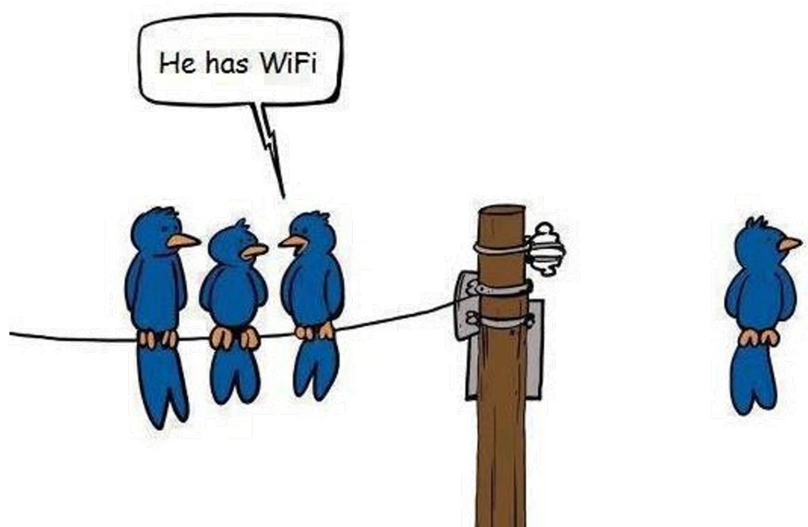
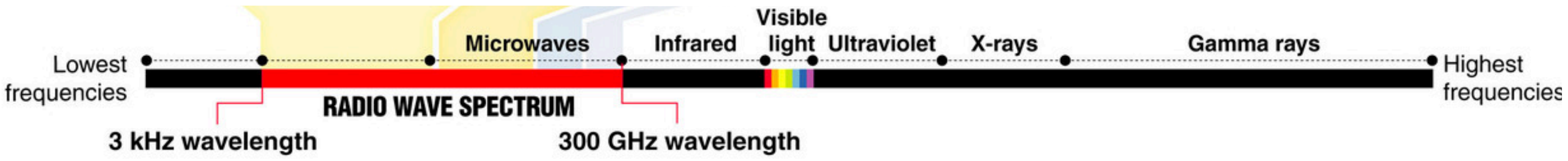
ECE 598HH: Advanced Wireless Networks and Sensing Systems

Lecture 2: Review: Wireless Communication

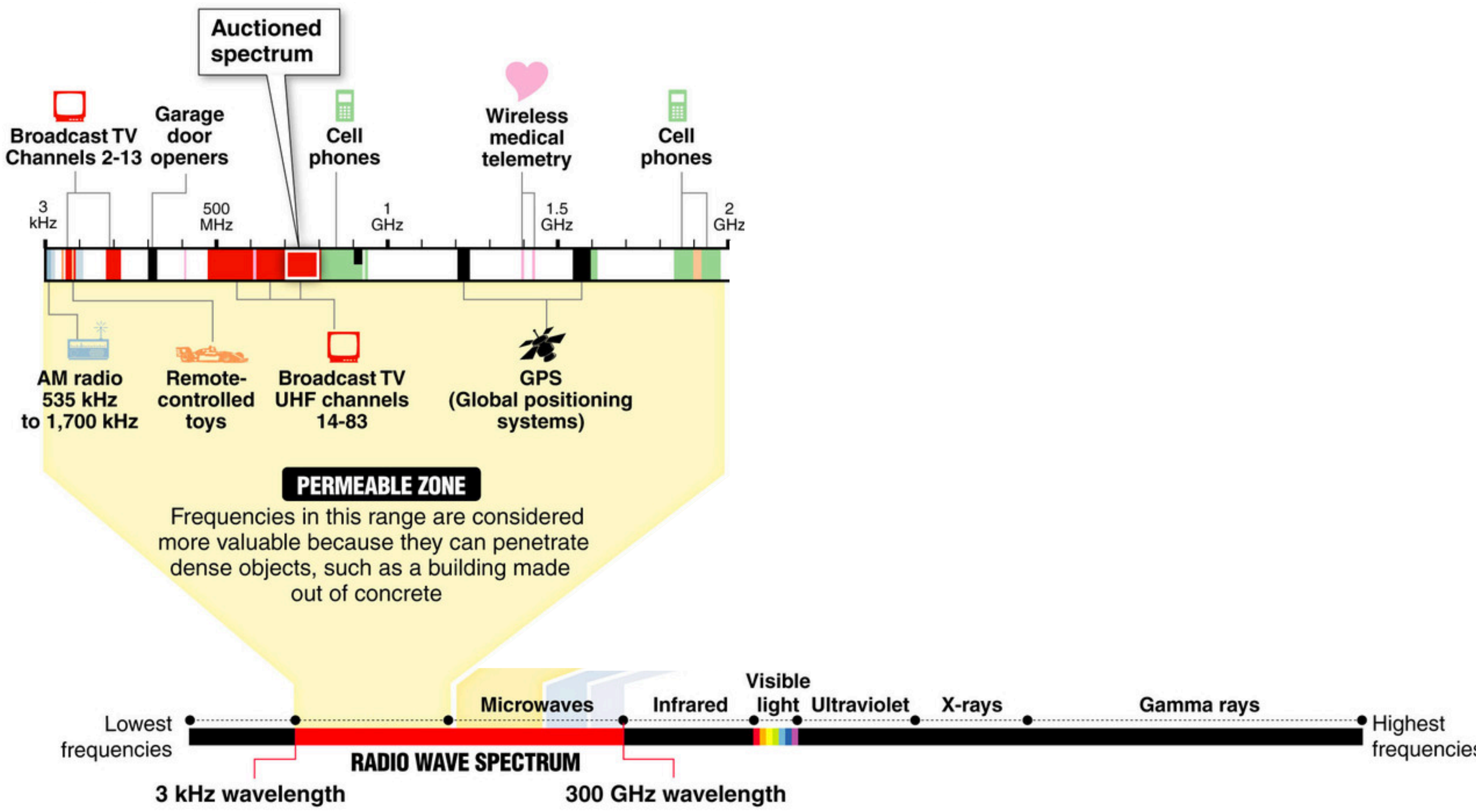
Haitham Hassanieh



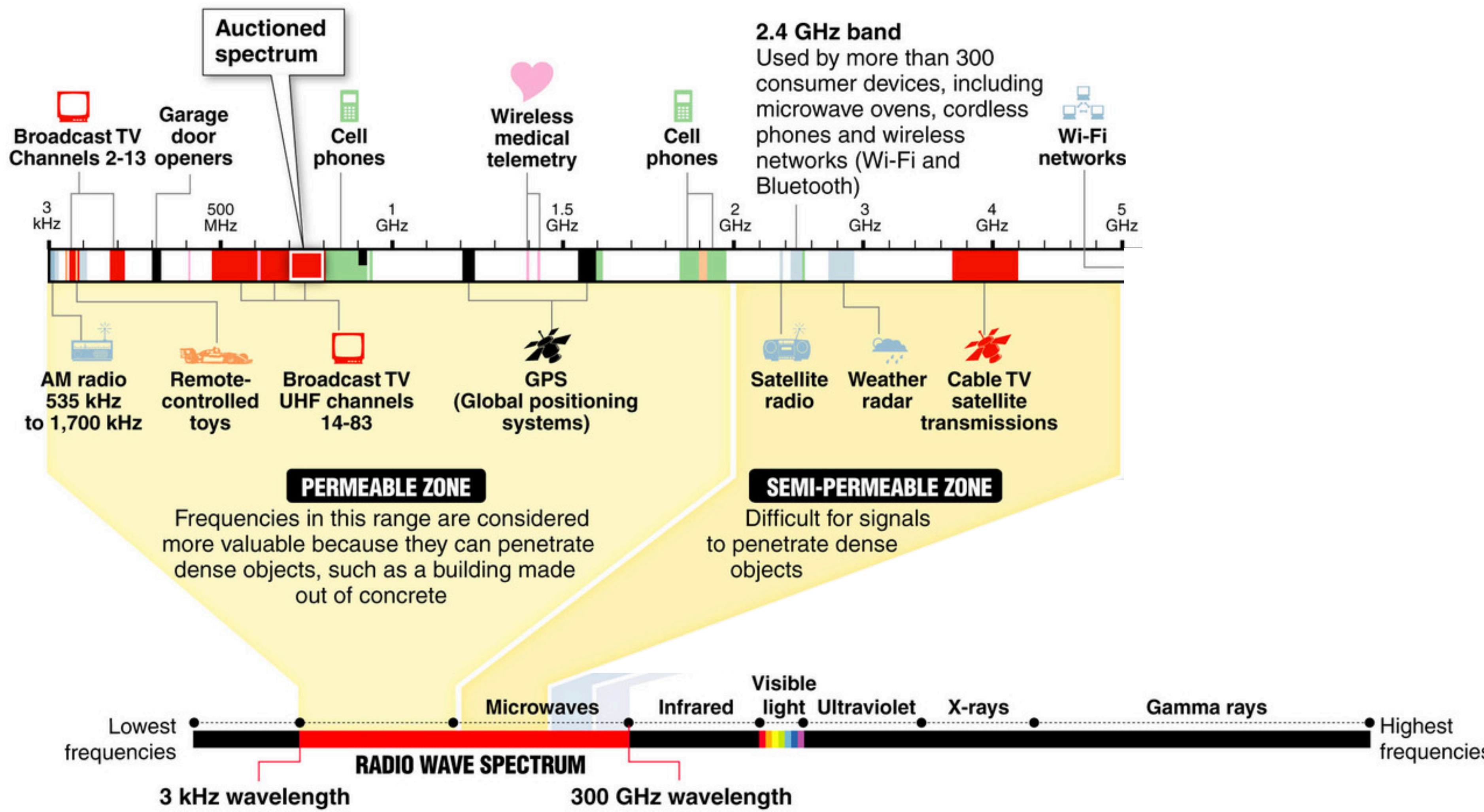
The Wireless Spectrum



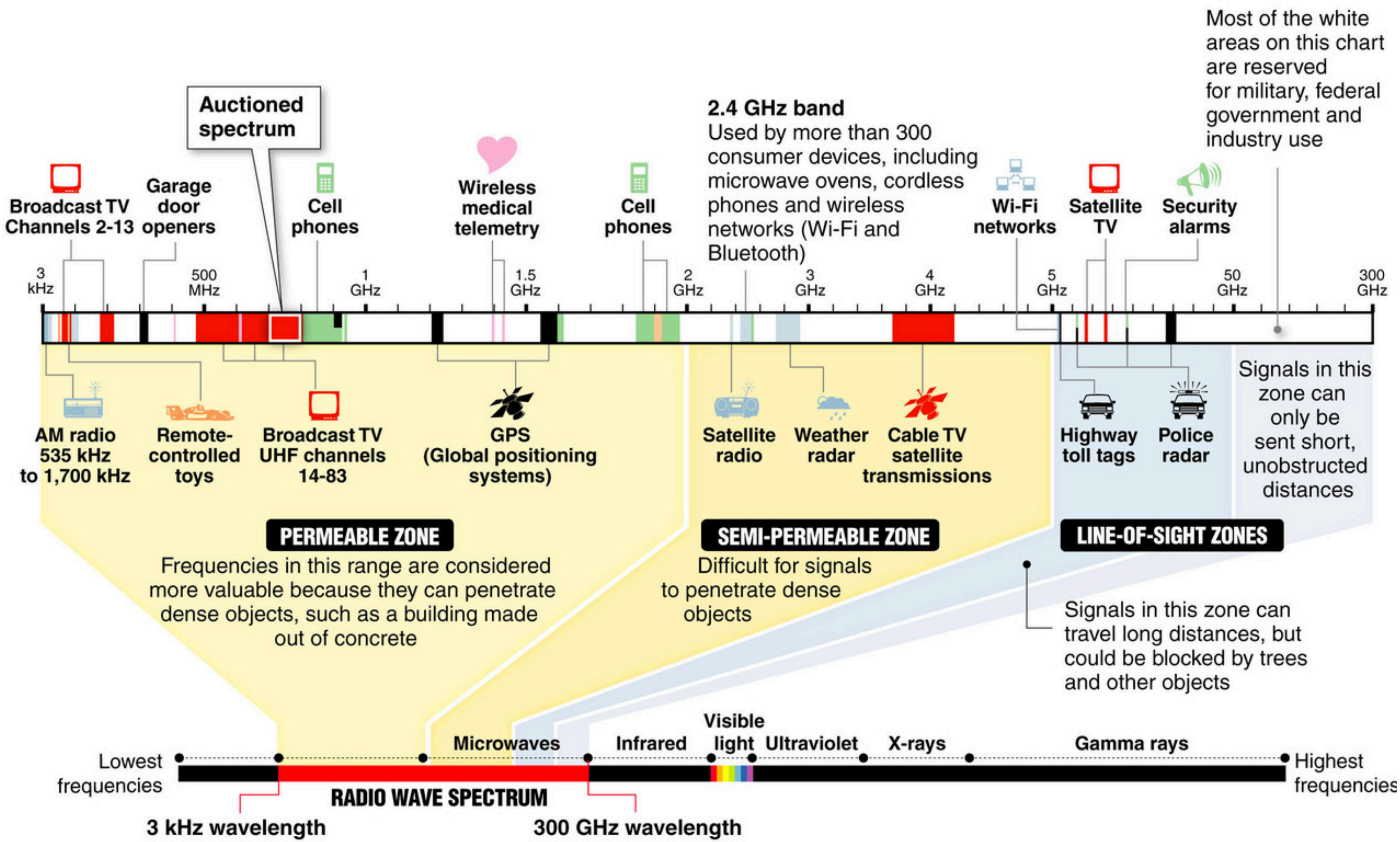
The Wireless Spectrum



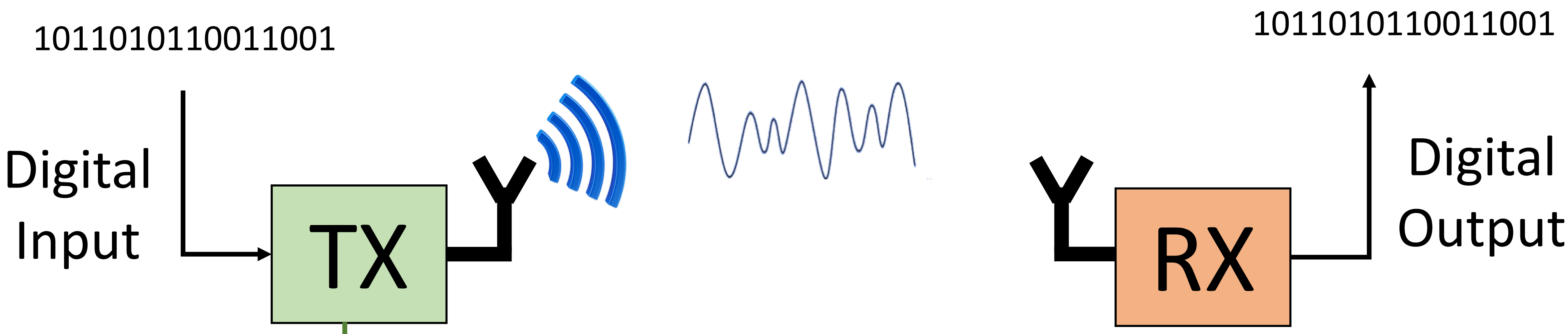
The Wireless Spectrum

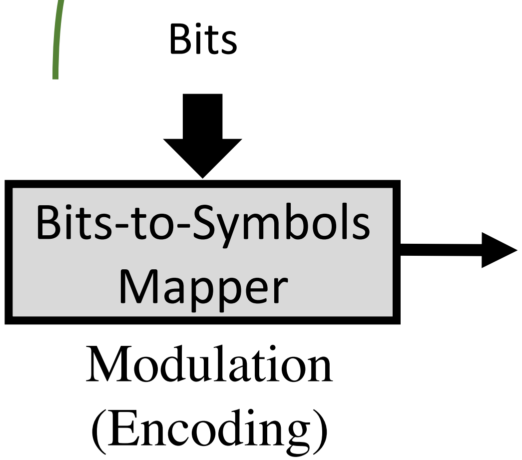


The Wireless Spectrum



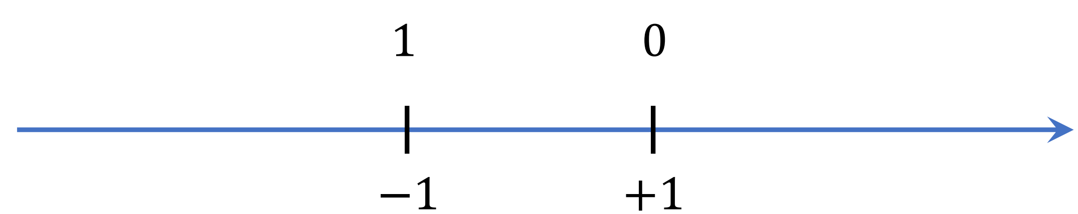
Wireless Communication System



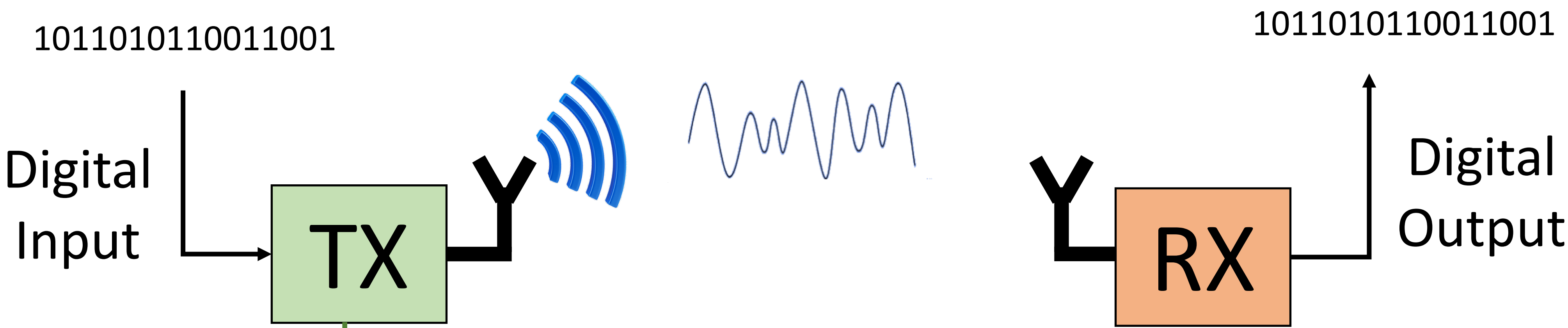


Modulation: Mapping of Bits to Symbols

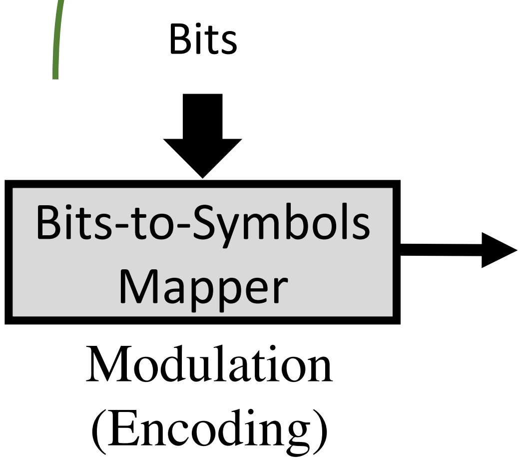
BPSK: 1 bits/symbol



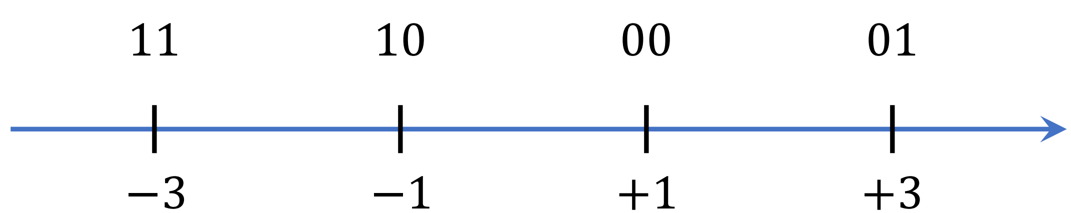
Wireless Communication System



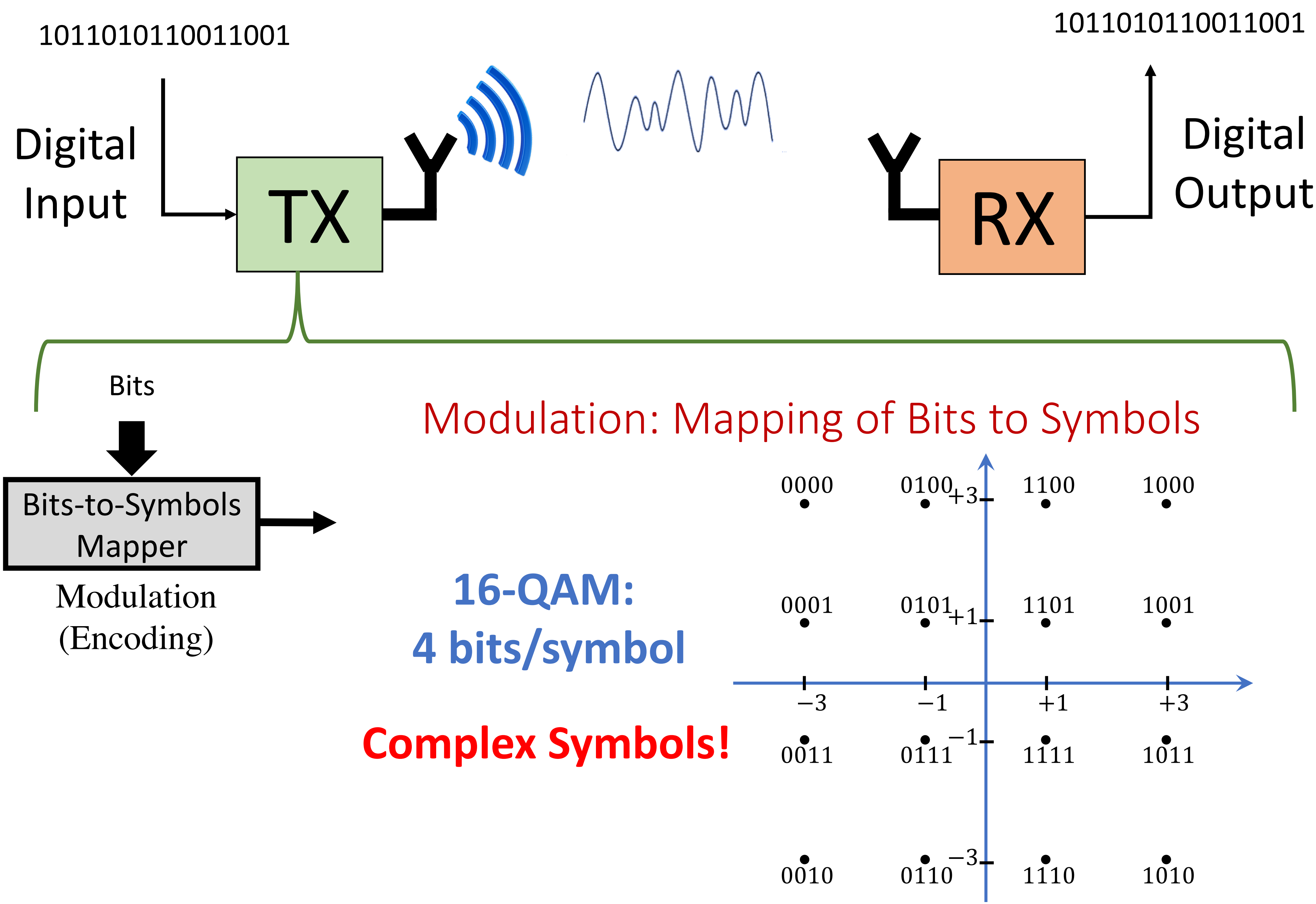
Modulation: Mapping of Bits to Symbols



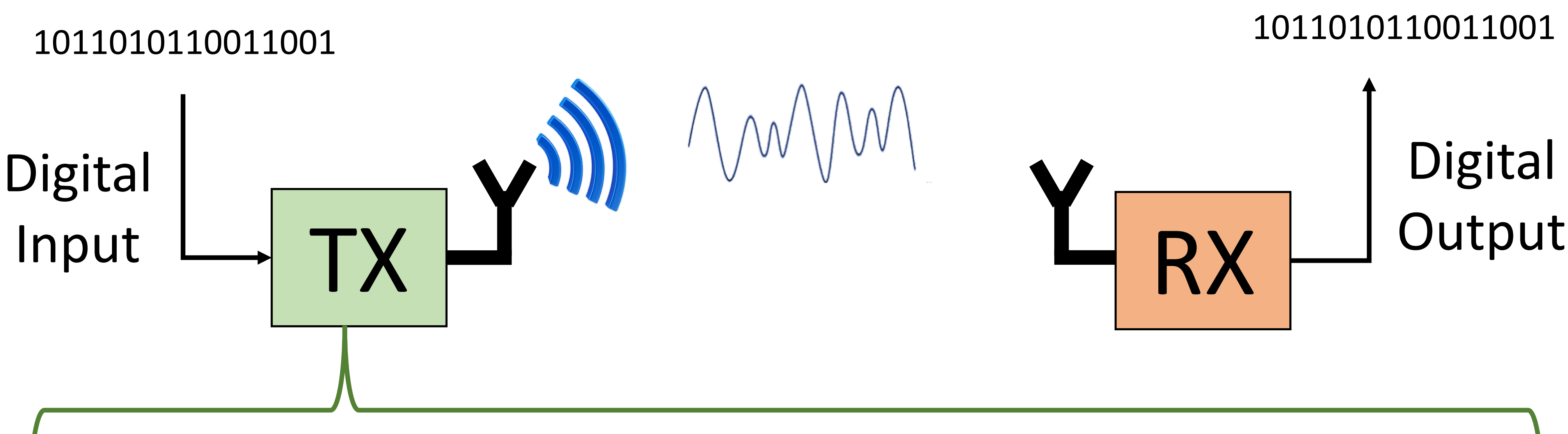
PAM: 2 bits/symbol

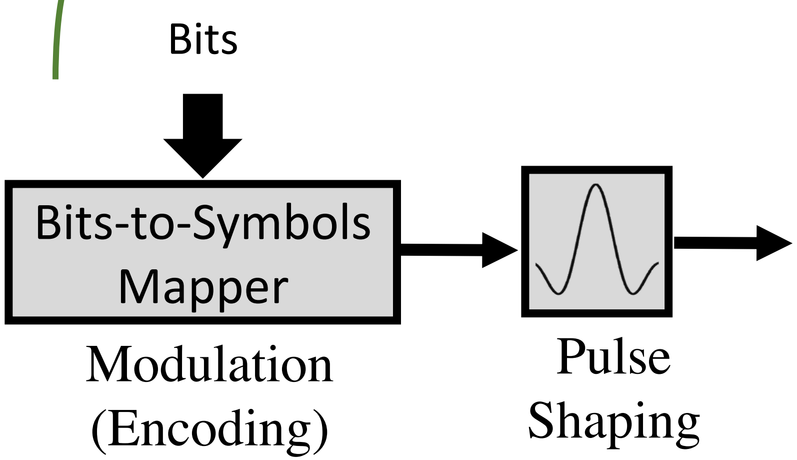


Wireless Communication System



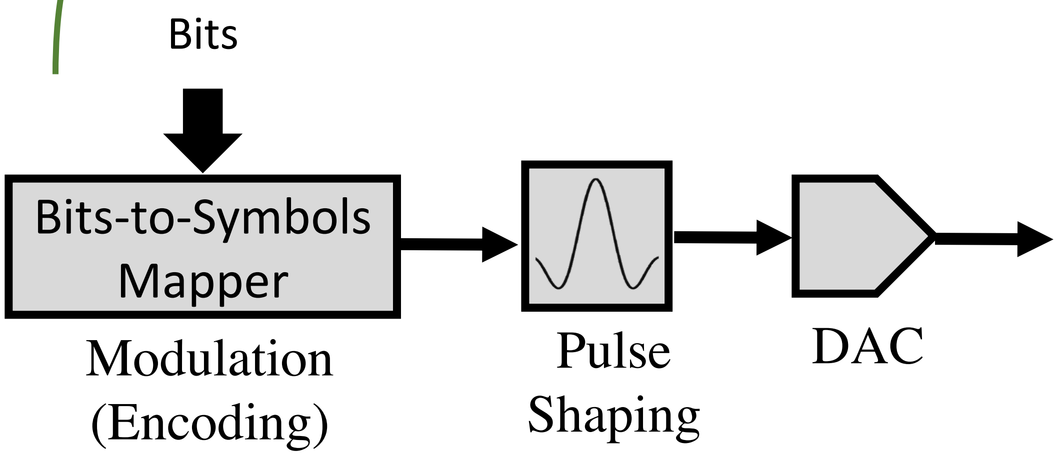
Wireless Communication System





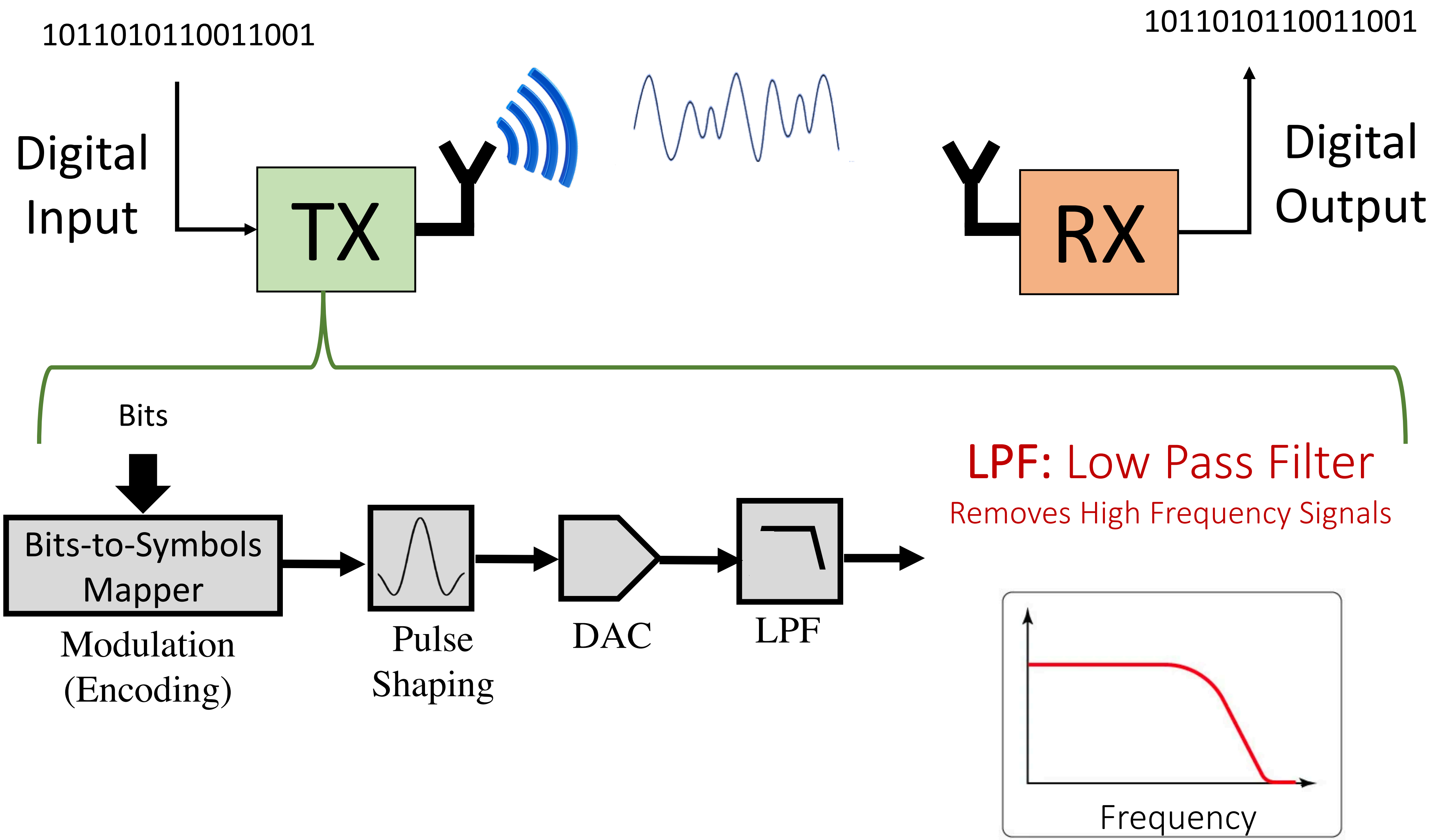
Pulse Shaping: Takes modulated symbol values and creates a smooth digital signal

Wireless Communication System

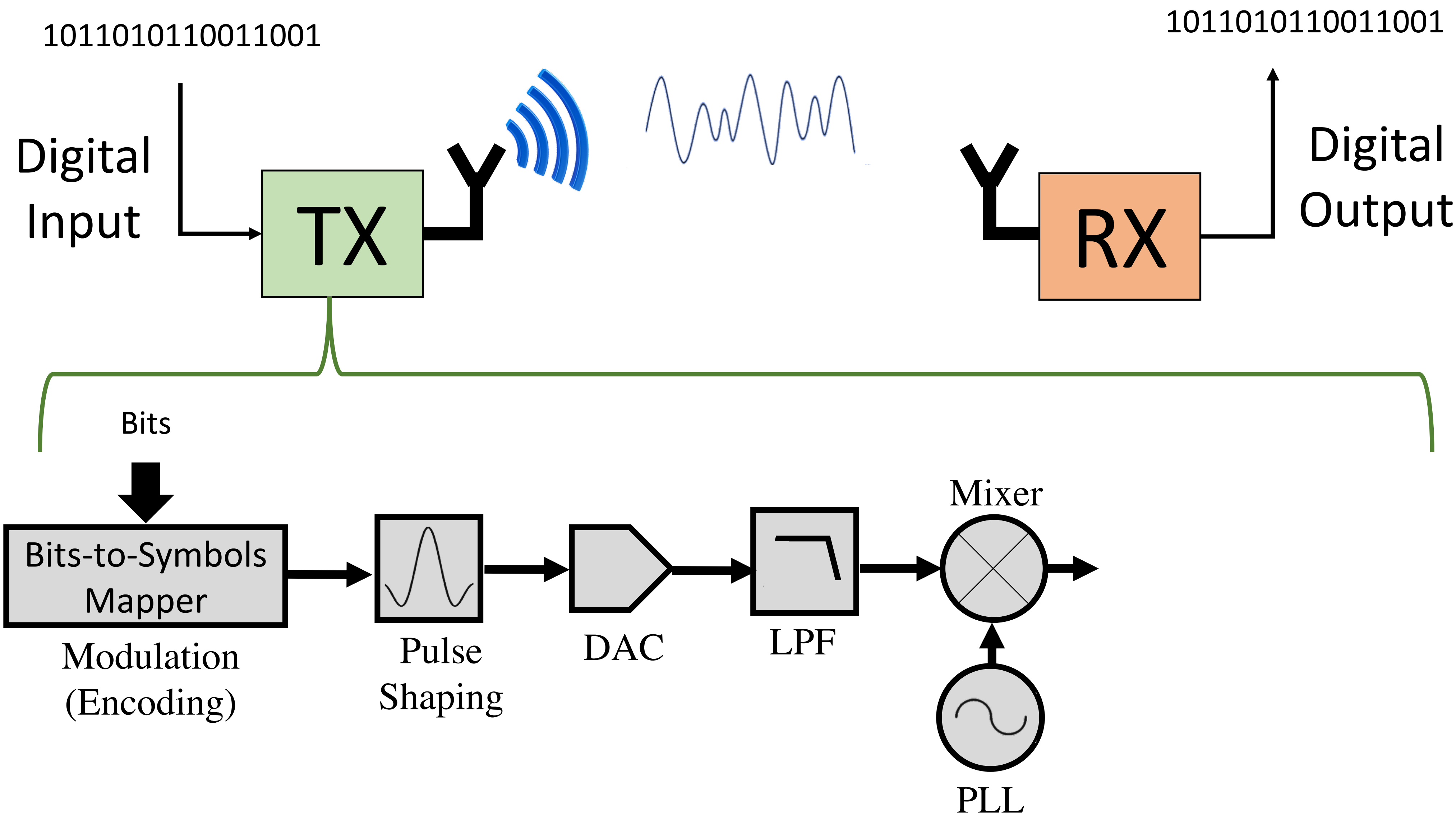


DAC: Digital-to-Analog Converter: Takes digital signal values and outputs analog signal i.e. current/voltage on the circuit.

Wireless Communication System

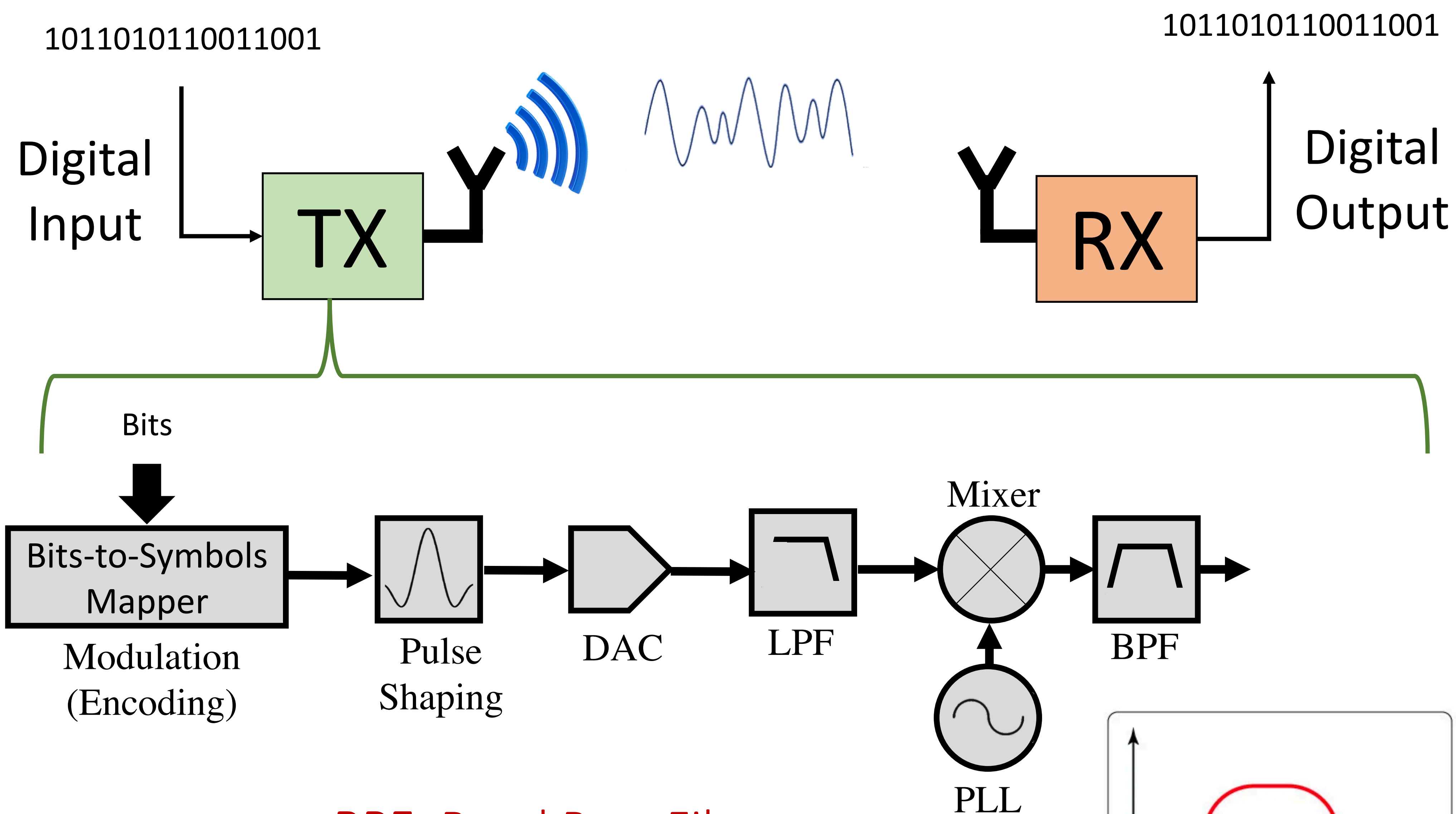


Wireless Communication System



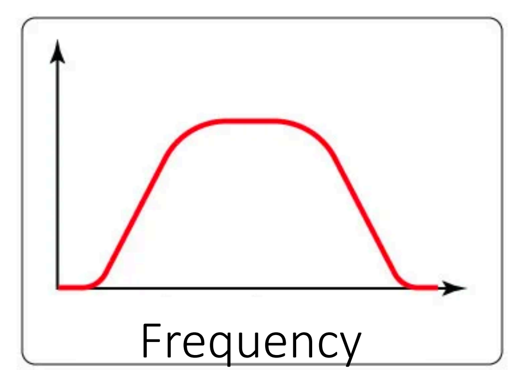
Mixer/PLL: Move signal to desired frequency of operation

Wireless Communication System

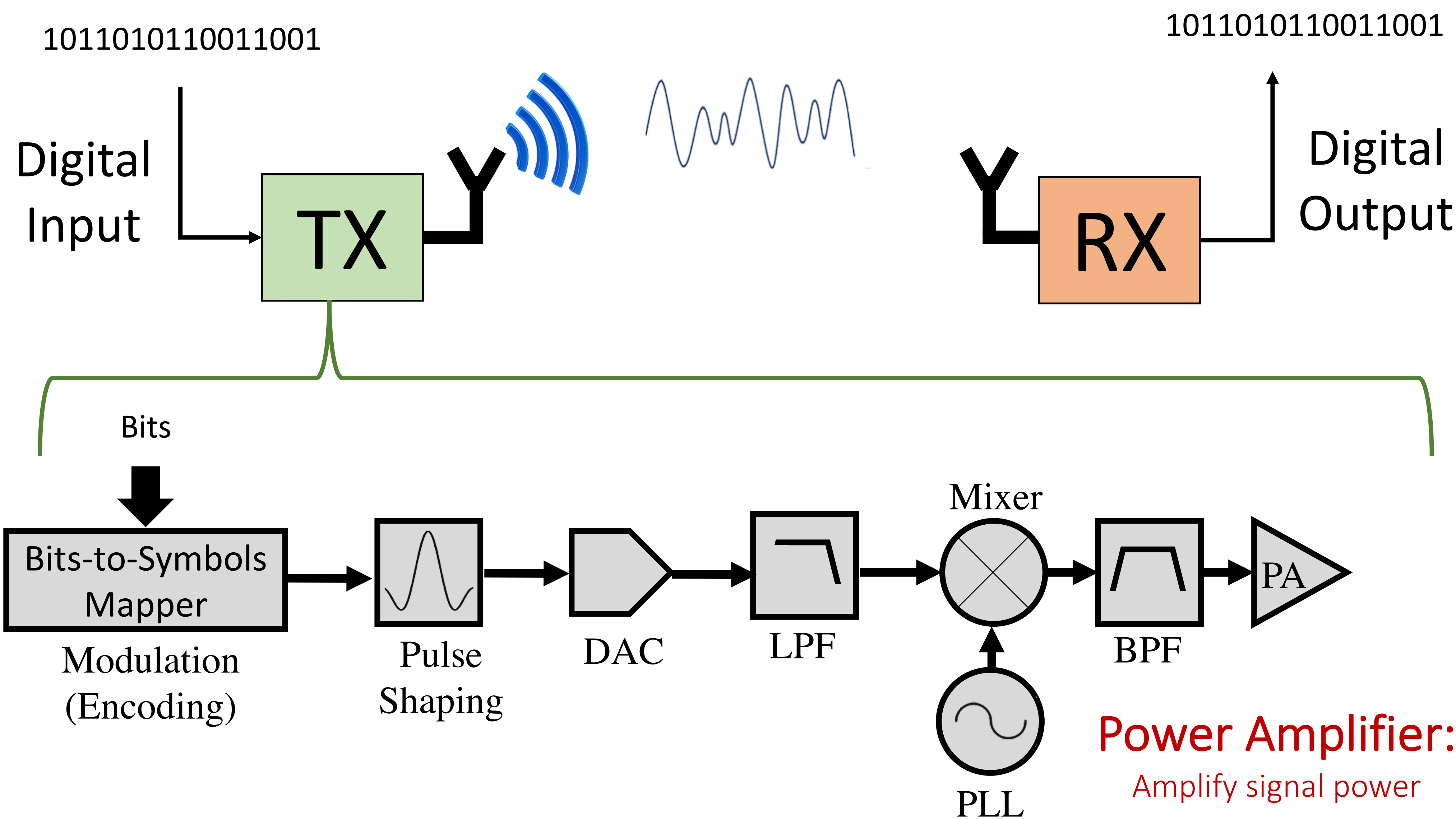


BPF: Band Pass Filter

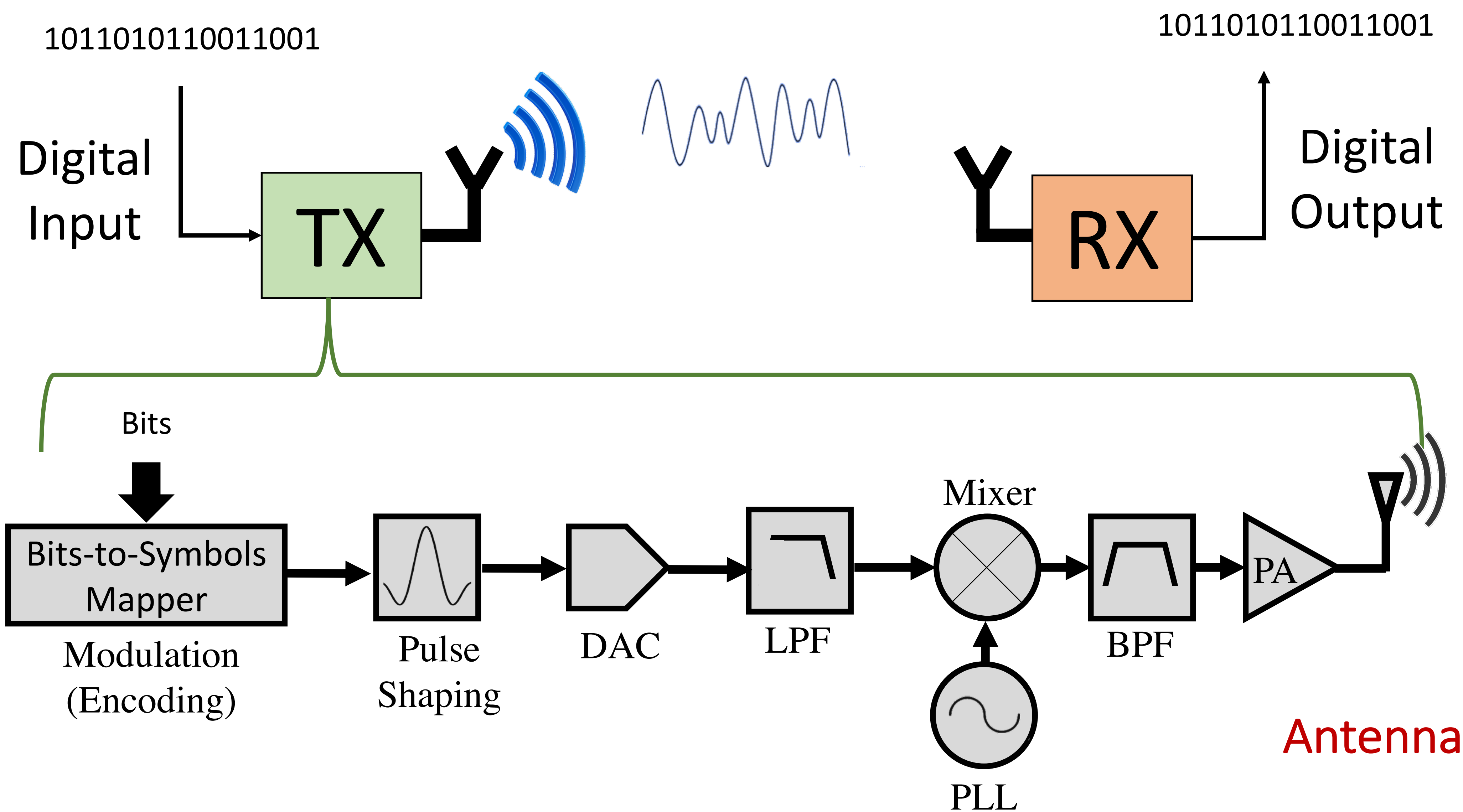
Removes Frequency Signals outside desired frequency of operation



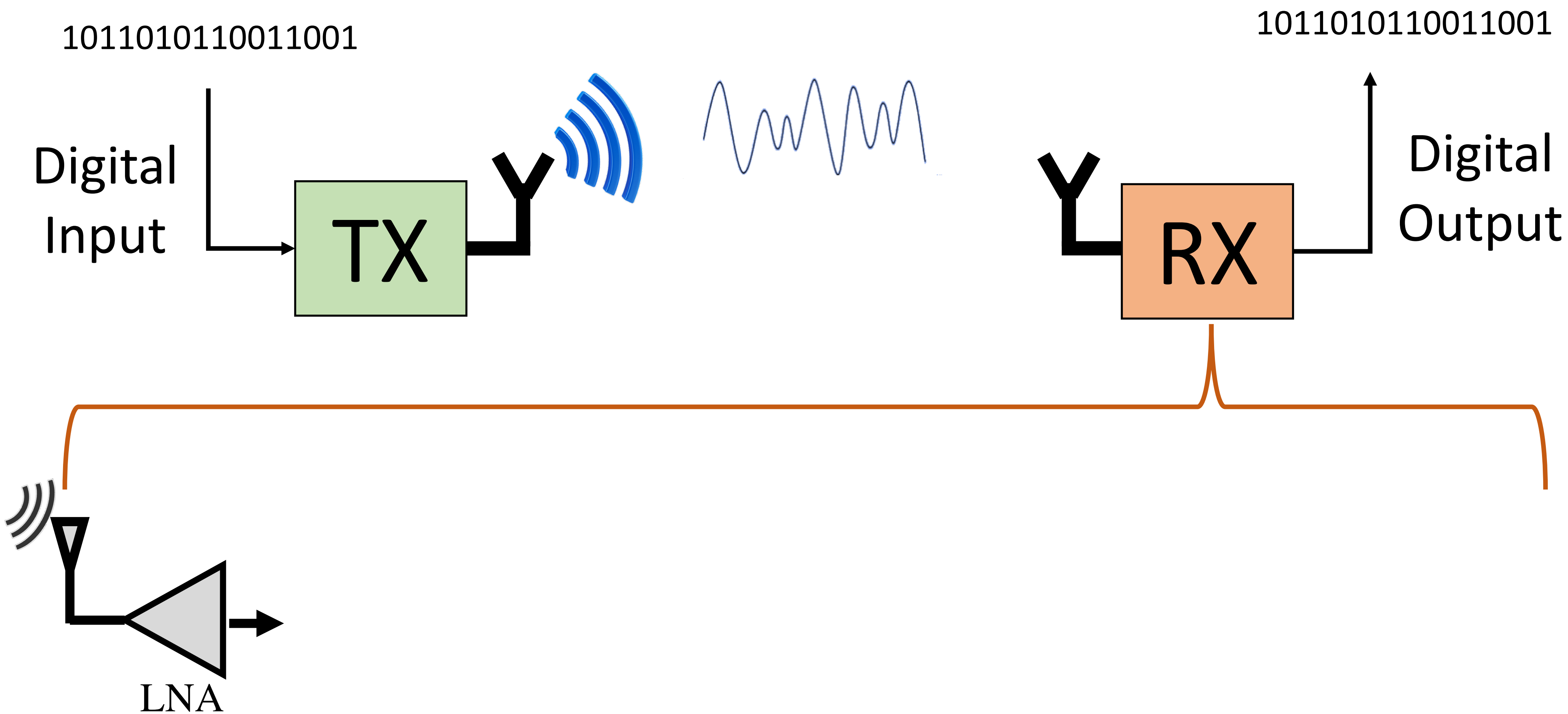
Wireless Communication System



Wireless Communication System



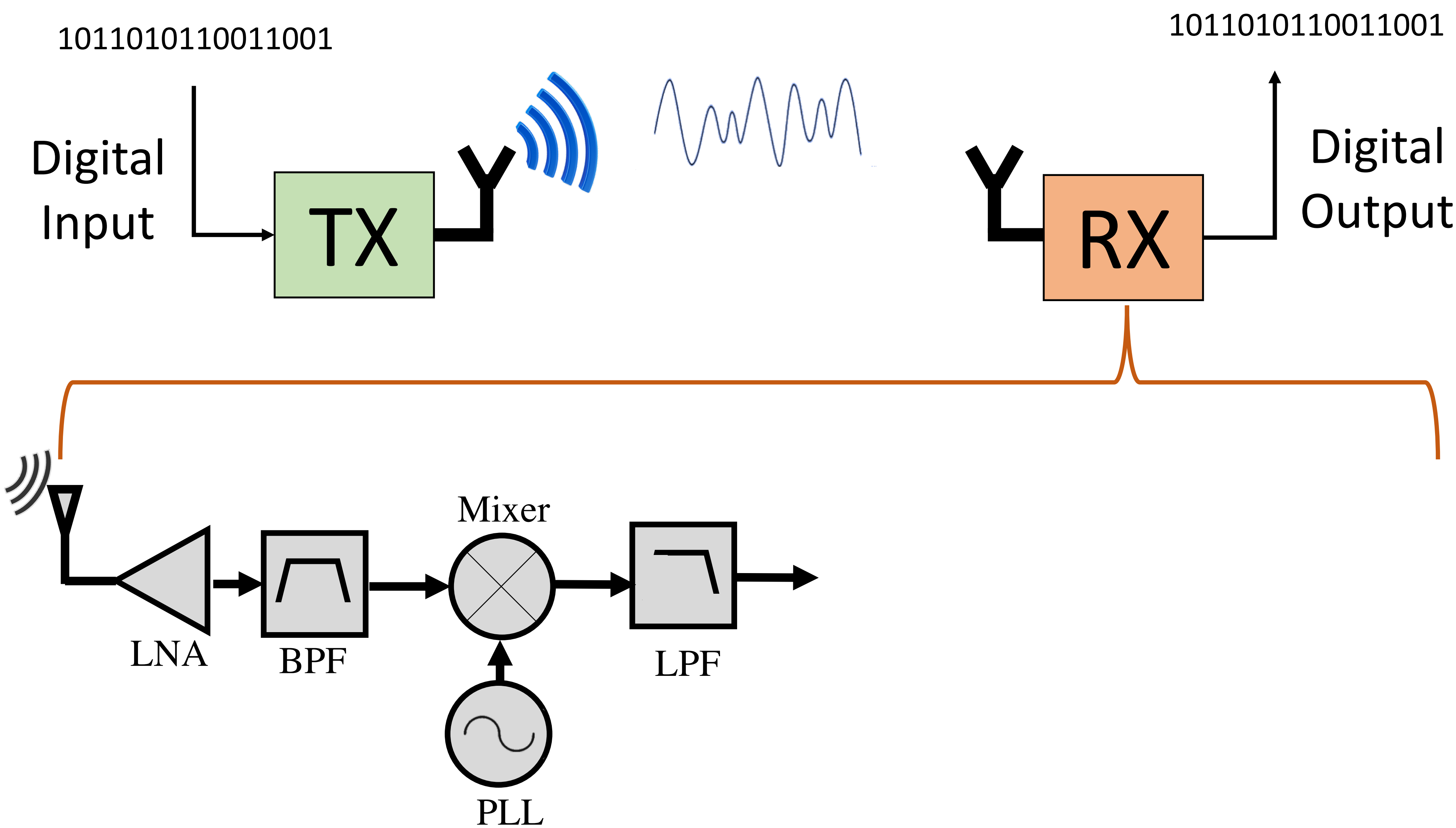
Wireless Communication System



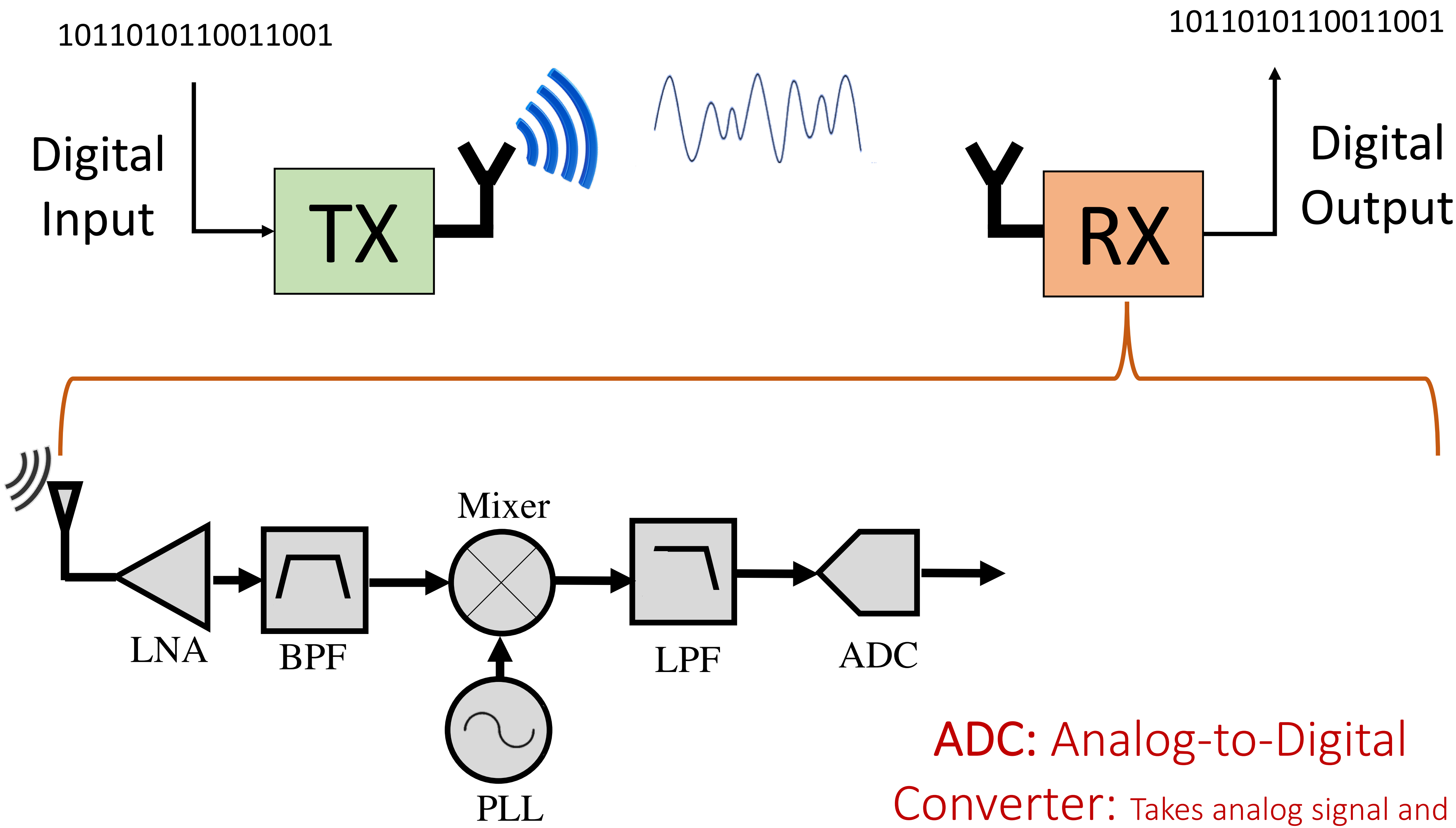
Low Noise Amplifier:

Amplify signal power with minimal noise

Wireless Communication System

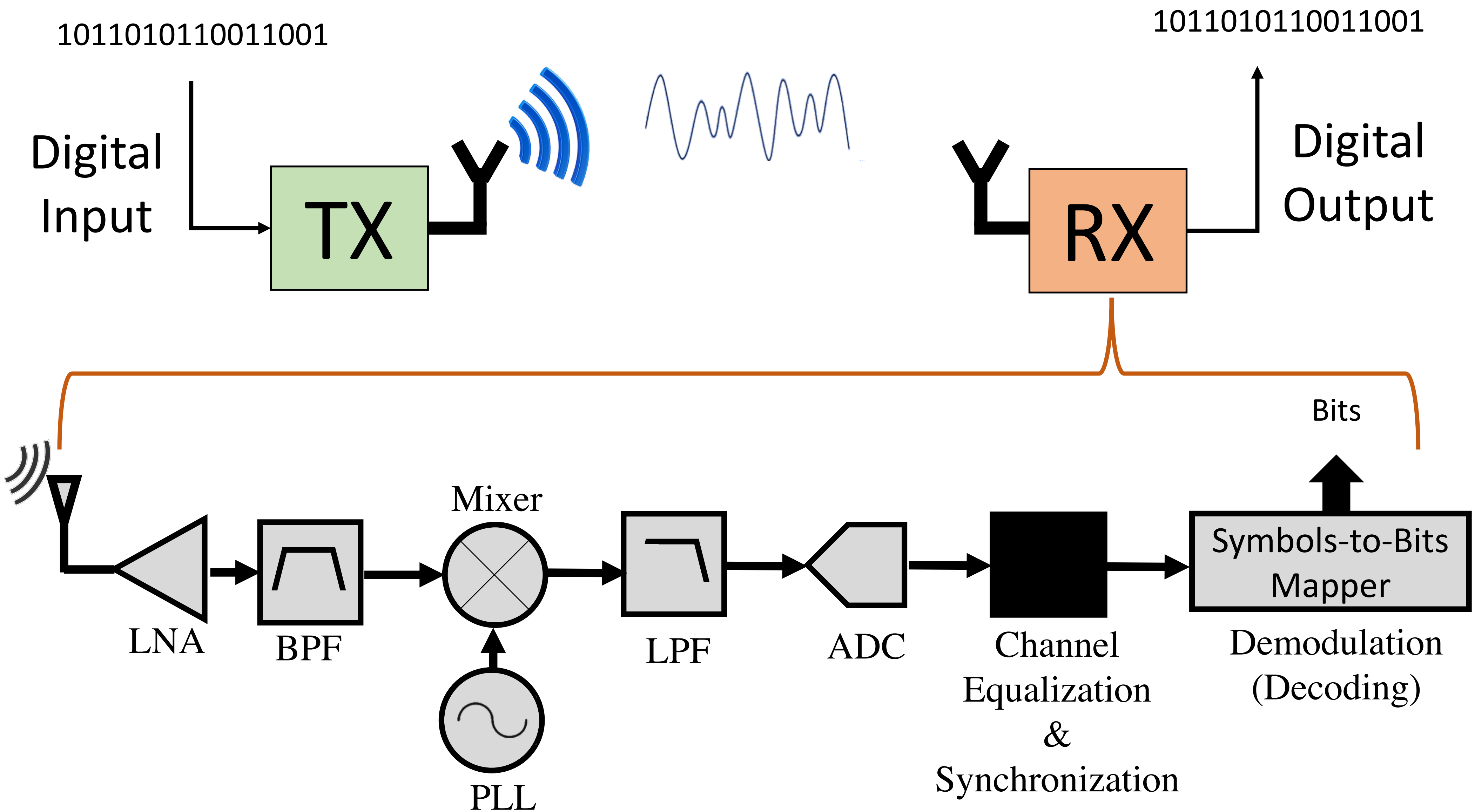


Wireless Communication System

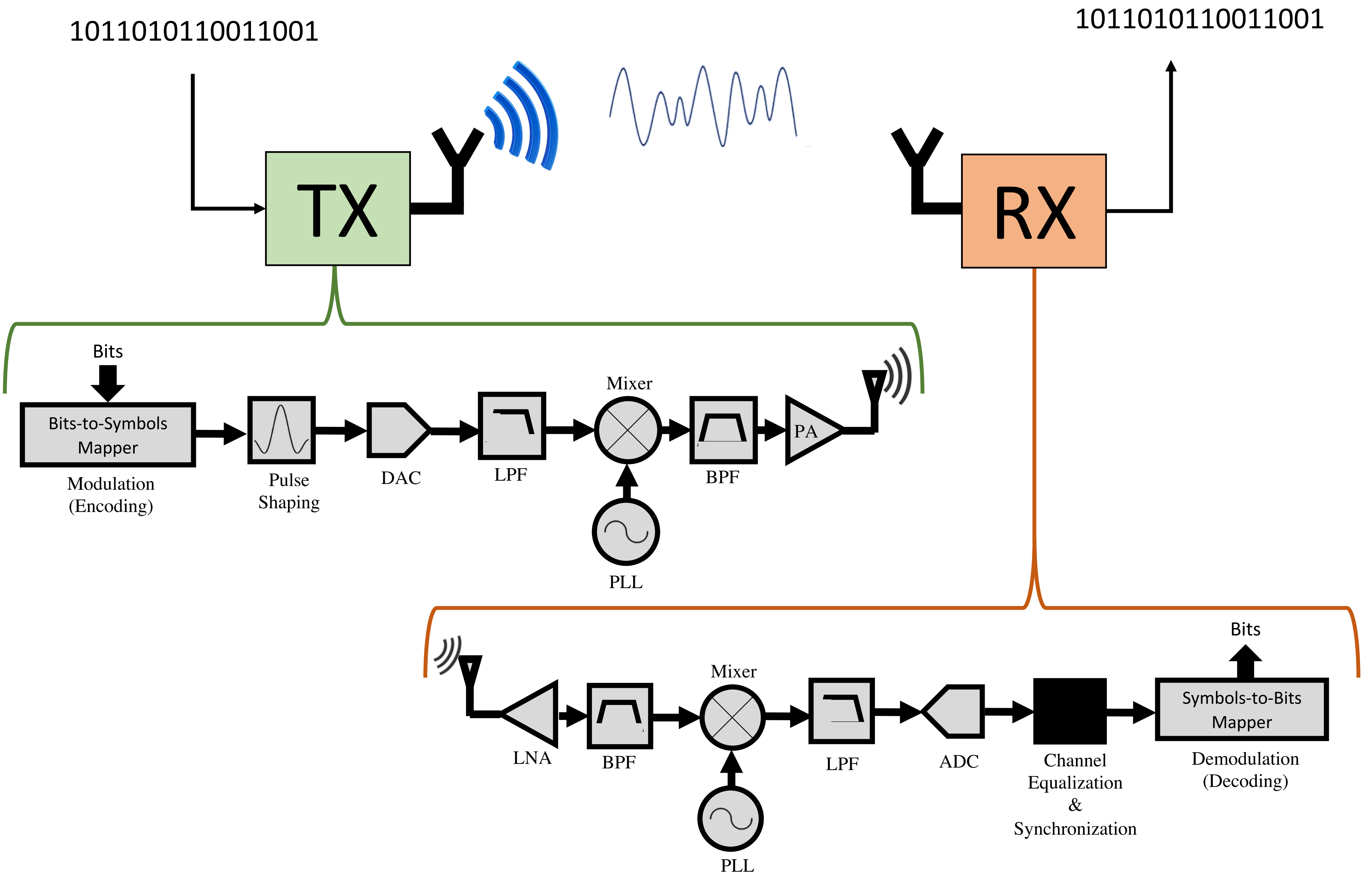


ADC: Analog-to-Digital Converter: Takes analog signal and digitizes it, i.e. samples and quantizes the signal values.

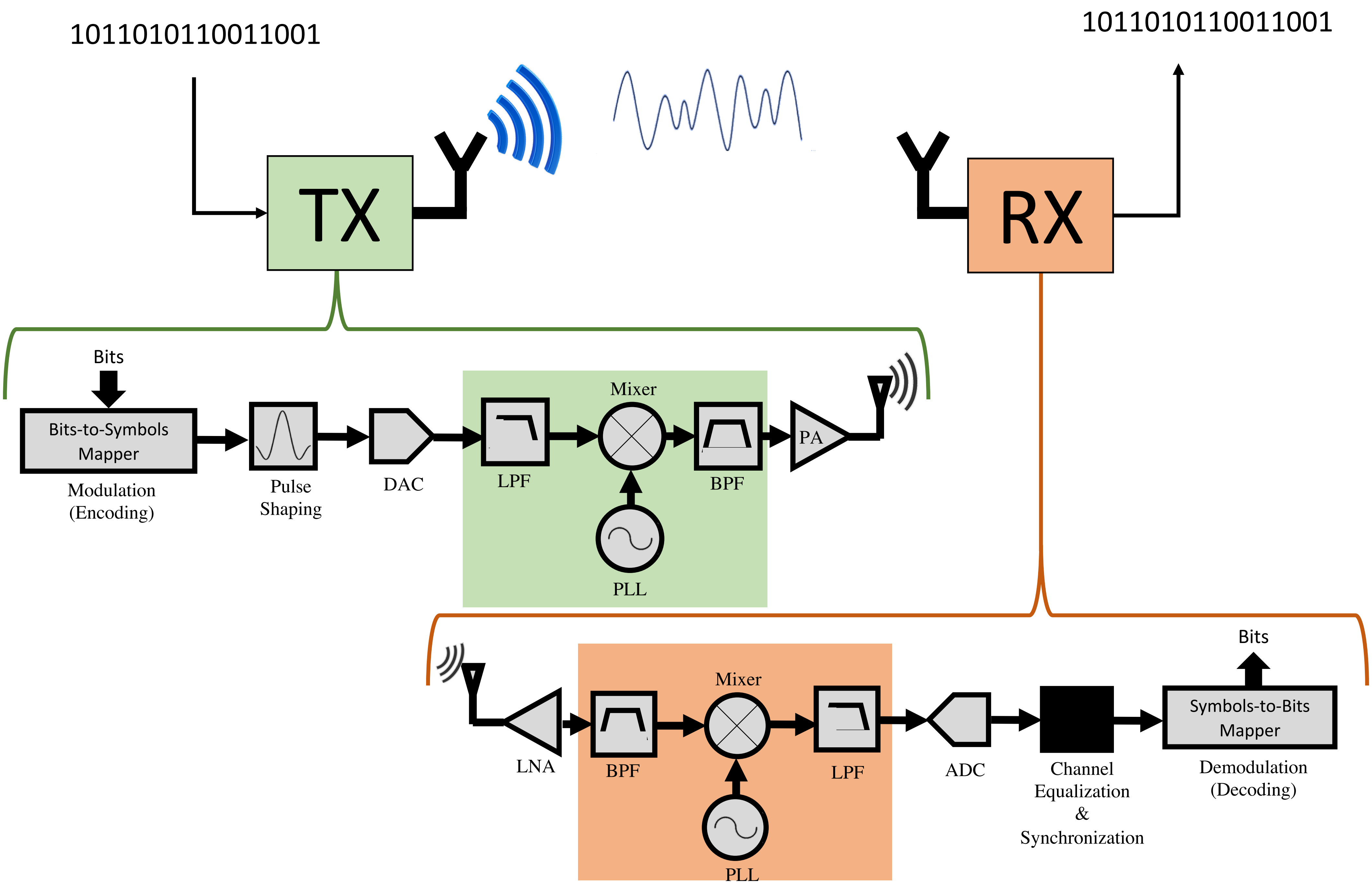
Wireless Communication System



Wireless Communication System

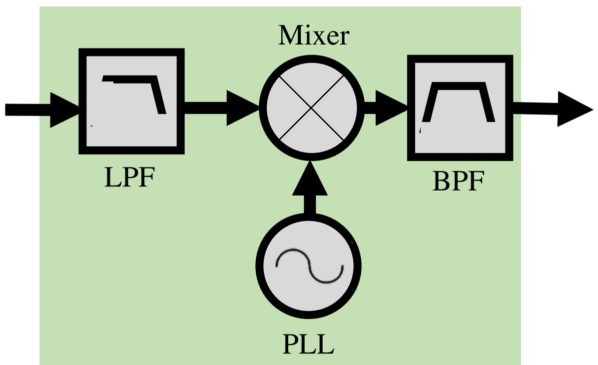


Wireless Communication System

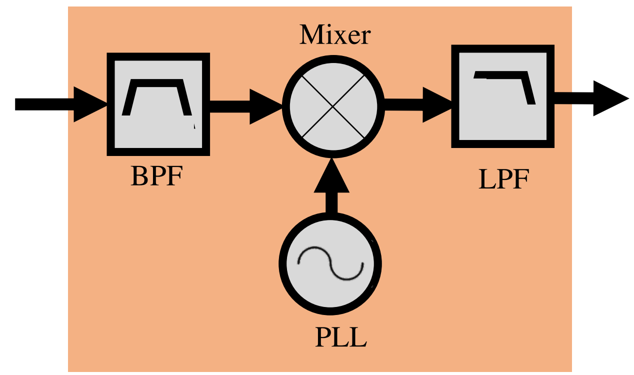


Up/Down Conversion

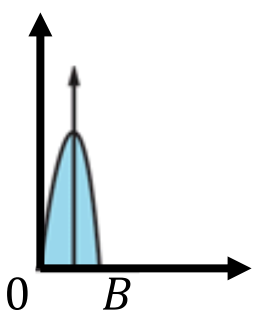
Transmitter
Up-conversion



Receiver
Down-conversion



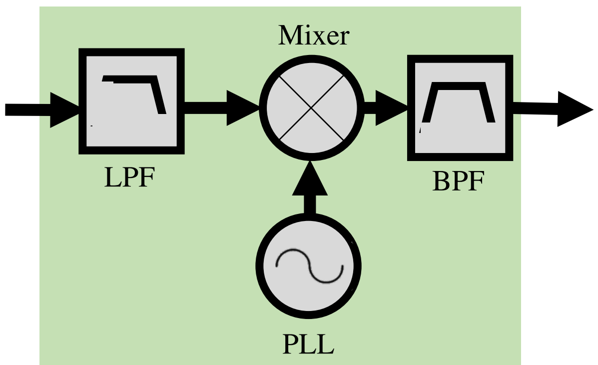
Baseband



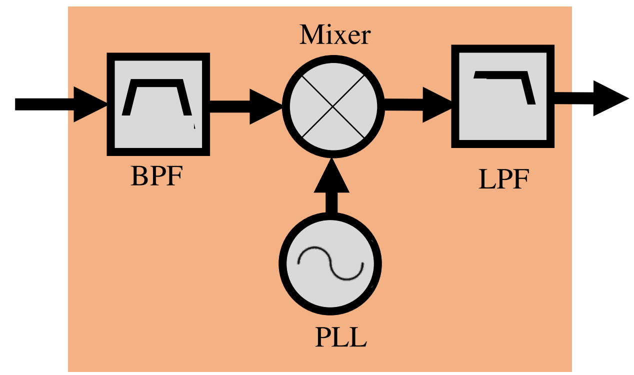
Passband

Up/Down Conversion

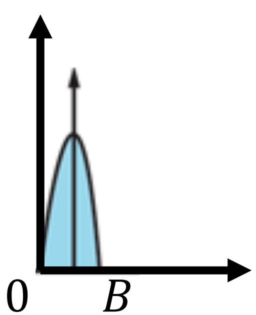
Transmitter
Up-conversion



Receiver
Down-conversion

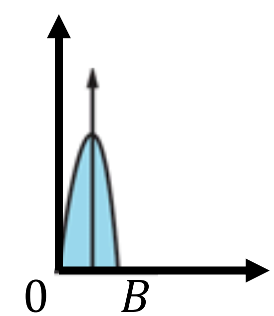


Baseband



Passband

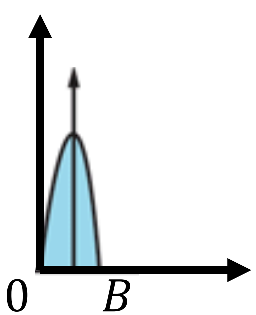
Baseband



Why do we need to up/down conversion?

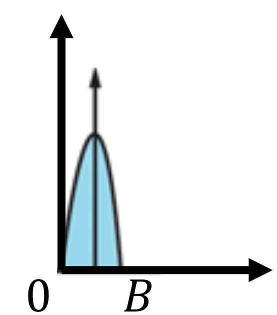
Up/Down Conversion

Baseband



Passband

Baseband



Why do we need to up/down conversion?

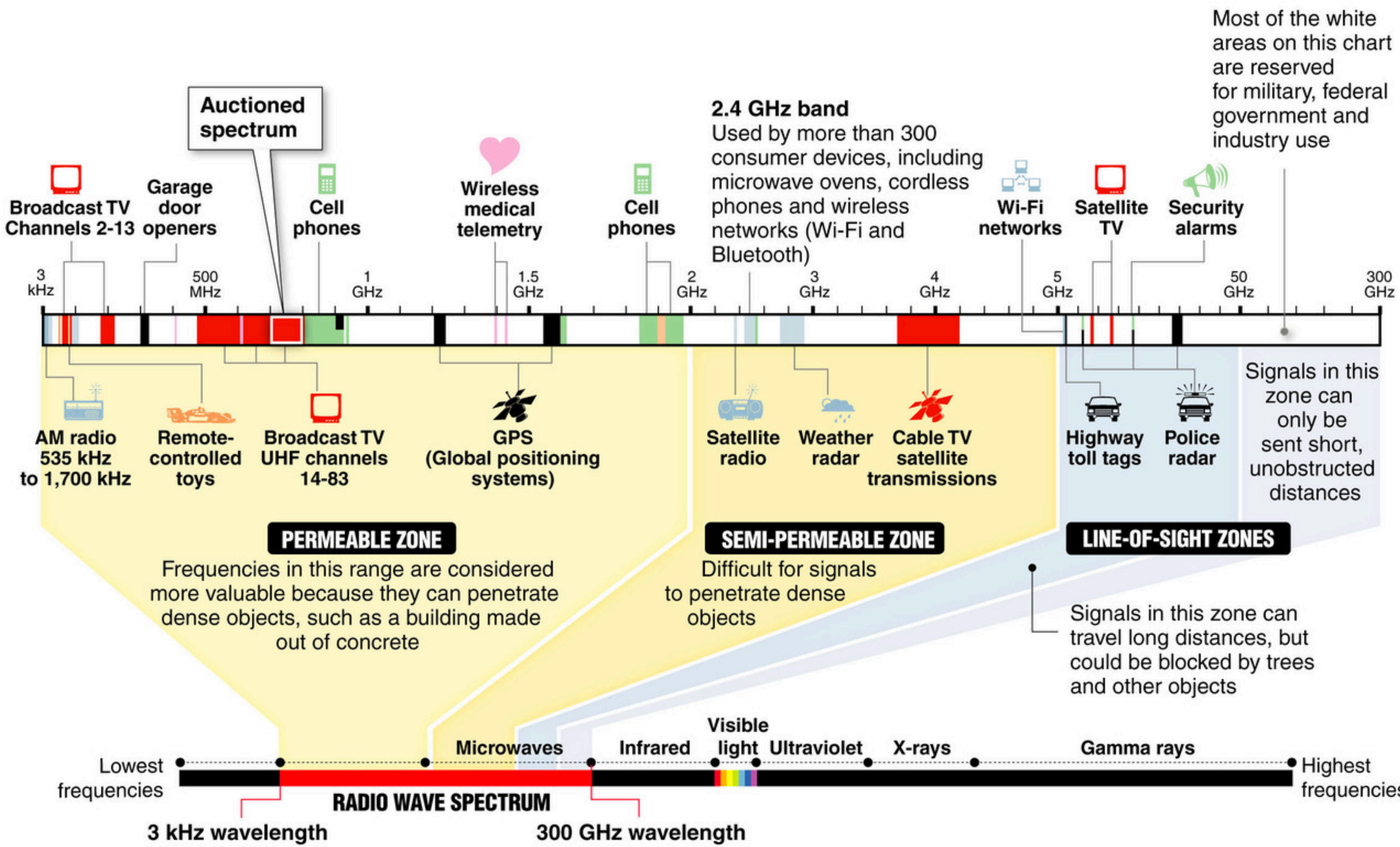
Up/Down Conversion

Baseband — Passband — Baseband

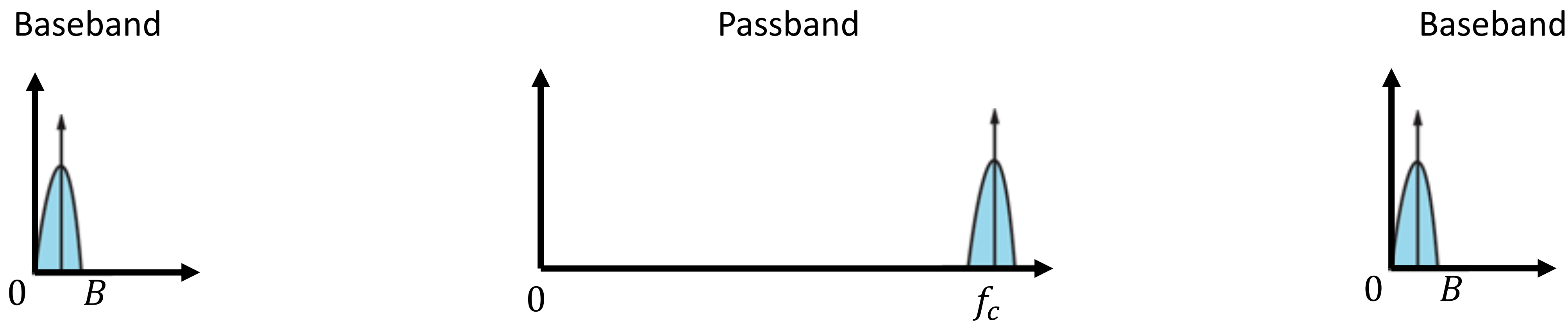
Why do we need to up/down conversion?

- Why not transmit everything at lower frequencies?
  - **Not enough bandwidth:**
    - Data rate ∝ bandwidth
    - Different Technologies
  - **Antenna size** ∝ wavelength

The Wireless Spectrum



Up/Down Conversion



Why do we need to up/down conversion?

- Cannot transmit everything at low frequencies.

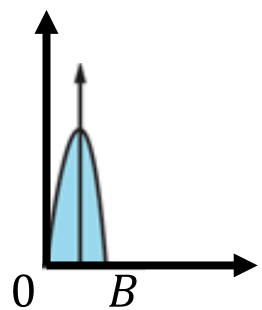
- Why not transmit & receive directly at high frequency?

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

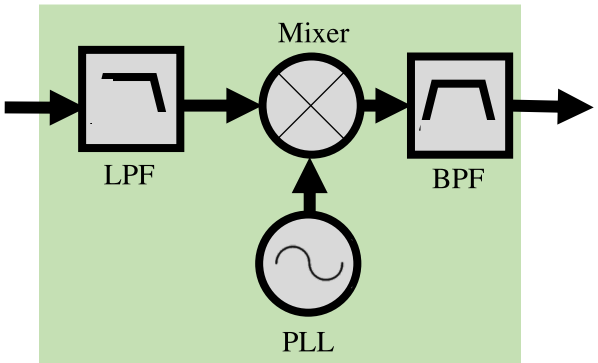
Passband

Sample at $2f_c + B$

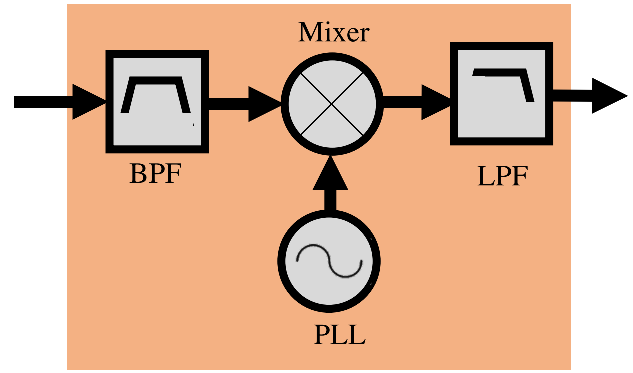
e.g. WiFi 802.11b $\approx$ 5 GS/s

Up/Down Conversion

Transmitter
Up-conversion



Receiver
Down-conversion



How to we do up/down conversion?

$$s(t) \longrightarrow \times \longrightarrow s(t)\cos(2\pi f_c t)$$

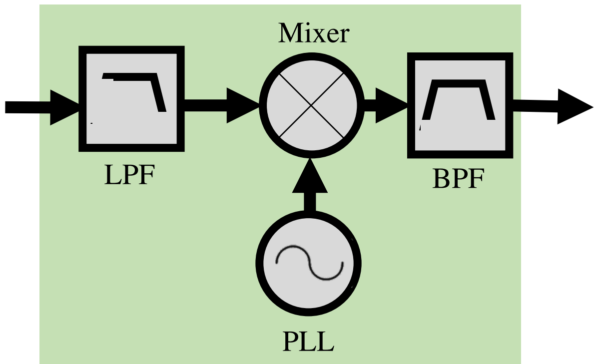
$$\uparrow$$

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

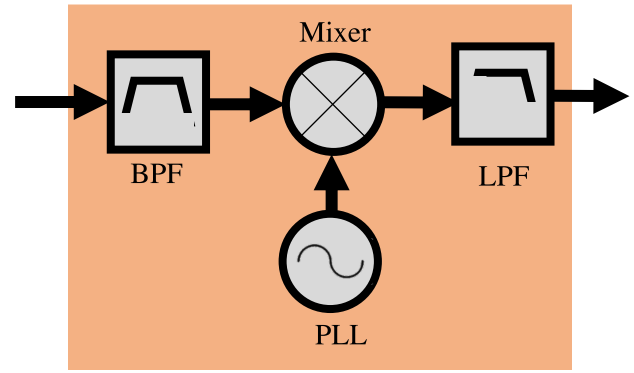
- PLL (Phased Lock Loop): create the cosine wave signal $\cos(2\pi f_c t)$
- Mixer: multiples the two signals

Up/Down Conversion

Transmitter
Up-conversion



Receiver
Down-conversion



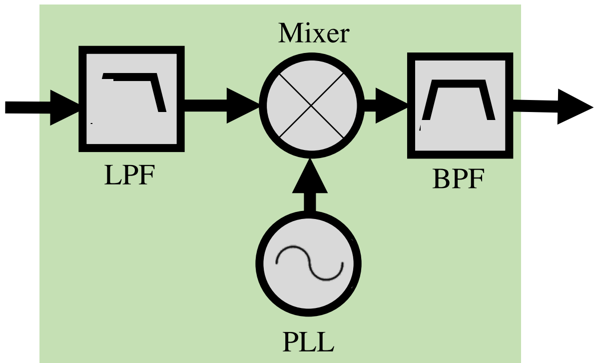
How to we do up/down conversion?

$$\begin{tikzcd} s(t) \arrow[r] & \times \arrow[r] & s(t)\cos(2\pi f_c t) \arrow[r] & \times \arrow[r] & s(t)\cos^2(2\pi f_c t) \\ & \cos(2\pi f_c t) \arrow[u] & & \cos(2\pi f_c t) \arrow[u] & \end{tikzcd}$$

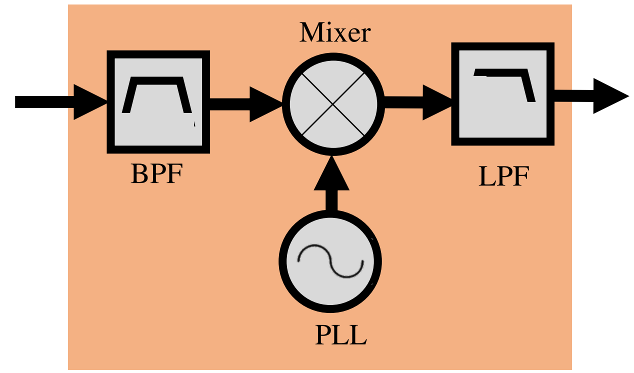
$$s(t)\cos^2(2\pi f_c t) = s(t)\left(\frac{1}{2} + \frac{1}{2}\cos(2\pi\, 2f_c\, t)\right)$$

Up/Down Conversion

Transmitter
Up-conversion



Receiver
Down-conversion



How to we do up/down conversion?

$$
\begin{tikzcd}
s(t) \arrow[r] & \times \arrow[r] & s(t)\cos(2\pi f_c t) \arrow[r] & \times \arrow[r] & s(t)\cos^2(2\pi f_c t) \\
& \cos(2\pi f_c t) \arrow[u] & & \cos(2\pi f_c t) \arrow[u] &
\end{tikzcd}
$$

Low Pass Filter

$$s(t)\cos^2(2\pi f_c t) = s(t)\left(\frac{1}{2} + \cancel{\frac{1}{2}\cos(2\pi\, 2f_c\, t)}\right) = \frac{1}{2}s(t)$$

Up/Down Conversion

$$
\begin{tikzcd}
s(t) \arrow[r] & \times \arrow[r] & s(t)\cos(2\pi f_c t) \arrow[r] & \times \arrow[r] & s(t)\cos^2(2\pi f_c t) \\
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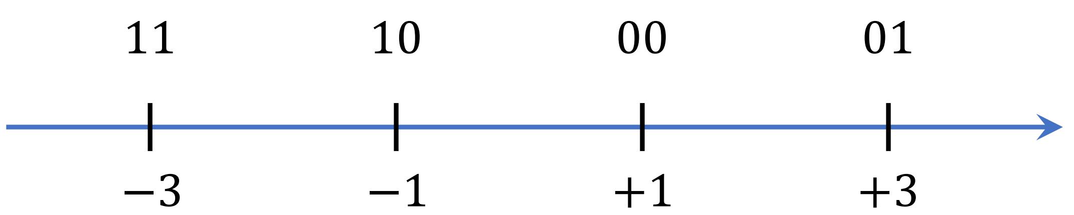
\end{tikzcd}
$$

Up/Down Conversion

$$\begin{tikzcd}
s(t) \arrow[r] & \times \arrow[r] & s(t)\cos(2\pi f_c t) \arrow[r] & \times \arrow[r] & s(t)\cos^2(2\pi f_c t) \\
& \cos(2\pi f_c t) \arrow[u] & & \cos(2\pi f_c t) \arrow[u] &
\end{tikzcd}$$

Consider using PAM: Pulse Amplitude Modulation

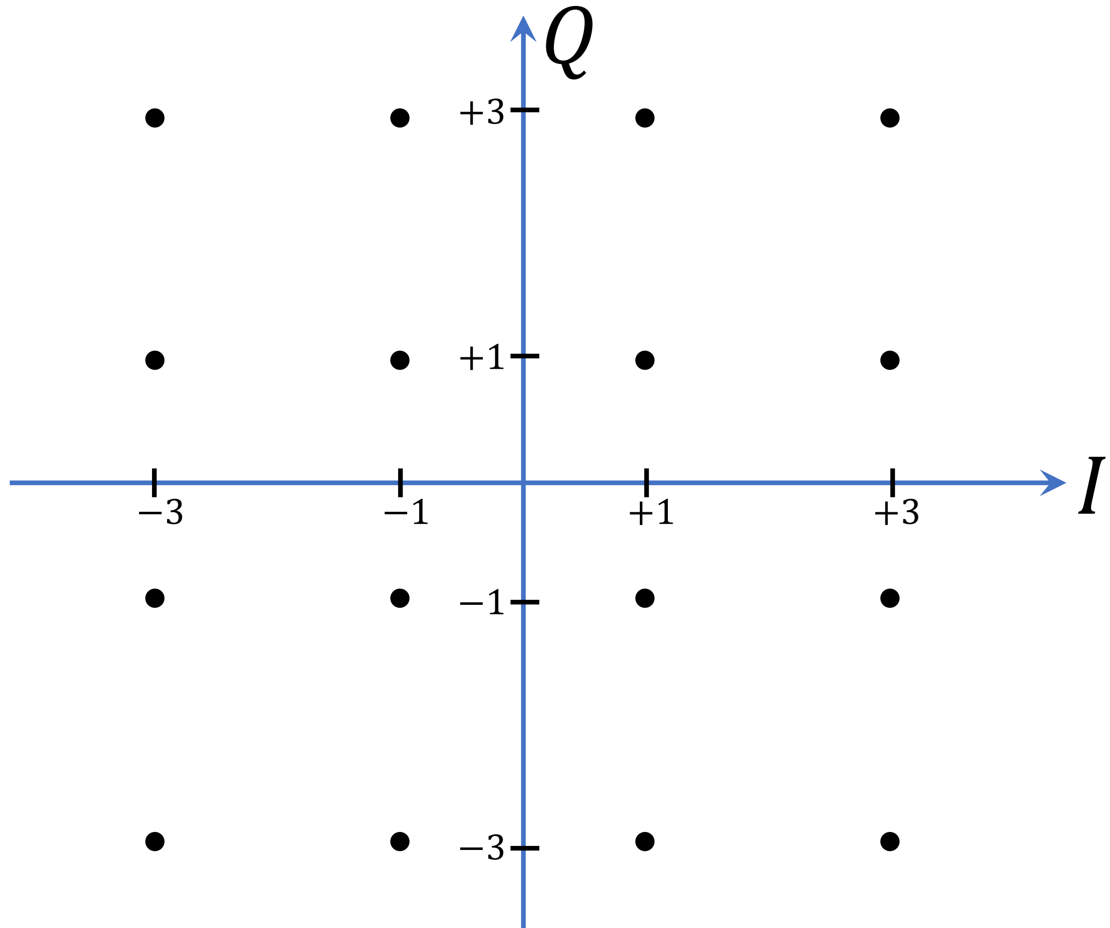
4 PAM:
2 bits/symbol



Up/Down Conversion

$$\begin{tikzcd} s(t) \arrow[r] & \times \arrow[r] & s(t)\cos(2\pi f_c t) \arrow[r] & \times \arrow[r] & s(t)\cos^2(2\pi f_c t) \\ & \cos(2\pi f_c t) \arrow[u] & & \cos(2\pi f_c t) \arrow[u] & \end{tikzcd}$$

Consider using QAM: Quadrature Amplitude Modulation

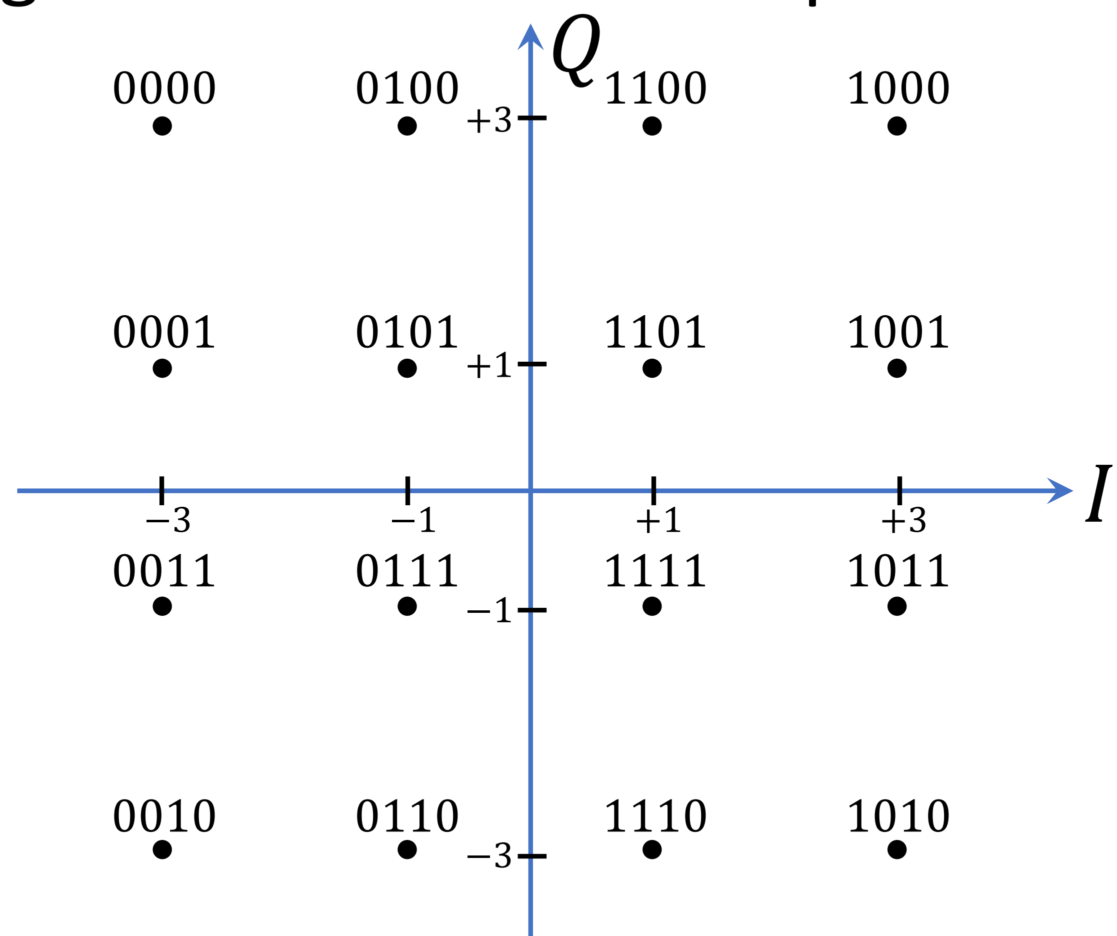


Up/Down Conversion

$$s(t) \longrightarrow \underset{\substack{\uparrow \\ \cos(2\pi f_c t)}}{\times} \longrightarrow s(t)\cos(2\pi f_c t) \longrightarrow \underset{\substack{\uparrow \\ \cos(2\pi f_c t)}}{\times} \longrightarrow s(t)\cos^2(2\pi f_c t)$$

Consider using QAM: Quadrature Amplitude Modulation

16 QAM:
4 bits/symbol



Up/Down Conversion

$$\begin{tikzcd} s(t) \arrow[r] & \times \arrow[r] & s(t)\cos(2\pi f_c t) \arrow[r] & \times \arrow[r] & s(t)\cos^2(2\pi f_c t) \\ & \cos(2\pi f_c t) \arrow[u] & & \cos(2\pi f_c t) \arrow[u] & \end{tikzcd}$$

Consider using QAM:Quadrature Amplitude Modulation

$s(t)$ is complex: $s(t) = I + jQ$

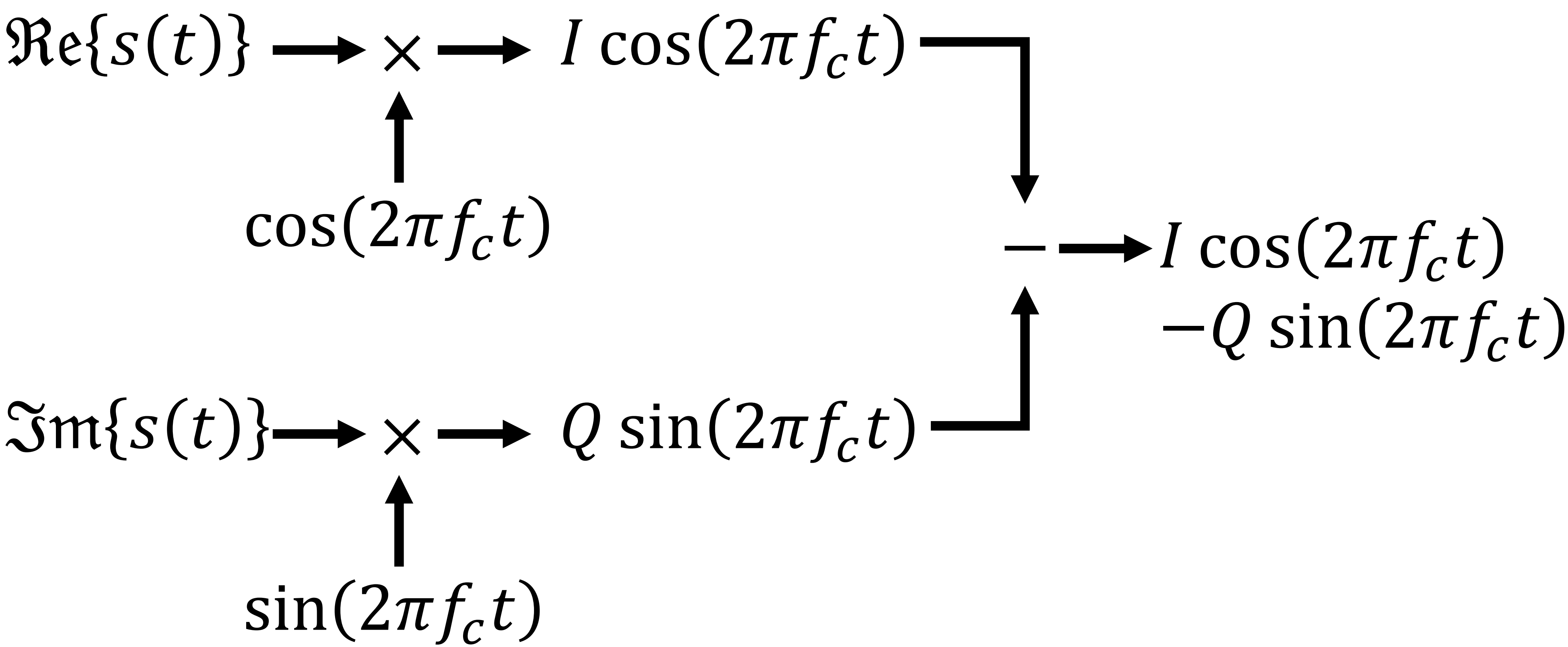
Up Conversion

$$
\begin{tikzcd}
s(t) \arrow[r] & \times \arrow[r] & s(t)\cos(2\pi f_c t) \\
& \cos(2\pi f_c t) \arrow[u] &
\end{tikzcd}
$$

Consider using QAM:Quadrature Amplitude Modulation

$s(t)$ is complex: $s(t) = I + jQ$

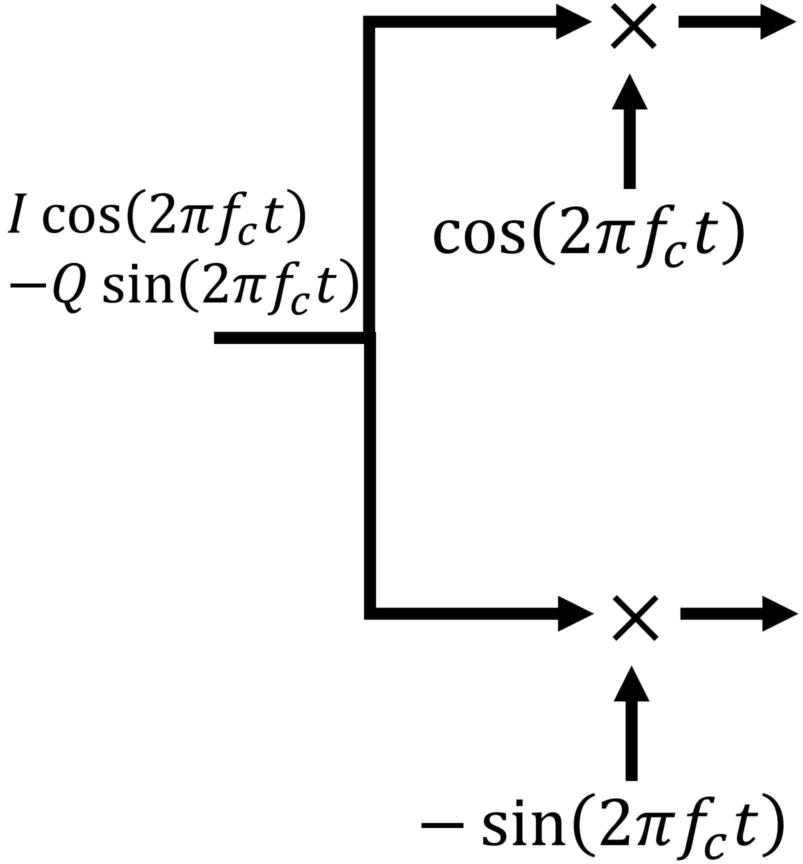
Up Conversion



Consider using QAM: Quadrature Amplitude Modulation

$s(t)$ is complex: $s(t) = I + jQ$

Down Conversion



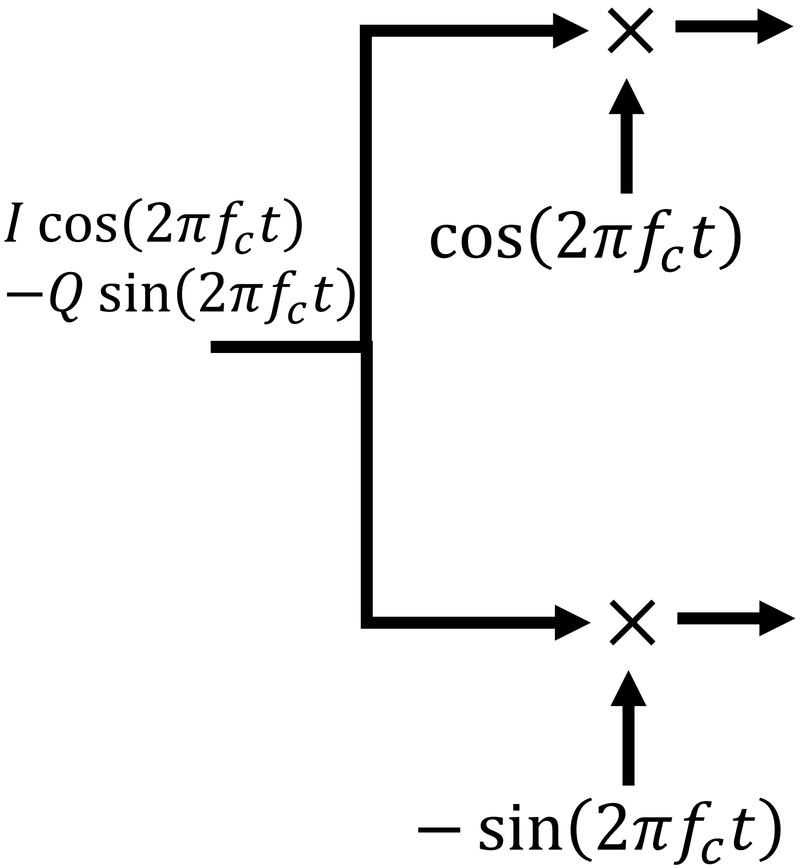
$$I\cos^2(2\pi f_c t) - Q\cos(2\pi f_c t)\sin(2\pi f_c t)$$

$$= \frac{1}{2} I\left(1 + \cos(2\pi\, 2f_c\, t)\right) - \frac{1}{2} Q\sin(2\pi\, 2f_c t)$$

$$Q\sin^2(2\pi f_c t) - I\cos(2\pi f_c t)\sin(2\pi f_c t)$$

$$= \frac{1}{2} Q\left(1 - \cos(2\pi\, 2f_c\, t)\right) - \frac{1}{2} I\sin(2\pi\, 2f_c t)$$

Down Conversion



$$I\cos^2(2\pi f_c t) - Q\cos(2\pi f_c t)\sin(2\pi f_c t)$$

$$= \frac{1}{2}I(1 + \cancelto{\text{Low Pass Filter}}{\cos(2\pi\, 2f_c t)}) - \cancelto{\text{Low Pass Filter}}{\frac{1}{2}Q\sin(2\pi\, 2f_c t)}$$

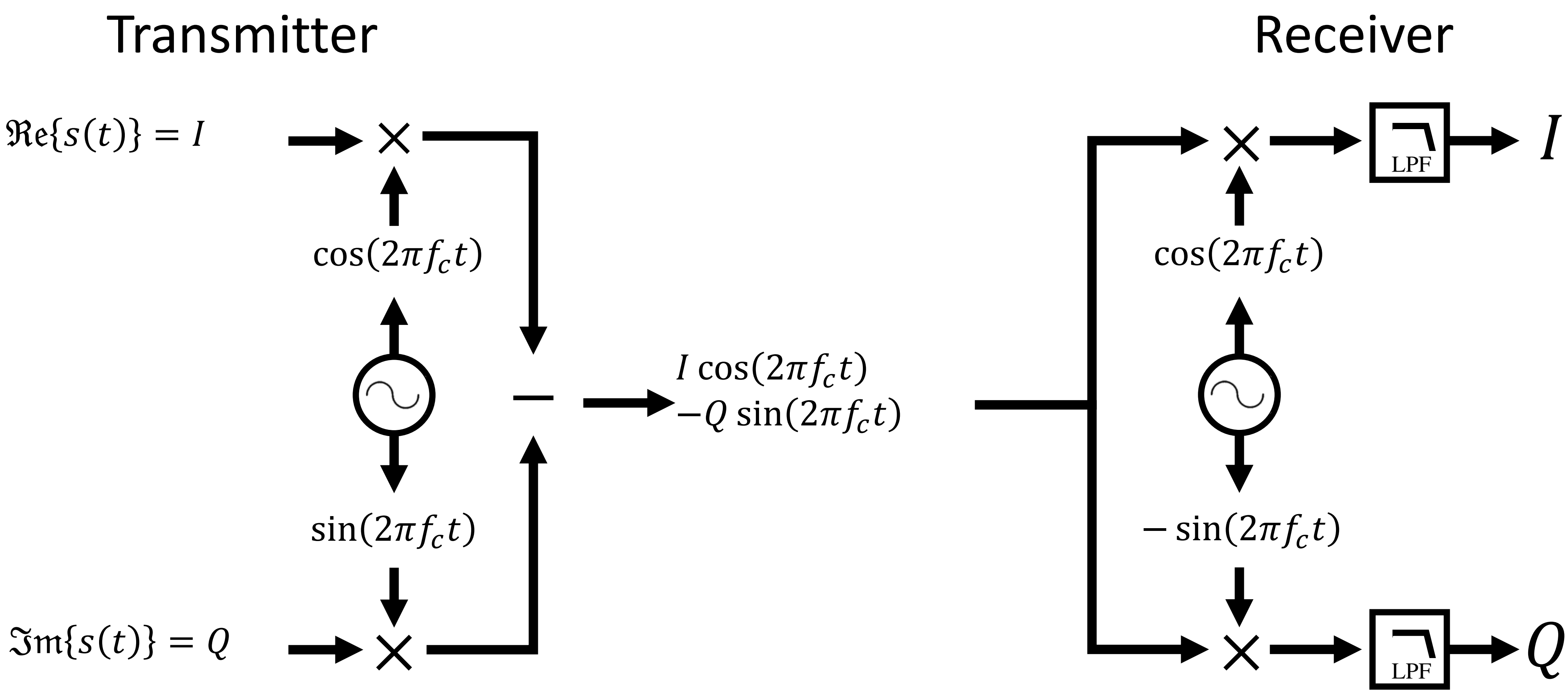
$$= \frac{1}{2}I$$

$$Q\sin^2(2\pi f_c t) - I\cos(2\pi f_c t)\sin(2\pi f_c t)$$

$$= \frac{1}{2}Q(1 - \cancelto{\text{Low Pass Filter}}{\cos(2\pi\, 2f_c t)}) - \cancelto{\text{Low Pass Filter}}{\frac{1}{2}I\sin(2\pi\, 2f_c t)}$$

$$= \frac{1}{2}Q$$

Up/Down Conversion



$$s(t) \times e^{j2\pi f_c t} \longrightarrow \Re\left\{s(t)e^{j2\pi f_c t}\right\} \longrightarrow \times e^{-j2\pi f_c t} \longrightarrow s(t)$$

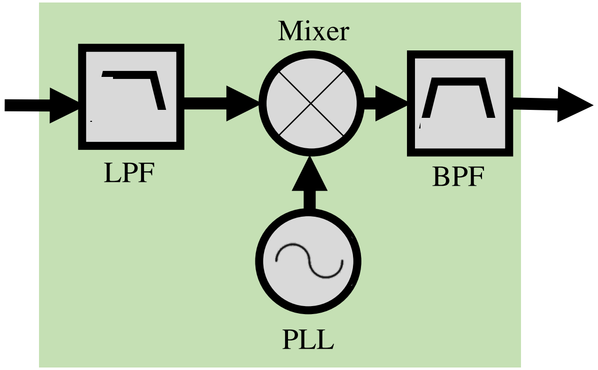
Up/Down Conversion

Transmitter | Receiver

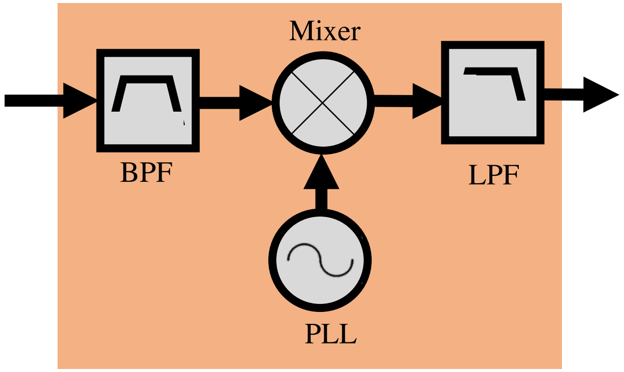
$$s(t) \times e^{j2\pi f_c t} \rightarrow \Re\mathrm{e}\left\{s(t)e^{j2\pi f_c t}\right\} \rightarrow \times e^{-j2\pi f_c t} \rightarrow s(t)$$

Up/Down Conversion

Transmitter
Up-conversion

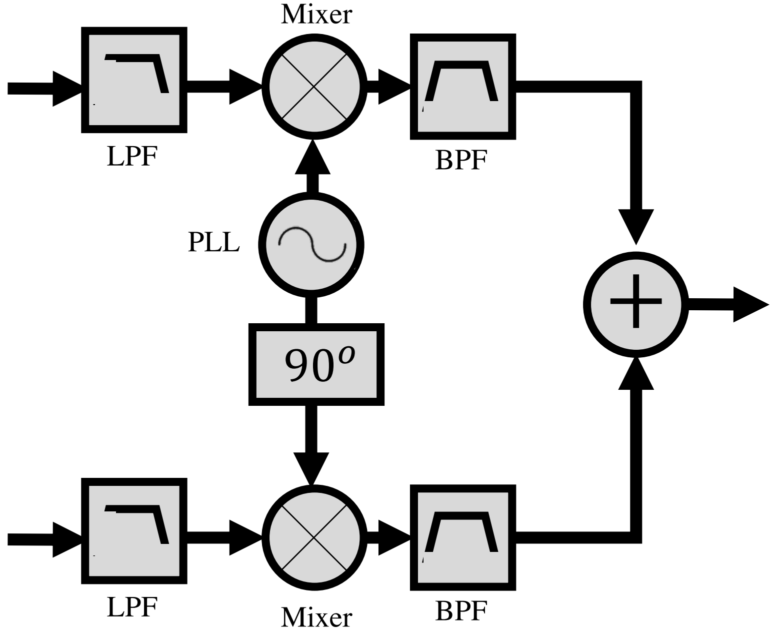


Receiver
Down-conversion

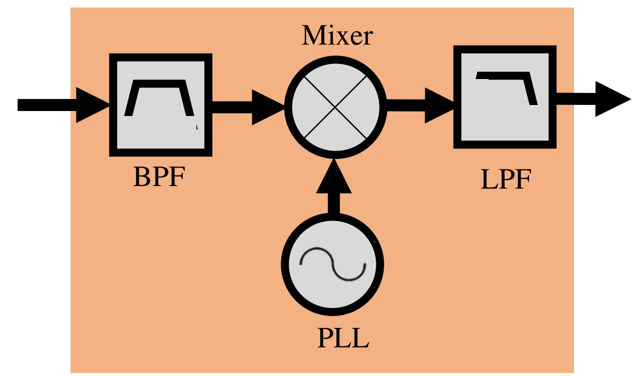


Up/Down Conversion

Transmitter
Up-conversion

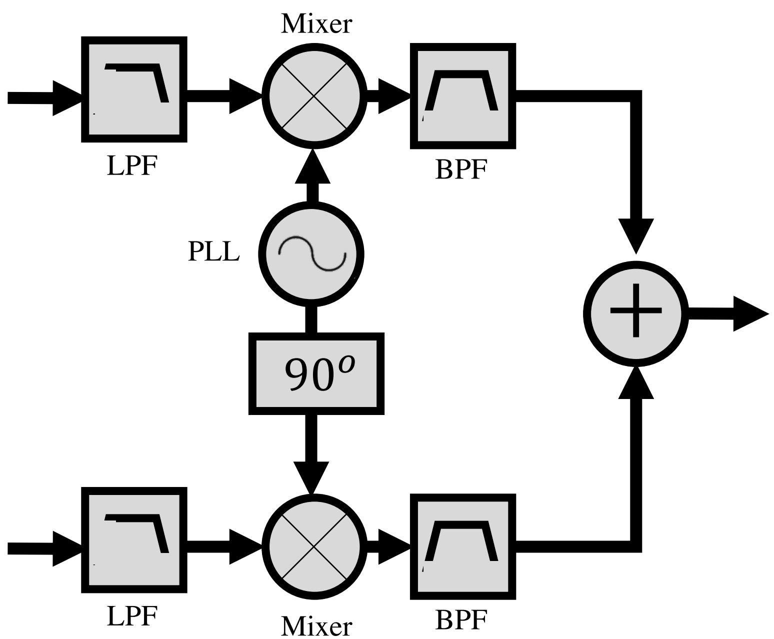


Receiver
Down-conversion

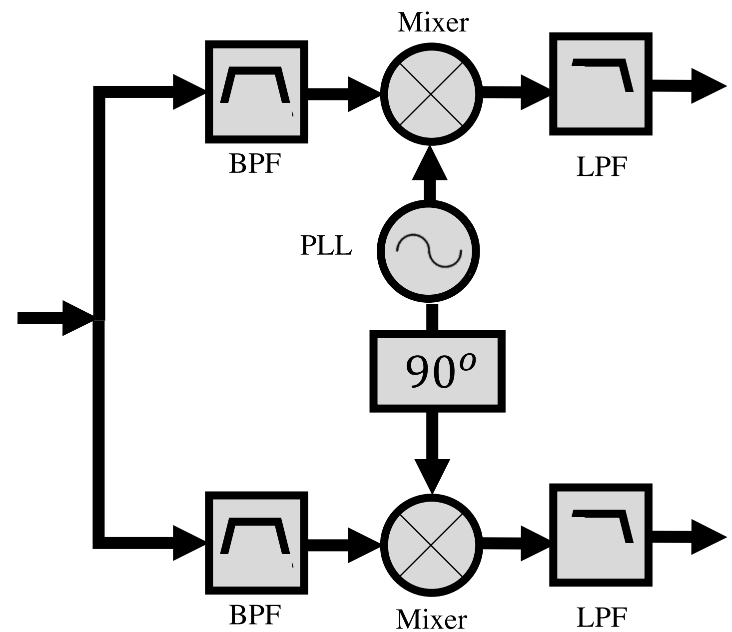


Up/Down Conversion

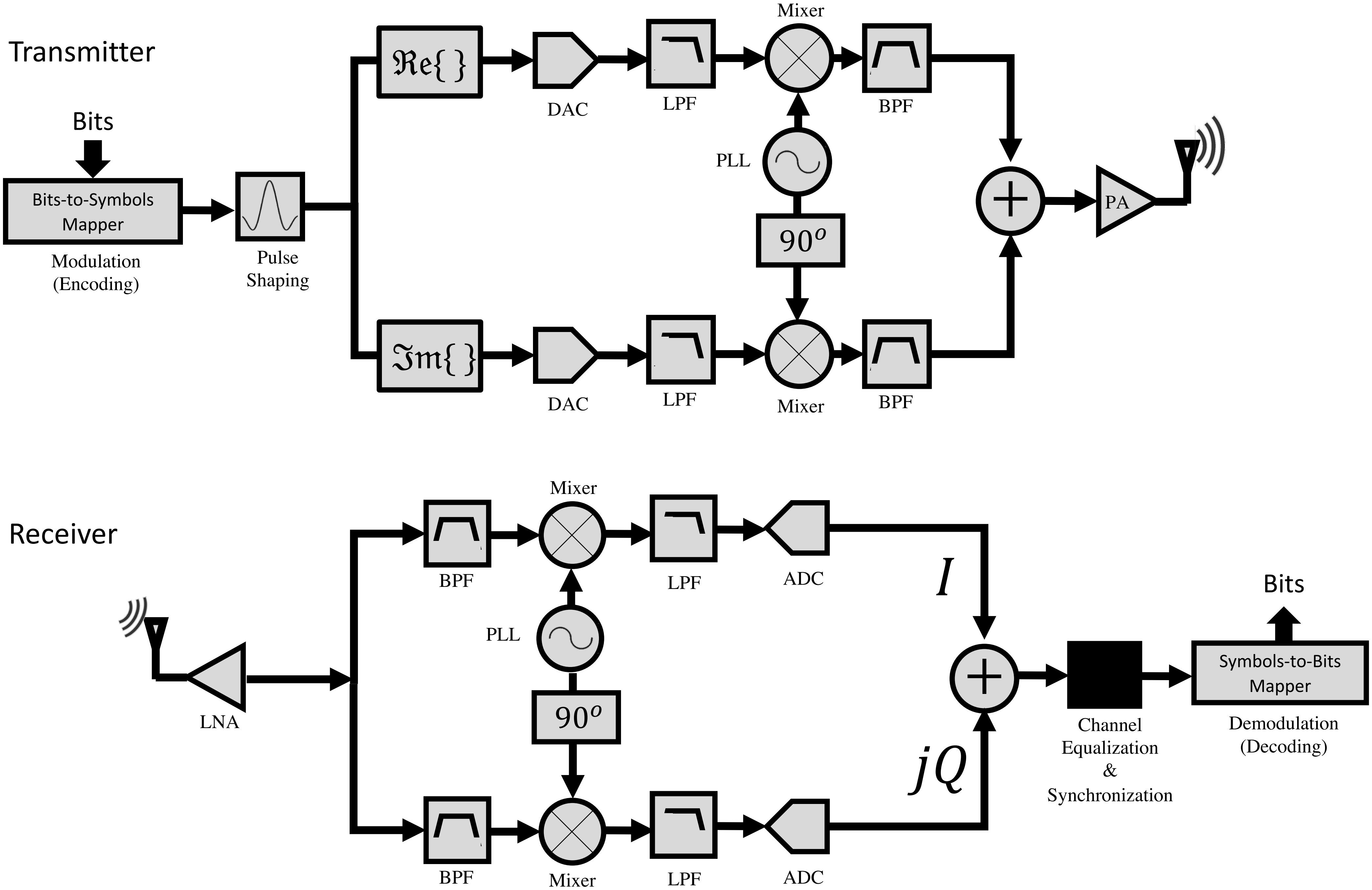
Transmitter
Up-conversion



Receiver
Down-conversion

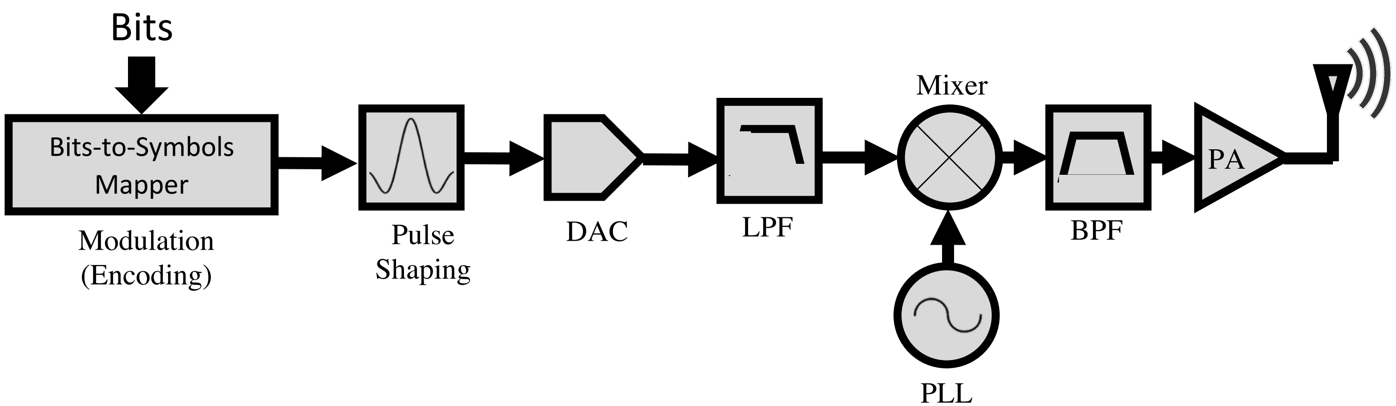


Wireless Communication System

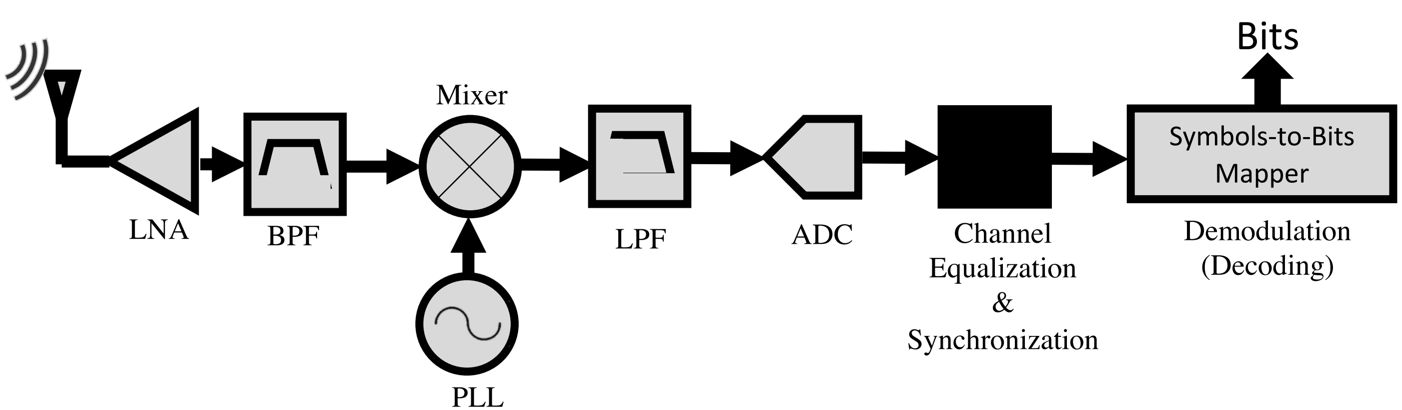


Wireless Communication System

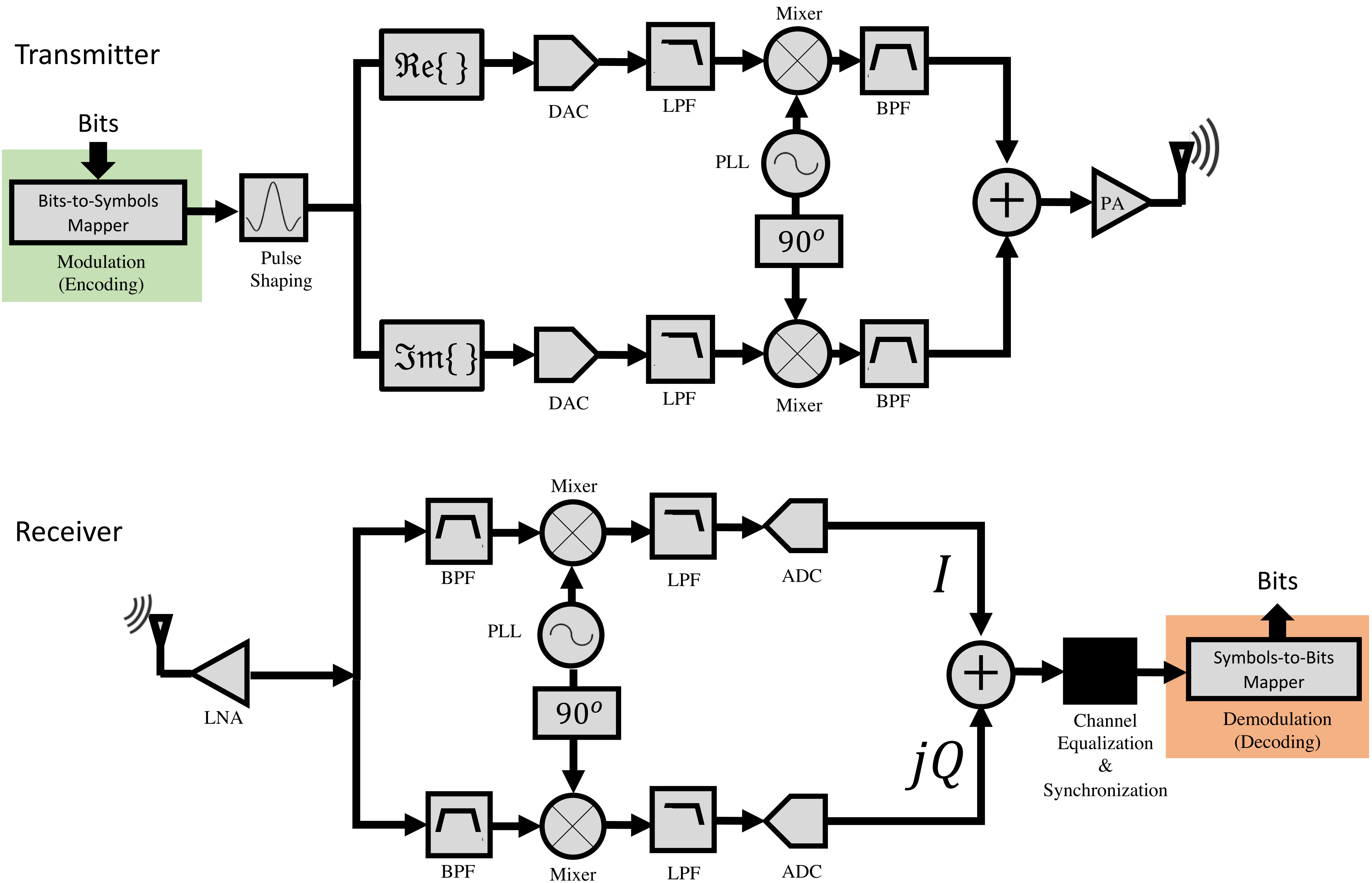
Transmitter



Receiver

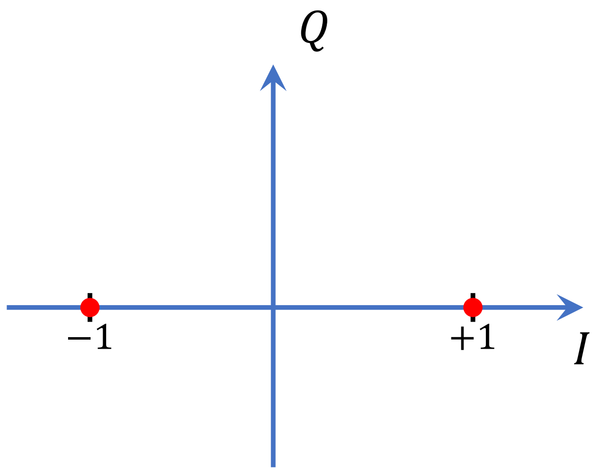


Wireless Communication System



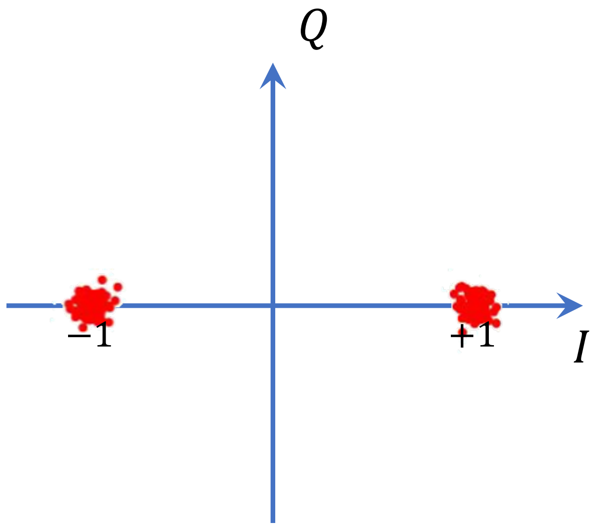
BPSK Modulation

$$0 \rightarrow -1$$
$$1 \rightarrow +1$$



$x(t)$

Transmitted Constellation

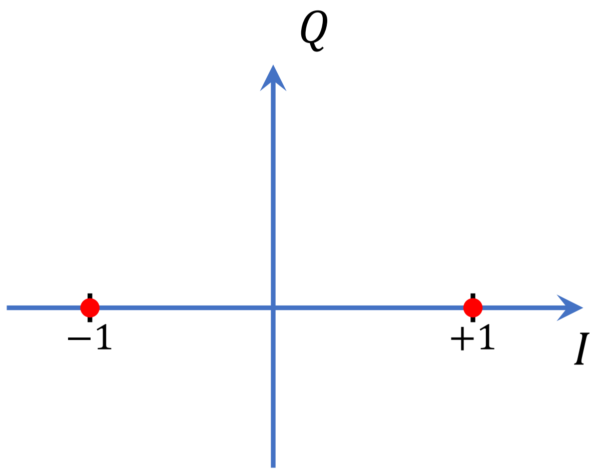


$y(t) = x(t) + v(t)$

Received Constellation

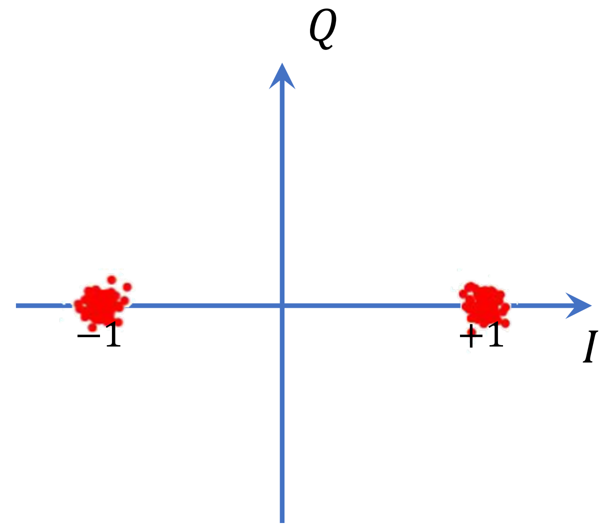
BPSK Modulation

$0 \rightarrow -1$
$1 \rightarrow +1$



$x(t)$

Transmitted Constellation



$y(t) = x(t) + v(t)$

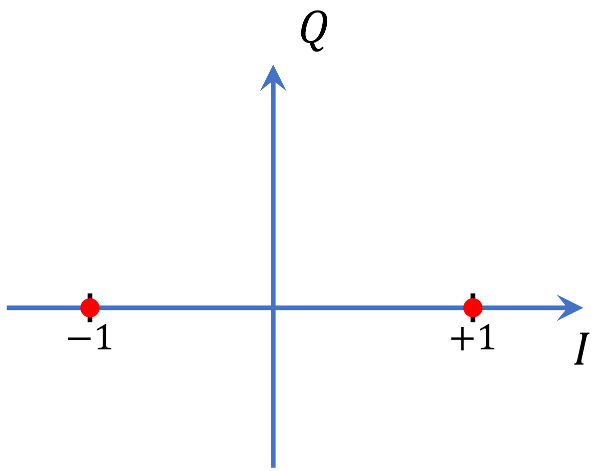
Received Constellation

How well we can decode depends on SNR?

$$SNR = \frac{Signal\ Power}{Noise\ Power} = \frac{E[|x(t)|^2]}{E[|v(t)|^2]} = \frac{E_s}{N_0}$$

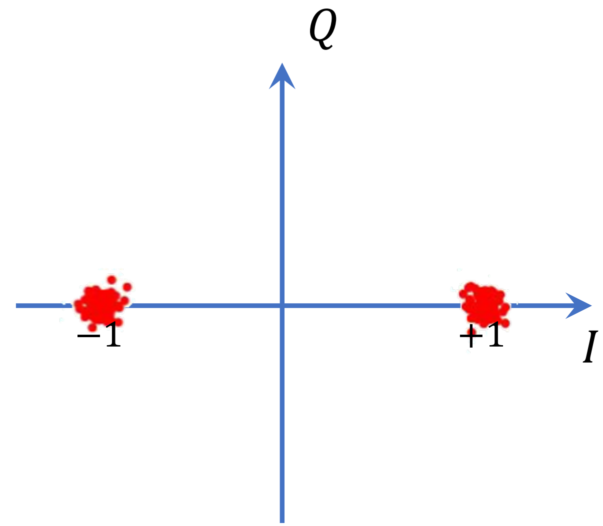
BPSK Modulation

$$0 \rightarrow -1$$
$$1 \rightarrow +1$$



$x(t)$

Transmitted Constellation



AWGN

$y(t) = x(t) + v(t)$

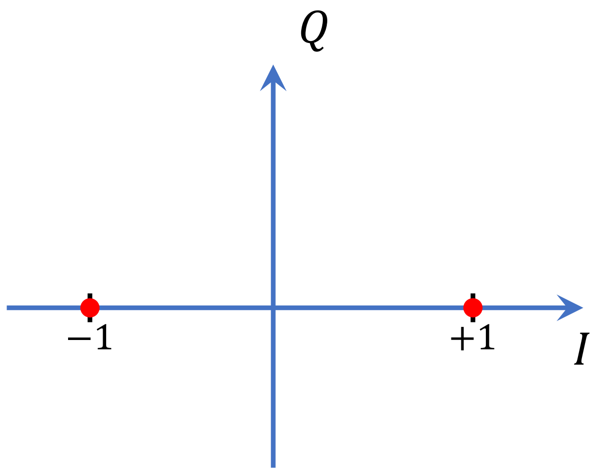
Received Constellation

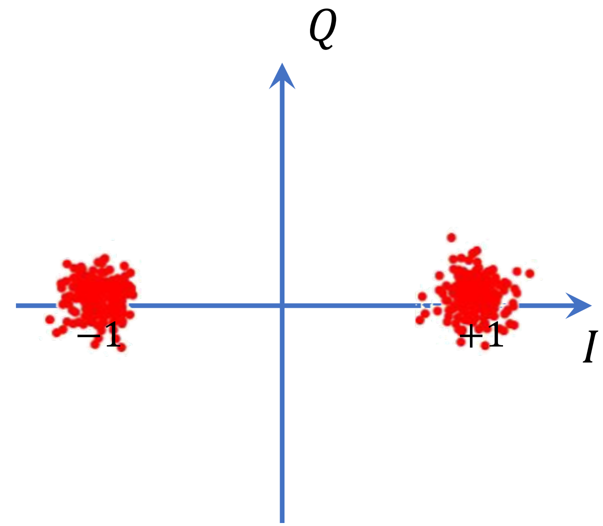
How well we can decode depends on SNR?

$$SNR = \frac{Signal\ Power}{Noise\ Power} \qquad = \frac{E_s}{N_0} \quad = 25\ \mathrm{dB}$$

BPSK Modulation

$0 \rightarrow -1$
$1 \rightarrow +1$





AWGN

$x(t)$

Transmitted Constellation

$y(t) = x(t) + v(t)$

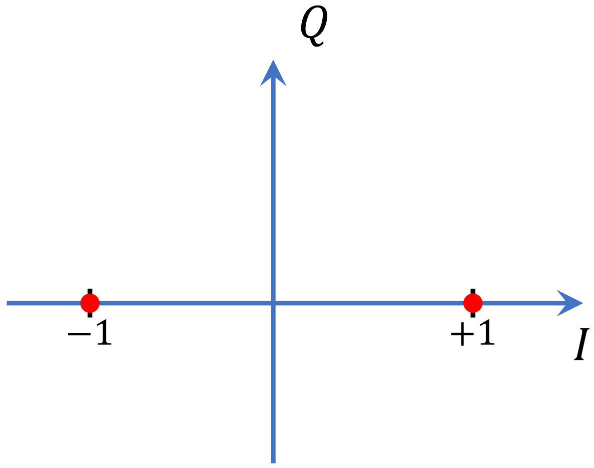
Received Constellation

How well we can decode depends on SNR?

$$SNR = \frac{Signal\ Power}{Noise\ Power} = \frac{E_s}{N_0} = 19\ \text{dB}$$

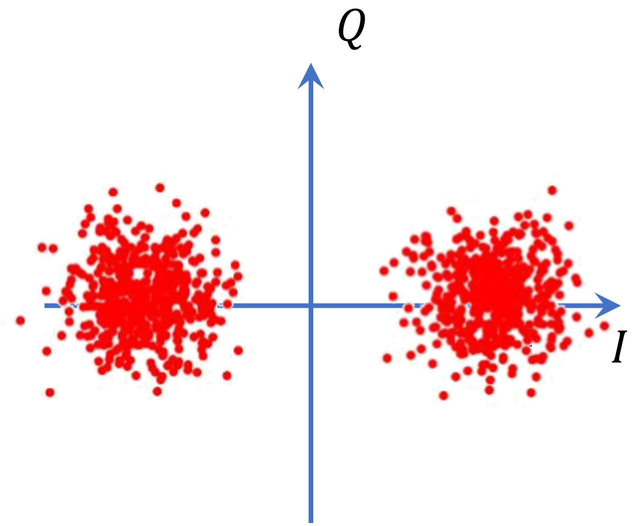
BPSK Modulation

$$0 \rightarrow -1$$
$$1 \rightarrow +1$$



$x(t)$

Transmitted Constellation



$y(t) = x(t) + v(t)$ AWGN

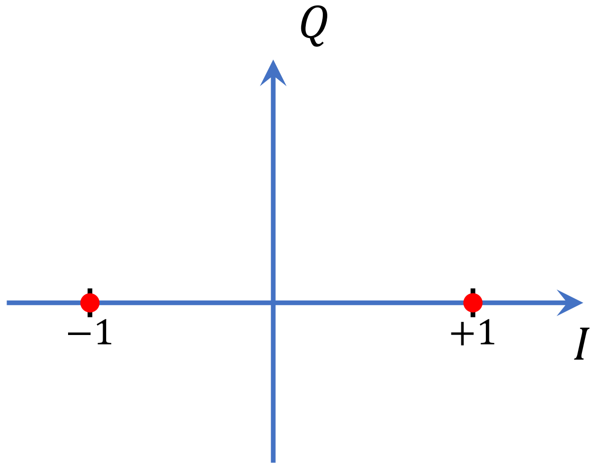
Received Constellation

How well we can decode depends on SNR?

$$SNR = \frac{Signal\ Power}{Noise\ Power} = \frac{E_s}{N_0} = 13\ \text{dB}$$

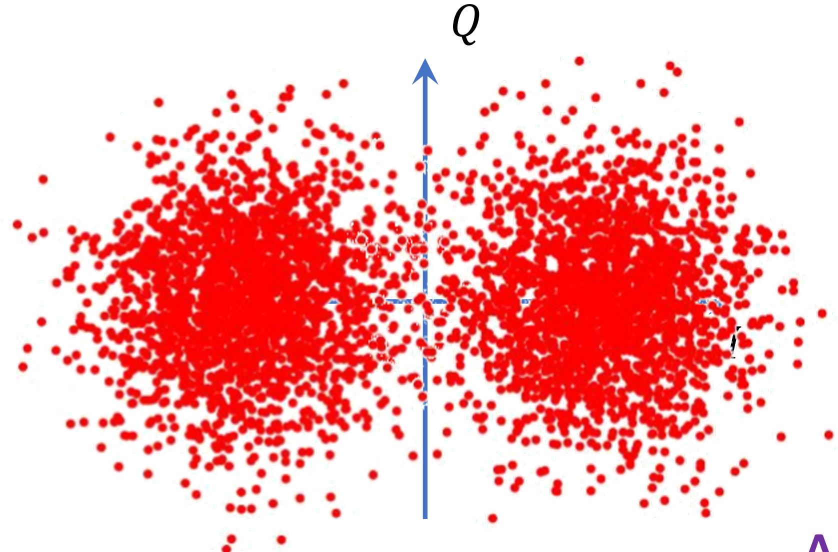
BPSK Modulation

$$0 \rightarrow -1$$
$$1 \rightarrow +1$$



$x(t)$

Transmitted Constellation



$y(t) = x(t) + v(t)$ AWGN

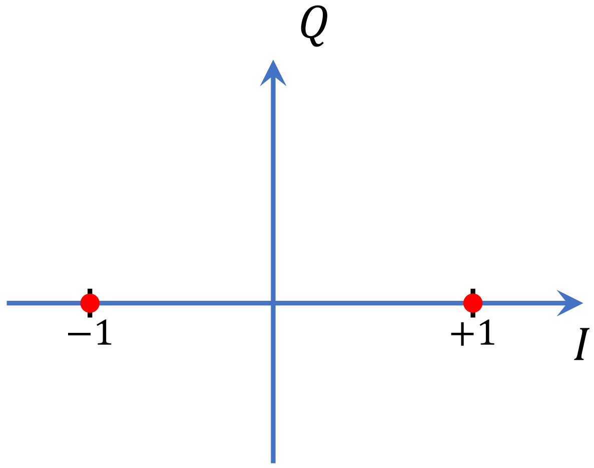
Received Constellation

How well we can decode depends on SNR?

$$SNR = \frac{Signal\ Power}{Noise\ Power} = \frac{E_s}{N_0} = 7\ \text{dB}$$

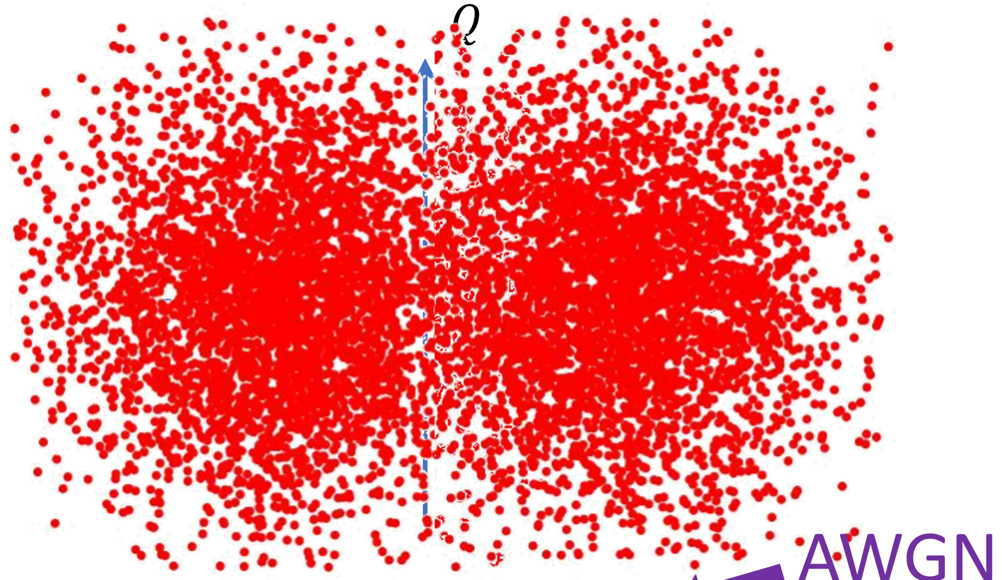
BPSK Modulation

$$0 \rightarrow -1$$
$$1 \rightarrow +1$$



$x(t)$

Transmitted Constellation



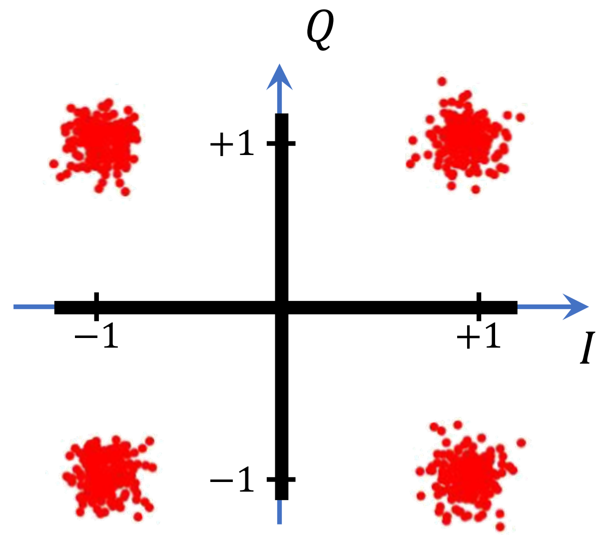
$y(t) = x(t) + v(t)$

Received Constellation

How well we can decode depends on SNR?

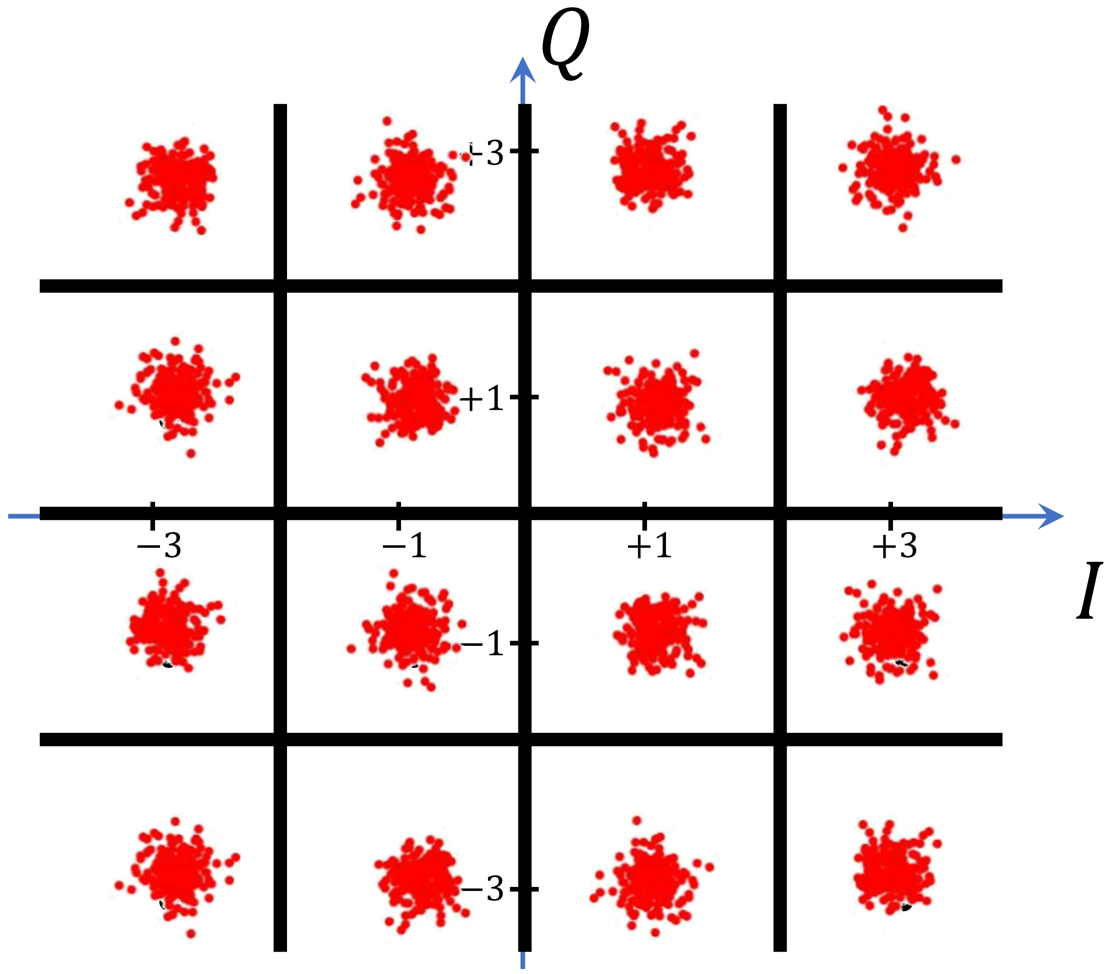
$$SNR = \frac{Signal\ Power}{Noise\ Power} \qquad = \frac{E_s}{N_0} \quad = 3.5\ \text{dB}$$

4-QAM



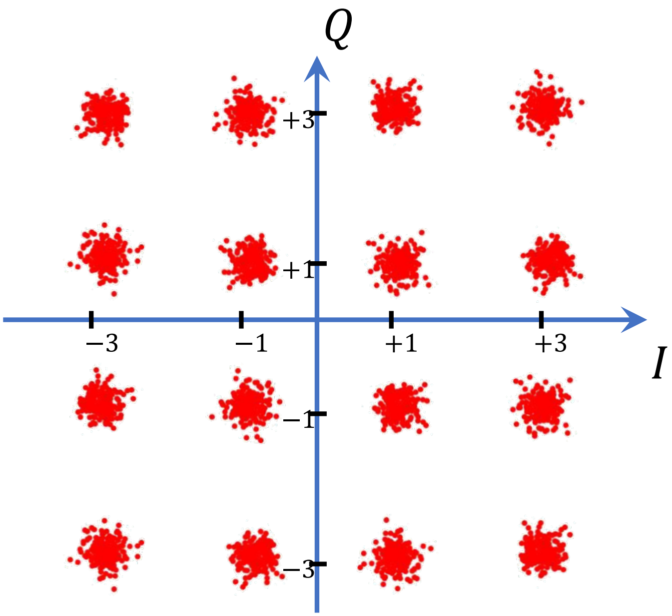
Encodes 2 bits per symbol ➔ Higher Data Rate

16-QAM

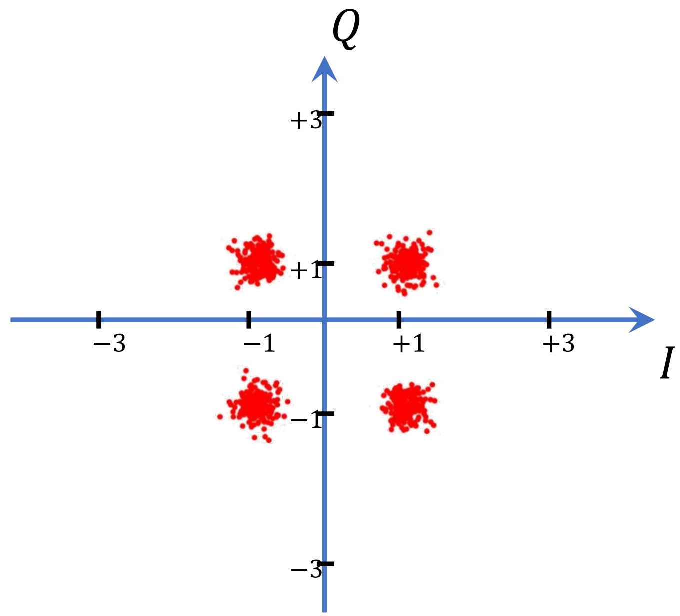


Encodes 4 bits per symbol ➔ Higher Data Rate

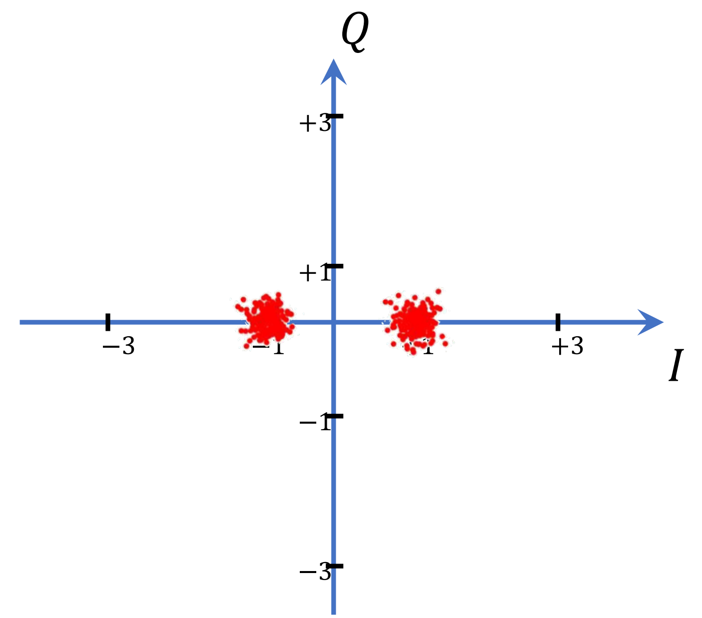
16-QAM



4-QAM



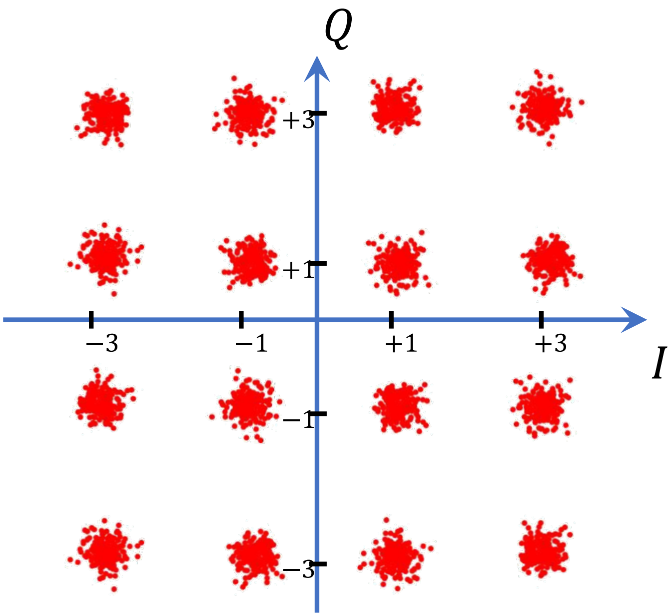
BPSK



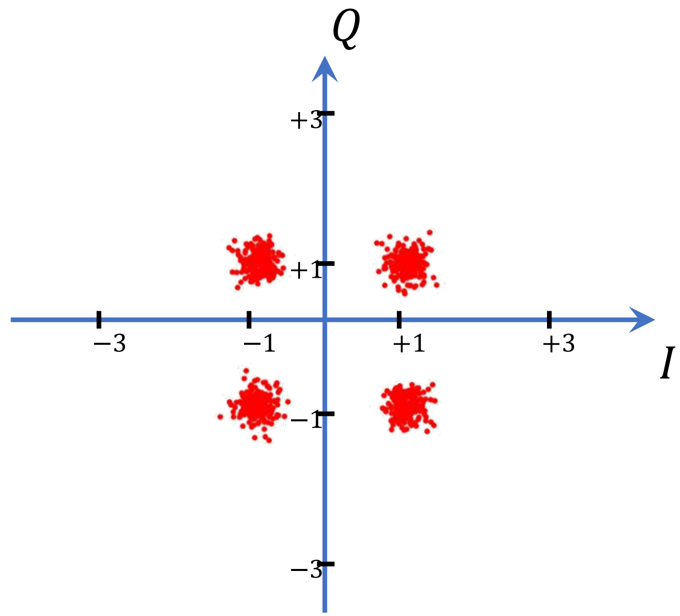
Is the SNR the same in these 3 constellations?

$$SNR = \frac{Signal\ Power}{Noise\ Power} = \frac{E[|x(t)|^2]}{E[|v(t)|^2]} = \frac{E_s}{N_0}$$

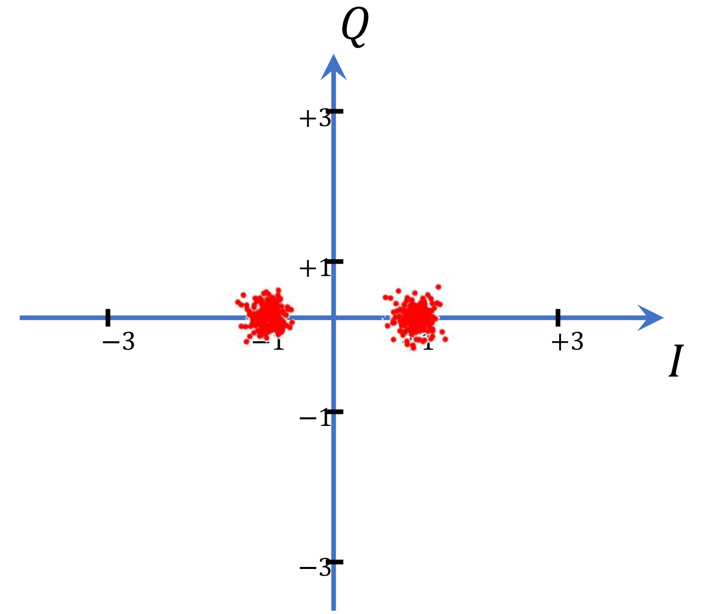
16-QAM



4-QAM



BPSK



$$SNR = \frac{E[|x(t)|^2]}{N_0}$$

$$SNR = \frac{(4\times2 + 8\times10 \\ +4\times18)/16}{N_0} = \frac{10}{N_0}$$

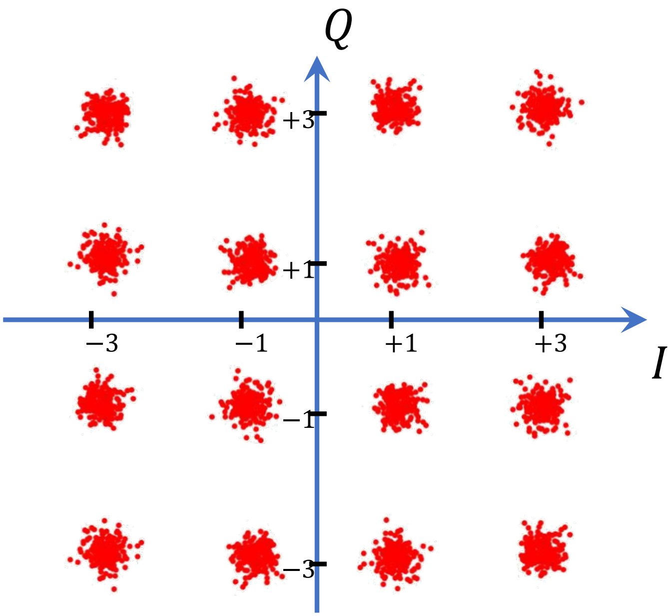
$>$

$$SNR = \frac{(2+2+2+2)/4}{N_0} = \frac{2}{N_0}$$

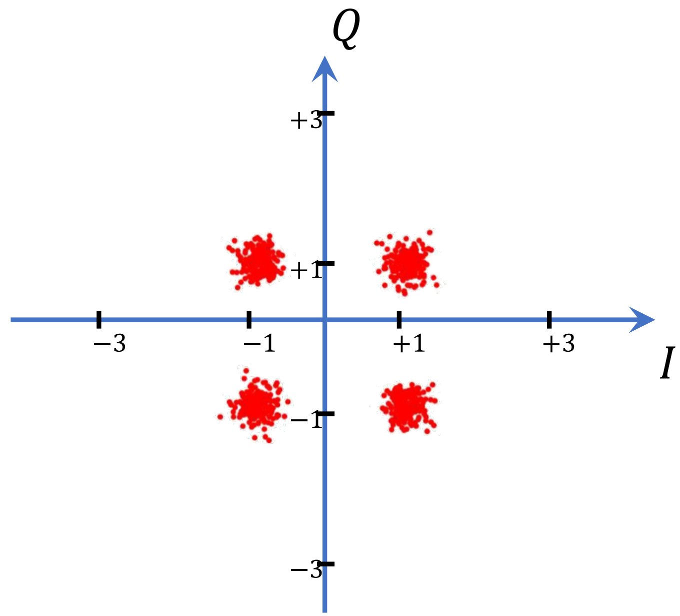
$>$

$$SNR = \frac{(1+1)/2}{N_0} = \frac{1}{N_0}$$

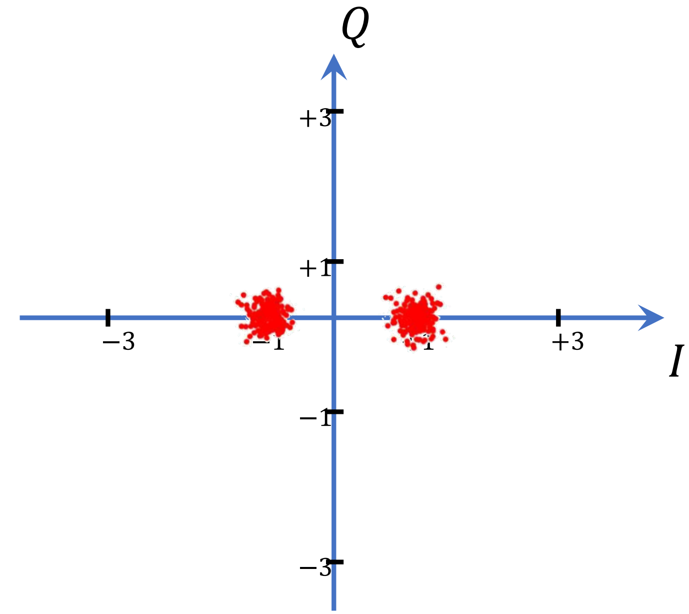
16-QAM



4-QAM



BPSK



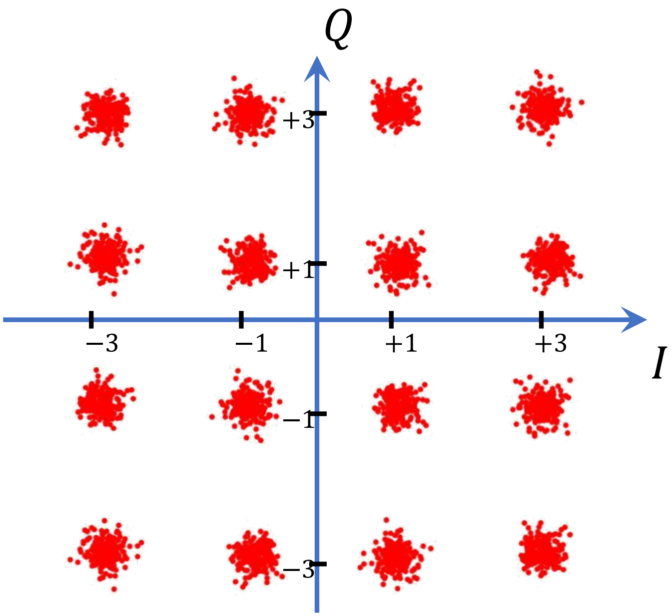
Transmit power is not the same!

$$SNR = \frac{(4\times2 + 8\times10 \ldots +4\times18 \ldots}{N_0} \quad \ldots \quad \frac{\ldots 1)/2}{N_0}$$

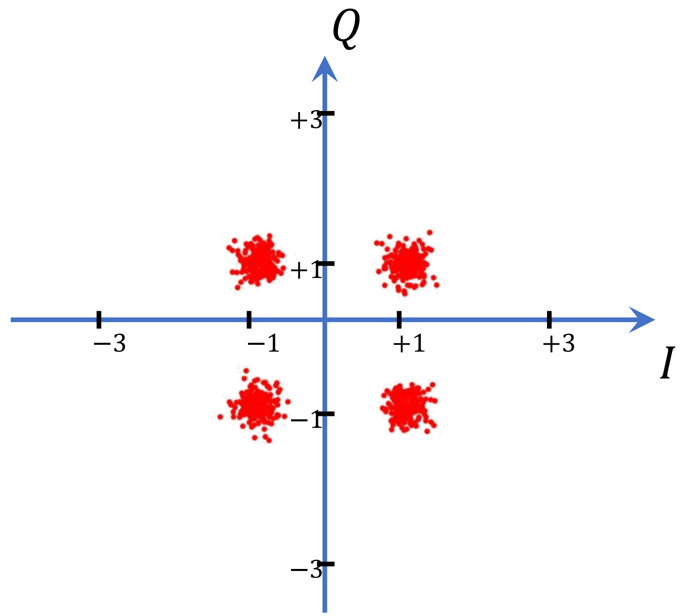
$$= \frac{10}{N_0}$$

Must not increase transmit power to use higher order modulation!

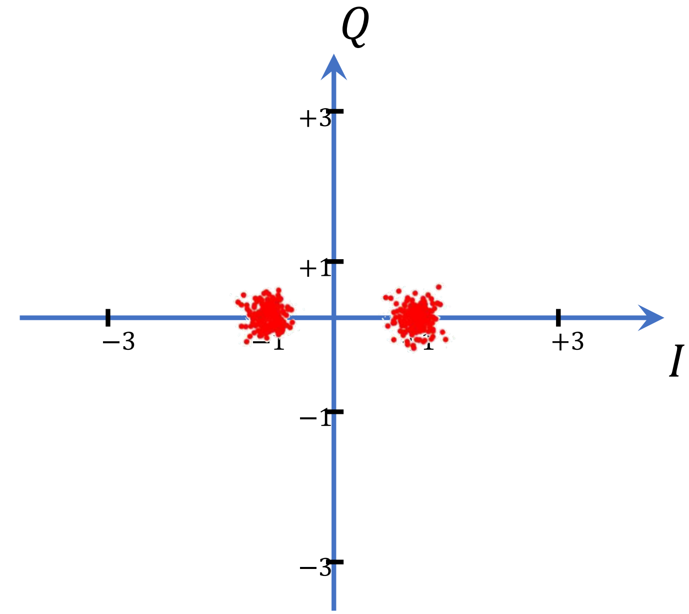
16-QAM



4-QAM



BPSK



Normalize to maintain constant transmit power.

$$SNR = \frac{\begin{matrix}(4\times 2 + 8\times 10 \\ +4\times 18)/16\end{matrix}}{N_0} = \frac{10}{N_0}$$

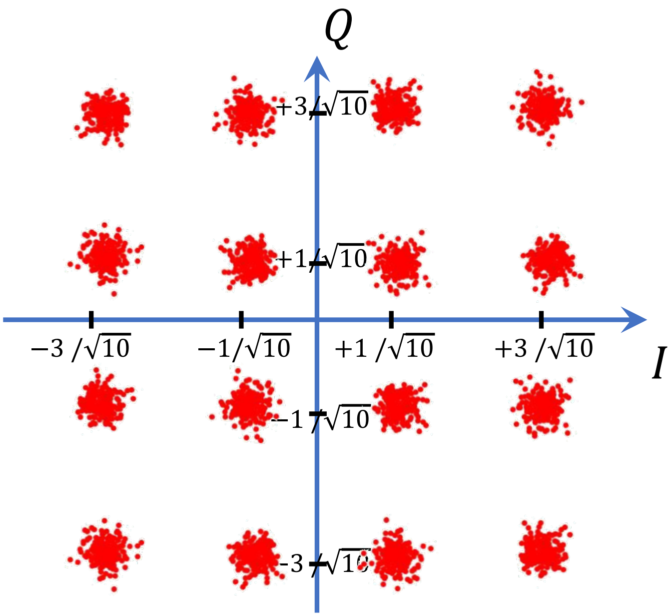
$>$

$$SNR = \frac{(2+2+2+2)/4}{N_0} = \frac{2}{N_0}$$

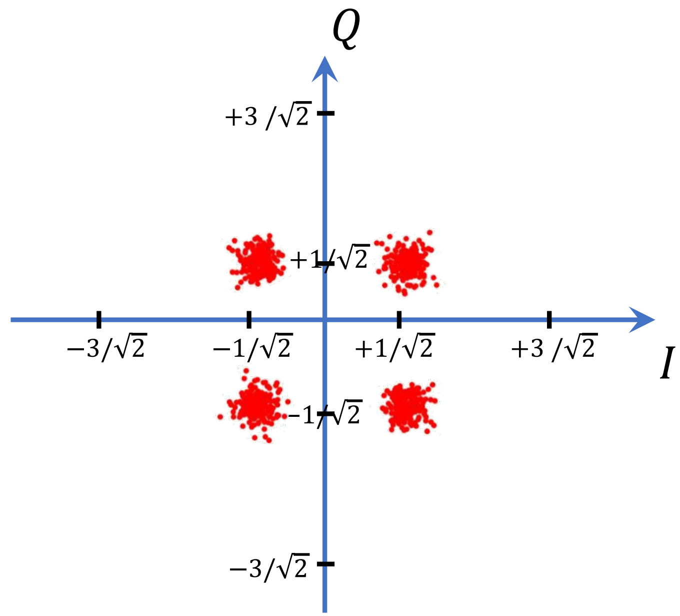
$>$

$$SNR = \frac{(1+1)/2}{N_0} = \frac{1}{N_0}$$

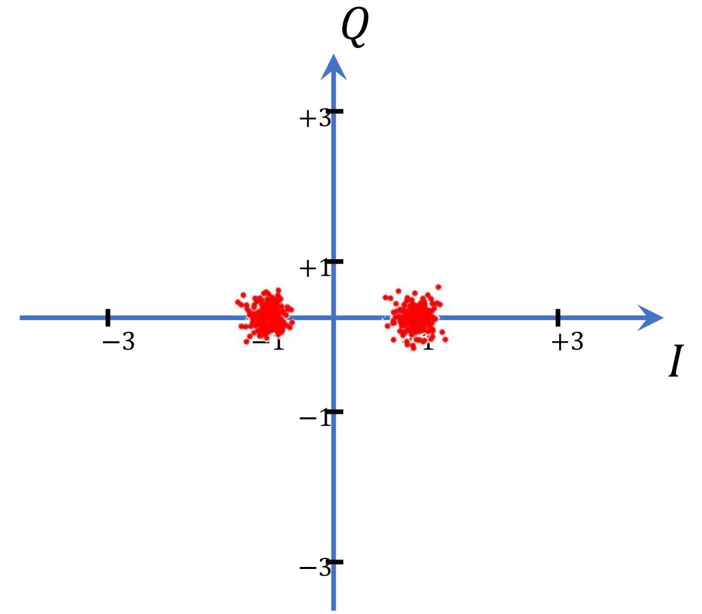
16-QAM



4-QAM



BPSK



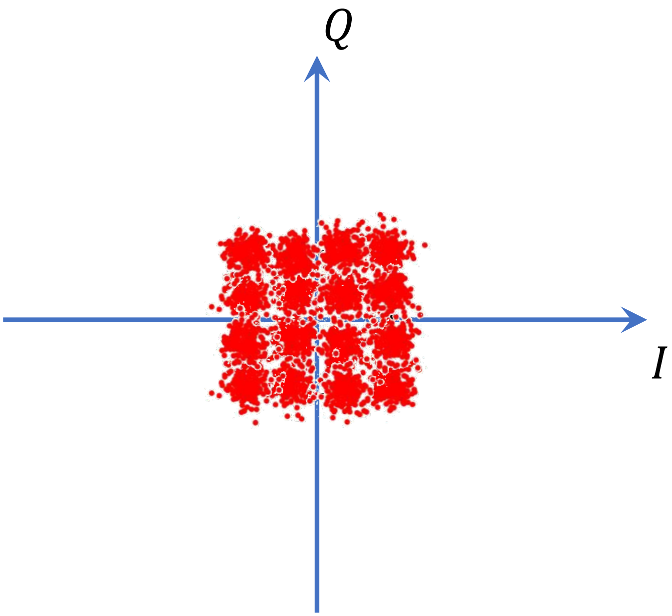
Normalize to maintain constant transmit power.

$$SNR = \frac{\begin{array}{c}(4\times 2/10 + 8\times 1\\ +4\times 18/10)/16\end{array}}{N_0} = \frac{1}{N_0}$$

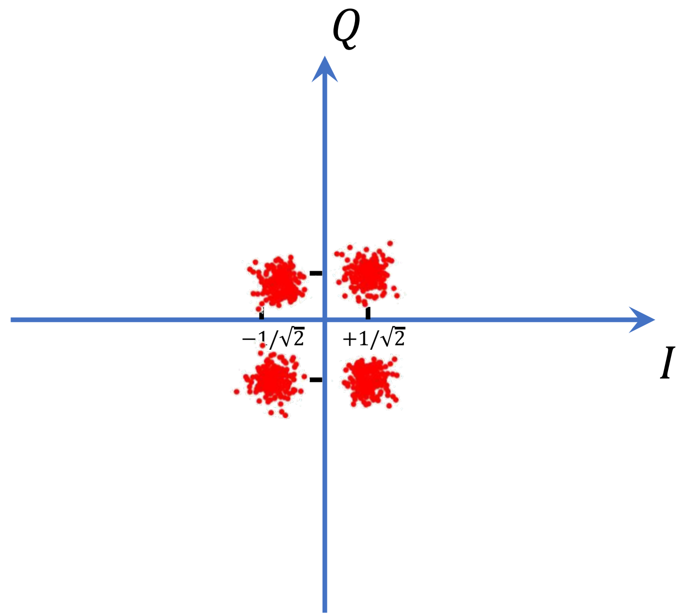
$$SNR = \frac{(1+1+1+1)/4}{N_0} = \frac{1}{N_0}$$

$$SNR = \frac{(1+1)/2}{N_0} = \frac{1}{N_0}$$

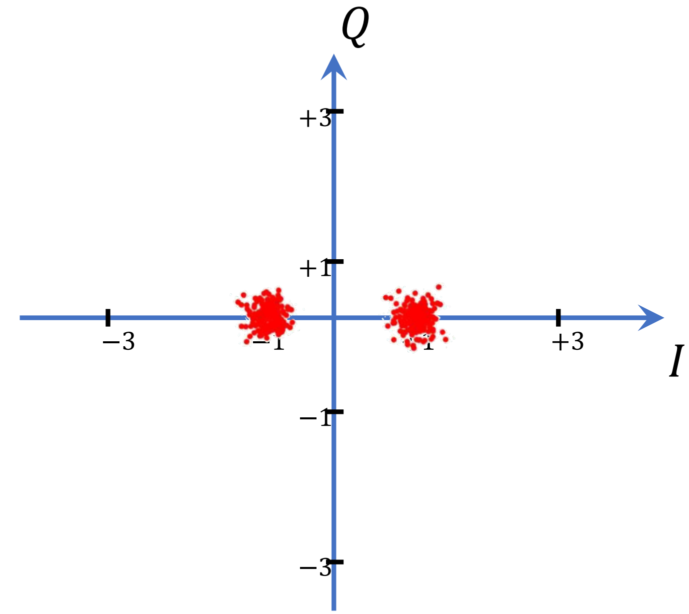
16-QAM



4-QAM



BPSK

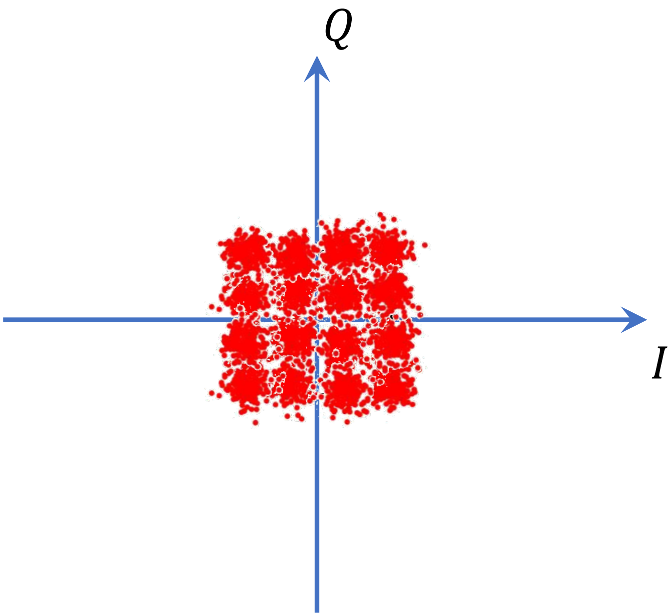


Normalize to maintain constant transmit power.

$SNR = \frac{1}{N_0}$ $SNR = \frac{1}{N_0}$ $SNR = \frac{1}{N_0}$

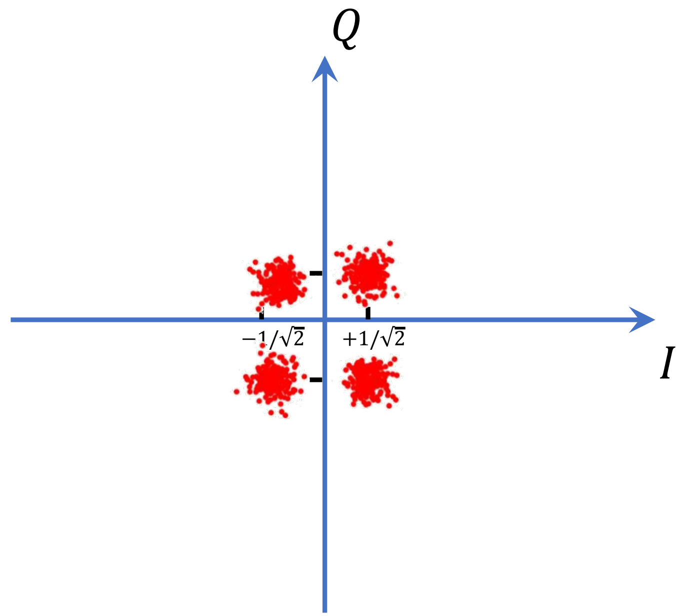
Need Higher SNR to Decode Higher Order Modulation.

16-QAM



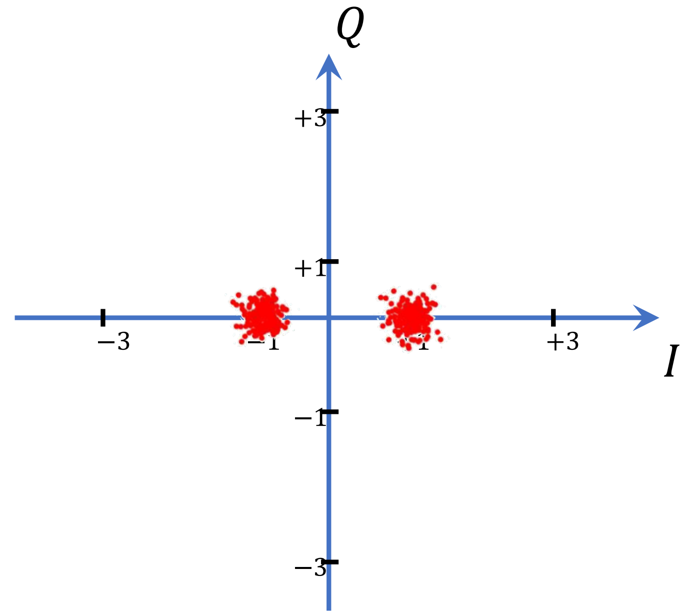
4 bits/symbol

4-QAM



2 bits/symbol

BPSK



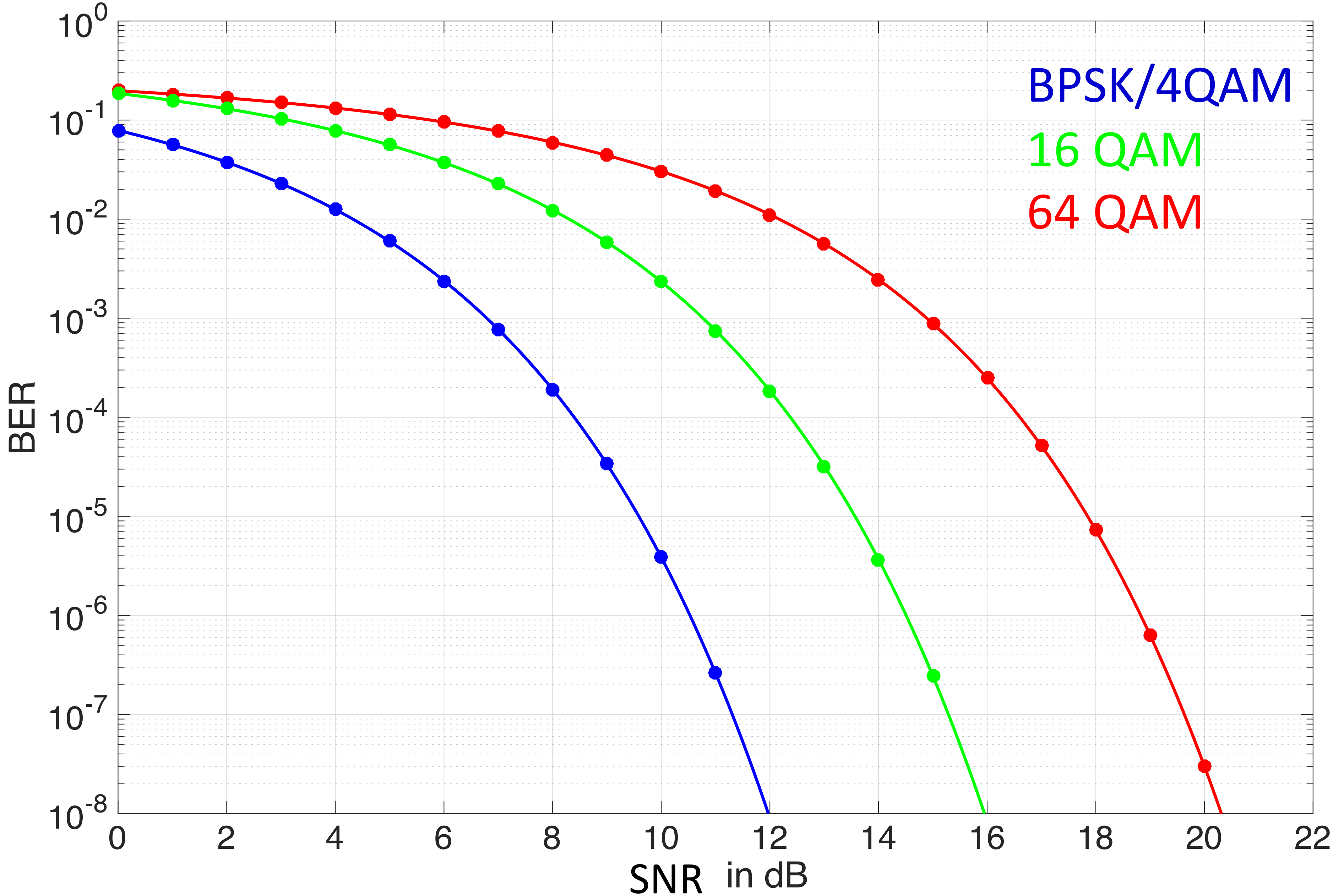
1 bit/symbol

Higher Order Modulation:

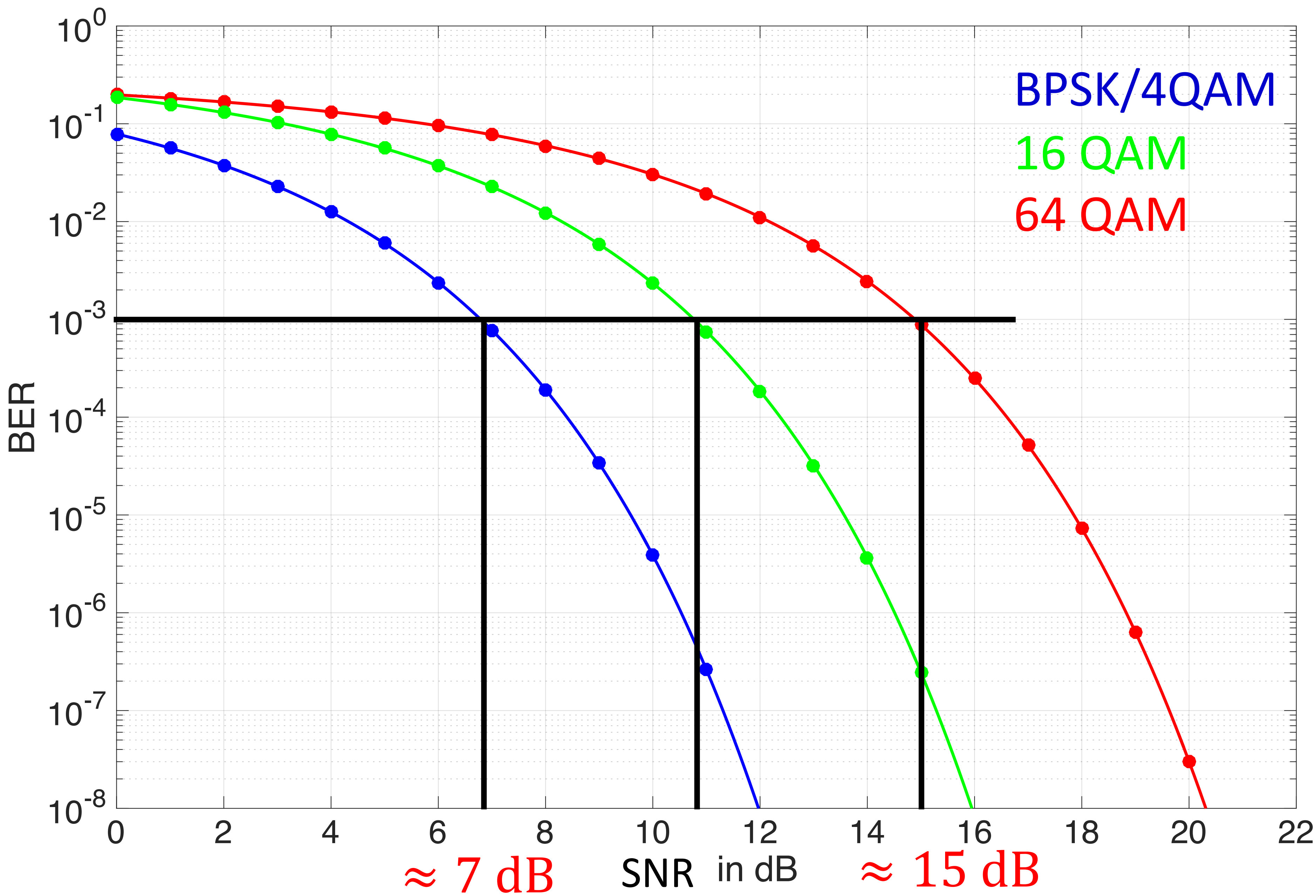
- Needs higher SNR to decode correctly.
- Achieves higher Bite Rate

Given an SNR, choose highest order modulation that guarantees minimal Bite Error Rate (BER)

Bit Error Rate (BER)

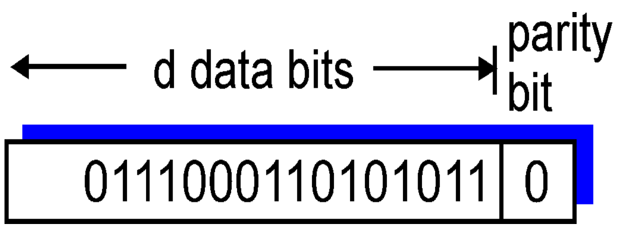


Bit Error Rate (BER)

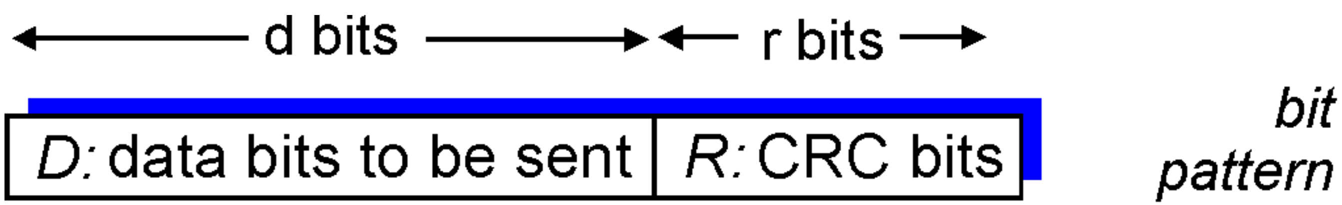


Error Detection

- Add Redundant bits in order to detect errors at receiver
- Checksums→ Detect Errors
  - Parity Check



  - CRC: Cyclic Redundancy Check



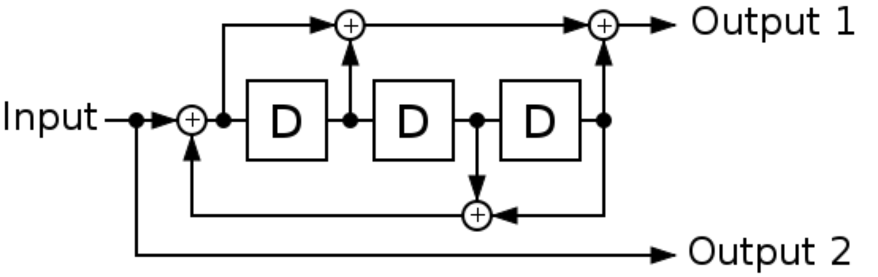
- If packet (frame, sequence of bits) fails the checksum test

  → Packet is dropped

  → Packet loss.

Coding: Forward Error Correction (FEC)

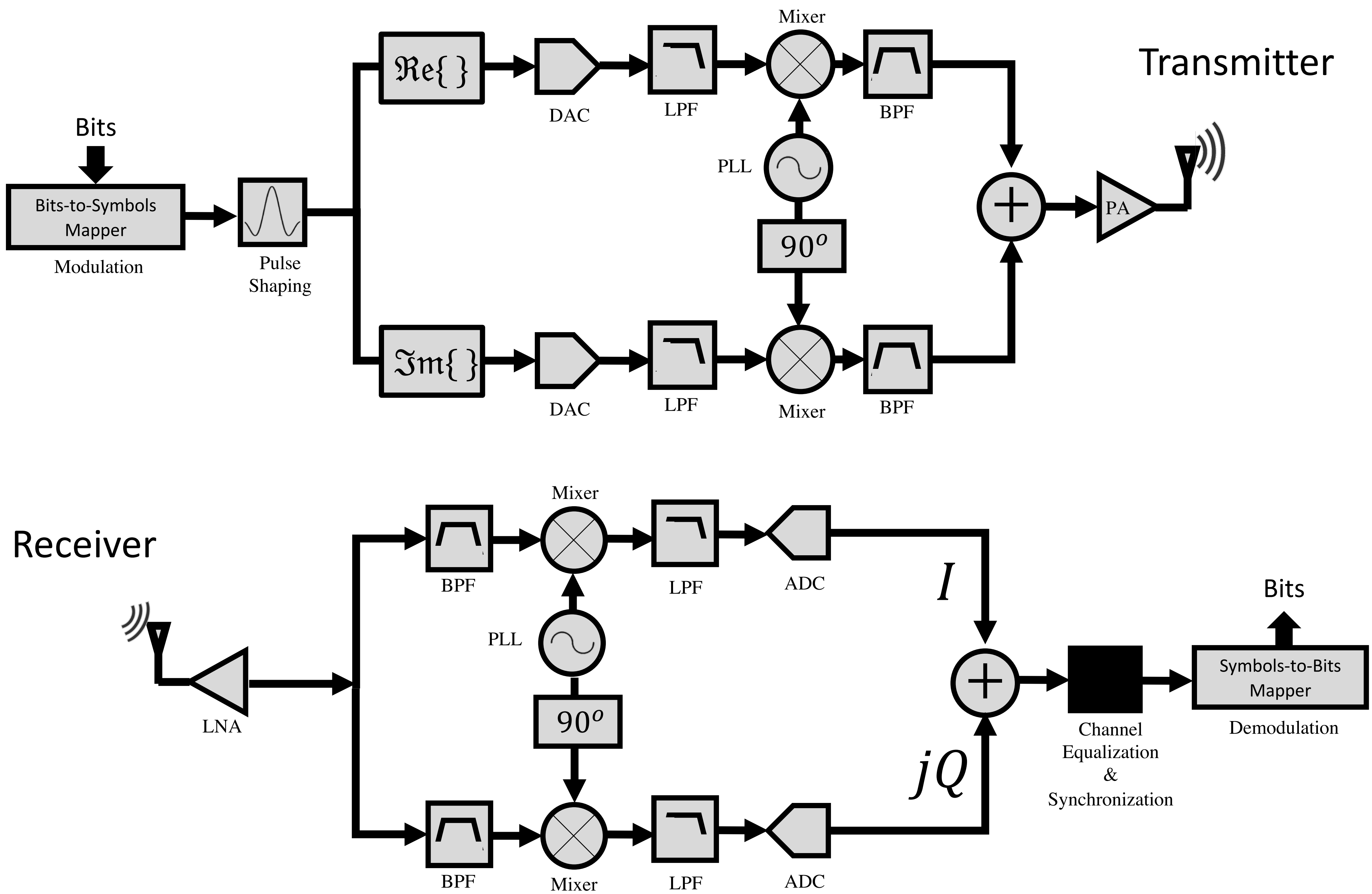
- Add Redundant bits in order to correct errors at receiver
- FEC: Forward Error Correction
  - Repetition Code
  - Convolutional codes
  - Reed Solomon codes
  - Turbo codes
  - Polar codes
  - LDPC codes



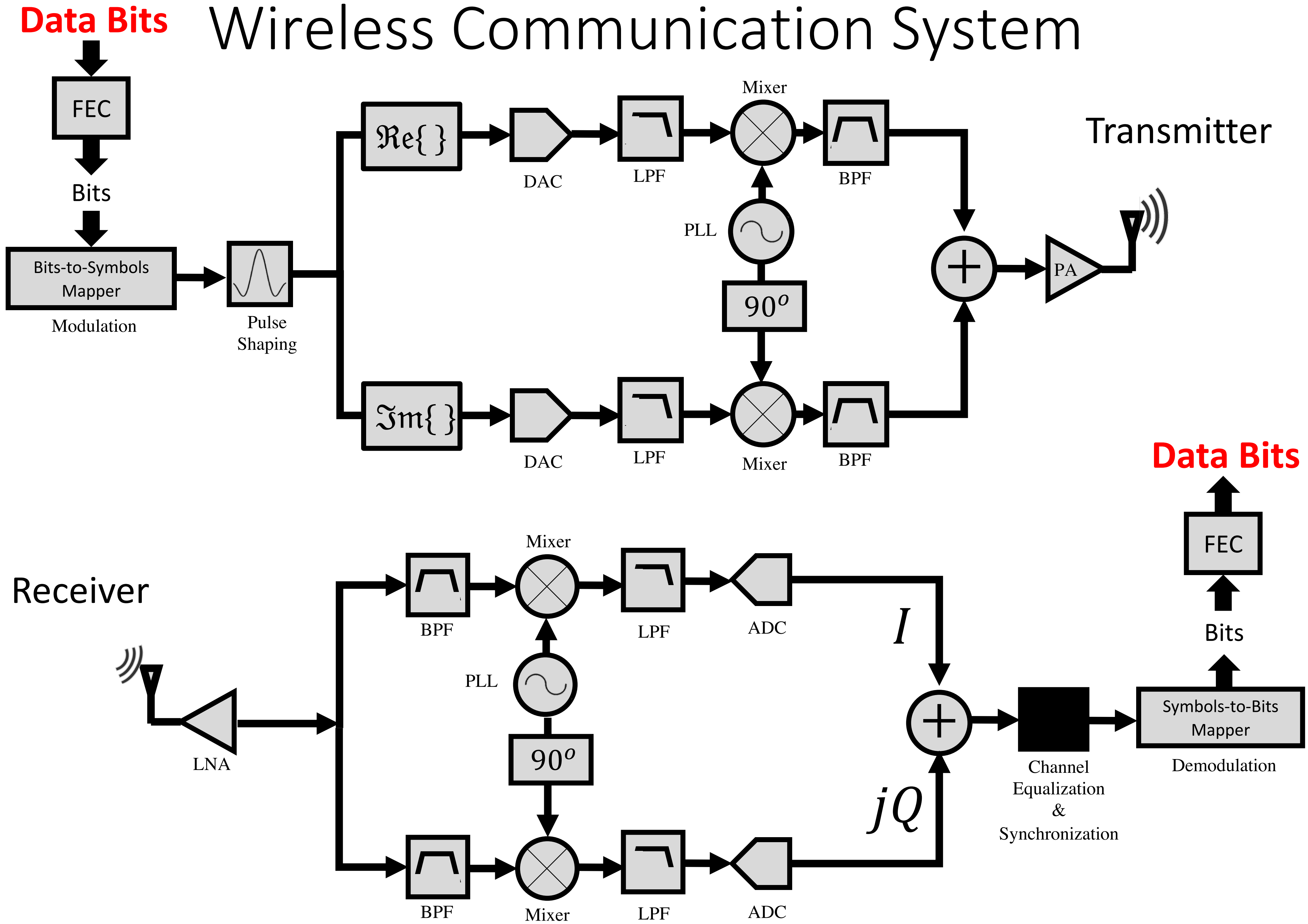
- Code Rate $= \dfrac{\#\ of\ \ data\ bits\ (uncoded)}{\#\ of\ \ transmitted\ bits\ (coded)}$

  - E.g. coding rate 2/3, for every 2 data bits, I transmit 3 bits.
  - ↘ code rate → ↘ redundancy → ↗ bit errors + ↗ data rate
  - ↗ code rate → ↗ redundancy → ↘ bit errors + ↘ data rate

Wireless Communication System



Wireless Communication System



Wireless Data Rates

- *Data Rate*
  - *Bandwidth: Samples/sec*
  - *Modulation: Bits/sample*
  - *Coding Rate: Data Bits/Coded Bits*

$$Data\ Rate = Bandwidth \times Bits/sample \times Code\ Rate$$

- *Capacity*
  - *Maximum Achievable Data Rate*
  - *Shannon Capacity Theorem:*

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