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

Lecture 1: Introduction Wireless Communications
Haitham Hassanieh
Class Logistics

**Time & Location:** 1 week, 2pm China time on Zoom

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Class Logistics

http://haitham.ece.illinois.edu/WirelessSU20/

• Series of 6 lectures
  • 2 hours each.
• TA office hours every day
• Ask questions!
• Final take home quiz
  • Should take around 2 hours to complete
  • Have 24 hours time to complete and upload
• Quiz will be mostly multiple choice and True/False questions + some short problems to solve
## Class Logistics

http://haitham.ece.illinois.edu/WirelessSU20/

All times and dates are listed in China standard time.

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<th>Lectures</th>
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<tr>
<td>1</td>
<td>Sun. Jul. 19</td>
<td>2:00 pm - 4:00 pm</td>
<td>[Vocabulary]</td>
<td>Lee 1. Introduction:</td>
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<td>[Slides]</td>
<td>• Overview &amp; Logistics</td>
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<td>• Wireless Spectrum</td>
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<td>9:00 pm - 10:00 pm</td>
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<td>• Pulse Shaping &amp; Matched Filter.</td>
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<td>2</td>
<td>Mon. Jul. 20</td>
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<td>Lee 2. Modulation:</td>
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<td>• Coherent &amp; Non-coherent modulation</td>
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<td>• BPSK, DBPSK, ASK, FSK</td>
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<td>• PSK, QAM</td>
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<td>• Maximum Likelihood, BER vs. SNR</td>
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<td>Mon. Jul. 20</td>
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<td>3</td>
<td>Tues. Jul. 21</td>
<td>2:00 pm - 4:00 pm</td>
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<td>Lee 3. Wireless Channel:</td>
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<td>• Frame Synchronization</td>
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<td>4</td>
<td>Wed. Jul. 22</td>
<td>2:00 pm - 4:00 pm</td>
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<td>Lee 4. OFDM:</td>
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<td>• Orthogonal Frequency Division Multiplexing</td>
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<td>• Frame Synchronization</td>
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<td>• Packet Detection</td>
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<td>Thurs. Jul. 23</td>
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<td>Lee 5. Internet of Things (IoT):</td>
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<td>• Bluetooth, FHSS, DSSS</td>
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<td>6</td>
<td>Fri. Jul. 24</td>
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<td>Lee 6. 5G &amp; WiFi 6:</td>
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<td>• Millimeter wave communication</td>
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<td>• WiFi 6 Background</td>
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<td>10</td>
<td>Sat. Jul. 26</td>
<td>2:00 pm - 1:59 pm</td>
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<td>Take home exam (24hrs)</td>
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Do you own a smartphone?

- Yes
- No
Increasing Demand for Wireless Connectivity
Wireless Networks Increasingly Prevalent

- **Wireless Homes**
- **Wireless Biomedical Implants**
- **Wireless Wearables**
- **Cellular Networks**
- **Wireless Sensors**
- **UAVs**
- **Wireless Data Centers**
- **Wireless VR**
- **Wireless Vehicles**
Increasing Demand for Wireless Connectivity

2020

- 4 BILLION Connected People
- $4 TRILLION Revenue Opportunity
- 25+ MILLION Apps
- 25+ BILLION Embedded and Intelligent Systems
- 50 TRILLION GBs of Data

Source: Mario Morales, IDC
Mobile Technologies from 1G to 5G

**1G**
- **Year:** Early 90s
- **Standards:** AMPS, TACS
- **Technology:** Analog
- **Bandwidth:** –
- **Data rates:** –

**2G**
- **Year:** 1991
- **Standards:** GSM, GPRS, EDGE
- **Technology:** Digital
- **Bandwidth:** Narrow Band
- **Data rates:** < 80 - 130 Kbit/s

**3G**
- **Year:** 2001
- **Standards:** UMTS / WCDMA
- **Technology:** Digital
- **Bandwidth:** Broad Band
- **Data rates:** up to 3 Mbps

**4G**
- **Year:** 2010
- **Standards:** LTE, LTE Advanced
- **Technology:** Digital
- **Bandwidth:** Mobile Broad Band
- **Data rates:** >500 Kbit/s

**5G**
- **Year:** 2020-2030
- **Technology:** Digital
- **Bandwidth:** Ubiquitous connectivity
- **Data rates:** Fiber-like experience

1 hr HD movie in 6 seconds

**People & Things**

- **5G is about Communication, Storage, Processing…**
- **Connected house**
  - Traffic priority
  - Domotics
- **eHealth**
- **Entertainment**
  - Apps beyond imagination
- **Smart Car**
  - Car-to-car communication
- **Smart grids**

**5G Applications**
- Audio/visual
- Body/brain
- Cloud computing
- E-health
- Gaming
- IoT
- Security
- Technology

**People**

- 5G
- People & Things
WiFi Standards from WiFi 1 to WiFi 5

- 802.11a (1999)
  - 54 Mbps

- 802.11b (1999)
  - 11 Mbps

- 802.11g (2003)
  - 54 Mbps

- 802.11n (2009)
  - 450 Mbps

- 802.11ac Wave 1 (2014)
  - 1.3 Gbps

- 802.11ac Wave 2 (2015)
  - Up to 3.4 Gbps
WiFi Standards from WiFi 1 to WiFi 5

11AX
THE PATH TO TRULY BRILLIANT WI-FI

11b 1999
11a/g 2003
11n 2009
11ac 2013
11ax 2019

4x BETTER IN DENSE ENVIRONMENTS
Improve average throughput per user by at least four times in dense or congested environments

FASTER THROUGHPUT
Deliver up to 40 percent higher peak data rates for a single client device

INCREASE NETWORK EFFICIENCY
By more than four times

EXTEND BATTERY LIFE
Of client devices
WiFi 6 & 5G Complement Each Other
IoT Technologies

- **WiFi**
- **Bluetooth**
- **NFC**
- **RFID**
- **Cellular**

- **ZigBee**
- **Z-Wave**

Applications and use cases:
- **Energy Conservation**
- **Home Entertainment Control**
- **Remote Home Management and Monitoring**
- **Safety & Security**
- **Comfort and Convenience**
Different Applications

- Need different data rates
- Have different power budget
- Require different form factor
- Require different mobility range
- Demand the use of different channel
- Have different cost limitations

Different Wireless Communication Technologies
Wireless Communication System

In this class:

• Learn the design of a basic principles of a wireless communication transceiver.
• Cover Some advanced topics: OFDM, CSS, BLE, ...
• Cover Emerging Technologies: 5G, WiFi 6, IoT
This Lecture:

- Class Logistics
- Introduction to Wireless Communications
  - Wireless Spectrum
  - Transmitter & Receiver System Components
  - Review of Fourier Transforms & Trigonometric Identities
  - Up Conversion & Down Conversion
Which of the following concepts are your already familiar with?

A. Digital Modulation (BPSK, QAM, ...)
B. Nyquist Sampling Rate
C. Convolution
D. Low Pass Filter
The Wireless Spectrum
Wireless Communication System

Bits-to-Symbols Mapper

Modulation (Encoding)

Modulation: Mapping of Bits to Symbols

BPSK: 1 bits/symbol

1 0

-1 +1
Wireless Communication System

1011010110011001 → TX → RX → 1011010110011001

Digital Input → Bits-to-Symbols Mapper → Bits

Modulation (Encoding)

Modulation: Mapping of Bits to Symbols

PAM: 2 bits/symbol

11 → −3
10 → −1
00 → +1
01 → +3
Wireless Communication System

1011010110011001

Digital Input

TX

1011010110011001

Digital Output

RX

Bits

Bits-to-Symbols Mapper

Modulation (Encoding)

Modulation: Mapping of Bits to Symbols

16-QAM: 4 bits/symbol

Complex Symbols!
Wireless Communication System

Bits-to-Symbols Mapper

Modulation (Encoding)

Bits

Pulse Shaping: Takes modulated symbol values and creates a smooth digital signal
Wireless Communication System

1011010110011001

Digital Input

TX

1011010110011001

Digital Output

RX

Bits

Bits-to-Symbols Mapper
Modulation (Encoding)

Pulse Shaping

DAC

DAC: Digital-to-Analog Converter: Takes digital signal values and outputs analog signal i.e. current/voltage on the circuit.
Wireless Communication System

1011010110011001

Digital Input

TX

1011010110011001

Digital Output

RX

Bits-to-Symbols Mapper

Modulation (Encoding)

Bits

Pulse Shaping

DAC

LPF

LPF: Low Pass Filter
Removes High Frequency Signals

Frequency
Wireless Communication System

Digital Input

1011010110011001

TX

Bits-to-Symbols Mapper
Modulation (Encoding)

Bits

Pulse Shaping

DAC

LPF

Mixer
PLL

RX

1011010110011001

Digital Output

Mixer/PLL: Move signal to desired frequency of operation
Wireless Communication System

Bits-to-Symbols Mapper

Modulation (Encoding)

BPF: Band Pass Filter
Removes Frequency Signals outside desired frequency of operation
Wireless Communication System

Bits-to-Symbols Mapper
Modulation (Encoding)

Bits

TX

Pulse Shaping

DAC

LPF

Mixer

BPF

PLL

Antenna

RX

Digital Input

1011010110011001

Digital Output

1011010110011001
Wireless Communication System

Digital Input \[\begin{array}{c}
1011010110011001
\end{array}\] \rightarrow TX \rightarrow RX \rightarrow Digital Output

\[\begin{array}{c}
1011010110011001
\end{array}\]

LNA

Low Noise Amplifier: Amplify signal power with minimal noise
Wireless Communication System

TX

Digital Input

RX

Digital Output

1011010110011001

1011010110011001

Digital Input

LNA

BPF

Mixer

PLL

LPF

Digital Output
Wireless Communication System

Digital Input → TX → Y → RX → Digital Output

Digital Input: 1011010110011001
Digital Output: 1011010110011001

ADC: Analog-to-Digital Converter: Takes analog signal and digitizes it, i.e. samples and quantizes the signal values.
Pace and Difficulty so Far

A. Too Fast & Too Hard
B. Too Fast & Not Too Hard
C. Good Speed & Too Hard
D. Good Speed & Not Too Hard
This Lecture:

✓ Class Logistics
✓ Introduction to Wireless Communications
✓ Wireless Spectrum
✓ Transmitter & Receiver System Components
❑ Review of Fourier Transforms & Trigonometric Identities
❑ Up Conversion & Down Conversion
Trigonometric Identities

\[ \cos^2(f) = \frac{1 + \cos(2f)}{2} \]

\[ \sin^2(f) = \frac{1 - \cos(2f)}{2} \]

\[ \cos(f) \sin(f) = \frac{\sin(2f)}{2} \]
Fourier Transform

\[ s(t) \rightarrow S(f) = \mathcal{F}\{s(t)\} = \int s(t)e^{-j2\pi tf} \, dt \]

\[ S(f) \rightarrow s(t) = \mathcal{F}^{-1}\{S(f)\} = \int S(f)e^{j2\pi tf} \, df \]
Fourier Transform

\[ s(t) = \Pi \left( \frac{t}{T} \right) \]

\[ S(f) = T \text{sinc}(\pi Tf) \]

\[ \text{sinc}(x) = \frac{\sin(x)}{x} \]
Unit Impulse

Pulse function: $\delta(t - a)$
Fourier Transform

\[ s(t) = \cos(2\pi f_c t) \quad \Rightarrow \quad S(f) = \frac{1}{2} \delta(f - f_c) + \frac{1}{2} \delta(f + f_c) \]

\[ s(t) = \sin(2\pi f_c t) \quad \Rightarrow \quad S(f) = \frac{1}{2} \delta(f - f_c) - \frac{1}{2} \delta(f + f_c) \]

\[ s(t) = e^{-j2\pi f_c t} \quad \Rightarrow \quad S(f) = \delta(f - f_c) \]

\[ s(t) = \delta(t - a) \quad \Rightarrow \quad S(f) = e^{-j2\pi fa} \]
Convolutions

\[ s(t) * h(t) = \int_{-\infty}^{+\infty} s(\tau)h(t - \tau)d\tau \]

\[ s[n] * h[n] = \sum_{-\infty}^{\infty} s[m]h[n - m] \]

\[ s(t) * \delta(t - a) = s(t - a) \]

Convolution in Time is equivalent to Multiplication in Frequency & vice versa

\[ s(t) * h(t) \rightarrow S(f) \times H(f) \]

\[ s(t) \times h(t) \rightarrow S(f) * H(f) \]
This Lecture:

✓ Class Logistics
✓ Introduction to Wireless Communications
✓ Wireless Spectrum
✓ Transmitter & Receiver System Components
✓ Review of Fourier Transforms & Trigonometric Identities

⚠ Up Conversion & Down Conversion
Wireless Communication System

1011010110011001

TX

Bits-

to-

Symbols

Mapper

Modulation
(Encoding)

Pulse

Shaping

DAC

LPF

Mixer

BPF

PA

PLL

Channel

Equalization
&

Synchronization

ADC

Demodulation
(Decoding)

RX

Symbols-

to-

Bits

Mapper
Wireless Communication System

Bits - to - Symbols Mapper

Modulation (Encoding)

Pulse Shaping

DAC

LPF

Mixer

BPF

PA

Bits - to - Symbols Mapper

Symbols-to-Bits Mapper

Channel Equalization & Synchronization

Demodulation (Decoding)
Up/Down Conversion

Transmitter
Up-conversion

Receiver
Down-conversion

Baseband

Passband
Why do we need to up/down conversion?
Up/Down Conversion

Why do we need to up/down conversion?
Why do we need to up/down conversion?

Why not transmit everything at lower frequencies?

- Not enough bandwidth:
  - Data rate $\propto$ bandwidth
  - Different Technologies
- Antenna size $\propto$ wavelength
The Wireless Spectrum

- **Auctioned spectrum**
- **Broadcast TV Channels 2-13**
- **Garage door openers**
- **Cell phones**
- **Wireless medical telemetry**
- **Cell phones**
- **2.4 GHz band**
  - Used by more than 300 consumer devices, including microwave ovens, cordless phones and wireless networks (Wi-Fi and Bluetooth)
- **Satellite TV**
- **Security alarms**

**PERMEABLE ZONE**
- Frequencies in this range are considered more valuable because they can penetrate dense objects, such as a building made out of concrete

**SEMI-PERMEABLE ZONE**
- Difficult for signals to penetrate dense objects

**LINE-OF-SIGHT ZONES**
- Signals in this zone can travel long distances, but could be blocked by trees and other objects

**Signals in this zone can only be sent short, unobstructed distances**

- **AM radio 535 kHz to 1,700 kHz**
- **Remote-controlled toys**
- **Broadcast TV UHF channels 14-63**
- **GPS (Global positioning systems)**
- **Satellite radio**
- **Weather radar**
- **Cable TV satellite transmissions**
- **Highway toll tags**
- **Police radar**
Why do we need to up/down conversion?

- Cannot transmit everything at low frequencies.
- Why not transmit & receive directly at high frequency?

Nyquist!
Nyquist Theorem

To recover the signal properly, we need to sample at twice the highest frequency, i.e. $2f_{\max}$

- **Baseband**
  - Sample at $2B$
  - E.g. WiFi 802.11b $\approx 40$ MS/s

- **Passband**
  - Sample at $2f_c + B$
  - E.g. WiFi 802.11b $\approx 5$ GS/s
Up/Down Conversion

**Transmitter**

- **Up-conversion**
  - LPF
  - PLL
  - Mixer
  - BPF

**Receiver**

- **Down-conversion**
  - BPF
  - PLL
  - Mixer
  - LPF

---

**How to we do up/down conversion?**

\[
s(t) \rightarrow \times \rightarrow s(t) \cos(2\pi f_c t)
\]

- **PLL (Phased Lock Loop):** create the cosine wave signal \(\cos(2\pi f_c t)\)
- **Mixer:** multiples the two signals
Up/Down Conversion

Transmitter
Up-conversion

Receiver
Down-conversion

How to we do up/down conversion?

\[ s(t) \rightarrow \times \rightarrow s(t) \cos(2\pi f_c t) \rightarrow \times \rightarrow s(t) \cos^2(2\pi f_c t) \]

\[ s(t) \cos^2(2\pi f_c t) = s(t) \left( \frac{1}{2} + \frac{1}{2} \cos(2\pi 2f_c t) \right) \]
How to we do up/down conversion?

\[ s(t) \longleftrightarrow \times \longleftrightarrow s(t) \cos(2\pi f_c t) \longleftrightarrow \times \longleftrightarrow s(t) \cos^2(2\pi f_c t) \]

\[ s(t) \cos^2(2\pi f_c t) = s(t) \left( \frac{1}{2} + \frac{1}{2} \cos(2\pi f_c t) \right) = \frac{1}{2} s(t) \]
Up/Down Conversion

\[ s(t) \times \cos(2\pi f_c t) \times \cos(2\pi f_c t) \]
Up/Down Conversion

\[ s(t) \times \cos(2\pi f_c t) \rightarrow \times \rightarrow s(t) \cos^2(2\pi f_c t) \]

Consider using PAM: Pulse Amplitude Modulation

4 PAM:
2 bits/symbol

\[ s(t) \text{ is real } \Rightarrow S(f) \text{ is symmetric around } 0 \]
Up/Down Conversion

\[ s(t) \rightarrow \times \rightarrow s(t) \cos(2\pi f_c t) \rightarrow \times \rightarrow s(t) \cos^2(2\pi f_c t) \]

\[ \cos(2\pi f_c t) \]

\[ S(f) \]

\[ \frac{1}{2} \delta(f - f_c) + \frac{1}{2} \delta(f + f_c) \]

\[ -f_c \rightarrow 0 \rightarrow f_c \]

\[ \frac{1}{2} S(f - f_c) + \frac{1}{2} S(f + f_c) \]

\[ -f_c \rightarrow 0 \rightarrow f_c \]
Up/Down Conversion

\[ s(t) \rightarrow \times \rightarrow s(t) \cos(2\pi f_c t) \rightarrow \times \rightarrow s(t) \cos^2(2\pi f_c t) \]

\[ \cos(2\pi f_c t) \]

\[ s(t) \rightarrow \times \rightarrow \frac{1}{2} S(f - f_c) + \frac{1}{2} S(f + f_c) \]

\[ \frac{1}{2} \delta(f - f_c) + \frac{1}{2} \delta(f + f_c) \]

\[ \rightarrow \ast \rightarrow \]

\[ \frac{1}{4} S(f - 2f_c) + \frac{1}{4} S(f) + \frac{1}{4} S(f) + \frac{1}{4} S(f + 2f_c) \]
Up/Down Conversion

\[ s(t) \rightarrow \times \rightarrow s(t) \cos(2\pi f_c t) \rightarrow \times \rightarrow s(t) \cos^2(2\pi f_c t) \]

\[ \cos(2\pi f_c t) \rightarrow \times \rightarrow \cos(2\pi f_c t) \]

\[
\begin{align*}
\frac{1}{2} & S(f - f_c) + \frac{1}{2} S(f + f_c) \\
\frac{1}{2} & \delta(f - f_c) + \frac{1}{2} \delta(f + f_c) \\
\frac{1}{4} & S(f - 2f_c) + \frac{1}{4} S(f + 2f_c) + \frac{1}{2} S(f)
\end{align*}
\]
Up/Down Conversion

\[ s(t) \rightarrow \times \rightarrow s(t) \cos(2\pi f_c t) \rightarrow \times \rightarrow s(t) \cos^2(2\pi f_c t) \]

\[ \cos(2\pi f_c t) \]

\[ \frac{1}{2} S(f - f_c) + \frac{1}{2} S(f + f_c) \]

\[ \frac{1}{2} \delta(f - f_c) + \frac{1}{2} \delta(f + f_c) \]

\[ \frac{1}{4} S(f - 2f_c) + \frac{1}{4} S(f + 2f_c) + \frac{1}{2} S(f) \]

Low Pass Filter

\[ -2f_c \quad -f_c \quad 0 \quad f_c \quad 2f_c \]
Is Up & Down conversion clear so far?

- Yes
- No
List of Mathematical Terms That Appeared in the Lecture

- \( f_c \): Carrier Frequency
- \( B \): Signal Bandwidth
- \( s(t) \): Baseband Signal
- \( S(f) \): Frequency Spectrum of Baseband Signal
- \( \delta(f) \): Impulse Function
- \( \ast \): Convolution Operator
- \( n \): Symbol index at TX
- \( x(t) \): Baseband Signal
- \( \Pi(\_\_) \): Rectangle Function
- \( \text{sinc}(\_\_) \): Sinc Function
- \( (\_\_\_\_)^* \): Complex Conjugate
- \( |\_\_\_| \): Magnitude
- \( \mathcal{F}\{\_\_\_\_\_\_\} \): Fourier Transform
- \( \mathcal{F}^{-1}\{\_\_\_\_\_\} \): Inverse Fourier Transform