Wireless Communications
From 5G and WiFi 6 to Low Power IoT

Lecture 6: 5G & WiFi 6
Haitham Hassanieh
Previous Lecture:

- IoT Intro.
- Spread Spectrum
- Low Power Wide Area Networks
- Backscatter Communication
- Bluetooth

This Lecture:

- WiFi Overview
- MIMO & Multi-User MIMO
- OFDMA
- 5G Overview
- Millimeter Wave
- Massive MIMO
WiFi Standards from WiFi 1 to WiFi 6

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## WiFi Standards from WiFi 1 to WiFi 6

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### Diagram

- **Channel 3**: 2422 MHz
- **Channel 11**: 2462 MHz

- Channel Center Frequency (GHz): 2.484 GHz
- Bandwidth: 22 MHz

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**Note**: The diagram and table provide a comprehensive overview of the evolution of WiFi standards from 1999 to 2009, highlighting the technological advancements and their impact on data rates.
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WiFi Standards from WiFi 1 to WiFi 6

- **2.4 GHz**
  - Bands: 1, 3
  - Channels: 7, 20
  - BW: 20 MHz
  - 3 Channels Allocated

- **5 GHz**
  - Bands: 25, 12, 6, 2
  - Channels: 20 MHz, 40 MHz, 80 MHz, 160 MHz
  - 25 Channels Allocated

- **6 GHz**
  - Bands: 59, 29, 14, 7
  - Channels: 20 MHz, 40 MHz, 80 MHz, 160 MHz
  - 59 Channels Available

More Channels & Bandwidth

More MIMO Antennas

WiFi 1 -> WiFi 5/6
MIMO: Multiple Input Multiple Output

So far: single input single output

MIMO: multiple input multiple output

Increase capacity of channel using multiple transmit and receive antennas.
So far: single input single output

MIMO: multiple input multiple output

Increase capacity of channel using multiple transmit and receive antennas.
MIMO: Multiple TX-RX streams

\[ y_1(t) = h_{11} x_1 + h_{12} x_2 \]
\[ y_2(t) = h_{21} x_1 + h_{22} x_2 \]

\[
\begin{bmatrix}
  y_1 \\
  y_2
\end{bmatrix}
= \begin{bmatrix}
  h_{11} & h_{12} \\
  h_{21} & h_{22}
\end{bmatrix}
\begin{bmatrix}
  x_1 \\
  x_2
\end{bmatrix}
\]

\[ y = Hx \]

How to recover \( x_1 \) and \( x_2 \)?

Estimate \( H \), compute \( H^{-1} \) and invert the channel!

\[ \tilde{x} = H^{-1}y = H^{-1}Hx = x \]

Transmit 2x at the same time!
MIMO: Multiple TX-RX streams

WiFi Access Points 2 to 8 MIMO

WiFi Devices 1 to 2 MIMO

• Power
• Form Factor & Antenna Separation
• Most mobile phones support 2 MIMO
Multi-User MIMO

\[ y_1 = h_{11}x_1 + h_{12}x_2 \]

\[ y_2 = h_{21}x_1 + h_{22}x_2 \]

\[ y = Hx \]

\[ \tilde{x} = H^{-1}y = H^{-1}Hx = x \]

Does not work! Receivers do not have access to each other’s signals.
MU-MIMO Beamforming

\[ y_1 = h_{11}x_1 + h_{12}x_2 \]
\[ y_2 = h_{21}x_1 + h_{22}x_2 \]

Send: \( \tilde{x} = H^{-1}x \)

Receive: \( y = H\tilde{x} = HH^{-1}x = x \)

Allows 1 AP to communicate with multiple users at the same time!

- Requires feedback from the receiver to know the channel at the transmitter.
- Introduces in 802.11ac but not widely used until 802.11ax
Channel Access in WiFi 1 – 5: CSMA

• CSMA: Carrier Sense Multiple Access
• Medium Access scheme in WiFi & Ethernet
• Simplified Version:
  1. Listen on the channel
  2. If no one is transmitting → back-off & wait for \( M \) slots
  3. If after \( M \) slots, still no one is transmitting, transmit.
  4. If collision, increase back-off time: \( M = 2 \times M \)
     If successful, decrease back-off window: \( M = 2 \)

Suffers from significant number of collisions & problems known as hidden terminals & exposed terminals.
WiFi 6: OFDMA

• OFDMA: Orthogonal Frequency Division Multiple Access
• Assign different OFDM subcarriers to difference users.
• Since subcarriers are orthogonal → small guard bands (Efficient).

Transmit and Receive from multiple users at the same time.

Requires users to be synchronized on the uplink! Needs good hardware & synchronization algorithms.
WiFi 6: OFDMA

802.11ac vs. 802.11ax: Fixed Overhead vs. Efficient Payload Delivery

OFDM vs. OFDMA:
- OFDM: Uses multiple subcarriers to transmit data simultaneously.
- OFDMA: Allocates dedicated resources to each user, reducing overhead.

Subcarriers:
- OFDM: wider channel width
- OFDMA: multiple resource units

Users:
- User 0 (Web Page)
- User 1 (Streaming)
- User 2 (WeChat/Instagram)

Source: Qorvo, Inc. ©2017 Qorvo, Inc.
WiFi 6: OFDMA

OFDM Symbol with 1024 Subcarriers in 802.11ax

1 User with 996 subcarriers

2 Users with 484 subcarriers each

4 Users with 242 subcarriers each

8 Users with 104 subcarriers each

16 Users with 52 subcarriers each

37 Users with 26 subcarriers each
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- Spread Spectrum
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- MIMO & Multi-User MIMO
- OFDMA
- 5G Overview
- Millimeter Wave
- Massive MIMO
Mobile Technologies from 1G to 5G

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<th>Generation</th>
<th>Device</th>
<th>Specifications</th>
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| **1G**     | ![Image](https://via.placeholder.com/150) | **Year:** 1980s  
**Standards:** AMPS, TACS  
**Technology:** Analog  
**Bandwidth:** –  
**Data rates:** – |
| **2G**     | ![Image](https://via.placeholder.com/150) | **Year:** 1997  
**Standards:** GSM, GPRS, EDGE  
**Technology:** Digital  
**Bandwidth:** Narrow Band  
**Data rates:** < 80 - 130 Kbit/s |
| **3G**     | ![Image](https://via.placeholder.com/150) | **Year:** 2001  
**Standards:** UMTS / WCDMA  
**Technology:** Digital  
**Bandwidth:** Broad Band  
**Data rates:** up to 2 MHz/s |
| **4G**     | ![Image](https://via.placeholder.com/150) | **Year:** 2010  
**Standards:** LTE, LTE Advanced  
**Technology:** Digital  
**Bandwidth:** Mobile Broad Band  
**Data rates:** >5G, like experience  
**1 hr HD movie in 6 minutes** |
| **5G**     | ![Image](https://via.placeholder.com/150) | **Year:** 2020-2030  
**Technology:** Digital  
**Bandwidth:** Ubiquitous connectivity  
**Data rates:** Fiber-like experience  
**1 hr HD movie in 6 seconds** |

**5G is about Communication, Storage, Processing…**

- **People**
  - **Connected house**
  - **Entertainment**
    - Apps beyond imagination
  - **Smart Car**
    - Car-to-car communication
  - **eHealth**
    - Traffic priority
  - **Internet of Things**
    - Smart grids

**People & Things**

- **Smart grids**
  - Data rates / applications

---

*European Commission*
5G: Unified Air Interface

Enhanced Mobile Broadband (eMBB)
- 100+ Mbps avg. throughput
- 10+ Gbps peak throughput

Massive Machine Type Communications (mMTC)
- $10^6$/km$^2$ connection density
- Low cost/energy connectivity

Ultra-Reliable, Low-Latency Communications (URLLC)
- 99.999% service availability
- 1 – 10 ms latency

Applications:
- Mobile video and gaming
- Cloud computing and storage
- High speed connectivity

- Billions of connected devices
- Sensor networks
- IoT / M2M / D2D

- Tactile Internet
- Natural disaster relief
- E-Medicine and Health care
5G: Underlying Technology

5G Radio Standard: NR (New Radio)

- Millimeter Wave
- Massive MIMO
- Small Cells (Extended from 4G)
- LDPC & Polar Codes
- Full Duplex
- F-OFDM
5G: Underlying Technology

5G Radio Standard: NR (New Radio)

- Millimeter Wave
- Massive MIMO
- Small Cells (Extended from 4G)
- LDPC & Polar Codes
- Full Duplex
- F-OFDM
Millimeter Wave Technology

Huge bandwidth available at millimeter wave frequencies

Currently we operate here

> 14 GHz of Unlicensed Spectrum
For WiFi 802.11ad
Millimeter Waves Suffer from Large Attenuation

\[ \text{O}_2 \text{ Absorption at 60GHz} \]
Small Wavelength enables thousands of antennas to be packed into small space

→ Extremely narrow beams

Millimeter Waves Suffer from Large Attenuation

**mmWave radios use phased antenna arrays to focus the power along one direction**
Antenna Arrays

\[
d_1 = d_0 - s \cos \theta
\]

\[
h_0 = \alpha e^{-j2\pi \frac{d_0}{\lambda}} = \alpha e^{-j\phi_0}
\]

\[
h_1 = \alpha e^{-j2\pi \frac{d_1}{\lambda}} = \alpha e^{-j2\pi \frac{d_0 - s \cos \theta}{\lambda}}
\]

\[
h_k = \alpha e^{-j2\pi \frac{d_k}{\lambda}} = \alpha e^{-j2\pi \frac{d_0 - ks \cos \theta}{\lambda}}
\]

\[
s = \frac{\lambda}{2}
\]
\[ d_1 = d_0 - s \cos \theta \]

\[ h_0 = \alpha e^{-j2\pi \frac{d_0}{\lambda}} = \alpha e^{-j\phi_0} \]

\[ h_1 = \alpha e^{-j2\pi \frac{d_1}{\lambda}} = \alpha e^{-j2\pi \frac{d_0 - s \cos \theta}{\lambda}} = \alpha e^{-j\phi_0 + j\pi \cos \theta} \]

\[ h_k = \alpha e^{-j2\pi \frac{d_k}{\lambda}} = \alpha e^{-j2\pi \frac{d_0 - ks \cos \theta}{\lambda}} = \alpha e^{-j\phi_0 + j\pi k \cos \theta} \]
Antenna Arrays

\[ d_1 = d_0 - s \cos \theta \]

\[ y_k(t) = h_k x(t) \]

To receive from direction \( \theta \):

\[ y_\theta(t) = \sum y_k(t) e^{-j\pi k \cos \theta} \]

\[ h_k = \alpha e^{-j\phi_0 + j\pi k \cos \theta} \]
$d_1 = d_0 - s \cos \theta$

$y_k(t) = h_k x(t)$

$h_k = \alpha e^{-j\phi_0 + j\pi k \cos \theta}$

To receive from direction $\theta$:

$y_\theta(t) = \sum y_k(t) e^{-j\pi k \cos \theta} = \sum h_k x(t) e^{-j\pi k \cos \theta}$

$= \sum x(t) e^{-j\phi_0} = N x(t) e^{-j\phi_0}$

Increased Transmit/Receiver power along $\theta$ by $N$ times.
Antenna Arrays

\[ d_1 = d_0 - s \cos \theta \]

\[ s = \frac{\lambda}{2} \]

Increased Transmit/Receiver power along \( \theta \) by N times.

To receive from direction \( \theta \):
\[
y_\theta(t) = \sum y_k(t) e^{-j\pi k \cos \theta}
\]

To transmit along direction \( \theta \):
\[
x_k(t) = x(t) e^{-j\pi k \cos \theta}
\]
Millimeter Wave Phased Arrays

- Small Wavelength at mmWave enables massive antenna arrays to be packed into small space
  - e.g. At 60 GHz, 1024 (32×32 ≈ 8cm×8cm)
  - Huge antenna gains
  - Very Narrow beams
  - Electronic Steering
Beamforming using Antenna Arrays

To receive from direction $\theta$:

$$ y_\theta(t) = \sum y_k(t) e^{-j\pi k \cos \theta} $$

Cannot have a TX/RX chain per antenna!

Cannot do digital beamforming
Beamforming using Antenna Arrays

To receive from direction $\theta$:

$$y_\theta(t) = \sum y_k(t)e^{-j\pi k \cos \theta}$$

Digital Beamforming

Analog Beamforming

Phase-Shifters
Millimeter Wave Uses Phased Arrays
Early Measurement of Millimeter Wave 5G Deployments

https://fivegophers.umn.edu/www20/

Figure 1: 5G coverage recorded at Minneapolis’s Commons Park. A color gradient from green to black indicates the percentage of observed 5G coverage (high to low respectively). We sampled 6.8 million data points to inform this visualization. Also indicated is a 5G mmWave base station.

Figure 5: TCP performance under LoS: throughput.

Figure 6: TCP performance under LoS: RTT.
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- Massive MIMO
Multi-User MIMO at < 6 GHz
More Antennas Multi-User MIMO at < 6 GHz
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Argos: World’s first Massive MIMO Testbed (2011)
Differences between Massive MIMO & Millimeter Wave

A. mmWave operates > 24GHz vs. Massive MIMO < 6 GHz

B. mmWave supports higher bandwidth → higher data rates

C. Massive MIMO has 1 TX/RX per antenna whereas mmWave has 1 TX/RX for all antennas

D. Massive MIMO can transmit/receive to multiple users at the same time where mmWave (no MIMO) can transmit/receiver from only 1 user at a time.
Opinion of this Class

A. I really enjoyed this class and learned a lot.

B. I only enjoyed the last part but not the first part.

C. I learned new stuff but did not enjoy the class.

D. This class is not at all what I expected. I did not like it.
In this Class

1. Components of Wireless Transmitter & Receiver
2. Modulation
3. Wireless Channel
4. OFDM
5. IoT
6. WiFi
7. 5G Cellular Networks