Agenda

- Wireless Basics
- MAC
- Modulation
- Auto Rate Adaptation
- MIMO
- Multi-User MIMO
- CoMP and Networked MIMO
- OFDM
- mmWave and Beamforming

Network System Capstone
@CS.NCTU

Lecture 1: Wireless Basics

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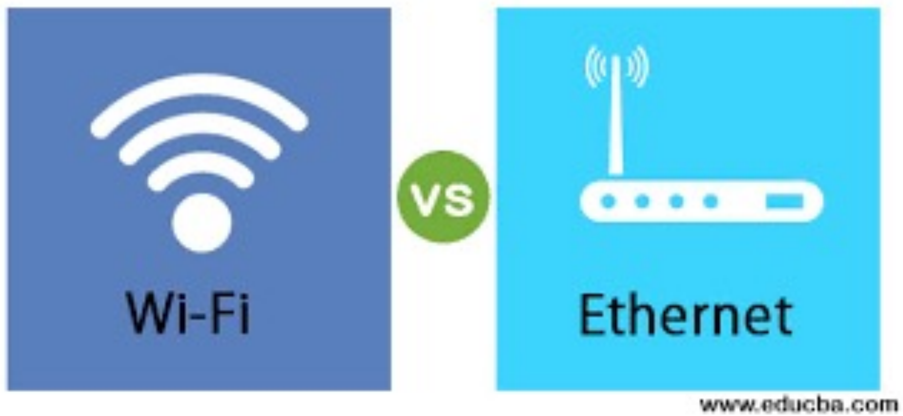
Wireless v.s. Wired Networks

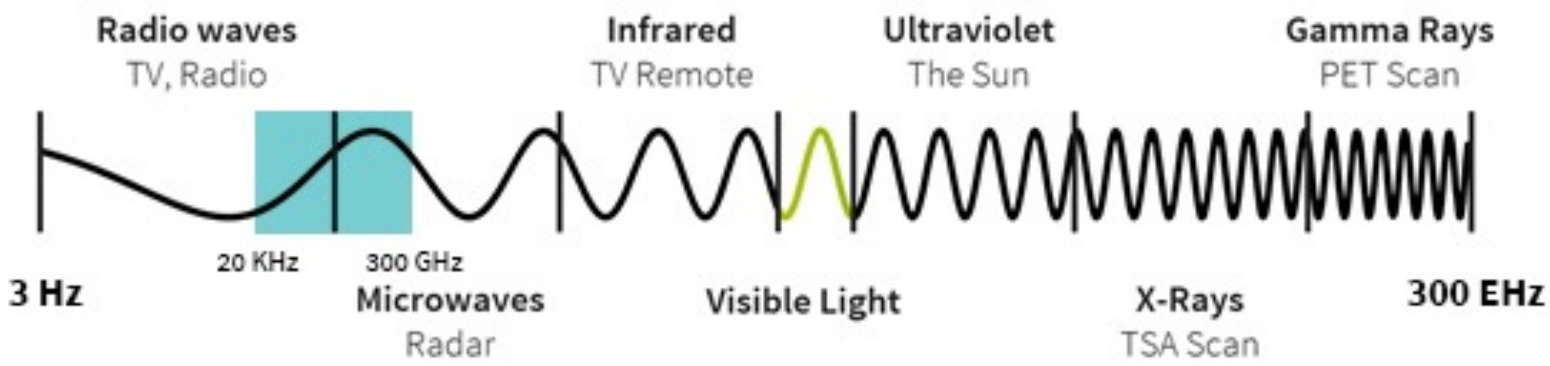


- Slow data rate
- Unreliable transfer
- Higher latnecy
- Easy to deploy and support mobility

- High data rate
- Reliable transfer
- Lower latency
- Expensive and static infrastructure

Wireless Spectrum

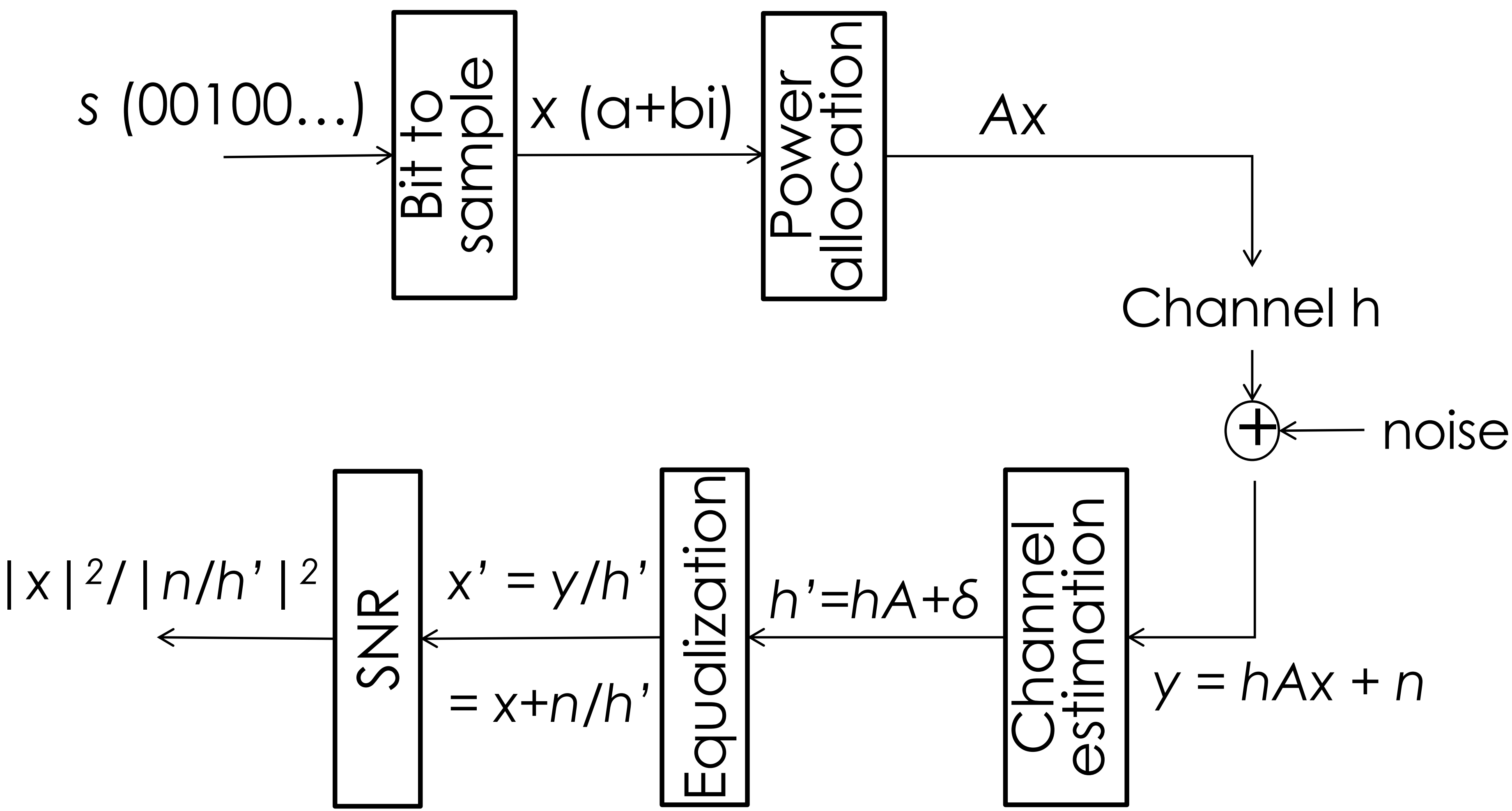
- Information that travels wirelessly uses **radio waves**
  - **Electromagnetic radiation** with a particular wavelength and frequency
- **Spectrum:**
  - Fixed and finite resources
  - In the U.S., the Federal Communications Commission (FCC) is responsible for spectrum management



Wireless Spectrum

- Different bands have different characteristics
- **Low-band (sub 3GHz)**
  - Long distance with minimal interruption
  - Low capacity
- **High-band (above 24GHz)**
  - High capacity
  - Sensitive to blockage
- **Mid-band (3-24 GHz)**
  - Providing a mix of coverage and capacity
  - LTE and WiFi
  - Densely used

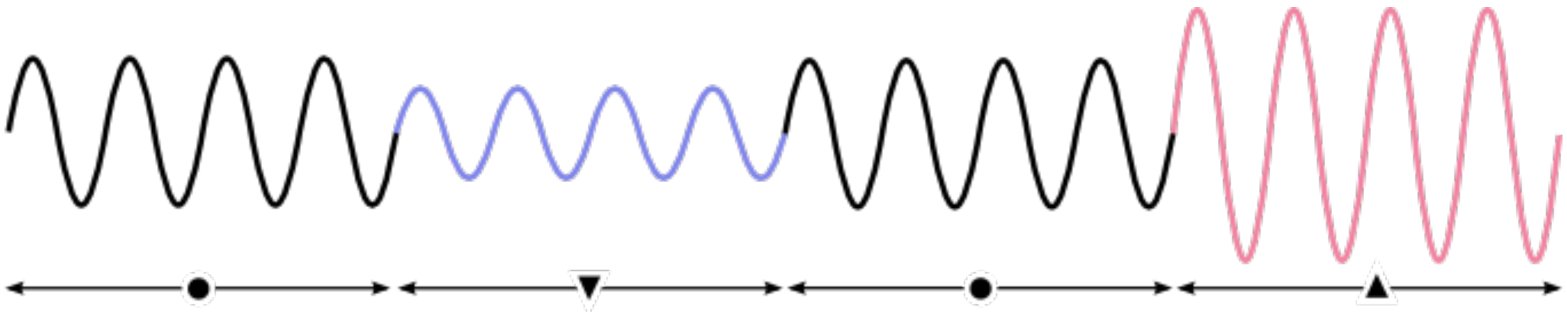
Transmitter



Receiver

Wireless Signal

- Sine wave $e^{ix} = \cos x + j \sin x$



channel

noise

$$y = hx + n$$

received signal

transmitted signal

phase change due to propagation delay

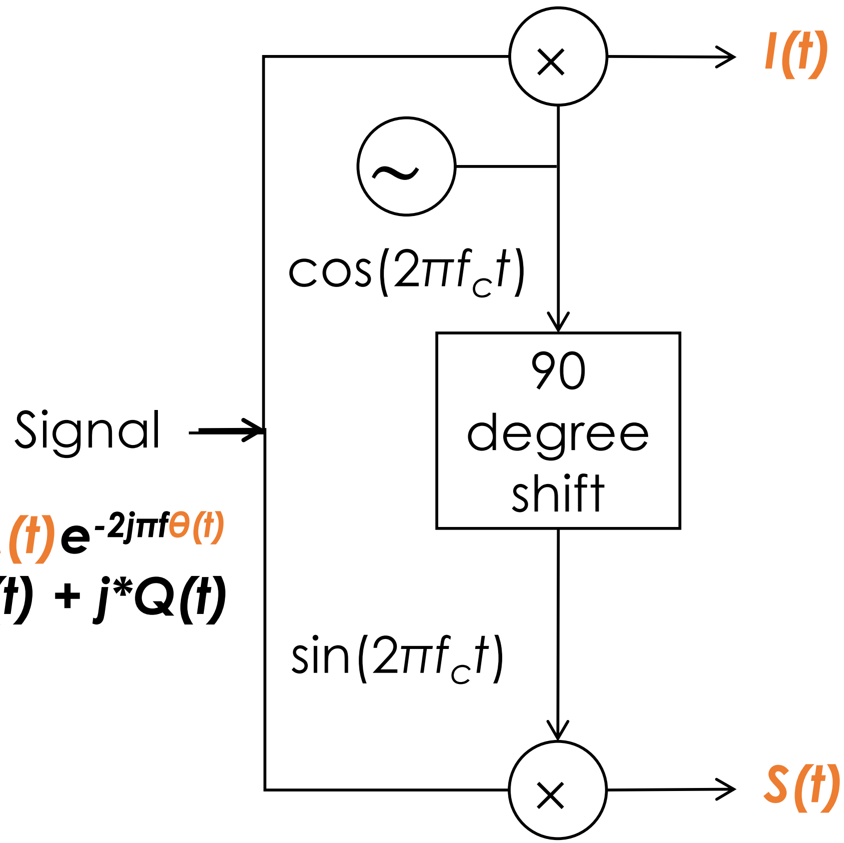
$$h = \alpha e^{-2j\pi f_c(t+\theta)}$$

amplitude

What is channel? Signal variation (amplitude and phase) over the air

Orthogonal Signals

- Wireless signals are typically sent using sin() and cos() (orthogonal waves)



$$x(t) = A(t)e^{-2j\pi f \theta(t)} = I(t) + j*Q(t)$$

Constellation Diagram

- Signal can be described as a sine wave

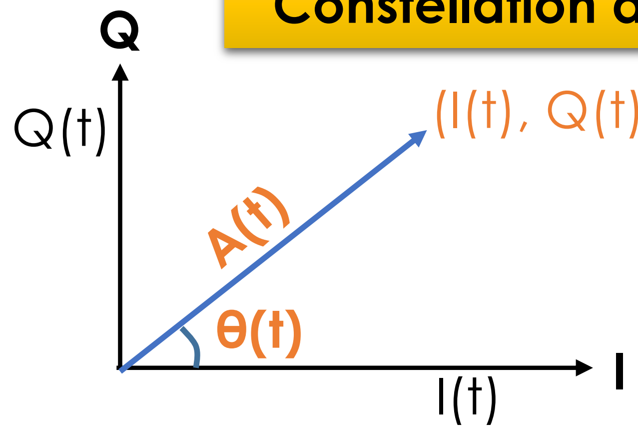
$$
\begin{aligned}
x(t) &= A(t)\cos(\omega t + \theta(t)) \\
&= A(t)\frac{e^{j(\omega t+\theta(t))} + e^{-j(\omega t+\theta(t))}}{2} \\
&= \mathrm{Re}[A(t)e^{-j(\omega t+\theta(t))}] \\
&= \mathrm{Re}[A(t)e^{-j\theta(t)}e^{-j\omega t}] \\
&= \mathrm{Re}[\tilde{x}(t)e^{-j\omega t}] \\
&= \mathrm{Re}[(I(t)+jQ(t))e^{-j\omega t}] \\
&= I(t)\cos(\omega t) + Q(t)\sin(\omega t)
\end{aligned}
$$

- Rearranged as **inphase** and **quadrature**

Constellation Diagram

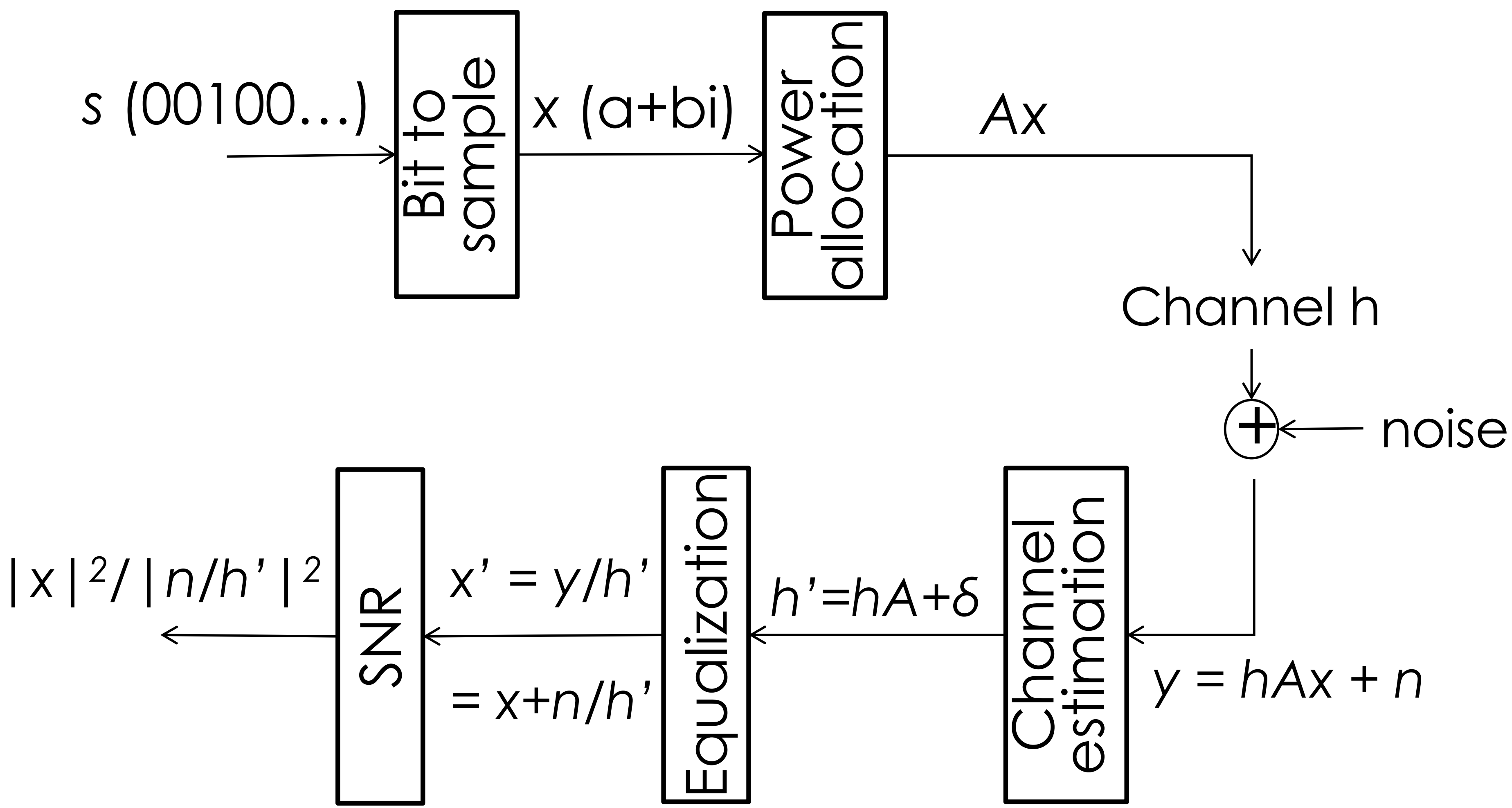
$$
\begin{aligned}
x(t) &= A(t)\cos(\omega t + \theta(t)) \\
&= I(t)\cos(\omega t) + Q(t)\sin(\omega t) \\
&= I(t) + jQ(t)
\end{aligned}
$$

Constellation diagram



- Represent a wireless signal as a complex number
  - Sine carrier: image part
  - Cosine carrier: real part
- Why complex value?
  - Sine and Cosine are orthogonal with each other
  - Two carriers on the same frequency → rate⬆️

Transmitter



Receiver

Equalization

- Reversal of distortion incurred by a signal transmitted through a channel
- **Equalizer**: recover the transmitted signal from the received signal
  - Also known as **decoding**

- Type of equalizers
  - **Optimum Trellis-based detection**
    - Viterbi decoding
  - **Linear equalization**
    - MMSE, Zero-forcing (ZF)

Equalization

- Optimum **Trellis-Based** Detectors
  - Trellis Diagram
    - Applying y to a linear filter viewed as a finite-state machine (FSM)
  - **Viterbi Decoding**
    - Posteriori probability maximization (MAP)
    - Maximum-likelihood (ML) decoding
- Linear Equalization
  - **Zero-forcing**
  - **MMSE** (Minimum-mean-squared-error) equalization

Zero-Forcing Equalizer

- Linear equalization algorithm
- Applies the inverse of the [frequency response]() of the channel
- Decoder = 1/channel response

$$y = hx + n \rightarrow d = \frac{1}{h}$$

$$\hat{x} = dy = \frac{1}{h}y = x + \frac{n}{h}$$

- Pros
  - Low complexity
- Cons
  - Noise amplified if the channel response (h) is weak!

MMSE Equalizer

- Bayesian estimation with **quadratic loss function**
- Assume that the samples and the noise are white random sequences uncorrelated with eath other
- Mean Square Error (MSE)

$$\mathrm{MSE} = \mathbb{E}[(\hat{x} - x)^T (\hat{x} - x)]$$

- MMSE Equalizer

$$\hat{x}_{\mathrm{MMSE}}(y) = \arg\min_{\hat{x}} \mathrm{MSE}$$

- Type of MMSE Equalizers
  - Exaustive search
  - Linear MMSE estimation
  - Sequential linear MMSE estimation

Channel Estimation

$$h = \alpha e^{-2j\pi f_c(t+\theta)}$$

$$y = hx + n \Rightarrow x' = \frac{y}{h} = x + \frac{n}{h}$$

- How to know the channel state information (CSI)?
  - Learn by sending **preambles** or **pilot symbols**, which are known by both the transmitter and receiver

Preamble	Data symbols 1	Data symbols 2	···	Data symbols N

$$y = hx_p + n$$

$$\hat{h} = \frac{y}{x_p}$$

$$y = hx + n$$

$$\hat{x} = \frac{y}{\hat{h}}$$

Coherence Time

- The time over which a propagating wave may be considered **coherent** (i.e., staying constant)
- Why this is important?
  - To decode the signal, we need to estimate the channel *h* within the coherence time
  - The time interval between consecutive channel estimation should be shorter than coherence time
  - What if we don't re-learn the channel after coherence time?
    - decoding can be erroneous due to incorrect channel *h*

Coherence Time

Coherence time

Re-learn CSI

Preamble | Data symbols 1 | … | Data symbols i | Data symbols i+1

$$y = hx_p + n$$

$$\hat{h} = \frac{y}{x_p}$$

$$y = hx + n$$

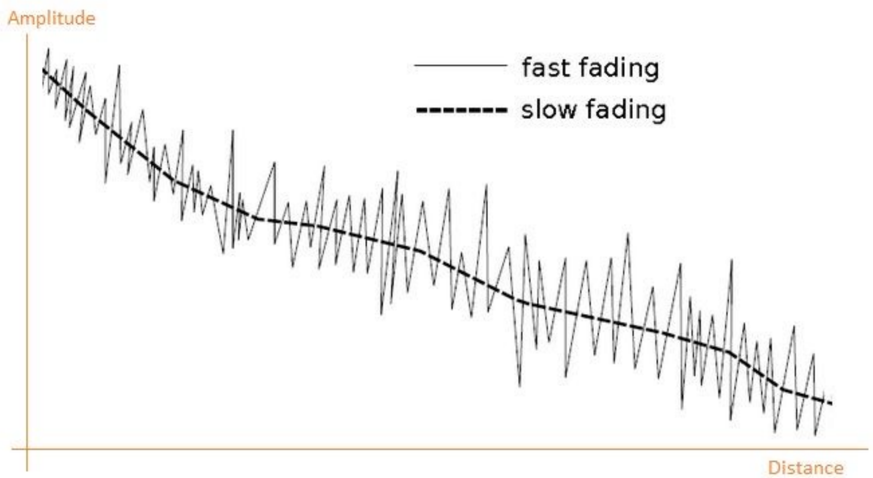
$$\hat{x} = \frac{y}{\hat{h}}$$

$$y = h'x + n$$

$$\hat{x} = \frac{y}{\hat{h}} = \frac{h'x + n}{\hat{h}} = \delta x + \frac{n}{\hat{h}}$$

Decoding error

Channel Fading



- Variation of the attenuation of a signal
- **Slow fading**
  - The coherence time of the channel is large relative to the delay requirement of the application
  - Channel can be considered roughly constant over the period of use
  - Slow fading can be caused by events such as **shadowing**
- **Fast fading**
  - The coherence time of the channel is small relative to the delay requirement of the application

Performance Metrics

- Signal-to-Noise Ratio (**SNR**)
- **Capacity**
- Bit Error Rate (**BER**)
- Packet Error Rate (**PER**)
- Data Rate / Throughput / Goodput
  - **Data rate**: number of bits conveyed per second
  - **Throughput**: successful message delivery over a wireless channel (including protocol overhead)
  - **Goodput**: application-layer throughput, i.e., number of useful bits per second

Signal Power

- Watt vs. Decibel (**dBm or dB$_{mW}$**)
  - dBm is usually used in radio
  - Converted from milliwatt
  - Able to express both very large and very small values in a short form

$$P_{dBm} = 10\log_{10}(1000P_W)$$

$$P_W = \frac{10^{P_{dBm}/10}}{1000}$$

- **dB**: difference between two dBm values
  - ratio of two power = difference between two dBm

$$\begin{aligned} \text{P1toP2}_{dB} &= 10\log_{10}(\frac{P_1}{P_2}) \\ &= 10\log_{10}(P_1) - 10\log_{10}(P_2) \\ &= P_{1,dBm} - P_{2,dBm} \end{aligned}$$

Power vs. dB

- Because of the log operation, double the power produces 3dB gain

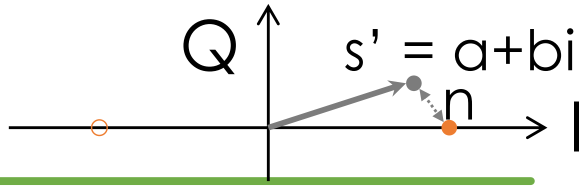
$$SNR_{dB} = 10\log_{10} SNR$$

$$P_1 = 2 * P_2$$

$$\Longrightarrow 10\log_{10}\frac{P_1}{N} = 10\log_{10}\frac{2 * P_2}{N}$$

$$P_{1,dB} = P_{2,dB} + 10\log_{10} 2 = P_{2,dB} + 3.0103(\mathrm{dB})$$

SNR



- Signal-to-Noise Ratio

$$\frac{S}{N}$$

- In dB

$$10\log_{10}\frac{S}{N}$$

- From equation (ratio)

$$y = hx + n$$

$$SNR = \frac{|h|^2}{\mathbb{E}[|n|^2]}$$

- Decoding SNR
  - Sent s=1+0i
    but receive s'= a+bi
  - Signal power
    = s^2 = | 1+0i | ^{2}
  - Noise power = | s-s' | ^{2}
    = | (a+bi) – (1+0i) | ^{2}
    = | (a-1)+bi | ^{2}

<u>sample SNR</u>

$$SNR = \frac{|1+0i|^2}{|(a-1)+bi|^2}$$

<u>average SNR</u>

$$SNR = \frac{s^2}{\text{mean}(n^2)}$$

Errors

- Symbol error rate (**SER**)
  - Ratio of errorneous symbols to the total number of symbols
- Bit error rate (**BER**)
  - Ratio of bit errors to the total number of transmitted bits
- Packet error rate (**PER**)
  - Ratio of failed packets to the total number of packets
  - CRC check: a packet is dropped if ANY bits are in error
  - PER of a packet of L bits = $1 - (1 - \mathrm{BER})^L$

Path Loss

- Attenuation reduction as the signal propagates through the air
- **Friis Transmission Formula**

$$\frac{P_r}{P_t} = D_t D_r \left(\frac{\lambda}{4\pi d}\right)^2 \quad \text{(in Watt)}$$

$$P_r - P_t = D_t + D_r + 20\log_{10}\left(\frac{\lambda}{4\pi d}\right) \quad \text{(in dB)}$$

  - λ: signal wavelength
  - Pt/Pr: transmitting/receiving power
  - Dt/Dr: directivity of transmitting/receiving antenna
- Loss ∝ distance^2

Shannon Capacity

- The tight **upper bound** on the data rate

$$C = B\log_2\left(1+\frac{S}{N}\right) = B\log_2\left(1+SNR\right)$$

- B: bandwidth (Hz), e.g., WiFi with 20MHz
- S and N is in Watt (SNR is power ratio, not in dB)
- Example: SNR=25dB, what is the capacity of 20MHz WiFi?

$$SNR_{dB} = 10 * \log_{10} SNR \Rightarrow SNR = 10^{SNR_{dB}/10} = 316.2278$$

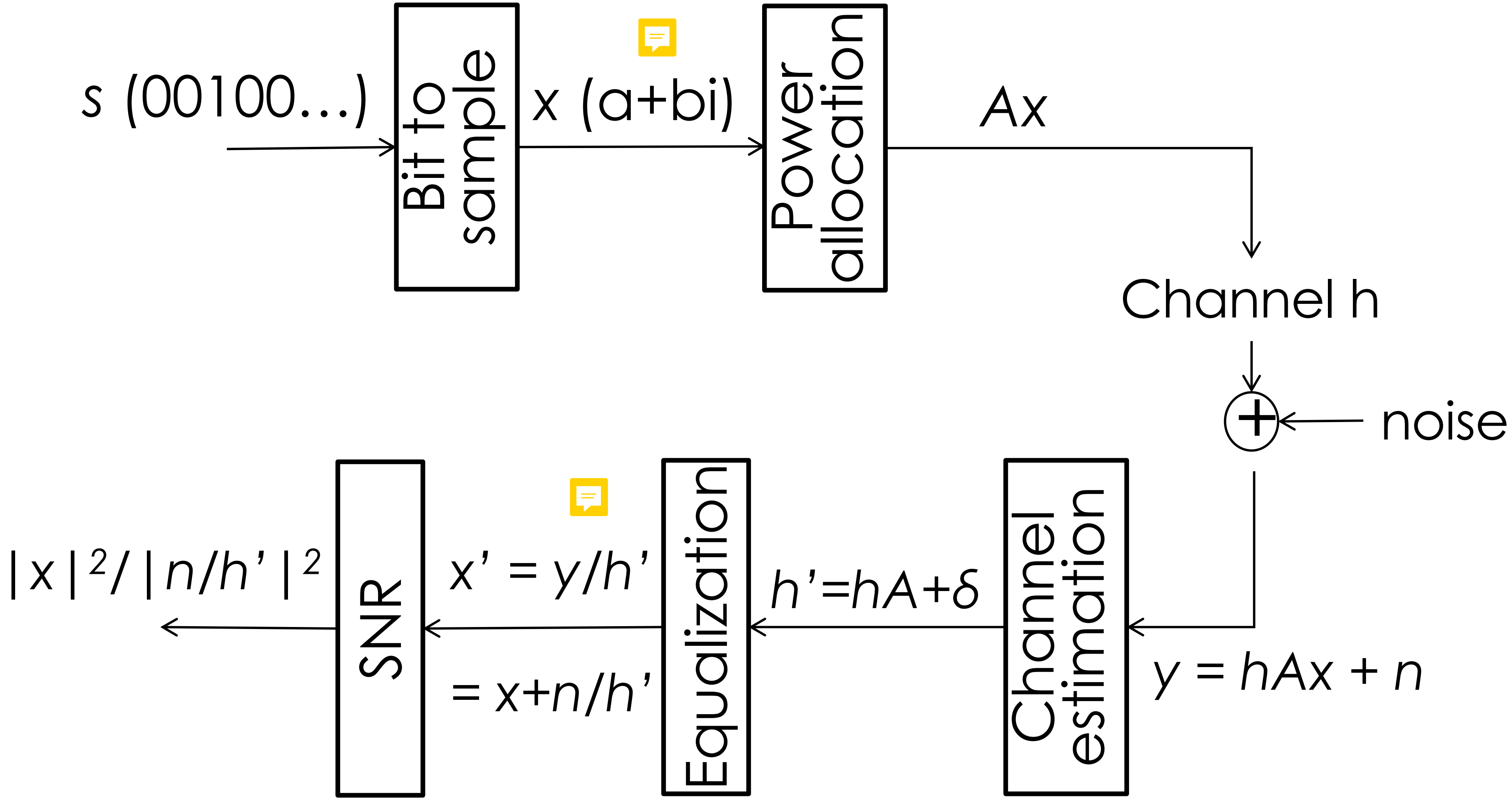
$$C = 20 * 10^6 * \log_2(1+316.2278) = 166.1875(\mathrm{Mbps})$$

Shannon Capacity

- In low SNR regime, increasing SNR can increase the rate significantly
- In high SNR regime, the increase in rate from SNR gain is relatively small

- 4dB → 7dB
  - SNR: 2.5119 → 5.0119
  - Capacity: 1.8123 → 2.5878 (1.43x) big enhancement
- 30dB → 33dB
  - SNR: 1000 → 1.9953e+03
  - Capacity: 9.9672 → 10.9631 (1.0999x) small enhancement

Transmitter



Receiver