CHAPTER 3:

WIRELESS LOCAL AREA NETWORKS

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WLANs are HOT !!!

- WiFi (Wireless Fidelity)
- IEEE 802.11 Standard
- Connect computers to each other and to the Internet
- THE access points to connect to the Internet
WLANs: Current Uses

- Homes, Airports, Convention Centers, Cafes, Train Stations, Airplanes, Malls, everywhere
- Hospitals
- Warehouses
- Universities
- Meeting rooms
- Retail stores
- Restaurants
- Car rental agencies

SIMPLY EVERYWHERE !!
WiFi Network Topologies

- **AP Based Topology** (Infrastructure Mode)
- **Peer to Peer Topology** (Ad Hoc Mode)
WIRELESS LANs Architecture

Infrastructure Network

Wired NW

Ad Hoc Network

AP: Access Point
Detailed Reference Architecture of Wireless LANs

- Station (STA)
- Basic Service Set (BSS) (CELL)
  - Group of STAs using the same radio frequency
- Access Point (Bridge)
- Portal
  - Bridge to other (wired) networks
- Extended Service Set (ESS) consists of two or more BSSs interconnected by a distribution system
- Distribution System ➔ a wired backbone LAN
MOBILITY TYPES

- **No Transition:**
  
  Either stationary or moves only within one BSS

- **BSS Transition:**

  Moves from BSS $\rightarrow$ BSS within the same ESS

- **ESS Transition:**

  Moves from BSS/ESS to another BSS/ESS
DETAILED LIST OF IEEE 802.11 STANDARDS

- IEEE 802.11: 1 Mbit/s and 2 Mbps; 2.4 GHz RF and IR standard (1997)
- IEEE 802.11a: 54 Mbps; 5 GHz standard (1999)
- IEEE 802.11b: Enhancements to 802.11 to support 5.5 Mbps and 11 Mbps (1999)
- IEEE 802.11c: Bridge operation procedures (2001)
- IEEE 802.11d: International (country-to-country) roaming extensions (2001)
- IEEE 802.11g: 54 Mbps; 2.4 GHz standard (backwards compatible with 802.11 b) (2003)
- IEEE 802.11h: Dynamic Spectrum Managed 802.11a (5 GHz) for EU (2004)
- IEEE 802.11k: Radio resource measurement interface to higher layers (2008)
- IEEE 802.11n: Higher-throughput (100+Mbps) improvements using MIMO (2009)
- IEEE 802.11p: Inter-Vehicle and Vehicle Road Side Com at 5.8GHz (2010)
DETAILED LIST OF IEEE 802.11 STANDARDS

IEEE 802.11r: Fast BSS transition (Romaing) (2008)
IEEE 802.11s: Mesh Networking; (ESS) (2011)
IEEE 802.11u: Inter-working with External Networks HotSpots and cellular network offload (2011)
IEEE 802.11v: Wireless Network Management (2011)
IEEE 802.11w: Protected Management Frames (2009)
IEEE 802.11z: Extensions to Direct Link Setup (DLS) for Power Save (2010)
IEEE 802.11aa: Audio Video Transport Streams (2012)
IEEE 802.11ac: Very High Throughput < 6 GHz; 802.11n extensions multi user MIMO (2013)
IEEE 802.11ad: Very High Throughput 60 GHz (2012)
IEEE 802.11af: TV Whitespace (2014)
IEEE 802.11ah: Sub 1 GHz for IoT (e.g., sensor network, smart metering) (~ August 2016)
902-928 MHz (USA); 868-868.6 (EU); 950-958 (Japan);
314-316MHz; 430-434MHz; 470-510MHz; 779-787MHz (China);
917-923.5MHz (Korea)
Co-existence with 802.15.4; Tx range 1km; Data rates: 1kbps

IEEE 802.11ai: Fast Initial Link Setup (~ Sept. 2016)

IEEE 802.11aj: China Millimeter Wave 59-64GHz and 45GHz (~ June 2017)

IEEE 802.11ak: General Links (~ May 2017)

IEEE 802.11aq: Pre-association Discovery (~ July 2017)

IEEE 802.11ax: High Efficiency WLAN (~ May 2018)

IEEE 802.11ay: Next Generation 60GHz (~ Nov 2019)

IEEE 802.11az: Next Generation Positioning (~ March 2020)
IEEE 802.11 EVOLUTION

Data Rates

- > 5Gbps
- 1-2Gbps
- 450 Mbps
- 54 Mbps
- 5-11Mbps
- 1-2Mbps

Years

- 1997
- 1999
- 2003
- 2009
- 2014
- 2018

IEEE 802.11 Standards:

- 802.11
- 802.11a
- 802.11b
- 802.11g
- 802.11n
- 802.11ac
- 802.11ax

Data Rates:

- 1-2Mbps: 1-2Mbps
- 5-11Mbps: 5-11Mbps
- 450 Mbps
- 54 Mbps
- > 5Gbps

Years:

- 1997
- 1999
- 2003
- 2009
- 2014
- 2018
WLAN: IEEE 802.11b

- Appeared in late 1999

- Frequency: 2.4 GHz (ISM) Band

- Data Rates
  - 1, 2, 5.5, 11 Mbps, depending on SNR (Interference problems)
  - User data rate max. approx. 6 Mbps

- Transmission range
  - 300m outdoor, 30m indoor
  - Max. data rate ~10m indoor
WLAN: IEEE 802.11b

Advantages:

• Many installed systems (available everywhere)
• Lots of experience
• Available worldwide
• Free ISM-band
• Many products and many vendors
• Integrated in laptops

* Simple system

Disadvantages:

– Limited Security
– Heavy interference on ISM-band
– Quality of Service Problems
  (Typ. Best Effort, no guarantees)
  (unless polling is used, limited support in products)
– Slow relative speed only
WLAN: IEEE 802.11a

- **Introduced in 2001**
- **Frequency: ~5GHz**
- **Frequency (Details)**
  - 5.15-5.25, 5.25-5.35, 5.725-5.825 GHz
- **Data rates**
  - 6, 9, 12, 18, 24, 36, 48, 54 Mbps, depending on SNR
  - User throughput (1500 byte packets):
    - 5.3 (6), 18 (24), 24 (36), 32 (54)
  - 6, 12, 24 Mbps mandatory
- **Transmission range**
  - 100m outdoor, 10m indoor
    - e.g., 54 Mbps up to 5m, 48 up to 12m, 36 up to 25m, 24 up to 30m, 18 up to 40m, 12 up to 60m
WLAN: IEEE 802.11a

Advantages:
- Fits into 802.x standards
- Licensed Band
- Available
- Simple system
- Uses less crowded 5GHz band

Disadvantages:
- Limited Security
- Quality of Service (No QoS)
  - Typ. best effort, no guarantees
  (same as all 802.11 products)
WLANs – 802.11 Compatibility

- **802.11a and 802.11b share the same MAC layer**

- **Significant differences at the PHY layer:**
  - 802.11b: 2.4 GHz, DHSS
  - 802.11a: 5 GHz, OFDM
  - Possible to operate both on the same network concurrently (using the same access points)

- **Interoperability**
  - WECA (Wireless Ethernet Compatibility Alliance):
  - Organization behind Wi-Fi that certifies products meeting the 802.11b specification
WLANs – 802.11 Protocol Architecture

- **Physical Layer (PHY)**
  - Point Coordination Function (PCF)
  - Distributed Coordination Function (DCF)
- **MAC**
  - Real Time Traffic
  - Normal Data Traffic
IEEE 802.11 - MAC Layer Overview

- **DFWMAC-DCF CSMA/CA with RTS/CTS and NAV**
  (Distributed Foundation Wireless Medium Access Control – Distributed Coordinated Function CSMA/CA)

- **DFWMAC- PCF (Optional)**
  Access point polls terminals according to a list
Pre-cursor MACs

- ALOHA
- S-ALOHA
- R-ALOHA
- CSMA
  - Non-persistent CSMA
  - p-persistent CSMA
  - 1-persistent CSMA
**DFWMAC CSMA/CA**

Contention Window

\[ CW_{\text{min}} = 31 \ \mu\text{sec} \]

(Randomized Back-off Mechanism)

- **Slot Time** = 20 msec

**Diagram:***

1. **Station 1** senses the channel and it is idle; Backs off for IFS time.
2. **Access the channel if it is still free**.
3. **Medium Busy**
   - Stations \( i=2,3,4 \) sense the channel and it is BUSY; Put them in a queue.
4. **IFS**
5. **Next Frame**
LISTEN TO THE MEDIUM (SENSE THE CHANNEL):

- IF IDLE  →  waits for IFS time and then transmit if the channel is still idle
- IF BUSY  →  continue to sense the channel and wait until the channel becomes IDLE
- Once the current transmission is over, the station delays for another IFS
- If the medium remains idle for this period, the station backs off using a binary exponential backoff scheme and again keeps sensing the medium
BINARY EXPONENTIAL BACKOFF ALGORITHM

- Each station maintains a Contention (Backoff) Window (CW)
- CW size is initially $CW_{\text{min}} = 31 \, \mu\text{sec} \ (802.11b)$, or $CW_{\text{min}} = 15 \, \mu\text{sec} \ (802.11a \text{ and } g)$
- CW is used to select the random backoff counter (BC) → (random backoff delay)
- BC is determined as a random integer
- Each station picks a random number of slots (slot time 20 \, \mu\text{sec}) drawn from a uniform distribution over the interval $[0, CW]$ → Random Backoff Counter/Clock (random integer)
- When the CONTENTION WINDOW starts, all contending stations start to decrease their BACKOFF COUNTERS/CLOCKS
- The first station whose COUNTER reaches 0, it starts transmission
- All the other stations freeze their COUNTERS/CLOCKS at that moment
- After the completion of the current transmission in the next contention period those stations restart to decrease their CLOCKS → again the station whose counter reaches 0, will transmit.
WHAT IF TWO STATIONS COLLIDE

- Initially and after each successful transmission, the CW value is reset to $CW_{min}$.

- After each unsuccessful attempt (COLLISIONS)
  \[ CW = \min\{2CW + 1, CW_{max}\} \]

**Example:** $CW_{min} = 3$ and $CW_{max} = 127$

3, 7, 15, 31, 63, 127, 127, 127, ...

<table>
<thead>
<tr>
<th></th>
<th>Slot Time</th>
<th>CWmin</th>
<th>CWmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11a</td>
<td>9 µsec</td>
<td>15</td>
<td>1023</td>
</tr>
<tr>
<td>802.11b</td>
<td>20 µsec</td>
<td>31</td>
<td>1023</td>
</tr>
<tr>
<td>802.11g</td>
<td>20 µsec</td>
<td>15;31</td>
<td>1023</td>
</tr>
</tbody>
</table>
EXAMPLE
Inter-frame Spaces (IFS)

Direct access if medium is free $\geq$ DIFS
Inter-frame Spaces (IFS)

Priorities are defined through different inter frame spaces

- SIFS (Short Inter Frame Spacing) \((10 \mu\text{sec})\)

  - Highest priority packets such as ACK, CTS, polling response
  - Used for immediate response actions
Inter-frame Spaces (IFS)

– PIFS (PCF IFS) – Point Coordination Function Inter-Frame Spacing

- Medium priority, for real time service using PCF
- SIFS + 1 slot time
- Used by centralized controller in PCF scheme when using polls
Inter-frame Spaces (IFS)

- **DIFS** (DCF, Distributed Coordination Function IFS) \( (50 \ \mu\text{sec}) \)

  - Lowest priority, for asynchronous data service
  - SFIS + 2 slot times
  - Used as minimum delay of stations for data transmission contending for access
All of the MAC parameters including SIFS, DIFS, Slot Time (Length), CW$_{\text{min}}$, and CW$_{\text{max}}$ are dependent on the underlying PHY layer.

Irrespective of the PHY:

\[
\text{DIFS} = \text{SIFS} + 2 \cdot \text{SlotTime}
\]

\[
\text{PIFS} = \text{SIFS} + \text{SlotTime}
\]

<table>
<thead>
<tr>
<th></th>
<th>802.11b</th>
<th>802.11a</th>
<th>802.11g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot Time</td>
<td>20 μsec</td>
<td>9 μsec</td>
<td>20 μsec</td>
</tr>
<tr>
<td>SIFS</td>
<td>10 μsec</td>
<td>16 μsec</td>
<td>10 or 16 μsec</td>
</tr>
</tbody>
</table>
DFWMAC-DCF CSMA/CA with ACK

- Station has to wait for DIFS before sending data
- Receiver ACKs immediately (after waiting for IFS < DIFS) if the packet was received correctly (CRC))
- Receiver transmits ACK without sensing the medium.
- If ACK is lost, retransmission done.
- Automatic retransmission of data packets in case of transmission errors (NAK)
DFWMAC-DCF CSMA/CA with ACK

Sender

Receiver

Other Stations

Data

Waiting Time

Contention Window

DIFS

SIFS

ACK

Contention Window

DIFS

Other Stations

Receiver

Sender

Data

Waiting Time

Contention Window

DIFS

SIFS

ACK

Contention Window
DFWMAC-DCF CSMA/CA with RTS/CTS

- Transmitter sends an RTS (Request To Send) after medium has been idle for time interval more than DIFS.

- Receiver responds with CTS (Clear To Send) after medium has been idle for SIFS.

- Then data is transmitted.

- RTS/CTS is used for reserving channel for data transmission so that the collision can only occur in control message.
DFWMAC-DCF CSMA/CA with RTS/CTS

- Use short signaling packets for Collision Avoidance

  - RTS (Request To Send) Packet (20 Bytes):
    A sender requests the right to send from a receiver with a short RTS packet before it sends a data packet

  - CTS (Clear To Send) Packet (16 Bytes):
    The receiver grants the right to send as soon as it is ready to receive

They contain: (Sender Address; Receiver Address; Packet Size)
DFWMAC-DCF CSMA with RTS/CTS
RTS Collisions

- Still possible – RTS packets can collide!
- Binary exponential backoff performed by stations that experience RTS collisions
- RTS collisions not as bad as data collisions in CSMA
VIRTUAL CARRIER SENSING
(Network Allocation Vector (NAV))

- Both Physical Carrier Sensing and Virtual Carrier Sensing used in 802.11
- If either function indicates that the medium is busy, 802.11 treats the channel to be busy
- Virtual Carrier Sensing is provided by the NAV (Network Allocation Vector)
Network Allocation Vector (NAV)

- 802.11 frames have a duration field (ID) → indicating how long the medium will be busy (can be used to reserve the medium for that duration)

- Tx sets the NAV to the time for which it expects to use the medium

- RTS has duration of (RTS + SIF + CTS + SIF + Frame + SIF + ACK)

- CTS has duration of (CTS + SIF + Frame + SIF + ACK)

- Frame has a duration of (Frame + Time + SIF + ACK)

- ACK has a duration of ACK
Network Allocation Vector (NAV)

- Tx sets the NAV to the time for which it expects to use the medium.
- Other stations set their NAV to that value and start counting down from NAV to 0.
- As long as NAV > 0, the medium is assumed to be busy.
- When NAV=0, then the PHY carrier sensing is conducted.
Illustration

Sender

Receiver

NAV

RTS

DATA

CTS

ACK

SIFS

SIFS
CSMA/CA with RTS/CTS and ACK and NAV

- RTS
- CTS
- SIFS
- NAV (RTS)
- NAV (CTS)
- DIFS
- NAV (RTS)
- Contention Window
WLANs – 802.11 Protocol Architecture

MAC

- **Point Coordination Function (PCF)**
- **Distributed Coordination Function (DCF)**
- **Physical Layer (PHY)**

**Real Time Traffic**

**Normal Data Traffic**
DFWMAC-PCF (OPTIONAL)

- **No guarantee for a maximum access delay or minimum transmission BW**

- **Point Coordination Function (PCF)**

- **Using PCF requires an Access Point (AP) which polls all the stations in a round robin for time sensitive traffic**

- **For regular data traffic, the basic MAC protocol is used**

- **Ad Hoc Networks cannot use the PCF function**
DFWMAC- PCF (Optional)

- PCF waits for PIFS before sending a poll
- PCF can seize the medium and locks out all asynchronous traffic while it issues polls and receives responses

- When PCF issues a poll to a station, the polled station may respond after SIFS and transmit if it has something to transmit.
- PCF then issues another poll to another station after waiting PIFS
- If PCF does not receive any response during the expected turnaround time, the PCF issues another poll to another station
The use of the SUPERFRAME (CONTENTION FREE PERIOD (CFP))
Switch between the AP transmitting and the stations transmitting.
EXAMPLE

Point Coordinator

Wireless Stations

Stations’ NAV

NAV

PIFS

SIFS

CF_end

Contention Period

Contention Free Period
## WLANs: IEEE 802.11 Protocol Architecture

The IEEE 802.11 standard defines the physical and MAC layers for wireless local area networks (WLANs). The standard supports multiple frequency bands and modulation schemes.

### Frequency Bands
- **2.4GHz**
  - 802.11 (DSSS)
  - 802.11b (DSSS)
  - 802.11g (DSSS, OFDM)
- **5GHz**
  - 802.11a (OFDM)
- **Infrared**
  - 802.11 Infrared

### Modulation Schemes
- **FHSS**
- **DSSS**
- **Narrow band**
- **OFDM**

### Layer Breakdown
- **MAC Layer**
  - **Point Coordination Function (PCF)**
  - **Distributed Coordination Function (DCF)**

### Service Types
- **Real Time Traffic**
  - Contention Free Service
- **Normal Data Traffic**
  - Contention Service

### Diagram:
- The diagram illustrates the relationships between the different components and service types of the IEEE 802.11 protocol architecture.
IEEE 802.11: PHYSICAL LAYER:
Physical Medium Specification

Three Physical Media:

- Infrared
- Narrowband Microwave
- Spread Spectrum
  - 802.11 \(\rightarrow\) FHSS (Frequency Hopping Spread Spectrum)
  - 802.11 \(\rightarrow\) DSSS (Direct Sequence Spread Spectrum)
  - 802.11a \(\rightarrow\) OFDM (Orthogonal Frequency Division Multiplexing)
  - 802.11b \(\rightarrow\) DSSS
  - 802.11g \(\rightarrow\) OFDM
Infrared signals are used to transmit data (similar to TV remotes!)

Line of sight & point-to-point configuration required (or reflection surface that reflects signals)

Too sensitive to obstacles, line-of-sight requirement, etc.

10m maximum range with no sunlight or heat interference

Infrared at 1 Mbps and 2 Mbps operating at a wavelength between 850 and 950nm

Higher data rates possible (than spread spectrum)
Narrowband Microwave

- Typically used to link two WLANs together
  (e.g., to link WLANs in two buildings)

- Microwave dishes required at both ends of the link

- Narrowband microwave requires FCC licensing
  Spread spectrum does not (operates in the ISM band)

- Exclusive license typically effective within a **17.5 mile radius**
SPREAD SPECTRUM COMMUNICATION: GENERAL MODEL
Spread spectrum is characterized by:

Wide Bandwidth and Low Power

Narrowband
(High Peak Power)

Spread Spectrum
(Low Peak Power)
Spread Spectrum Use

In the 1980s, FCC implemented a set of rules making Spread Spectrum available to the public

* Cordless Telephones
* Global Positioning Systems (GPS)
* Cell Phones
* Personal Communication Systems
* Wireless video cameras

● Local Area Networks

* Wireless Local Area Networks (WLAN)
* Wireless Personal Area Networks (WPAN)
* Wireless Metropolitan Area Networks (WMAN)
* Wireless Wide Area Networks (WWAN)
FCC Specifications

The Code of Federal Regulations (CFR) Part 15 originally only described two spread spectrum techniques to be used in the licensed free Industrial, Scientific, Medical (ISM) band, 2.4 GHz, thus 802.11 and 802.11b:

* Frequency Hopping Spread Spectrum (FHSS) and
* Direct Sequence Spread Spectrum (DSSS)
Transmitter broadcasts signals over a seemingly random series of radio frequencies, hopping from frequency to frequency at fixed intervals.

Receiver, hopping between frequencies in synchronization with the transmitter, picks up the message.
FHSS Inventors

Hedy LaMarr and George Antheil
US Patent 2,292,387, August 1942
Frequency Hopping SS

- **Hopping Sequence**
  - Channel sequence dictated by the spreading code
  - Pseudorandom number serves as an index into a table of frequencies
  - A predetermined pseudorandom pattern

- **CHIPS:** Sender transmits redundant information called “chips” between actual data bits

- **CHIP PERIOD:** Time spent on each channel
  - FCC regulation → 2.5 hops/sec; maximum dwell time of 400 ms
  - IEEE 802.11 standard → 300 ms

- **Chipping rate → Hopping rate**
OVERVIEW: Frequency Hopping Spread Spectrum for WiFis

Transceiver changes frequency (HOPS) according to a Pseudorandom Sequence

* Pseudorandom sequence is a list of frequencies
* Tx hops through this list of frequencies
* Tx then repeats this pattern
* During Dwell Time, Tx remains at a certain frequency
* During Hop Time, Tx hops to the next frequency
* Data is spread over 83 MHz in the 2.4 GHz ISM band
FHSS for IEEE 802.11

- **Dwell Time**
  
  Dwell time per frequency is around 100ms
  
  (FCC specifies a dwell time of 400ms per carrier frequency in any 30 second time period)
  
  ➔ Longer dwell time = **Greater throughput**
  
  ➔ Shorter dwell time = **Less throughput**

- **Hop Time**
  
  Measured in (microsecs) and is ~ 200-300 μs.
FHSS

ADVANTAGES

* Immunity from noise and multipath distortion (interference mitigation) and jamming

→ Resembles noise; Hard to detect; Hard to intercept
   Can be used for hiding and encrypting signals

* Masks transmitted signal in background noise to prevent eavesdropping

* Several users can independently use the same channel at the same time with higher BW with very little interference

DISADVANTAGES

- Not as fast as a wired LAN or the newer WLAN Standards

- Lower throughput due to interference

   FHSS is subject to interference from other frequencies in the ISM band because it hops across the entire frequency spectrum
Each bit in the original signal is represented by multiple bits in the transmitted signal, using a spreading code.

The spreading code spreads the signal across a wider frequency band in direct proportion to the number of bits used.

Therefore, a 10-bit spreading code spreads the signal across a frequency band that is 10 times greater than a 1-bit spreading code.
Direct Sequence Spread Spectrum (DSSS)

TECHNIQUE:
Combine the digital information stream with the spreading code bit stream using an Exclusive-OR (XOR).

The XOR obeys the following rules:

0x0 = 0        0x1 = 1        1x0 = 1        1x1 = 0
EXAMPLE: DSSS

Info bit ‘1’ inverts the spreading code bits in the combination,

Info bit ‘0’ causes the spreading code bits to be tx’ed without inversion.

The combination bit stream has the data rate of the original spreading code sequence, so it has a wider bandwidth than the information stream.

Here the spreading code bit stream is clocked at 4 times the information rate.
Direct Sequence SS

Transmitter

Data input A

Locally generated PN bit stream

Transmitted signal $C = A \oplus B$

$T$

Receiver

Received signal $C$

Locally generated PN bit stream identical to $B$ above

Data output $A = C \oplus B$
DSSS Channels in 802.11

- 14 channels are identified, but FCC specifies only 11 channels for non-licensed ISM band

- Each channel is a contiguous band of frequencies 22MHz wide with each channel separated by 5 MHz
  * Channel 1 = 2.401 – 2.423 (2.412 plus/minus 11 MHz)
  * Channel 2 = 2.406 – 2.429 (2.417 plus/minus 11 MHz)

- Only Channels 1, 6 and 11 do not overlap
DSSS Frequency Assignments in 802.11

- Channel 1: 2.412 GHz
- Channel 6: 2.437 GHz
- Channel 11: 2.462 GHz
DSSS Non-overlapping Channels in 802.11

Channel 1
Channel 6
Channel 11

2.401 GHz
2.473 GHz

22 MHz
3 MHz

P

f
Signal Spreading in DSSS
DSSS Encoding Schemes

DSSS (802.11b) employs two types of encoding schemes depending upon the speed of transmission:

* **Barker Chipping Code:**
  * Spreads 1 data bit across 11 redundant bits at both 1Mbps and 2Mbps

* **Complementary Code Keying (CCK):**
  * Maps 4 data bits into a unique redundant 8 bits for 5.5 Mbps
  * Maps 8 data bits into a unique redundant 8 bits for 11 Mbps
Barker Chipping Code

* **802.11** adopted an 11-bit Barker chipping code

* **Transmission**
  * The Barker sequence, 10110111000, was chosen to spread each 1 and 0 signal
    * The Barker sequence has 6 “1”s and 5 “0”s
  * Each data bit, 1 and 0, is modulo-2 (XOR) added to the 11-bit Barker sequence
    * If a “1” is encoded, all bits change
    * If a “0” is encoded, all bits stay the same

* **Reception**
  * A “0” bit corresponds to an 11-bit sequence of 6 “1”s
  * A “1” bit corresponds to an 11-bit sequence of 6 “0”s
Direct Sequence Spread Spectrum

Diagram:

- Single Data Bit: 1
  - Expanded Data Bit: 1111111111
  - Chipped Sequence: 01001000111
  - Spreading Sequence: 10110111000

- Single Data Bit: 0
  - Expanded Data Bit: 0000000000
  - Chipped Sequence: 10110111000
  - Spreading Sequence: 10110111000

- XOR operations are indicated in the diagram.
Complementary Code Keying (CCK)

- Barker encoding along with DBPSK and DQPSK modulation schemes allow 802.11b to transmit data at 1 and 2 Mbps

- Complementary Code Keying (CCK) allows 802.11b to transmit data at 5.5 & 11Mbps

- CCK employs an 8 bit chipping code
  
  * The 8 chipping bit pattern is generated based upon the data to be transmitted

  - At 5.5 Mbps, 4 bits of incoming data is mapped into a unique 8 bit chipping pattern.
  - At 11 Mbps, 8 bits of data is mapped into a unique 8 bit chipping pattern.
DSSS Modulation Schemes

DSSS (802.11b) employs two types of modulation schemes depending upon the speed of transmission:

* **Differential Binary Phase Shift Keying (DBPSK):**
  Two phase shifts with each phase shift representing one transmitted bit

* **Differential Quadrature Phase Shift Keying (DQPSK):**
  Four phase shifts with each phase shift representing two bits
Differential Binary Phase Shift Keying (DBPSK)

A “0” phase shift from the previous symbol is interpreted as a ”0”

A 180 degree phase shift from the previous symbol is interpreted as a “1”
Differential Quadrature Phase Shift Keying (DQPSK)

- A “0” phase shift from the previous symbol is interpreted as a “00”
- A 90 degree phase shift from the previous symbol is interpreted as a “01”
- A 180 degree phase shift from the previous symbol is interpreted as a “11”
- A 270 degree phase shift from the previous symbol is interpreted as a “10”
## DSSS Summary

<table>
<thead>
<tr>
<th>Data Rate</th>
<th>Encoding</th>
<th>Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Barker Coding</td>
<td>11 chips encoding 1 bit</td>
</tr>
<tr>
<td>2</td>
<td>Barker Coding</td>
<td>11 chips encoding 1 bit</td>
</tr>
<tr>
<td>5.5</td>
<td>CCK Coding</td>
<td>8 chips encode 8 bits</td>
</tr>
<tr>
<td>11</td>
<td>CCK Coding</td>
<td>8 chips encode 4 bits</td>
</tr>
</tbody>
</table>
FHSS vs DSSS

* DSSS is more susceptible to narrow band noise
  * DSSS channel is 22Mhz wide whereas FHSS is 79Mhz wide

* FCC regulated that DSSS uses a max of 1 watt of transmitter power in Point-to-Multipoint system

* DSSS provides better coverage

* DSSS requires much higher sampling rates

* DSSS has a throughput ~5-6 Mbps while FHSS \(\rightarrow\) ~1-2 Mbps

* Both FHSS and DHSS are equally insecure

* DSSS has gained much wider acceptance due to its high speed and interoperability
FHSS vs DSSS

Date Rate in Mbps vs Number of Co-located Systems

- 11 Mbps DSSS
- 3 Mbps FHSS (sync.)
- 3 Mbps FHSS (no sync.)
IEEE 802.11e

- Standard for WLAN QoS
- Provide essential services for delay-sensitive applications e.g., Voice over Wireless LANs and streaming multimedia.

* AP $\rightarrow$ QAP (QoS Access Point)
* STA $\rightarrow$ QSTA2 (QoS Station)
* BSS $\rightarrow$ QBSS (QoS Basic Service Set)

* PCF $\rightarrow$ Hybrid Coordination Function (HCF) to provide QoS support

* Enhanced Distributed Channel Access (EDCA)
  Distributed, contention-based channel access mechanism

* HCF Controlled Channel Access (HCCA)
  Centrally controlled, contention-free channel access mechanism
New Features

- Introduction of 4 Access Categories (AC) with 8 Traffic Classes (TC)
- Transmission Opportunity (TXOP)
  Time period during which a QSTA has the right to transmit
- Starting time and a maximum duration (TXOP Limit)
- TXOP Time Limit is specified by the QAP
- AIFS – Arbitration Interframe Space
- Up to 4 Queues:
  Each Q gets different sets of 4 parameters: $CW_{\text{min}}/CW_{\text{max}}$; AIFS and TOXP
IEEE 802.11e

BSS (Basic Service Set)

QBSS (Basic Service Set for QoS)

<table>
<thead>
<tr>
<th>PCF</th>
<th>DCF</th>
</tr>
</thead>
</table>

| HCCA | EDCA |
Hybrid Coordinator

HC

PIFS

HCCA

EDCA

DATA

AIFS

SIFS

AIFS

PIFS

DATA
IEEE 802.11e MAC

HCF Hybrid Coordination Function

PCF

HCCA

DCF

EDCA

802.11-1997

802.11a

802.11b

802.11g

Draft 802.11n
### Access Categories Traffic Classes

<table>
<thead>
<tr>
<th>Priority</th>
<th>User Priority (UP)</th>
<th>Access Category (AC)</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest</td>
<td>1</td>
<td>AC_BK</td>
<td>Background</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>AC_BK</td>
<td>Background</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>AC_BE</td>
<td>Best Effort</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>AC_VI</td>
<td>Video</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>AC_VI</td>
<td>Video</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>AC_VI</td>
<td>Video</td>
</tr>
<tr>
<td>Highest</td>
<td>6</td>
<td>AC_V0</td>
<td>Voice</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>AC_V0</td>
<td>Voice</td>
</tr>
</tbody>
</table>
Access Category Queues

- Every station maintains 4 transmit queues one for each AC, and 4 independent EDCAFs, one for each queue.

- EDCAF is the same as CSMA/CA and backoff, but based on the parameters specific to the AC it is contending for 4.

Mapping to Access Category

Transmit Queues

Per-queue channel access functions
**EDCA Parameters**

Immediate access when Medium is free DIFS=AIFS[i]

802.11a
SIFS=16 µsec
PIFS=25 µsec
DIFS=34 µsec
AIFS>=34µsec

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AIFS</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>CW_min</td>
<td>3</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>CW_max</td>
<td>7</td>
<td>15</td>
<td>1023</td>
</tr>
</tbody>
</table>
Access Category based Back-offs

AIFS[AC], $CW_{\text{min}}[AC]$, $CW_{\text{max}}[AC]$ and TXOP Limit[AC] are periodically advertised by the QAP.

QAP can adapt these parameters dynamically depending on the network conditions.
IEEE 802.11e Access Category

IEEE 802.11e station with four backoff entities

Eight priorities 0-7 according to 802.1D are Mapped to four access actegories (Acs)

Four access categories (Acs) representing four priority to four access actegories (Acs)

Upon parallel access at the same slot, the higher-priority AC Backoff entity transmits; the other backoff entity entities act as if Collision occurred
AIFS (Arbitration Inter-Frame Space)

- DIFS (in DCF) → here variable value, AIFS, that depends on the AC

\[ \text{AIFS} = \text{AIFSN} \times \text{SlotTime} + \text{SIFSTime} \]

where AIFSN is Arbitration Inter-Frame Space Number

- AIFSN specifies the number of time slots in addition to the SIFS time period

- Each AC uses different AIFSN value (high priority ACs use smaller values)

\[ (\text{AIFSN}_{\text{min}} = 1) \rightarrow \text{PIFS} = 1 \times \text{SlotTime} + \text{SIFSTime} \]

- DIFS = 2 × SlotTime + SIFSTime → Minimum length of AIFS = DIFS.
TXOP

- TXOP is a maximum time a station can send data (not to exceed max value)
- HC grants TXOP to each station
- TXOP determined from negotiated traffic spec. and observed station activity
- TXOP=/0 → Large frames which cannot be sent in a single TXOP, can be fragmented into and sent in smaller frames (not to exceed the TXOP value)
- TXOP=0 → Send only a single MAC frame
## Calculation of Contention Windows

<table>
<thead>
<tr>
<th>Class</th>
<th>CWmin</th>
<th>CWmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background (AC_BK)</td>
<td>$CW_{\text{min}}$</td>
<td>$CW_{\text{max}}$</td>
</tr>
<tr>
<td>Best Effort (AC_BE)</td>
<td>$CW_{\text{min}}$</td>
<td>$CW_{\text{max}}$</td>
</tr>
<tr>
<td>Video (AC_VI)</td>
<td>$(CW_{\text{min}}+1)/2 - 1$</td>
<td>$CW_{\text{min}}$</td>
</tr>
<tr>
<td>Voice (AC_VO)</td>
<td>$(CW_{\text{min}}+1)/4 - 1$</td>
<td>$(CW_{\text{min}}+1)/2 - 1$</td>
</tr>
</tbody>
</table>
## Default EDCA Parameters

<table>
<thead>
<tr>
<th></th>
<th>CWmin</th>
<th>CWmax</th>
<th>AIFS</th>
<th>TXOP Limit 11b</th>
<th>TXOP Limit 11 a/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background (AC_BK)</td>
<td>15</td>
<td>1023</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Best Effort (AC_BE)</td>
<td>15</td>
<td>1023</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Video (AC_VI)</td>
<td>7</td>
<td>15</td>
<td>2</td>
<td>6.016ms</td>
<td>3.008ms</td>
</tr>
<tr>
<td>Voice (AC_VO)</td>
<td>3</td>
<td>7</td>
<td>2</td>
<td>3.264ms</td>
<td>1.504ms</td>
</tr>
</tbody>
</table>

AIFS → Priority order is Voice or video, best effort, background (lowest).

$CW_{max}$ → Voice has higher priority than video

TXOP → Video is allowed more throughput than voice
EXAMPLE 2
HCCA

- Evolution of the Point Coordination Function (PCF) protocol

- PCF has 2 periods: CFP and CP

- HCCA can request a Contention Free Period (CFP) (Controlled Access Phase (CAP)) at any time during CP by sending a Control Contention (CC) frame (not in RR)

- Introduces advanced traffic priority (Traffic Class (TC) and Traffic Streams (TS)) (Strict QoS requirements (data rate, jitter, etc.) ; e.g., VoIP and video streaming)
HCCA

- During the CFP, the HC allows stations to send data by sending CF-Poll frames
- Stations only need to be able to respond to poll messages
- Every station sends a Reservation Request frame to request to access the medium from the HC
- HC grants access to the station to use the medium for specific time (TXOP)
- Stations give info about the lengths of their queues for each Traffic Class (TC)
- HC can use this info to assign priority to each station or better adjust its scheduling mechanism
- HC needs a scheduler and queuing mechanism is needed
- HCCA is not mandatory in 802.11e ➔ few APs offer HCCA
Further Specifications

- **Automatic Power Save Delivery**
- **No ACKs**
- **Block ACKs**
- **Direct Link Setup**
Automatic Power Save Delivery (APSD)

- Unscheduled APSD (U-APSD):
  - AP announces waiting frames in the beacon
  - When stations wake-up, they listen to beacon
  - Send a polling frame to AP
  - AP sends frames

- Scheduled APSD (S-APSD):
  - Station goes to sleep until next service
  - Station tells AP its wakeup schedule
  - AP sends frame on schedule. No need for polling.

- Pre-802.11e: AP announces in Beacon. STA polls.
  AP sends one frame with more bit. STA polls. AP sends next frame...
No ACKs

- Asks the receiver not to send an ACK for that frame.
- Useful for highly time-critical data
Block ACKs

- ACK multiple frames by a Block ACK to reduce the overhead
Direct Link Protocol

- **Within an Infrastructure BSS**
  - Within transmitting range of the source
  - Not in power save mode

- **Before DLP handshake via the AP**
  - Exchange capability (security)
  - Tear down via the AP
WLAN: IEEE 802.11g

- Introduced in 2003
- Combines the features of 802.11a and 802.11b
- Data rate: 54 – 108 Mbps (realistic: 31.4Mps)
- Spectrum 2.4GHz
- Compatible with 802.11b
- Uses same MAC and PHY Layer
  (OFDM and CCK and DBPSK/DQPSK+DSSS)
IEEE 802.11g Throughput Computation

- Assume a data packet of 2000 bytes needs to be sent
- IEEE 802.11g frame timing diagram

<table>
<thead>
<tr>
<th></th>
<th>DIFS</th>
<th>Back-off</th>
<th>RTS</th>
<th>SIFS</th>
<th>CTS</th>
<th>SIFS</th>
<th>PPDU</th>
<th>SIFS</th>
<th>ACK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (µs)</td>
<td>50</td>
<td>207</td>
<td>10</td>
<td>203</td>
<td>10</td>
<td>2000+MAC info</td>
<td>10</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

- MAC frame has a header of 36 bytes
- Total of 2036 bytes of data is present in the PPDU
Throughput Computation

- Assume that we use an effective data rate of 12 Mbps

- Time to send 2036 bytes = $2036 \times \frac{8}{12} e^6 \approx 1357 \mu s$

- The average number of slots backed off is $\frac{CW}{2}$

- Assuming $CW=15$, average number of back-off slots = 7.5

- Average back-off time = $7.5 \times 20 \mu s = 150 \mu s$
## Throughput Computation

<table>
<thead>
<tr>
<th></th>
<th>DIFS</th>
<th>Back-off</th>
<th>RTS</th>
<th>SIFS</th>
<th>CTS</th>
<th>SIFS</th>
<th>PPDU</th>
<th>SIFS</th>
<th>ACK</th>
</tr>
</thead>
<tbody>
<tr>
<td>µs</td>
<td>50</td>
<td>150</td>
<td>207</td>
<td>10</td>
<td>203</td>
<td>10</td>
<td>1357</td>
<td>10</td>
<td>30</td>
</tr>
</tbody>
</table>

- **Total time for transmission = 2027 µs**
- **Actual data size sent = 2000 bytes**
- **Effective throughput = 2000 x 8 / 2027 µs = 7.89 Mbps**
OFDM: Orthogonal Frequency Division Multiplexing

For very high data rates, traditional communication (single carrier) becomes complex

BASIC IDEA:

• Use a large number of parallel narrow-band sub-carriers (multiple carrier frequencies) to carry the information instead of a single wide-band carrier

• Each stream is transmitted by modulating N distinct carriers

• Subcarriers are transmitted simultaneously

• Subcarriers need to be orthogonal to be separated at the receiver

Each subcarrier is modulated with a conventional digital modulation scheme (such as QPSK, 16QAM, etc.) at low symbol rate.
Frequency Division Multiplexing: FDM

* Total amount of spectrum is divided into a number of frequencies/channels

Guard band

$f_1$  $f_2$  $f_3$  $f_4$
OFDM

- FDMA
  - Needs guard band between carriers
  - Wastes spectrum
- OFDM uses much narrower spacing of subcarriers
**SUBCARRIERS**

- **Subcarriers**
  - Rectangular shape in time domain
  - $\sin(x)/x$ shape in frequency domain
OFDM

Transmits a signal over several subsignals for higher efficiency
Example: OFDM in 802.11a

- 64 subchannels are used, among which 48 are used for data transmission, the remaining 16 are for other purposes.

- Symbol rate of each channel is 250 kilo symbols per second (kps).s

- Actual data rate for the user is $48 \times 250$ kps = 12 Msps

- Overall bandwidth is 20 MHz
OFDM for IEEE 802.11a

- A mathematical process that allows 52 *channels* to overlap without losing their orthogonality (individuality)

* 48 sub-channels are used for data
  * Each sub-channel is used to transmit data

* 4 sub-channels are used as pilot carriers
  * The pilot sub-channels are used to monitor path shift and shifts in sub-channel frequencies (Inter Carrier Interference (ICI))

* OFDM selects channels that overlap but do not interfere with one another

* Channels are separated based upon orthogonality
IEEE 802.11a Channels

* 802.11a uses the lower and middle UNII 5 GHz bands to create 8 channels
  * Each Channel is 20 MHz each
  * Each channel is broken into 52 sub-channels with each sub-channel 300 KHz each.
    * 48 sub-channels are used to transmit data
    * 4 sub-channels are used as Pilot Carriers to monitor the channel
## OFDM Encoding/Modulation

Either BPSK, QPSK or QAM depending upon the speed of transmission

<table>
<thead>
<tr>
<th>Data Rate (Mbps)</th>
<th>Modulation</th>
<th>Bits / Transition</th>
<th>R</th>
<th>Length of 1 Symbol</th>
<th>Data bits encoded by 1 symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>DBPSK</td>
<td>1</td>
<td>1/2</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>9</td>
<td>DBPSK</td>
<td>1</td>
<td>3/4</td>
<td>48</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>DQPSK</td>
<td>2</td>
<td>1/2</td>
<td>96</td>
<td>48</td>
</tr>
<tr>
<td>18</td>
<td>DQPSK</td>
<td>2</td>
<td>3/4</td>
<td>96</td>
<td>72</td>
</tr>
<tr>
<td>24</td>
<td>16-QAM</td>
<td>4</td>
<td>1/2</td>
<td>192</td>
<td>96</td>
</tr>
<tr>
<td>36</td>
<td>16-QAM</td>
<td>4</td>
<td>3/4</td>
<td>192</td>
<td>144</td>
</tr>
<tr>
<td>48</td>
<td>64-QAM</td>
<td>6</td>
<td>2/3</td>
<td>288</td>
<td>192</td>
</tr>
<tr>
<td>54</td>
<td>64-QAM</td>
<td>6</td>
<td>3/4</td>
<td>288</td>
<td>216</td>
</tr>
</tbody>
</table>
Advantages & Disadvantages of OFDM

Advantages:

* Saves bandwidth
• Carries more data than a conventional carrier
• Very easy and efficient in dealing with multi-path
* Robust against narrow-band interference

Disadvantages:

• Sensitive to frequency offset and phase noise
• Pilot Contamination Problem
• PAPR Problem
• Synchronization Problem
IEEE 802.11n

- **Data rates:** 600 Mbps
- **OFDM Modulation**
  - 64 (20MHz) and 128 (40MHz) subcarriers are used
  - Only 56 (20MHz) and 114 (40MHz) are actually used
  - OFDM symbol - 4us including CP of 0.8us or 0.4us (short guard interval (GI))
IEEE 802.11n: New Technologies

1. MIMO
2. Multipath/Spatial Diversity
3. Beam Forming
4. MIMO Power Save (Use multiple antennas only when needed)
5. Frame Aggregation
6. Lower FEC Overhead (5/6 instead of ¾ code rate)
7. Reduced Guard Interval
IEEE 802.11n: New Technologies

8. Reduced Interframe Spacing (SIFS=2usec instead of 10usec)

9. Greenfield Mode (Optionally eliminate support for a/b/g)
   (shorter and higher rate preamble)

10. Dual Band: 2.4 and 5.8 GHz

11. Space Time Block Code

12. Channel Bonding

13. More SubCarriers 52+4 instead of 48+4 with 20MHz; 108+6 with 40MHz
   4 Streams x 64QAMx5/6FECx40MHz with 400ns $\rightarrow$ 600Mbps
What is MIMO?

SISO: Single Input (transmit) Single Output (receive)

MIMO: Multiple Input Multiple Output
- Spatial diversity (transmitter and receiver)
- Spatial multiplexing

M x N system (N >1, M>1)
Single User MIMO (SU-MIMO)

- **SPATIAL DIVERSITY**
  - Several Replicas of Same Data Stream
  - Improved Reliability
  - Space-freq. block coding
  - Freq. Shift Time Diversity

- **SPATIAL MULTIPLEXING**
  - Several Data Streams Simultaneous
  - Increased Data Rates
  - Code-book based Precoding at tx to orthogonalize the streams

- **BEAMFORMING**
  - Directional Beam Pattern
  - Extended Coverage (Cell Edges)
MIMO TECHNIQUES
Basic Modes of Operation

**MU-MIMO**

Multiple users served on the same frequency & time resources

Increased number of supported users

CAPACITY IMPROVED!!
2. Multipath/Spatial Diversity

* Multiple antenna/radios send/receive signals
* Different signals reach receivers at different times
* Combine signals for greater quality
  * Each stream can carry separate data
  * Select the best subset of antennas
RECEIVER DIVERSITY

- User multiple receive antenna
- Selection combining: Select antenna with highest SNR
- Threshold combining: Select the first antenna with SNR above a threshold
- Maximal Ratio Combining:
  - Phase is adjusted so that all signals have the same phase.
  - Then weighted sum is used to maximize SNR
TRANSMITTER DIVERSITY

- Use multiple antennas to transmit the signal. Ample space, power, and processing capacity at the transmitter (but not at the receiver).
- If the channel is known, phase each component and weight it before transmission so that they arrive in phase at the receiver and maximize SNR.
- If the channel is not known, use space time block codes.
3. BEAMFORMING

* Makes signals from separate antenna arrive in sync
* Out of sync leads to interference

* In sync leads to greater signal strength
Beam Forming

- **Phased Antenna Arrays:**
  Receive the same signal using multiple antennas

- By phase-shifting various received signals and then summing → Focus on a narrow directional beam

- **Digital Signal Processing (DSP) is used for signal processing → Self-aligning**
5. Frame Aggregation

- Aggregate multiple frames destined for a specific AP and send them together to reduce overhead

- Pack multiple input frames inside a frame → Less overhead → More throughput
FRAME AGGREGATION

- Frame Bursting: Transmit multiple PDUs together

- Frame Fragmentation: SDU fragment in a PDU

- Frame Aggregation: Multiple SDUs in one PDU
  All SDUs must have the same transmitter and receiver address

- Can combine any 2 or all of the above
FRAME AGGREGATION
802.11n MAC FRAME
7. Reduced Guard Interval

- Guard interval is a time of radio silence
- Used to avoid interference
- Reduce from 800 nsec to 400nsec

- Rule of Thumb: Guard Interval = 4 × Multi-path delay spread

- Initial 802.11a design assumed 200ns delay spread → 800 ns GI + 3200 ns data → 20% overhead

- Most indoor environment shave smaller 50-75 ns

- So if both sides agree, 400 ns can be used in 802.11n → 400 ns GI + 3200 ns data → 11% overhead
12. CHANNEL BONDING

- Use 2 adjacent 20 MHz channels
- OFDM: 52+4 instead of 48+4 with 20 MHz, 108+6 with 40MHz (No guard subcarriers between two bands)
- Primary 20 MHz Channel: Used with stations not capable of channel bonding
- Secondary 20 MHz Channel: Just below or just above primary
IEEE 802.11n Throughput Computation

- Assume there are 100 packets of data, 20 bytes each and frame aggregation is not allowed.

- Duration of PPDU is \((20+36) \times 8 / 12 \times 10^6 = 37.33 \, \mu s\)

- Effective Throughput = \(20 \times 8 / 707 \, \mu s = 0.226 \, Mbps\)
IEEE 802.11n Throughput Computation

- If we allow frames to be aggregated and sent together as a single frame, assuming multiple SDUs are sent in a single PDU

- Duration of PPDU is \((20 \times 100 + 36) \times 8 / 12 \times 10^6 = 1357.33\, \mu s\)

<table>
<thead>
<tr>
<th>DIFS</th>
<th>Back-off</th>
<th>RTS</th>
<th>SIFS</th>
<th>CTS</th>
<th>SIFS</th>
<th>PPDU</th>
<th>SIFS</th>
<th>ACK</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 \mu s</td>
<td>150 \mu s</td>
<td>207 \mu s</td>
<td>10 \mu s</td>
<td>203 \mu s</td>
<td>10 \mu s</td>
<td>1357 \mu s</td>
<td>10 \mu s</td>
<td>30 \mu s</td>
</tr>
</tbody>
</table>

- Effective throughput = \(20 \times 100 \times 8 / 2027\, \mu s = 7.89\, Mbps\)

- Compare with the 0.226 Mbps (with no frame aggregation)
## 802.11 Summary Characteristics

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Release Date</th>
<th>Op. Frequency</th>
<th>Throughput (Typ)</th>
<th>Data Rate (Max)</th>
<th>Modulation Technique</th>
<th>Range (Radius Indoor)</th>
<th>Range (Radius Outdoor) Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11a</td>
<td>1999</td>
<td>5 GHz</td>
<td>23 Mbps</td>
<td>54 Mbps</td>
<td>OFDM</td>
<td>~35 Meters</td>
<td>~120 Meters</td>
</tr>
<tr>
<td>802.11b</td>
<td>1999</td>
<td>2.4 GHz</td>
<td>4.3 Mbps</td>
<td>11 Mbps</td>
<td>DSSS-CCK</td>
<td>~38 Meters</td>
<td>~140 Meters</td>
</tr>
<tr>
<td>802.11g</td>
<td>2003</td>
<td>2.4 GHz</td>
<td>19 Mbps</td>
<td>54 Mbps</td>
<td>OFDM &amp; DSSS</td>
<td>~38 Meters</td>
<td>~140 Meters</td>
</tr>
<tr>
<td>802.11n</td>
<td>June 2009 (est.)</td>
<td>2.4 GHz 5 GHz</td>
<td>74 Mbps</td>
<td>248 Mbps</td>
<td>OFDM MIMO</td>
<td>~70 Meters</td>
<td>~250 Meters</td>
</tr>
</tbody>
</table>

CCK-Complementary Code Keying

OFDM-Orthogonal Frequency Division Multiplexing

DSSS-Direct Sequence Spread Spectrum

MIMO-Multi-Input Multi-Output
IEEE 802.11ac

Very Large Throughput WLANs
IEEE 802.11ac Data Rates

- 802.11ac significantly improves the data rates up to 10x from 802.11n
  - Up to a theoretical max of 6900 Mbps

- Achieved from several advances in Channel Bonding, higher order MIMO, etc
802.11ac Features and Technologies

- Higher order MIMO and MU-MIMO
- 5GHz Operation with advanced Channel Bonding
- 256 QAM Modulation Support

802.11ac
11ac supports only 5GHz operation
- Dual band devices can use 802.11n on 2.4GHz

Must support 80MHz channel width
- Optional 160MHz

Maximum benefit for Single Access Point by using very large bandwidth in the 5GHz band
802.11ac: Frequency Band Operation

- Channel bonding across several contiguous and non-contiguous

- Achieving up to 160MHz (80+80 MHz)

- Same transmission can carry twice the amount of data
Advanced MIMO: Higher order MIMO

- **802.11ac** supports up to 8 spatial streams (from 4 in .11n) using 8x8 MIMO
  - Difficult to achieve spatial separation of 8 streams in real-life deployments
  - May work over a short-range
Advanced MIMO: MultiUser-MIMO

- Traditional MIMO allows multiple spatial streams between two devices using multiple antennas

- Multi-user MIMO:
  - Spatial streams to multiple clients, e.g., 4 antennas at AP can serve User 0 and 1 with 1 antenna each and User 2 with 2 antennas

- Benefits: (802.11ac supports up to 4 spatial streams)
  - Spatial sharing of frequency bandwidth; With 4 Tx antennas at AP, theoretically 4x data rates can be achieved compared to 1x1 antenna
  - Clients do not need to support multiple antenna technology; only number of AP antennas need to increase
256-QAM Modulation

- 256-QAM modulation packs more points on the constellation allowing more bits to be transmitted
- 256-QAM improves efficiency by 33%
- More prone to distortion (from power amplifier), channel noise
  - More suitable when clients are closer to access point
### 802.11ac Data Rates

<table>
<thead>
<tr>
<th>Feature</th>
<th>IEEE 802.11n</th>
<th>IEEE 802.11ac</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BANDS</strong></td>
<td>2.4GHz and 5 GHz</td>
<td>5 GHz</td>
</tr>
<tr>
<td><strong>CHANNEL BANDWIDTH</strong></td>
<td>20, 40 MHz</td>
<td>20, 40, 80, (optional 160) MHz</td>
</tr>
<tr>
<td><strong>Spatial Stream</strong></td>
<td>1 to 4</td>
<td>1 to 8 total</td>
</tr>
<tr>
<td><strong>Multiuser MIMO</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Single Streams (1x1) Maximum Client Data Rate</strong></td>
<td>150 Mbps</td>
<td>450 Mbps</td>
</tr>
<tr>
<td><strong>Three streams (3x3) Maximum Data Rate</strong></td>
<td>450 Mbps</td>
<td>1.3 Gbps</td>
</tr>
</tbody>
</table>
IEEE 802.11ax

High Efficiency WLAN
Challenges in Dense WiFi Deployments

- **Channel Access through CSMA and Clear Channel Assessment:**
  - Stations and APs backoff upon listening to nearby transmissions
  - Efficiency decreases as number of stations and BSS increases

- **Single user transmission in dense environments ➔ Inefficient**
  - Single users may occupy entire 160MHz without needing as much bandwidth
  - Even a 20MHz user can interfere with 160MHz and render the other 140MHz ineffective
  - Reduced latency for new traffic types and device types (e.g., surveillance, video streaming, VoIP)
IEEE 802.11ax: High Efficiency WLANs

Target Scenarios

- **Goals:** Increase physical bit rate but also mitigate inter-BSS interference and improve spatial reuse for dense deployments

- **Scenarios:**
  - Stadiums
  - Trains
  - Dense residential, e.g., apartments

![WLAN coverage area](image1)

![Short-range WLAN](image2)
# 802.11ax: PHY enhancements

<table>
<thead>
<tr>
<th></th>
<th>802.11ac</th>
<th>802.11ax</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BANDS</strong></td>
<td>5 GHz</td>
<td>2.4 GHz and 5 GHz</td>
</tr>
<tr>
<td><strong>CHANNEL BANDWIDTH</strong></td>
<td>20 MHz, 40 MHz, 80 MHz, 80+80 MHz &amp; 160 MHz</td>
<td>20 MHz, 40 MHz, 80 MHz, 80+80 MHz &amp; 160 MHz</td>
</tr>
<tr>
<td><strong>FFT SIZES</strong></td>
<td>64, 128, 256, 512</td>
<td>256, 512, 1024, 2048</td>
</tr>
<tr>
<td><strong>SUBCARRIER SPACING</strong></td>
<td>312.5 kHz</td>
<td>78.125 kHz</td>
</tr>
<tr>
<td><strong>OFDM SYMBOL DURATION</strong></td>
<td>3.2 us + 0.8/0.4 us cyclic prefix</td>
<td>12.8 us + 0.8/1.6/3.2 us cyclic prefix</td>
</tr>
<tr>
<td><strong>HIGHEST MODULATION</strong></td>
<td>256-QAM</td>
<td>1024-QAM</td>
</tr>
<tr>
<td><strong>DATA RATES</strong></td>
<td>433 Mbps (80 MHz, 1 SS)</td>
<td>600.4 Mbps (80 MHz, 1 SS)</td>
</tr>
<tr>
<td></td>
<td>6933 Mbps (160 MHz, 8 SS)</td>
<td>9607.8 Mbps (160 MHz, 8 SS)</td>
</tr>
</tbody>
</table>
Multiuser Transmissions: MU-MIMO

- Extends 802.11ac MU-MIMO to beamform packets to 8 simultaneous STAs on uplink and downlink

- Enhancements to MU-MIMO:
  - Each stream can have its own Modulation and Coding
  - Different number of streams
  - New Trigger Frame from APs to STAs to initiate uplink MU-MIMO
Multiuser Transmissions: MU-MIMO

**Trigger Frame:**

- to support synchronized uplink MU-MIMO transmission
- AP notifies exact start time and duration of MU-MIMO transmission from stations to AP
Multiuser Transmissions: MU-OFDMA

- Introduce OFDMA (such as in LTE, WiMax systems) for multiuser transmissions
- Chunks of OFDM tones called Resource units can be assigned to each user

- Flexible use of radio resources and time-frequency diversity gains from scheduling
- Allow lower latency communication using OFDMA
BSS Coloring based Spatial Reuse:

- New Spatial Reuse technique for dense deployments
- Stations can identify overlapping BSS signals
  - Useful for contention decisions and interference management
- Use adjustable thresholds for CCA
  - APs can adaptively set these parameters
Advanced Spatial Reuse Mechanisms

**BSS Coloring based Spatial Reuse:**

- Use adjustable thresholds for CCA
  - APs can adaptively set these parameters

- Set different NAVs for inter-BSS and intra-BSS
  - Allows STAs to distinguish future traffic for own BSS and other BSS
  - STAs can transmit even when other BSS’s NAV is active

Achieve overall increased area throughput
Power Savings with Target Wakeup Time

Pre-agreement of medium access using Target Wakeup Time (TWT)

- AP negotiates with STAs for TWT cycle
- Avoid unnecessary contention and provide energy savings