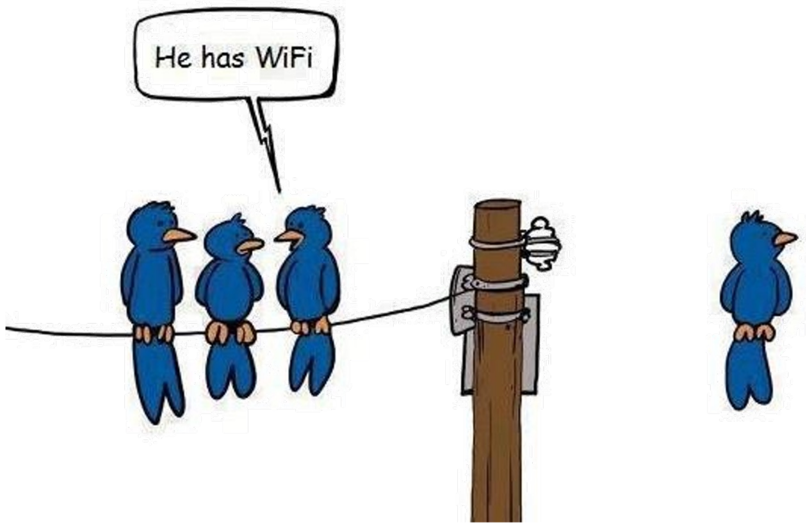
# COM-405: Mobile Networks

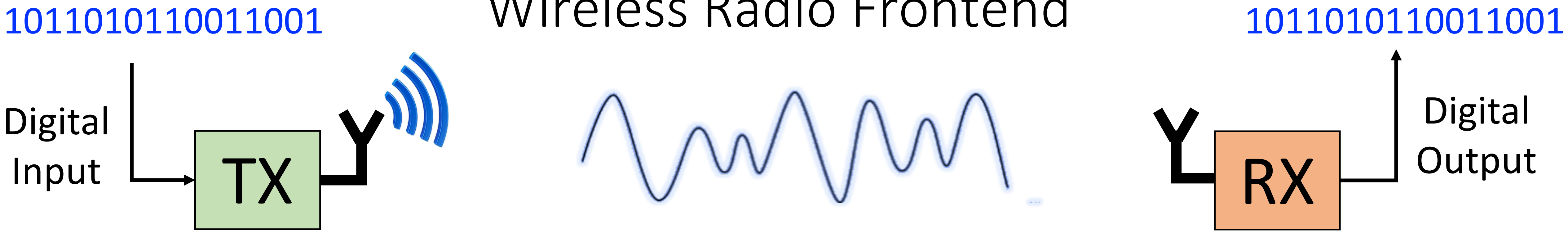
## Lecture 1.1: Wireless Radio

Haitham Hassanieh

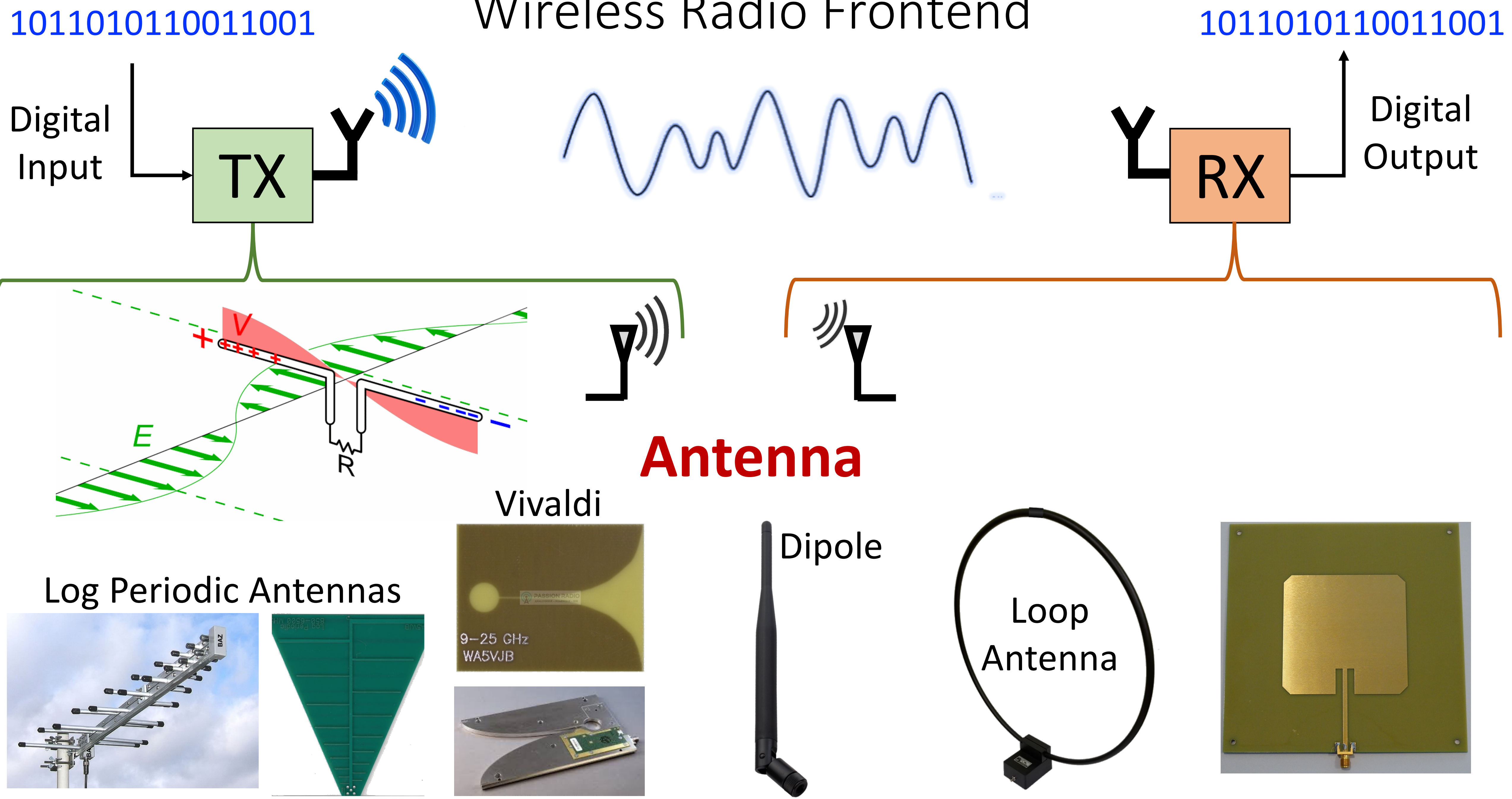



Laboratory of SEnsing
& Networking Systems

# Wireless Radio Frontend



# Wireless Radio Frontend



The size of the antenna increases with the frequency of operation i.e., the higher the frequency the larger the size.

A. *True*

B. *False*

The size of the antenna increases with the frequency of operation i.e., the higher the frequency the larger the size.

wave length $\lambda = \frac{c}{f}$

A. True

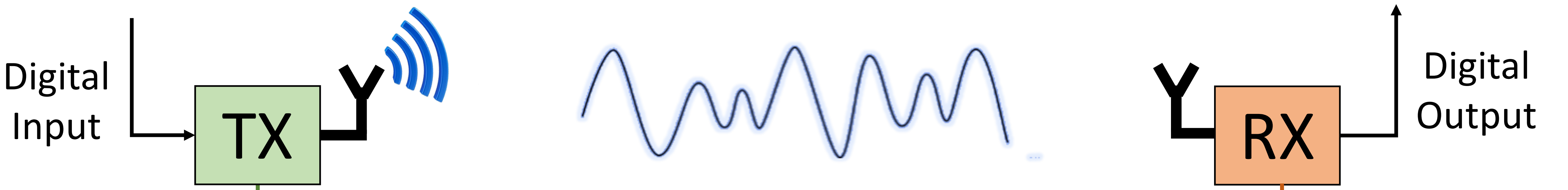
size antenna $\propto \lambda \propto \frac{1}{f}$

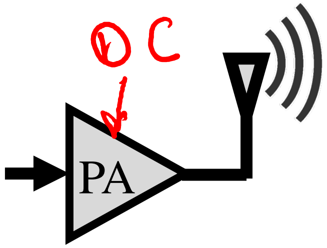
B. False

# Wireless Radio Frontend

1011010110011001

1011010110011001



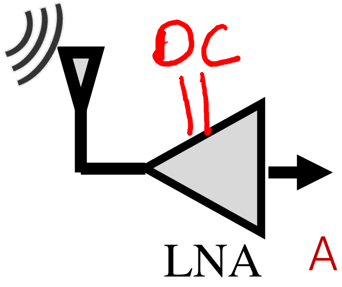




## Power Amplifier:

Amplify signal power

Radio Components → Passive, → Active

$$\text{Efficiency} = \frac{\text{Output Power}}{\text{Input Power}}$$




## Low Noise Amplifier:

Amplify signal power with minimal noise

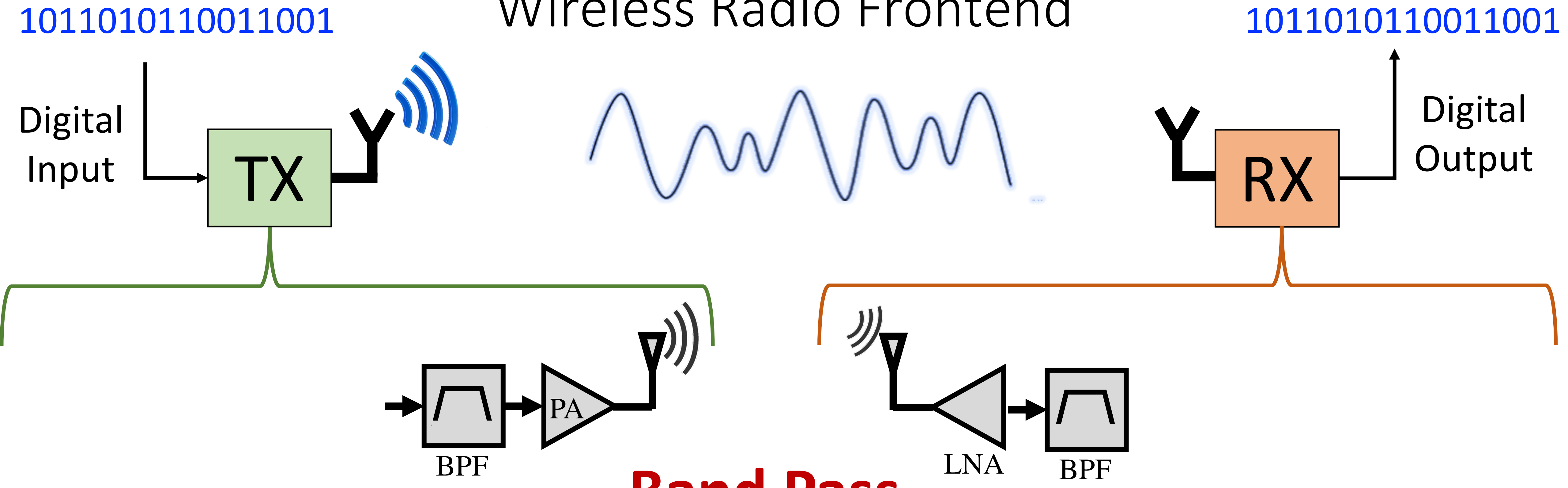
# Amplifiers

- Gain → 20dB → 100x, → 10 dB → 10x
- Efficiency
- Saturation

dB scale $= 10\log_{10} \mathit{Gain}$

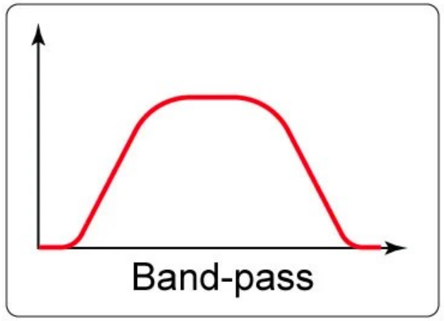
dBm $= 10\log_{10}\frac{\mathit{Power}}{1mW}$

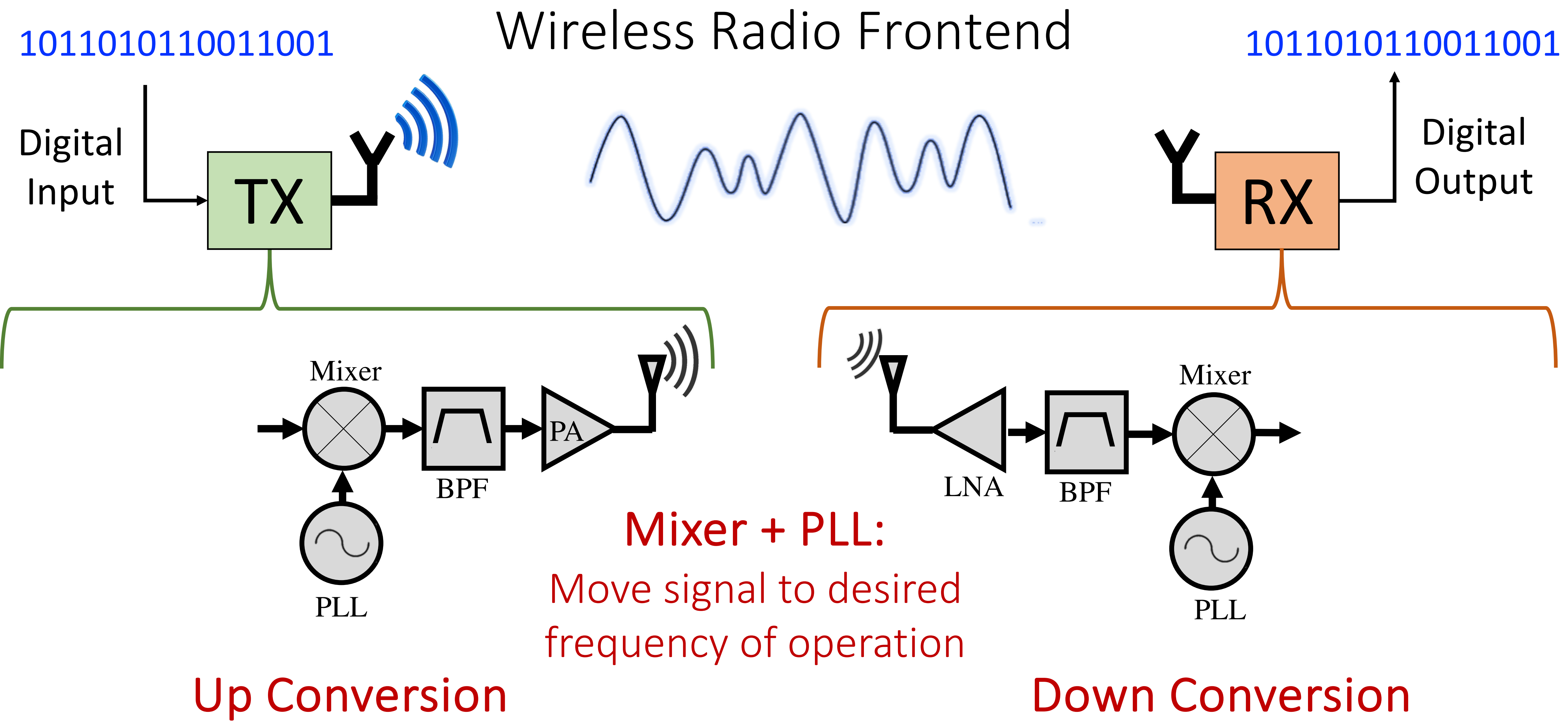
# Wireless Radio Frontend




## Band Pass Filters

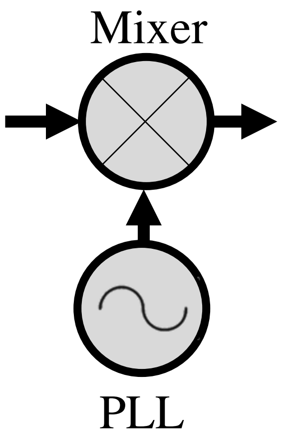
Removes Frequency Signals outside desired frequency of operation



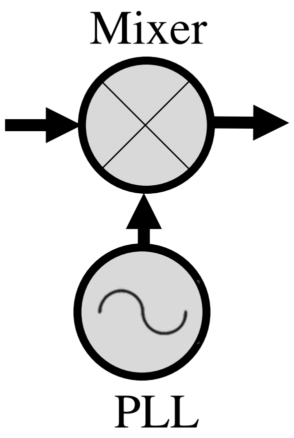

Wireless Radio Frontend
1011010110011001
Digital
Input
TX
1011010110011001
Digital
Output
RX
Mixer
BPF
PA
PLL
LNA
BPF
Mixer
PLL
Mixer + PLL:
Move signal to desired
frequency of operation
Up Conversion
Down Conversion

# Up/Down Conversion

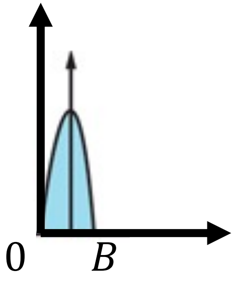
Transmitter
Up-conversion




Receiver
Down-conversion



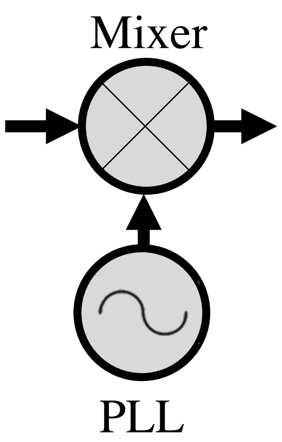

Baseband



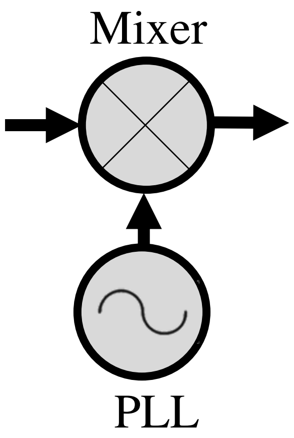

Passband

# Up/Down Conversion

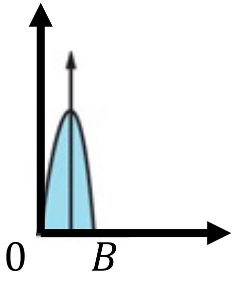
Transmitter
Up-conversion



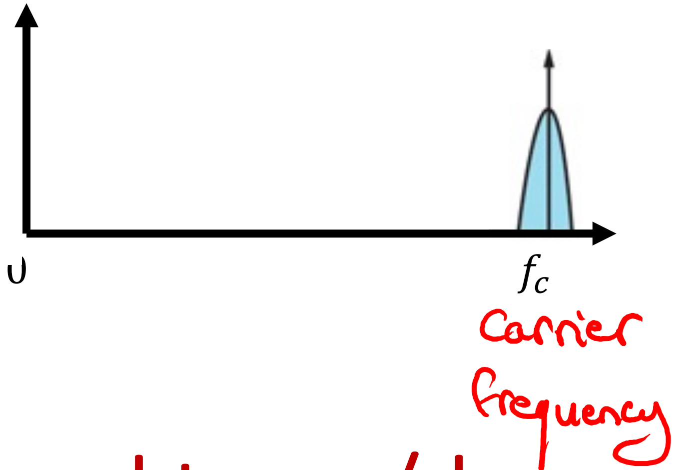

Receiver
Down-conversion



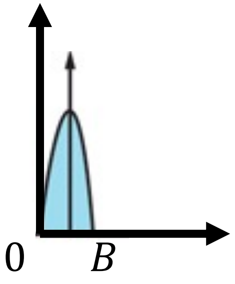

Baseband




Passband

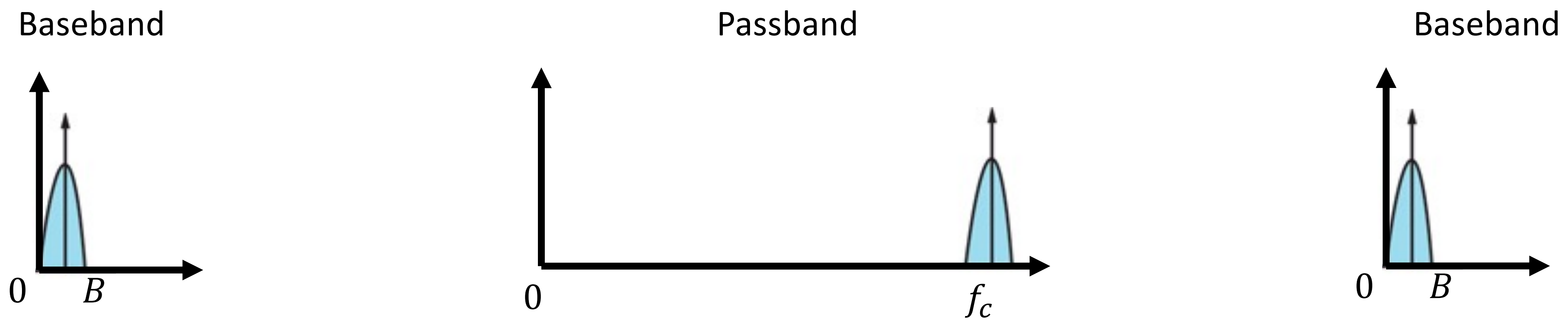



Baseband



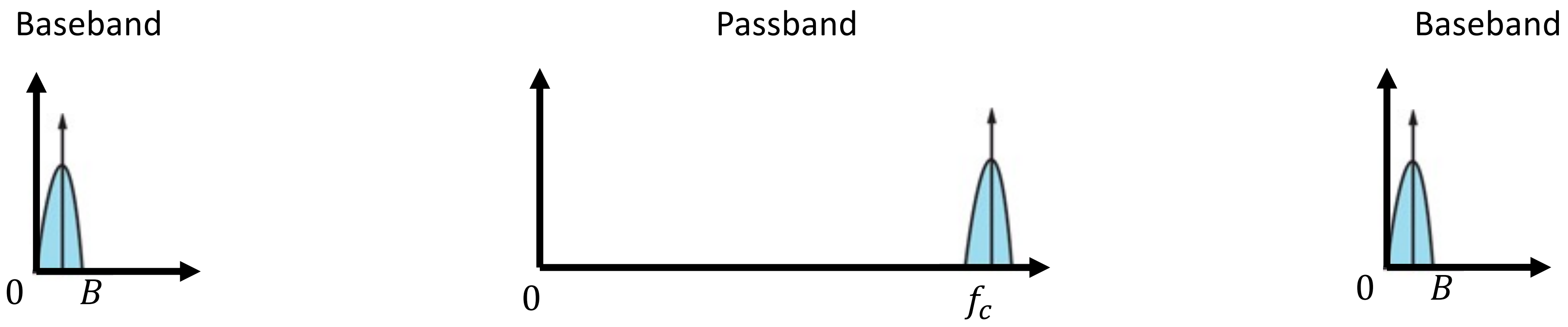

Why do we need to up/down conversion?

# Up/Down Conversion




**Why do we need to up/down conversion?**

# Up/Down Conversion




**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

# UNITED STATES FREQUENCY ALLOCATIONS

## THE RADIO SPECTRUM

### RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- INTER-SATELLITE
- RADIO ASTRONOMY
- AERONAUTICAL MOBILE SATELLITE
- LAND MOBILE
- RADIODETERMINATION SATELLITE
- AERONAUTICAL RADIONAVIGATION
- LAND MOBILE SATELLITE
- RADIOLOCATION
- AMATEUR
- MARITIME MOBILE
- RADIOLOCATION SATELLITE
- AMATEUR SATELLITE
- MARITIME MOBILE SATELLITE
- RADIONAVIGATION
- BROADCASTING
- MARITIME RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- BROADCASTING SATELLITE
- METEOROLOGICAL
- SPACE OPERATION
- EARTH EXPLORATION SATELLITE
- METEOROLOGICAL SATELLITE
- SPACE RESEARCH
- FIXED
- MOBILE
- STANDARD FREQUENCY AND TIME SIGNAL
- FIXED SATELLITE
- MOBILE SATELLITE
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

### ACTIVITY CODE

- FEDERAL EXCLUSIVE
- FEDERAL/NON-FEDERAL SHARED
- NON-FEDERAL EXCLUSIVE

### ALLOCATION USAGE DESIGNATION

| SERVICE | EXAMPLE | DESCRIPTION |
|---|---|---|
| Primary | FIXED | Capital Letters |
| Secondary | Mobile | 1st Capital with lower case letters |

This chart is a graphic single-point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it may not completely reflect all aspects, i.e. footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.


**U.S. DEPARTMENT OF COMMERCE**
**National Telecommunications and Information Administration**
Office of Spectrum Management

JANUARY 2016

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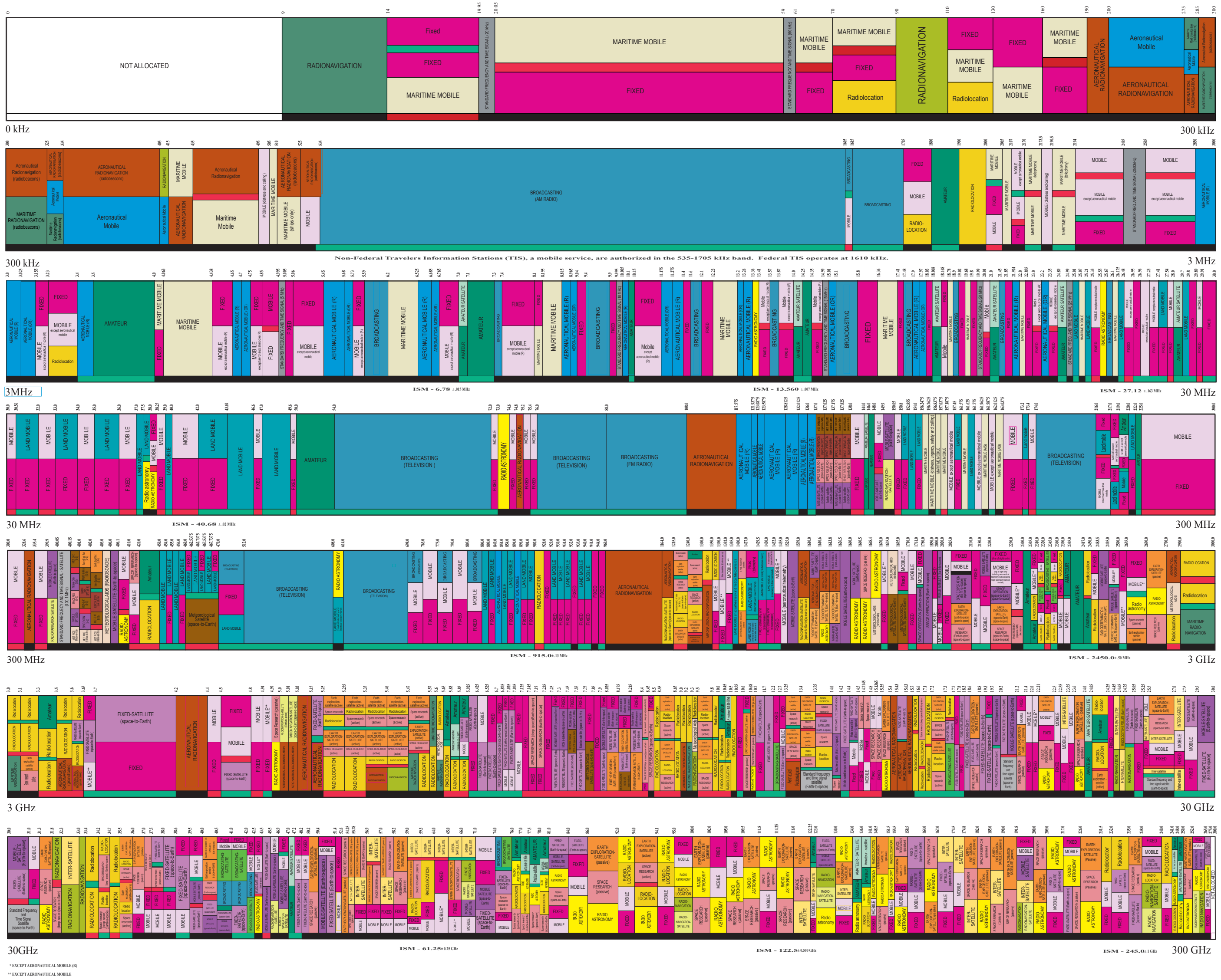
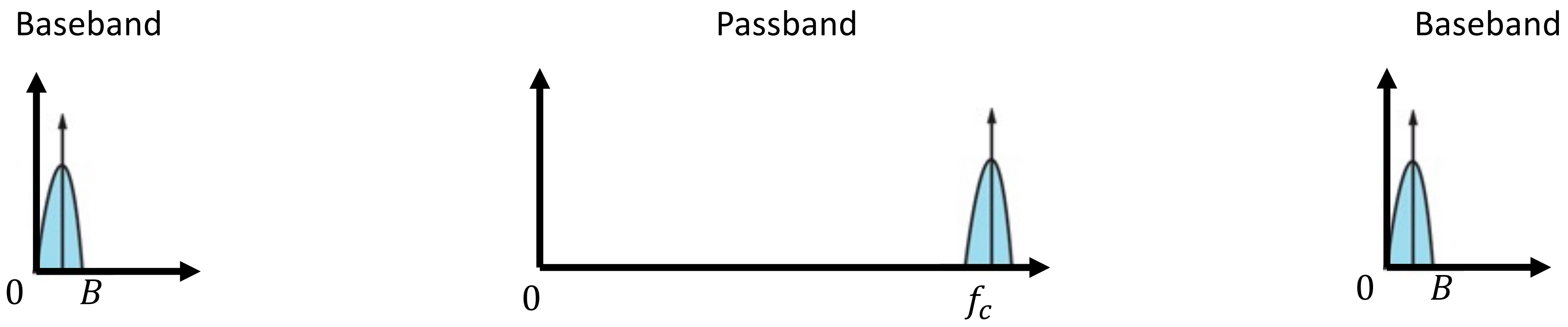



PLEASE NOTE: THE SPACING ALLOTTED THE SERVICES IN THE SPECTRUM SEGMENTS SHOWN IS NOT PROPORTIONAL TO THE ACTUAL AMOUNT OF SPECTRUM OCCUPIED.

# Up/Down Conversion




## Why do we need to up/down conversion?

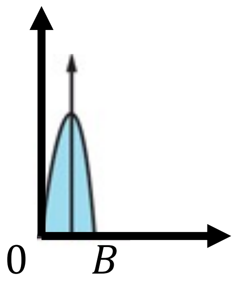
- Why not transmit everything at lower frequencies?
  - **Not enough bandwidth:**
    - Data rate ∝ bandwidth
    - Different Technologies
  - **Antenna size** ∝ wavelength
- Why not transmit & receive directly at high frequency?

**Nyquist!**

# Nyquist Theorem

*To recover the signal properly, we need to sample at twice the highest frequency, i.e.* $2f_{max}$

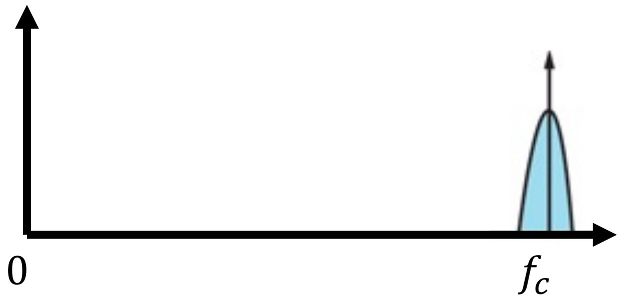
Baseband




Sample at $2B$

e.g. WiFi 802.11b ≈ 40 MS/s

Passband

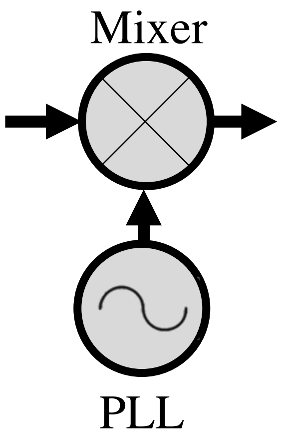



Sample at $2f_c + B$

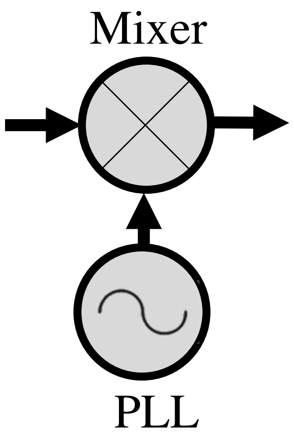
e.g. WiFi 802.11b ≈ 5 GS/s

# Up/Down Conversion

Transmitter
Up-conversion




Receiver
Down-conversion




## How to we do up/down conversion?

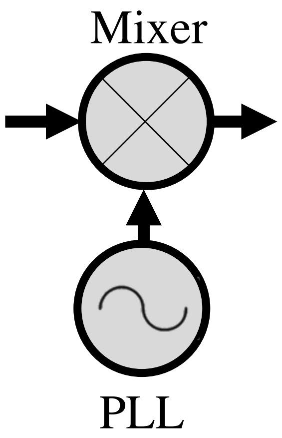
$$s(t) \longrightarrow \underset{\uparrow \atop \cos(2\pi f_c t)}{\times} \longrightarrow s(t)\cos(2\pi f_c t) \longrightarrow \underset{\uparrow \atop \cos(2\pi f_c t)}{\times} \longrightarrow s(t)\cos^2(2\pi f_c t)$$

---

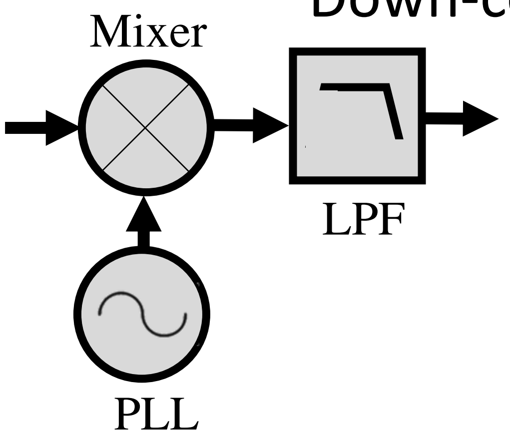
$$s(t)\cos^2(2\pi f_c t) = s(t)\left(\frac{1}{2} + \frac{1}{2}\cos(2\pi\, 2f_c\, t)\right)$$

# Up/Down Conversion

Transmitter
Up-conversion




Receiver
Down-conversion

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

---

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

Low Pass Filter

# Up/Down Conversion

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

# Up/Down Conversion

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

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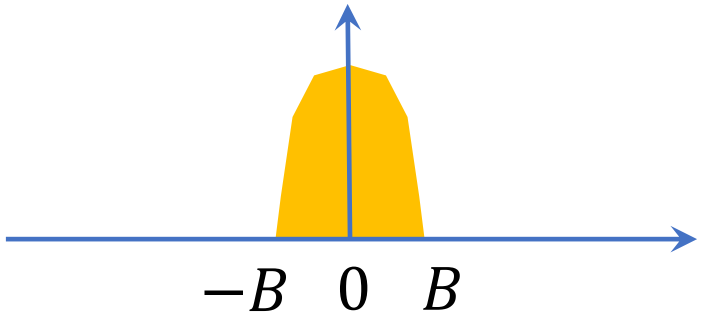
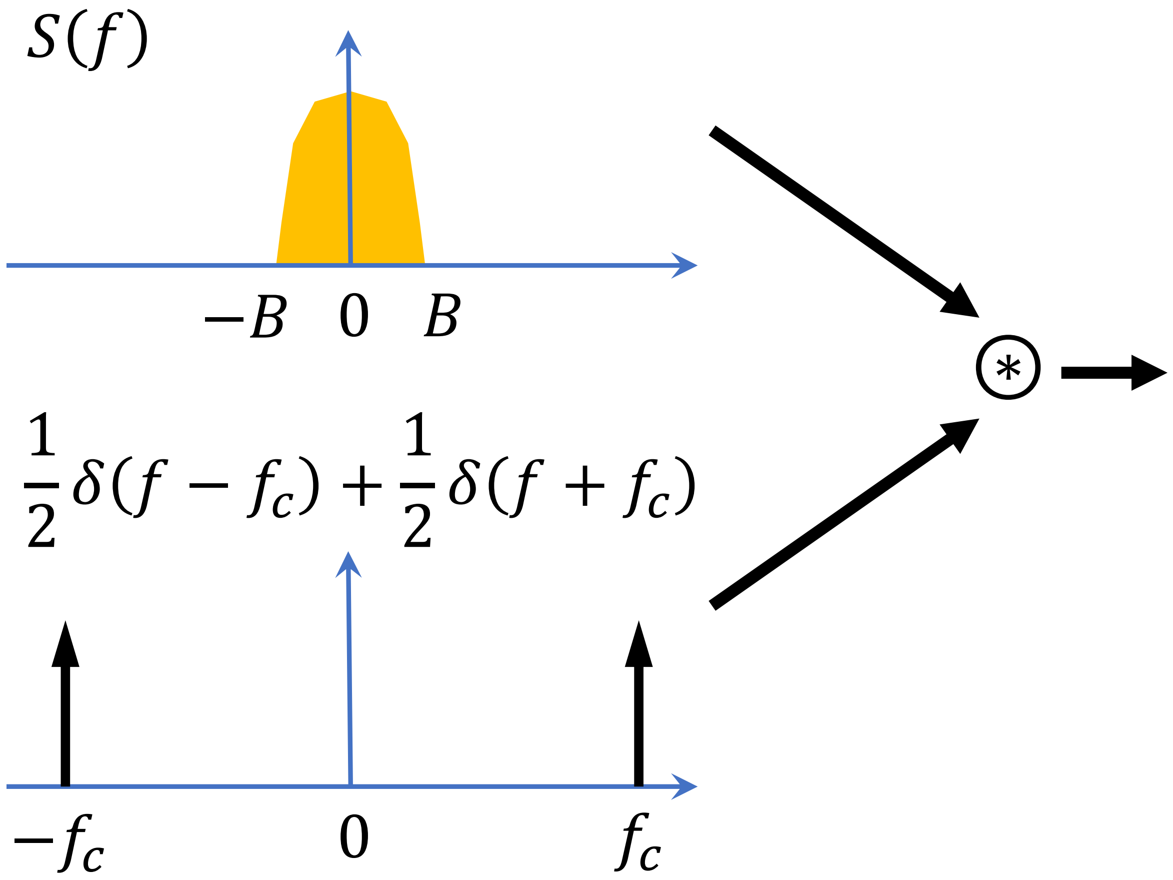
$s(t)$ is real ➔ $S(f)$ is symmetric around 0



# Up/Down Conversion

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



# Up/Down Conversion

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

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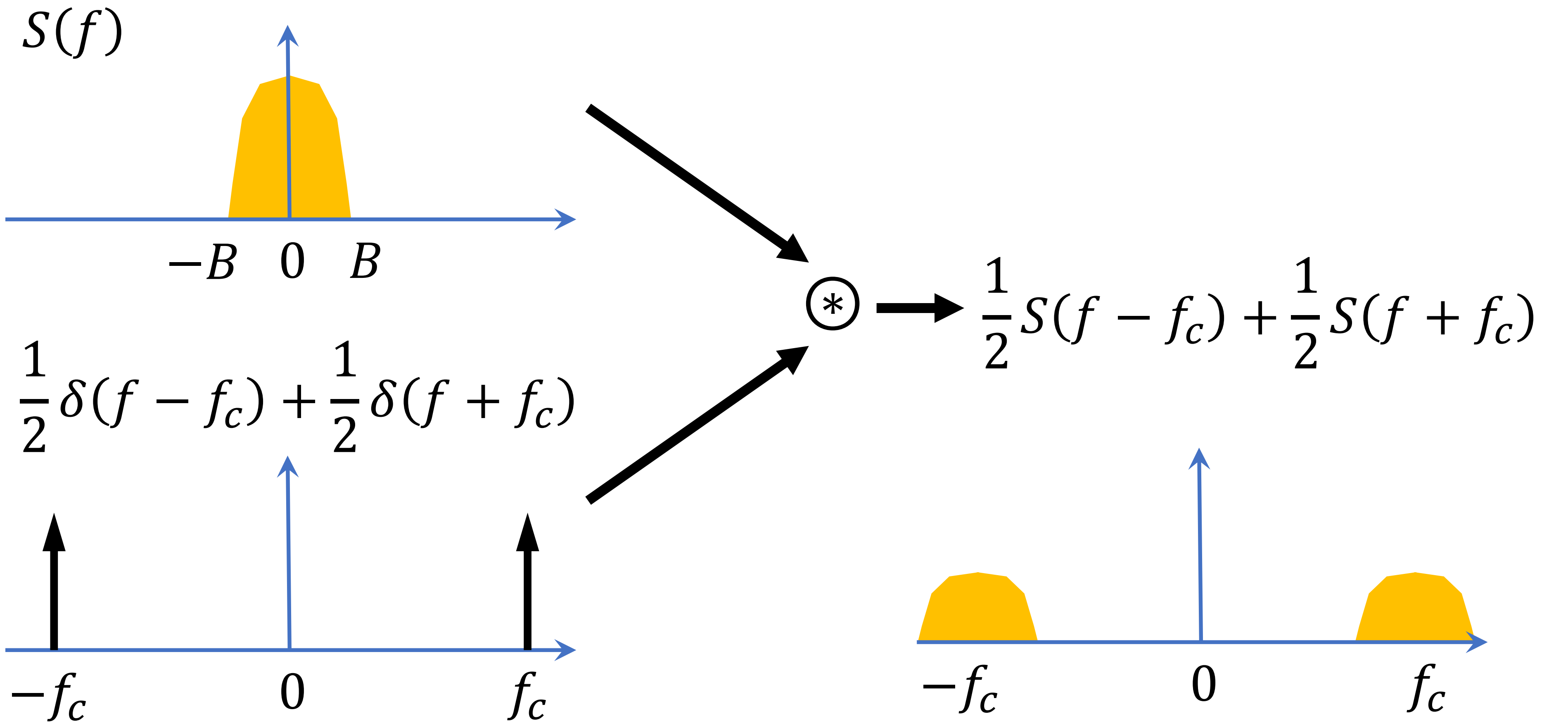
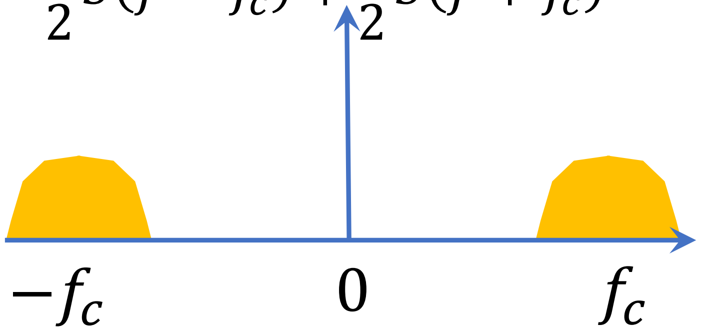


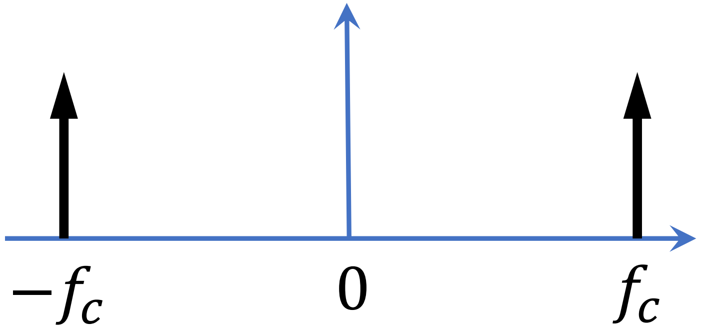
# Up/Down Conversion

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

$$\frac{1}{2}S(f-f_c)+\frac{1}{2}S(f+f_c)$$




$$\frac{1}{2}\delta(f-f_c)+\frac{1}{2}\delta(f+f_c)$$



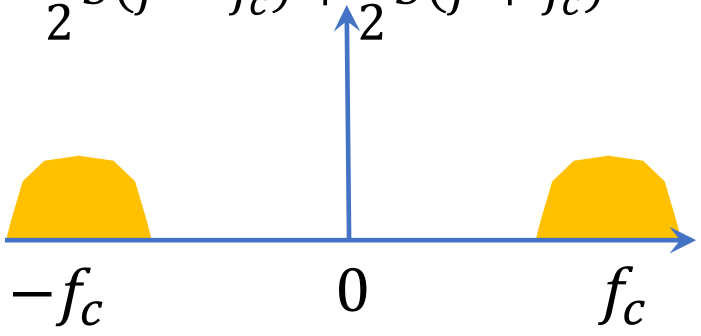

$$\circledast \rightarrow \frac{1}{4}S(f-2f_c)+\frac{1}{4}S(f)$$
$$+\frac{1}{4}S(f)+\frac{1}{4}S(f+2f_c)$$

# Up/Down Conversion

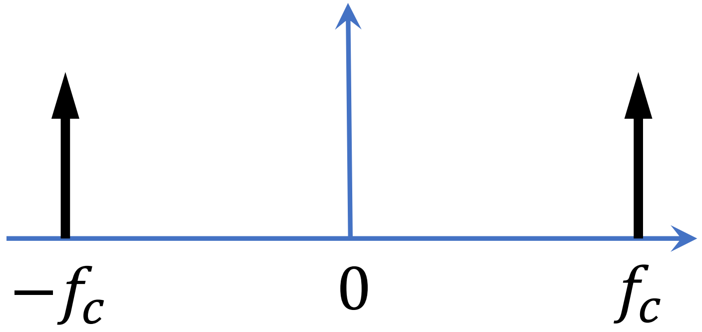
$$s(t) \longrightarrow \underset{\uparrow \atop \cos(2\pi f_c t)}{\times} \longrightarrow s(t)\cos(2\pi f_c t) \longrightarrow \underset{\uparrow \atop \cos(2\pi f_c t)}{\times} \longrightarrow s(t)\cos^2(2\pi f_c t)$$

---

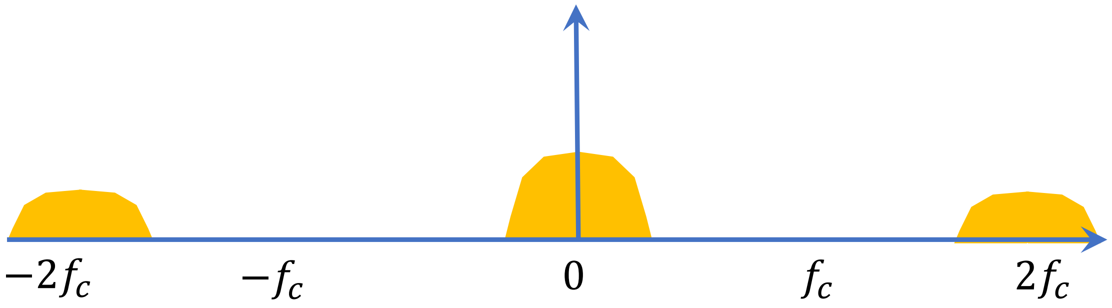
$$\frac{1}{2}S(f-f_c)+\frac{1}{2}S(f+f_c)$$




$$\frac{1}{2}\delta(f-f_c)+\frac{1}{2}\delta(f+f_c)$$



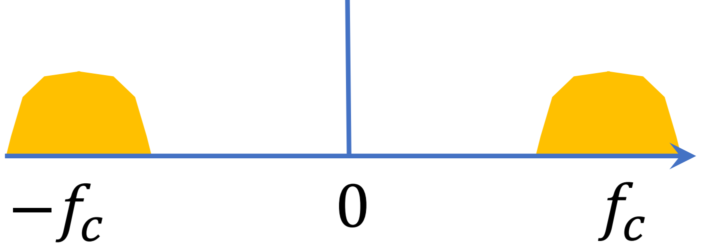

$$\circledast \longrightarrow \frac{1}{4}S(f-2f_c)+\frac{1}{4}S(f+2f_c)+\frac{1}{2}S(f)$$



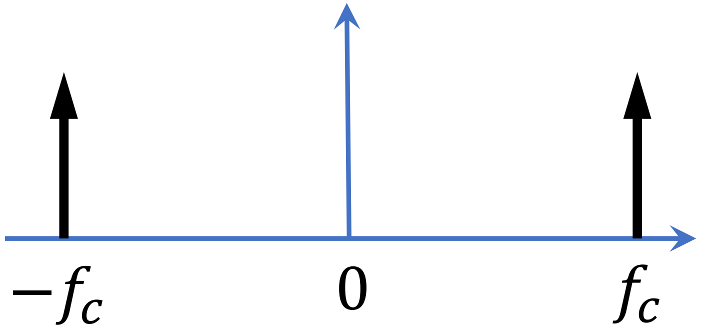
# Up/Down Conversion

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

$$\frac{1}{2}S(f-f_c)+\frac{1}{2}S(f+f_c)$$

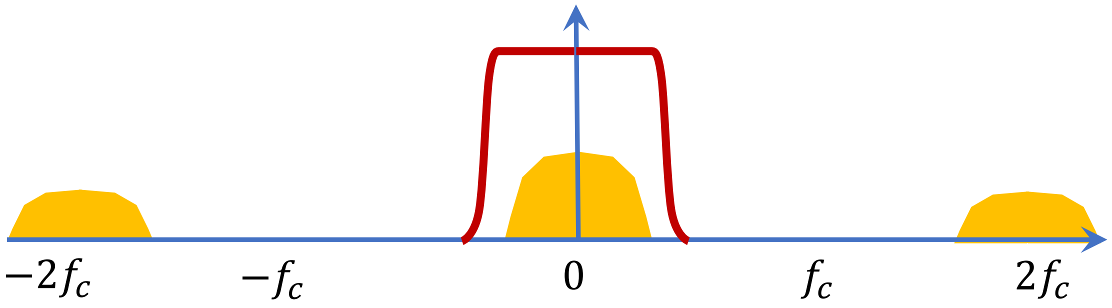



$$\frac{1}{2}\delta(f-f_c)+\frac{1}{2}\delta(f+f_c)$$




$$\circledast \rightarrow \cancel{\frac{1}{4}S(f-2f_c)+\frac{1}{4}S(f+2f_c)}+\frac{1}{2}S(f)$$

Low Pass Filter



# Up/Down Conversion

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

$$\uparrow \qquad\qquad\qquad\qquad\qquad \uparrow$$

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

---

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

# Up Conversion

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

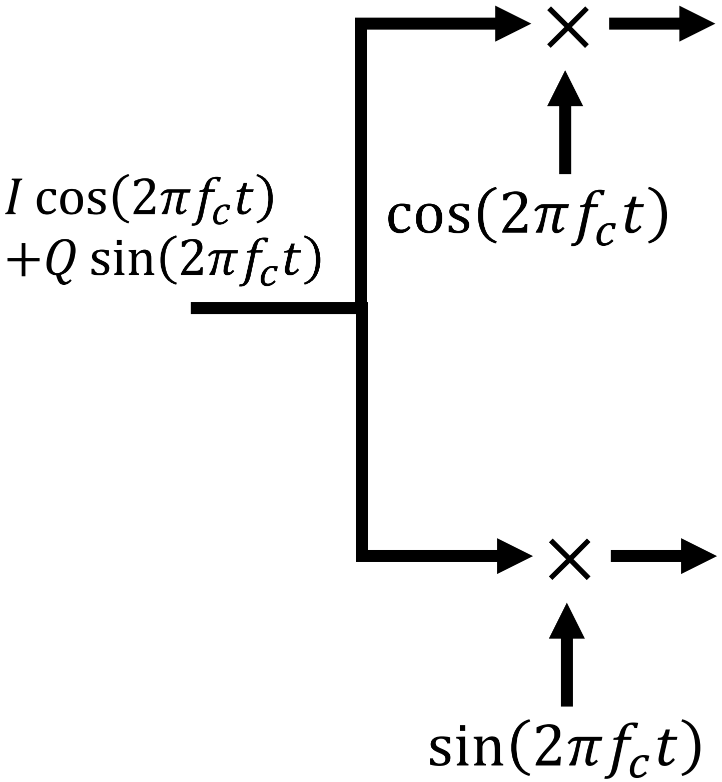
---

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

# Up Conversion

$$
\begin{tikzcd}
\mathfrak{Re}\{s(t)\} \arrow[r] & \times \arrow[r] & I\cos(2\pi f_c t) \arrow[dr] & & \\
& \cos(2\pi f_c t) \arrow[u] & & + \arrow[r] & \begin{array}{l} I\cos(2\pi f_c t) \\ +Q\sin(2\pi f_c t) \end{array} \\
\mathfrak{Im}\{s(t)\} \arrow[r] & \times \arrow[r] & Q\sin(2\pi f_c t) \arrow[ur] & & \\
& \sin(2\pi f_c t) \arrow[u] & & &
\end{tikzcd}
$$

# Down Conversion



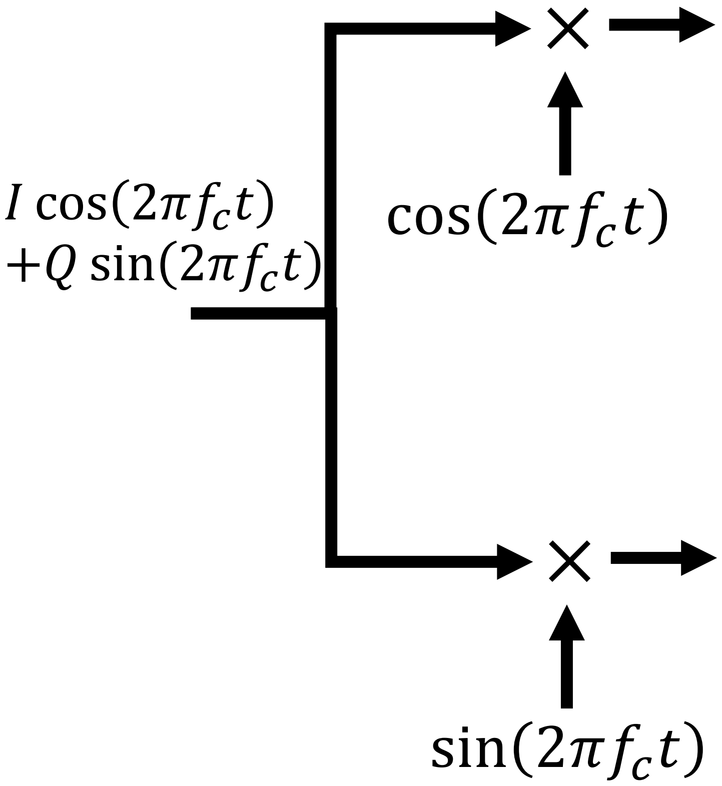

$$I\cos^2(2\pi f_c t) + Q\cos(2\pi f_c t)\sin(2\pi f_c t)$$

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

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

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

# Down Conversion




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

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

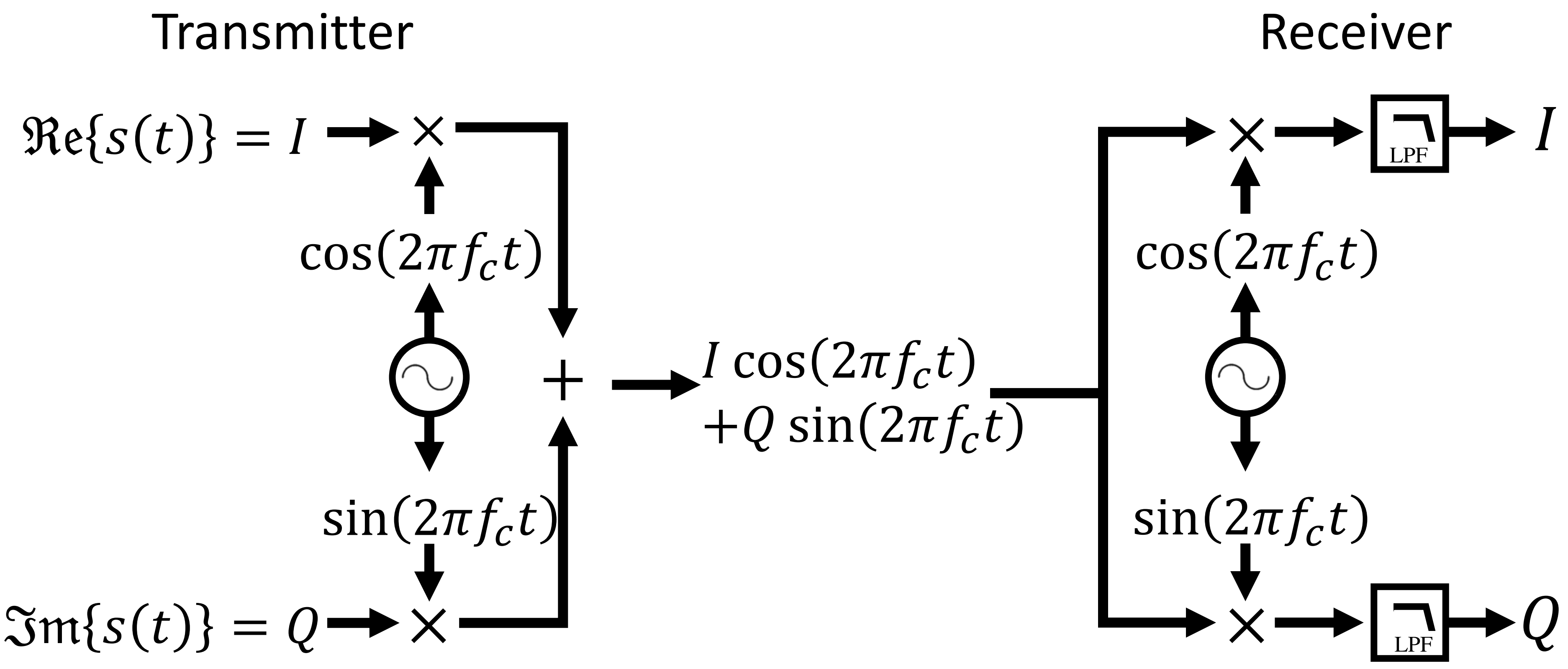
$$= \frac{1}{2}I$$

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

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

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

# Up/Down Conversion




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

$$= \frac{1}{2}s(t)e^{-j2\pi f_c t} + \frac{1}{2}s^*(t)e^{j2\pi f_c t} \rightarrow = \frac{1}{2}s(t) + \cancel{\frac{1}{2}s^*(t)e^{j2\pi 2 f_c t}}$$

Low Pass Filter

# Up/Down Conversion

Transmitter

Receiver

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

$$= \frac{1}{2}s(t)e^{-j2\pi f_c t} + \frac{1}{2}s^*(t)e^{j2\pi f_c t} \rightarrow = \frac{1}{2}s(t) + \cancel{\frac{1}{2}s^*(t)e^{j2\pi 2 f_c t}}$$

Low Pass Filter

# Up/Down Conversion

**Transmitter** | **Receiver**

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

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Low Pass Filter

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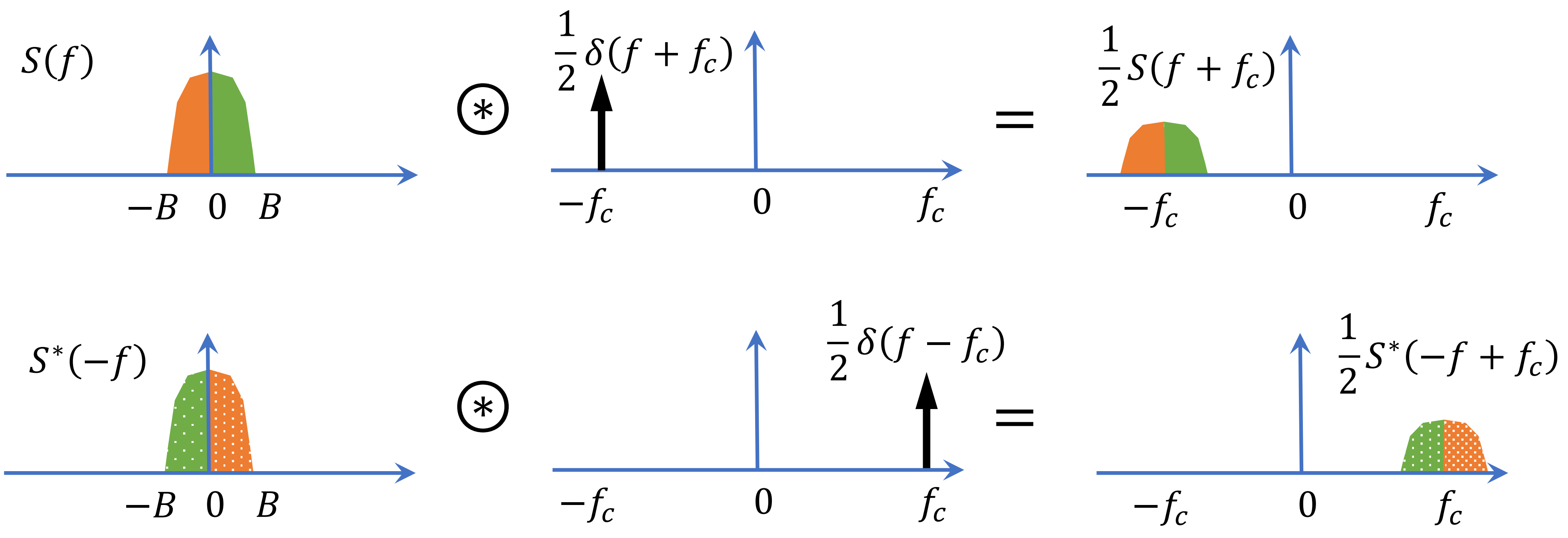

# Up/Down Conversion

**Transmitter** | **Receiver**

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

$$= \frac{1}{2}s(t)e^{-j2\pi f_c t} + \frac{1}{2}s^*(t)e^{j2\pi f_c t} \rightarrow = \frac{1}{2}s(t) + \cancel{\frac{1}{2}s^*(t)e^{j2\pi 2 f_c t}}$$

Low Pass Filter

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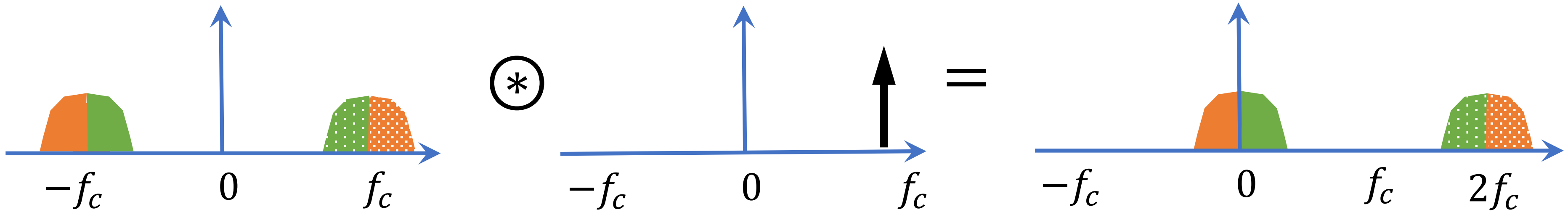
$$\frac{1}{2}S(f+f_c) + \frac{1}{2}S^*(-f+f_c) \qquad \delta(f-f_c) \qquad \frac{1}{2}S(f) + \frac{1}{2}S^*(-f+2f_c)$$



# Up/Down Conversion

**Transmitter** | **Receiver**

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

$$= \frac{1}{2}s(t)e^{-j2\pi f_c t} + \frac{1}{2}s^*(t)e^{j2\pi f_c t} \rightarrow = \frac{1}{2}s(t) + \cancel{\frac{1}{2}s^*(t)e^{j2\pi 2f_c t}}$$

Low Pass Filter

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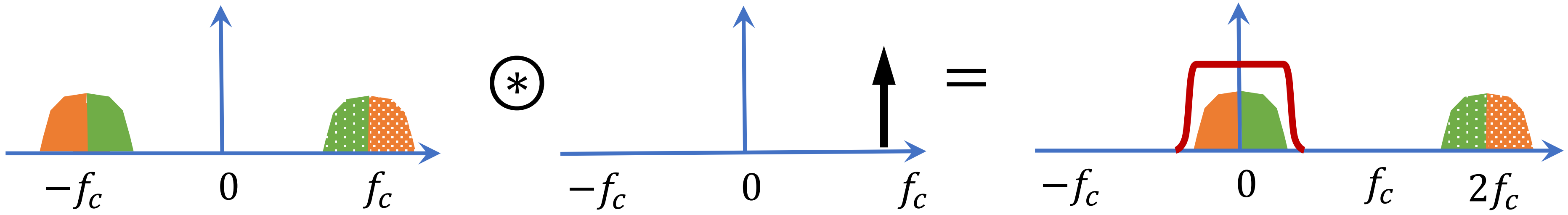
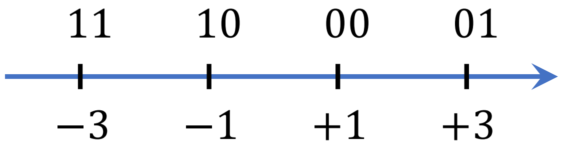
$$\frac{1}{2}S(f+f_c) + \frac{1}{2}S^*(-f+f_c) \qquad \delta(f-f_c) \qquad \frac{1}{2}S(f) + \cancel{\frac{1}{2}S^*(-f+2f_c)}$$

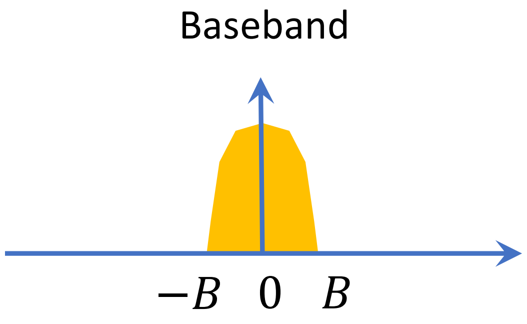
Low Pass Filter

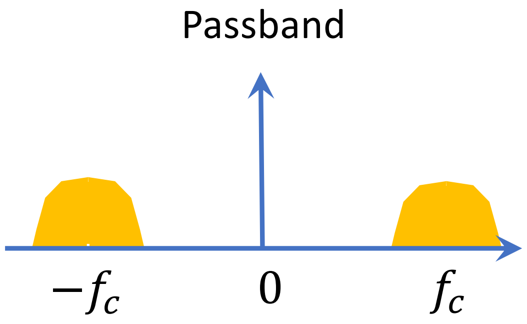


# Up/Down Conversion

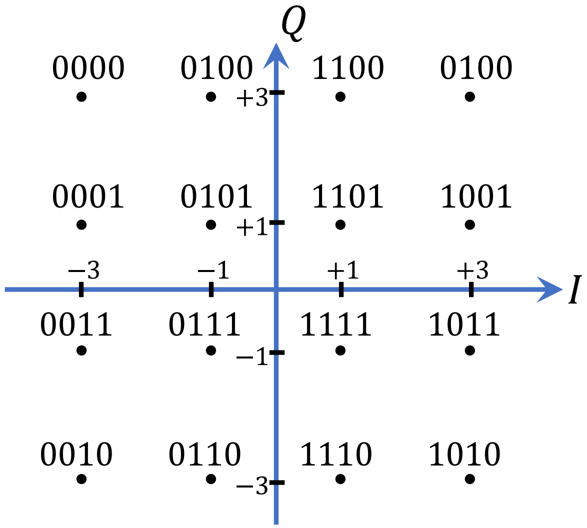
## Sends $B$ real symbols/sec with $k$ bits/symbol

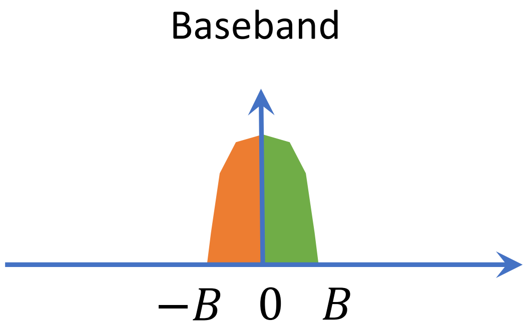


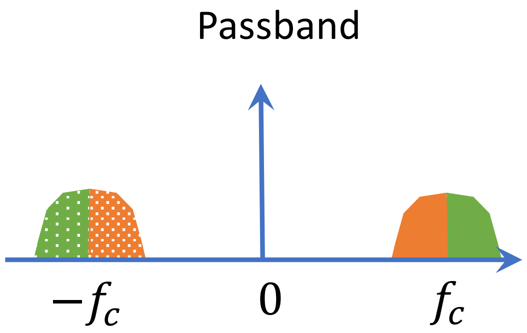




## Sends $B$ complex symbols/sec with $2k$ bit/symbol

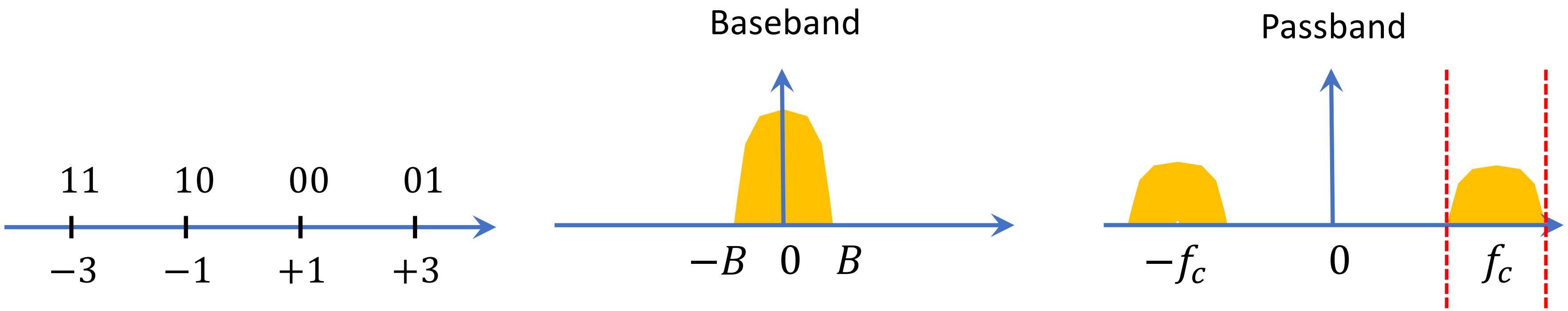


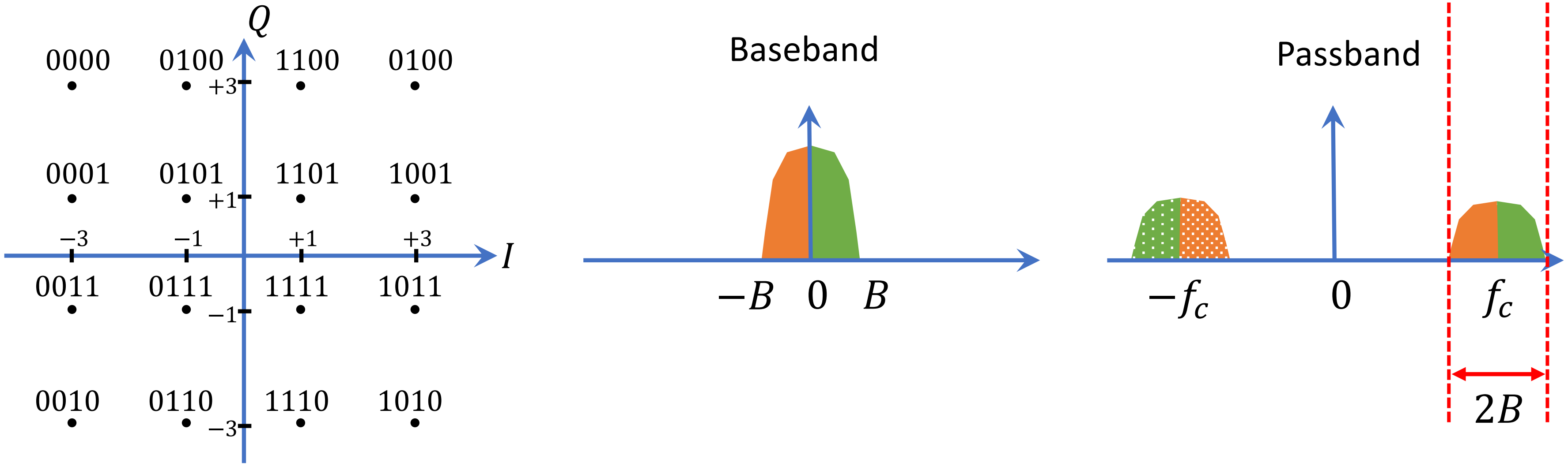



# Up/Down Conversion

## PAM: Sends $B$ real symbols/sec with $k$ bits/symbol




## QAM: Sends $B$ complex symbols/sec with $2k$ bit/symbol



# Up/Down Conversion

PAM: Sends $B$ real symbols/sec with $k$ bits/symbol

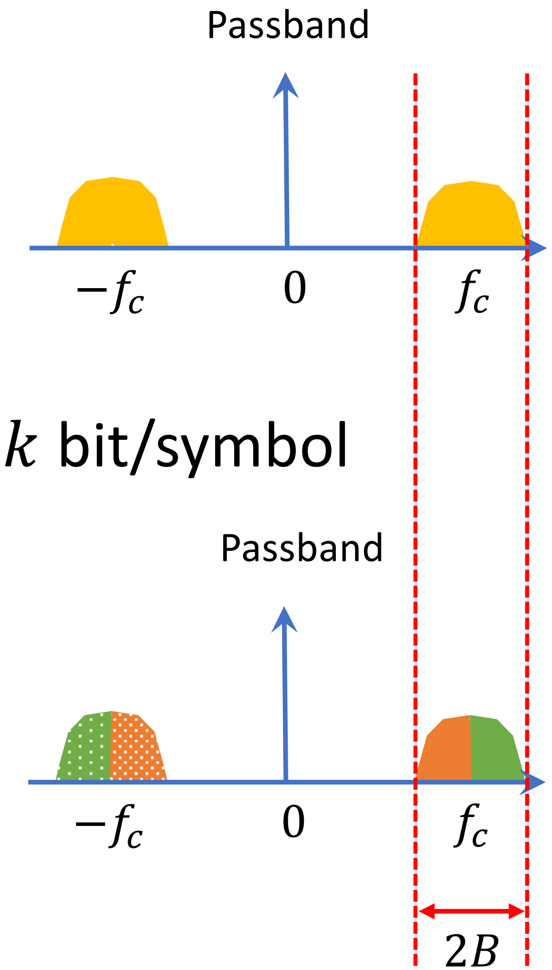
Spectral Efficiency:

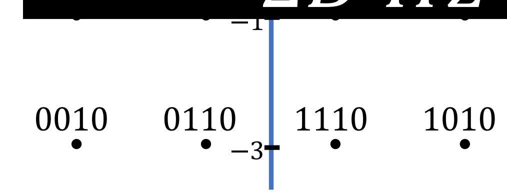
$$\frac{B \times k \text{ bits/sec}}{2B\ Hz} = \frac{k}{2} \text{ bits/Hz}$$

QAM: Sends $B$ complex symbols/sec with $2k$ bit/symbol

Spectral Efficiency:

$$\frac{B \times 2k \text{ bits/sec}}{2B\ Hz} = k \text{ bits/Hz}$$



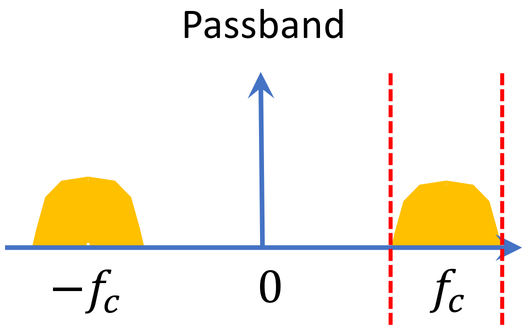



# Up/Down Conversion

Sends $B$ real symbols/sec with $k$ bits/symbol

**Spectral Efficiency:**

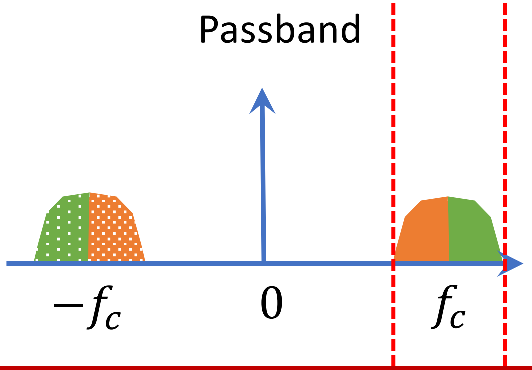
$$\frac{B \times k \text{ bits/sec}}{2B\ Hz} = \frac{k}{2} \text{ bits/Hz}$$




Sends $B$ complex symbols/sec with $2k$ bit/symbol

**Spectral Efficiency:**

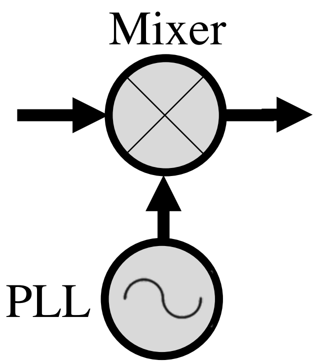
$$\frac{B \times 2k \text{ bits/sec}}{2B\ Hz} = k \text{ bits/Hz}$$



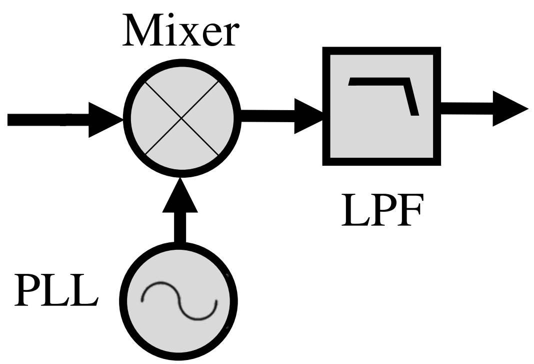

Complex Modulation → More efficient use of the same bandwidth

# Up/Down Conversion

## Transmitter Up-conversion

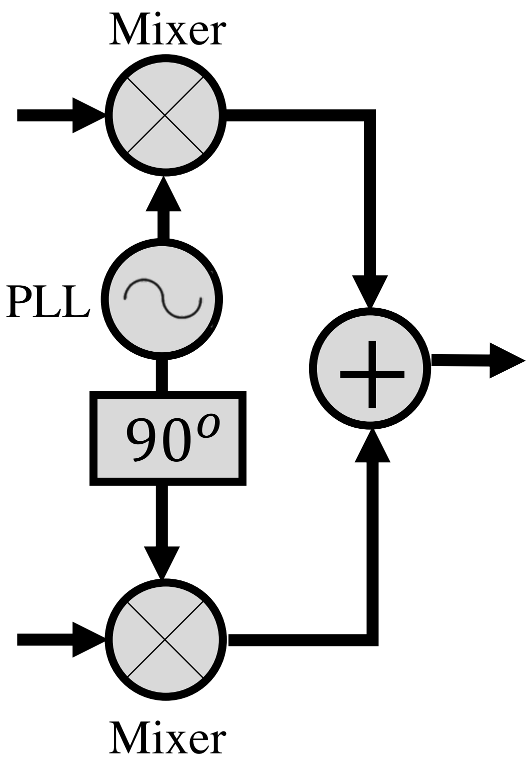



## Receiver Down-conversion

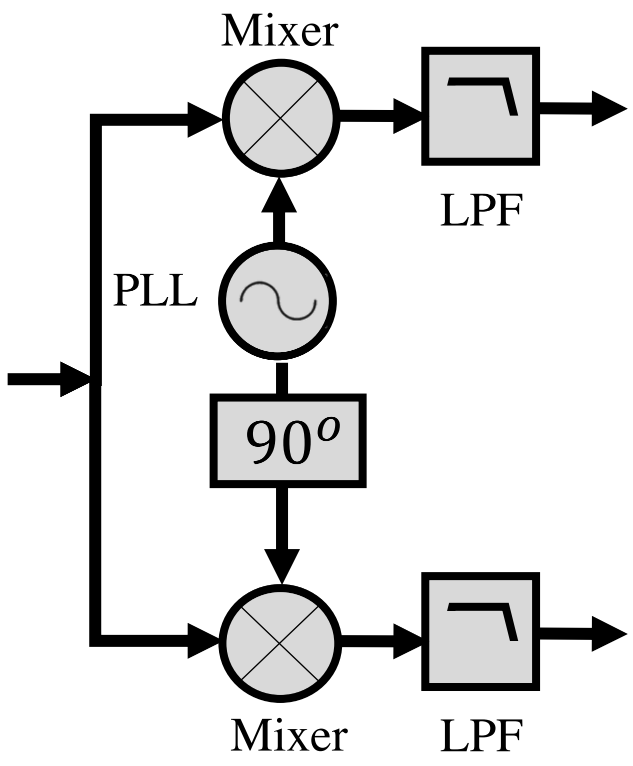


# Up/Down Conversion

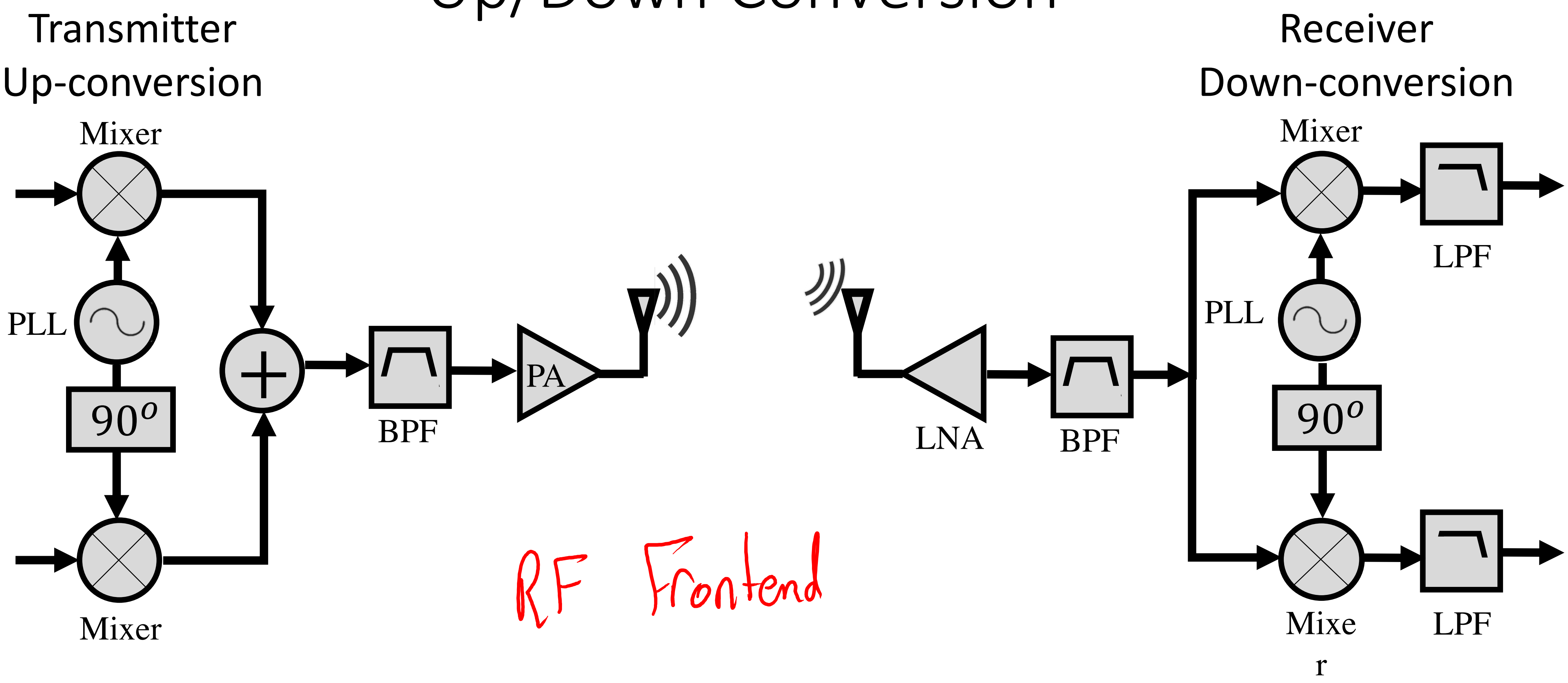
## Transmitter
## Up-conversion



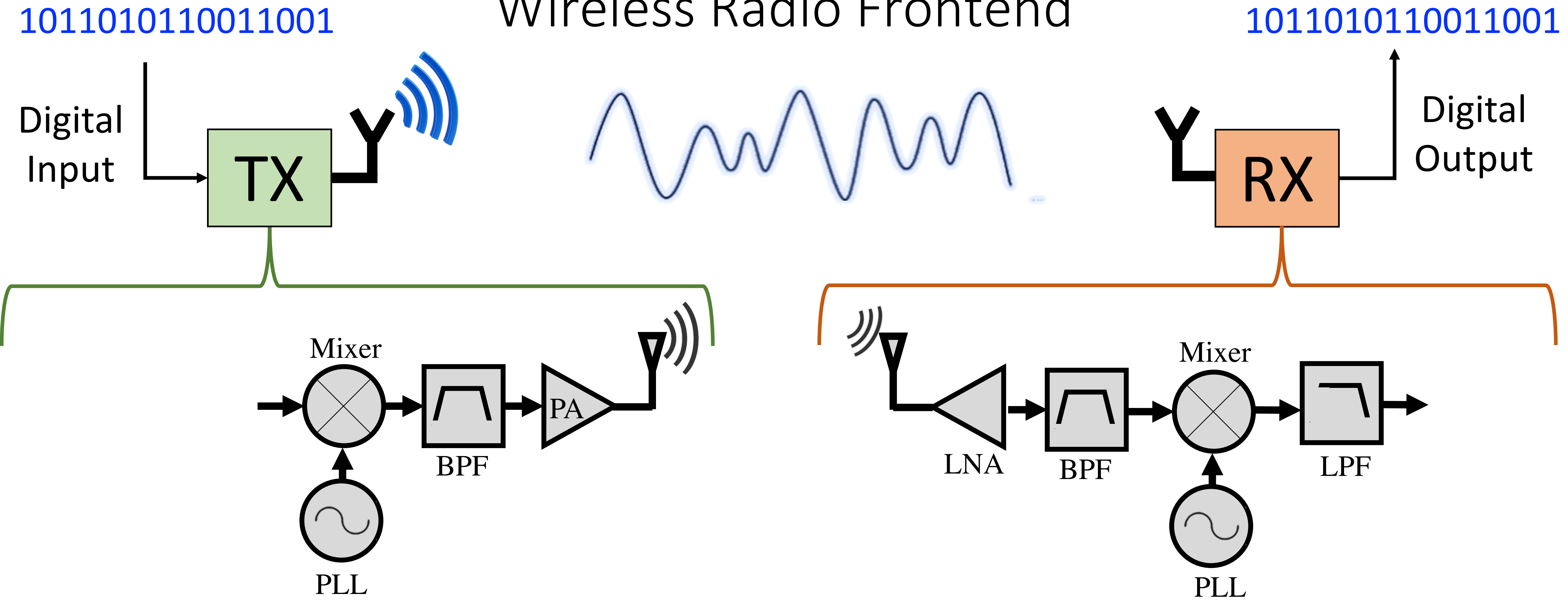

## Receiver
## Down-conversion



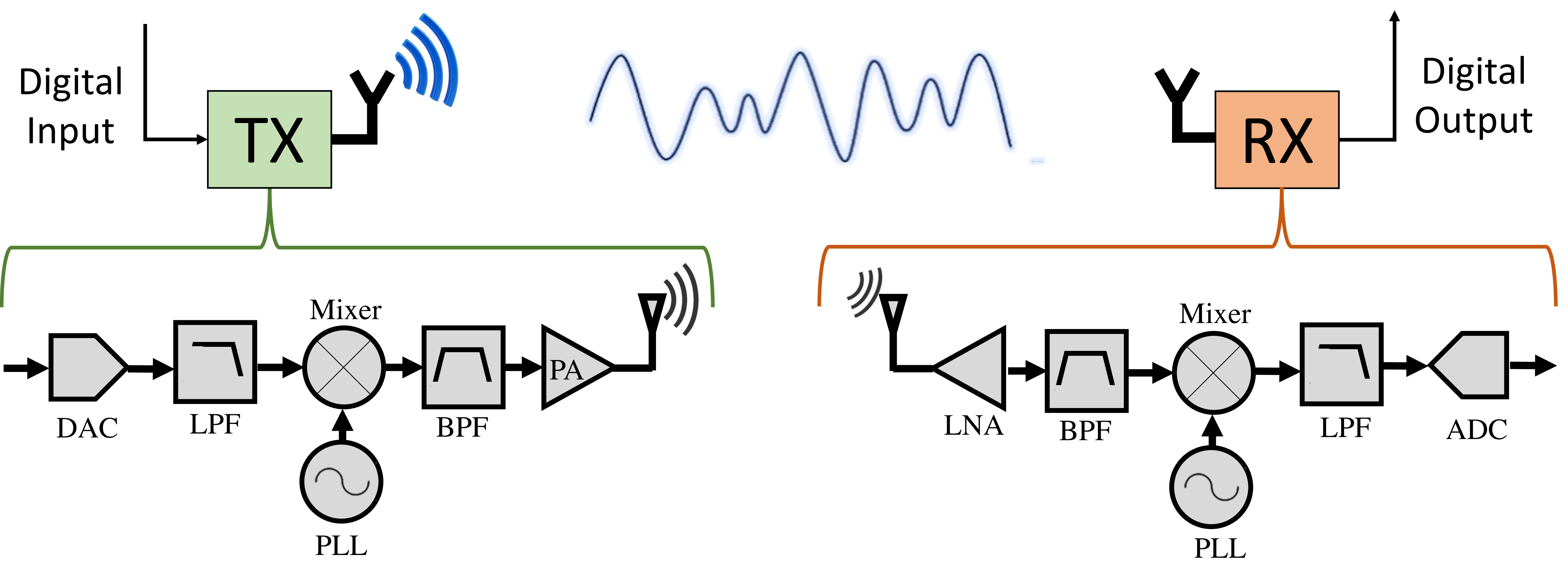
# Up/Down Conversion



# Wireless Radio Frontend



# Wireless Radio Frontend




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

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