**Note: We will start at 12:53 pm ET**



→

# 18-441/741: Computer Networks
# Lect yer IV



Swarun

# Physical Layer: Outline

- Digital networks
- Characterization of Communication Channels
- Fundame nsmission
- Line Codi
- Modems and Digital Mo
- Error Detection and Cor d.)
- Wired PHY 101
- Wireless PHY 101

# Recap: CRC = Polynomial Codes

- Do "Long Division" on (mod 2) polynomials
- Let i(x) ts in polynomial form
- Then:

$$
\begin{array}{r l}
 & \quad q(x) \\
g(x) \,\big) & \overline{x^{n-k} i(x)} \longrightarrow \\
 & \underline{\qquad\qquad} \\
 & \quad r(x) \longrightarrow
\end{array}
$$

Add

Codeword

$x^{n-k} i(x)$ + r(x)

# The *Pattern* in Polynomial Coding

- All codewords satisfy the following **pattern**:

in modular

$$b(x) = x^{n-k}i(x) + r(x) = q(x)g(x) + r(x) + r(x) = q(x)g(x)$$



- All codewor /

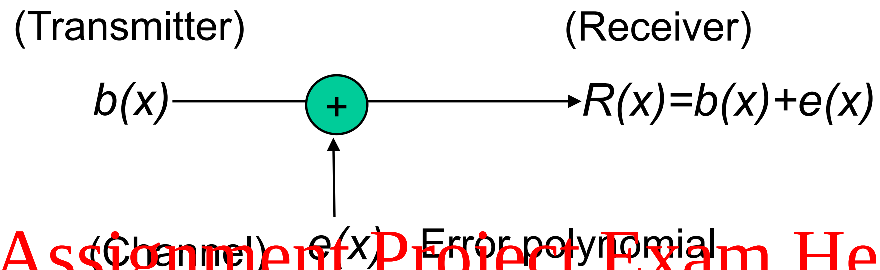


- Receiver should divide rec le by g(x) and check if remainder is



- If remainder is non-zero, then received n-tuple is not a codeword

# Undetectable error patterns






- $e(x)$ has 1's i here
- Receiver divi  $R(x)$ by $g(x)$
- Undetectable error: If $e(x)$ is a $(x)$, that is, $e(x)$ is a non-zero codeword, t 

$$R(x) = b(x) + e(x) = q(x)g(x) + q'(x)g(x)$$

- *The set of undetectable error polynomials is the set of nonzero code polynomials*
- *Choose the generator polynomial so that selected error patterns can be detected.*

# Designing good polynomial codes

- Select generator polynomial so that likely error patterns are not multiples of *g(x)*
- *Detecting Single Errors*

  - $e(x) = x^i$ for error in location *i+1*
  - If *g(x)* has  $x^i$
- *Detecting D*
  - $e(x) = x^i + x^j = x^i(x^{j-i}+1)$ where $j>i$

  - If *g(x)* has more than 1 term, it c
  - If g(x) is a *primitive* polynomial, it cannot divide $x^m+1$ for all $m<2^{n-k}-1$ (Need to keep codeword length less than $2^{n-k}-1$)
  - Primitive polynomials can be found by consulting coding theory books

# Standard Generator Polynomials

CRC = cyclic redundancy check

- CRC-8: $= x^8 + x^2 + x + 1$ ATM



- CRC-16:



- CCITT-16: $= x^{16} + x^{12} + x^5 + 1$ HDLC, XMODEM, V.41

- CCITT-32: IEEE 802, DoD, V.42

$$= x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x + 1$$

# Hamming Codes

- Class of *error-correcting* codes
- Capable of *or* patterns
- Provably o
- Very less redundancy, e. r proof – adds O(log n) bits of redundanc equences

# m=3 Hamming Code

- Information bits are $b_1$, $b_2$, $b_3$, $b_4$
- Equations for parity checks $b_5$, $b_6$, $b_7$



$$b_7 = \quad + b_2 + b_3$$



- There are $2^4$=16 codewords
- (0,0,0,0,0,0,0) is a codeword

# My "simple" proof of optimality



Assume you got the following 7 bit seque and make the followi checks:





$$b_5 = b_1 + b_3 + b_4$$
$$b_6 = b_1 + b_2 + b_4$$
$$b_7 = + b_2 + b_3 + b_4$$

| Case | $b_5$ match | $b_6$ match | $b_7$ match |
|---|---|---|---|
| | | | |
| 1 | | | |
| $b_2$ flipped | | | |
| $b_3$ flipped | | | |
| $b_4$ flipped | | | |
| $b_5$ flipped | | | |
| $b_6$ flipped | | | |
| $b_7$ flipped | | | |

# My ”simple” proof of optimality



Assume you got the following 7 bit seque and make the followi checks:





$$b_5 = b_1 + b_3 + b_4$$

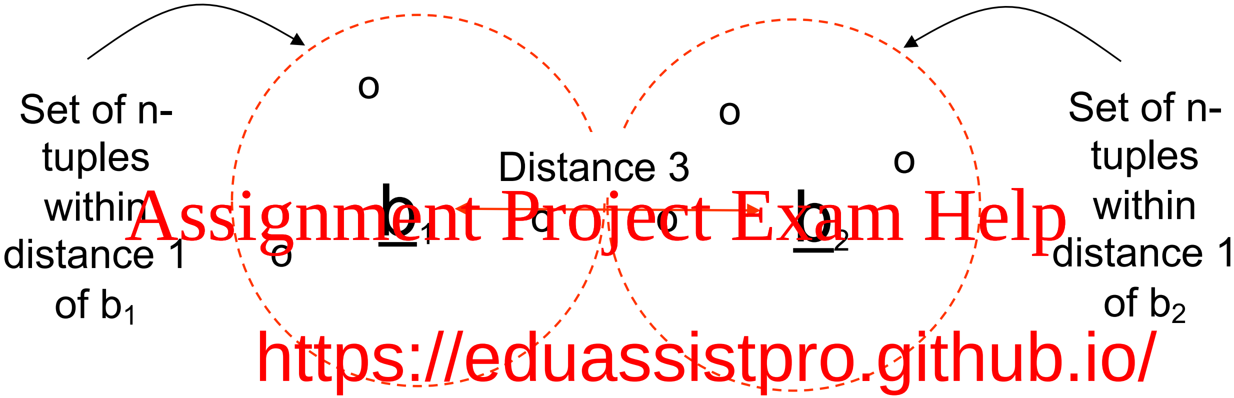
$$b_6 = b_1 + b_2 + b_4$$

$$b_7 = b_2 + b_3 + b_4$$

| Case | $b_5$ match | $b_6$ match | $b_7$ match |
|---|---|---|---|
| | | ✓ | ✓ |
| 1 | | X | ✓ |
| $b_2$ flipped | | X | X |
| $b_3$ flipped | | | X |
| $b_4$ flipped | X | X | X |
| $b_5$ flipped | X | ✓ | ✓ |
| $b_6$ flipped | ✓ | X | ✓ |
| $b_7$ flipped | ✓ | ✓ | X |

Electrical & Computer ENGINEERING

# Why is Hamming a “good code”?






- Two valid bit sequences have a minim t flips
- Spheres of distance 1 around each codeword do not overlap
- If a single error occurs, the resulting n-tuple will be in a unique sphere around the original codeword
- Thus, receiver can correct erroneous reception back to original codeword

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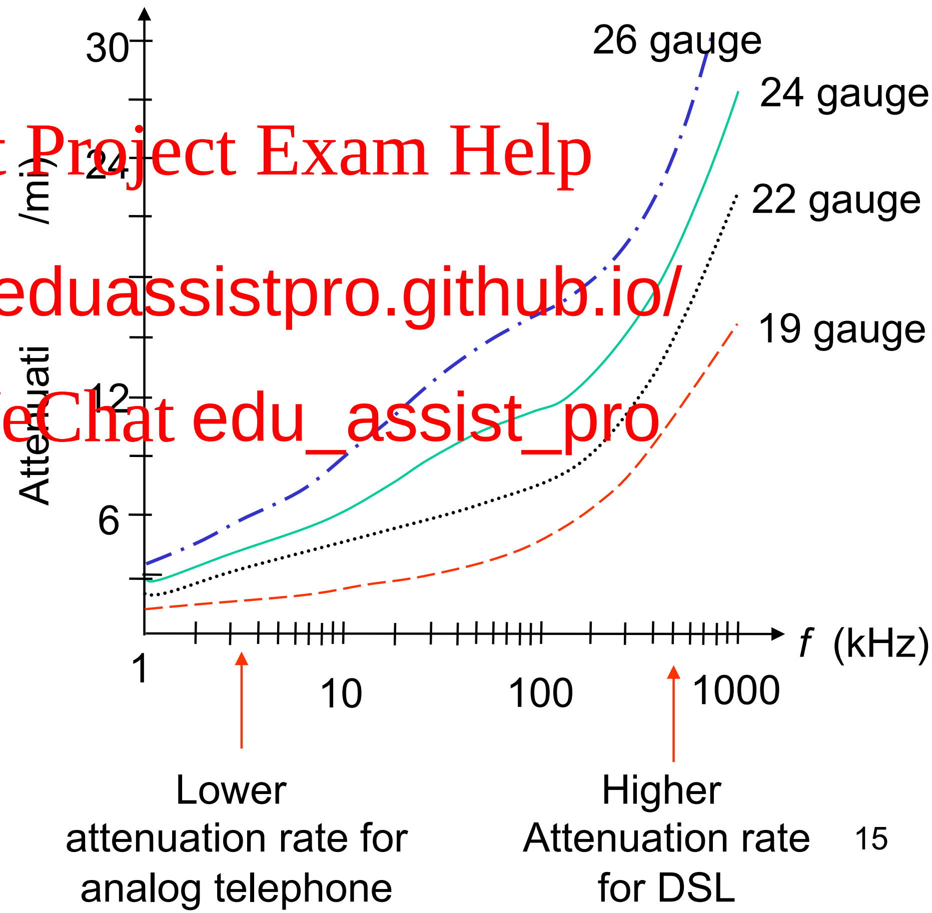
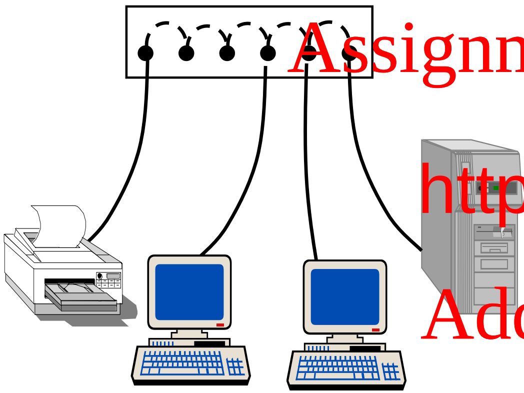
# Twisted Pair

- Two insulated copper wires arranged in a regular spiral pattern to minimize interference
- Various thicknesses, e.g. 0.016 inch (24 ga
- Low cost
- Telephone subscriber loop from customer to CO
- Old trunk plant connecting telephone COs
- Intra-building telephone from wiring closet to desktop



# Ethernet LANs



- Evolved from 10 -> 100 → 1000 Mbps to now 10Gbps
- All use twisted pair in some form!



net

and, Twisted pair

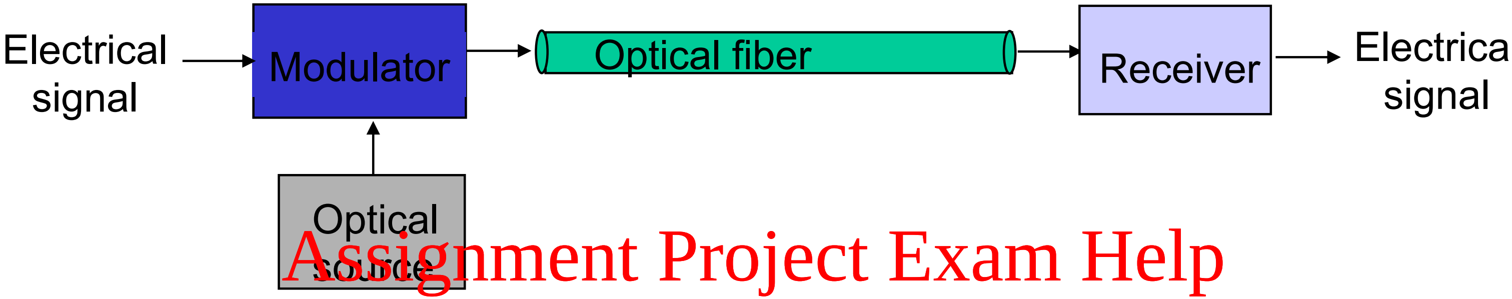


  – Tw
  – Ma 100 meters



- 100B Ethernet
  – 100 Mbps, Baseband, Twisted pair
  – Four Cat3 pairs
  – Three pairs for one direction at-a-time
  – 100/3 Mbps per pair;
  – 3B6T line code, 100 meters
- 1000BASE-T
  – 8b10b encoding, Four pairs

# Optical Fiber






- Light source ulses of light that are transmit



  - Very long distances (>1000 km)

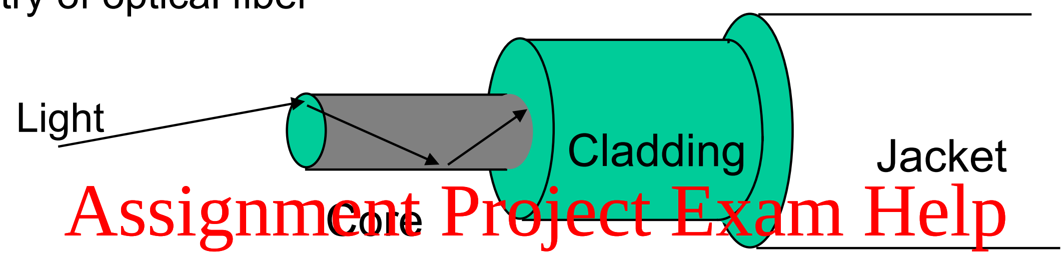


  - Very high speeds (>40 Gbps/wa
  - Nearly error-free (BER of $10^{-15}$)
- Profound influence on network architecture
  - Dominates long distance transmission
  - Distance less of a cost factor in communications
  - Plentiful bandwidth for new services

# Transmission in Optical Fiber

don't fold

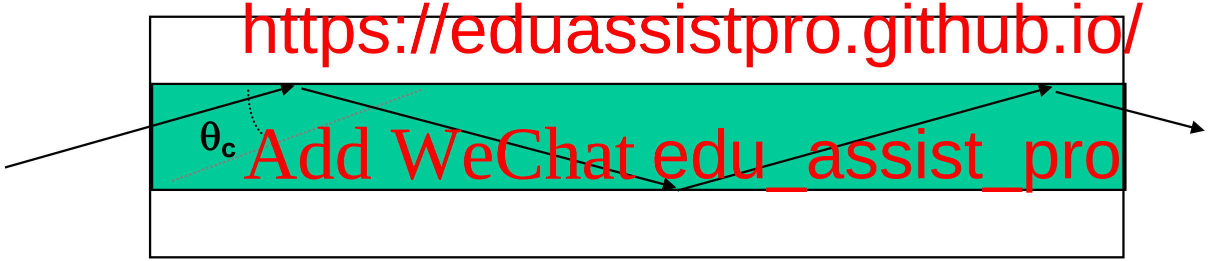
Geometry of optical fiber






Total Internal Reflect



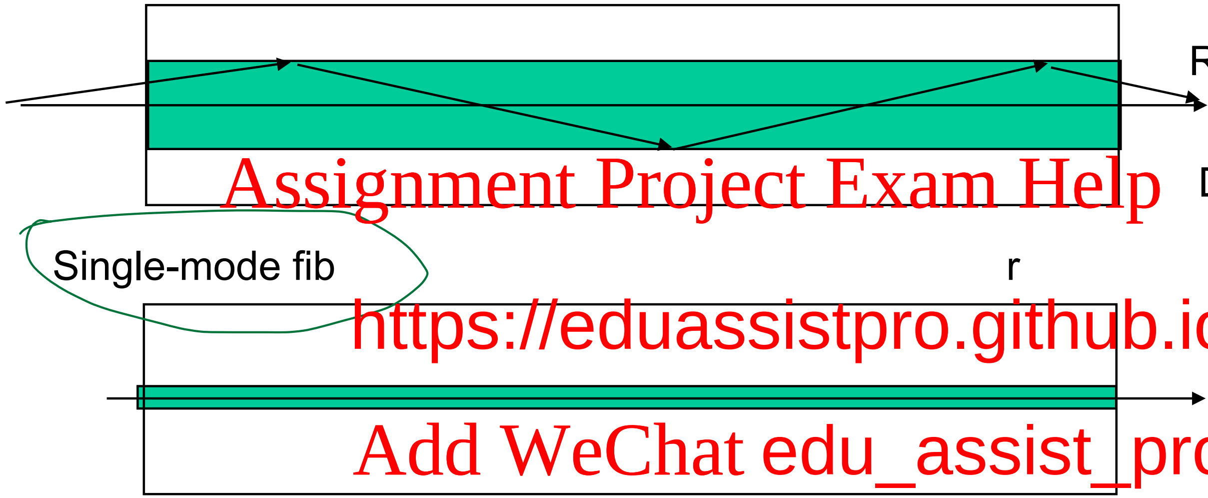





- Very fine glass cylindrical core surrounded by concentric layer of glass (cladding)
- Core has higher index of refraction than cladding
- Light rays incident at less than critical angle $\theta_c$ is completely reflected back into the core

# Multimode & Single-mode Fiber

Multimode fiber: multiple rays follow different paths






- Multi Mode: Thicker core, shorter reach
  - Rays on different paths interfere causing dispersion & limiting bit rate
- Single Mode: Very thin core supports only one mode (path)
  - More expensive lasers, but achieves very high speeds

# Huge Available Bandwidth

- Optical range from $\lambda_1$ to $\lambda_1+\Delta\lambda$ contains bandwidth

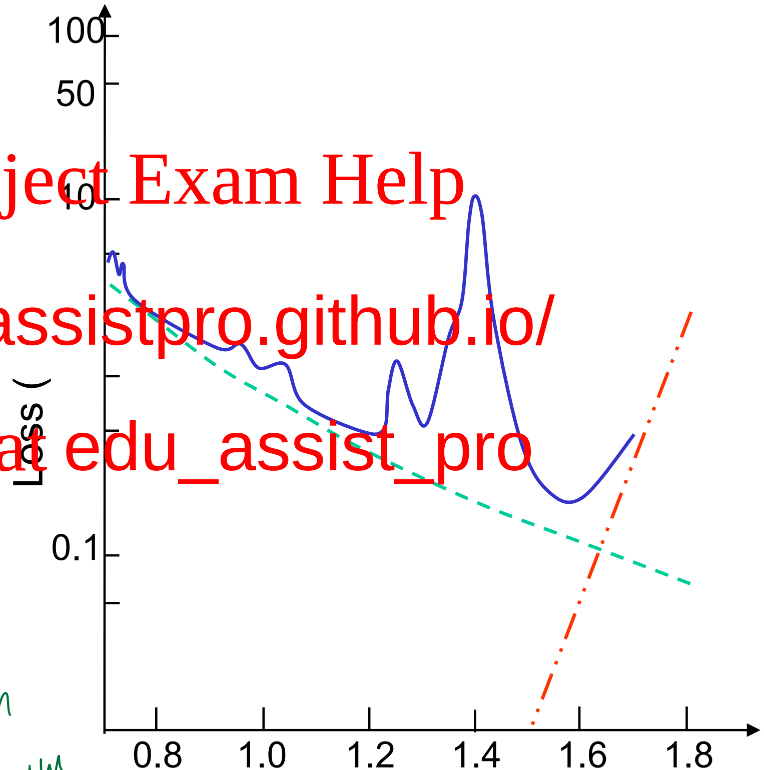


$$B = f_1 - f_2 = \frac{\nu}{\lambda_1} - \frac{\nu}{\lambda_1+\Delta\lambda}$$



$$= \frac{\nu}{\lambda_1}\left\{\frac{\Delta\lambda/\lambda_1}{1+\Delta\lambda/\lambda_1}\right\} \cong \frac{\nu\Delta\lambda}{\lambda_1^2}$$






why v, not c ?

lights has diff speed in diff medium.

# Quiz Question

How much optical fiber bandwidth is available between:



$\lambda_1$ 0 nm:



$\Delta\lambda = 200\,\mathrm{nm}$

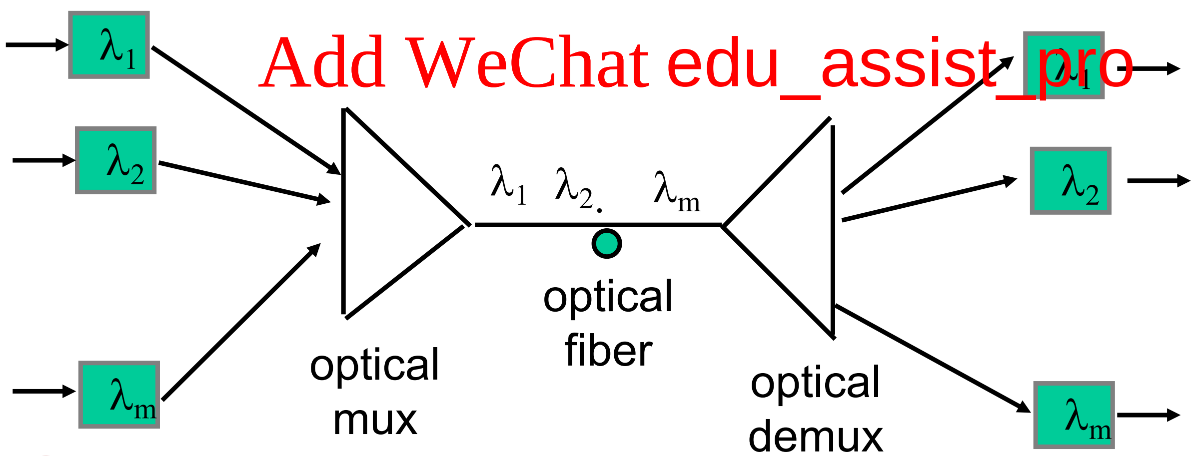


Answer: $B = \dfrac{2(10^8)\,\mathrm{m/s}\ 200\mathrm{n}}{(1450\,\mathrm{nm})^2}$

# Wavelength-Division Multiplexing

- Different wavelengths carry separate signals
- Multiplex into shared optical fiber
- Each wavelength like a separate circuit
- A single fib hs, 10 Gbps per wavele





# How Do We Extend Range

- Use combinations of optical amplifiers and regenerators

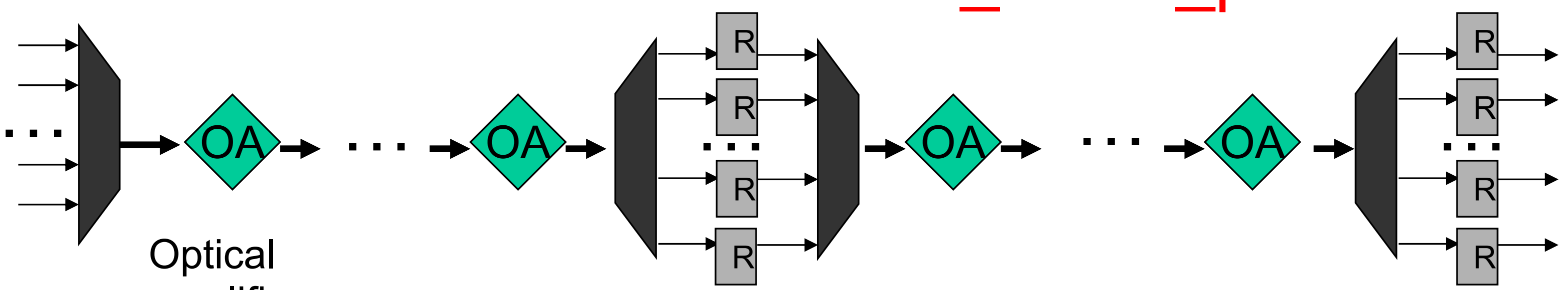
- More amplifiers than regenerators (why?)





cheaper






Optical amplifier

# Physical Layer: Outline

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- Wired PHY 101
- Wireless PHY 101

# Wireless vs. Wired

- Wireless is “flaky”
  - Environment, people, mobility affects signals



- Wireless
  - Collisio
  - Interference
  - Noise



- Wireless is half-duplex
  - Only transmit or receive.. Not both

# Outline - Wireless

- WiFi PHY
  - Wireless channel
  - OFDM
  - Multiple



- Cellular Whirlwind (2G

# But hey, we already know Wi-Fi



(Noisy) Wireless Channel

# Wireless signals: Basic Equation

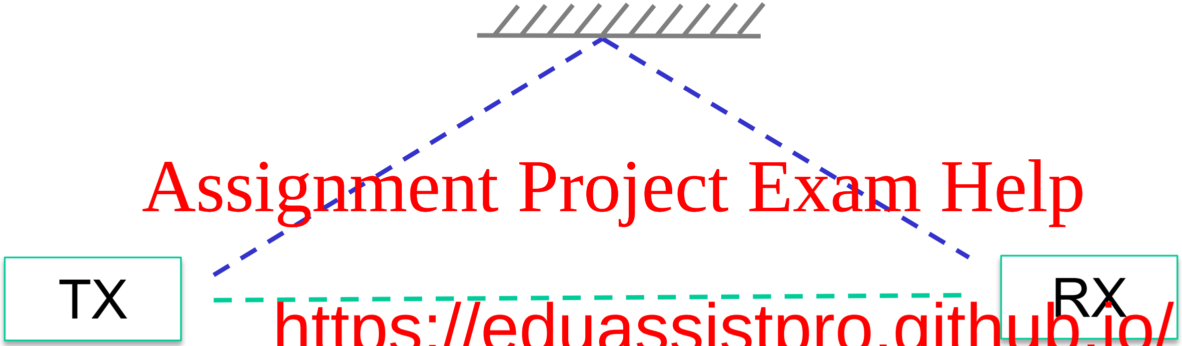
- In narrowband:






$$y(t) = hx(t) + n(t).$$

# But in the real world…






“Multipath”

# Wireless signals

- More generally:

delay

# Wireless signals

- But time is continuous!



s(t) → x

# <u>Challenges:</u> How do I estimate h?



*Send known x(t) as "preamble"*

➔ $h \approx y(t)/x(t)$

# But… what *is* the channel?

- “Attenuation” & “Phase shift”



TX - - - - - - - - - - - - - - - - - - - - RX



$$h = 1/d * e^{j2\pi d/\lambda}$$

- Consistent with $1/d^2$ power fading

# But… what *is* the channel?

- "Attenuation" & "Phase shift"



TX - - - - - - - - - - - - - - - - - - - - - - - - - - RX



$$h = 1/d * e^{j2\pi d/\lambda}$$

- $d/\lambda = d*f/c = f*t$, where "t" is signal time

# But… what *is* the channel?

- “Attenuation” & “Phase shift”



TX - - - - - - - - - - - - - - - - - - - - RX

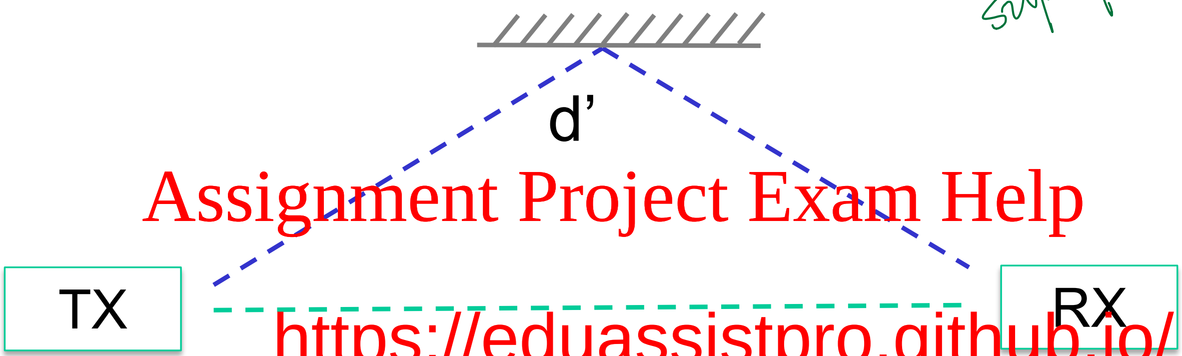


$$h = 1/d * e^{j2\pi d/\lambda} = 1/d * e^{j2\pi ft}$$

- $d/\lambda = d*f/c = f*t$, where “t” is signal time

# How do channels capture multipath?

superposition






$$h = 1/d * e^{j2\pi d/\lambda} + 1/d' * e^{j2\pi d'/\lambda}$$

Channels can combine differently on different frequencies

→ Channels are frequency-selective

# **Challenge:** Frequency Selective Fading

Fourier

# FDM

*Frequency Division Multiplexing*

- Divide bandwidth into small chunks: “subcarri



gaps

But… so much waste!

# OFDM

*Orthogonal Frequency Division Multiplexing*



- Get rid of guard bands by “orthogonal” frequenc

# OFDM

*Orthogonal Frequency Division Multiplexing*



WiFi, LTE uses OFDM!

# MIMO

multiple input
multiple output

- Why so many antennas?

single in single out

# Recap: SISO PHY

- Our discussion so far had single antenna transmitters and receivers



- "Single In

# SISO: Channel Model

(Assuming narrowband)

# MIMO

*Multiple Input Multiple Output*



- 2 x More data



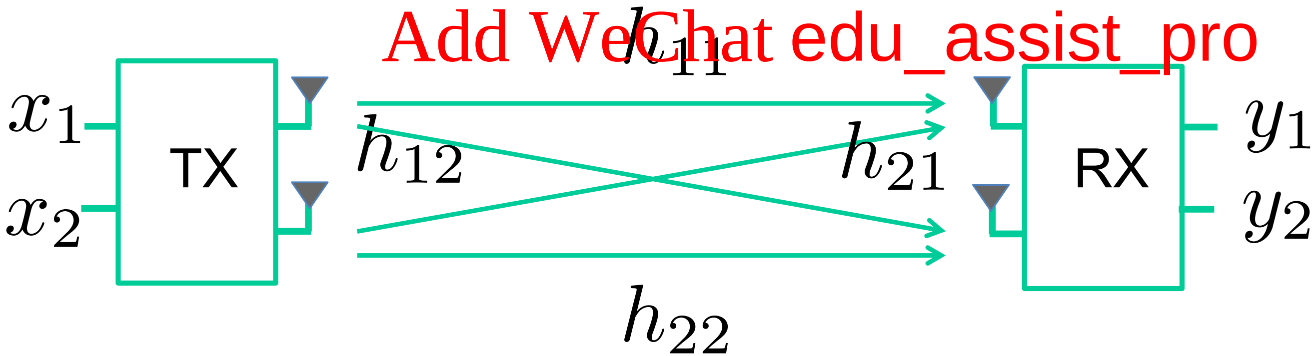
# MIMO

$$y_1 = h_{11}x_1 + h_{21}x_2$$



2

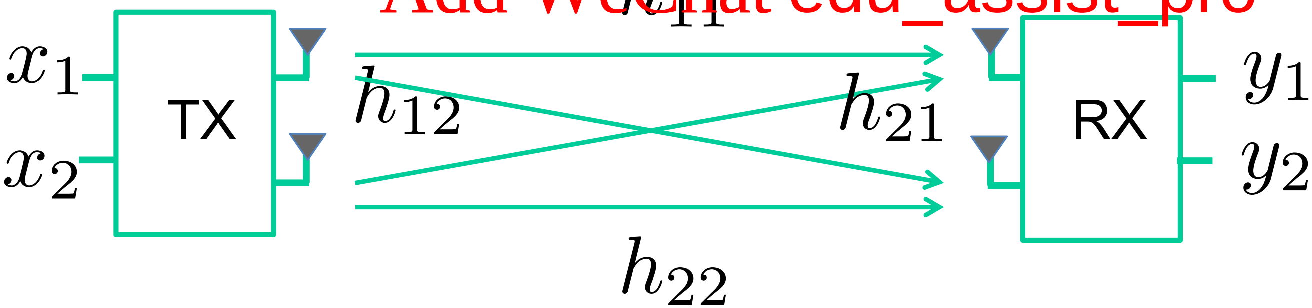




# MIMO

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{21} \\ h & h \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$



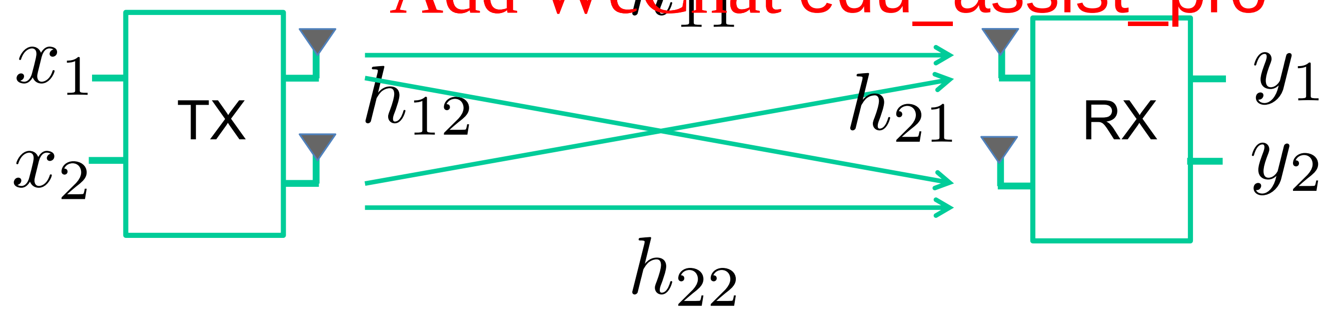



**How do you solve?**

# MIMO

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{bmatrix}^{-1} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}$$





# Estimating Channels

| Preamble 1 | Preamble 2 | … Data … |
| --- | --- | --- |





$h_{11}$ $\quad$ $_{21}$ → enna 1



$h_{12}$ $\quad$ $h_{22}$ → Measure on Antenna 2

# Gains of MIMO

- 2 antennas → 2$\times$ data: $[y_1 \quad y_2]$


- n antennas → n$\times$


**Assumption: H is invertible**

# Quiz Question

Which of these has a gain (in Shannon Capacity) that is identical to that of doubling the number of antennas available on your wireless transmitter & receiver:



[A] Doubling



[B] Doubling Signal Power

log $\frac{2S}{N}$



[C] Doubling Noise Power

[D] Halving Noise Power

**New Shannon Formula: C = n B log(1+SNR)**

# Outline - Wireless

- WiFi PHY
  - Wireless channel
  - OFDM
  - Multiple



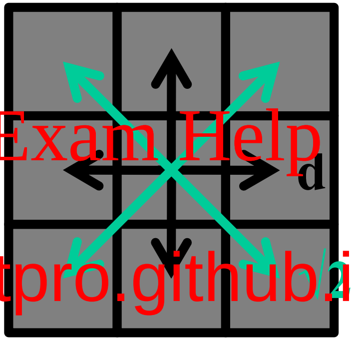
- Cellular Whirlwind (2G

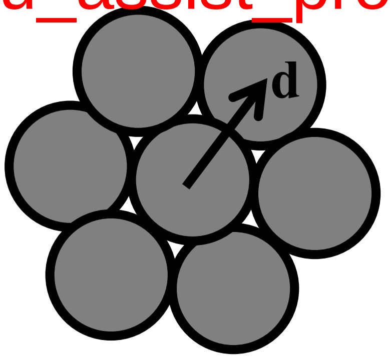
# The Advent of Cellular Networks

- Mobile radio telephone system was based on:
  - High power transmitter/receivers
  - Could su
  - in a radiu
- To increase network capacit
  - Multiple low-power transmitter )
  - Small transmission radius -> area split in cells
  - Each cell with its own frequencies and base station
  - Adjacent cells use different frequencies
  - The same frequency can be reused at sufficient distance

# Cellular Network Design Options

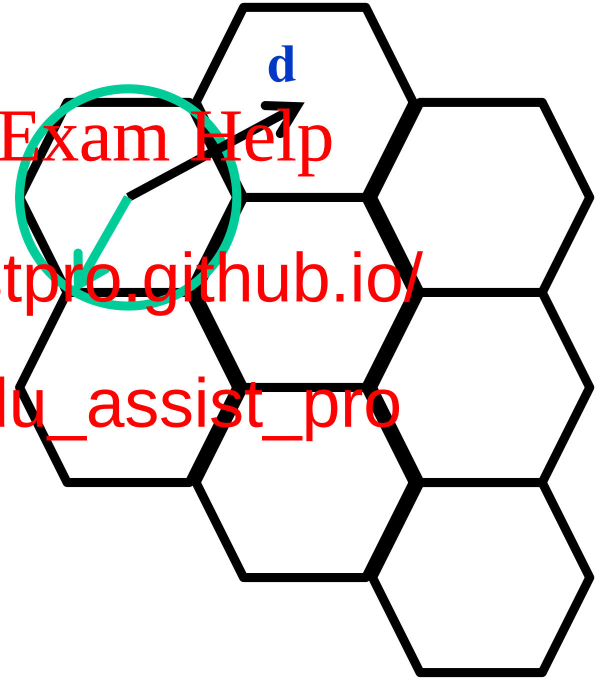
- Simplest layout
  - Adjacent antennas not equidist
    handle
    of the cell?
- Ideal layout
  - But we know signals travel whatever way they feel like



# The Hexagonal Pattern

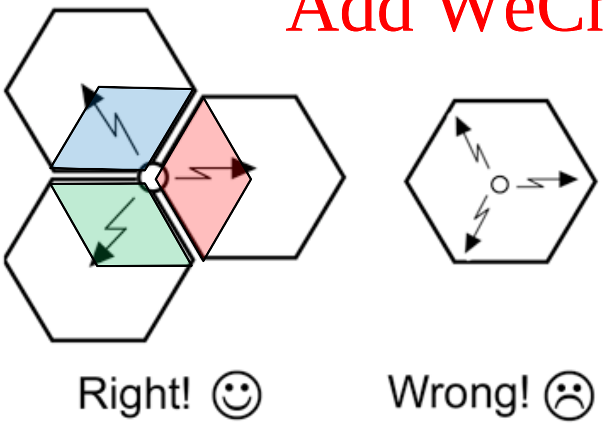
- A hexagon pattern can provide equidistant access to neighboring cell towers
  - Used as th planning
  - d = √3R
- In practice, variations from ideal due to topological reasons
  - Signal propagation
  - Tower placement



# Cell sectoring

- Cell divided into wedge shaped sectors
- 3-6 sectors per cell, each with own channels
- Use of directional antennas
- Even m big cells!





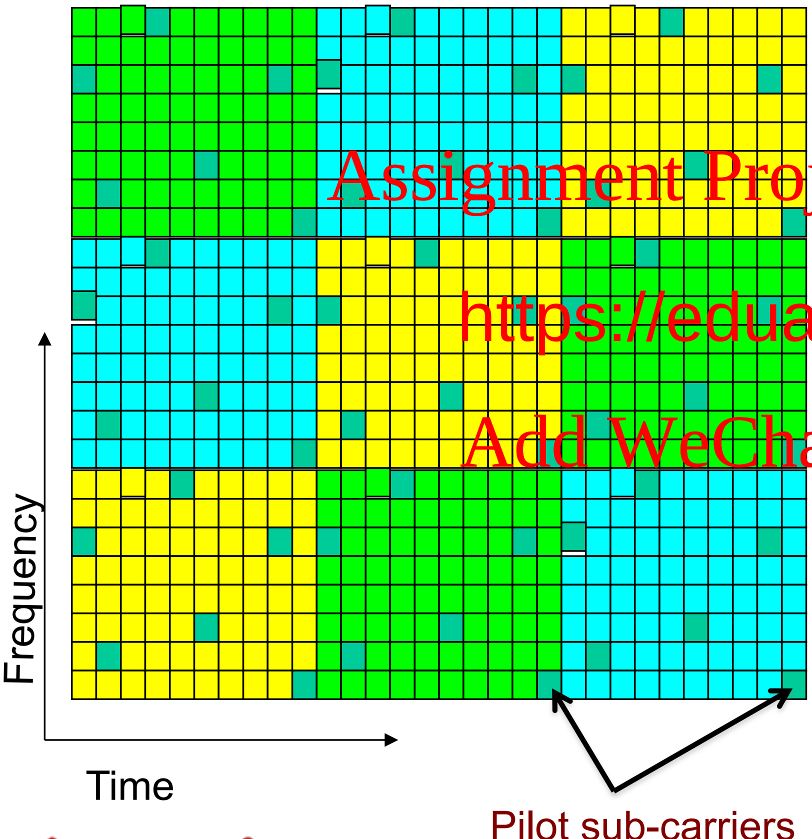
# Cellular Standards

- 1G systems: analog voice
  - Not unlike a wired voice line (without the wire)
- 2G syste
  - Many st
  - Example: GSM - FDMA/ widely deployed, 200 countries, a billion people
- 2.5G systems: voice and data channels
  - Example: GPRS - evolved from GSM, packet-switched, 170 kbps (30-70 in practice)

# Cellular Standards

- 3G: voice (circuit-switched) and data (packet-switched)
  - Several standards
  - Uses Co (CDMA) – UMTS
- 4G: 10 Mbps and up, sea ility between different cellular technologies
  - LTE the dominating technology
  - Packet switched (took them so long!)
- 5G: mm-wave, more bandwidth, massive MIMO

# LTE in a Nutshell: Essentially OFDM




- Each color represents a user
- Each user is assigned a frequency-time tile which consists of pilot sub- data sub-carriers
- ing of each user's tile for iversity



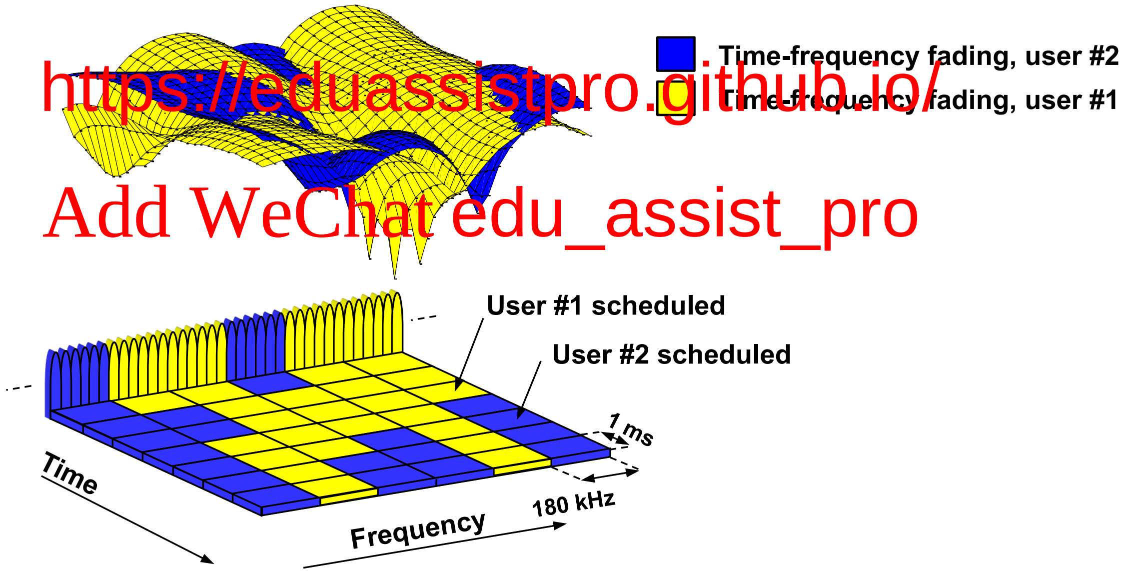


Courtesy: Harish Vishwanath

# LTE in a Nutshell: Or rather, OFDM-A!

- Call a chunk of subcarrier-time “resource blocks”
- Assign each user a chunk of resource blocks coordinated by the cell tower






Courtesy: Zoltán Turányi

# 5G in one slide(!)

- LTE bandwidths (in US) ~ 10-20 MHz
- 5G plays three games to increase based on C = n B log(1+S(I)
  - Increase
  - Increase B (option 1): mm-wa
  - Increase B (option 2): buy mo sts $$)
  - Reduce I: smaller cells (femto cells)
- Only major change to PHY: allow subcarrier width to change (fixed in LTE), otherwise mostly same as LTE (still uses OFDMA, etc.)