

CSE610 Special Topics on Mobile Network & Mobile sensing

Lecture 2: Wireless Communication

Yaxiong Xie

Wireless communication

- Ancient Systems: Smoke Signals, Carrier Pigeons, ...



International Morse Code

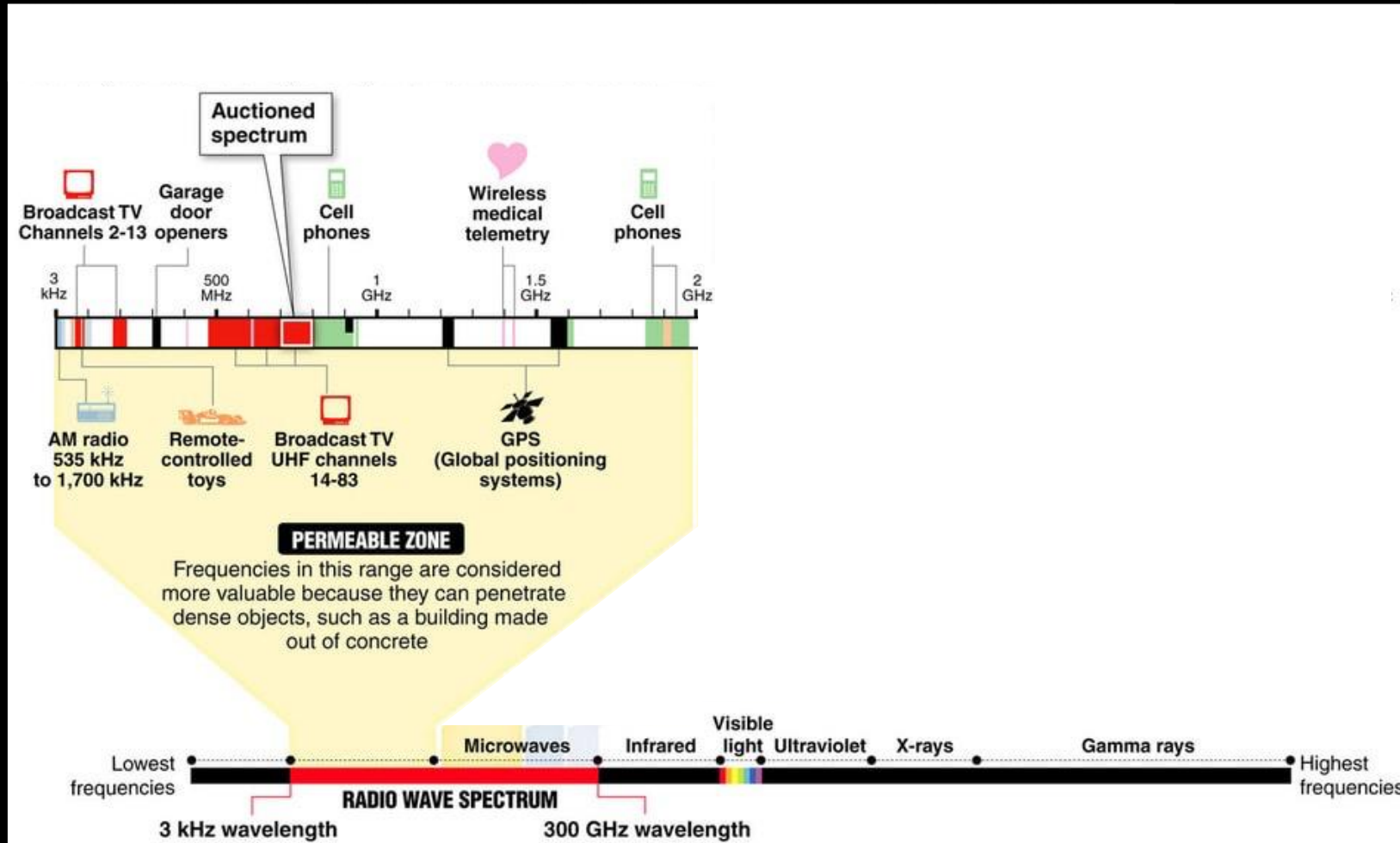
1. The length of a dot is one unit.
2. A dash is three units.
3. The space between parts of the same letter is one unit.
4. The space between letters is three units.
5. The space between words is seven units.

| | | | |
|---|---------|---|-----------|
| A | • — | U | • • — |
| B | — • • • | V | • • • — |
| C | — • — • | W | • — — |
| D | — • • | X | — • • — |
| E | • | Y | — • — — |
| F | • • — • | Z | — — • • |
| G | — — • | | |
| H | • • • • | | |
| I | • • | | |
| J | • — — — | | |
| K | — • — | 1 | • — — — — |
| L | • — • • | 2 | • • — — — |
| M | — — | 3 | • • • — — |
| N | — • | 4 | • • • • — |
| O | — — — | 5 | • • • • • |
| P | • — • • | 6 | — • • • • |
| Q | — — • — | 7 | — — • • • |
| R | • — • | 8 | — — — • • |
| S | • • • | 9 | — — — — • |
| T | — | 0 | — — — — — |

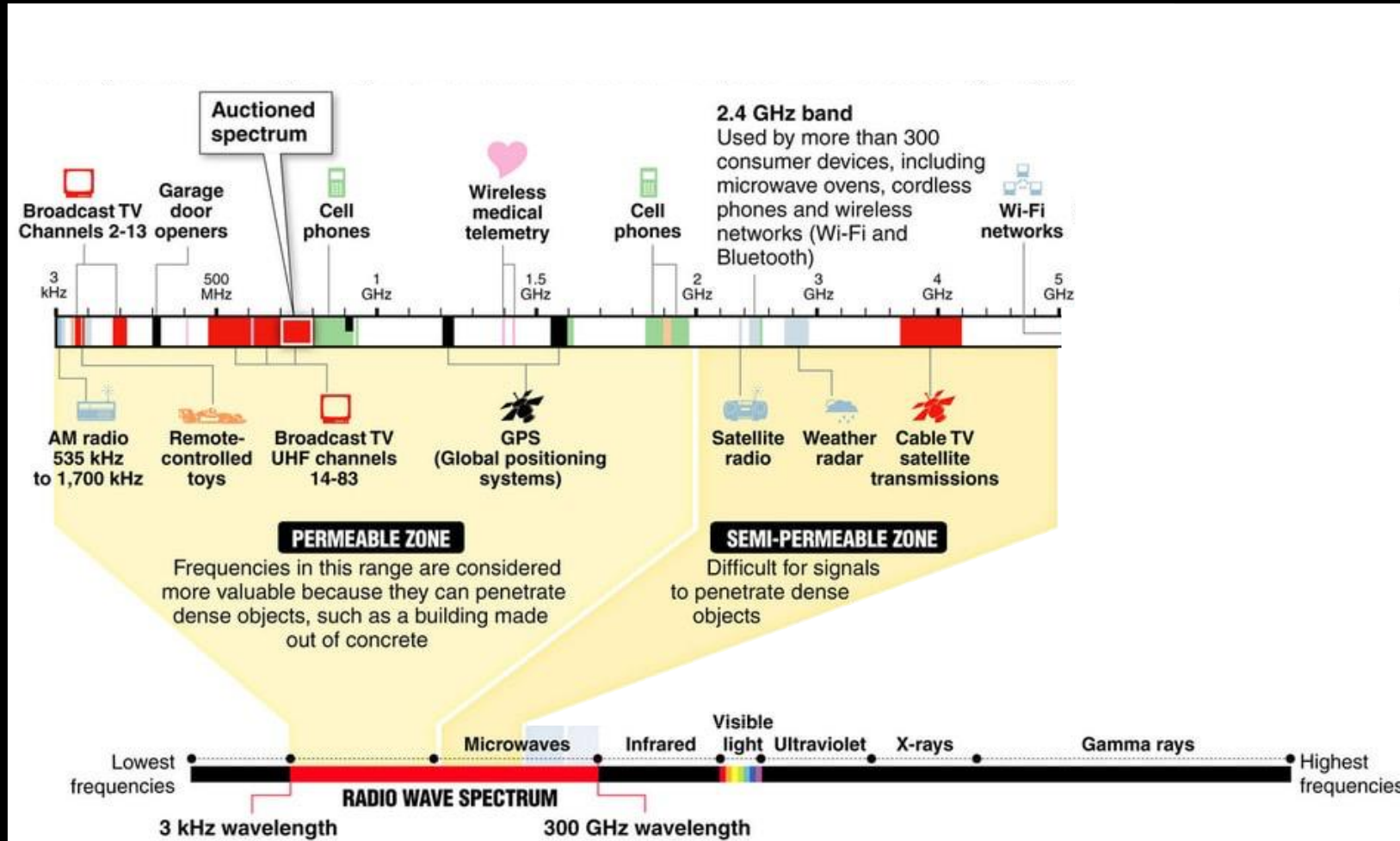
- Radio based wireless communication invented by Marconi



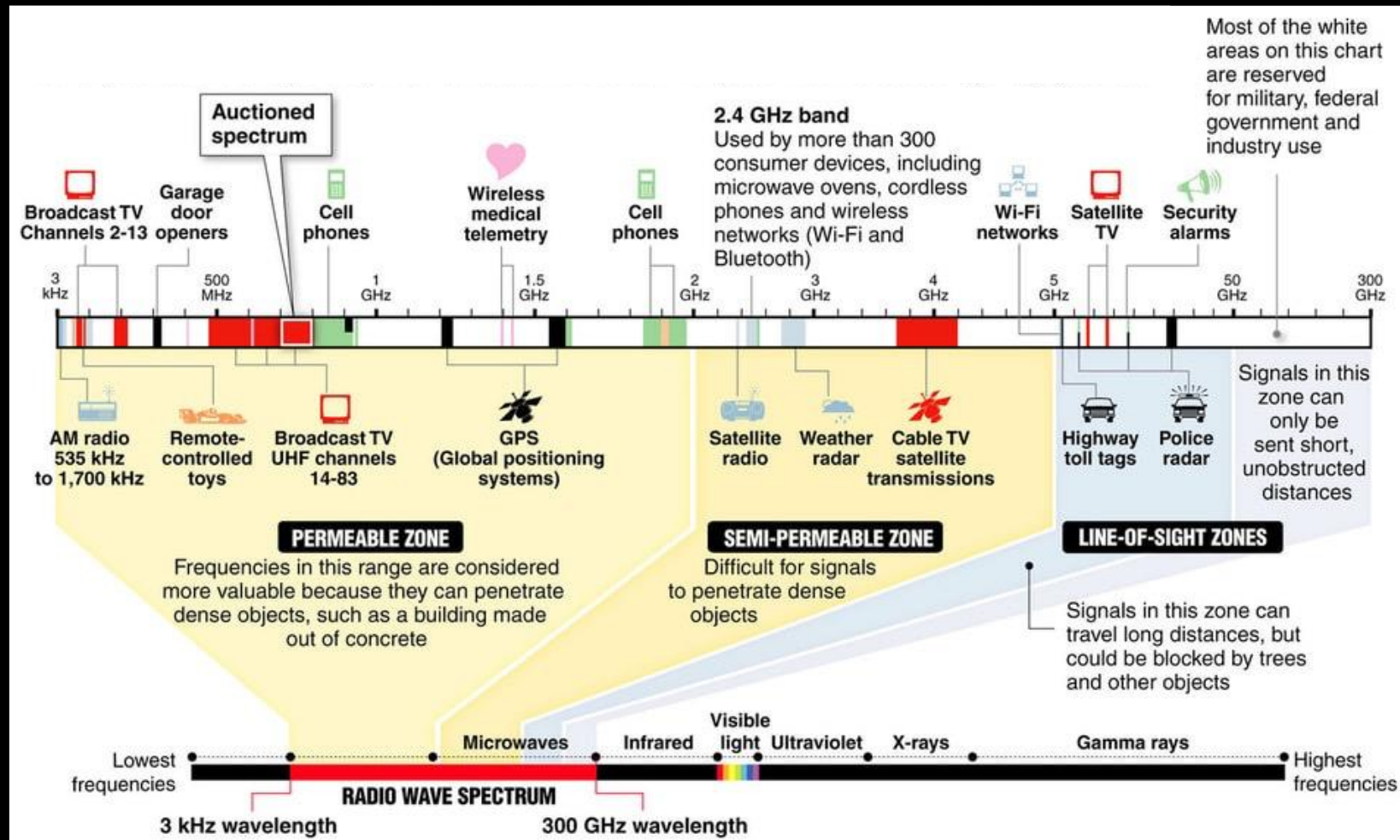
Wireless Spectrum



Wireless Spectrum



Wireless Spectrum



Wireless Spectrum

MID-BAND SPECTRUM AUCTION —

Verizon and AT&T dominate spectrum auction, spending combined \$69 billion

Top two carriers buy licenses nationwide, outspending T-Mobile and US Cellular.

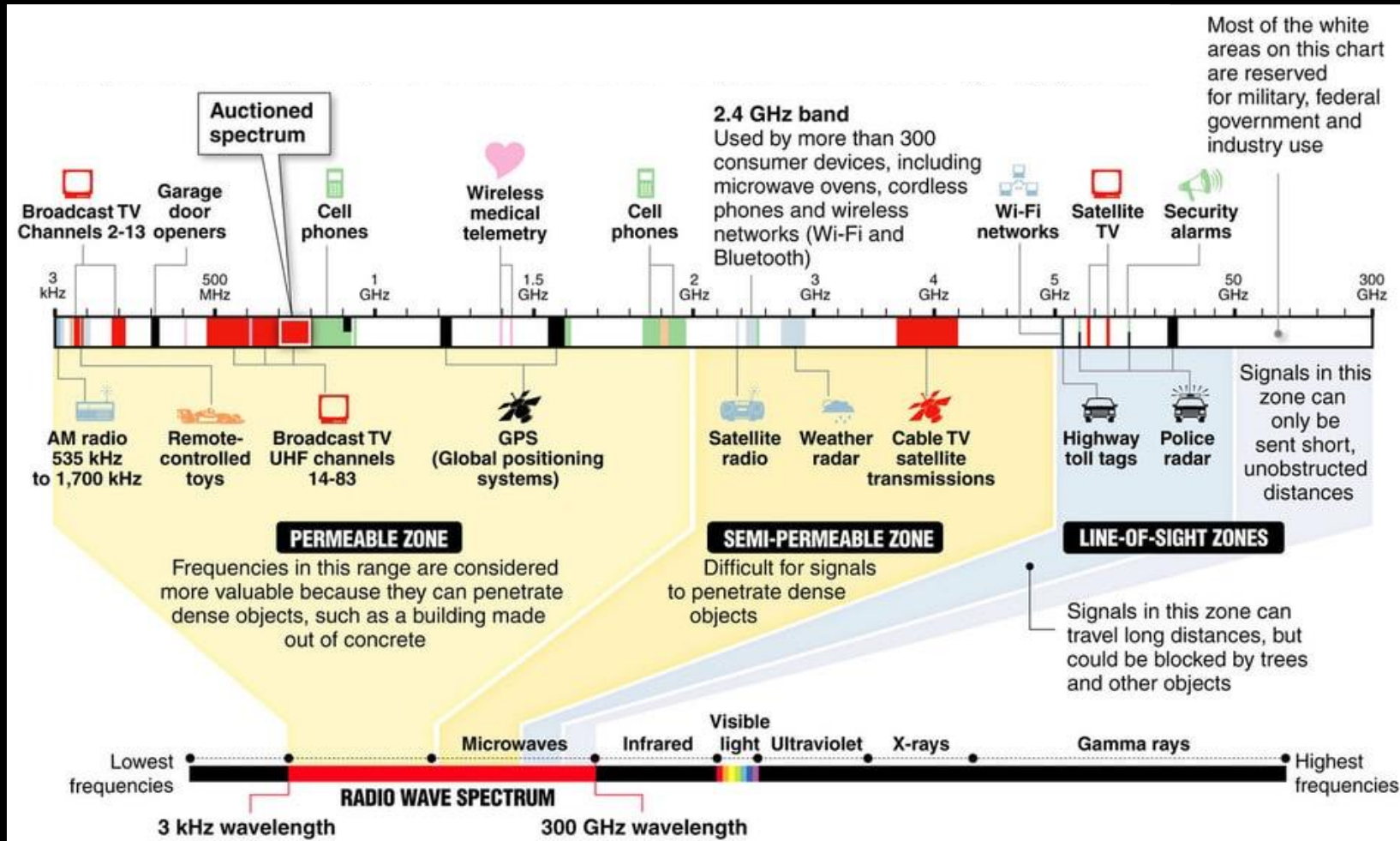
JON BRODKIN - 2/25/2021, 11:14 AM

Verizon and AT&T dominated the US government's latest spectrum auction, spending a combined \$68.9 billion on licenses in the upper 3GHz band.

Verizon's winning bids totaled \$45.45 billion, while AT&T's came in at \$23.41 billion. T-Mobile was third with \$9.34 billion as the three biggest wireless carriers accounted for the vast majority of the \$81.17 billion in winning bids, the Federal Communications Commission said in results released yesterday. US Cellular, a regional carrier, was a distant fourth in spending, at \$1.28 billion, but came in third, ahead of T-Mobile, in the number of licenses won.

Wireless Spectrum: ISM band

Radio spectrum reserved internationally for *Industrial, Scientific, and Medical* (ISM) purposes



Wireless Spectrum: ISM band

Radio spectrum reserved internationally for *Industrial, Scientific, and Medical* (ISM) purposes

902 MHz - 928 MHz
26 MHz

2.4 GHz – 2.5 GHz
100MHz

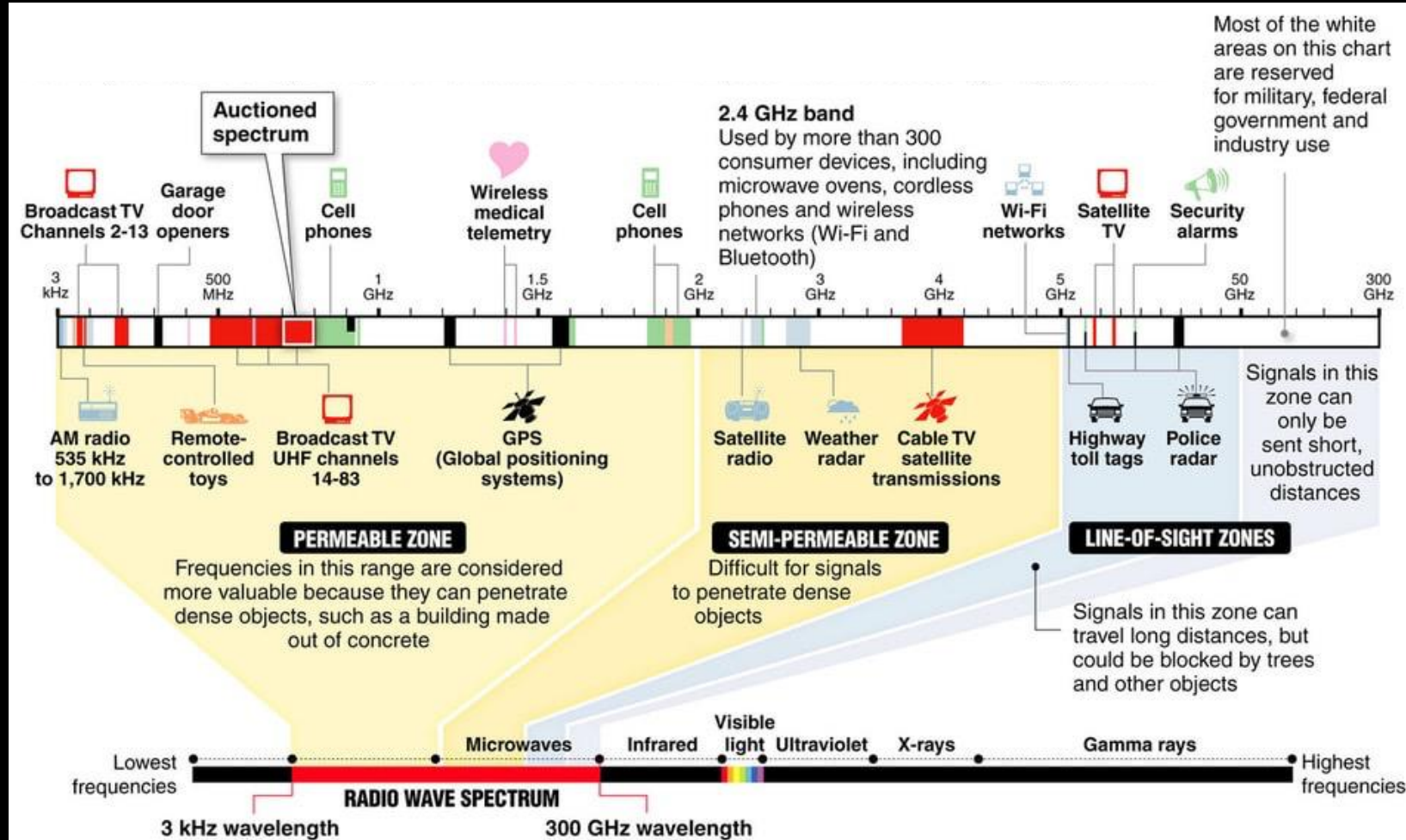
5.725 GHz – 5.825 GHz
150MHz



LTE 5G unlicensed

Wireless Spectrum: ISM band

Radio spectrum reserved internationally for **Industrial, Scientific, and Medical** (ISM) purposes



902 MHz - 928 MHz
26 MHz

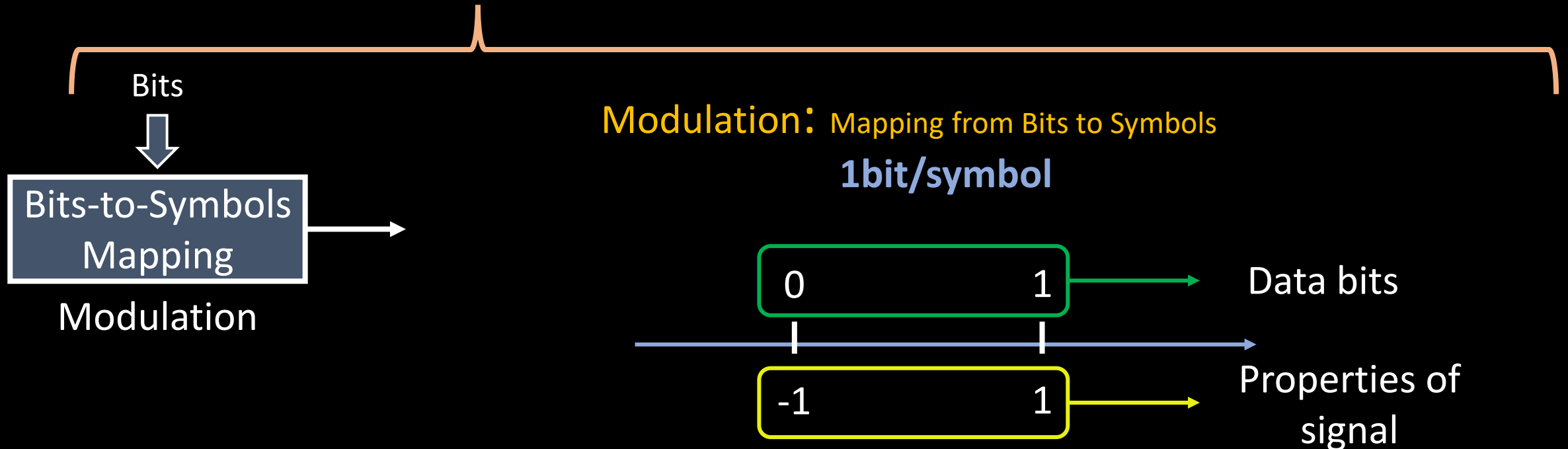
2.4 GHz – 2.5 GHz
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5.725 GHz – 5.825 GHz
150MHz

Wireless communication system

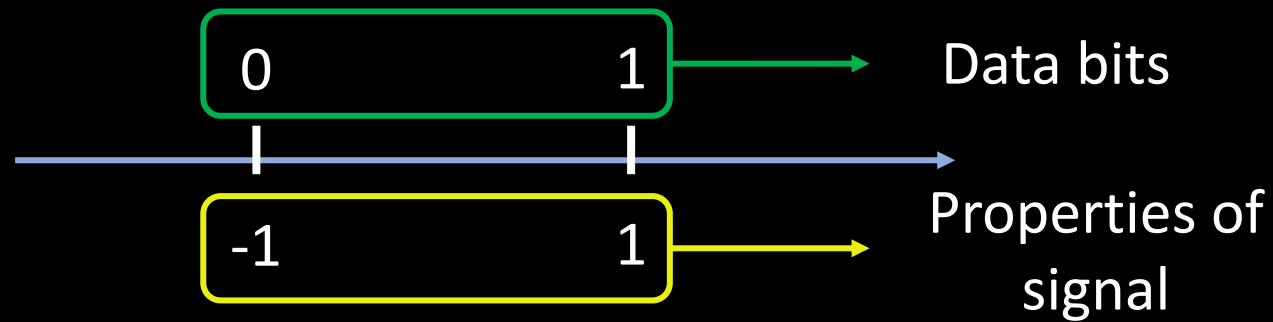


Wireless communication system

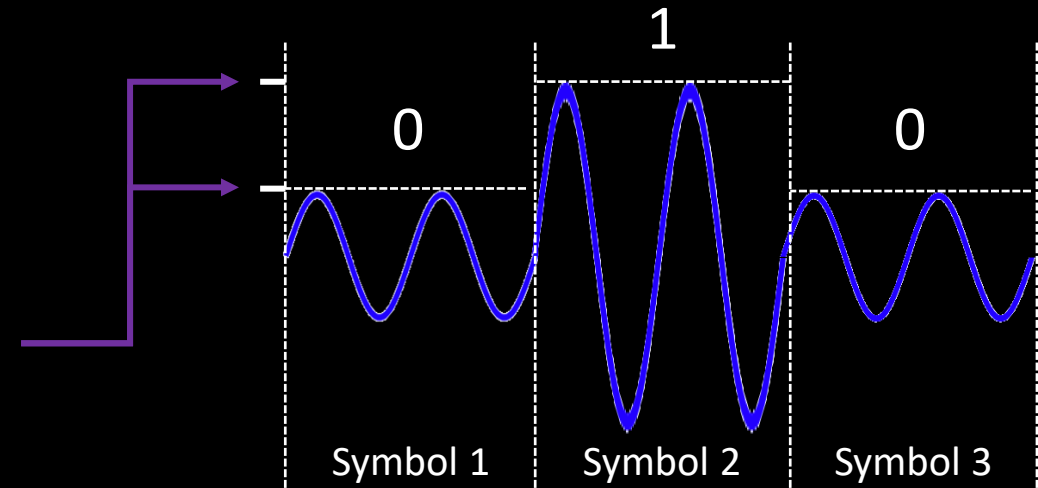


Wireless communication system

Modulation: Mapping from Bits to Symbols
1bit/symbol

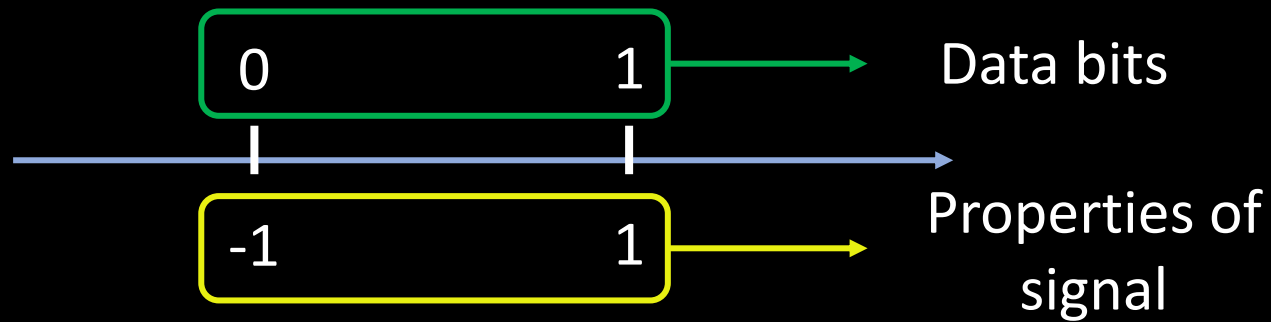


Amplitude Modulation

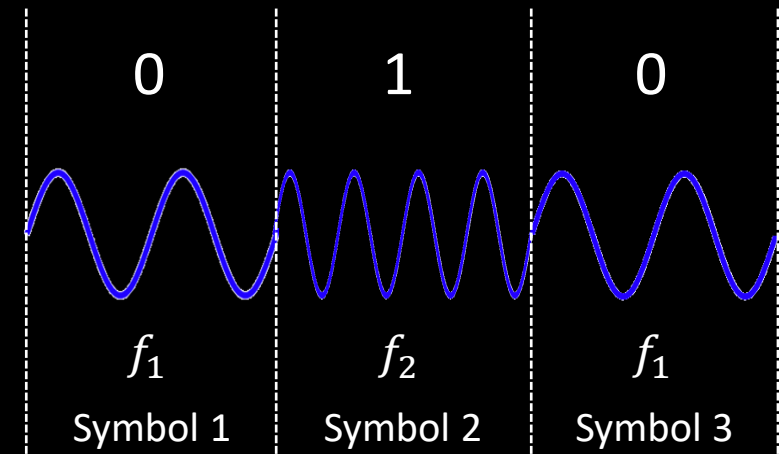


Wireless communication system

Modulation: Mapping from Bits to Symbols
1bit/symbol

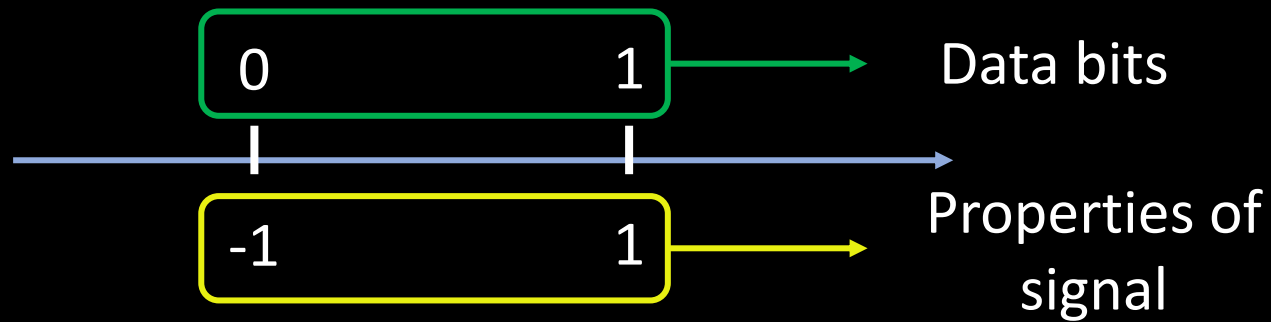


Frequency Modulation



Wireless communication system

Modulation: Mapping from Bits to Symbols
1bit/symbol



Phase Modulation

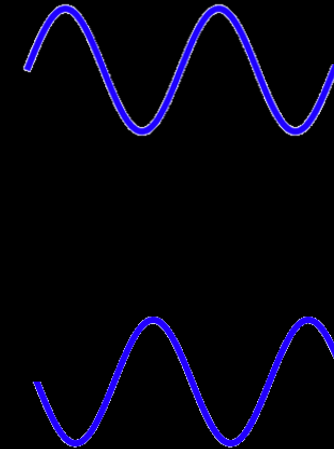
$$\sin(\omega t + 0)$$



$$\sin(\omega t + \theta)$$

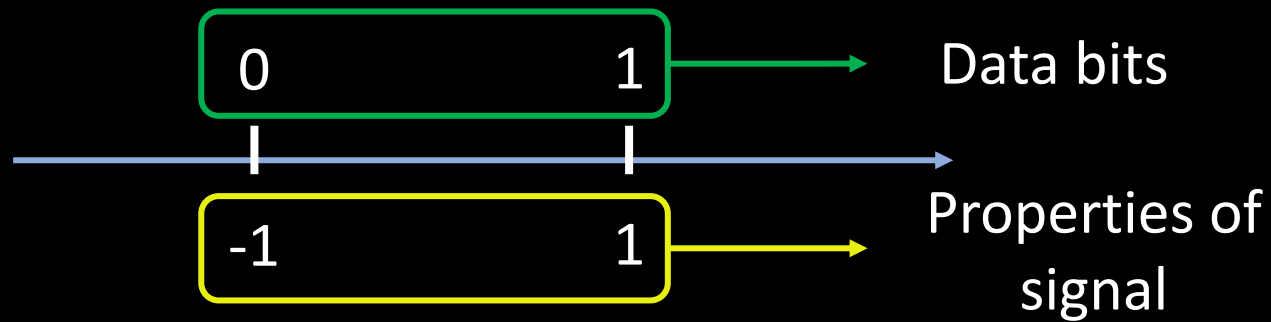


$$\sin(\omega t + \pi)$$

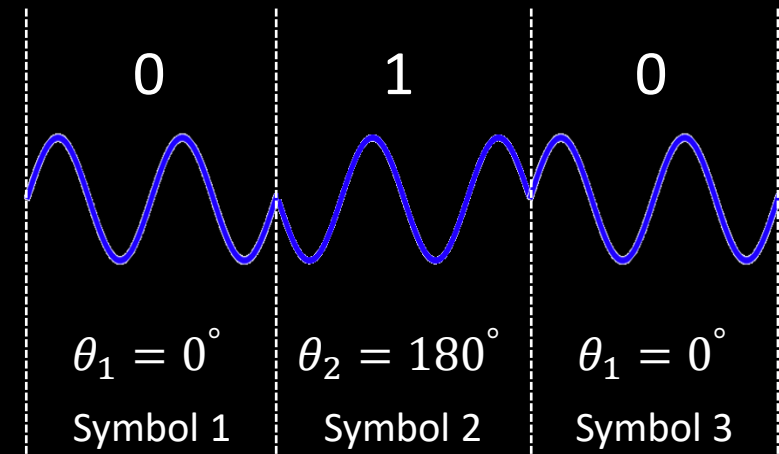


Wireless communication system

Modulation: Mapping from Bits to Symbols
1bit/symbol

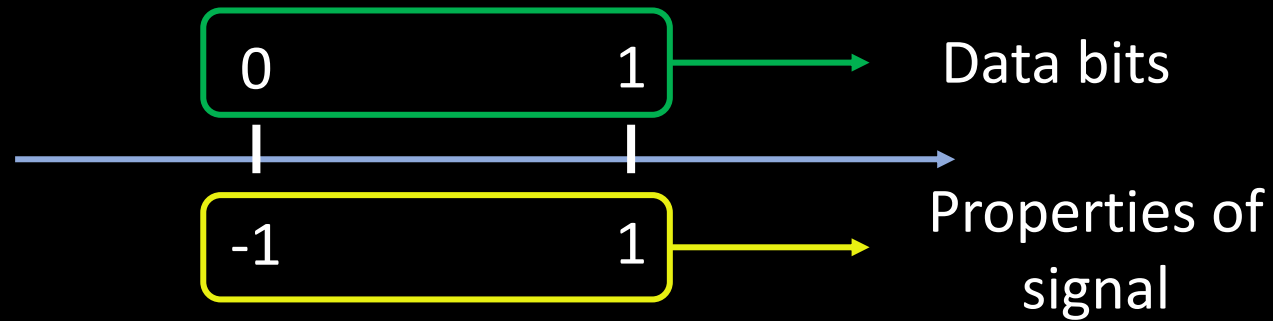


Phase Modulation



Wireless communication system

Modulation: Mapping from Bits to Symbols
1bit/symbol

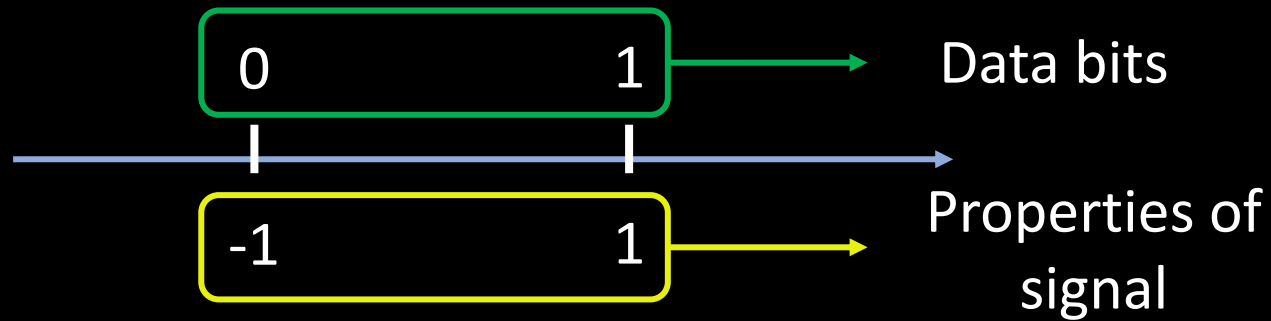


BPSK: 1bit/symbol

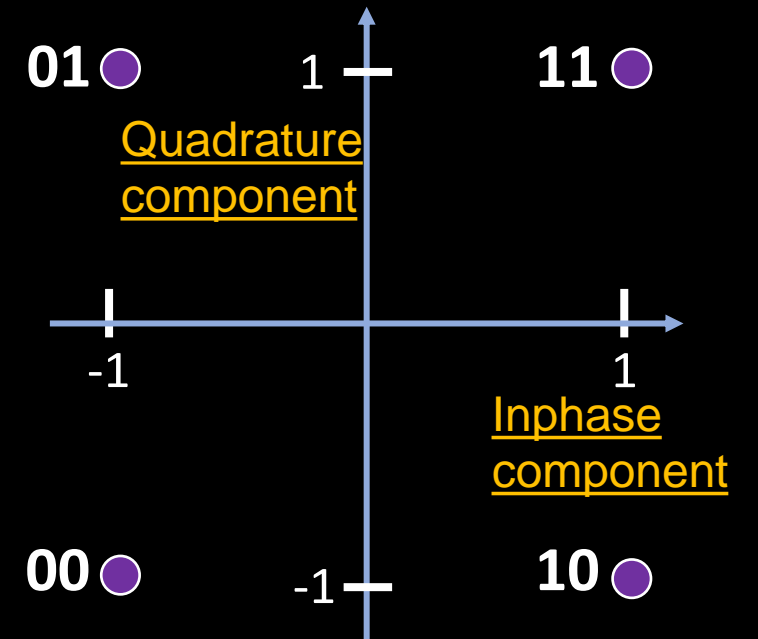


Wireless communication system

Modulation: Mapping from Bits to Symbols
1bit/symbol



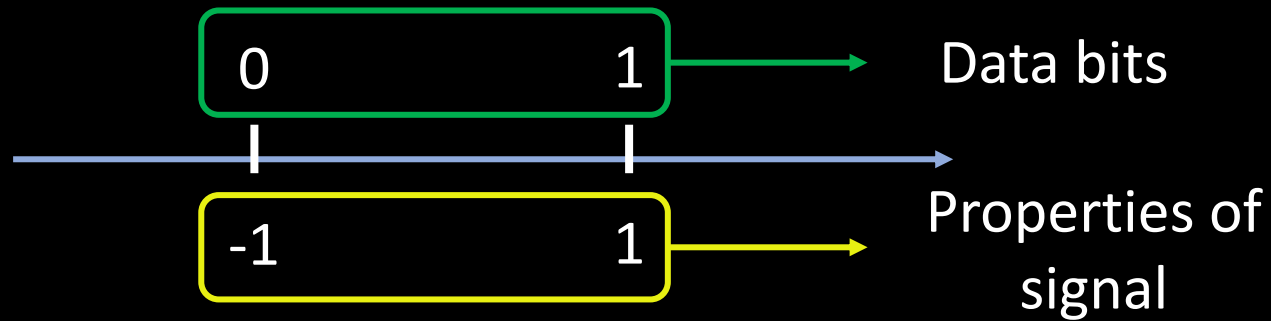
QPSK: 2bit/symbol



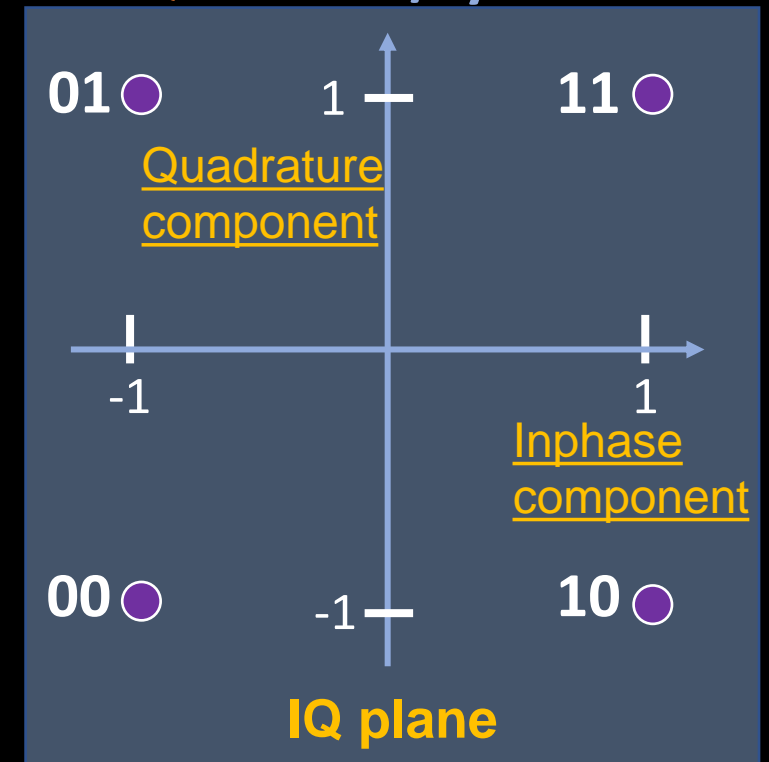
Wireless communication system

Modulation: Mapping from Bits to Symbols

1bit/symbol

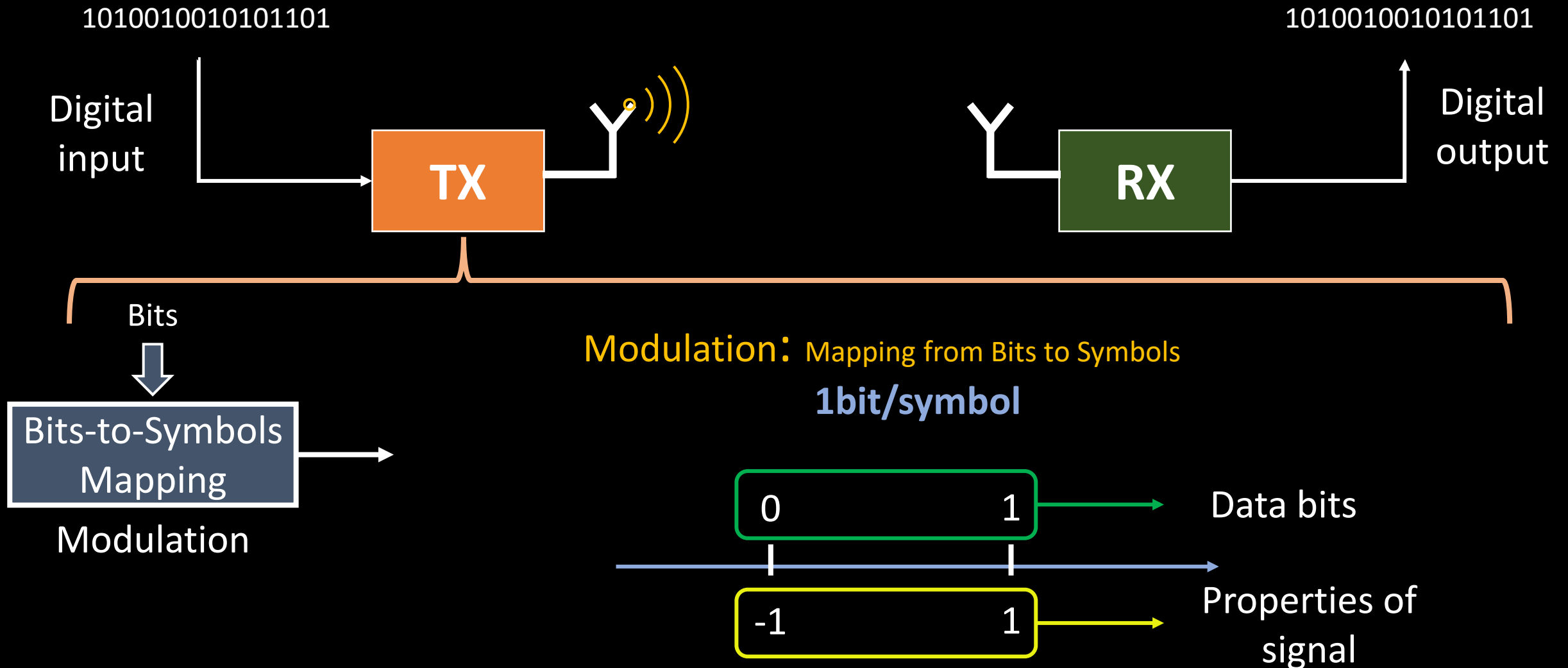


QPSK: 2bit/symbol

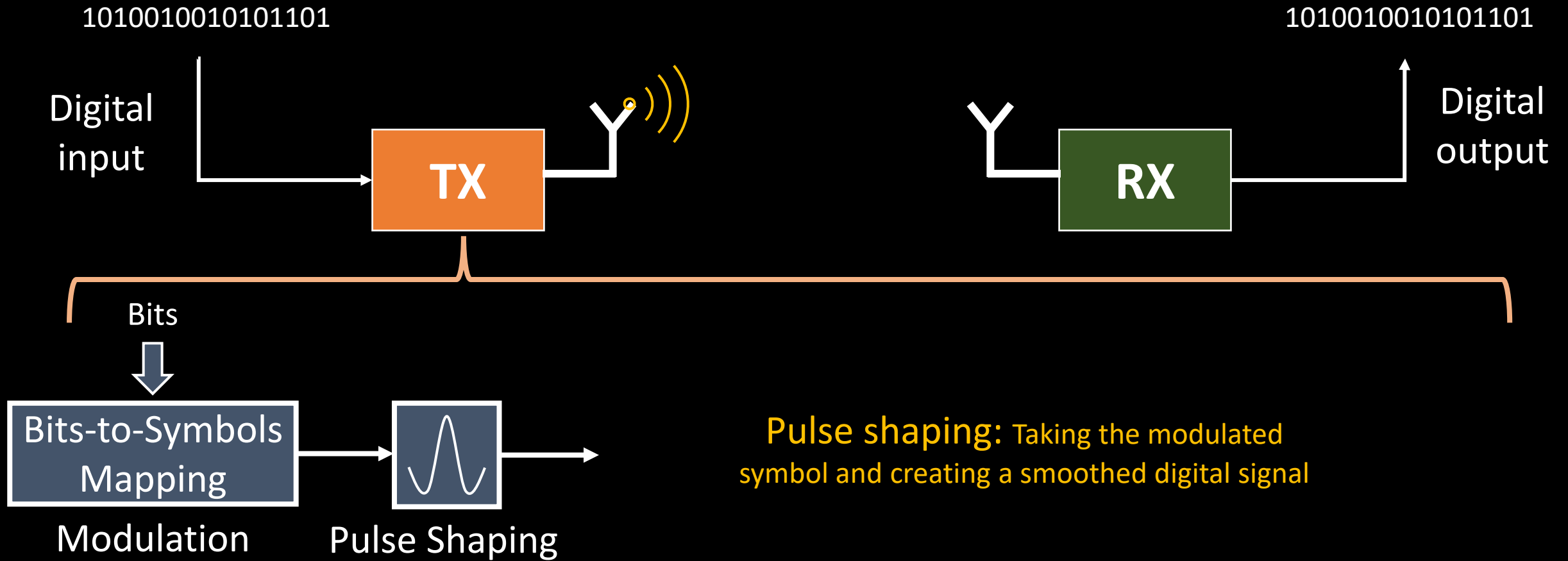


Complex Symbols: $a + bj$

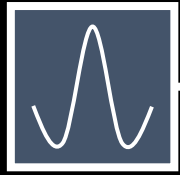
Wireless communication system



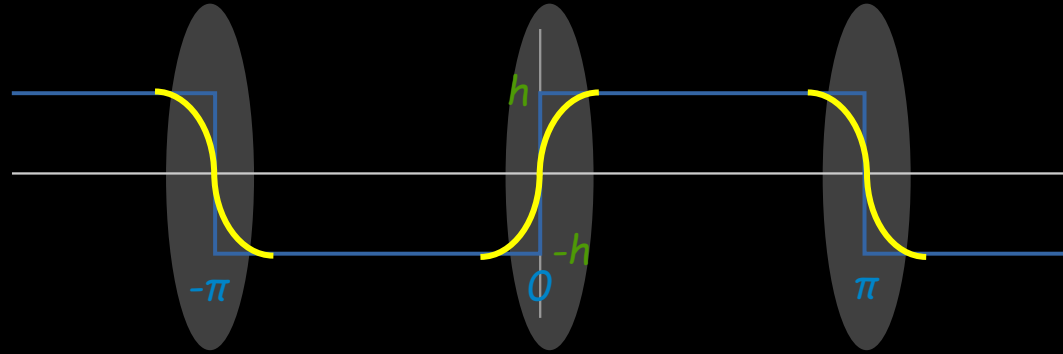
Wireless communication system



Wireless communication system

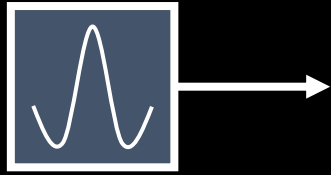


Pulse Shaping



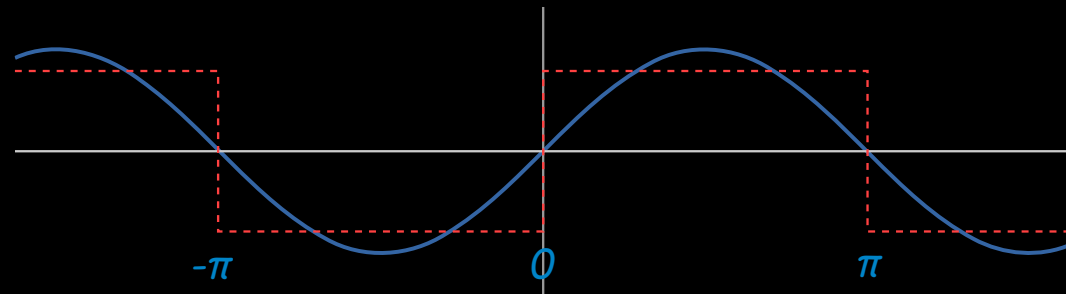
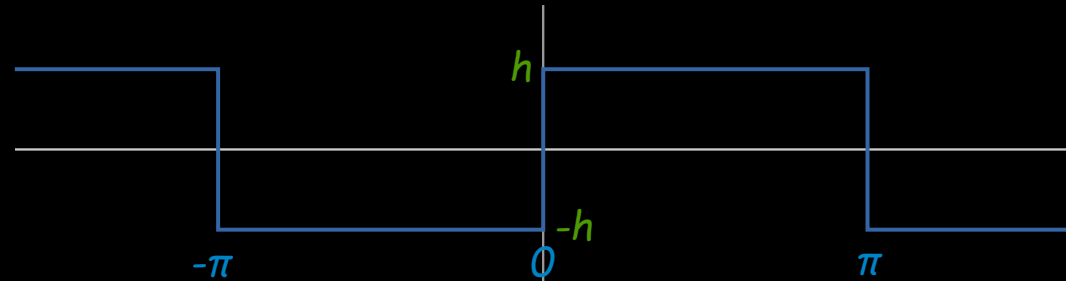
Pulse shaping: Taking the modulated symbol and creating a smoothed digital signal

Wireless communication system

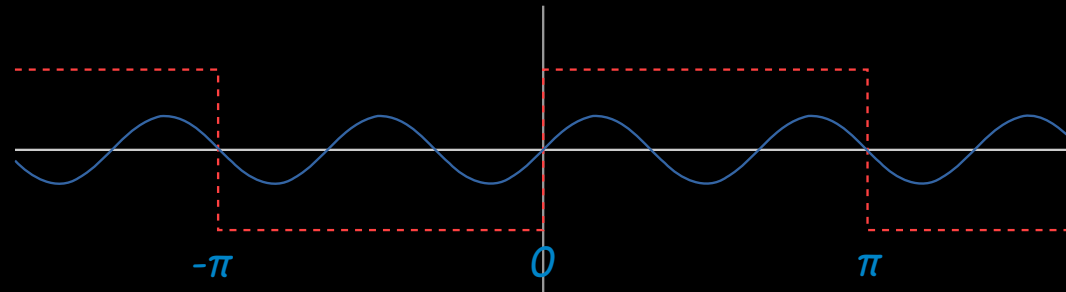


Pulse Shaping

Pulse shaping: Taking the modulated symbol and creating a smoothed digital signal

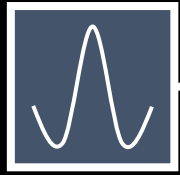


$\sin x$

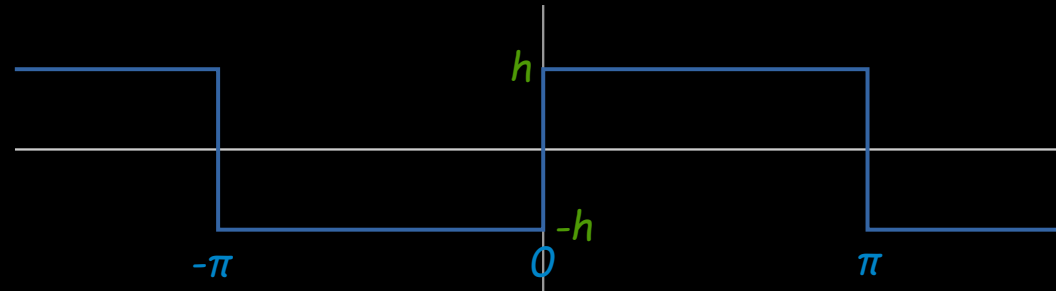


$\frac{1}{3} \sin 3x$

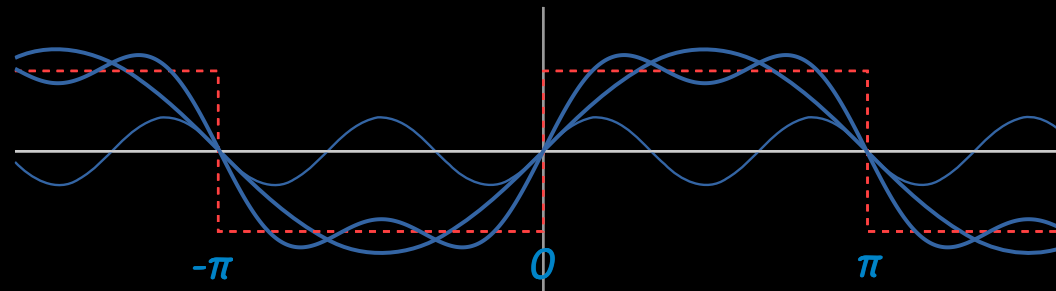
Wireless communication system



Pulse Shaping

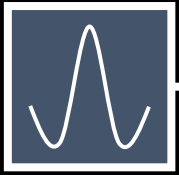


Pulse shaping: Taking the modulated symbol and creating a smoothed digital signal



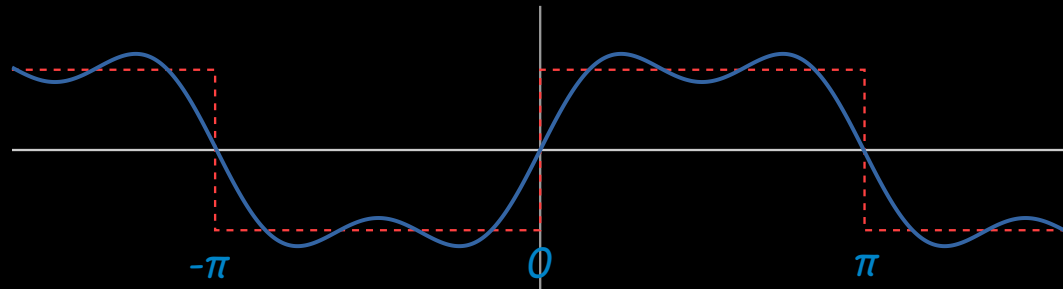
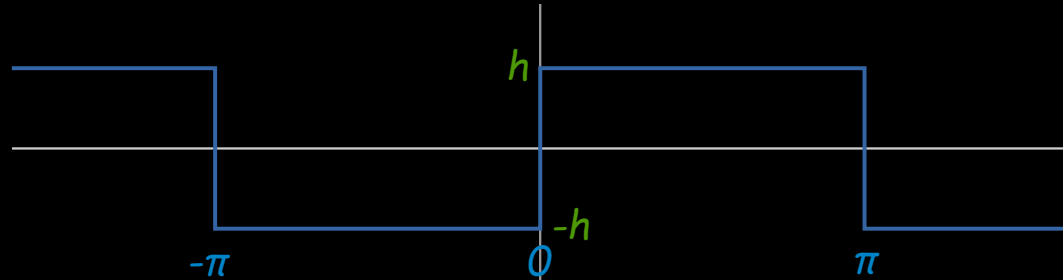
$$\sin x + \frac{1}{3} \sin 3x$$

Wireless communication system

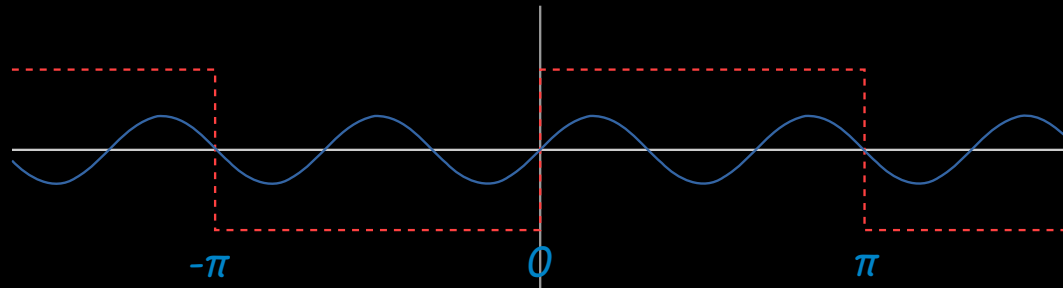


Pulse Shaping

Pulse shaping: Taking the modulated symbol and creating a smoothed digital signal

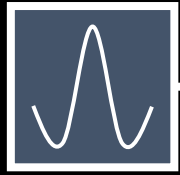


$$\sin x + \frac{1}{3} \sin 3x$$

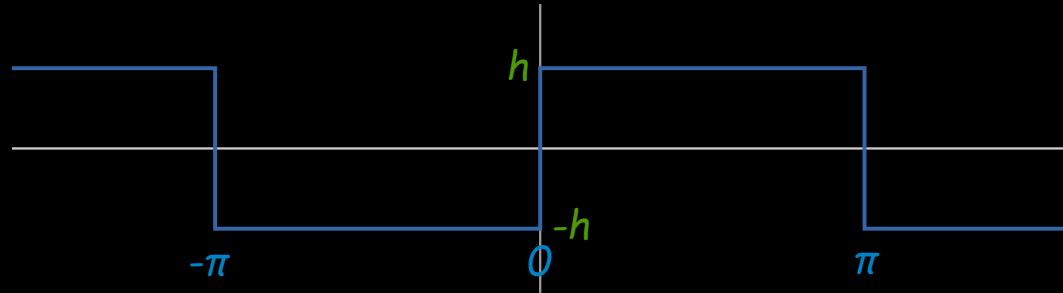


$$\frac{1}{5} \sin 5x$$

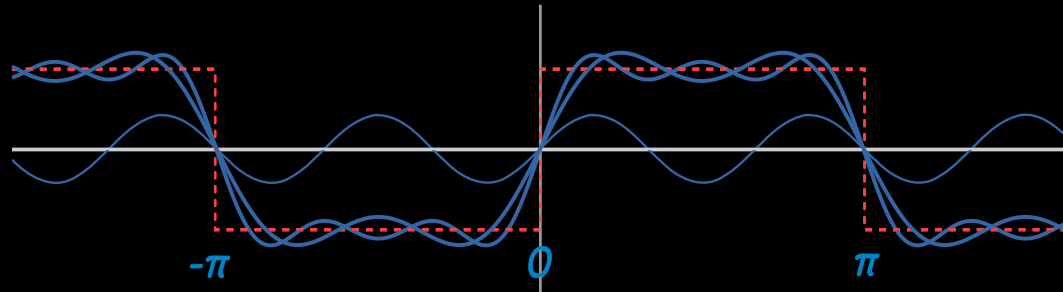
Wireless communication system



Pulse Shaping

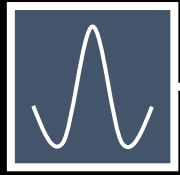


Pulse shaping: Taking the modulated symbol and creating a smoothed digital signal

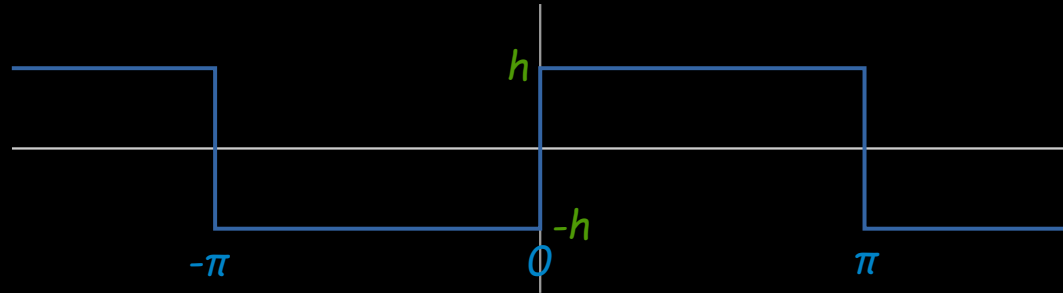


$$\sin x + \frac{1}{3} \sin 3x + \frac{1}{5} \sin 5x$$

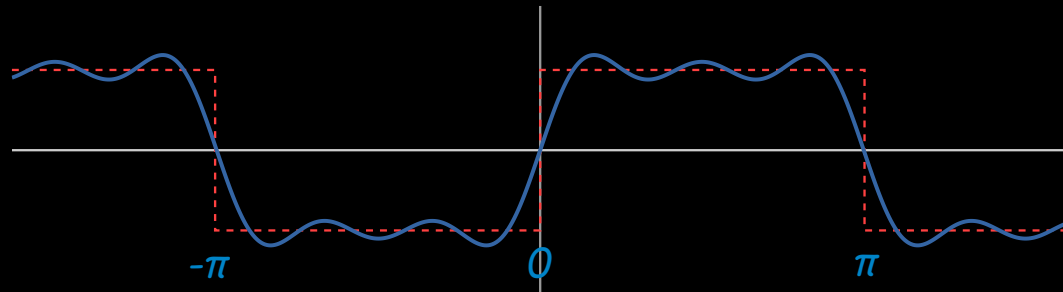
Wireless communication system



Pulse Shaping

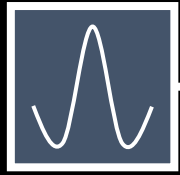


Pulse shaping: Taking the modulated symbol and creating a smoothed digital signal

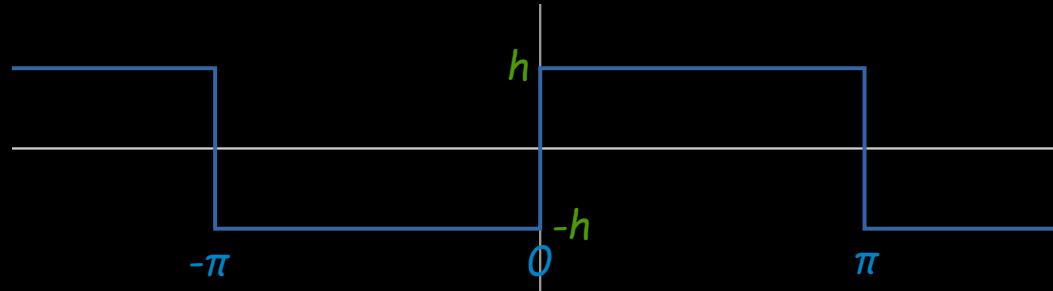


$$\sin x + \frac{1}{3} \sin 3x + \frac{1}{5} \sin 5x$$

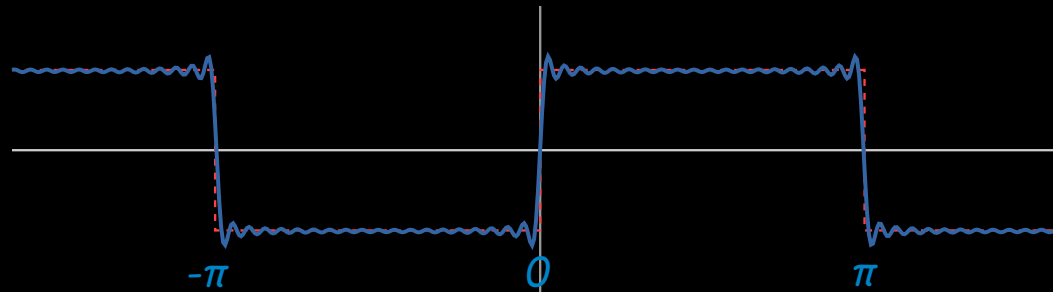
Wireless communication system



Pulse Shaping

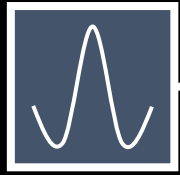


Pulse shaping: Taking the modulated symbol and creating a smoothed digital signal

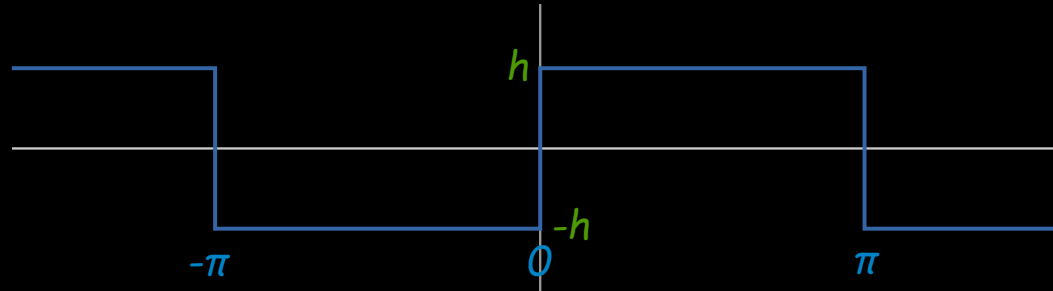


$$\sin x + \frac{1}{3} \sin 3x + \frac{1}{5} \sin 5x + \dots + \frac{1}{39} \sin 39x$$

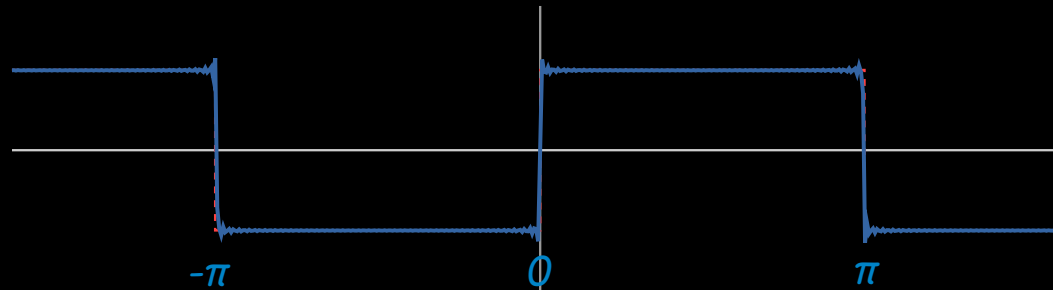
Wireless communication system



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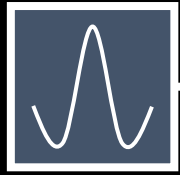


Pulse shaping: Taking the modulated symbol and creating a smoothed digital signal



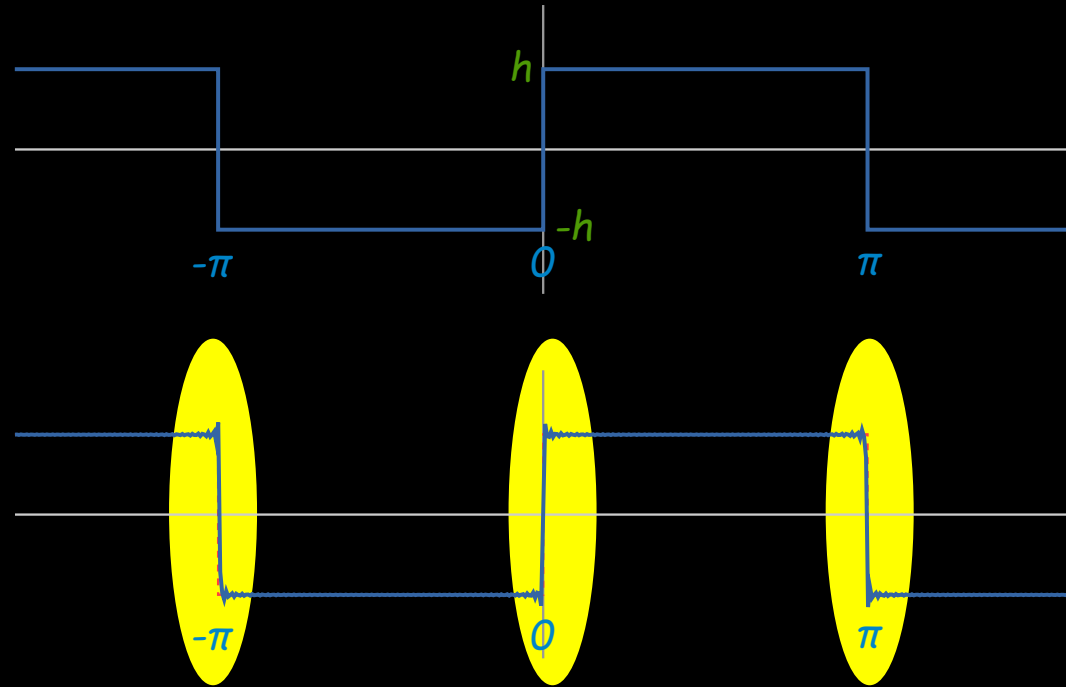
$$\sin x + \frac{1}{3} \sin 3x + \frac{1}{5} \sin 5x + \dots + \frac{1}{199} \sin 199x$$

Wireless communication system

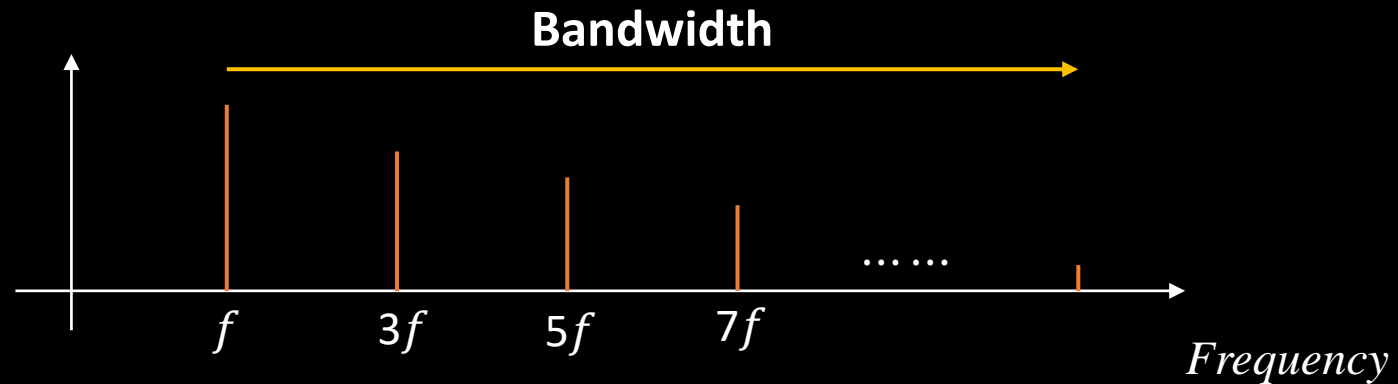


Pulse Shaping

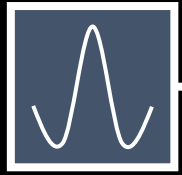
Pulse shaping: Taking the modulated symbol and creating a smoothed digital signal



$$\sin x + \frac{1}{3} \sin 3x + \frac{1}{5} \sin 5x + \dots + \frac{1}{199} \sin 199x$$

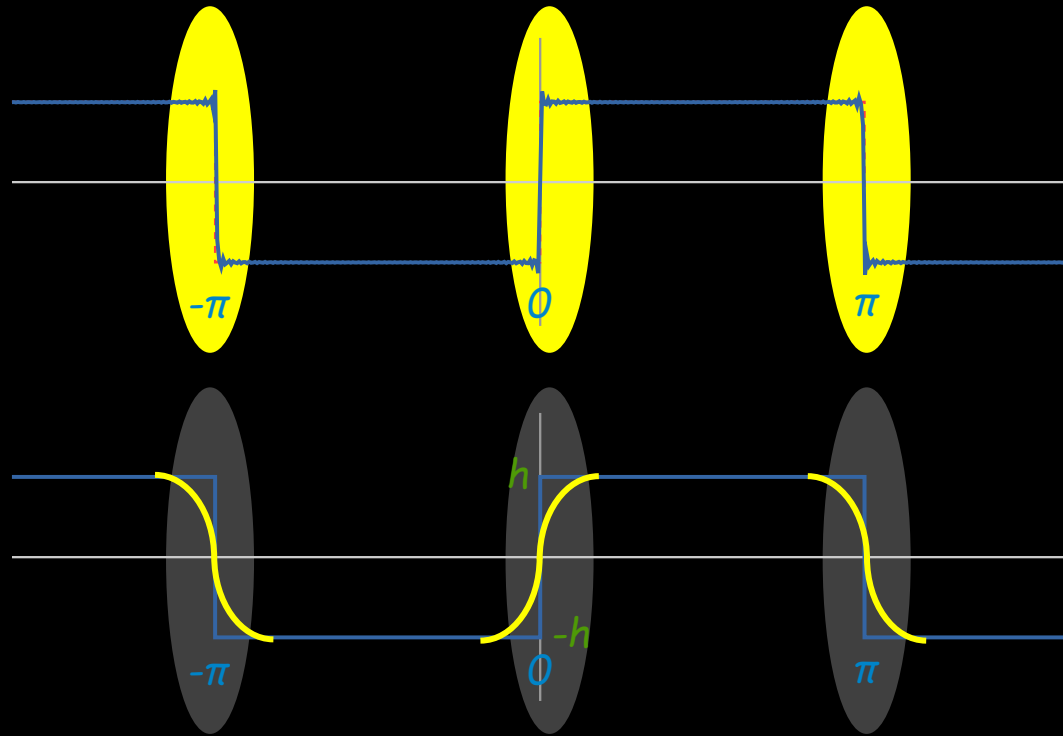


Wireless communication system



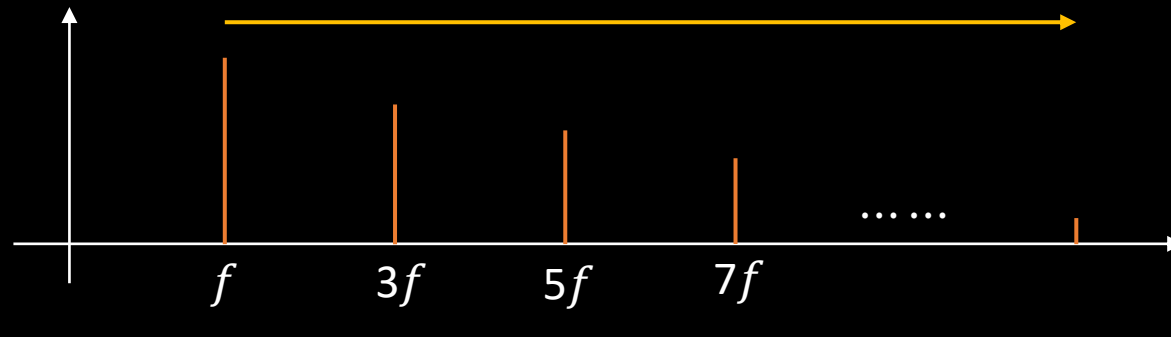
Pulse Shaping

Pulse shaping: Taking the modulated symbol and creating a smoothed digital signal

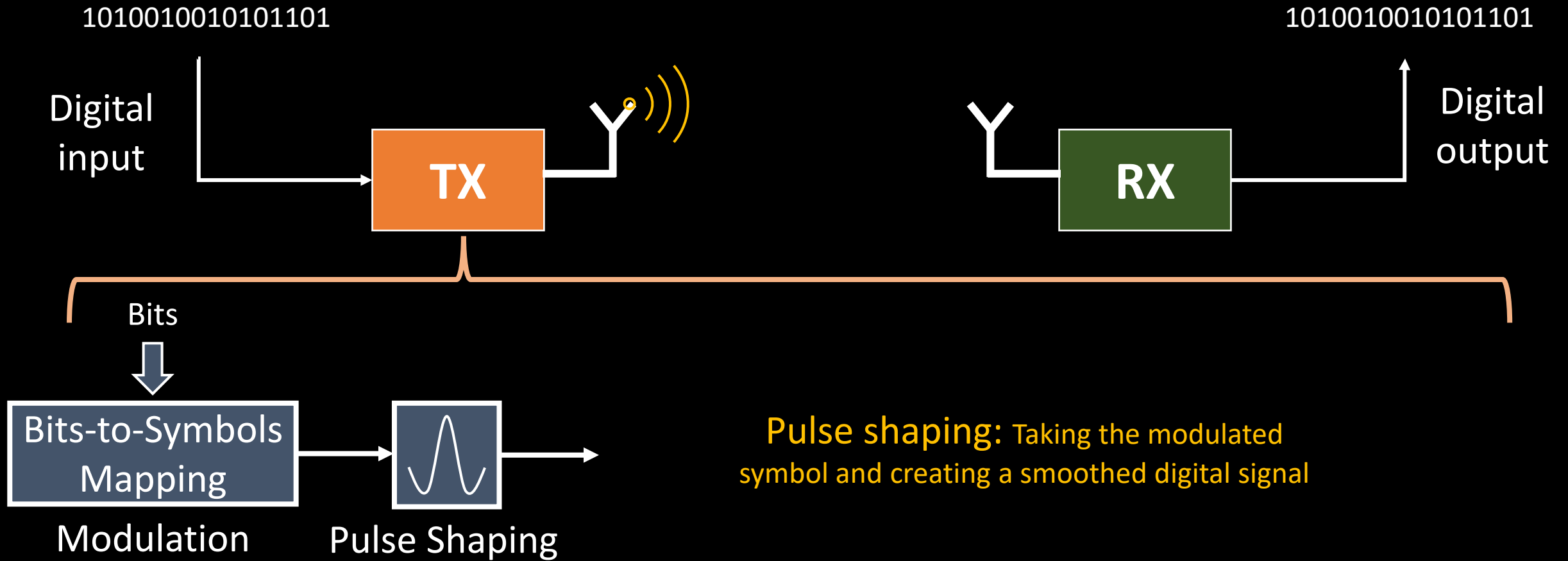


$$\sin x + \frac{1}{3} \sin 3x + \frac{1}{5} \sin 5x + \dots + \frac{1}{199} \sin 199x$$

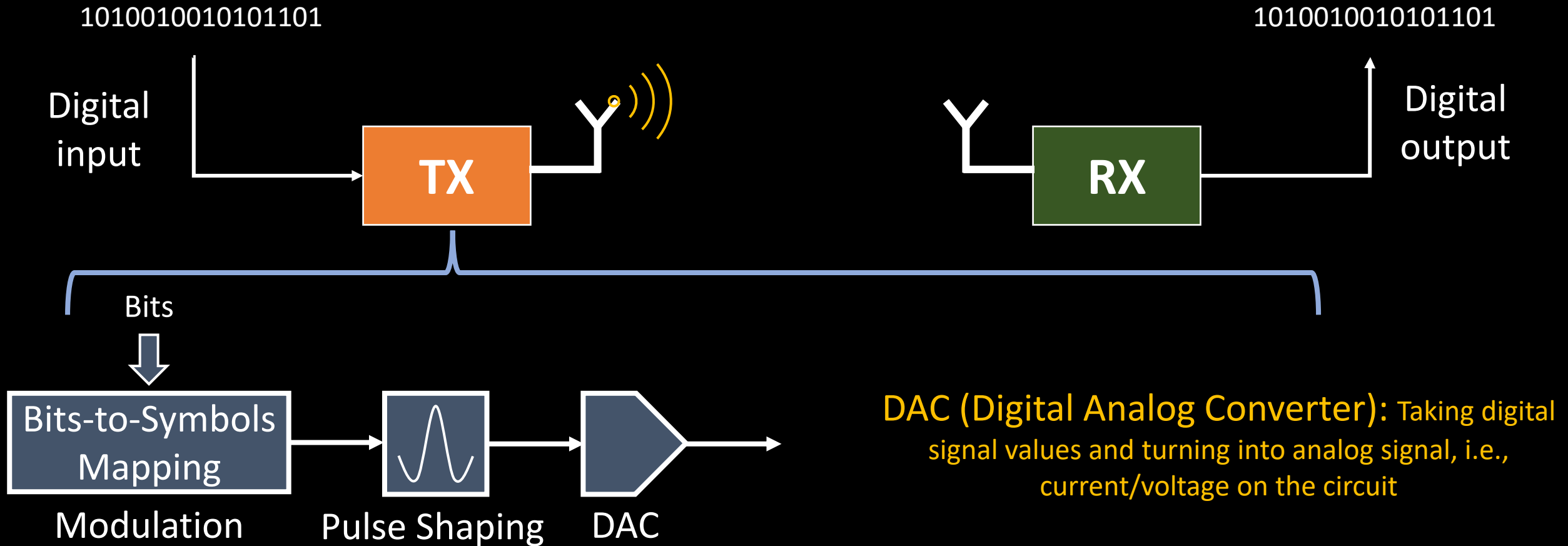
Bandwidth



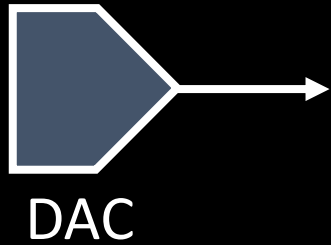
Wireless communication system



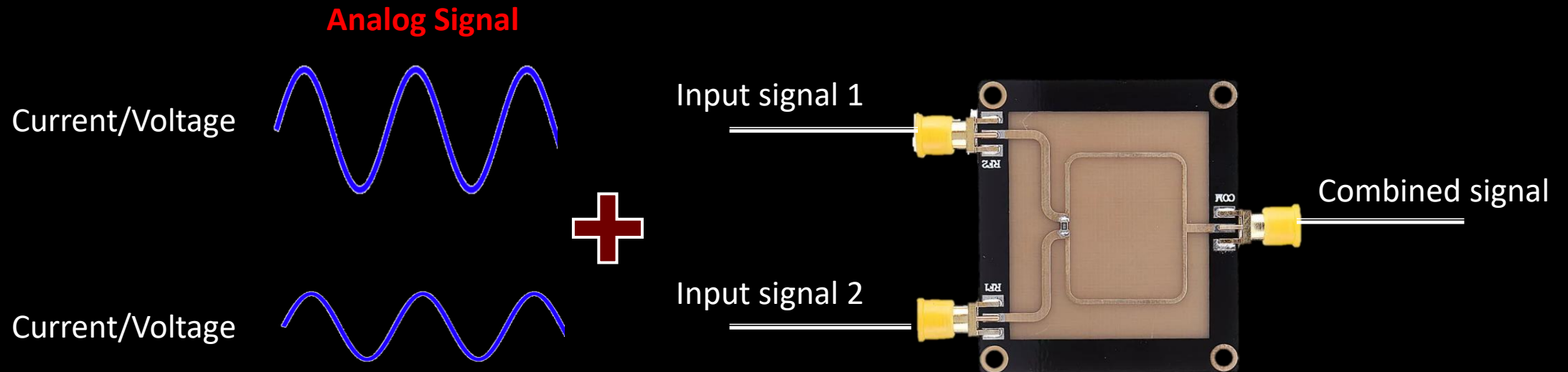
Wireless communication system



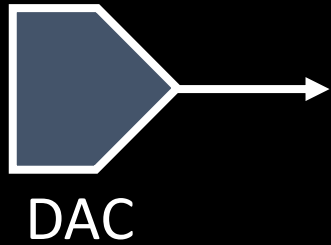
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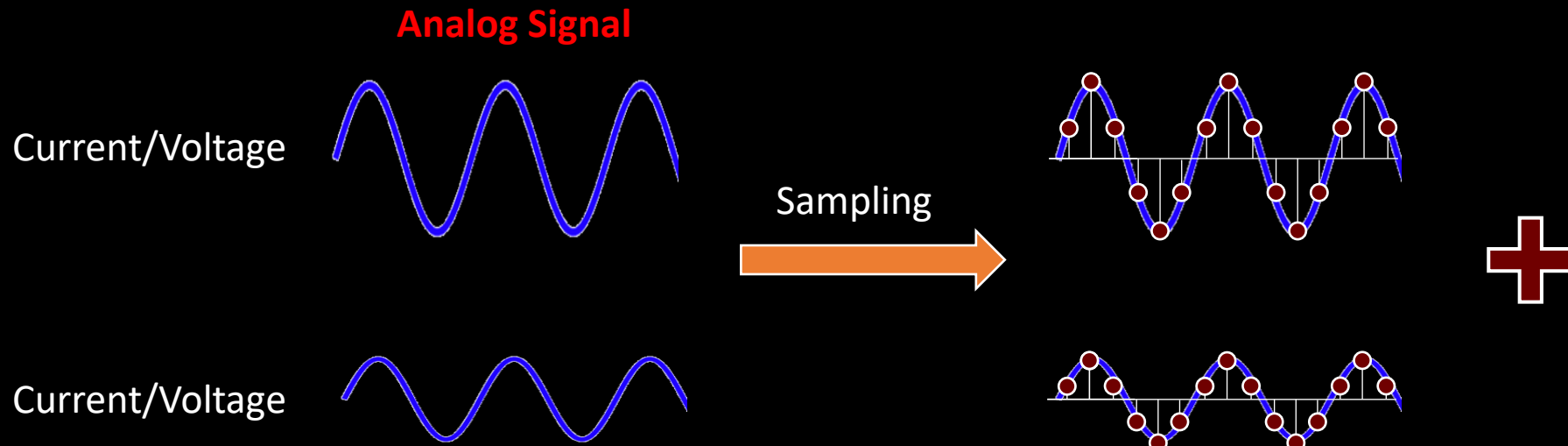
DAC (Digital Analog Converter): Taking digital signal values and turning into analog signal, i.e., current/voltage on the circuit



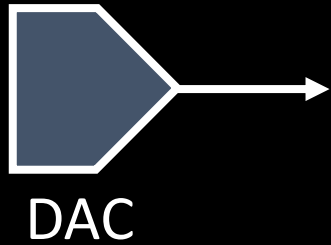
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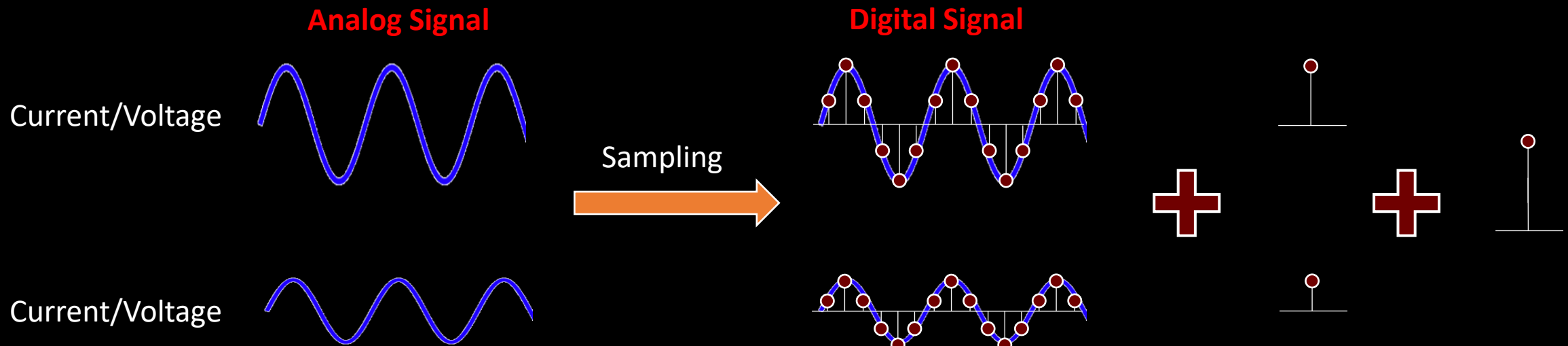
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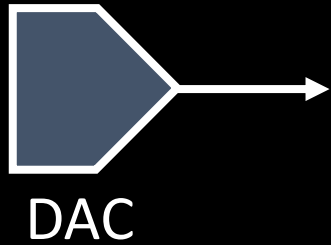
Wireless communication system



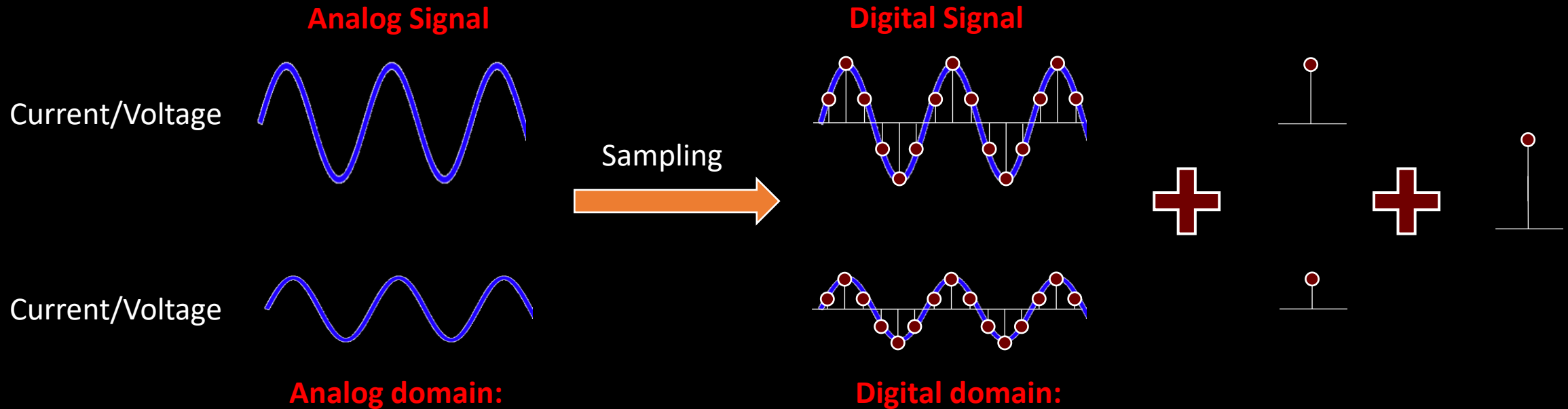
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Wireless communication system



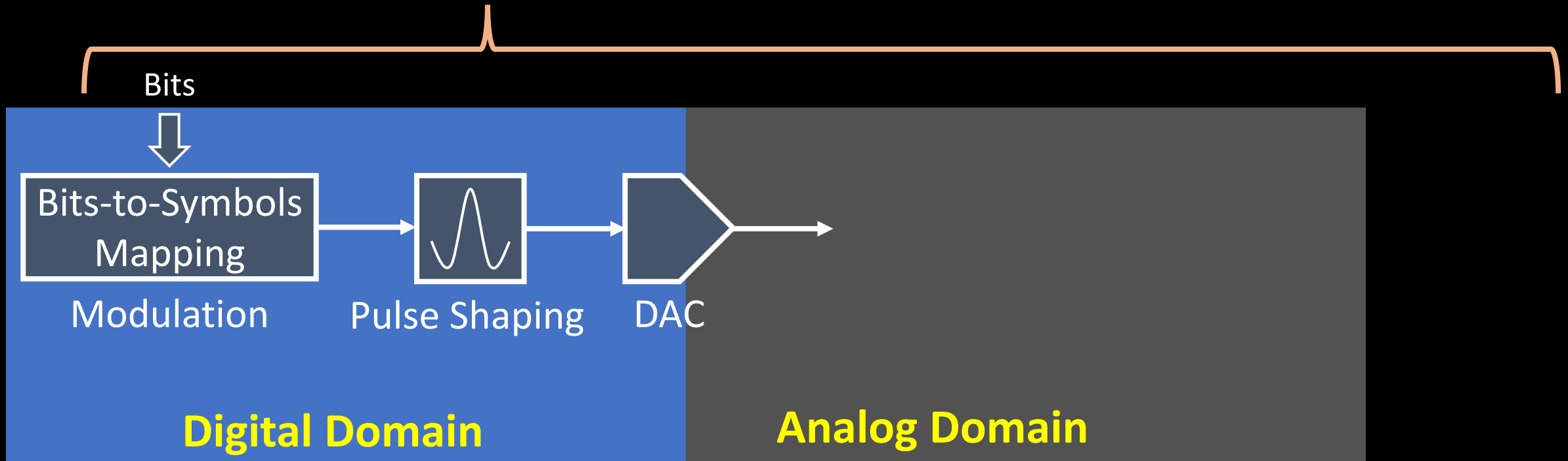
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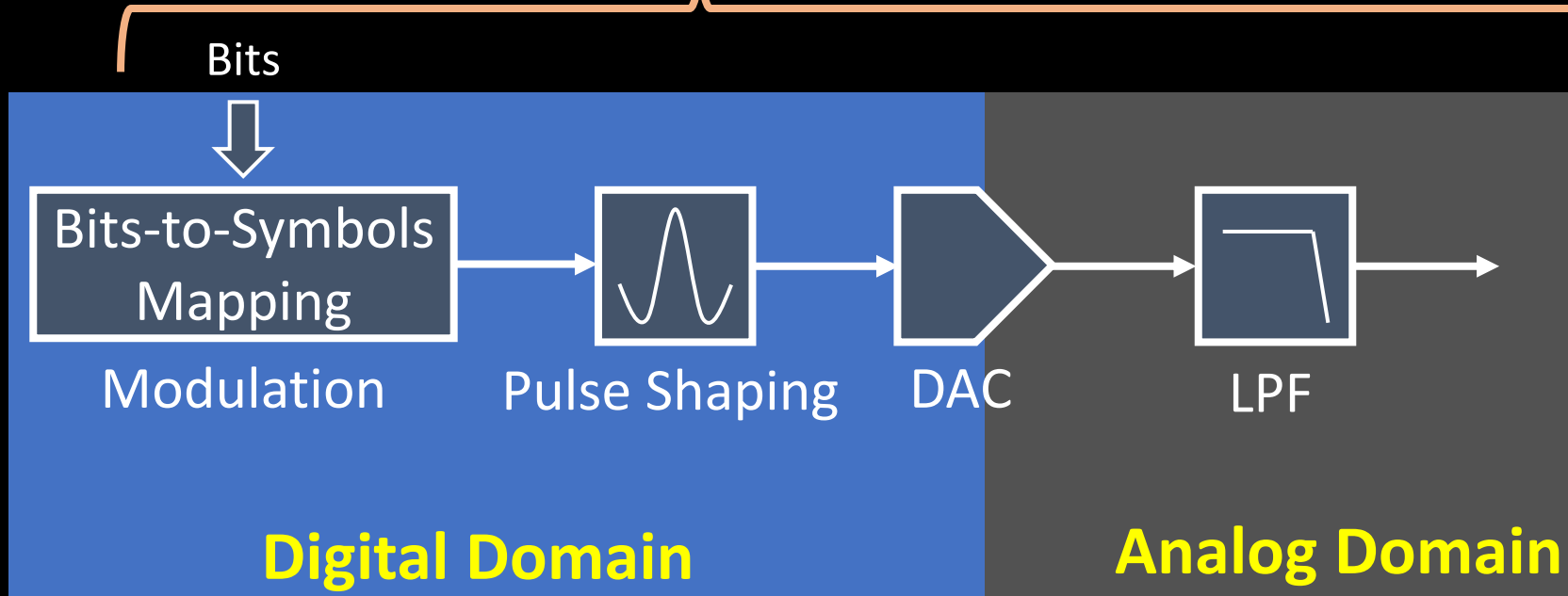
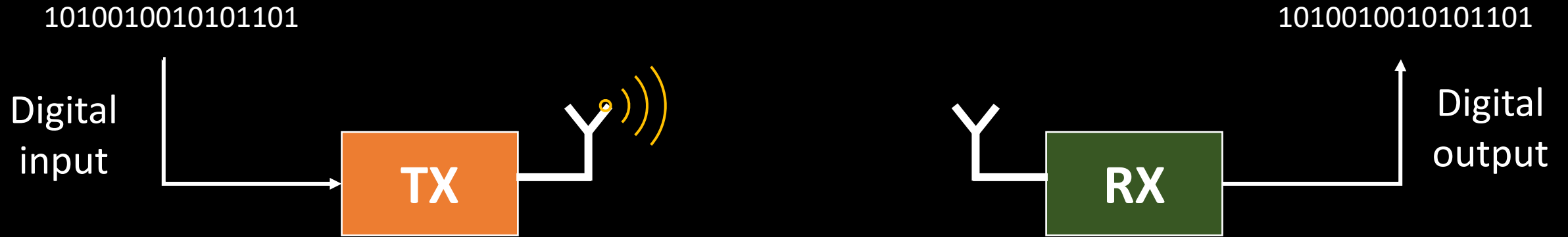
Analog signal processing is complicated! 😞

Digital signal processing is much easier! 😊

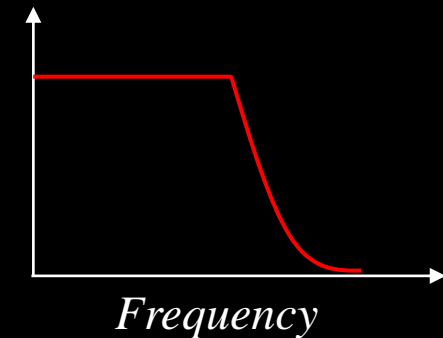
Wireless communication system



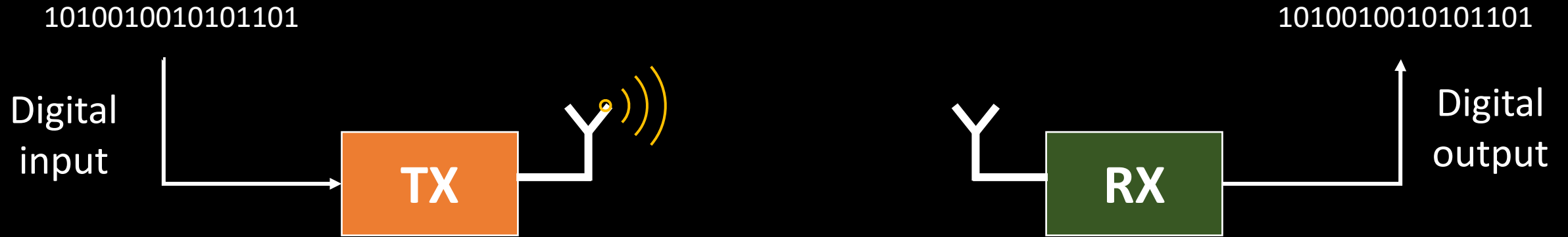
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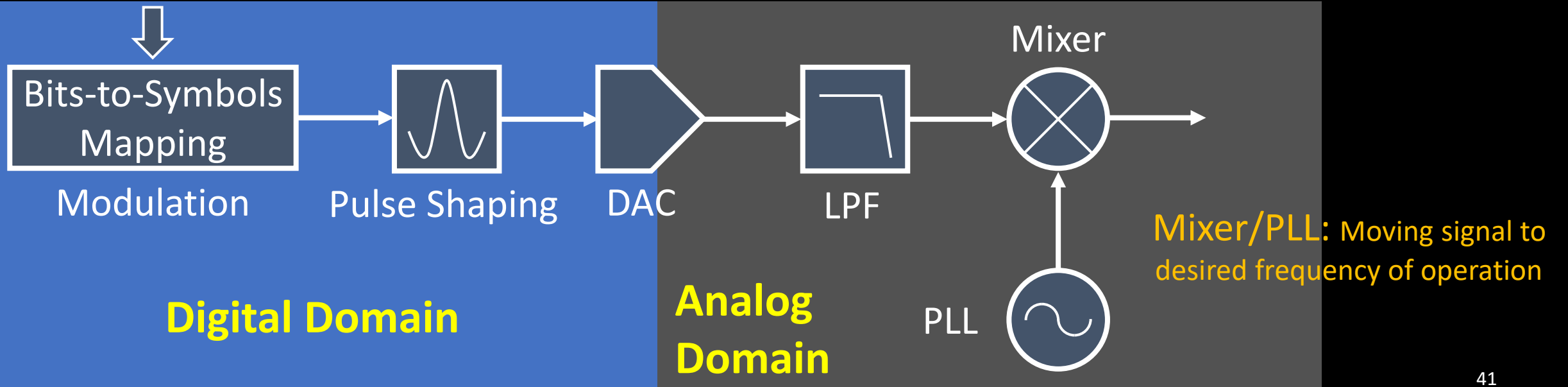
LPF (Low Pass Filter):
Removing high frequency signals



Wireless communication system



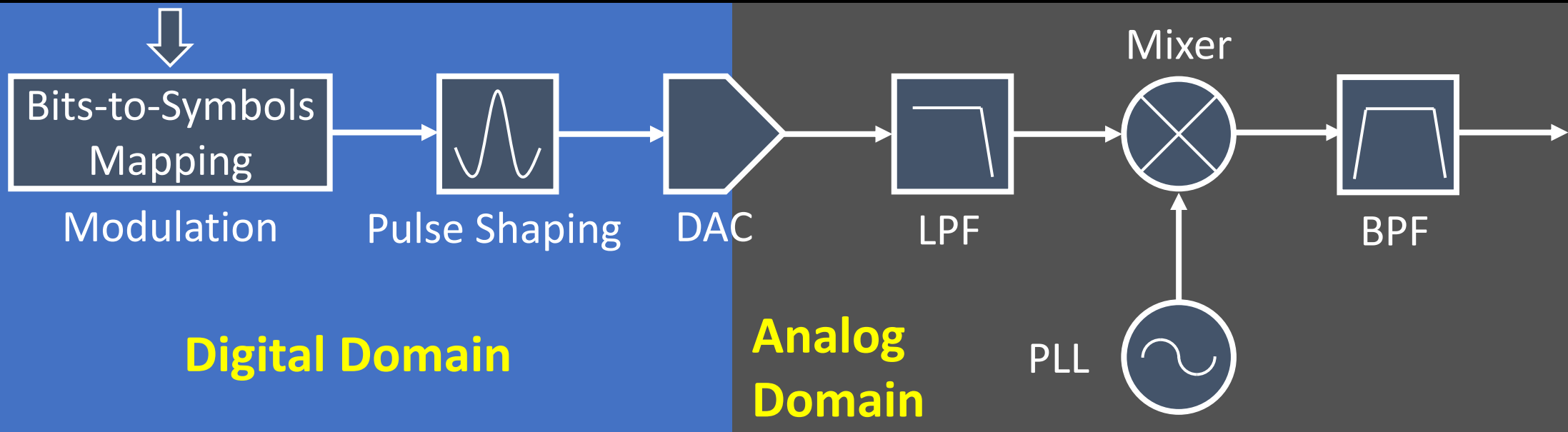
Bits



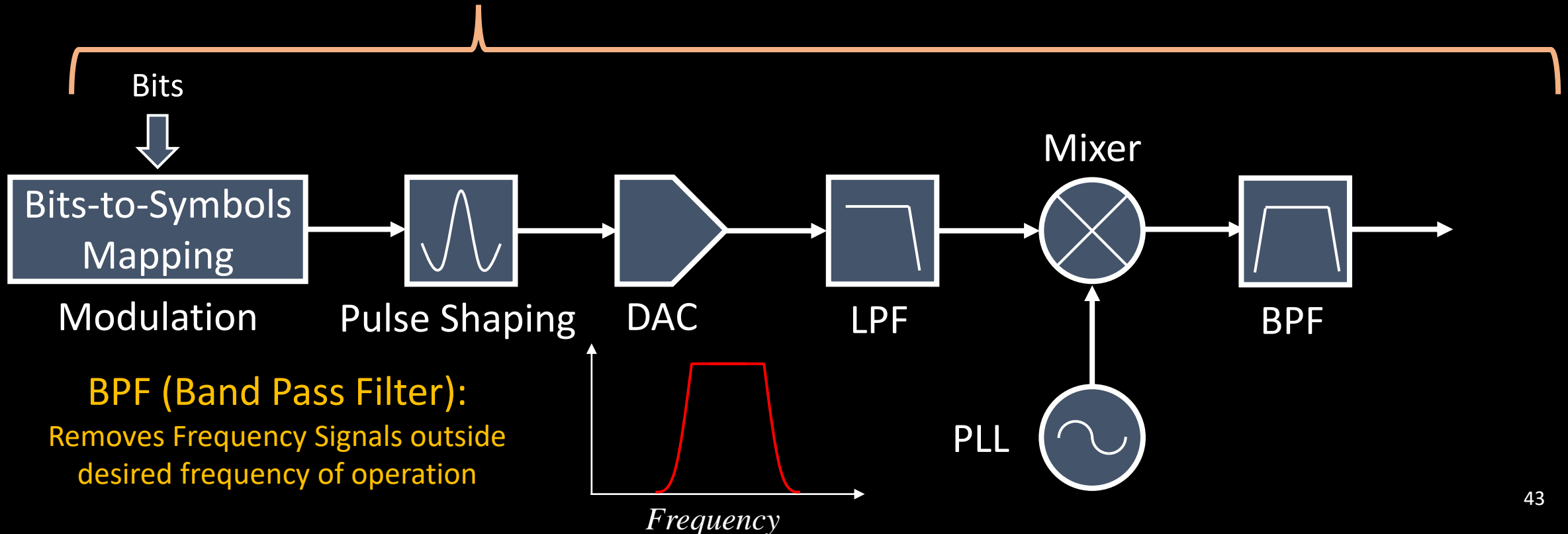
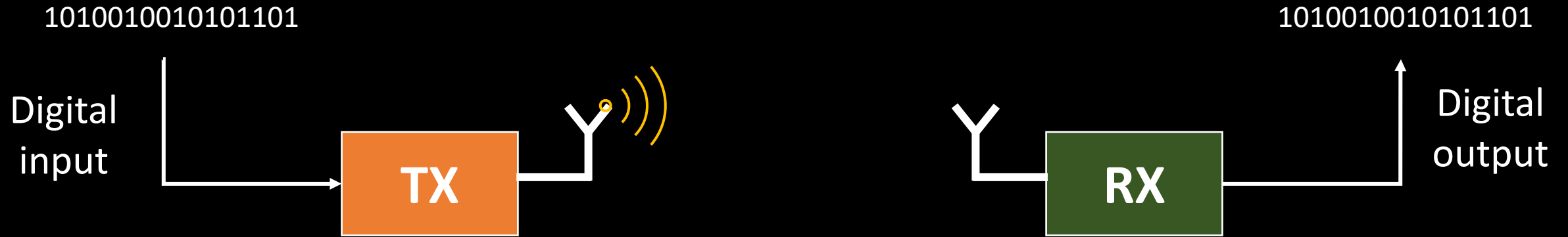
Wireless communication system



Bits



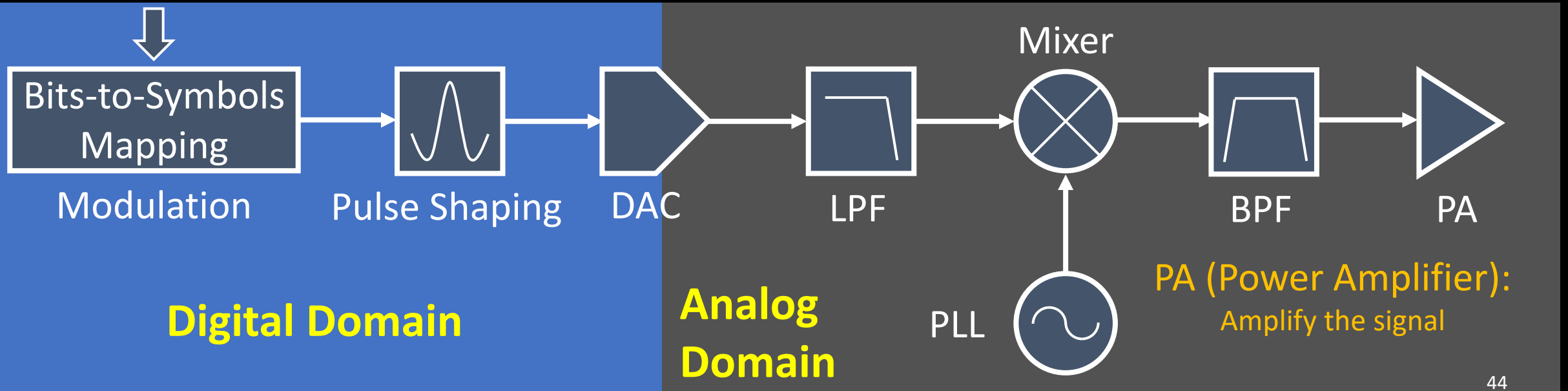
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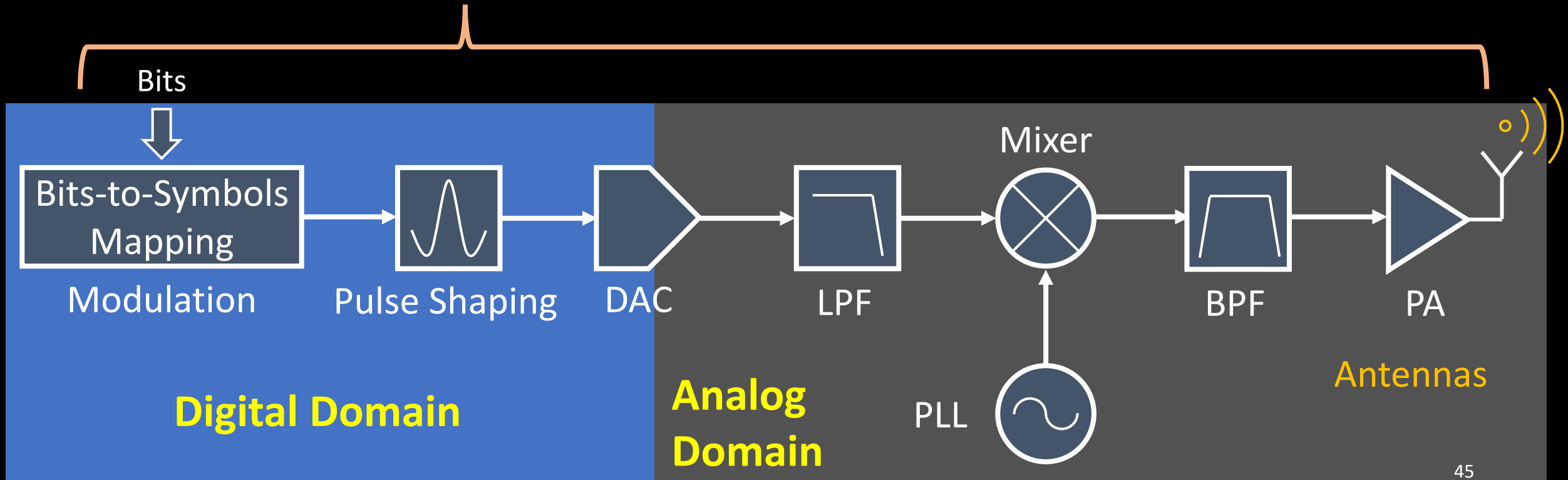
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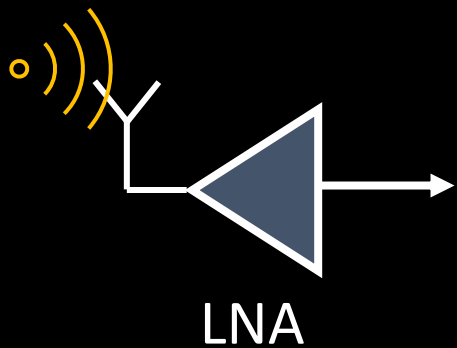
Bits



Wireless communication system

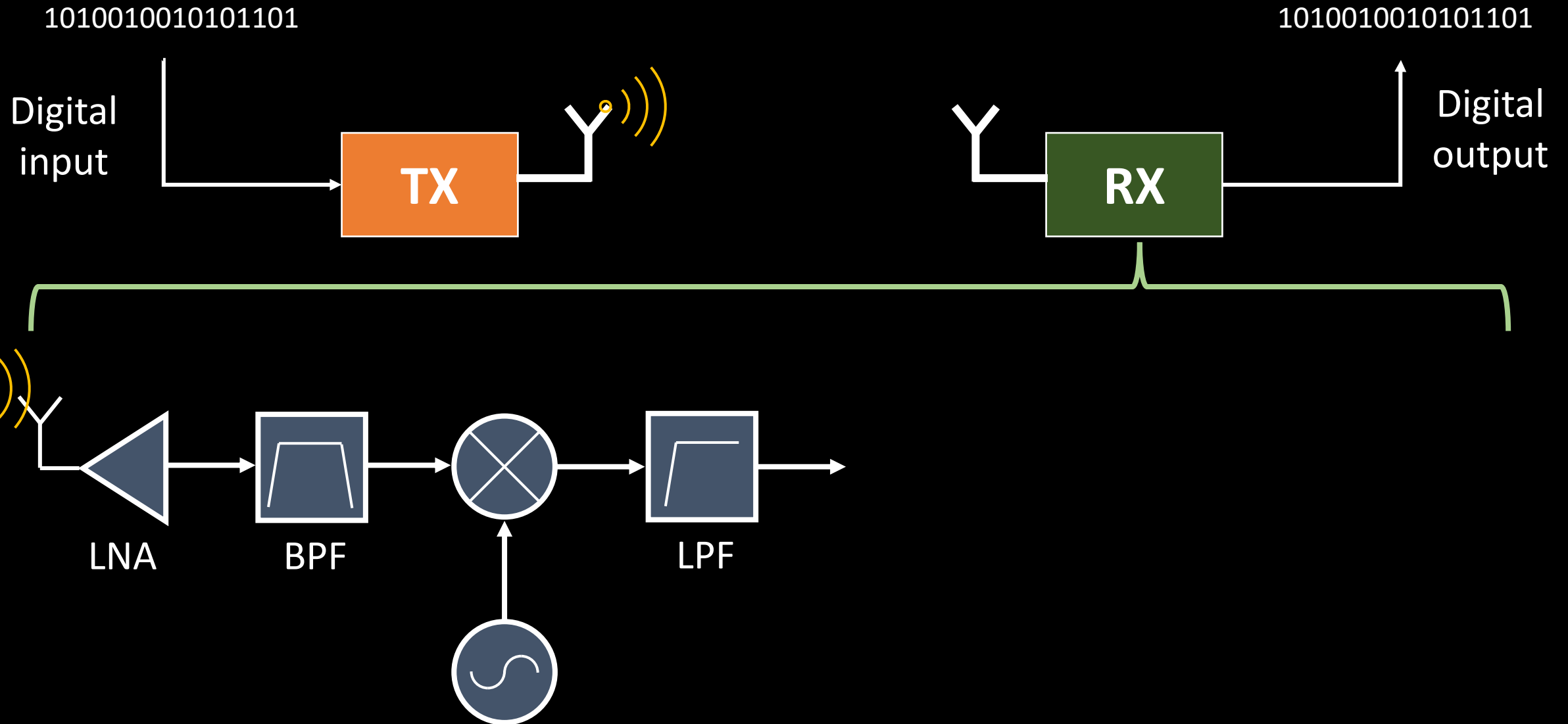


Wireless communication system

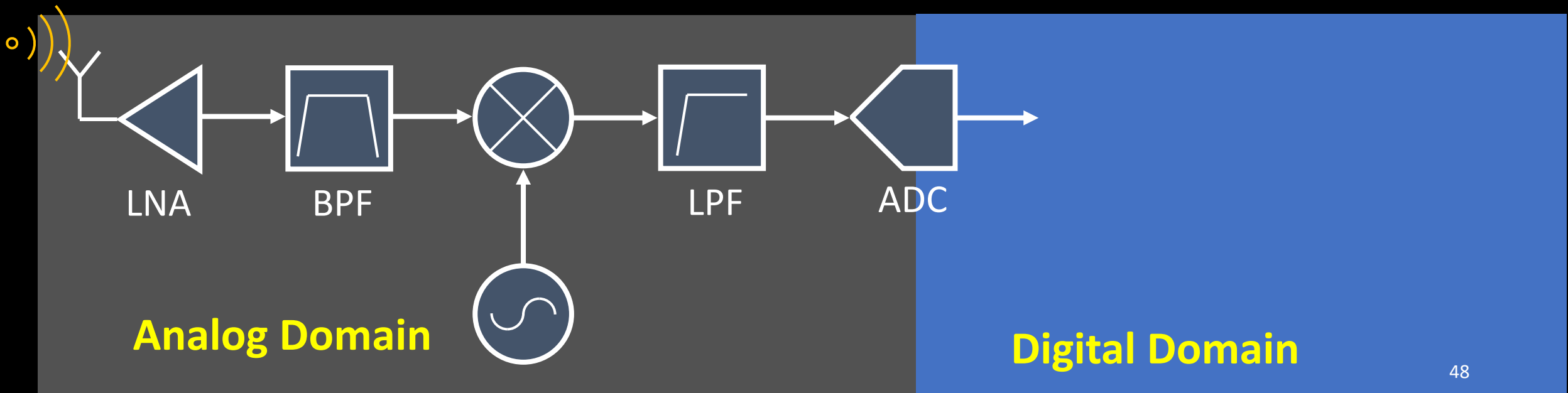


LNA (Low Noise Amplifier):
Amplify the signal with minimal noise

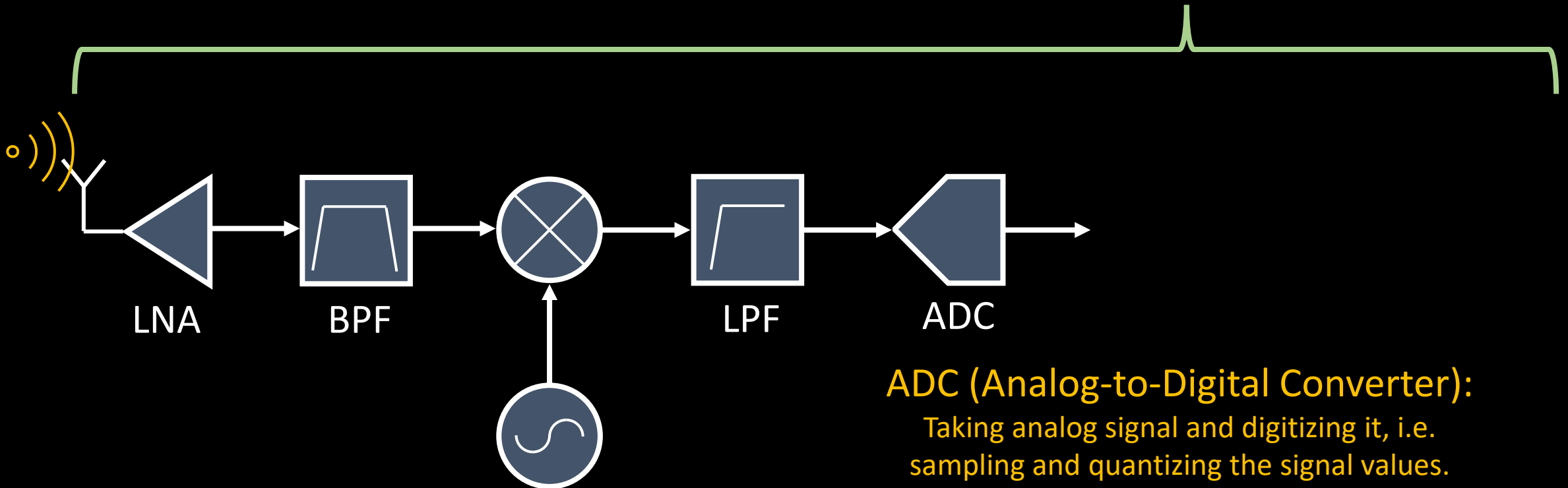
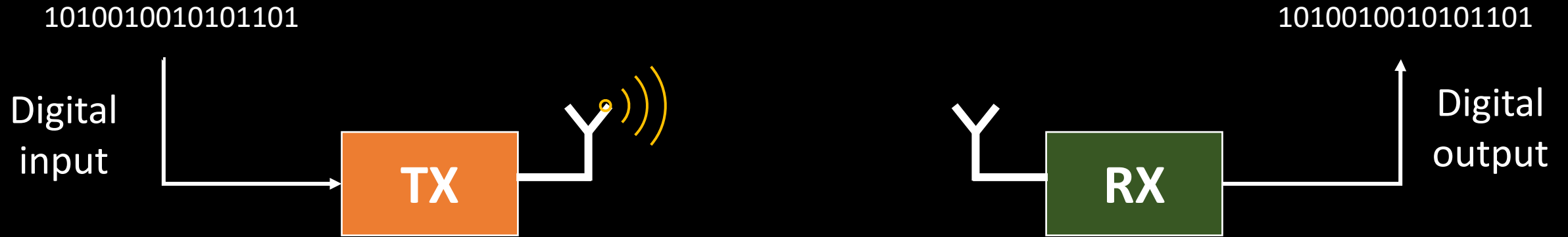
Wireless communication system



Wireless communication system



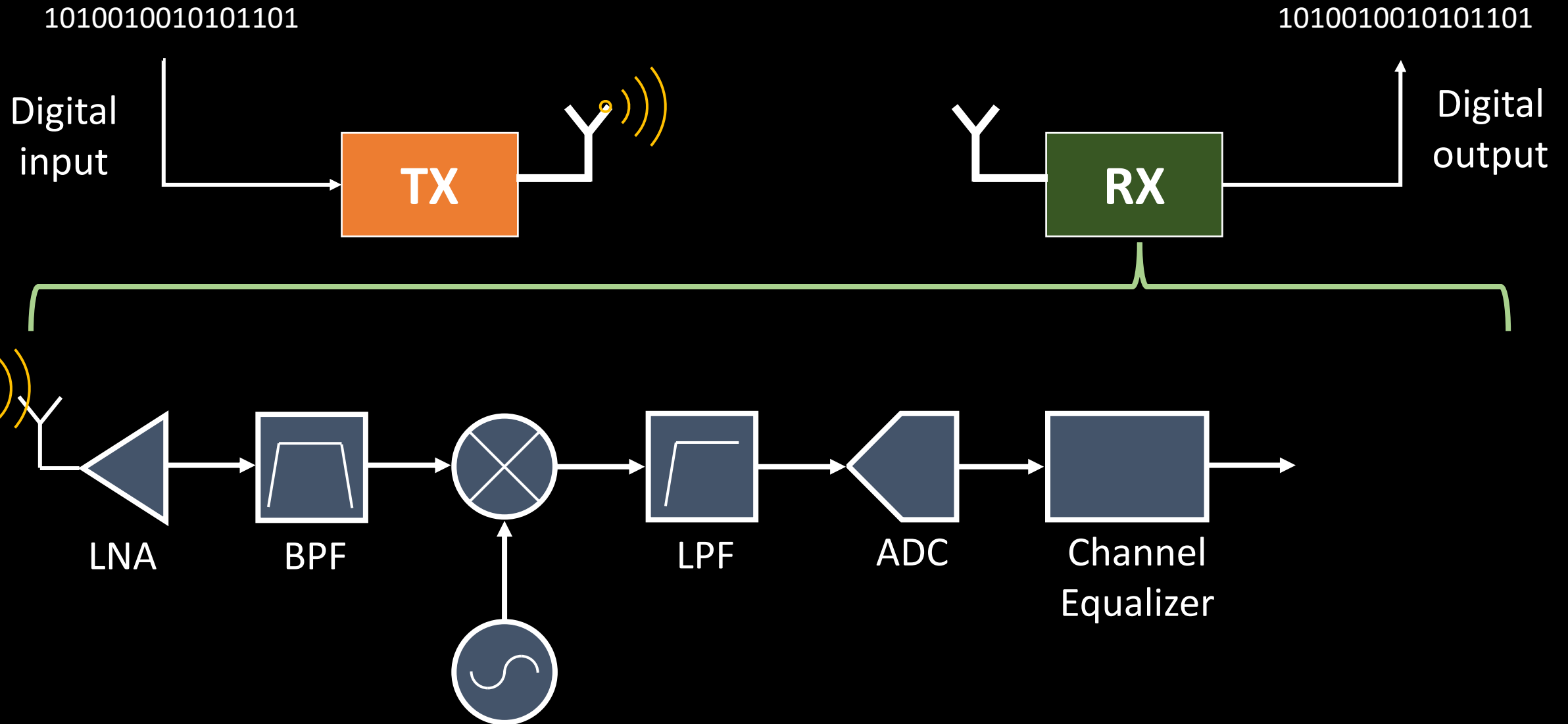
Wireless communication system



ADC (Analog-to-Digital Converter):

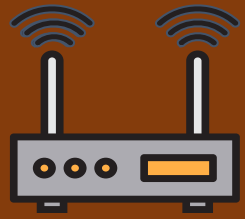
Taking analog signal and digitizing it, i.e. sampling and quantizing the signal values.

Wireless communication system



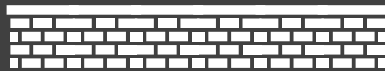
Wireless channel

Transmitter



Wi-Fi AP 1

Wireless Channel

Wall 

Multipath 1

Multipath 2

Multipath 3



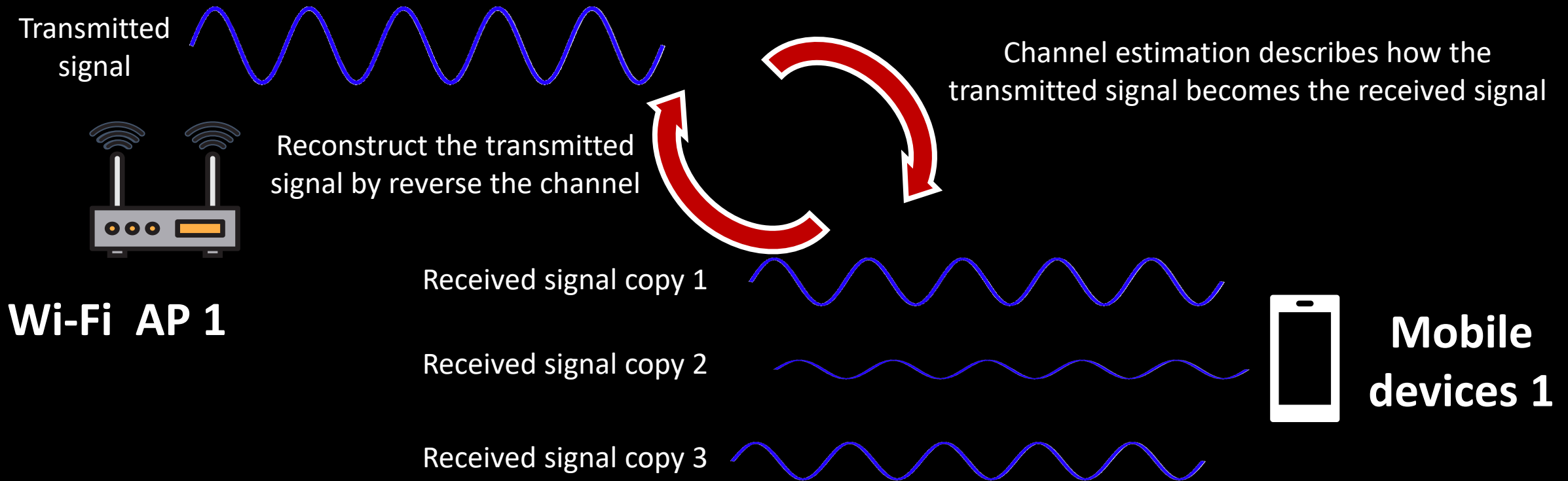
Receiver



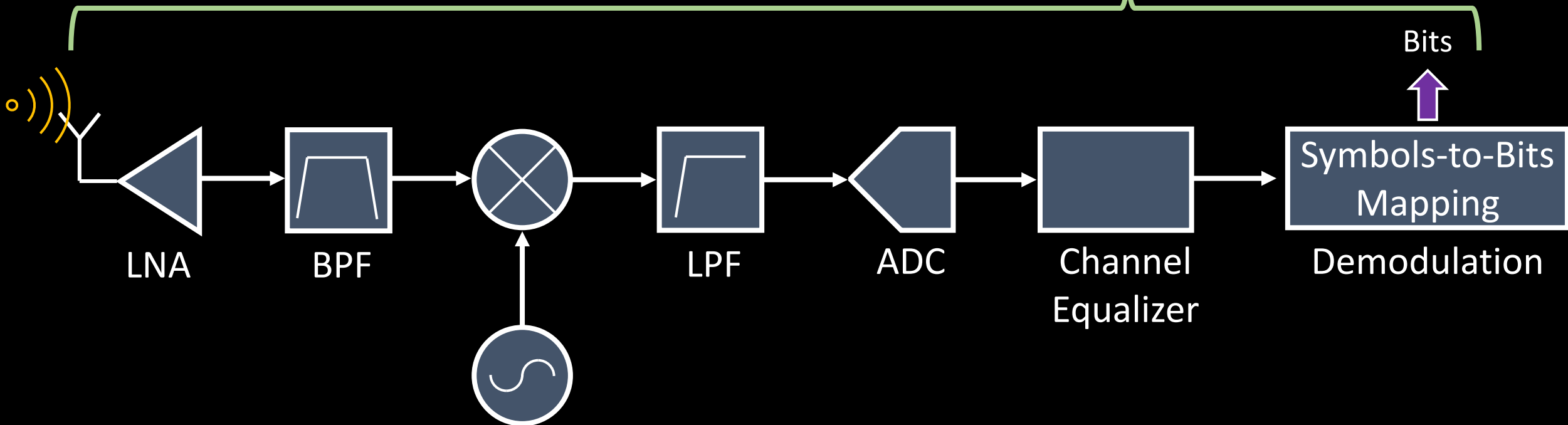
Mobile devices 1

Wireless channel changes the received signal!

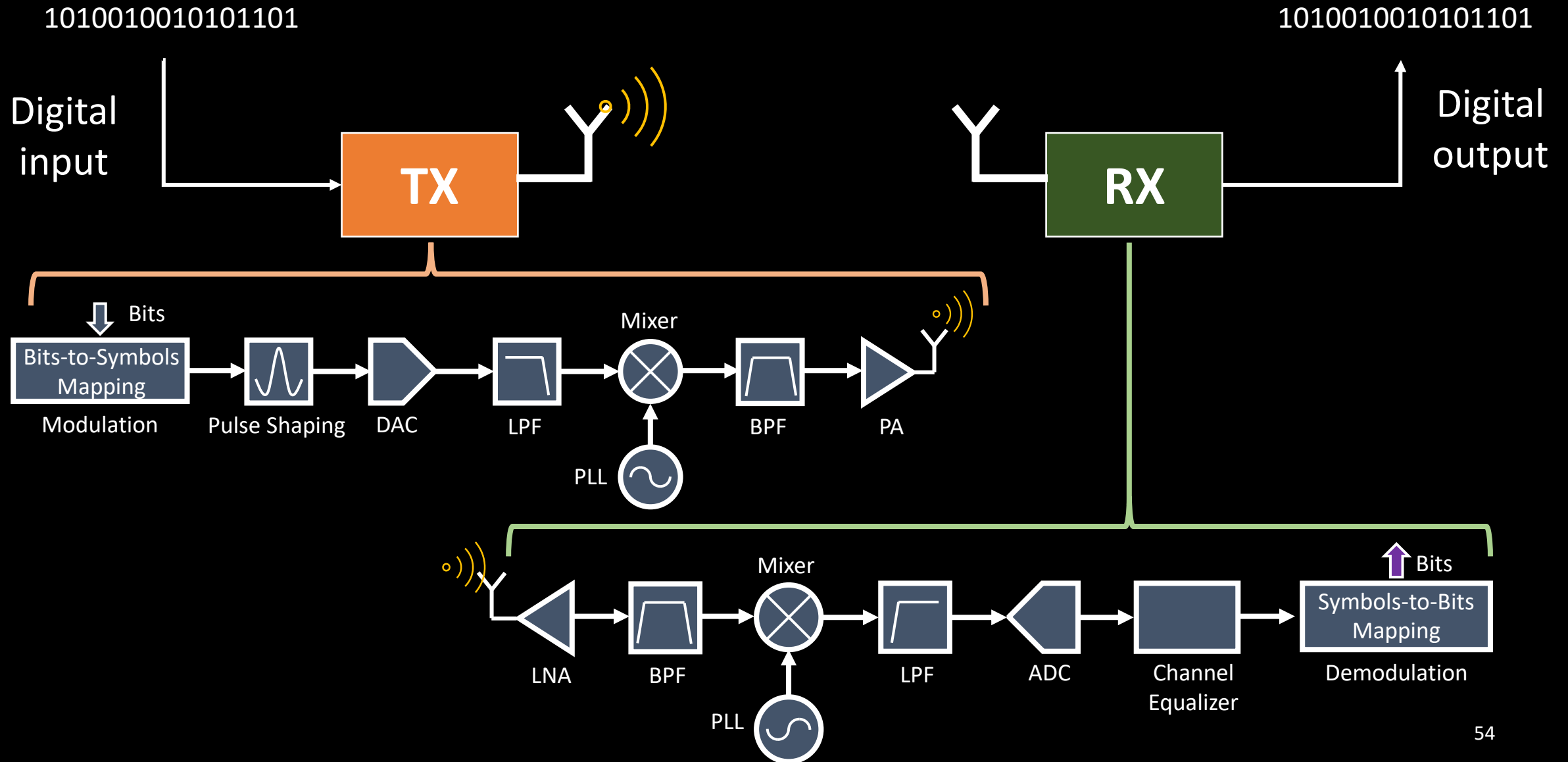
Wireless channel estimation



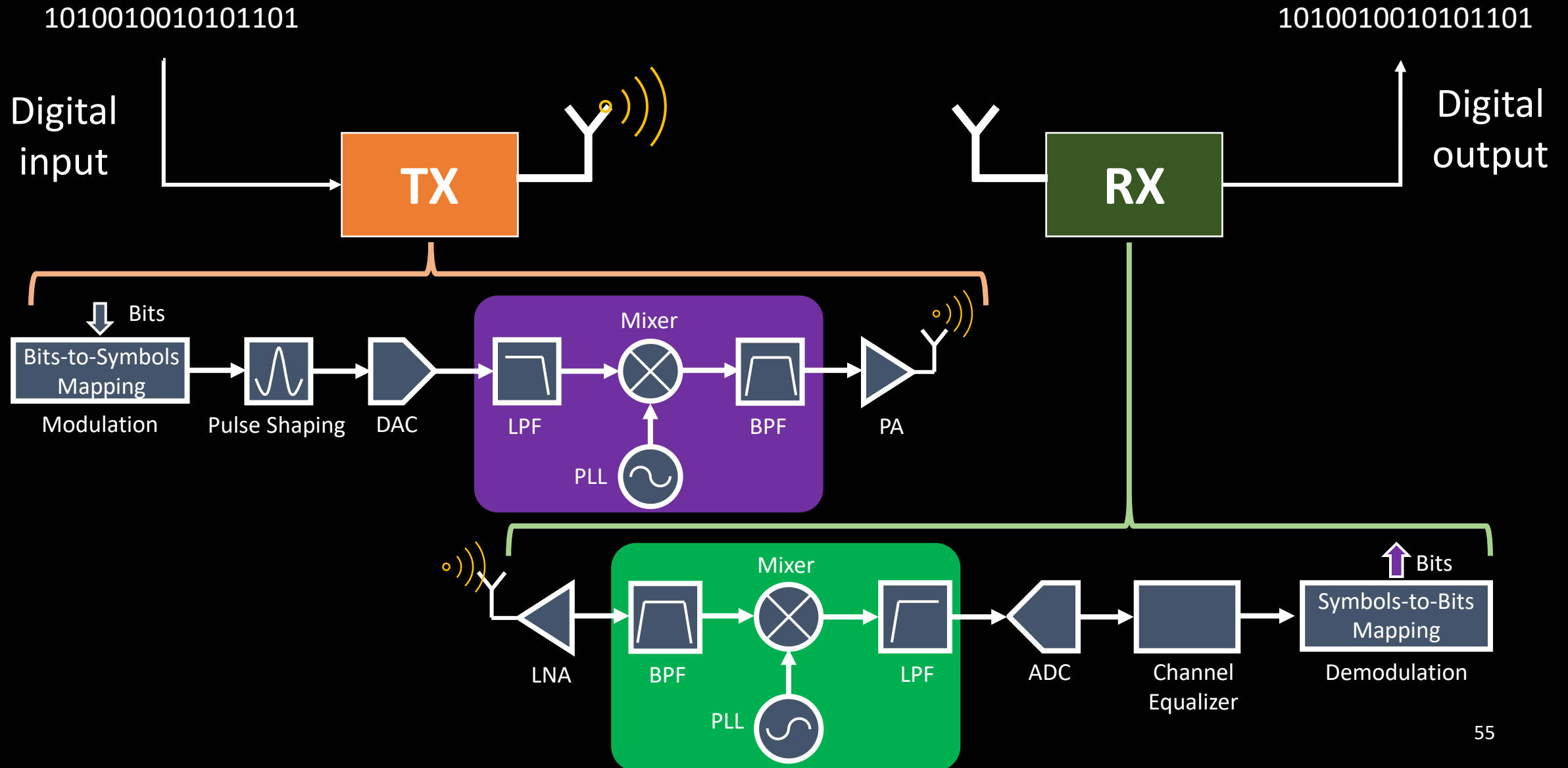
Wireless communication system



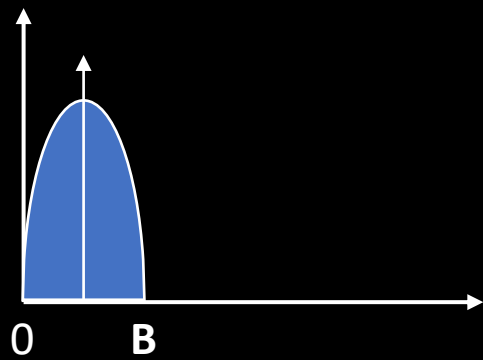
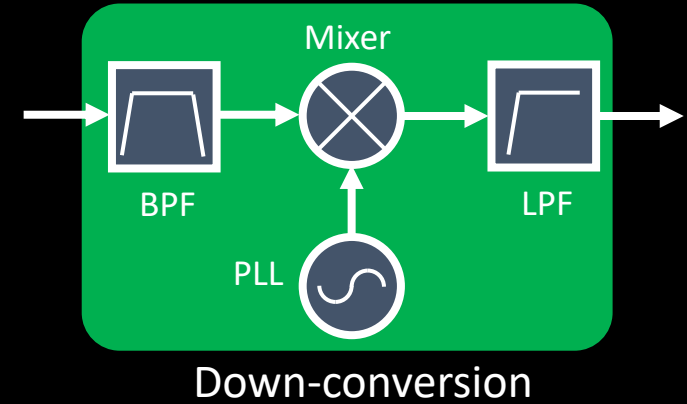
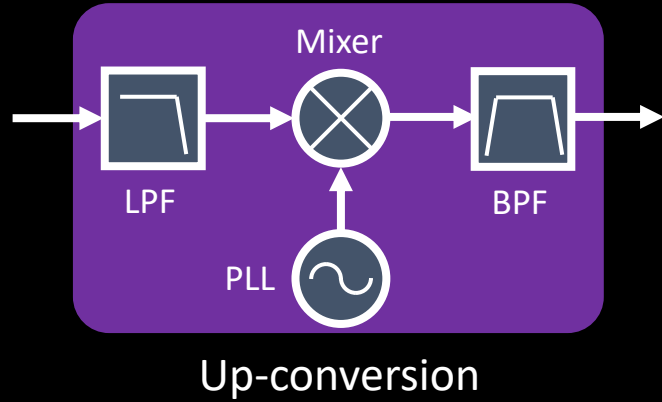
Wireless communication system



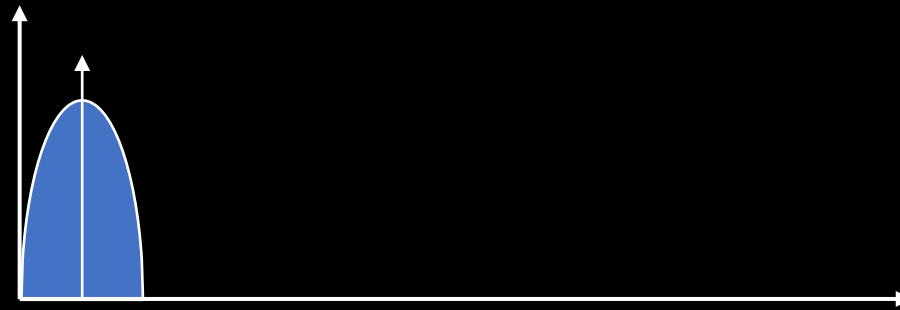
Wireless communication system



Up/Down Conversion

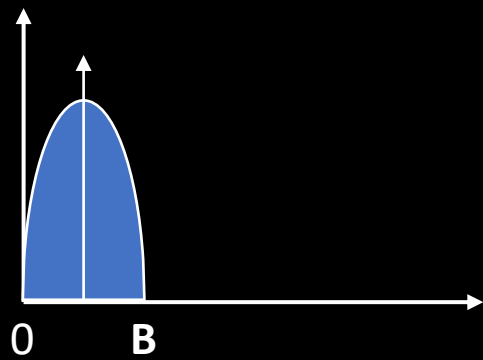
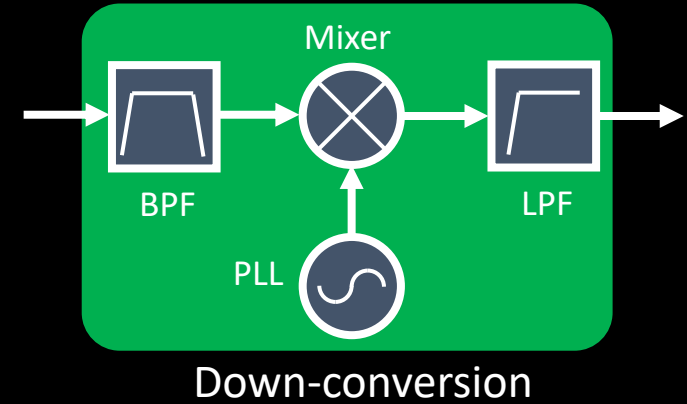
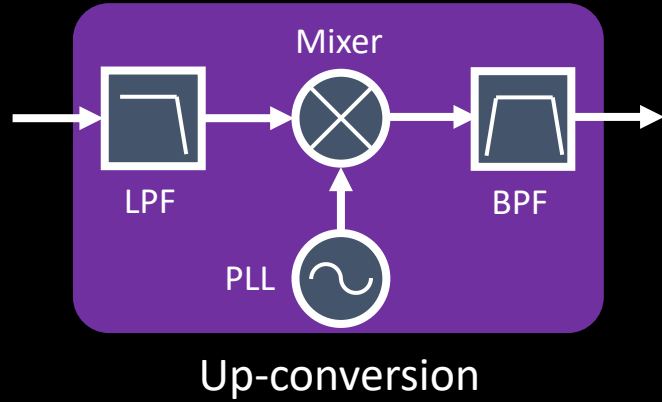


Baseband

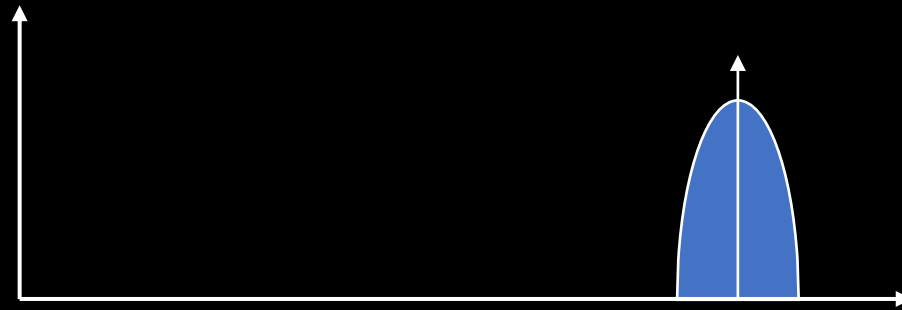


Passband

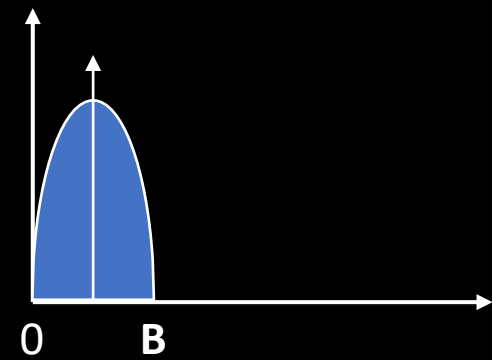
Up/Down Conversion



Baseband

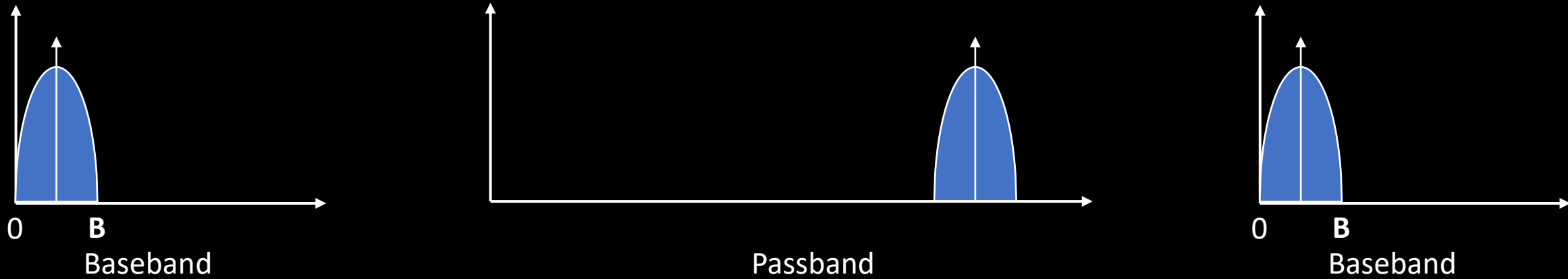


Passband



Baseband

Up/Down Conversion



Why do we need the up/down conversion ?

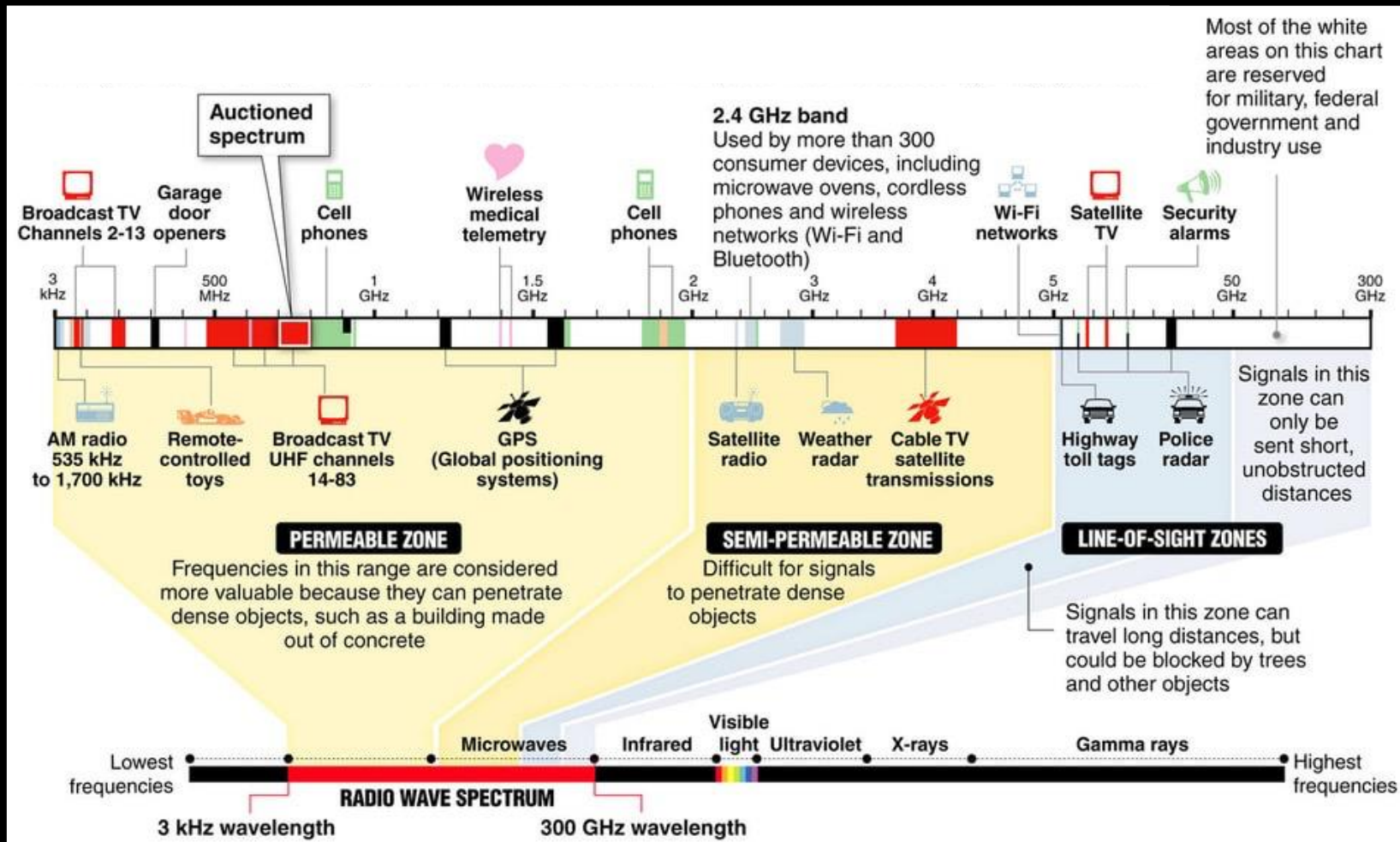
❖ Why not transmit everything at baseband (low frequency band)?

Not enough bandwidth

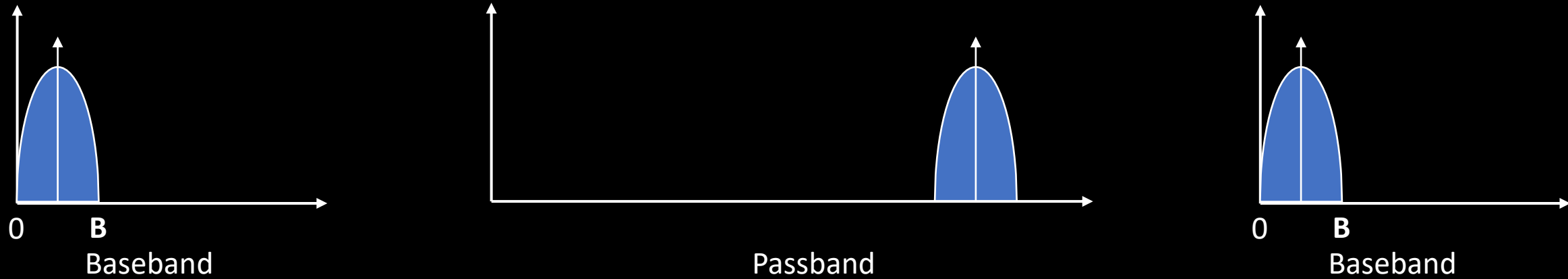
Data rate \propto bandwidth

Frequency band becomes crowded

Wireless Spectrum



Up/Down Conversion



Why do we need the up/down conversion ?

❖ Why not transmit everything at baseband (low frequency band)?

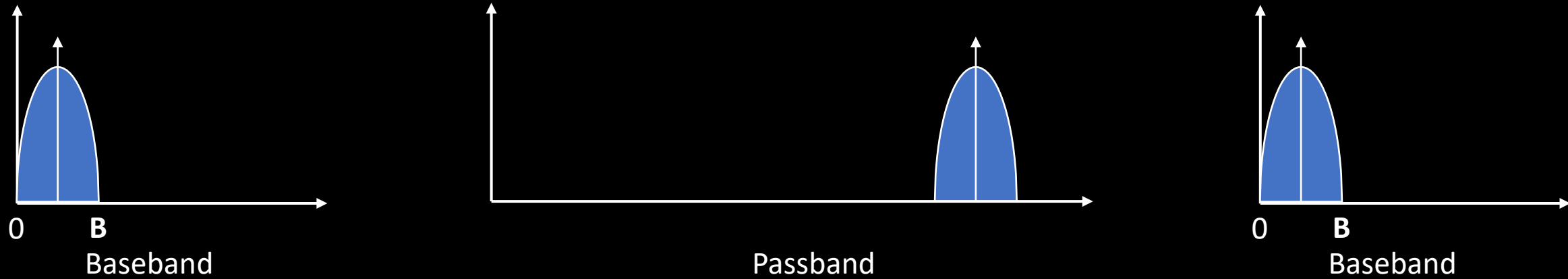
→ **Not enough bandwidth**

→ **Data rate \propto bandwidth**

→ **Frequency band becomes crowded**

→ **Antenna size \propto wavelength**

Up/Down Conversion



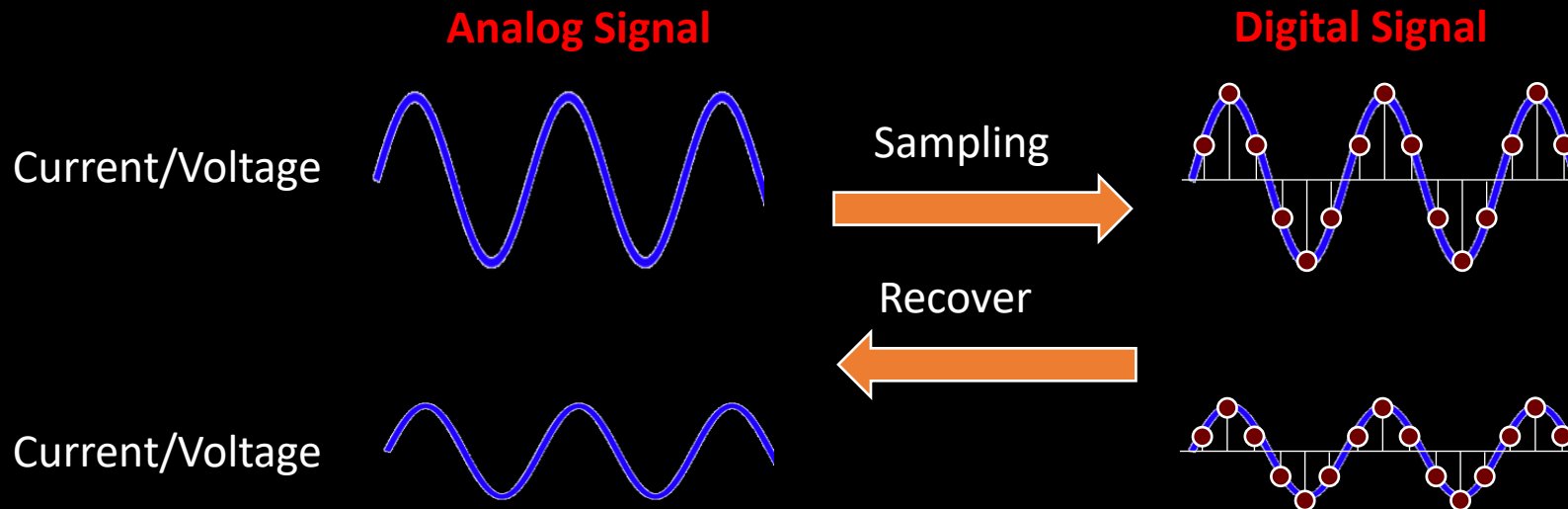
Why do we need the up/down conversion ?

- ❖ Why not transmit everything at baseband (low frequency band)?
- ❖ Why not directly transmit at passband (high frequency band)?

Nyquist!

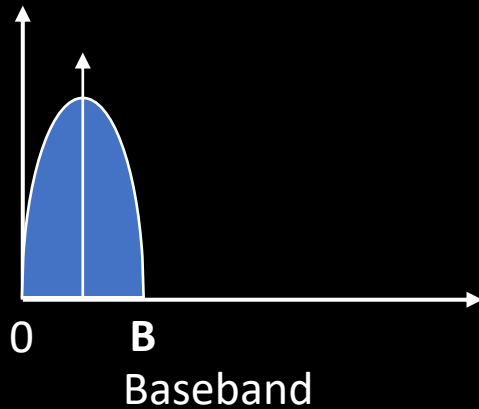
Nyquist sampling theorem

To truthfully recover a signal, we need to sample at twice the highest frequency, i.e., $2f$



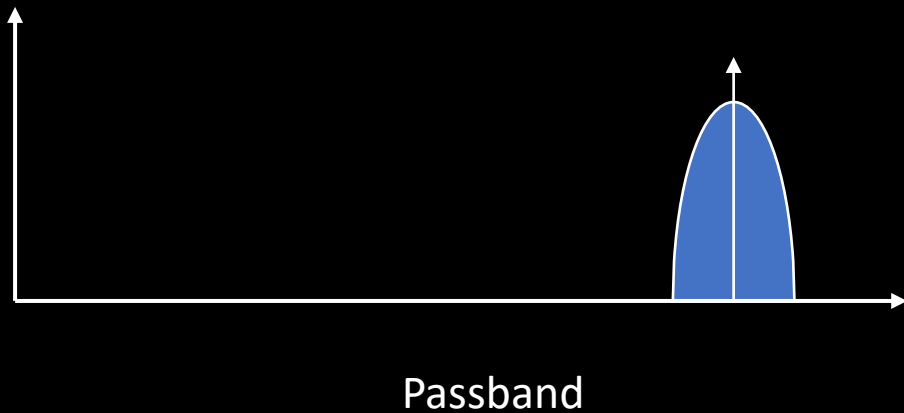
Nyquist sampling theorem

To truthfully recover a signal, we need to sample at twice the highest frequency, i.e., $2f$



Sampling
→

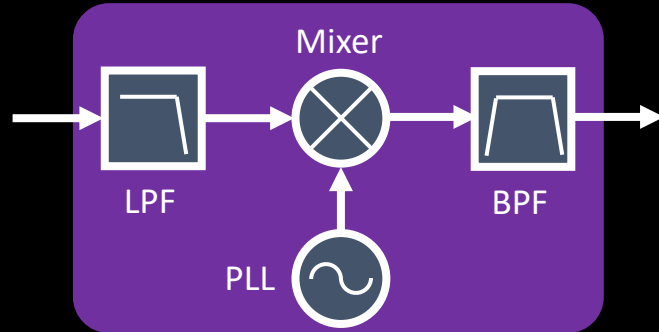
Sample the signal at $2B$
e.g., for Wi-Fi 802.11 b ≈ 40 MS/s



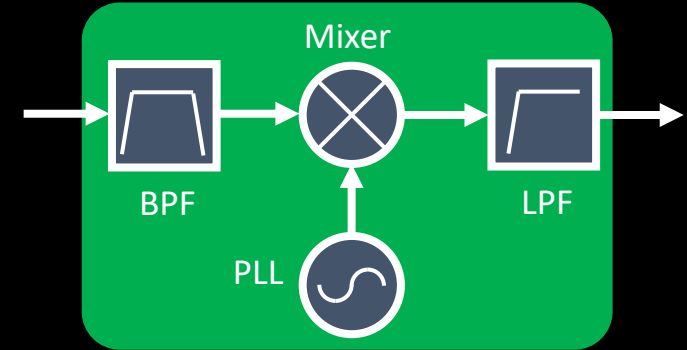
Sampling
→

Sample the signal at $2f_c + B$
e.g., for Wi-Fi 802.11 b ≈ 5 GS/s

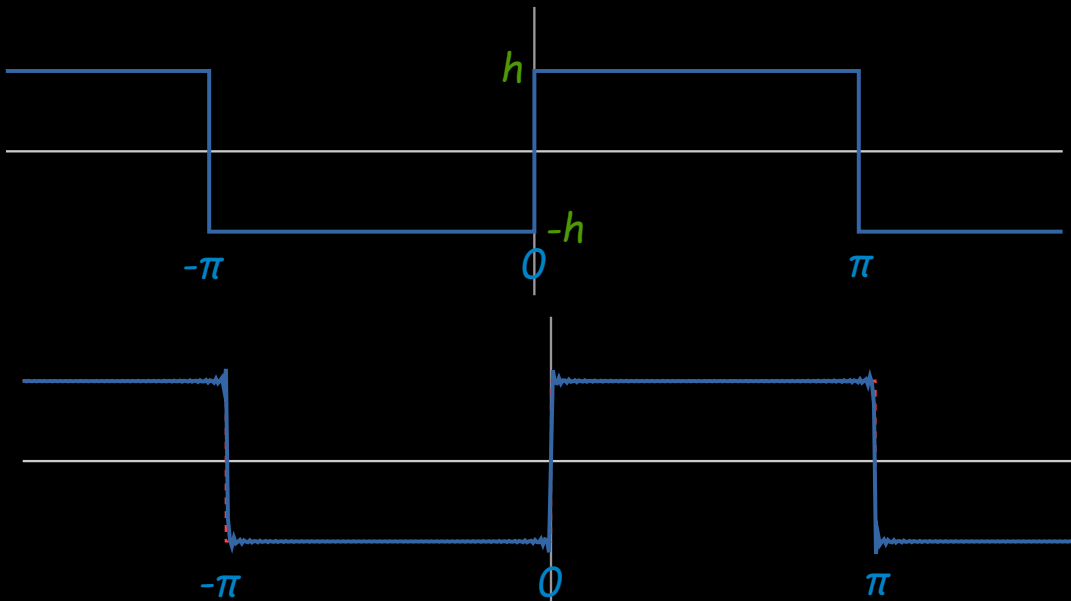
How do we do the Up/Down conversion?



Up-conversion

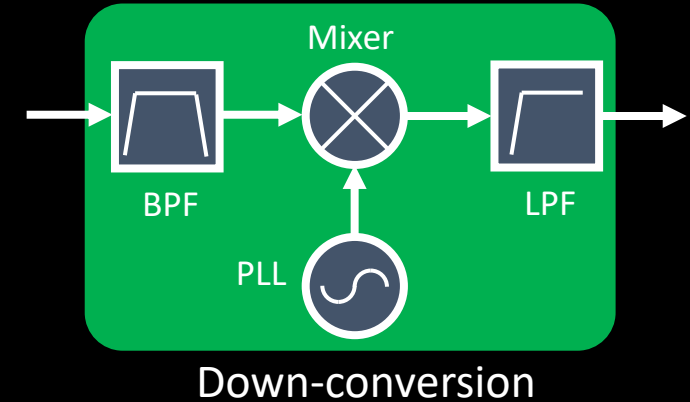
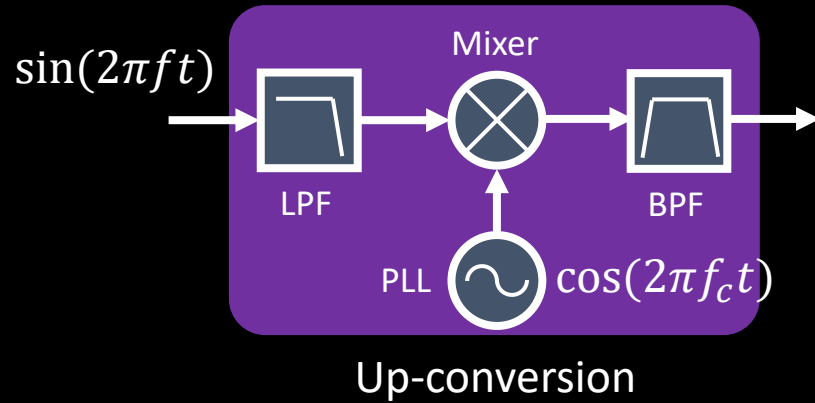


Down-conversion

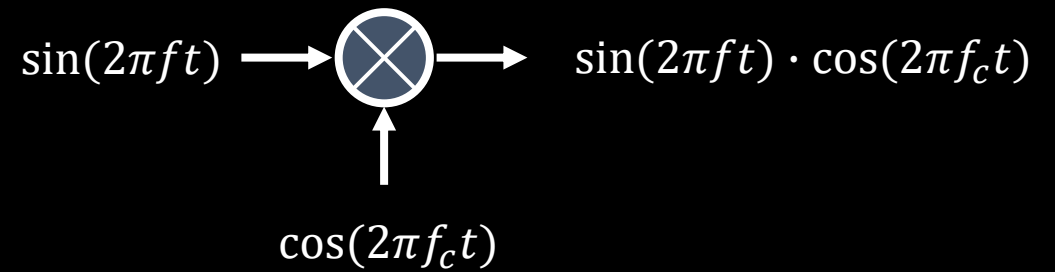


$$\sin x + \frac{1}{3} \sin 3x + \frac{1}{5} \sin 5x \\ + \dots + \frac{1}{199} \sin 199x$$

How do we do the Up/Down conversion?

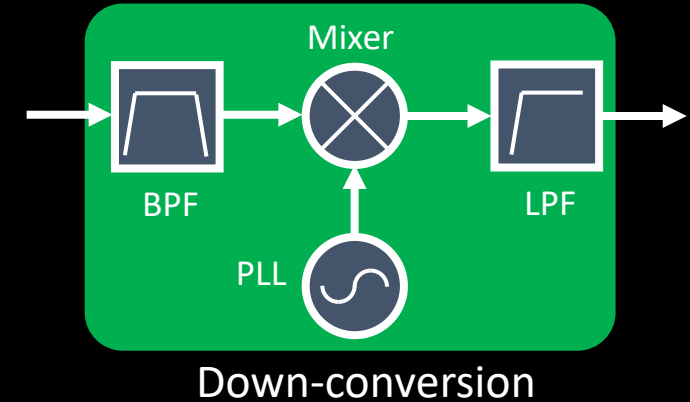
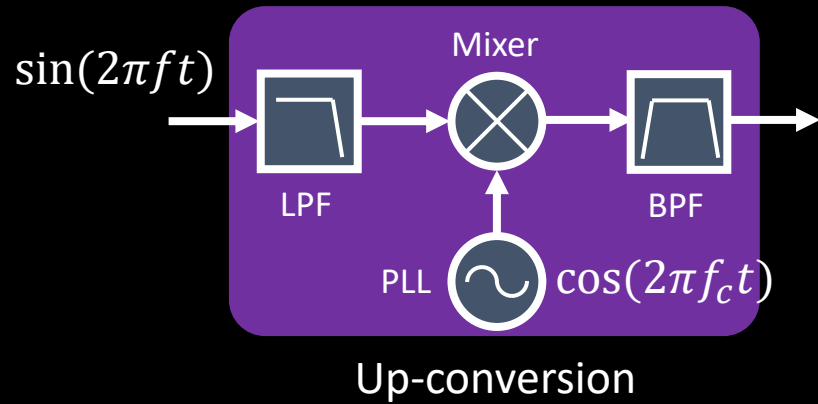


PLL (Phase Locked Loop): create a sine wave $\cos(2\pi ft)$



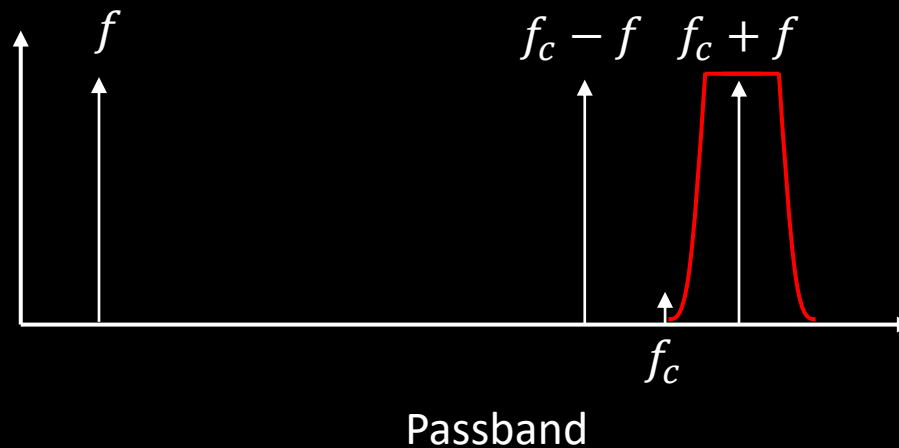
Mixer: mix/multiply two signal

How do we do the Up/Down conversion?



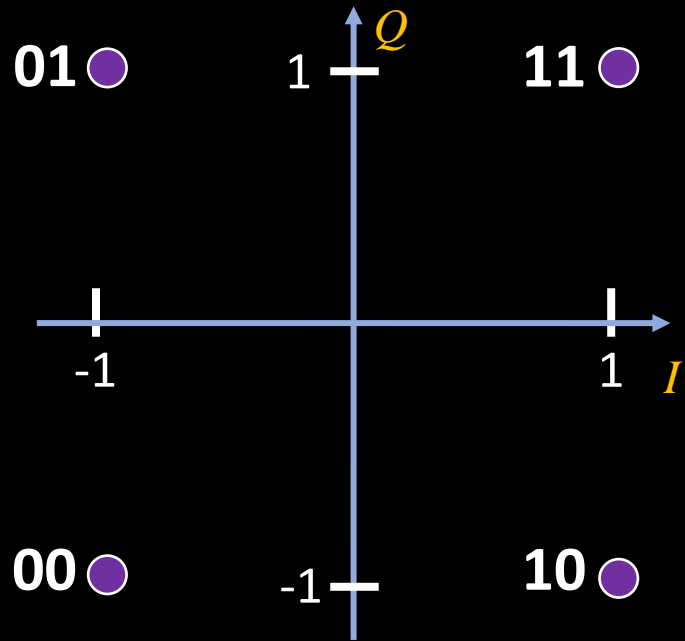
$$\sin(2\pi ft) \rightarrow \text{Mixer} \rightarrow \sin(2\pi ft) \cdot \cos(2\pi f_c t) = \frac{1}{2} [\sin(2\pi(f_c + f)t) - \sin(2\pi(f_c - f)t)]$$

$\cos(2\pi f_c t)$



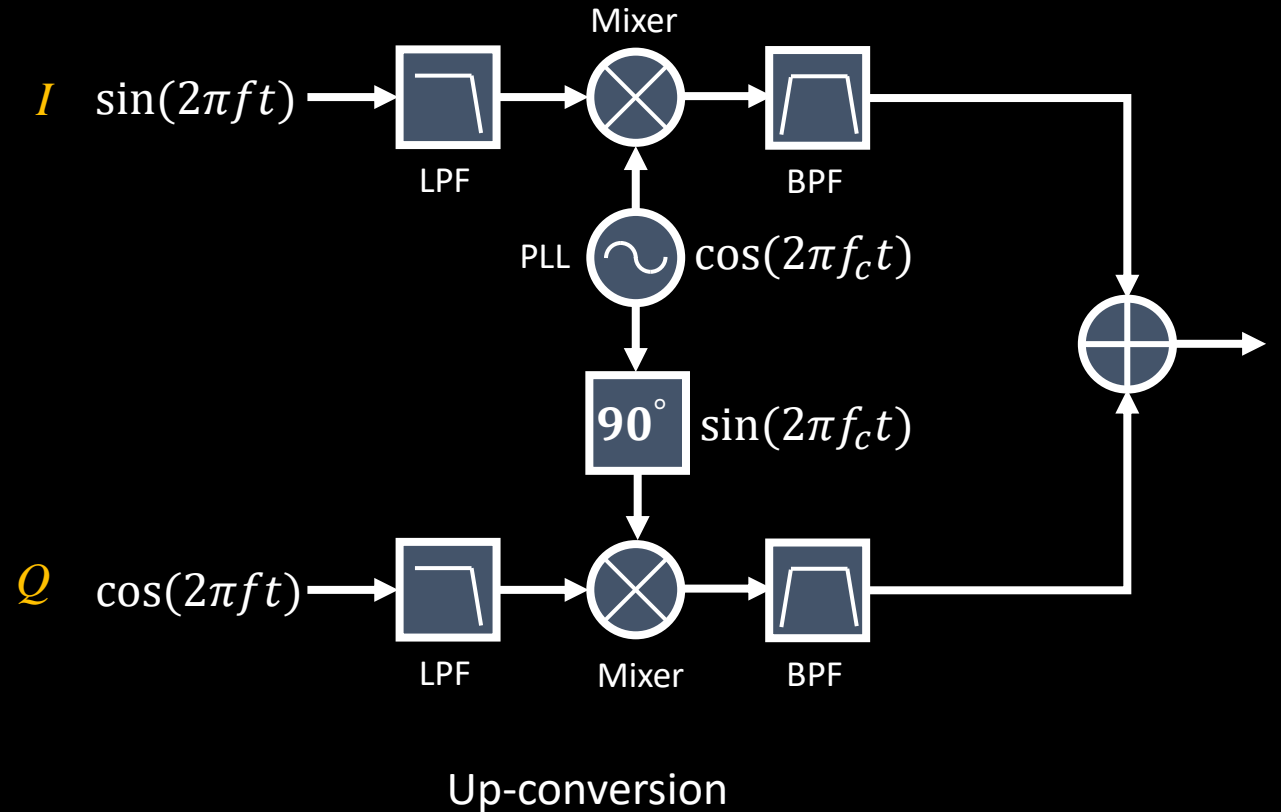
I-Q plane and

QPSK: 2bit/symbol

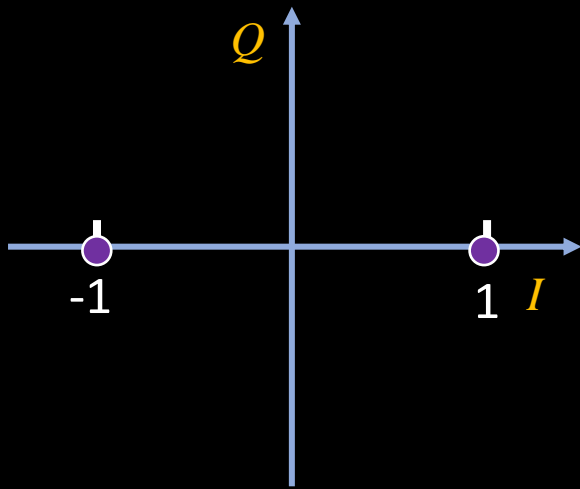


IQ plane

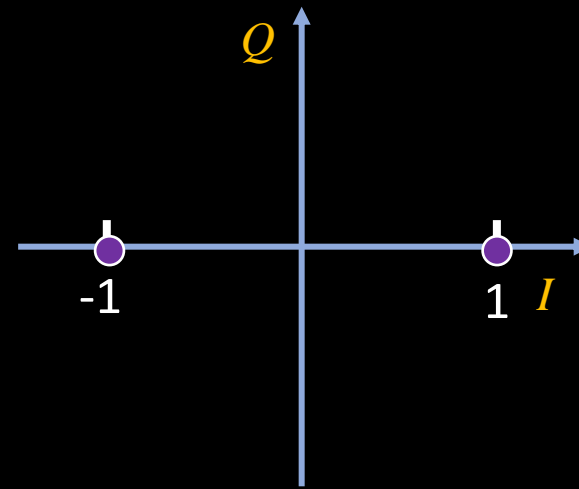
Complex Symbols: $a + bj$



Demodulation in presence of noise

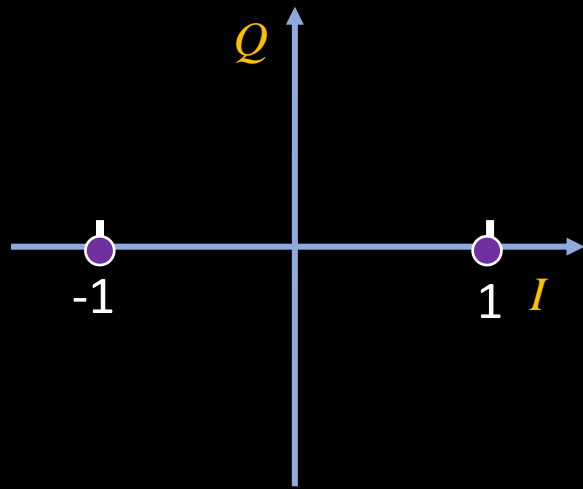


Transmitted Constellation

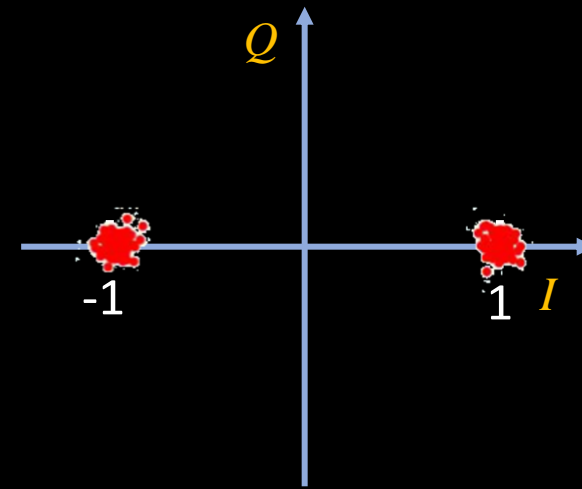


Received Constellation

Demodulation in presence of noise

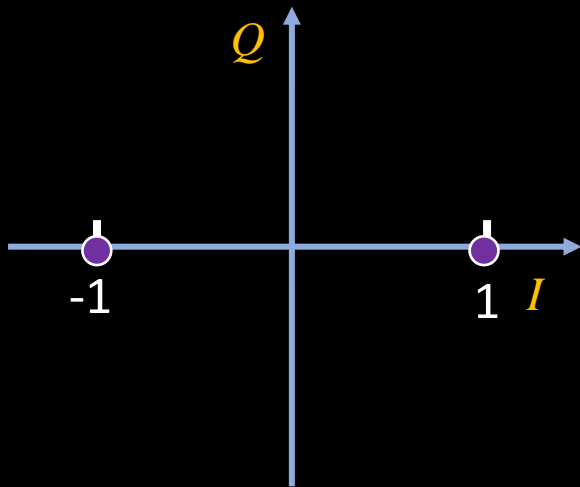


Transmitted Constellation



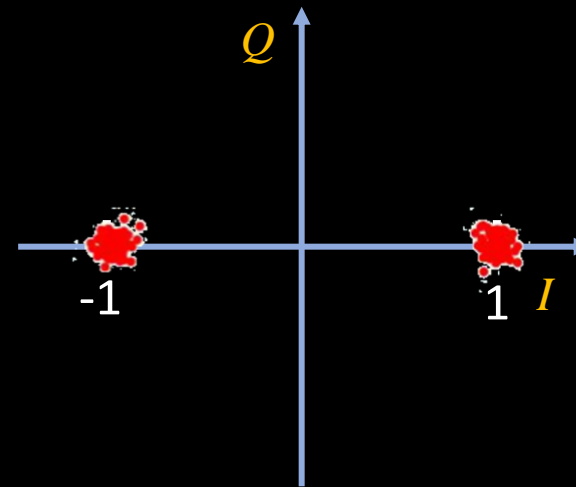
Received Constellation

Demodulation in presence of noise



Transmitted Constellation

$$x(t)$$

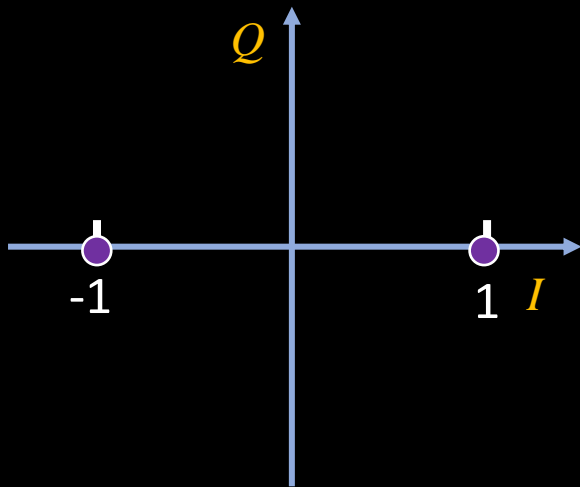


Received Constellation

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

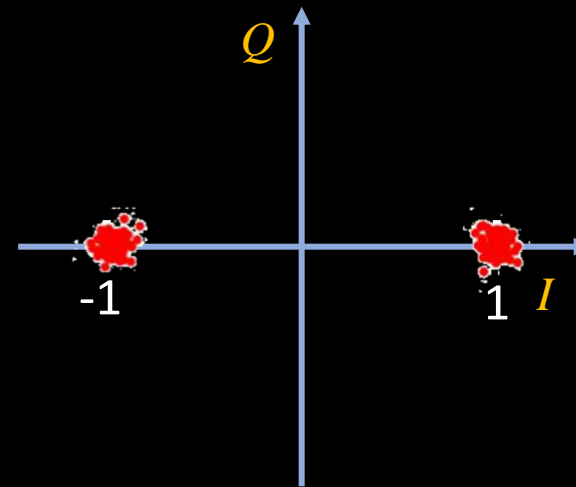
$$SNR = \frac{\text{Signal Power}}{\text{Noise Power}}$$

Demodulation in presence of noise



Transmitted Constellation

$$x(t)$$

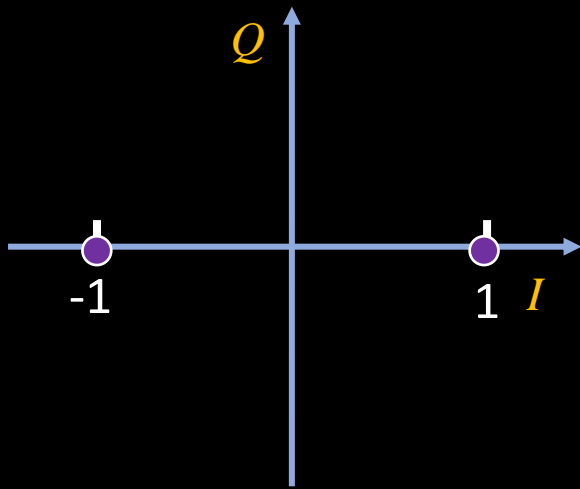


Received Constellation

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

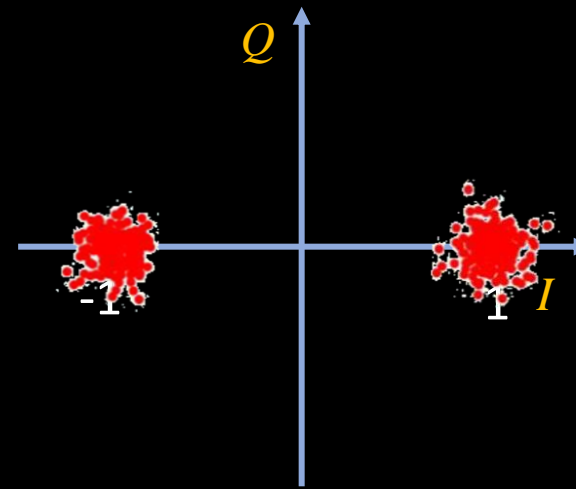
$$SNR = \frac{\text{Signal Power}}{\text{Noise Power}} = 25dB$$

Demodulation in presence of noise



Transmitted Constellation

$$x(t)$$

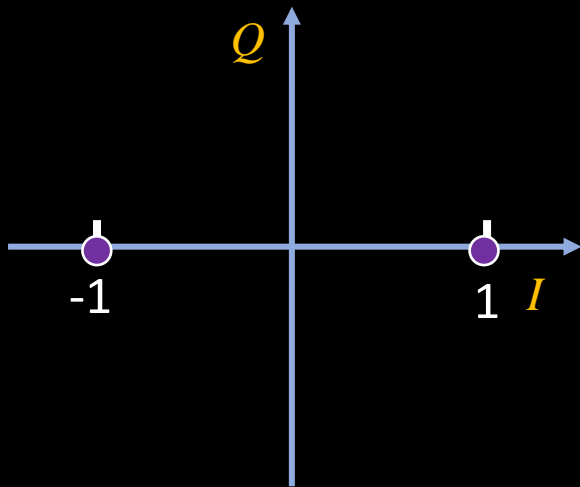


Received Constellation

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

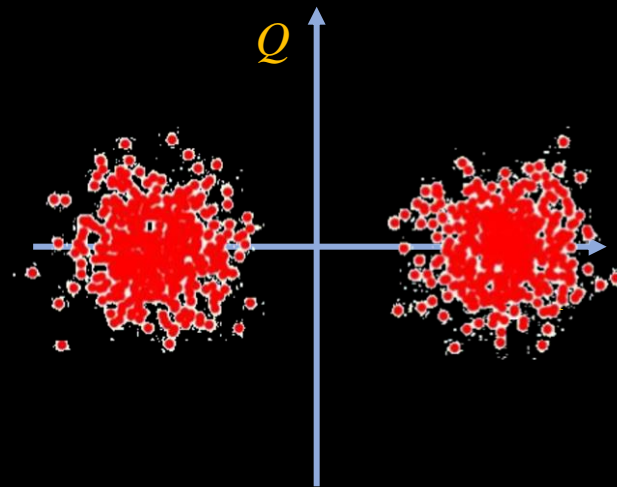
$$SNR = \frac{\text{Signal Power}}{\text{Noise Power}} = 19dB$$

Demodulation in presence of noise



Transmitted Constellation

$$x(t)$$

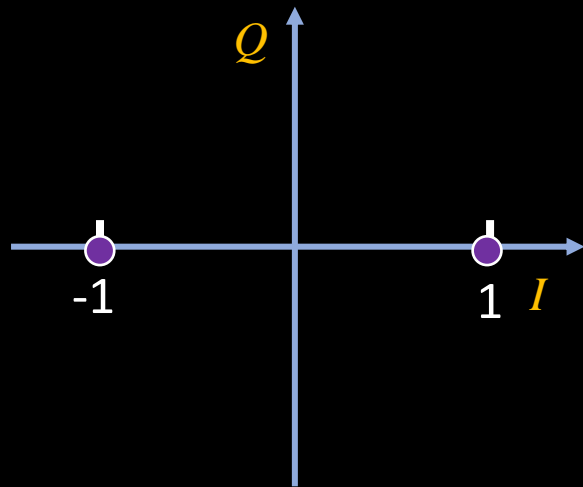


Received Constellation

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

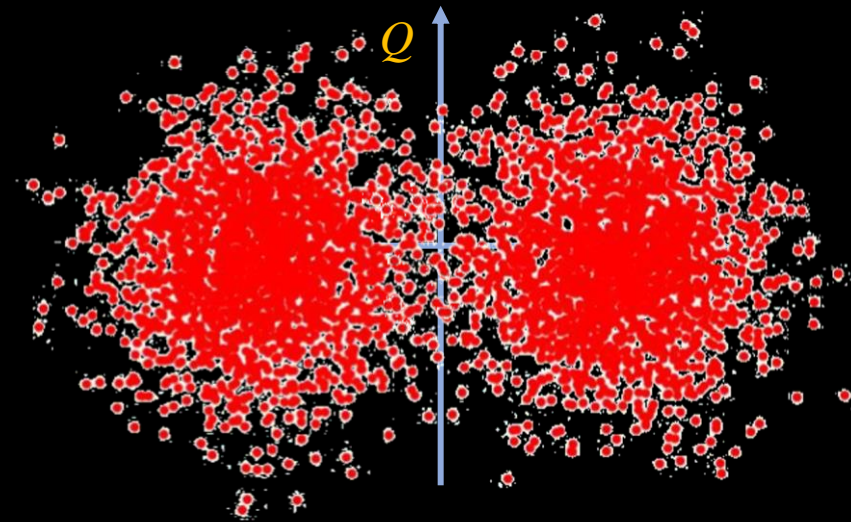
$$SNR = \frac{\text{Signal Power}}{\text{Noise Power}} = \mathbf{13dB}$$

Demodulation in presence of noise



Transmitted Constellation

$$x(t)$$

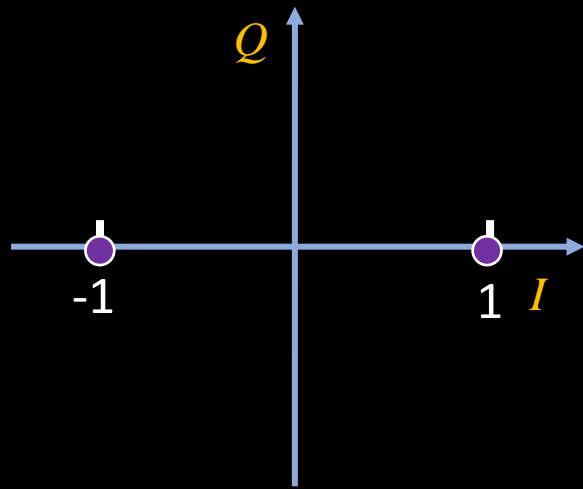


Received Constellation

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

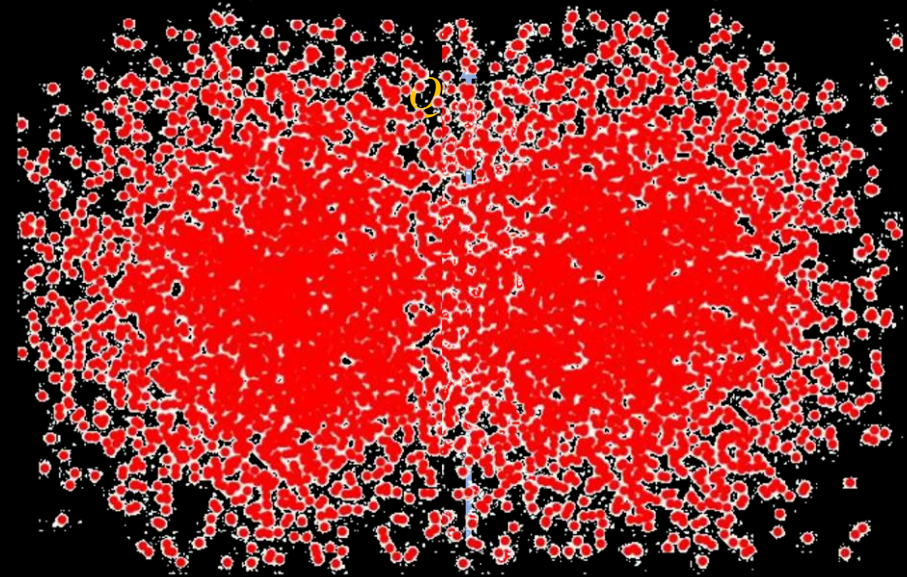
$$SNR = \frac{\text{Signal Power}}{\text{Noise Power}} = 7\text{dB}$$

Demodulation in presence of noise



Transmitted Constellation

$$x(t)$$

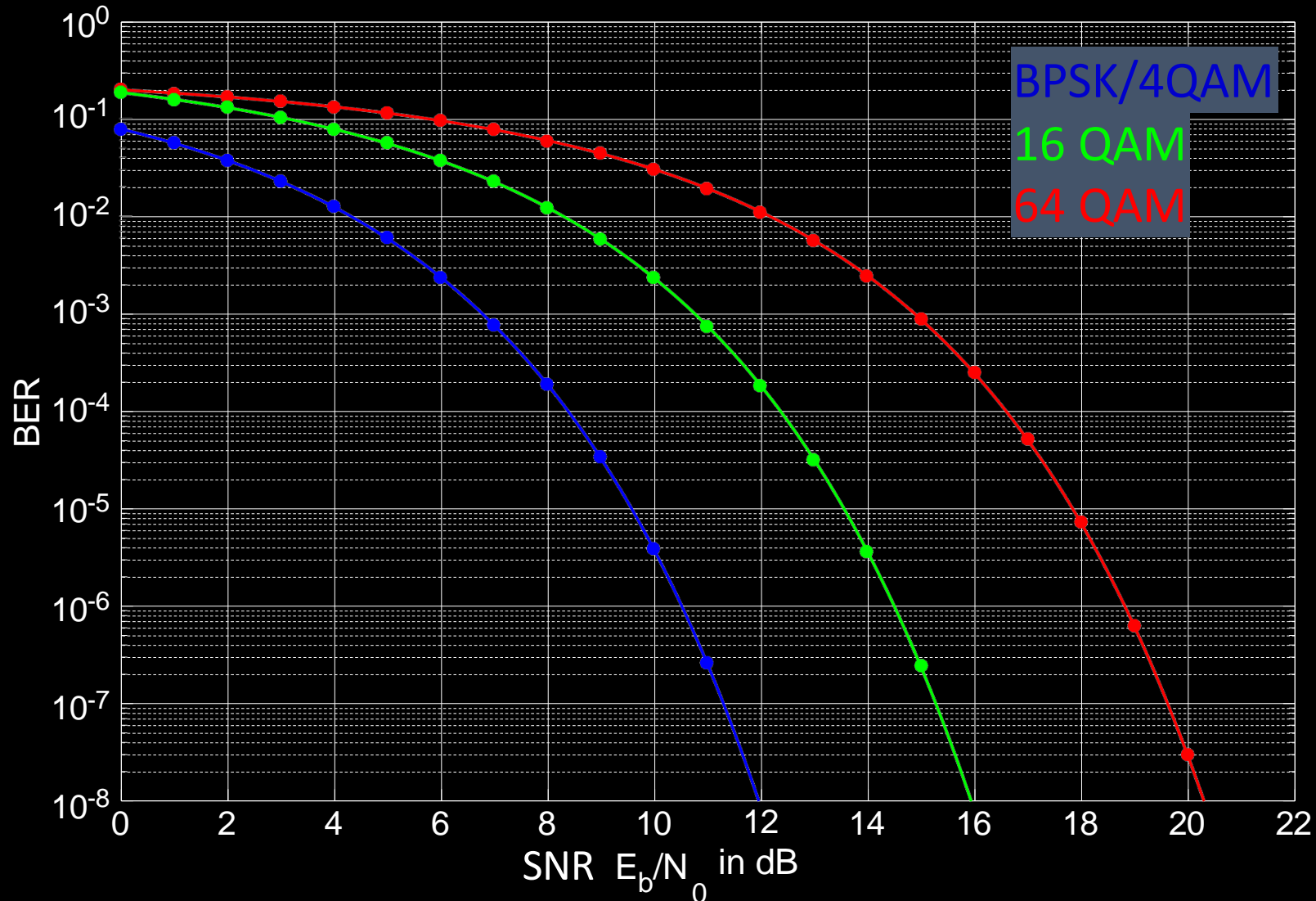


Received Constellation

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

$$SNR = \frac{\text{Signal Power}}{\text{Noise Power}} = 3.5dB$$

Demodulation in presence of noise



Demodulation in presence of noise

