[ R_K \leq \log_2 \left( 1 + \frac{P_K |h_K|^2}{N_0} \right). \]

  ✔ **Orthogonal Access**

  \[ R_k \leq \alpha_k \log_2 \left( 1 + \frac{P_k |h_k|^2}{\alpha_k N_0} \right), \quad \sum_{k=1}^K \alpha_k = 1. \]

  **Downlink**

  \[ |h_1|^2 \leq |h_2|^2 \leq \cdots \leq |h_K|^2 \]

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

  \[ \cdots \]

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

  ✔ **Superposition Coding**

  \[ R_i \leq \log_2 \left( 1 + \frac{P_1 |h_i|^2}{|h_i|^2 \sum_{k=2}^K P_k + N_0} \right), \]

  \[ \cdots \]

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

  ✔ **Orthogonal Division**

  \[ R_k \leq \alpha_k \log_2 \left( 1 + \frac{P_k |h_k|^2}{\alpha_k N_0} \right), \quad \sum_{k=1}^K P_k = P, \sum_{k=1}^K \alpha_k = 1. \]
K-User Capacity

- **Sum Capacity**
  \[ C_{\text{sum}} = \max_{R_1, \ldots, R_K} \sum_{k=1}^{K} R_k \]

**Uplink**

\[ C_U^{\text{sum}} = \log_2 \left( 1 + \sum_{k=1}^{K} \frac{P_k |h_k|^2}{N_0} \right) \]

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 \(|h_1|^2 \leq |h_2|^2 \leq \cdots \leq |h_K|^2|\):

\[ C_D^{\text{sum}} = \log_2 \left( 1 + \frac{P |h_K|^2}{N_0} \right) \]

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: \[ C = \mathbb{E}_h [\log_2 (1 + |h|^2 \frac{P}{N_0})] \]

- K-user:
  \[
  C_{sum} = \mathbb{E}_h \left[ \log_2 \left( 1 + \sum_{k=1}^{K} \frac{|h_k|^2 P_k}{N_0} \right) \right]
  \leq \log_2 \left( 1 + \sum_{k=1}^{K} \frac{\mathbb{E}_h |h_k|^2 P_k}{N_0} \right)
  = \log_2 \left( 1 + \frac{\sum_{k=1}^{K} P_k}{N_0} \right)
  \]

Fading always hurts if no CSI is available at the transmitter side!
Ergodic Uplink Sum Capacity with CSIT

- Single-user:

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

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

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

Waterfilling power allocation

- \(K\)-user:

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

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

\[ P_{k,l}^{optimal} = \begin{cases} 
\left( \mu - \frac{N_0}{|h_{k,l}|^2} \right)^+ & \text{if } |h_{k,l}| = \max_{i=1,\ldots,K} |h_{i,l}| \\
0 & \text{otherwise}
\end{cases} \]
Ergodic Uplink Sum Capacity with CSIT

- Single-user:
  \[ C = E_h \left[ \log_2 \left( 1 + \frac{P^*(h) |h|^2}{N_0} \right) \right] \]

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

- K-user:
  \[ C_{sum} = E_h \left[ \log_2 \left( 1 + \frac{P_k^*(h) |h_k|^2}{N_0} \right) \right] \quad h = [h_1, h_2, ..., h_K] \]

  \[ P_k^*(h) = \begin{cases} \left( \mu - \frac{N_0}{|h_k|^2} \right)^+ & \text{if } |h_k| = \max_{i=1,...,K} |h_i| \\ 0 & \text{otherwise} \end{cases} \]

  where \( \mu \) satisfies \( \sum_{k=1}^K E_h[P_k^*(h)] = KP \)

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.
• **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 $\{0, 1, \ldots, \lfloor 1/q \rfloor\}$ 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.
    
    - 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

- **WPAN**
  - IEEE 802.15.4
  - IEEE 802.15.3
- **WLAN**
  - IEEE 802.11 b
  - IEEE 802.11 a/g
  - IEEE 802.11 n
- **WWAN**
  - 3G
  - 3.5G
  - 4G
  - LTE
  - LTE Advanced

Data rate:
- 1 Gbps
- 100 Mbps
- 10 Mbps
- 1 Mbps

Coverage:
- Room: 1m
- Building: 10m
- Community: 100m
- Kms
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

- **802.11g**
  - 2.4 GHz
  - up to 54 Mbps
  - OFDM in physical layer

- **802.11b**
  - 2.4 GHz unlicensed spectrum
  - up to 11 Mbps
  - DSSS in physical layer

- **802.11n**
  - 2.4 GHz
  - up to 200 Mbps
  - OFDM, Multiple antennas (4)

- **802.11ac**
  - 5 GHz
  - up to 900 Mbps
  - OFDM, Multiple antennas (8)

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

- **BSS 1**
  - AP
  - hub, switch or router

- **BSS 2**
  - AP

**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.

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.
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

- RTS(A)
- RTS(B)
- reservation collision
- CTS(A)
- DATA (A)
- ACK(A)
- defer
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