ECE 598HH: Advanced Wireless Networks and Sensing Systems

Lecture 2: Review: Wireless Communication

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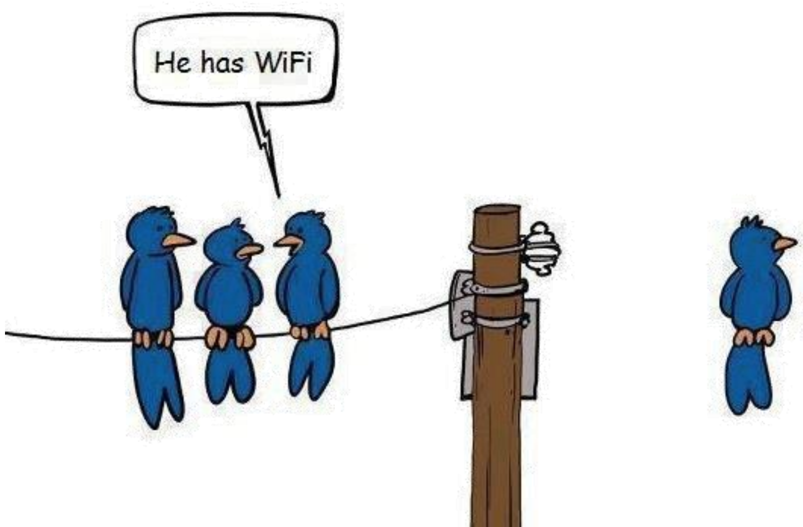

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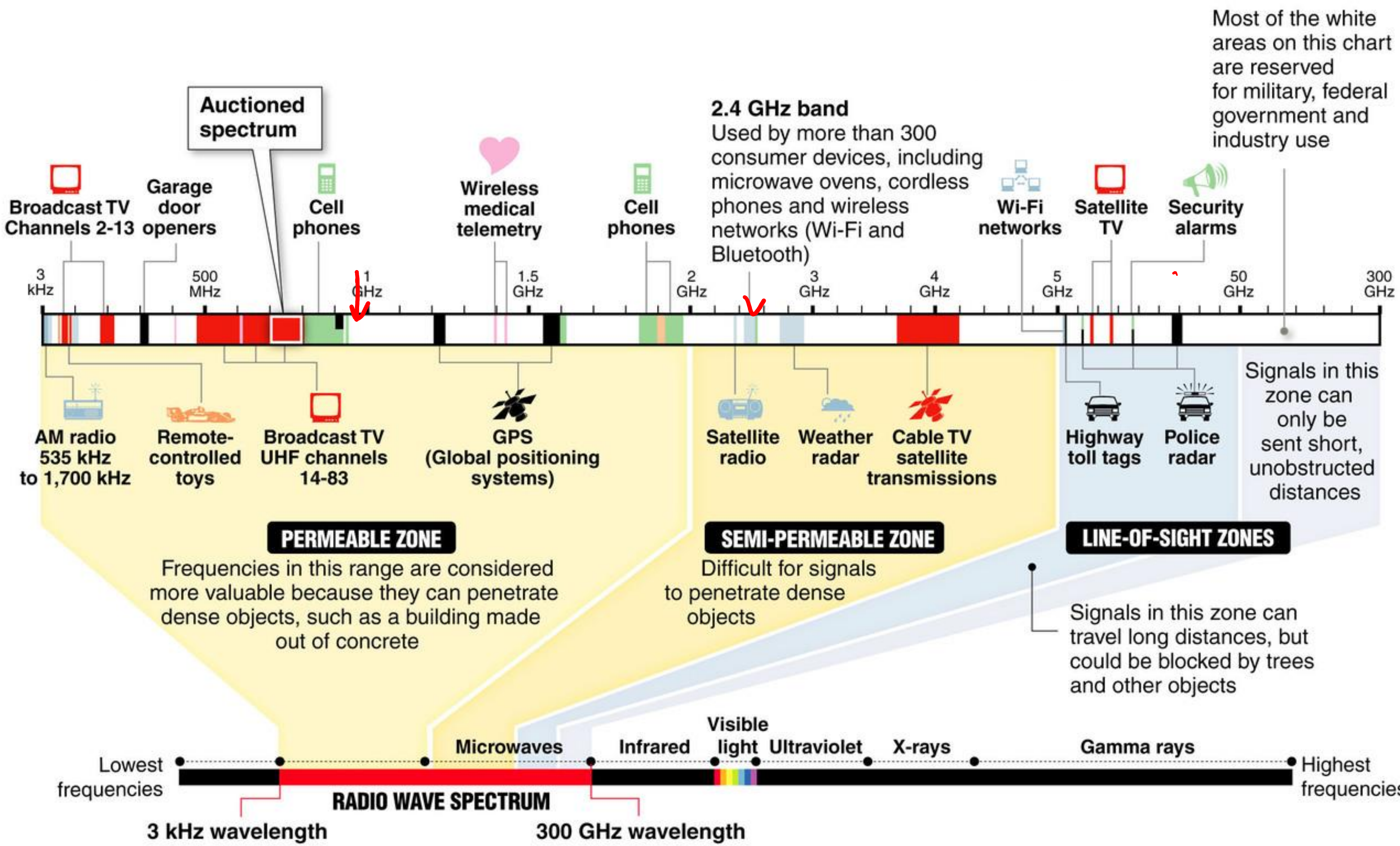
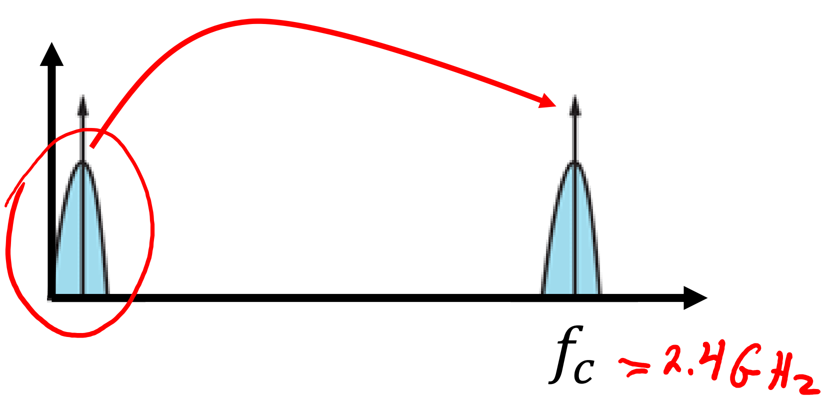
The Wireless Spectrum



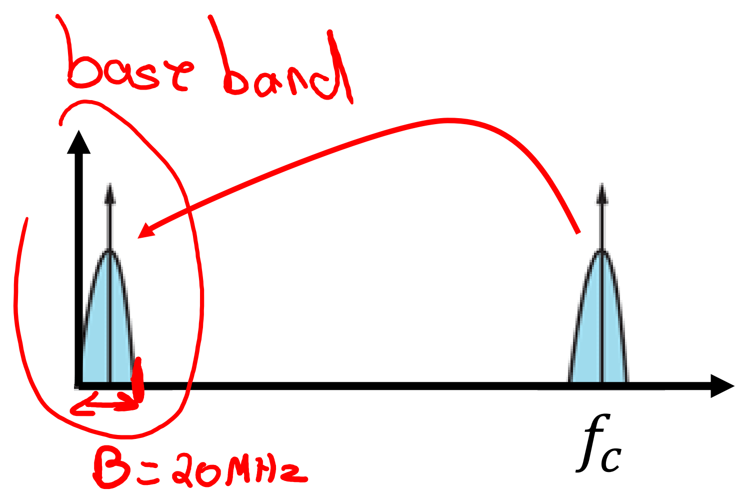
Transmitting & Receiving at Frequency f_c

- To recover signal, must sample at Nyquist: $2f_c$

- Upconvert and Downconvert the signal from baseband



At TX



At RX

- In Baseband: sample at $2 \times Bandwidth$

Up Conversion & Down-Conversion

$$x(t)\cos(2\pi f_c t)$$

$$y(t) = x(t)\cos(2\pi f_c t)$$

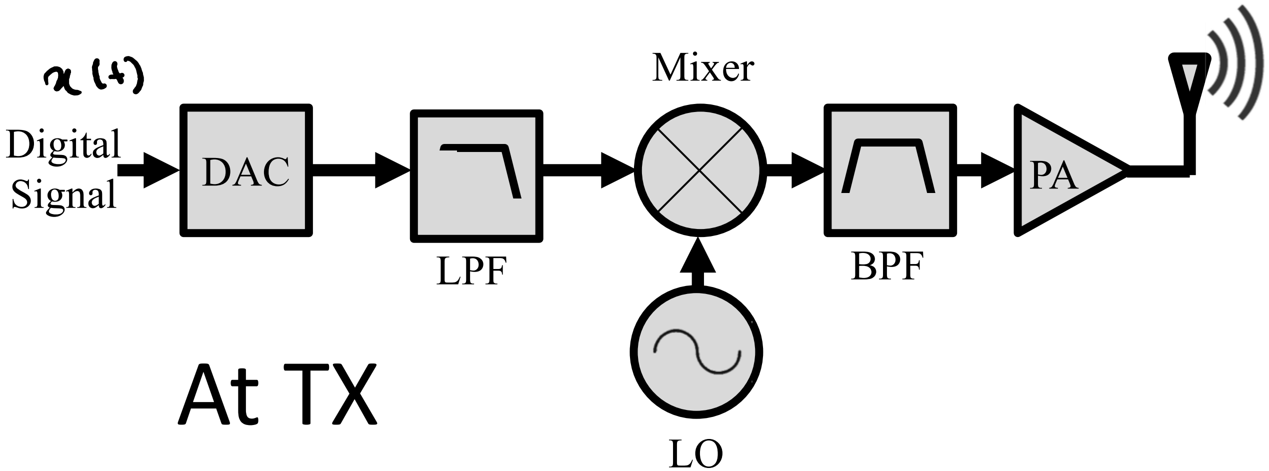
$$y(t) \times \cos(2\pi f_c t) = x(t)\cos^2(2\pi f_c t)$$

LPF

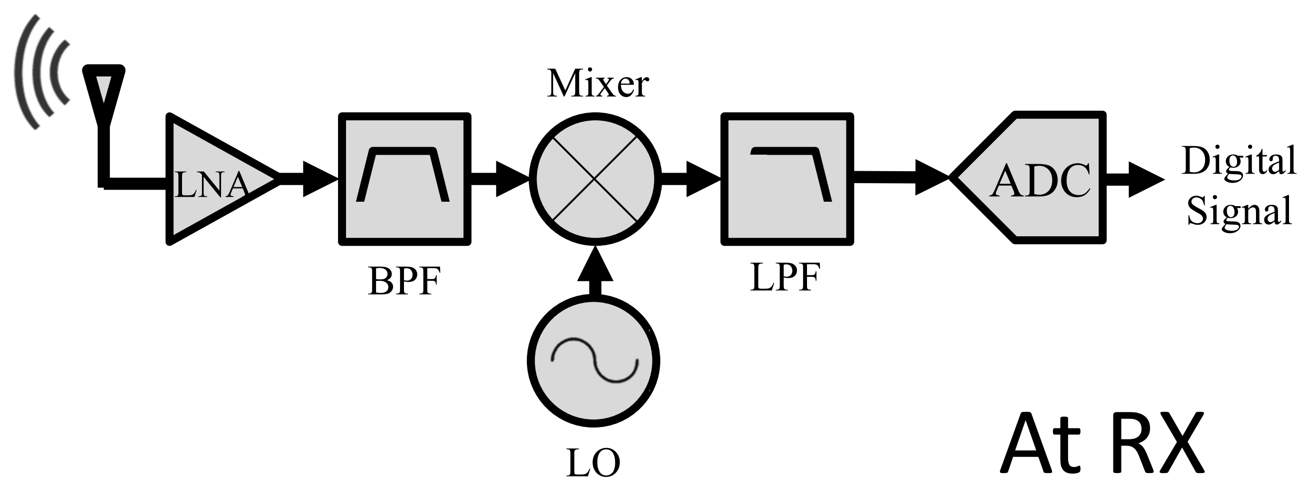
$$= \underbrace{x(t)}_{\text{original}} \times \frac{1}{2}\left(1 + \underbrace{\cos(2\pi\, 2f_c t)}_{\text{high frequency}}\right)$$

$$= \frac{x(t)}{2}$$

Up Conversion & Down-Conversion



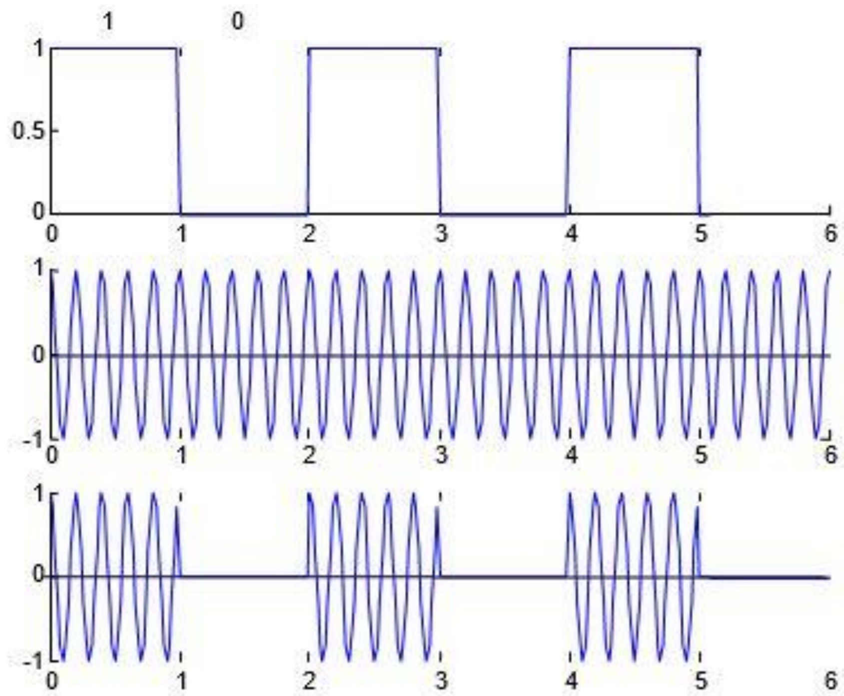
At TX

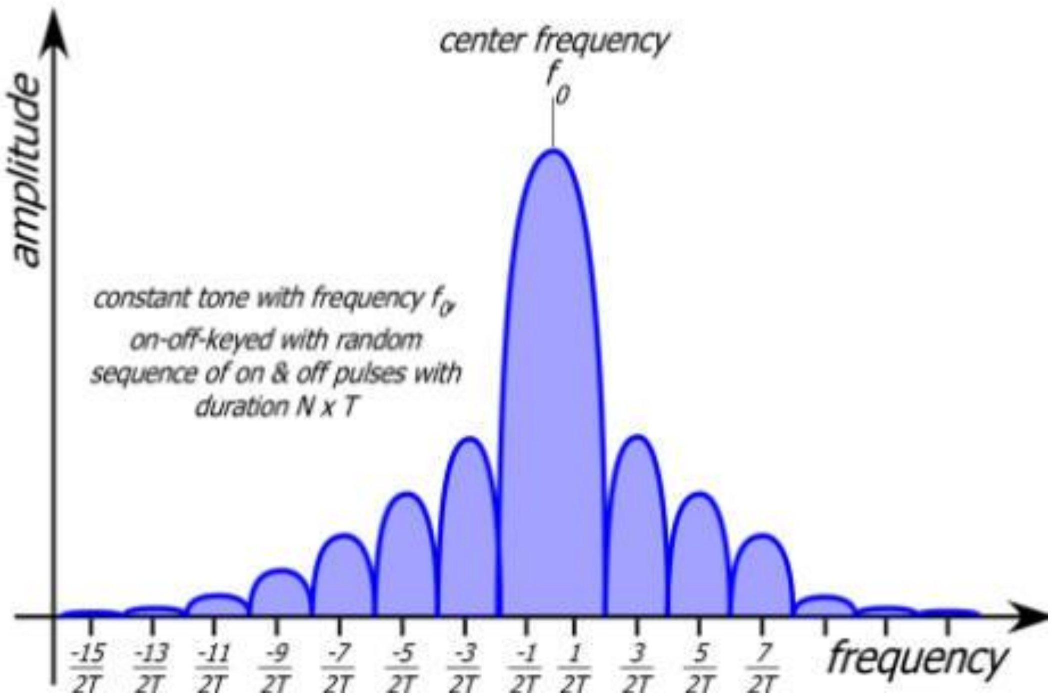


At RX

Digital Modulation

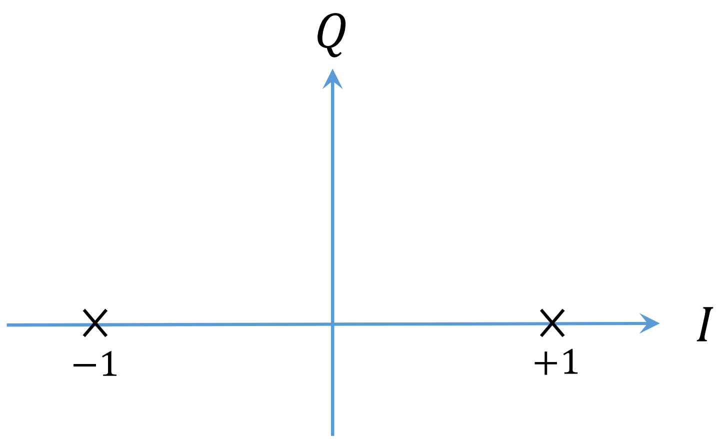
- Map Bits to Signal Values
- On-Off Keying (ASK):





Digital Modulation

- BPSK : Binary Phase Shift Keying



$\pm 1 \cos(2\pi f_c t) = \cos(2\pi f_c t + \pi) = -1 \Big\}$ phase coherence

- DBPSK : Differential Binary Phase Shift Keying

$\cos(2\pi f_c t + \phi)$

$\cos(2\pi f_c t + \phi + \pi) \longrightarrow 1$

$\cos(2\pi f_c t + \phi) \longrightarrow 0$

SNR: Signal-To-Noise Ratio

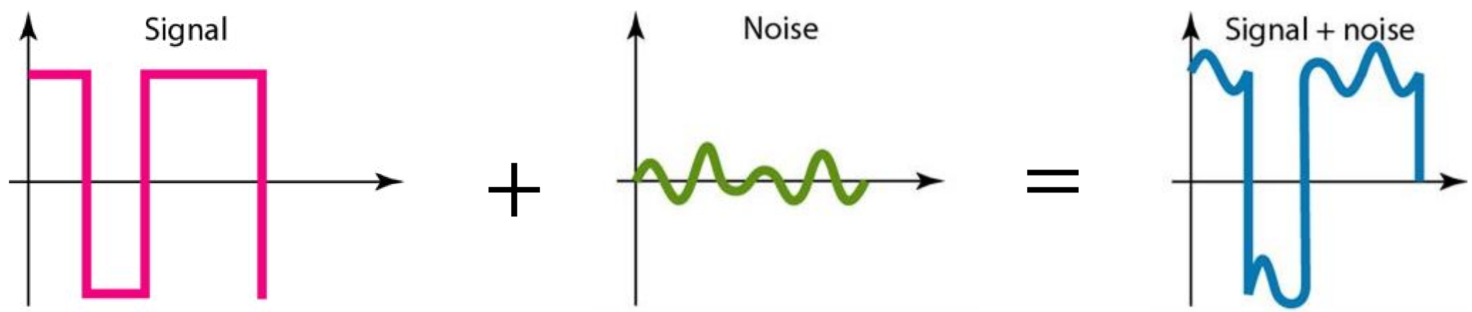
$$SNR = \frac{Received\ Signal\ Power}{Noise\ Power\ at\ RX}$$

Tx power

wirelechannel

Hardware

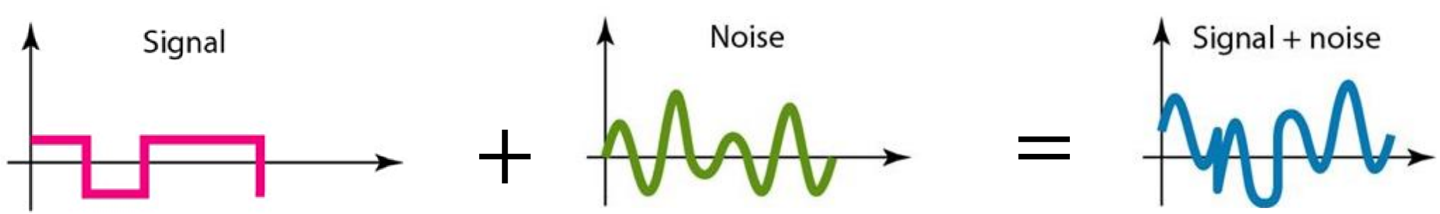
– High SNR – easier to extract signal from noise (a "good thing")



Bits: 0 1 0 0

0 1 0 0

– Low SNR – hard to extract signal from noise (a "bad thing")



Bits: 0 1 0 0

SNR: Signal-To-Noise Ratio

$$SNR = \frac{Received\ Signal\ Power}{Noise\ Power\ at\ RX}$$

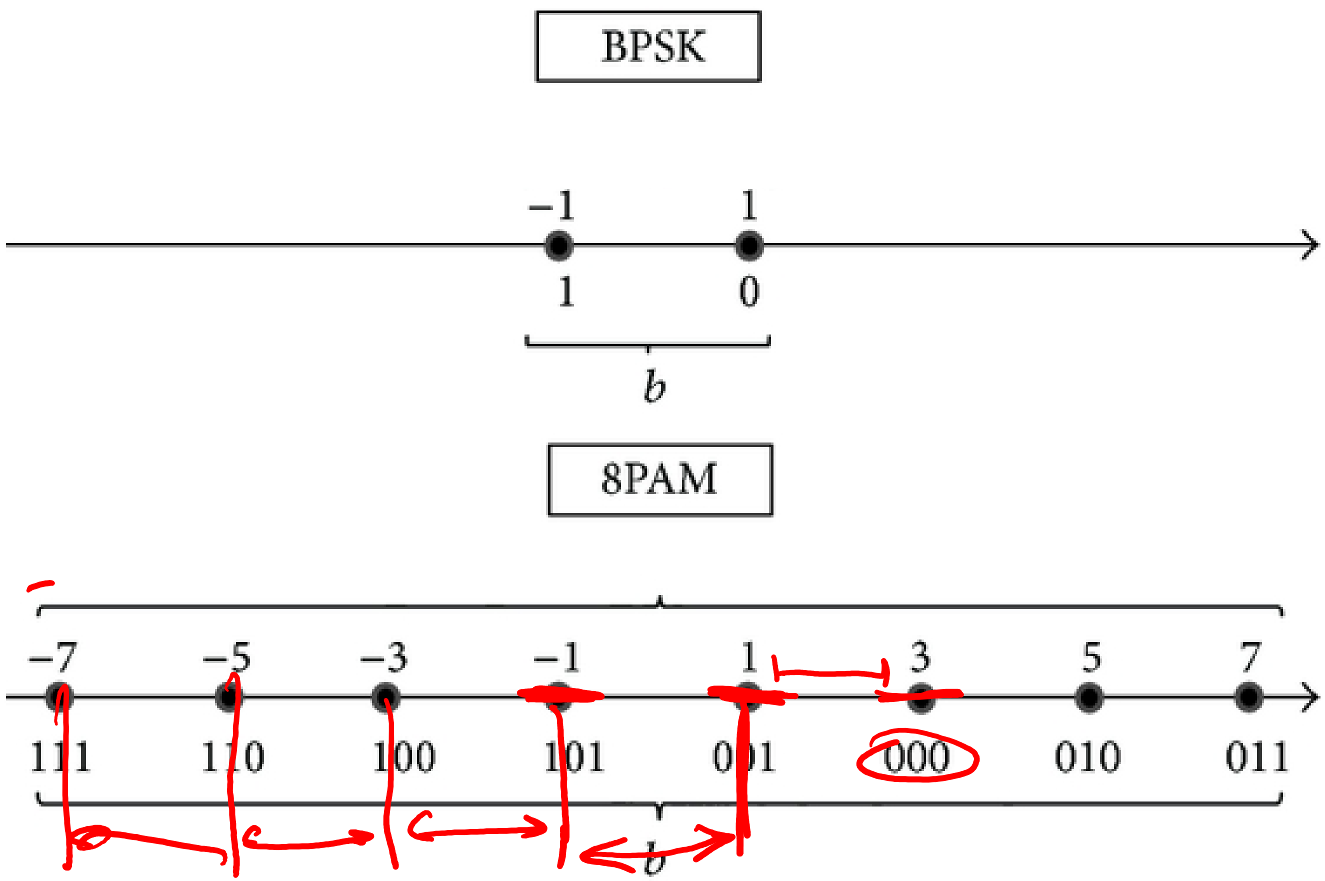
Why not increase SNR by increasing your transmit power?

- FCC regulation
- Battery
- Heat / Circuit limitations

$\Bigg\}$ Power budget $= P$

Higher Order Modulation

- High SNR ➔ Lower Bit Error ➔ Use higher order modulation i.e. pack more bits per symbol

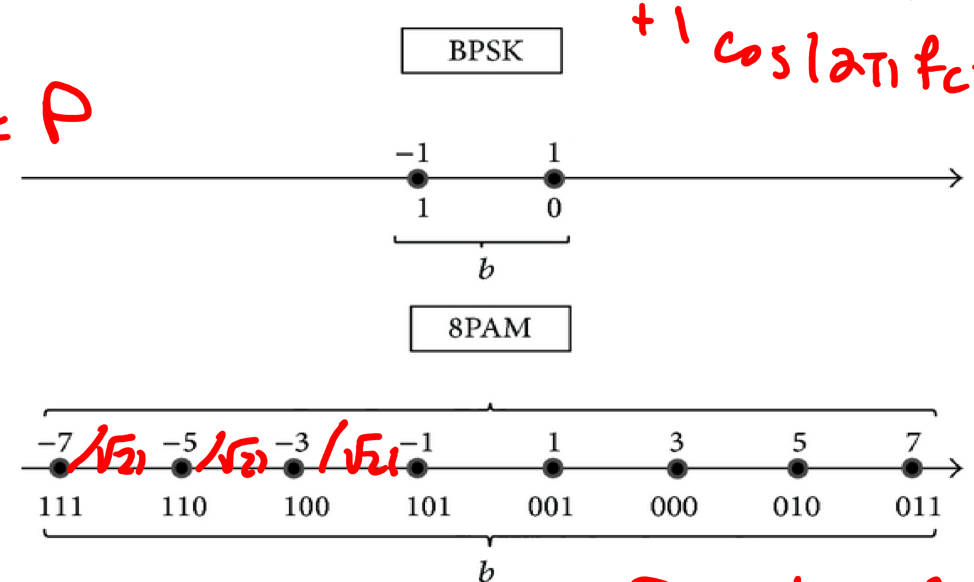


Digital Modulation

- PAM : Pulse Amplitude Modulation
  - Scale to maintain total average power

$\sqrt{P}$ $-1\cos(2\pi f_c t)$
$+1\cos(2\pi f_c t)$

$$P_{avg} = \frac{1}{2}\left((-1\times\sqrt{P})^2 + (1\times\sqrt{P})^2\right) = P$$



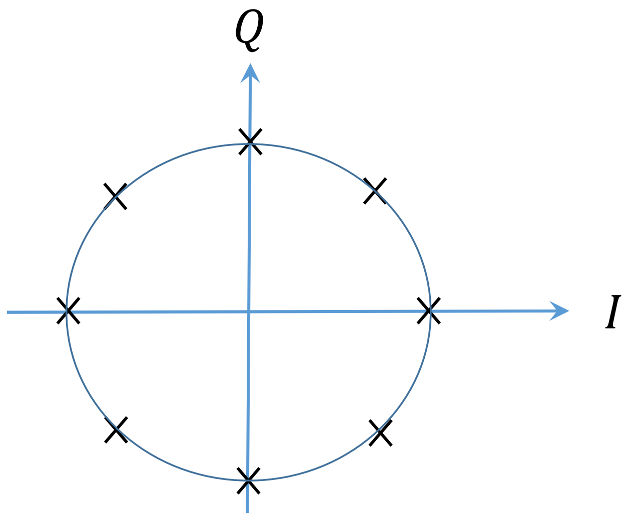
$$P_{avg} = \frac{1}{8}\left(\frac{49+25+9+1}{21}\right)\times 2$$

$$= \frac{21P}{21} = P$$

$-7\cos(2\pi f_c t)$

Digital Modulation

- QPSK : Quadrature Phase Shift Keying



ϕ

$\cos(2\pi f_c + 0) \Rightarrow 000$

$\cos(2\pi f_c + \pi/4) \Rightarrow 001$

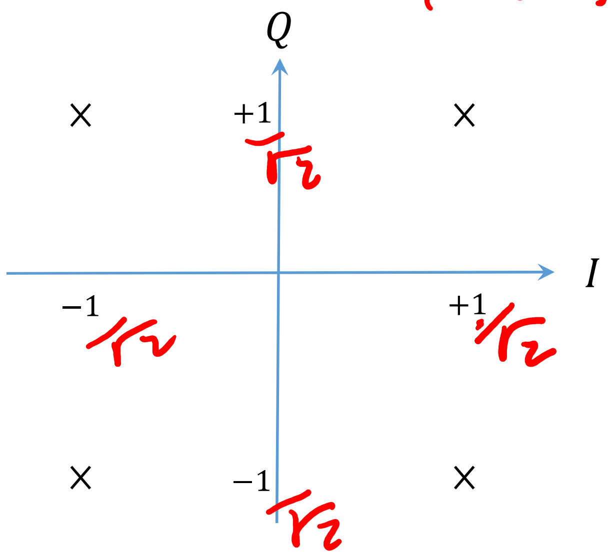
$\vdots$

- DQPSK : Differential Quadrature Phase Shift Keying

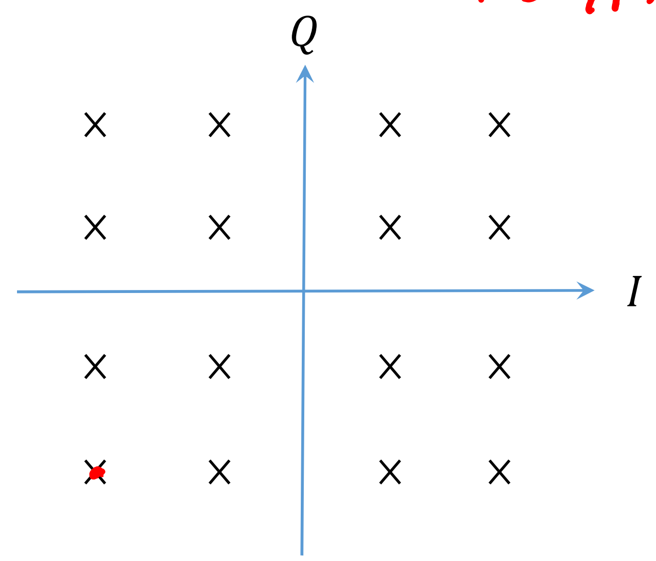
Digital Modulation

- QAM : Quadrature Amplitude Modulation

4QAM



16QAM



$-3-3j$

Quadrature Modulation

$$y(t) = I\cos(2\pi f_c t) + Q\sin(2\pi f_c t) \qquad x(t) = I + Qj$$

$$y(t)\cos(2\pi f_c t) = I\cos^2(2\pi f_c t) + Q\cos(2\pi f_c t)\sin(2\pi f_c t)$$

$$= \frac{I}{2} + \cancel{\frac{I}{2}\cos(2\pi\, 2 f_c t)} + \cancel{\frac{Q}{2}\sin(2\pi\, 2 f_c t)}$$

$$= \frac{I}{2}$$

$$y(t)\sin(2\pi f_c t) = \cancel{I\cos(2\pi f_c t)\sin(2\pi f_c)} + Q\sin^2(2\pi f_c t)$$

$$= \frac{Q}{2}$$

Quadrature Modulation

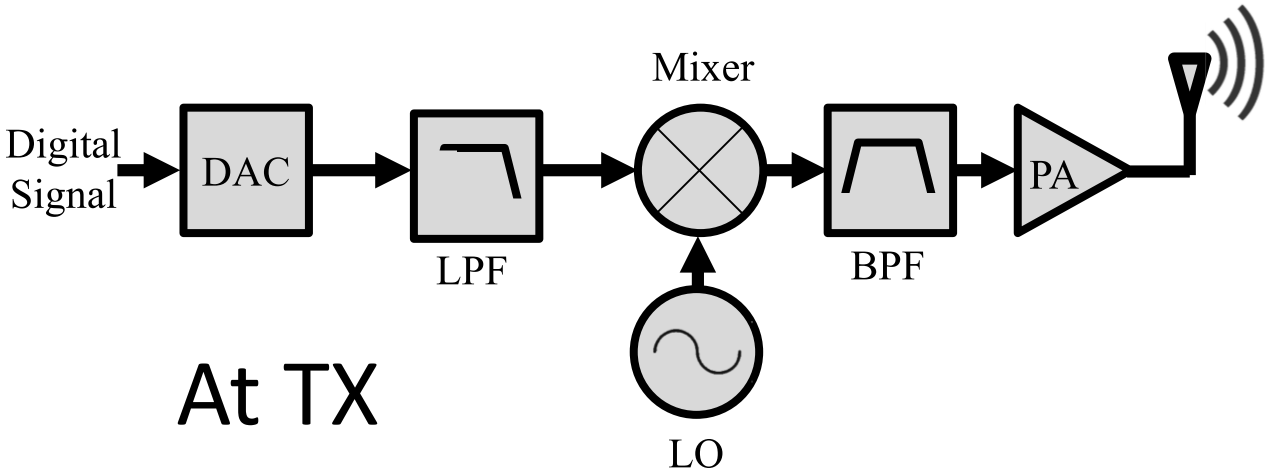
$$y(t) = I\cos(2\pi f_c t) + Q\sin(2\pi f_c t)$$

$$= \mathrm{Re}\left\{ x(t)\, e^{-j2\pi f_c t} \right\}$$

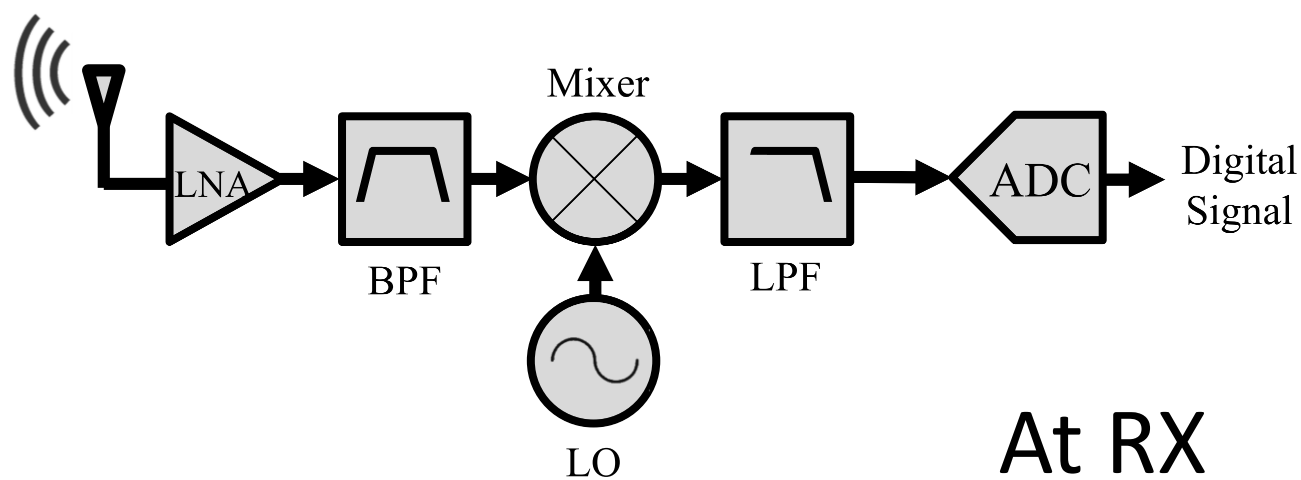
$$y(t) = x(t)\, e^{-j2\pi f_c t}$$

$$y(t)\, e^{j2\pi f_c t} = x(t)\, e^{-j2\pi f_c t}\, e^{j2\pi f_c t} = x(t)$$

Up Conversion & Down-Conversion

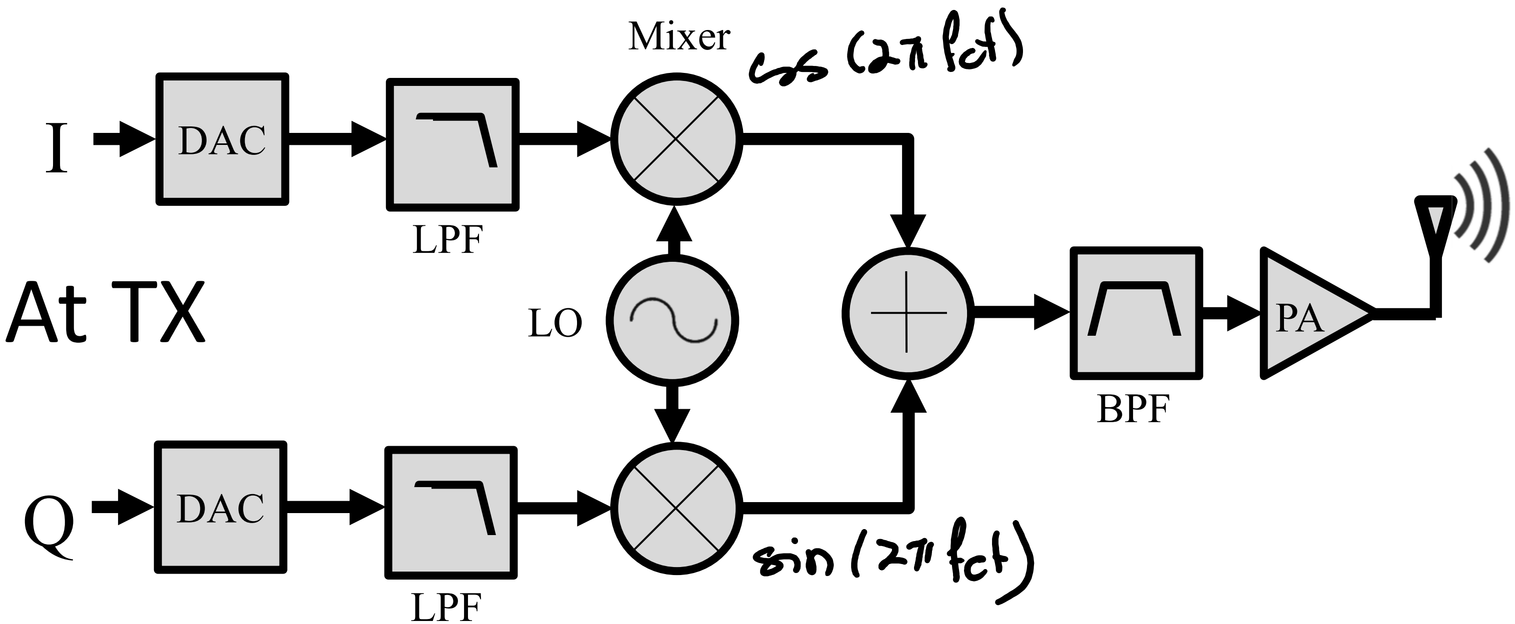


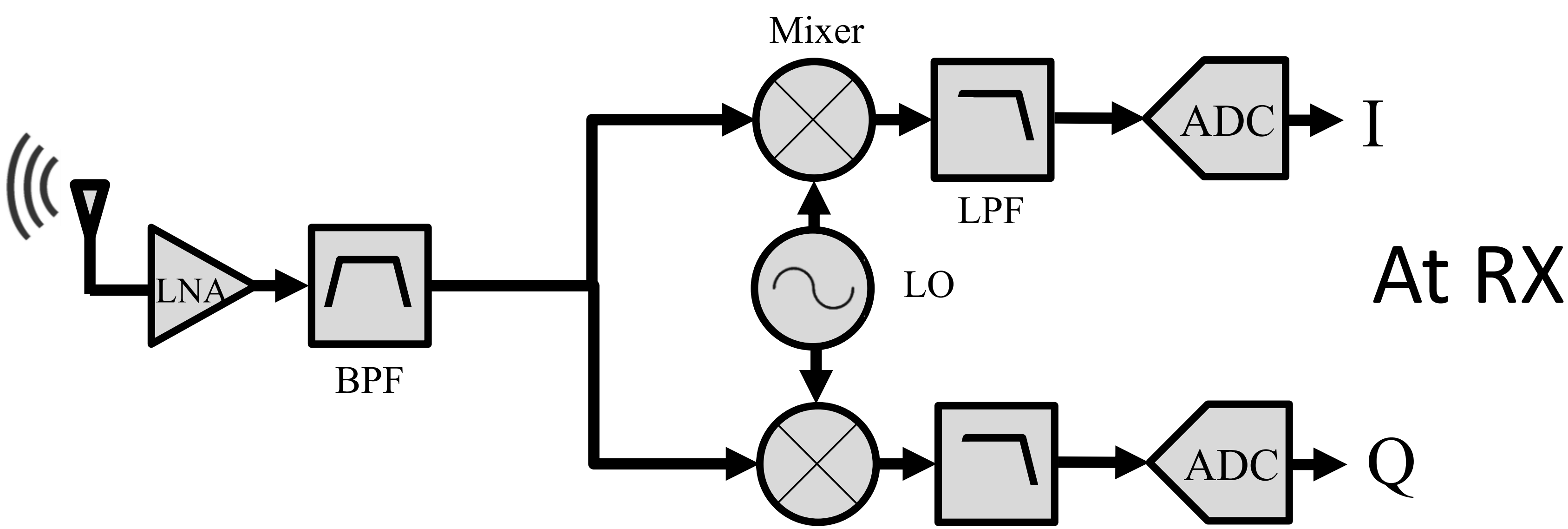
At TX



At RX

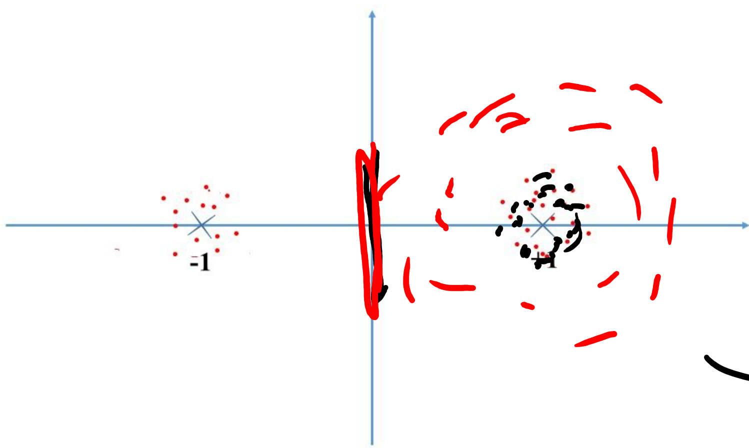
Up Conversion & Down-Conversion



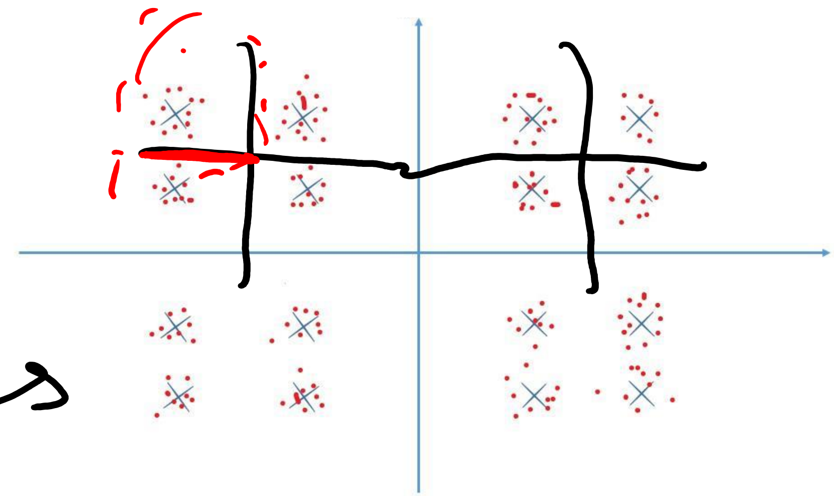


Additive White Gaussian Noise

BPSK: 1 bit per symbol



16 QAM: 4 bits per symbol



Maximum Likelihood Decoder

$b=0 \rightarrow Y$

$$P(Y \mid b=0) \underset{b=1}{\overset{b=0}{\gtrless}} P(Y \mid b=1)$$

$b = \Rightarrow x = \pm 1$

$Y = X + N \rightarrow \mathcal{N}(0, \sigma)$

Given $b=0 \Rightarrow Y \sim \mathcal{N}(1, \sigma)$

$b=1 \Rightarrow Y \sim \mathcal{N}(-1, \sigma)$

$$P(y \mid b=0) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(y-1)^2}{2\sigma^2}}$$

Maximum Likelihood Decoder

$$\frac{1}{\cancel{\sqrt{2\pi}\sigma}} e^{-\frac{(y-1)^2}{2\sigma^2}} \underset{1}{\overset{0}{\gtrless}} \frac{1}{\cancel{\sqrt{2\pi}\sigma}} e^{-\frac{(y+1)^2}{2\sigma^2}}$$

$$-\frac{(y-1)^2}{\cancel{2\sigma^2}} \underset{1}{\overset{0}{\gtrless}} -\frac{(y+1)^2}{\cancel{2\sigma^2}}$$

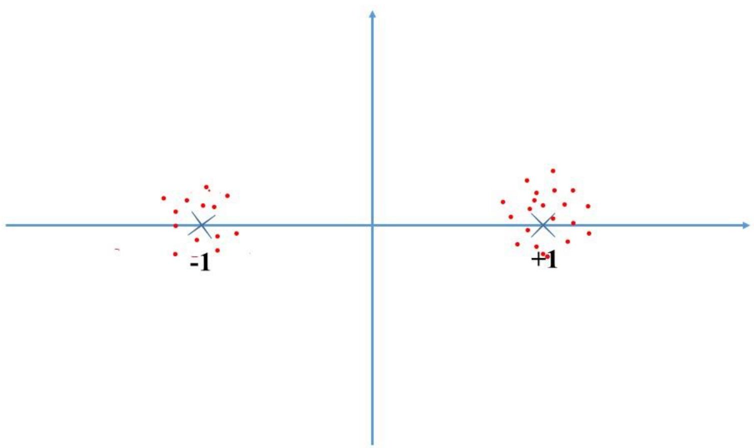
$$-\cancel{y^2}+2y\cancel{-1} \underset{1}{\overset{0}{\gtrless}} -y^2-2y\cancel{-1}$$

$$y \underset{1}{\overset{0}{\gtrless}} 0$$

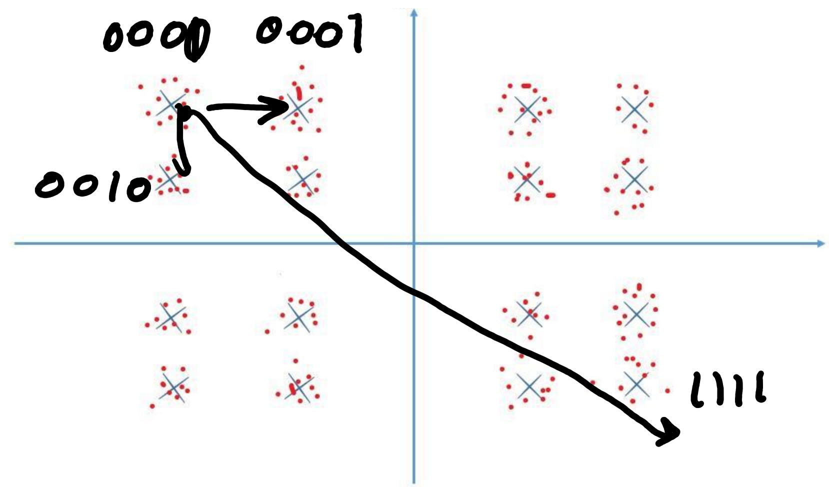
Maximum Likelihood Decoder

Additive White Gaussian Noise

BPSK: 1 bit per symbol



16 QAM: 4 bits per symbol



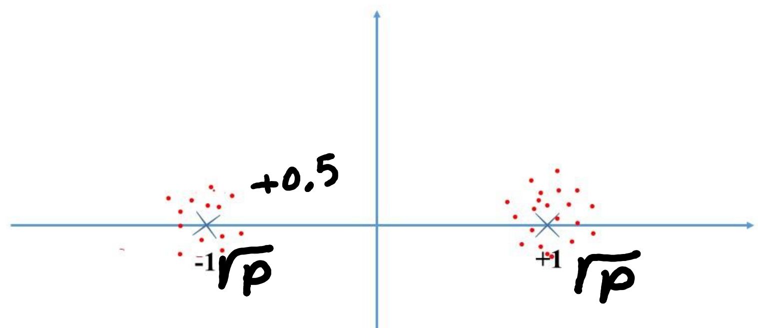
How to map the bits to constellation points?

Nearby constellation points have 1 bit difference

Gray Codes

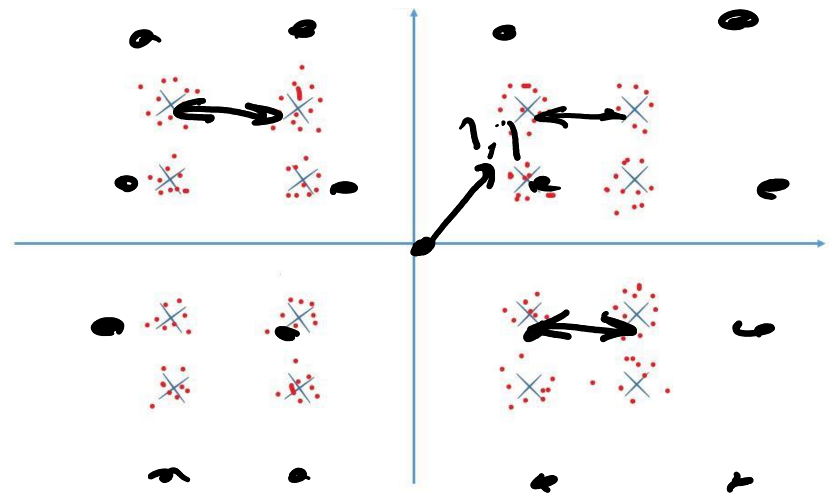
Additive White Gaussian Noise

BPSK: 1 bit per symbol



$\Rightarrow \frac{P+P}{2} = P$ $2\sqrt{P}$

16 QAM: 4 bits per symbol



Why is constellation centered at 0?

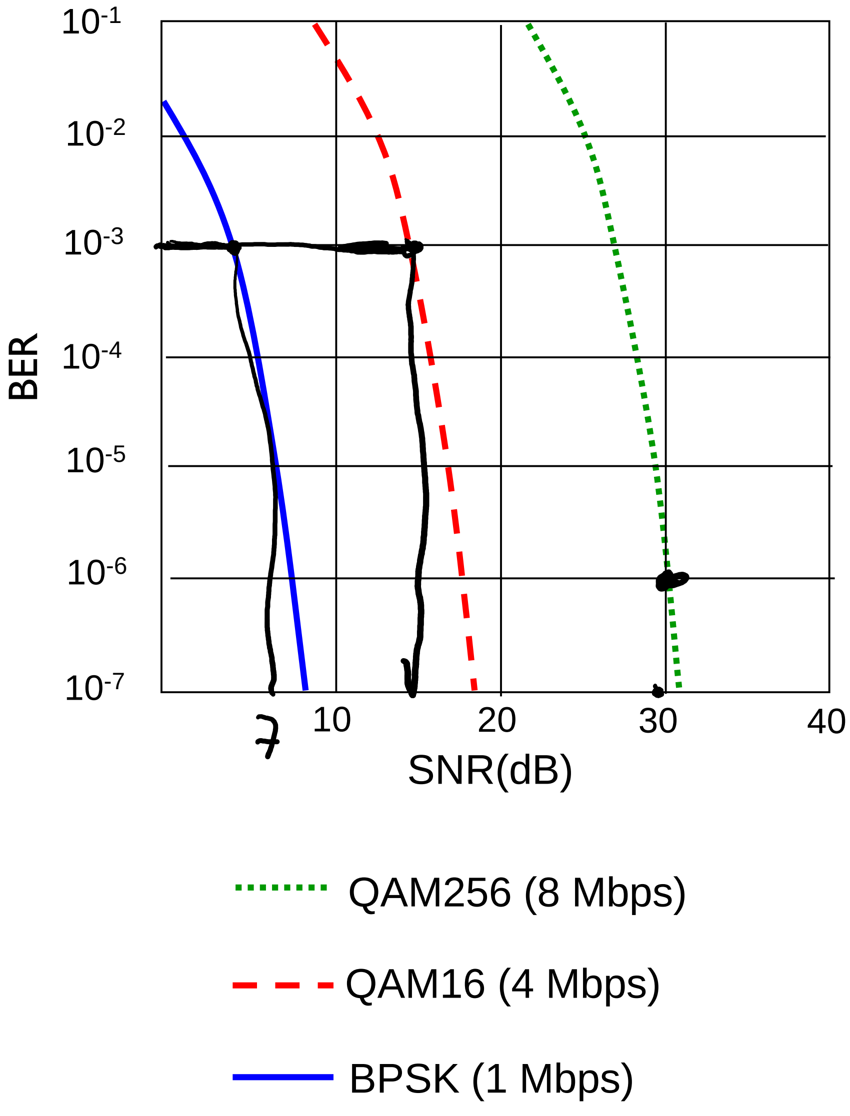
$0.5\sqrt{P}$ $1.5\sqrt{P}$ $\Rightarrow \frac{1}{2}\left(\frac{1}{4}P + \frac{9}{4}P\right) = 1.25\,P$

Bit-Error-Rate

- *SNR versus BER tradeoffs*
  - *given physical layer modulation:*

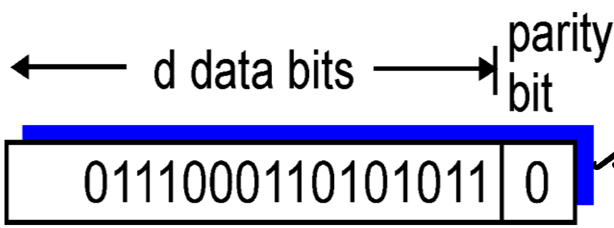
    Higher SNR → Low BER

  - *given SNR:* choose physical layer that meets BER requirement, giving highest throughput



Error Detection and Correction

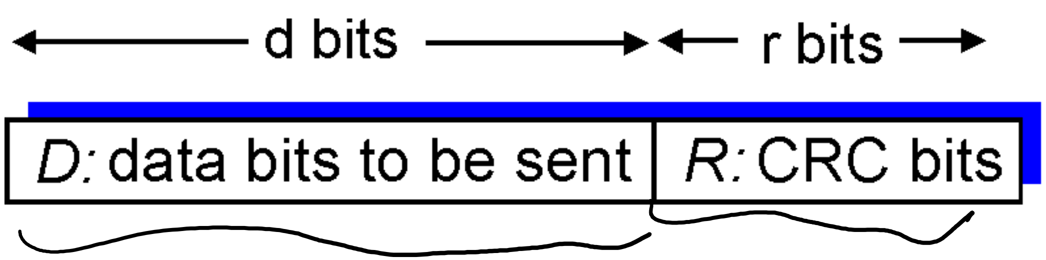
- Add Redundant bit to
- Checksums→ Detect Errors
  - Parity Check



even # of 1 ⇒ 0
odd # of 1 ⇒ 1

1 bit error
odd number of bit flips

  - CRC: Cyclic Redundancy Check

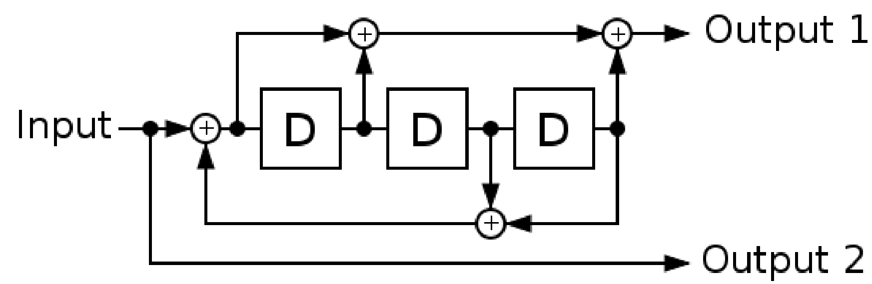


bit pattern

larger r
⇒ detect more errors

Error Detection and Correction

- FEC: Forward Error Correction
  - Repetition Code
  - Convolutional codes
  - Reed Solomon codes
  - Turbo codes
  - LDPC codes

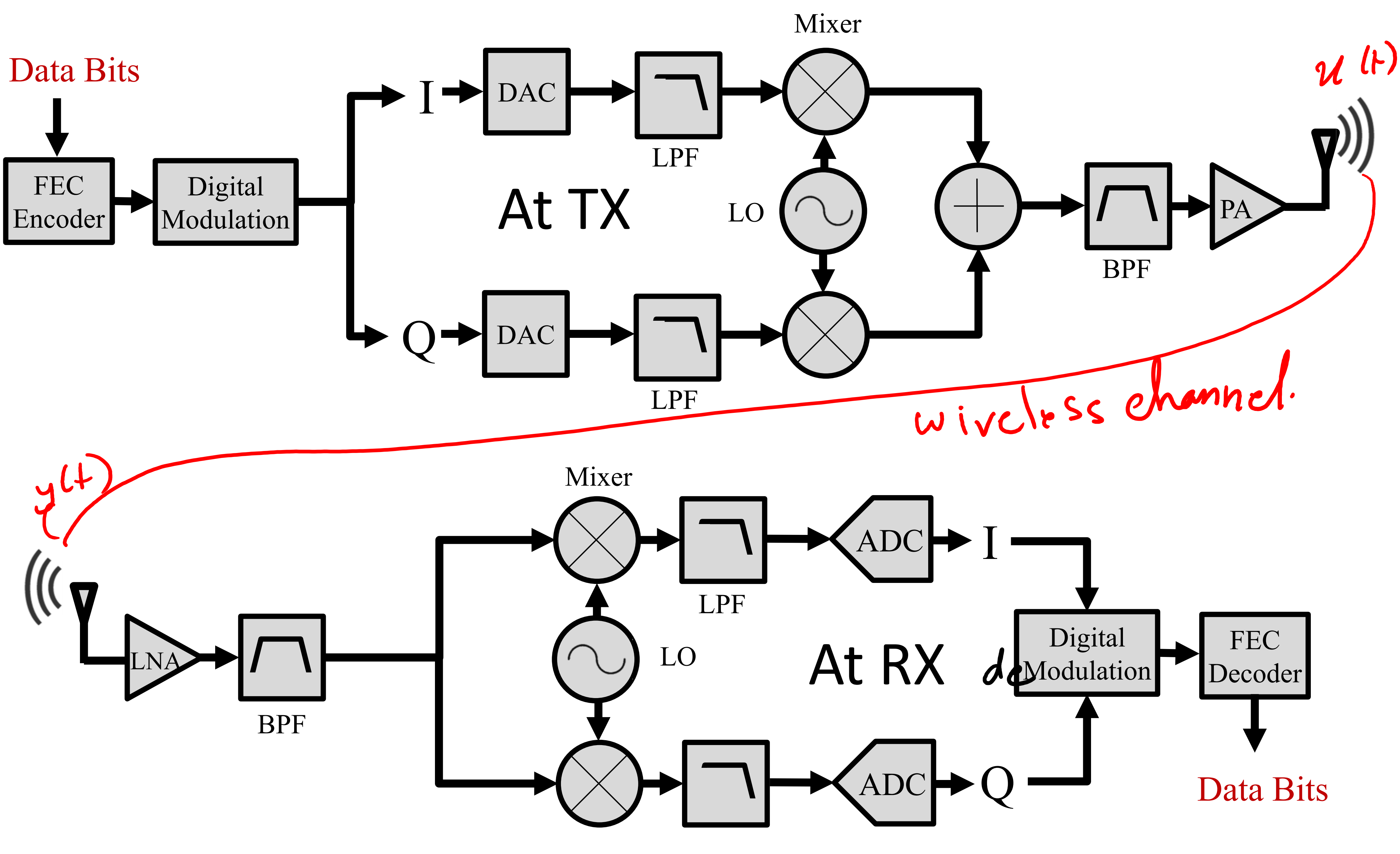


- Coding Rate $= \frac{2}{3}$ → every two bits add 1 more bit

↗ coding rate ⇒ less correct

↙ coding rate ⇒ ↗ redundancy ⇒ ↗ correct bits

Transmitter & Receiver Circuits



Data Rate

- Depends on Modulation & FEC

Bandwidth = B

$$\text{Data rate} = B \times \underbrace{\text{bits/sample}}_{\text{Modulation}} \times \underbrace{\text{coding rate}}_{\text{FEC Coding}}$$

Capacity of Wireless Channel

- *Given SNR, what is maximum rate that we can achieve?*
  - *Shannon Capacity Theorem:*

$$Capacity = Bandwidth \times \log_2(1 + SNR)$$