PHY FUNDAMENTALS I

Co dulation

Overview

1. Frequency, Wavelength, Amplitude, and Phase
2. Electromagnetic Spectrum
3. Time and Frequency Domains
4. Decibels
5. Coding and mo
6. Channel Capaci on's Theorems)
7. Hamming Distance and Error
8. Multiple Access Methods (TDMA, FDMA, CDMA)
9. Spread Spectrum (Frequency Hopping and Direct Sequence)
10. Doppler Shift, Doppler Spread, Coherence Time
11. Duplexing

Frequency, Period, and Phase

- A Sin(2pft + ɸ), A = Amplitude, f=Frequency,
  ɸ = Phase, Period T = 1/f,
  Frequency is measured in Cycles/sec or **Hertz**

Amplitude = 0.5

Cycle

Phase = 45°

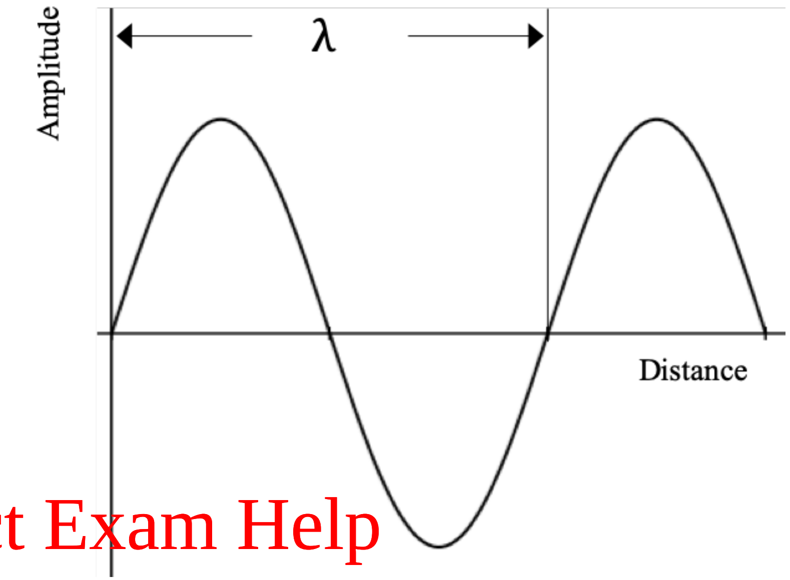
Phase and Amplitude: 2D Representation

- Sine wave with a phase of 45°

$$
\begin{aligned}
\sin(2\pi ft + \frac{\pi}{4}) &= \sin(2\pi ft)\cos(\frac{\pi}{4}) + \cos(2\pi ft)\sin(\frac{\pi}{4}) \\
&= \frac{1}{\sqrt{2}}\sin(2\pi ft) + \frac{1}{\sqrt{2}}\cos(2\pi ft)
\end{aligned}
$$

In-phase component I + Quadrature component Q

Wavelength



- Distance occupied by one cycle

- Distance between [illegible]nding phase in two consecutive cycle

- Wavelength = λ
- Assuming signal velocity v
  - $\lambda = vT$
  - $\lambda f = v$
  - $c = 3 \times 10^8$ m/s (speed of light in free space) = *300 m/µs*

Example: converting frequency to wavelength

- Frequency = 2.5 GHz

Example: converting wavelength to frequency

- Wavelength = λ = 5 mm

Frequency = f = c/λ

= $(3 \times 10^{8}$ m/s) / $(5 \times 10^{-3}$ m)

60

Well-known frequencies & wavelengths

- The higher the frequency, the smaller the wavelength
- 900 MHz has a wavelength of 33.33 cm

- 2.4 GHz has a wa

- 60 Ghz has a wav is technology is called *millimeter wave or mmWa*

Time and Frequency Domains

Electromagnetic Spectrum

- Wireless transmissions use the airwaves
  - Airwaves are radio frequencies
- Useful frequencies constitute the Spectrum

- Spectrum is ‘vir
  - We cannot t

- A gift from nature (the force f

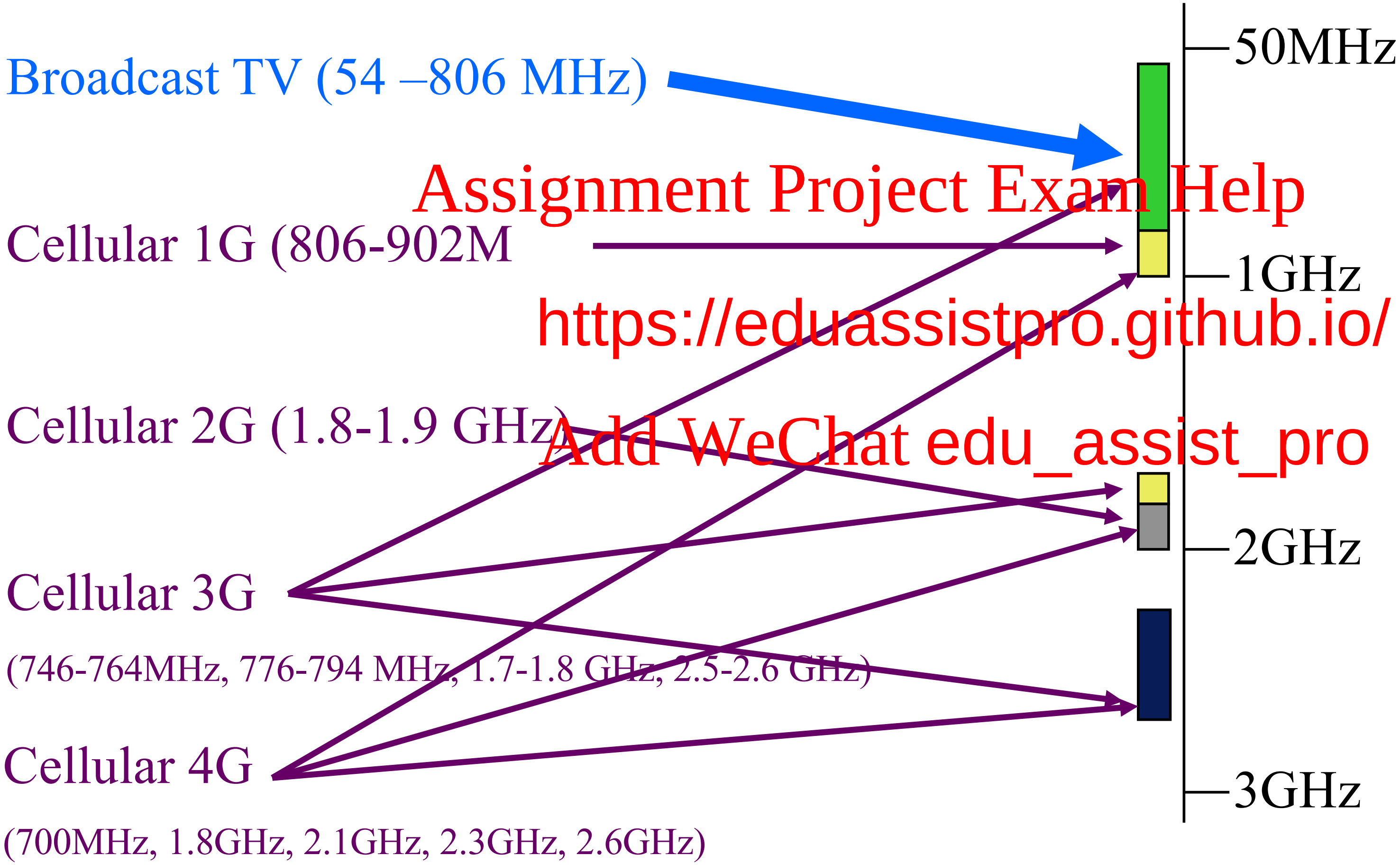
  - Has been there ever since e eated
- A (limited) natural resource

Electromagnetic Spectrum

Wireless

- Wireless communication mostly uses 100 kHz to 6 GHz
- > 6 GHz are currently being explored and 60 GHz is used in some latest WiFi products

Spectrum use by TV and cellular services



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Spectrum regulation and licensing

- Many users use the same airspace
  - Recipe for collision
  - No one would get anything useful done
- Spectrum use is
  - By govt. auth A)
- Spectrum is often licensed
  - By big companies, eg Telstra
  - Gives exclusive rights to certain freq. bands
  - Interference avoidance by regulation

Spectrum allocation

- Bulk of it reserved for government use
  - Scientific exploration
  - Public safety
  - Military
- Some for com
  - TV broadcast
  - Mobile phone
- Some for free-to-use
  - High-speed wireless local area network (WiFi)
  - Cordless phone handsets at home
  - Can you name a few more?

Key principles of spectrum allocation

- Maximize spectrum utilization
- Spectrum made available to new technologies and services

  - Adapt to ne

- Fair licensing

- Promote competition
- Ensure spectrum availability for public safety, health, defense, scientific experiments…

Free/unregulated/license-exempt spectrum

- Not subject to license
- Has rules for products (eg *power limitation*)
- More frequencies are being released as license-exempt
- Some current li s
  - 900 MHz
  - 2.4 GHz ISM band (WiFi, Micro
  - 5.2/5.3/5.8 GHz (WiFi, Cordless phone etc.)
  - Can you identify more?

Decibel

- Tx_power for practical mobile systems vary by many orders of magnitude
  - 100kW or kilowatt (FM radio station)
  - 500mW or milliwatt (cellular phone tx power)
  - 2.5mW (Bluetooth with ~10m range)
  - 100pW or picowatt
  - Femto watt? (nano
  - 1 W = 10^3 mW = 10^6 µW = 10^9 nW = 10^{12}
- Decibel is a more convenient (logarit it to compare these powers, which are many orders of magnitude apart
- Also path loss (attenuation) can be many orders of magnitude
  - Path loss therefore is usually expressed in decibels

Decibel (dB) Formula

- In Honour of Graham Bell
- The number of decibels is ten times the logarithm to base 10 of the ratio of two power quantities (dB = $10\log_{10}(P_1/P_2)$)

  - The quantity "Be ... ot used

- Decibel can be used

  1. Path Loss: To express path loss or ... $_1$ = transmit power; P_2 = receive power]

  2. SNR: To express signal (P_1) to noise (P_2) ratio at the receiver
  3. Signal Power: To express signal power (P_1), which can be either transmit or receive power, to a reference power (P_2)

Decibel Examples for Path Loss

- **Example 1**: $P_t = 10$ mW, $P_r = 5$ mW (power reduced by half)
  Attenuation (path loss) = $10 \log_{10} (10/5) = 10 \log_{10} 2 = 3$ dB

- **Example 2**: $P_t = 100$ mW, $P_r = 1$ mW (power reduced by a factor of 100)
  Attenuation = $10 \log_{10} (100/1) = 10 \log_{10} 100 = 20$ dB

Power Ratio	
10,000,000,000 (ten billion tim	10 x 10)
1,000,000 (1 million times)	60 (10 x 6)
10 (ten times)	10 (10 x 1)
0.001 (10^{-3})	-30 (10 x -3)
0.0001 (10^{-4})	-40 (10 x -4)

Decibel Examples for Signal-to-Noise Ratio

- **Example 1**: P_{signal} = 1 mW (received signal strength), P_{noise}= 100 μW

  $SNR = 10 \log_{10} (1000/100) = 10 \log_{10} 10 = 10$ dB

- **Example 2**: Received signal strength is measured at 10 mW. What is the noise power if SNR

  $SNR = 10 \text{ dB} = 10 \log_{10} (10\text{mW}/P_{noise})$

P_{noise} = 1 mW

Expressing Power in dBm

- dBm is in reference to 1 milliwatt
- First, express power in milliwatt
- Then apply the following formula to obtain dBm

Power in dBm = 10 log (power in milliwatt)

Conversion to dBW

- dBW is in reference to 1 watt
- First express power in watt
- Then apply the tain dBW

Power in dBW = 10 log (power in watt)

Relationship between dBm & dBW

- Note that 1 W = 1000 mW
- This gives us following relationship
  - Note log(a

$$\text{dBm} = \text{dBW} + 30$$

If you've calculated a power in dBW, you can simply derive the equivalent dBm by adding 30 to dBW, and vice versa.

Examples for converting Watt to dBm/dBW

- Example 1: Express 1 mW power in units of dBm

$$10 \log (1) = 1 \quad \text{Bm}$$

So, ZERO dBm does not mean there is no power !

Example (2)

- Example 2: Express 50 W in
  - (a) dBW
  - (b) dBm

(a) P(dBW) = 10 log (5 … BW

(b) P(dBm) = 10 log (50x1000) dBm

= 10 log (50) + 10 log (1000) dBm

= 17 + 30 = 47 dBm

Coding Terminology

- **Symbol:** **the smallest element of a signal with a given amplitude, frequency, and phase that can be detected**

1 0

- **Modulation Rate**: = 1/symbol_duration = Baud rate (or symbol rate)

- **Data Rate**: Bits per second (bps

- A symbol may carry multi
  - A binary signal with only two different symbols would carry 1 bit per symbol (baud rate = data rate)
  - For an M-ary signal, data rate = baud rate x $\log_2(M)$

Modulation

- Digital version of modulation is called **keying**
  - **Amplitude Shift Keying (ASK)**
  - **Frequency Shift Keying (FSK)**
  - **Phase Shift Keying (PSK):** Binary PSK (BPSK)

Modulation (Cont)

- **Differential BPSK:** Does not require reference signal
- **Quadrature Phase Shift Keying (QPSK)**

QAM

- Quadrature Amplitude and Phase Modulation
- 4-QAM, 16-QAM, 64-QAM, 256-QAM, …
- Used in DSL and wireless networks
- Constellation diagram (shows combinations of amplitudes and phases)

- 4-QAM $\Rightarrow$ 2 bits/symbol, 16-QAM $\Rightarrow$ 4 bits/symbol, …

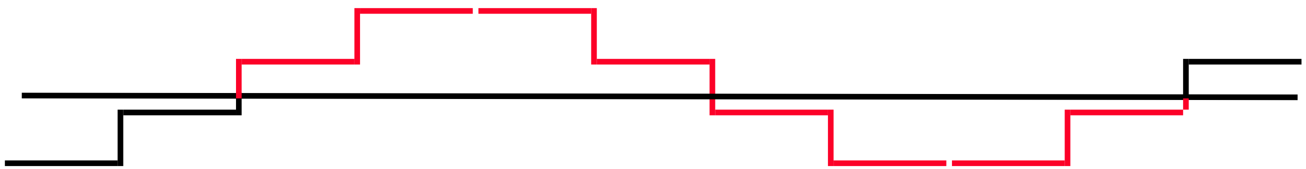
QAM in Action

Wireless Technology	QAM Supported
4G	256 QAM
5G	
WiFi 802.11n	16
WiFi5 802.11ac	256 QAM
WiFi6 802.11ax	1024 QAM

Channel Capacity

- Capacity = Maximum data rate (bps) for a channel
- **Nyquist Theorem (noiseless channel)**: Bandwidth = B Hz
  Baud rate $\leq$ 2 B
- Bi-level Encoding: Max. Data rate = 2 × Bandwidth

- Multilevel: Capacity = 2 × Bandwidth × log $_2$ M
  M = Number of levels



Example: M=4, Capacity = 4 × Bandwidth

Example

Assume that you have discovered a novel material that has negligible electrical noise. What is the maximum data rate that this material could achieve over a phone wire having a bandwidth of 3100 Hz if data was encoded with 64-QAM?

Solution

We have B= 3100 M =

Data rate $=2\times3100\times\log_2 64=37{,}200$ bps

Shannon's Theorem (noisy channel)

- Bandwidth = B Hz
  Signal-to-noise ratio = S/N
- Maximum number of bits/sec = B $\log_2$ (1+S/N) [error free communication]

- Example: Pho 3100 Hz

$$10 \log_{10} S$$

$$\log_{10} S/N = 3$$

$$S/N = 10^3 = 1000$$

$$\text{Capacity} = 3100 \log_2 (1+1000) = 30{,}894 \text{ bps}$$

Hamming Distance

- Hamming Distance between two sequences
  = Number of bits in which they disagree
- Example: 011011

Difference 101010 ⇒ 3

Error Correction Example

- 2-bit words transmitted as 5-bit/word

Data	**Codeword**
00	00000
01	00111
10	11001
11	

Received = 00100 ⇒ No ... ror

Distance (00100,00000) = 1 Distan ... 11) = 2

Distance (00100,11001) = 4 Distan ... 10) = 3

⇒ Most likely 00000 was sent. Corrected data = 00

b. Received = 01010 Distance(…,00000) = 2 = Distance(…,11110)

Error detected but cannot be corrected

c. Three-bit errors will not be detected. Sent 00000, Received 00111.

Multiple Access Methods

ess

(c g turns)

Code Division Multiple Access

(all communicating groups are talking at the same time)

Multiple Access

FDMA (frequency division multiple access)

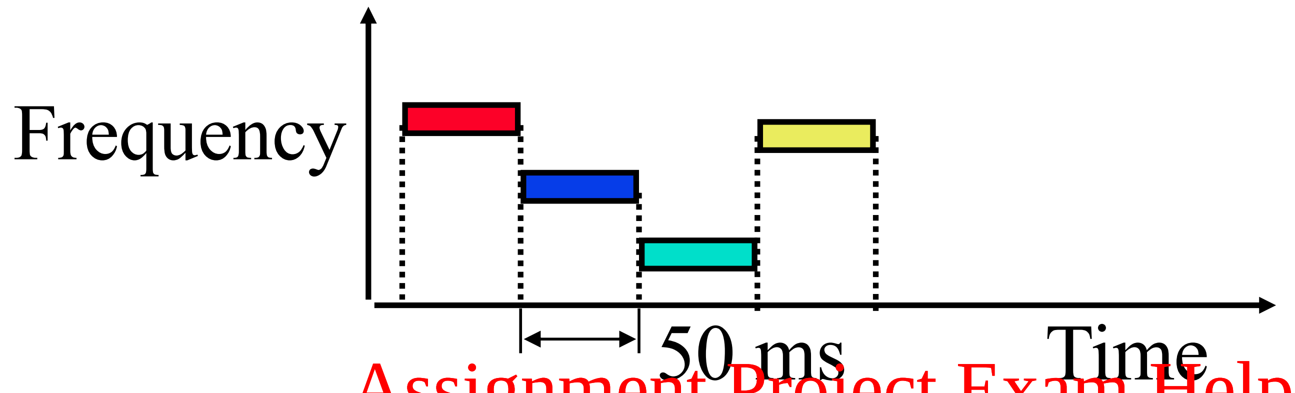
CDMA

- Each communicating group is using a different "code"
- You can understand a conversation only if you know the code used in that conversation

- Much like a *mult* ple from different languages are all code = language)

- Two popular coding methods for CDMA
  - Frequency hopping spread spectrum (FHSS)
  - Direct sequence spread spectrum (DSSS)

Frequency Hopping Spread Spectrum



- Transmit over a narr itch (hop) frequency over a wide spectrum

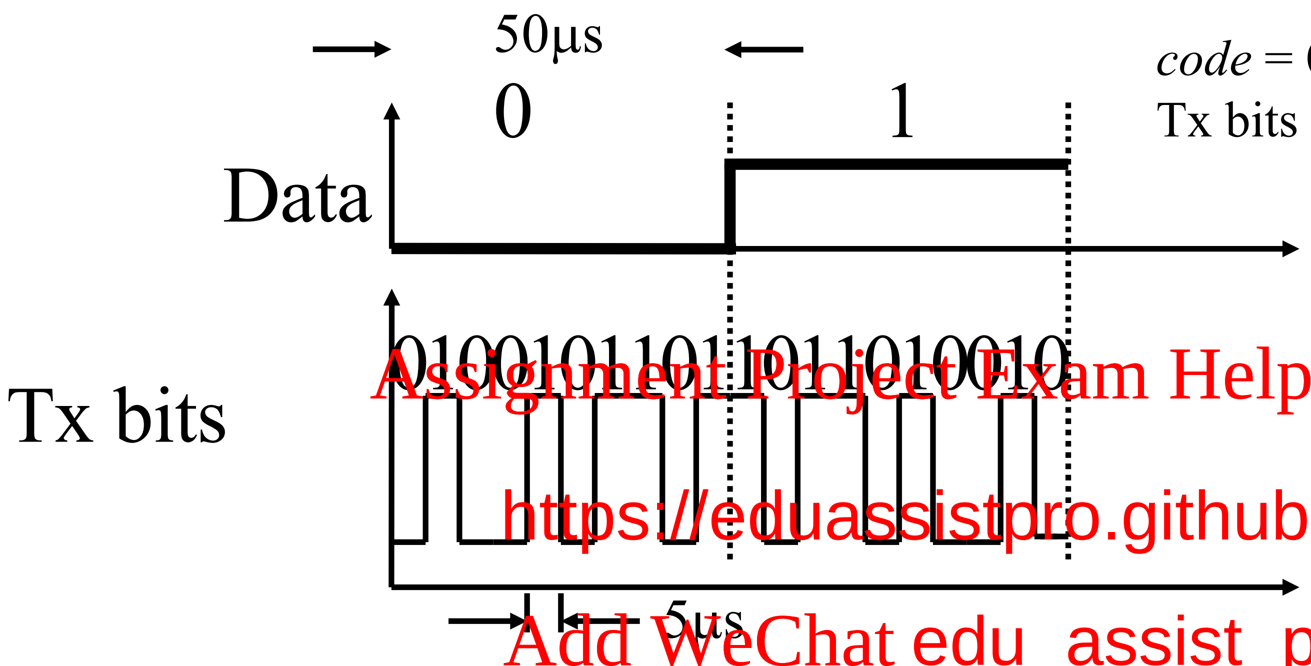
  - Spreads the transmission (power) o ctrum

    ⇒ Spread Spectrum
- Pseudo-random frequency hopping (both transmitter and receiver use the same pseud-random number sequence = code)
  - Developed initially for military
  - Patented by actress Hedy Lamarr (idea came while playing a piano; tone changes continuously)

FHSS Advantages and Disadvantages

- Advantages
  - Difficult to intercept (appears as random 'blips')
  - Narrowband interference can't jam
- Disadvantages
  - Requires increase mly hop between 1000 frequencies → 10
  - Both time and frequency synchroni

Direct-Sequence Spread Spectrum

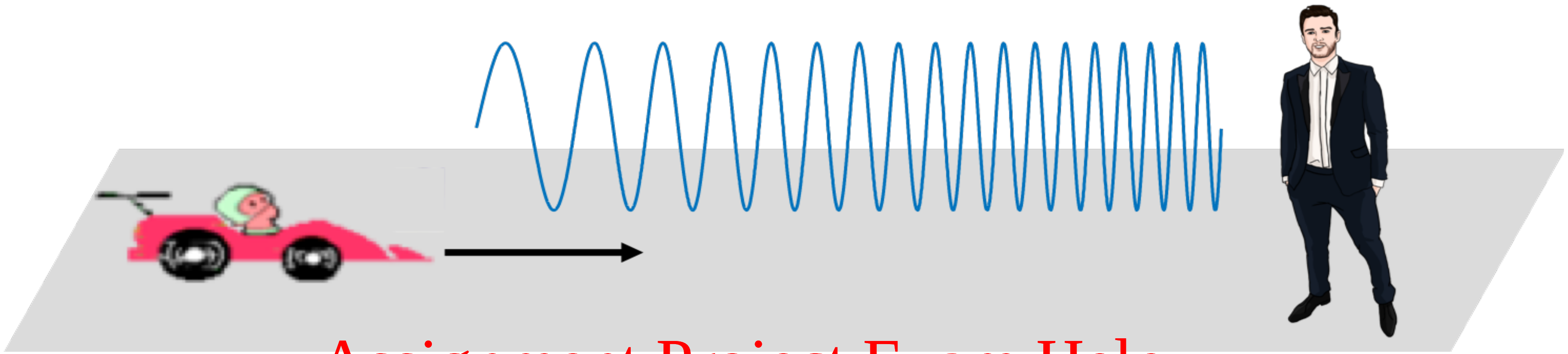


code = 0100101101

Tx bits = *data* **EXOR** *code*

- Many bits are transmitted for each data bit
- Spreading factor = Code bits/data bit, 10-100 commercial (Min 10 by FCC), 10,000 for military
- Signal bandwidth >10 × data bandwidth
- Code sequence synchronization
- Correlation between codes ⇒Interference (Orthogonal to avoid interference)

Doppler Shift



- If the transmitter or receiver or both are mobile the frequency of received signal
- Moving towards increases
- Moving away from each other ⇒ decreases

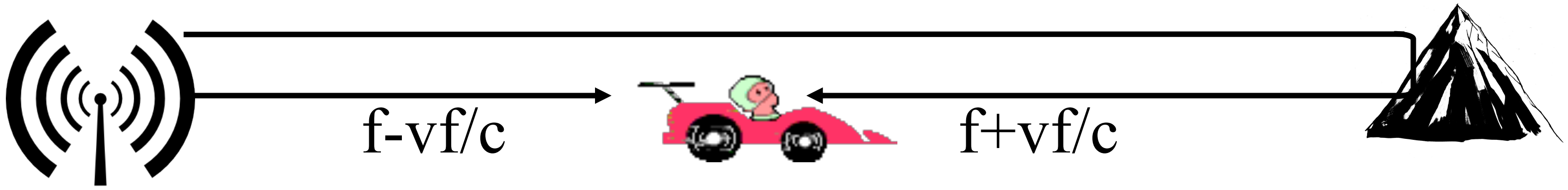
Frequency difference = velocity/Wavelength = v/λ = vf/c

Example: 2.4 GHz ⇒ $\lambda = 3\text{x}10^8/2.4\text{x}10^9 = 0.125\text{m}$

v = 120km/hr = 120x1000/3600 = 33.3 m/s

Freq diff (Doppler shift) = 33.3/0.125 = 267 Hz

Doppler Spread and Coherence Time



- Two rays will be tion)

- **Doppler Spread** hift
- They will add or cancel-out each s receiver moves

- **Coherence time**: Time during which the channel response is constant = 1/Doppler spread = $c/2vf = \lambda/2v$

Example

- What is the *coherence time* for a 2.4 GHz wifi link connecting a car travelling at 72 km/hr?

V=(72 x 1000)/3600 = 20 m/s

Doppler spread = $2vf$ = 320 Hz

Coherence time = 1/320 = 0.003125 s

Duplexing

- Duplex = Bi-Directional Communication
- Frequency division duplexing (FDD) (Full-Duplex)

Base — Frequency 1 → Subscriber

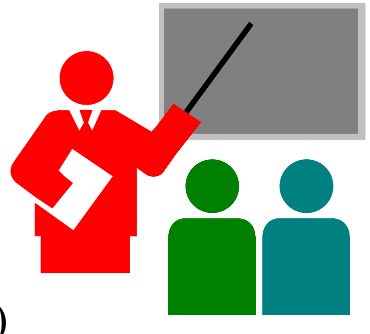
Base ← Frequency 2 — Subscriber

- Time division du

Base → ← → ← Subscriber

- Many LTE deployments will use TDD.
  - Allows more flexible sharing of DL/UL data rate
  - Does not require paired spectrum
  - Easy channel estimation $\Rightarrow$ Simpler transceiver design
  - Con: All neighboring BS should time synchronize

Summary



1. Electric, Radio, Light, X-Rays, are all electromagnetic waves
2. Wavelength and frequency are inversely proportional (wavelength = c/f)
3. Historically, wireless communications mostly used frequencies below 6 GHz, but beyond 6 GHz is actively explored in modern wireless networks.
4. Hertz and bit rate are related by Nyquist and Shannon's Theorems
5. Nyquist's theorem explains
6. Shannon's capacity takes S
7. By spreading the original si nd, spread spectrum can provide better immunity against interference and j allowing multiple parties to communicate over the same frequency at the sam
8. FHSS and DSSS are two fundamental methods of realizing spread spectrum
9. Doppler effect explains the shift in frequency experienced by mobile objects
10. Doppler spread is twice the Doppler shift
11. Channel coherence time is inversely proportional to doppler spread
12. FDD and TDD are two fundamental methods of resource allocation between the transmitter and the receiver so they both can exchange information with each other