ECE 463: Digital Communications Lab.

Lecture 2: Up/Down Conversion & SDRs

Haitham Hassanieh

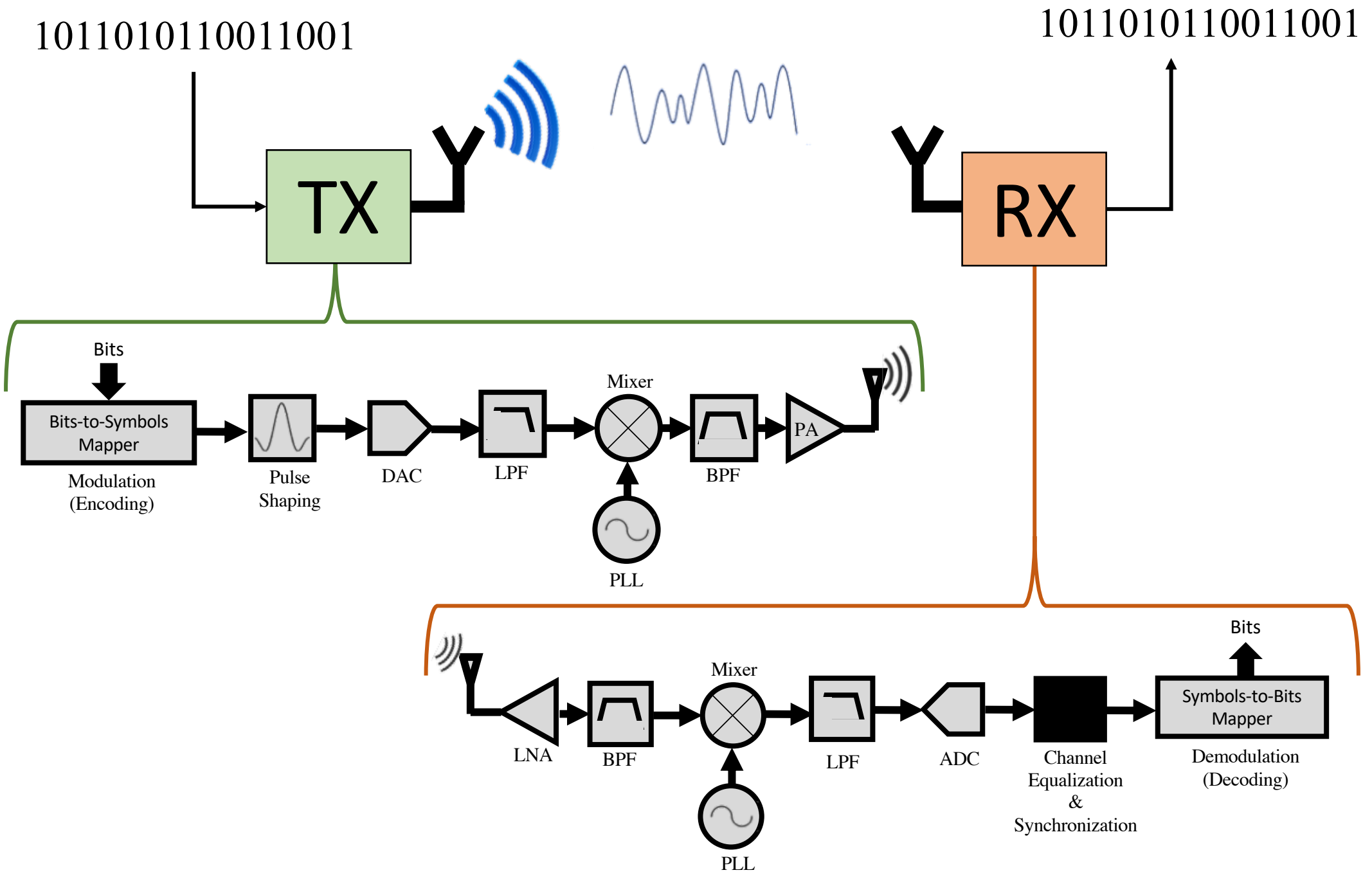
Previous Lecture:

- ✓ Intro to digital communications
- ✓ Analog vs. Digital Communications
- ✓ TX/RX system Components
- ✓ Course Logistics

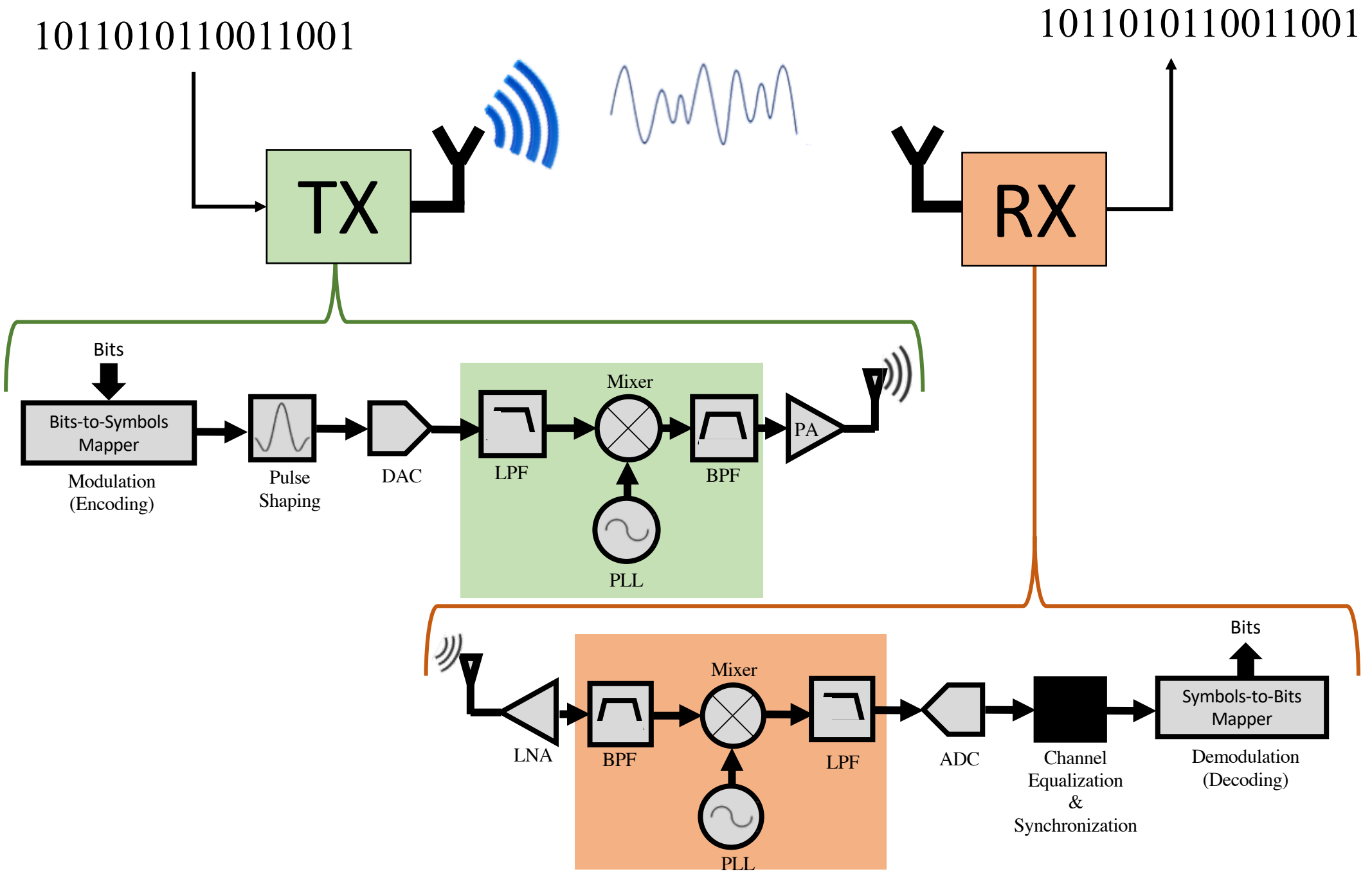
This Lecture:

- ❑ Up Conversion & Down Conversion
- ❑ Software Defined Radios

Digital Communication System

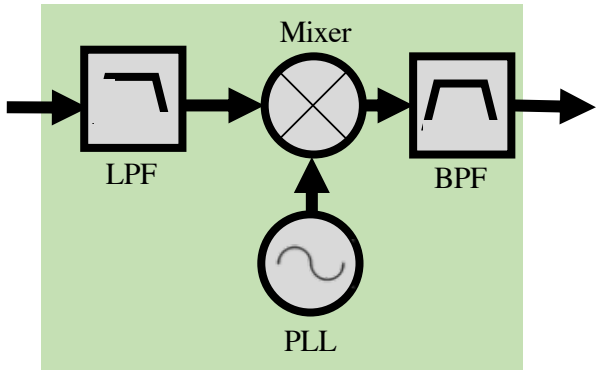


Digital Communication System

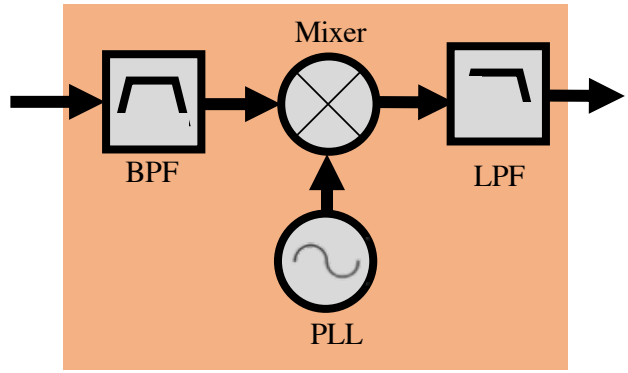


Up/Down Conversion

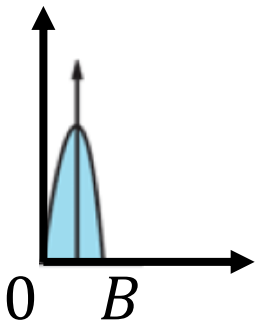
Transmitter
Up-conversion



Receiver
Down-conversion



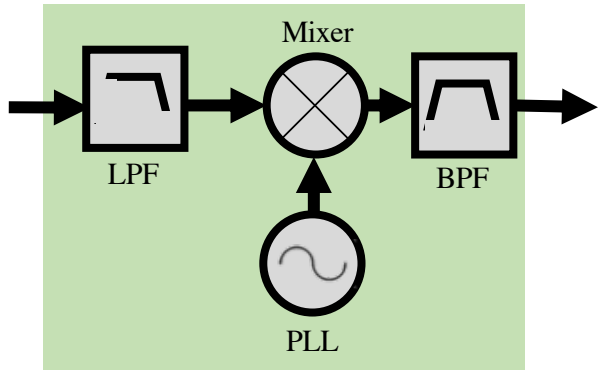
Baseband



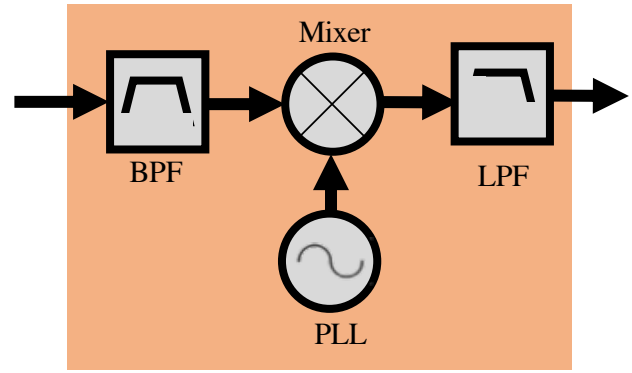
Passband

Up/Down Conversion

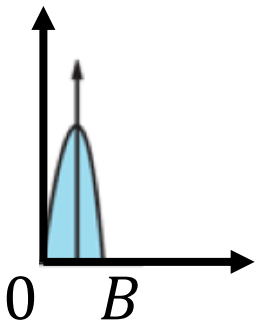
Transmitter
Up-conversion



Receiver
Down-conversion

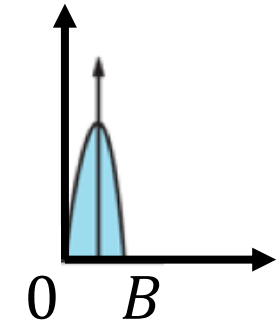


Baseband



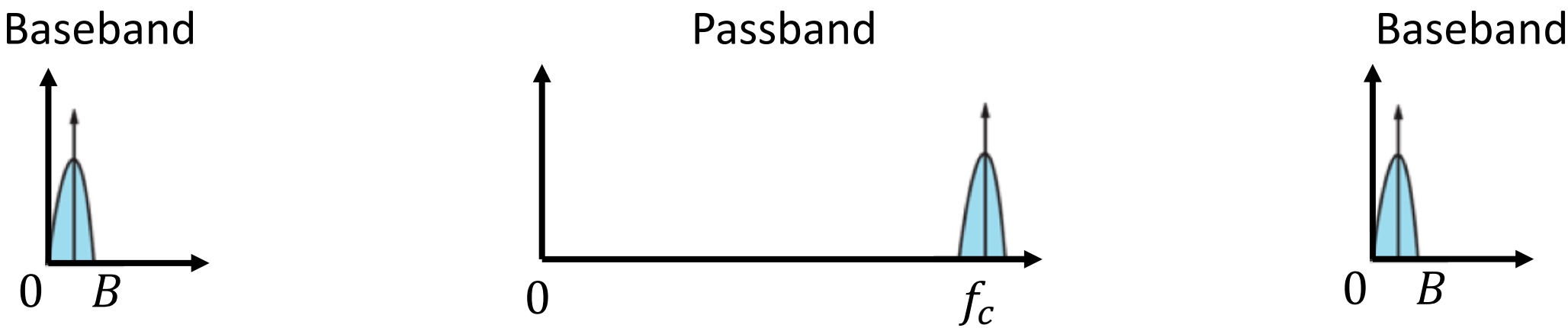
Passband

Baseband



Why do we need to up/down conversion?

Up/Down Conversion



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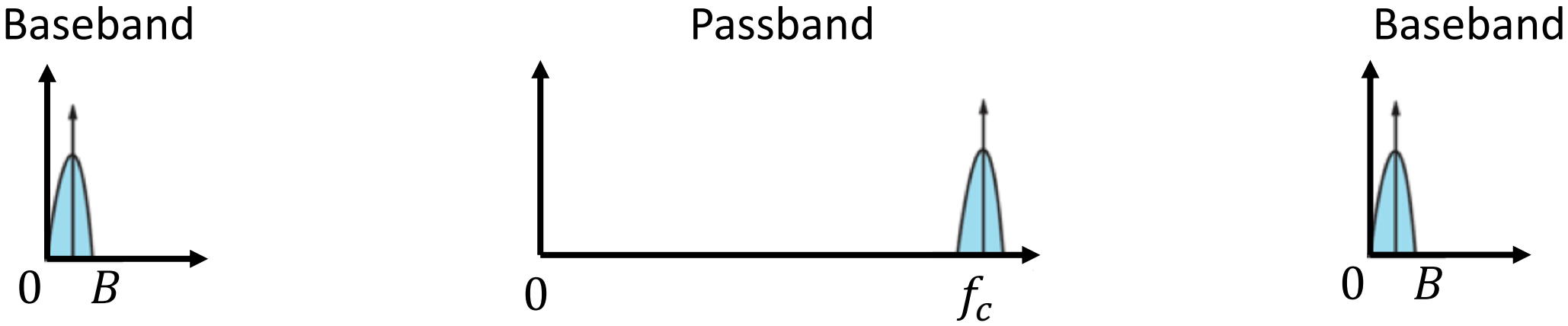
Up/Down Conversion



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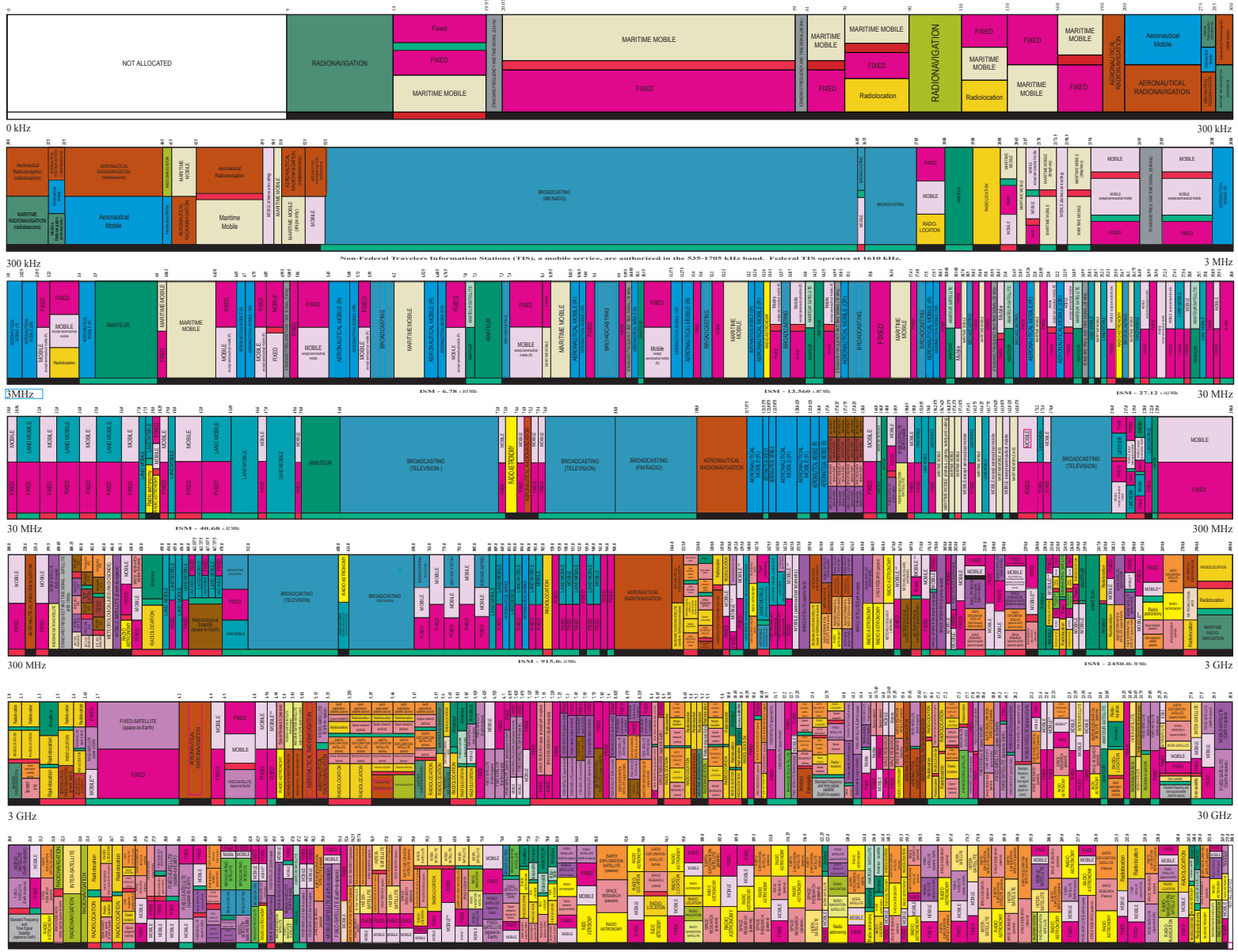
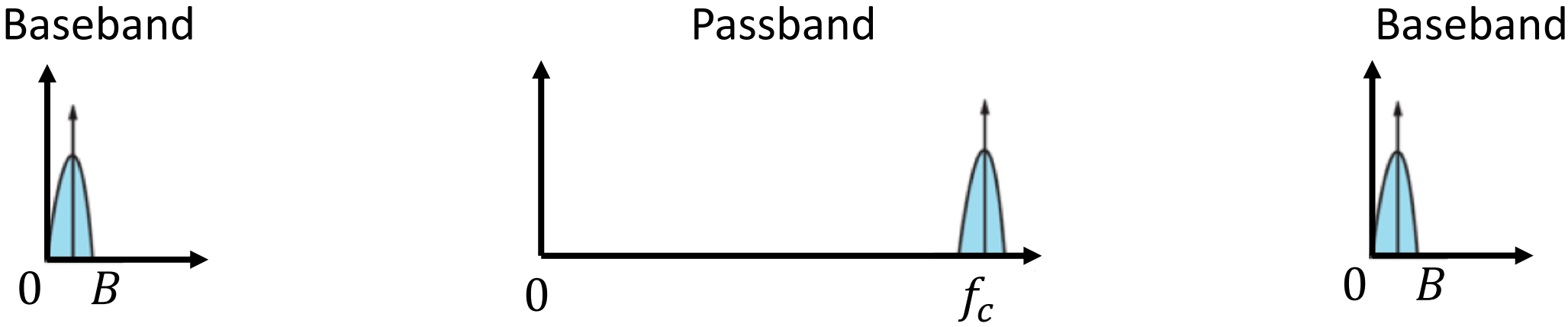


* EXCEPT AERONAUTICAL MOBILE (R)

** EXCEPT AERONAUTICAL MOBILE

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?

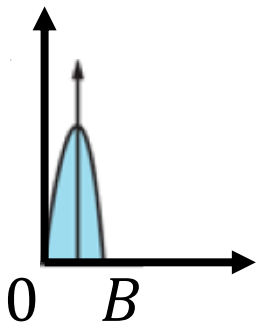
- Why not transmit everything at lower frequencies?
  - **Not enough bandwidth:**
    - Data rate ∝ bandwidth
    - Different Technologies
  - **Antenna size ∝ wavelength**
- Why not transmit & receive directly at high frequency?

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

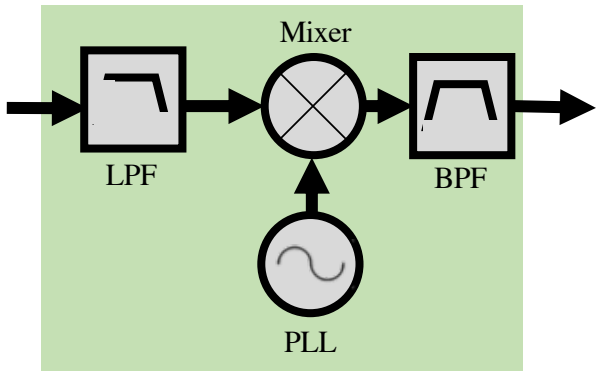
Passband

➡ Sample at $2f_c + 2B$

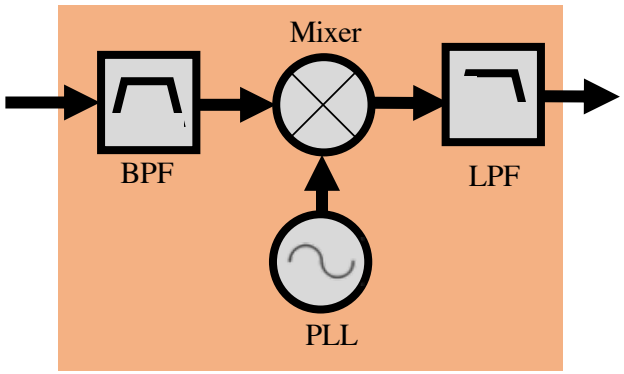
e.g. WiFi 802.11b ≈ 5 GS/s

Up/Down Conversion

Transmitter
Up-conversion



Receiver
Down-conversion



How to we do up/down conversion?

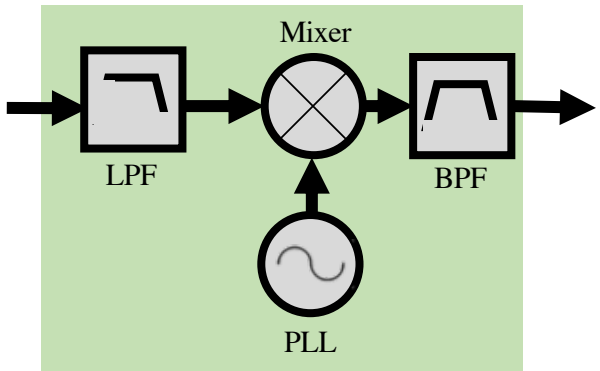
$$s(t) \longrightarrow \times \longrightarrow s(t)\cos(2\pi f_c t) \longrightarrow \times \longrightarrow s(t)\cos^2(2\pi f_c t)$$

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

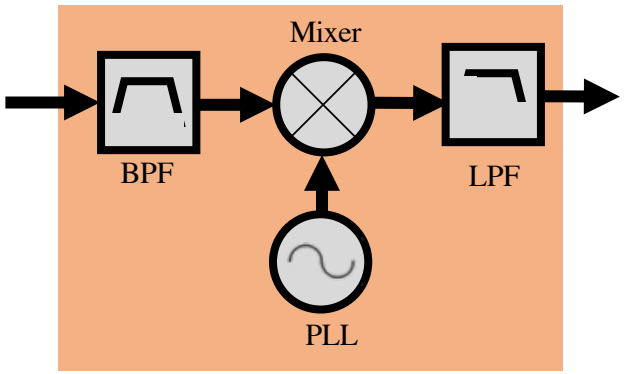
$$s(t)\cos^2(2\pi f_c t) = s(t)\left(\frac{1}{2} + \frac{1}{2}\cos(2\pi\, 2f_c\, t)\right)$$

Up/Down Conversion

Transmitter
Up-conversion



Receiver
Down-conversion



How to we do up/down conversion?

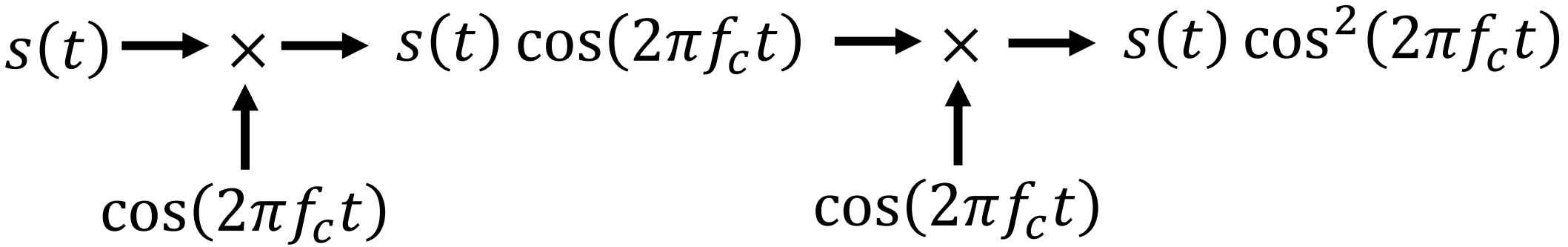
$$s(t) \longrightarrow \times \longrightarrow s(t)\cos(2\pi f_c t) \longrightarrow \times \longrightarrow s(t)\cos^2(2\pi f_c t)$$

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

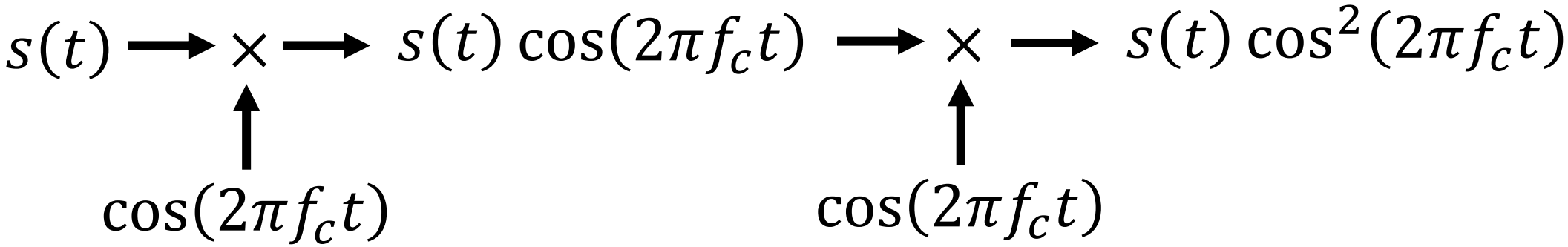
$$s(t)\cos^2(2\pi f_c t) = s(t)\left(\frac{1}{2} + \frac{1}{2}\cos(2\pi \cdot 2 f_c t)\right) = \frac{1}{2}s(t)$$

Low Pass Filter

Up/Down Conversion

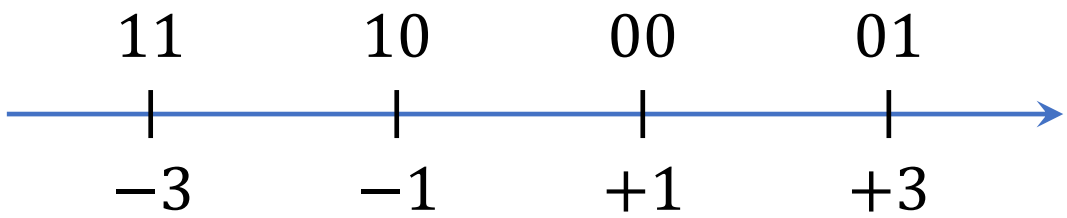


Up/Down Conversion

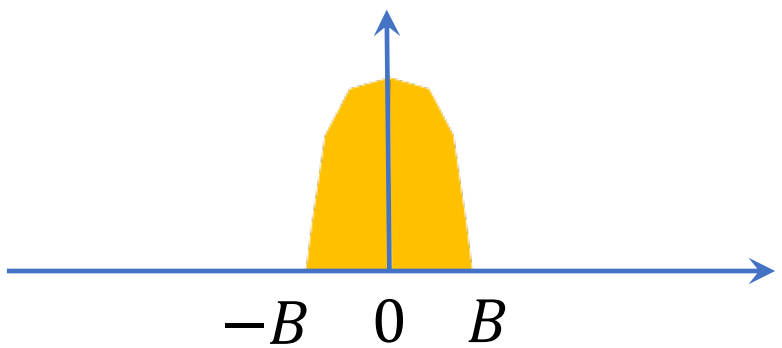


Consider using PAM: Pulse Amplitude Modulation

4 PAM:
2 bits/symbol



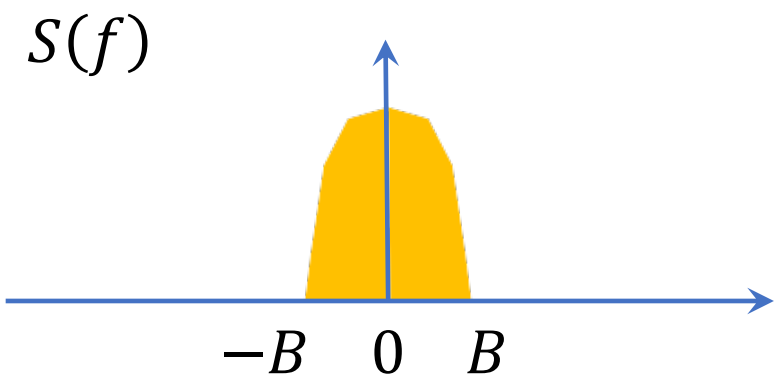
$s(t)$ is real ➔ $S(f)$ is symmetric around 0



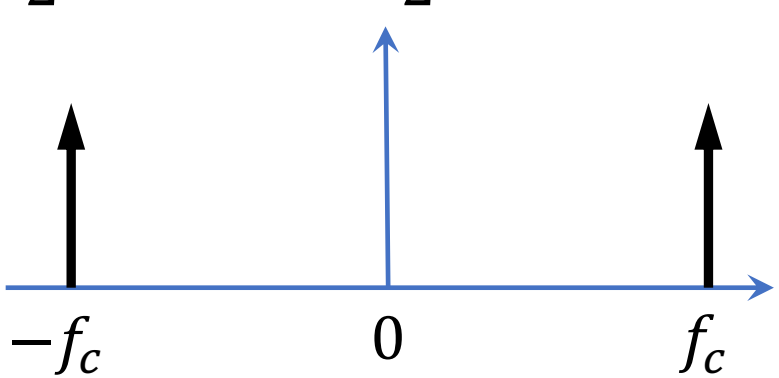
Up/Down Conversion

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

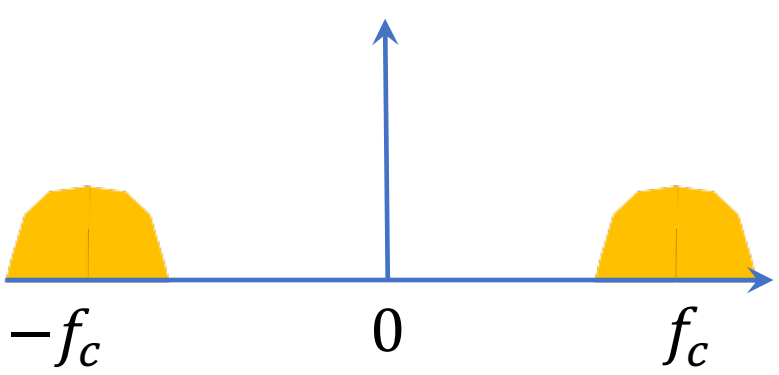
$\cos(2\pi f_c t)$ $\qquad$ $\cos(2\pi f_c t)$



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



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

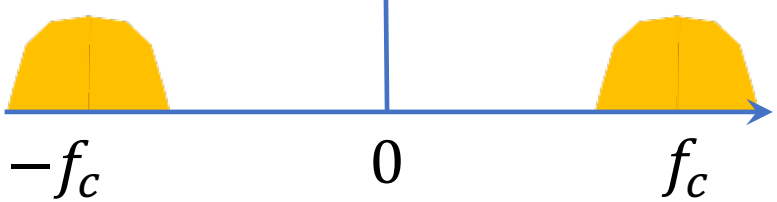


Up/Down Conversion

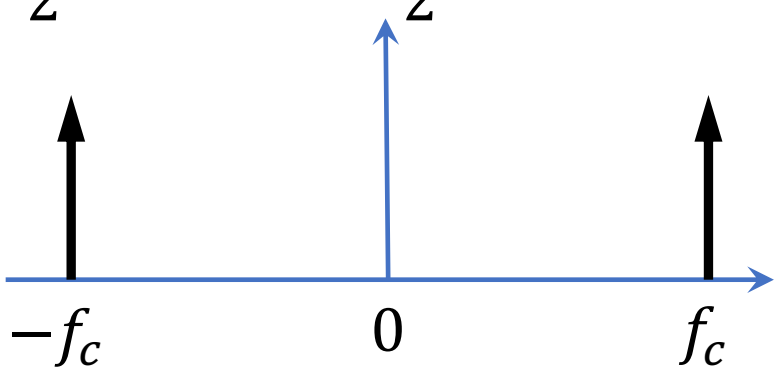
$s(t) \rightarrow \times \rightarrow s(t)\cos(2\pi f_c t) \rightarrow \times \rightarrow s(t)\cos^2(2\pi f_c t)$

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

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



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



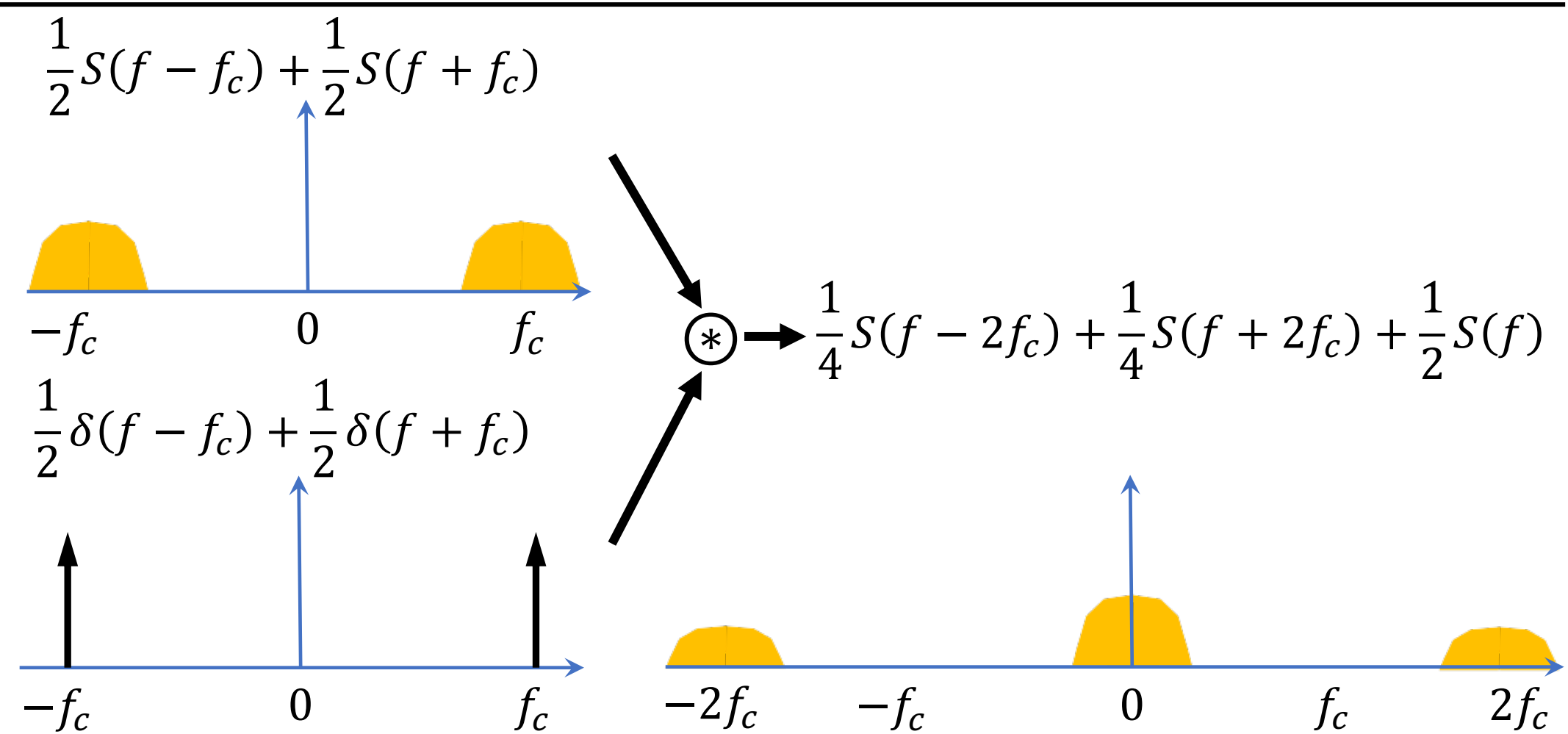
$\circledast \rightarrow \frac{1}{4}S(f-2f_c)+\frac{1}{4}S(f)$

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

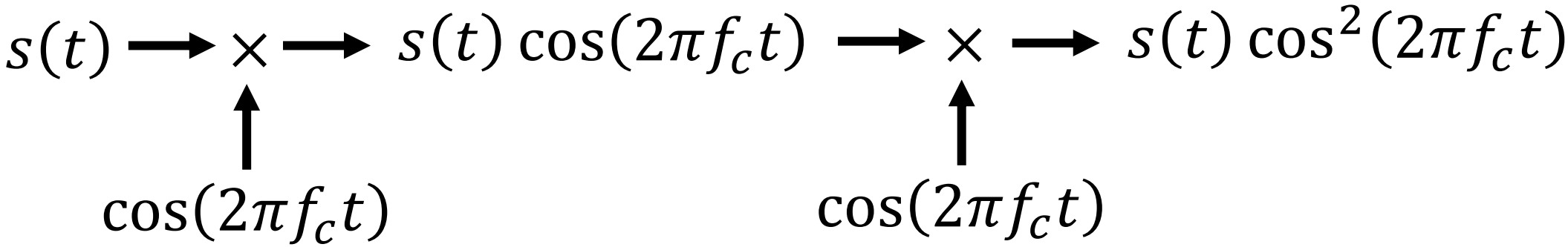
Up/Down Conversion

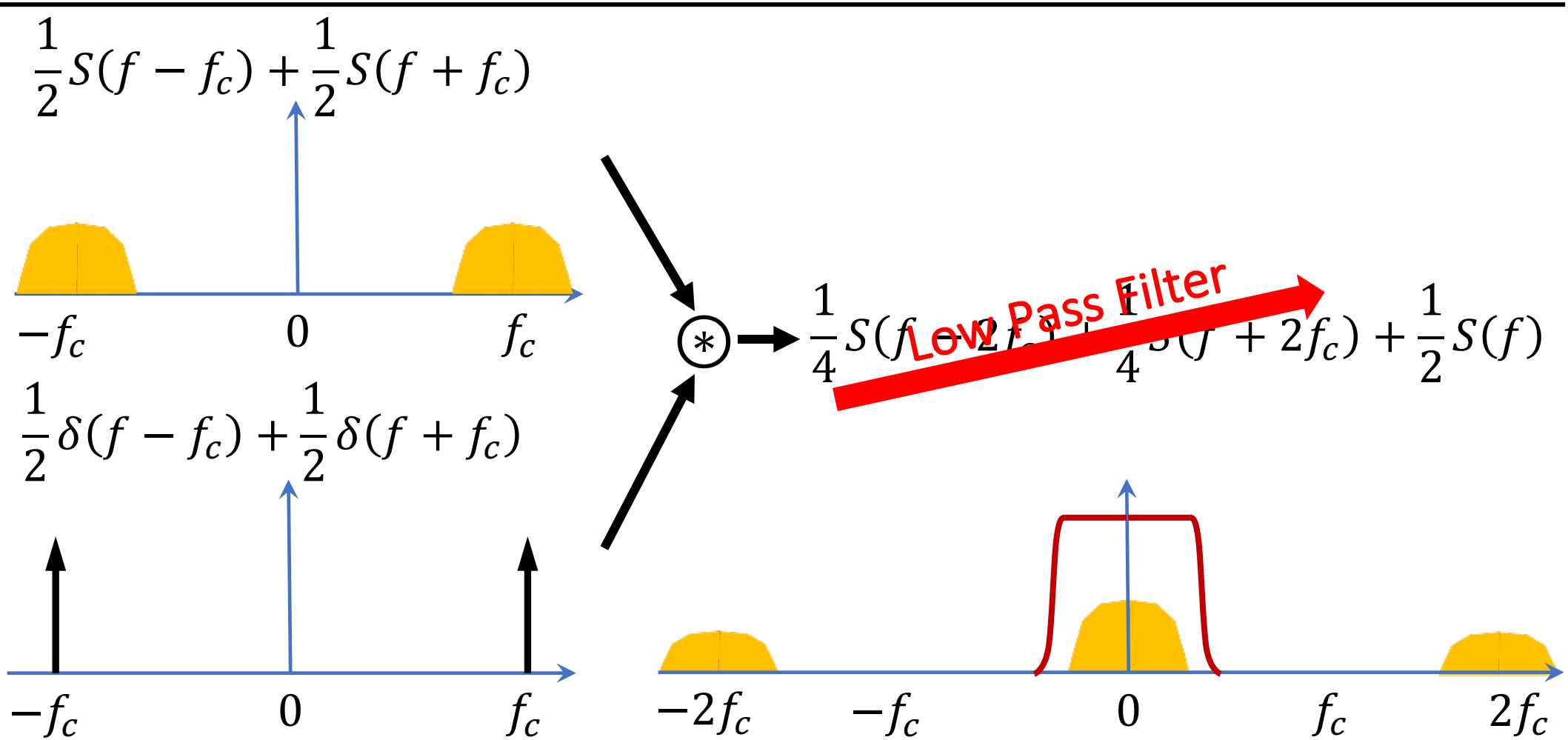
$s(t) \rightarrow \times \rightarrow s(t)\cos(2\pi f_c t) \rightarrow \times \rightarrow s(t)\cos^2(2\pi f_c t)$

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



Up/Down Conversion





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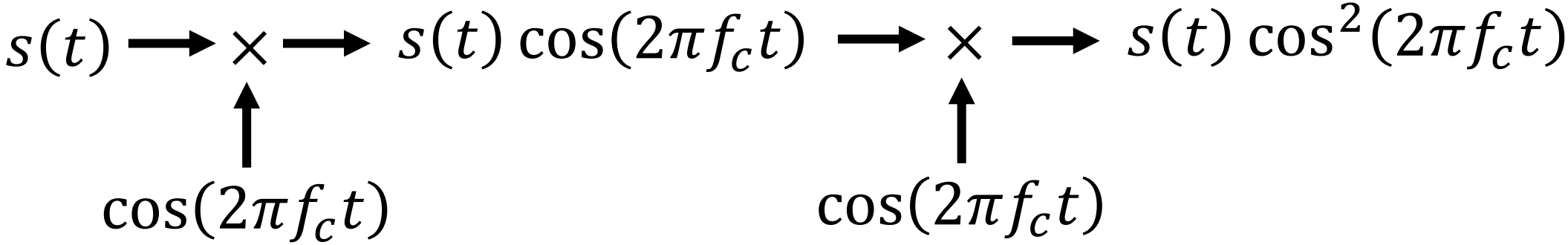
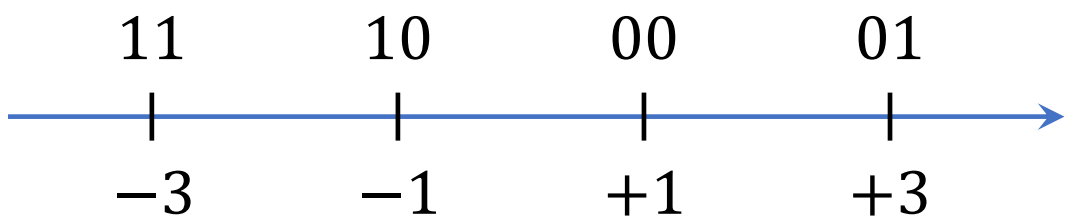


Consider using QAM:Quadrature Amplitude Modulation



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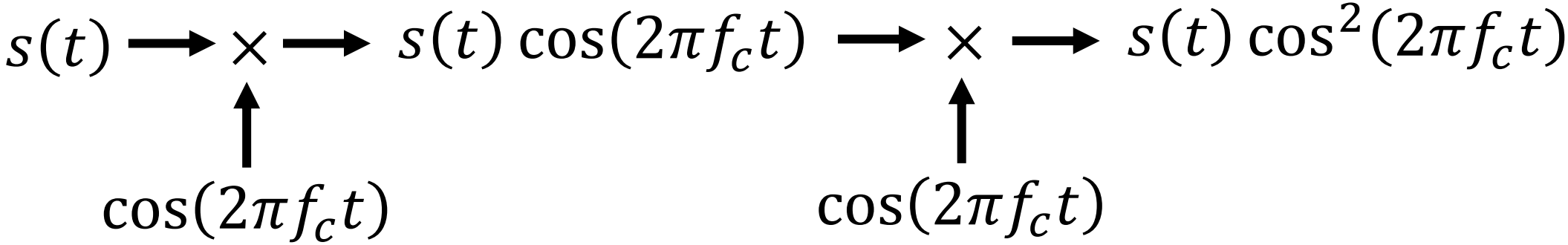

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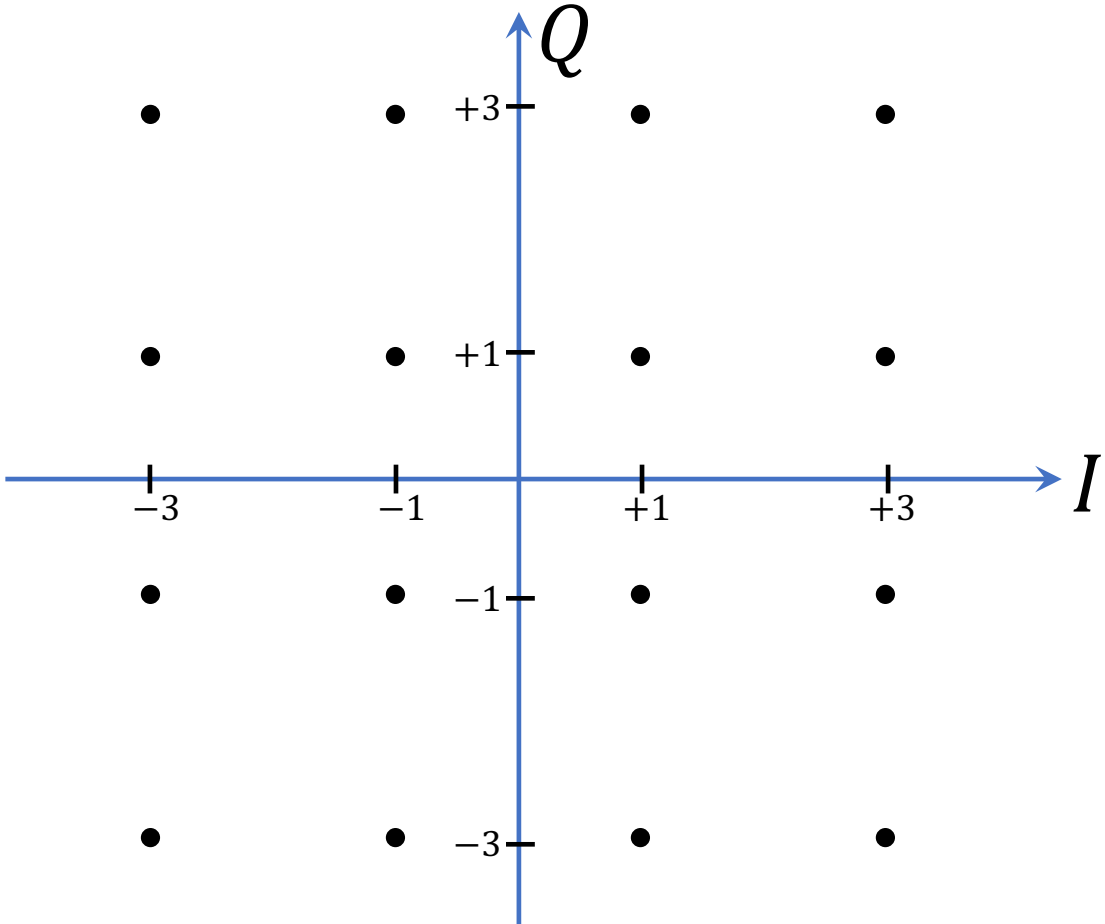


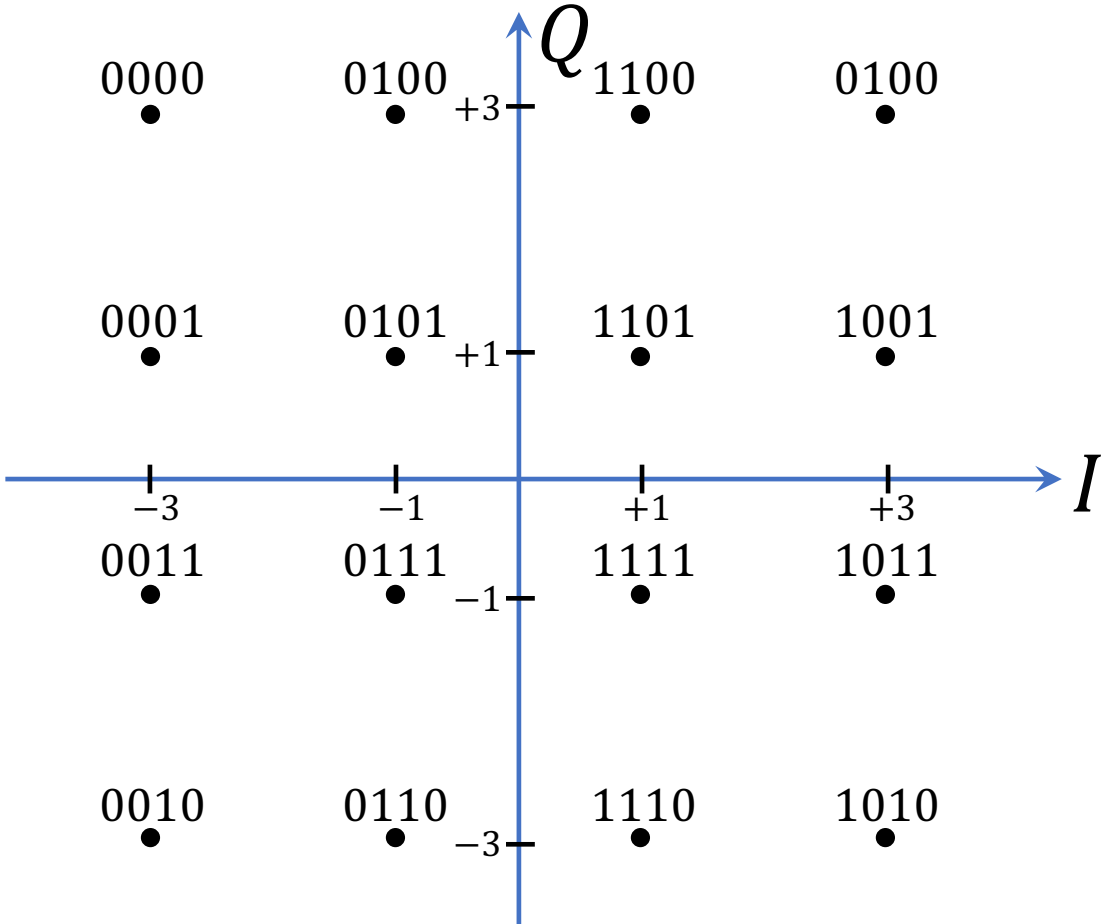
Up/Down Conversion

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

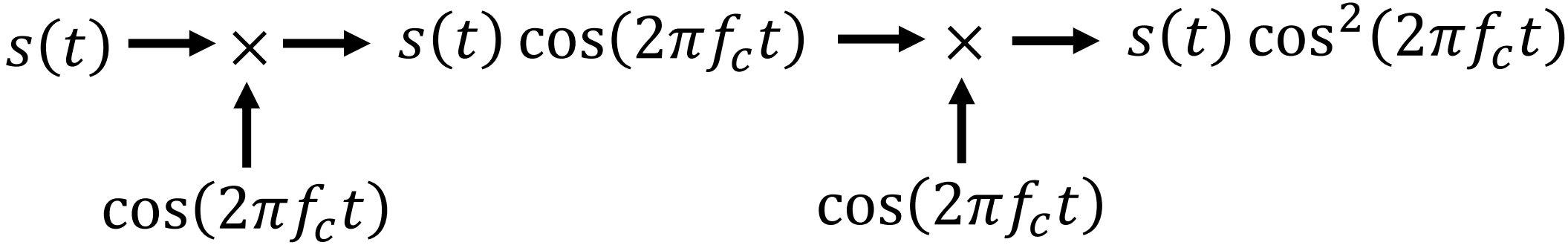
$\cos(2\pi f_c t)$ $\cos(2\pi f_c t)$

Consider using QAM:Quadrature Amplitude Modulation

16 QAM:
4 bits/symbol



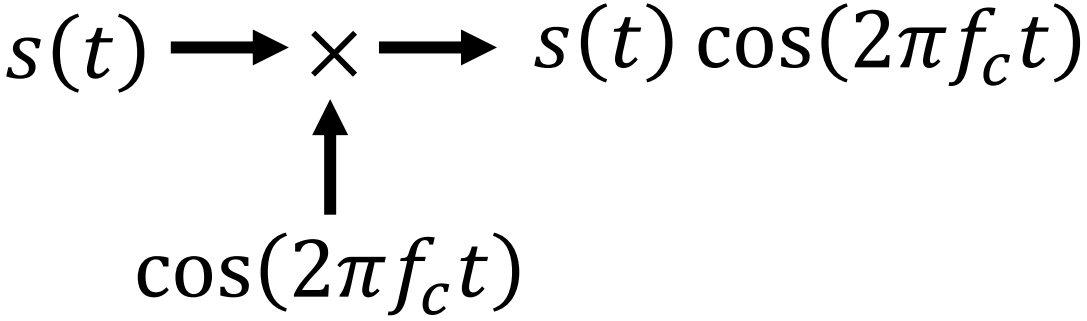
Up/Down Conversion



Consider using QAM:Quadrature Amplitude Modulation

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

Up Conversion



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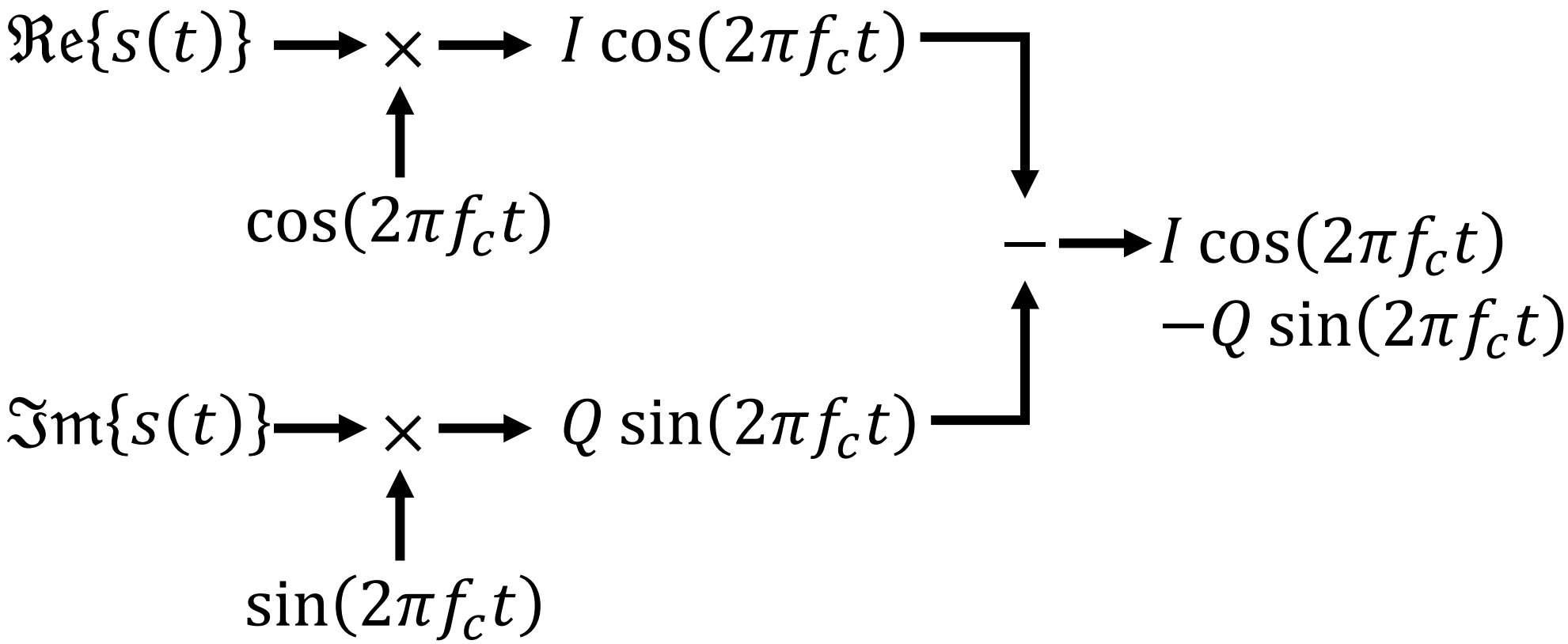
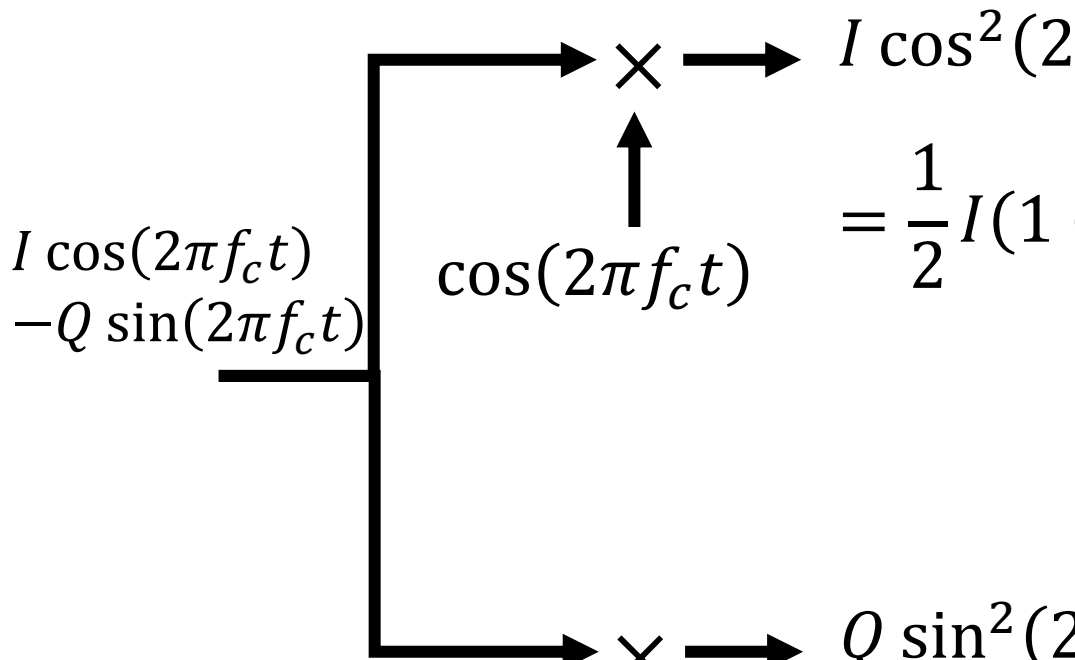
Up Conversion



Down Conversion



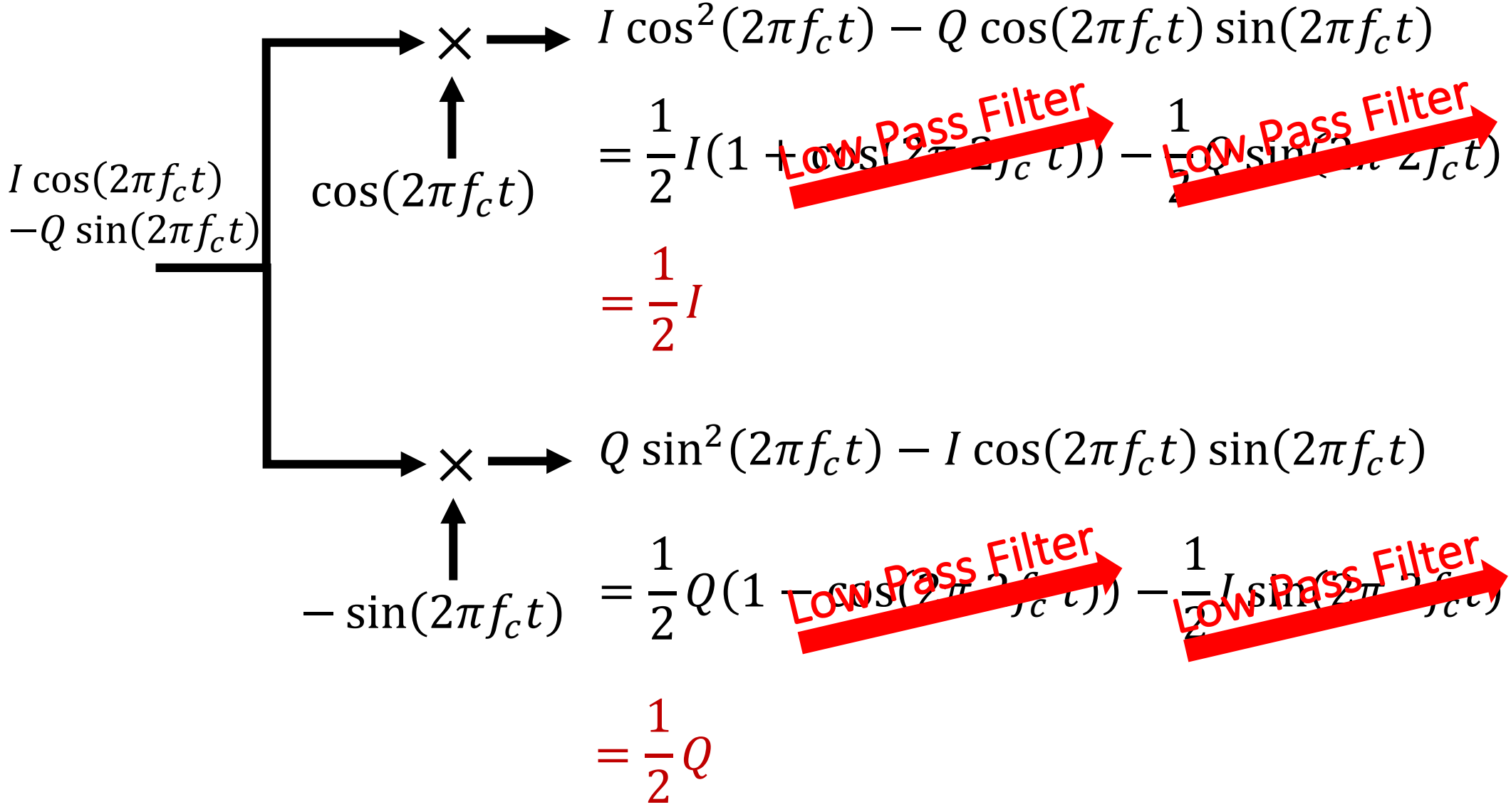
$$I\cos^2(2\pi f_c t) - Q\cos(2\pi f_c t)\sin(2\pi f_c t)$$

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

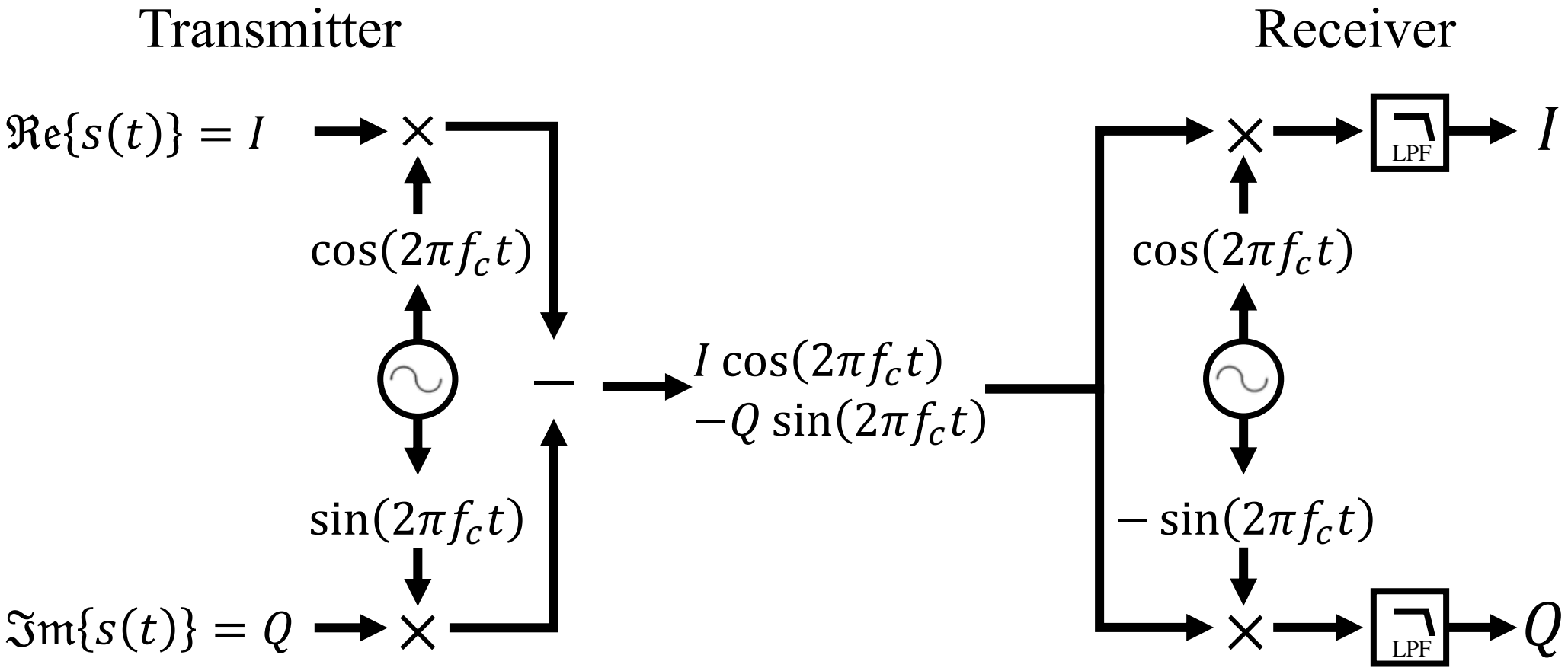
$$Q\sin^2(2\pi f_c t) - I\cos(2\pi f_c t)\sin(2\pi f_c t)$$

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

Down Conversion



Up/Down Conversion



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

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

Low Pass Filter

Up/Down Conversion

Transmitter

Receiver

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

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

Low Pass Filter

Up/Down Conversion

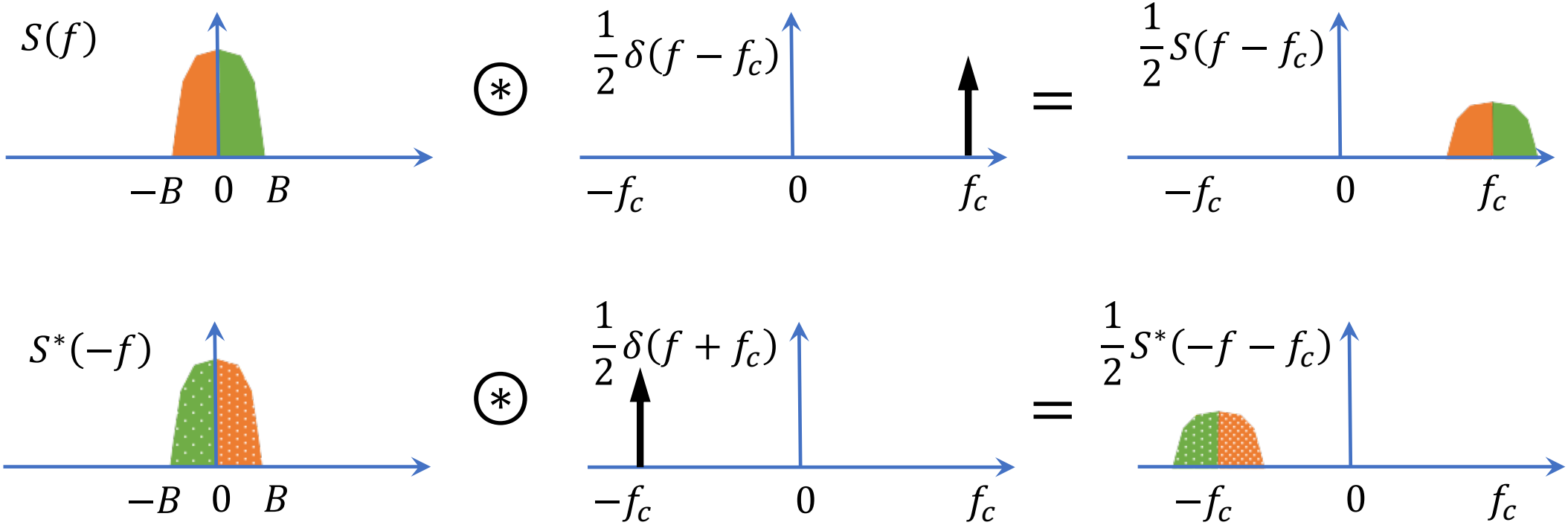
Transmitter

Receiver

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

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

Low Pass Filter



Up/Down Conversion

Transmitter

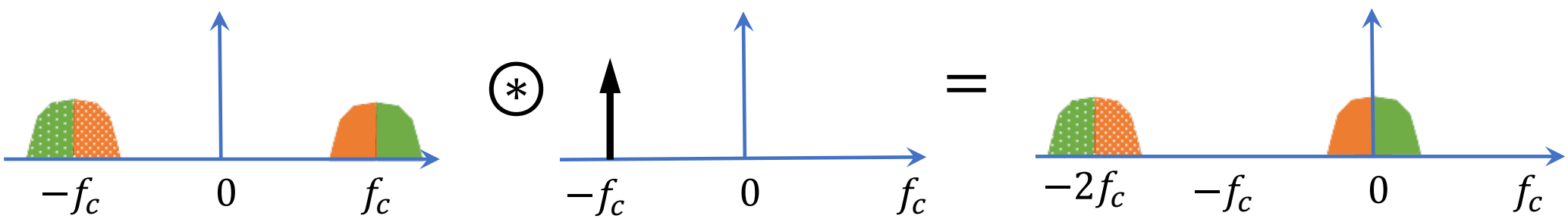
Receiver

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

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

Low Pass Filter

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



Up/Down Conversion

Transmitter

Receiver

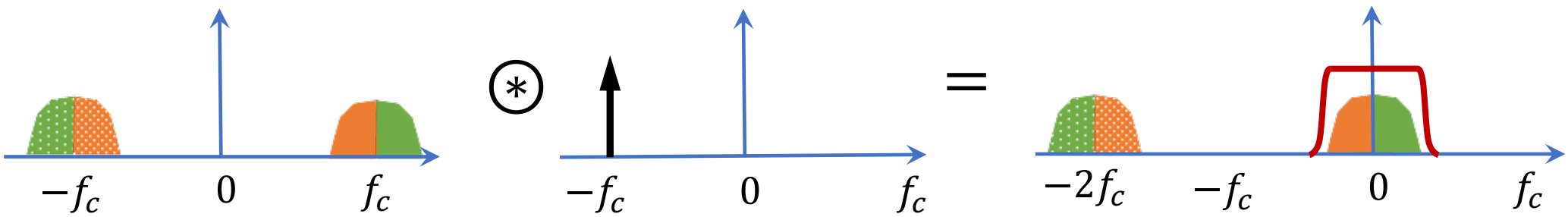
$$s(t) \times e^{j2\pi f_c t} \rightarrow \Re e\{s(t)e^{j2\pi f_c t}\} \rightarrow \times e^{-j2\pi f_c t} \rightarrow s(t)$$

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

Low Pass Filter

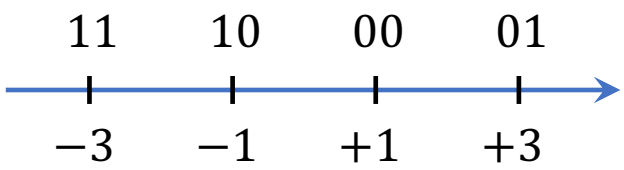
$$\frac{1}{2}S(f-f_c) + \frac{1}{2}S^*(-f-f_c) \qquad \delta(f+f_c) \qquad \frac{1}{2}S(f) + \frac{1}{2}S^*(-f-2f_c)$$

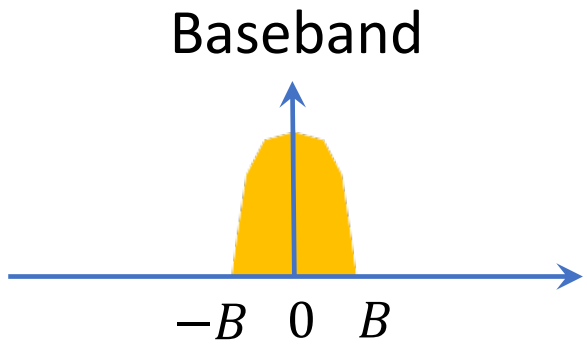
Low Pass Filter

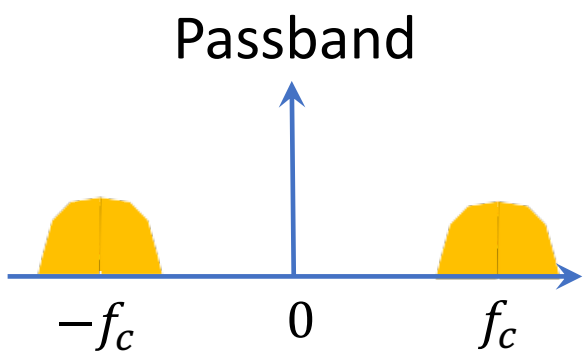


Up/Down Conversion

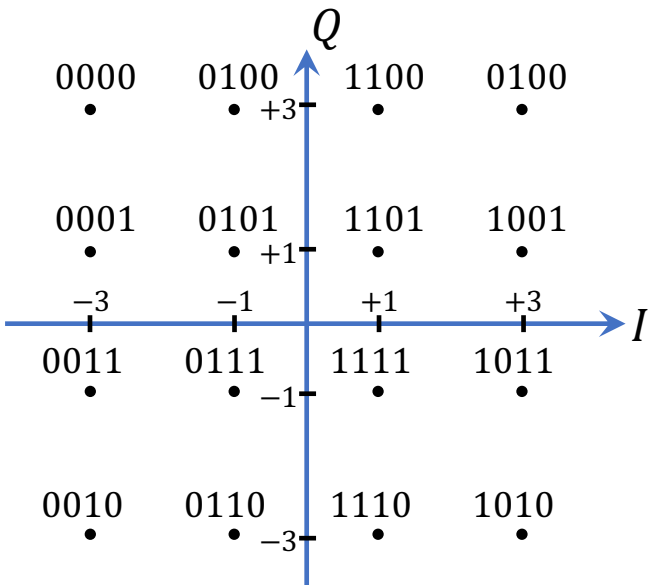
PAM: Sends B real symbols/sec with k bits/symbol

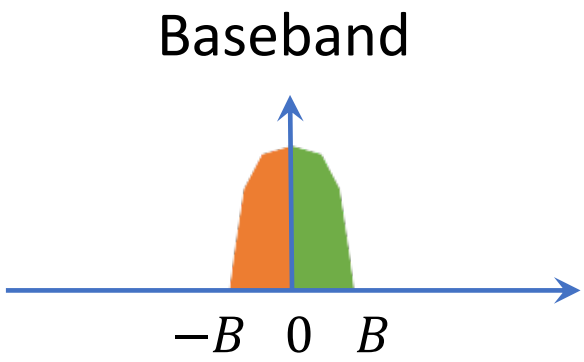


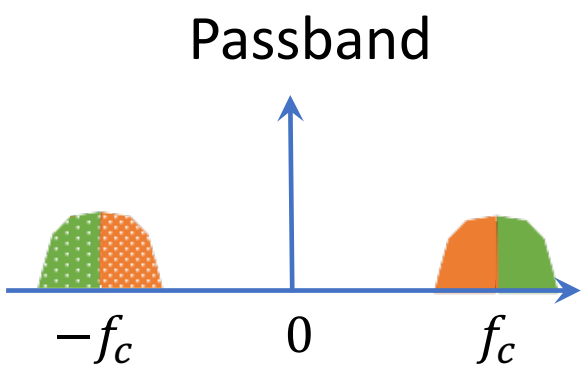




QAM: Sends B complex symbols/sec with $2k$ bit/symbol

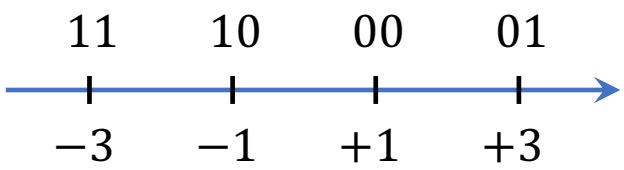


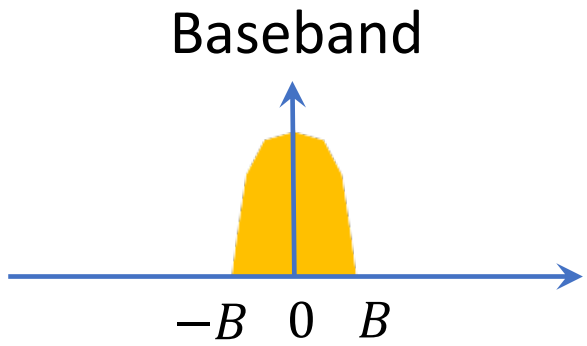


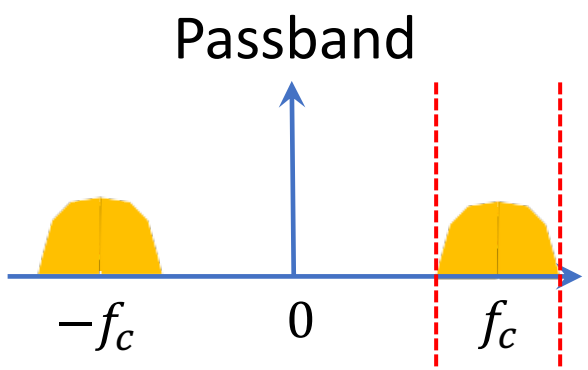


Up/Down Conversion

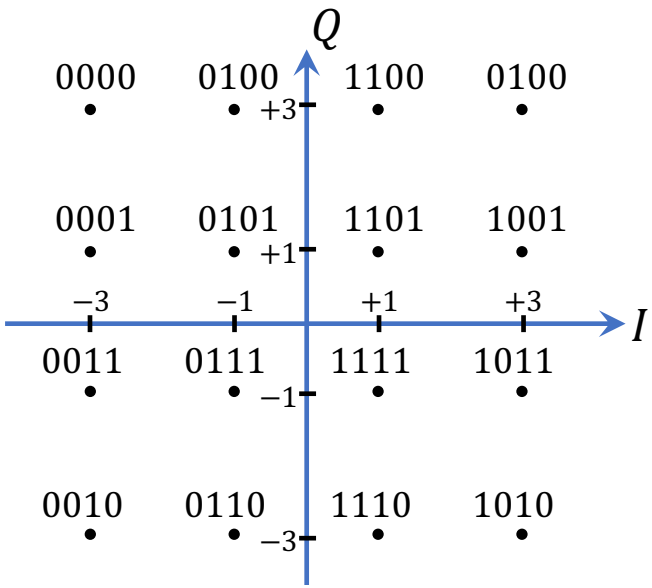
PAM: Sends B real symbols/sec with k bits/symbol

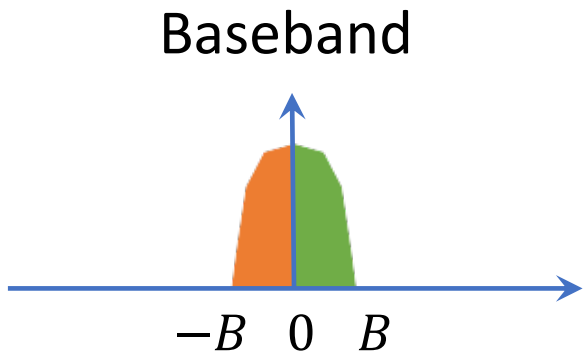


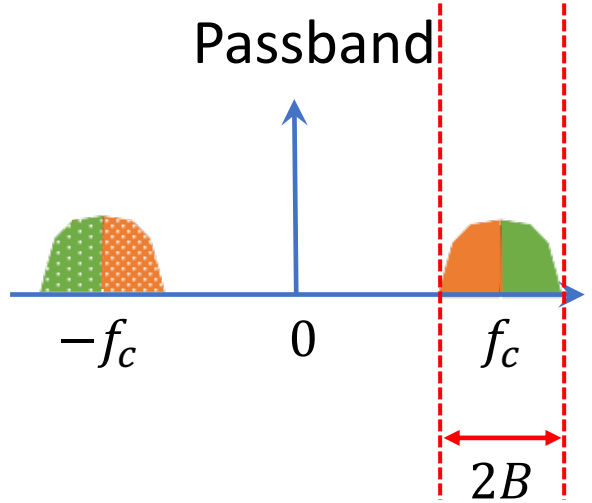




QAM: Sends B complex symbols/sec with $2k$ bit/symbol





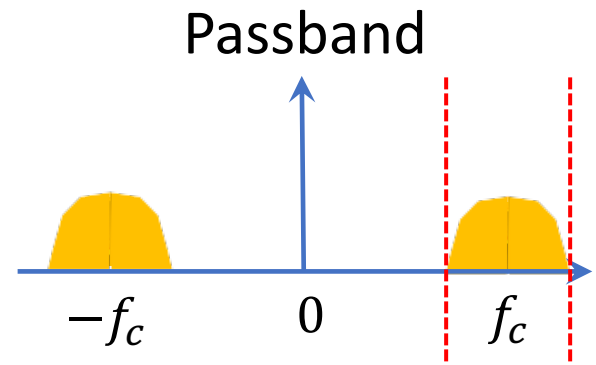


Up/Down Conversion

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

Spectral Efficiency:

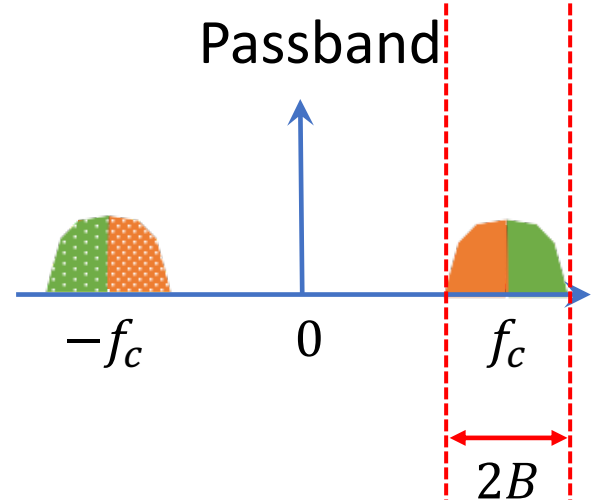
$$\frac{B \times k \text{ bits/sec}}{2B \ Hz} = \frac{k}{2} \text{ bits/Hz}$$

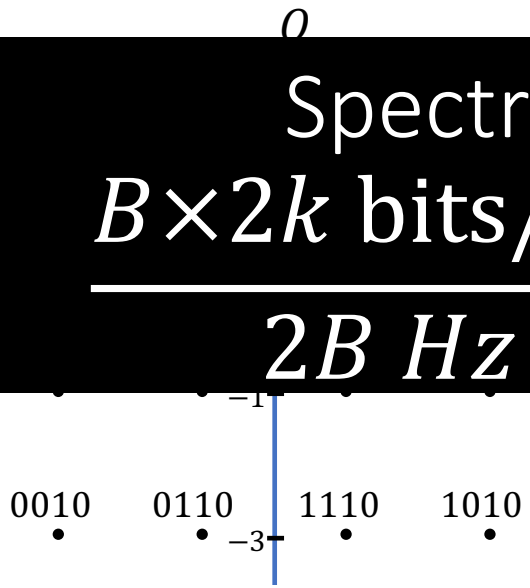


QAM: Sends B complex symbols/sec with $2k$ bit/symbol

Spectral Efficiency:

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



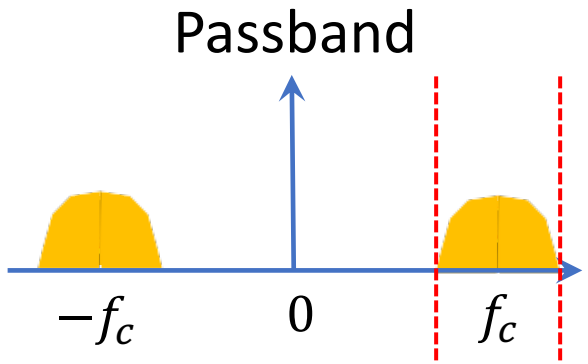


Up/Down Conversion

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

Spectral Efficiency:

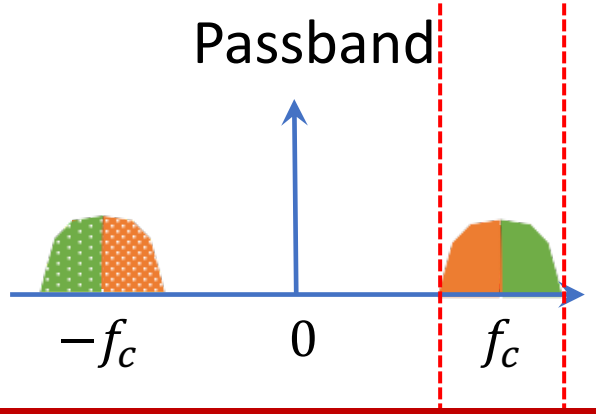
$$\frac{B \times k \text{ bits/sec}}{2B \text{ Hz}} = \frac{k}{2} \text{ bits/Hz}$$



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

Spectral Efficiency:

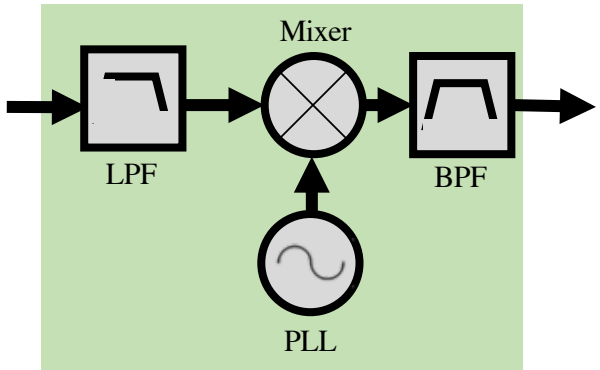
$$\frac{B \times 2k \text{ bits/sec}}{2B \text{ Hz}} = k \text{ bits/Hz}$$



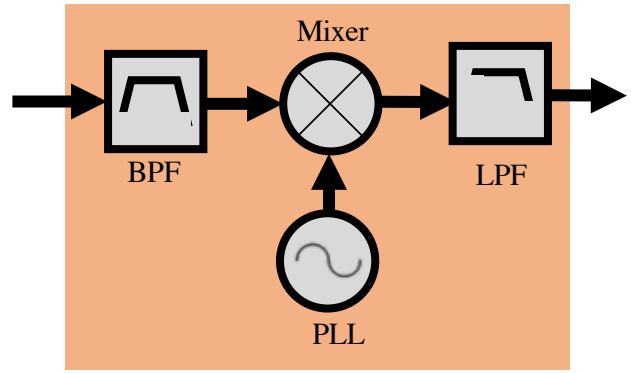
Quadrature Modulation ➔ More efficient use of the same bandwidth

Up/Down Conversion

Transmitter
Up-conversion

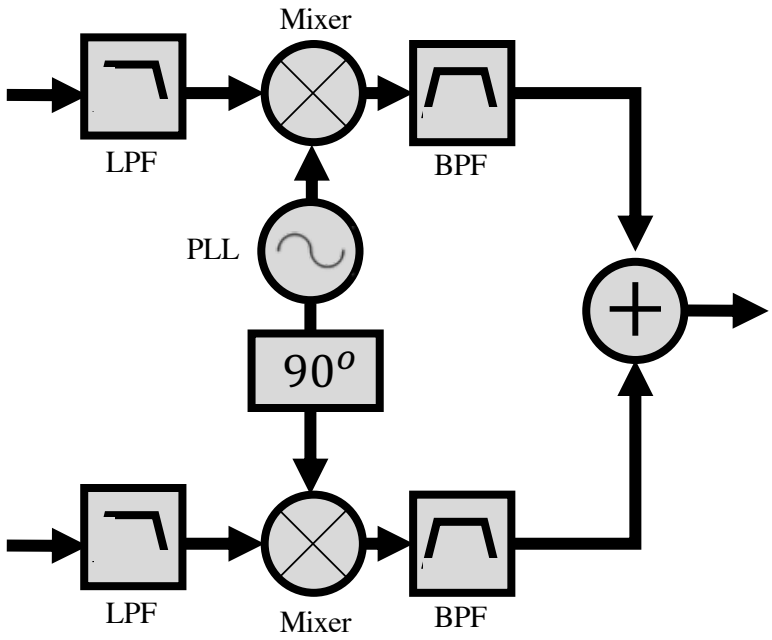


Receiver
Down-conversion

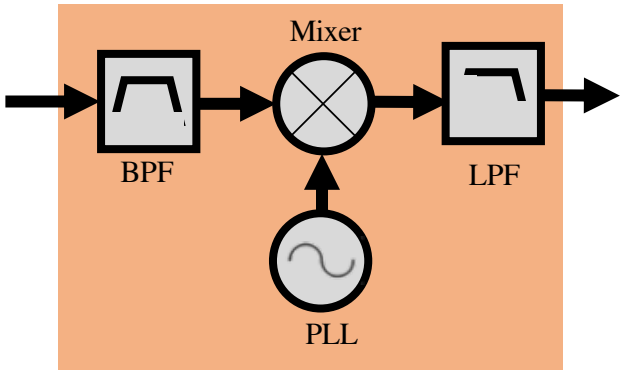


Up/Down Conversion

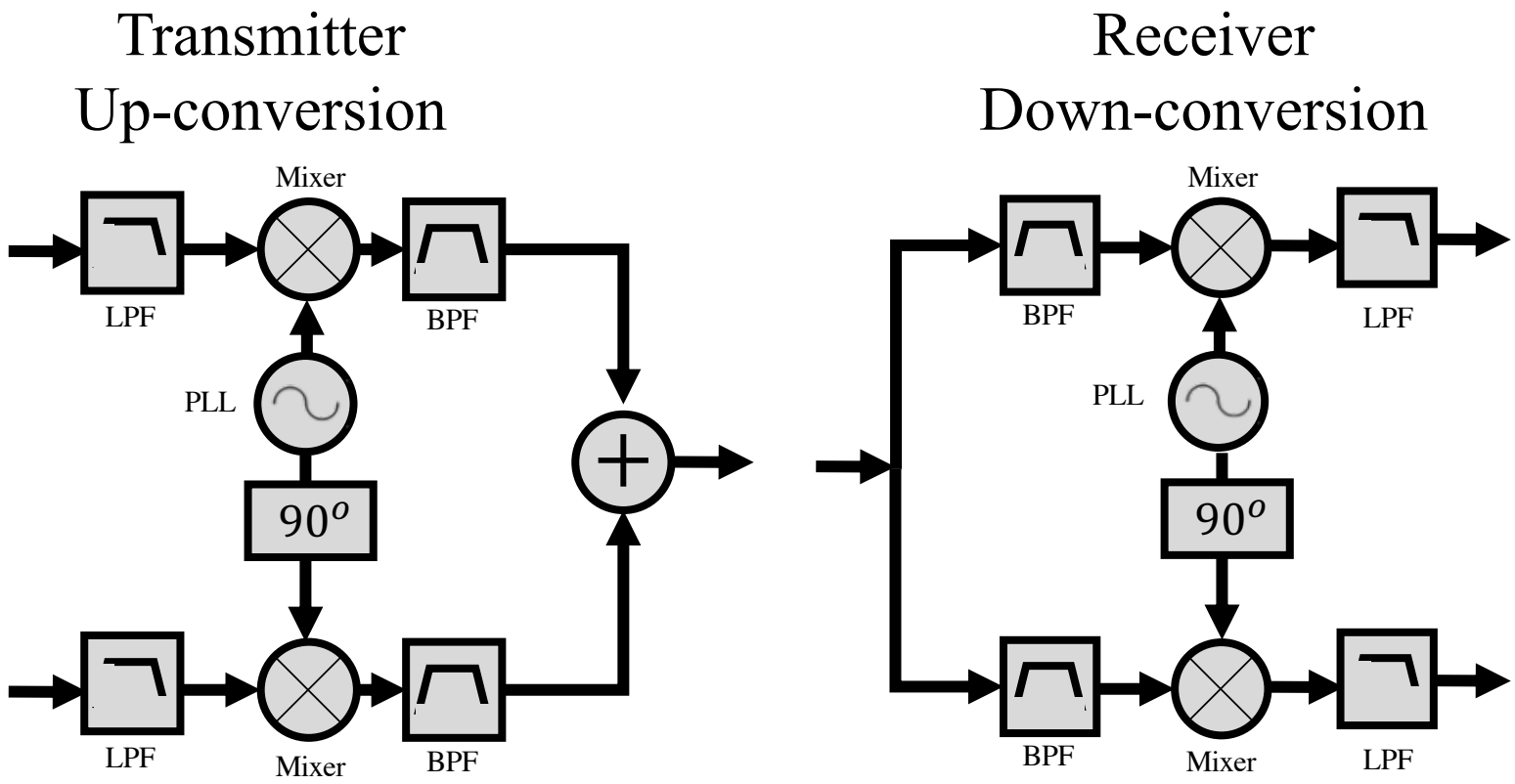
Transmitter
Up-conversion



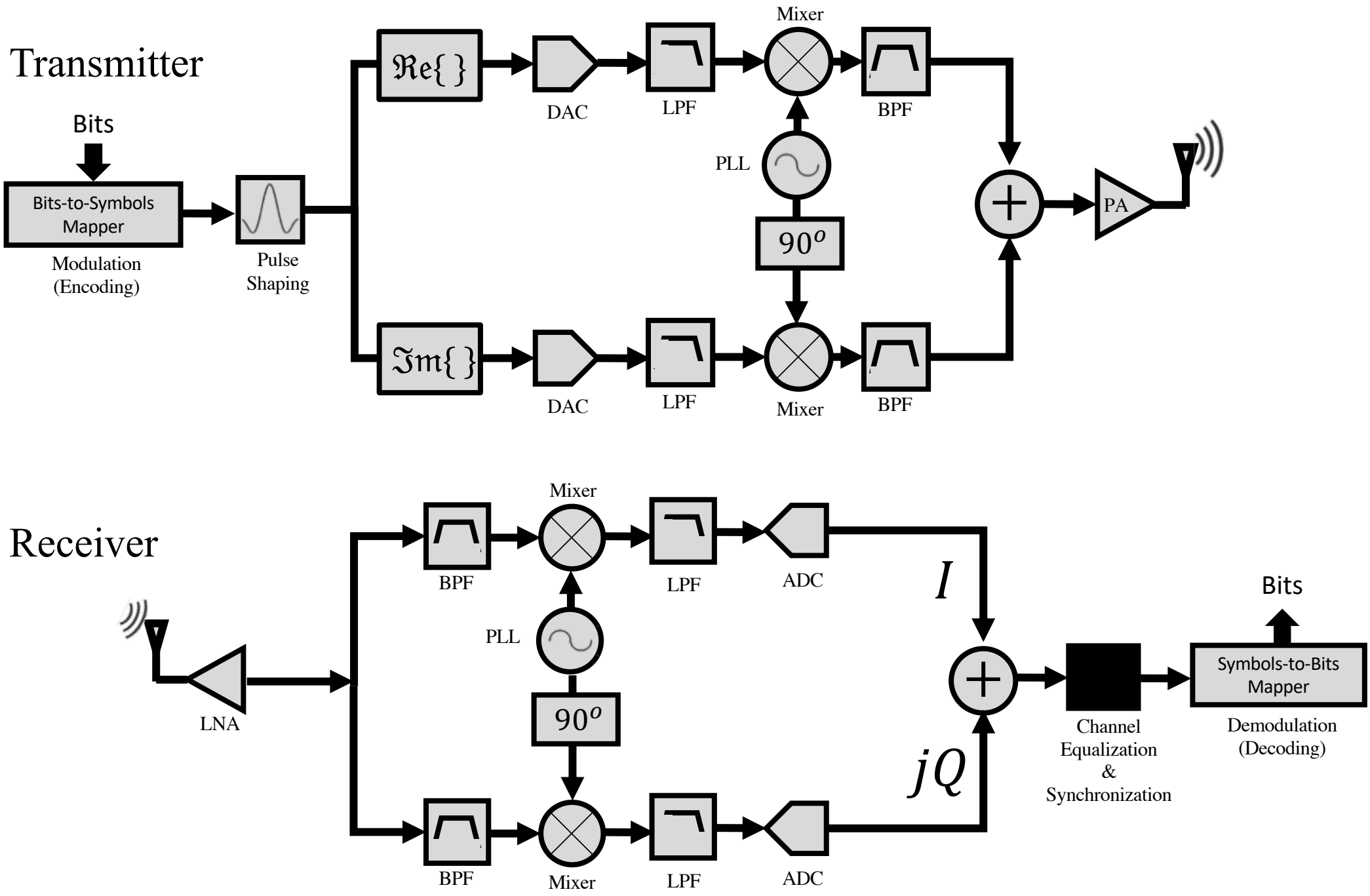
Receiver
Down-conversion



Up/Down Conversion

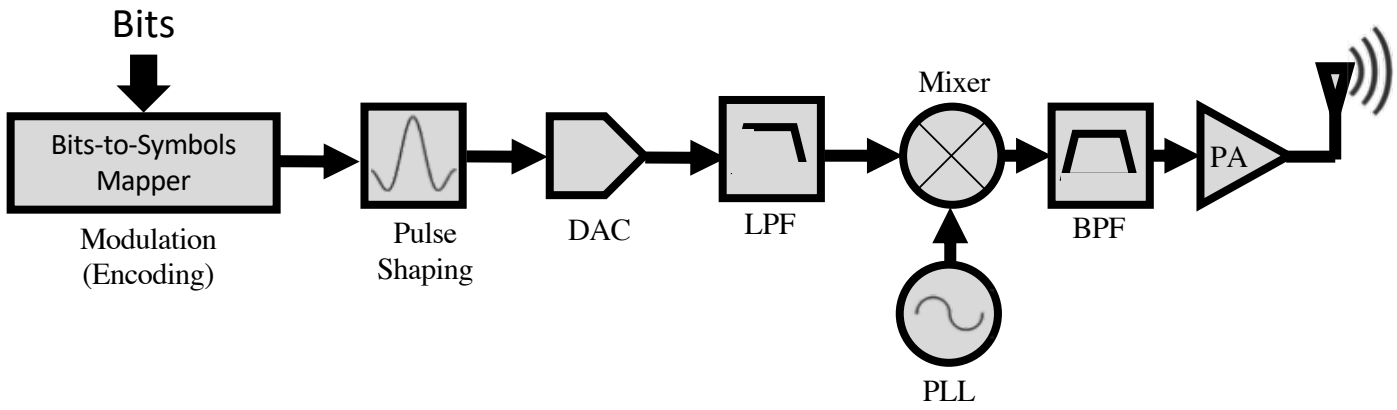


Digital Communication System

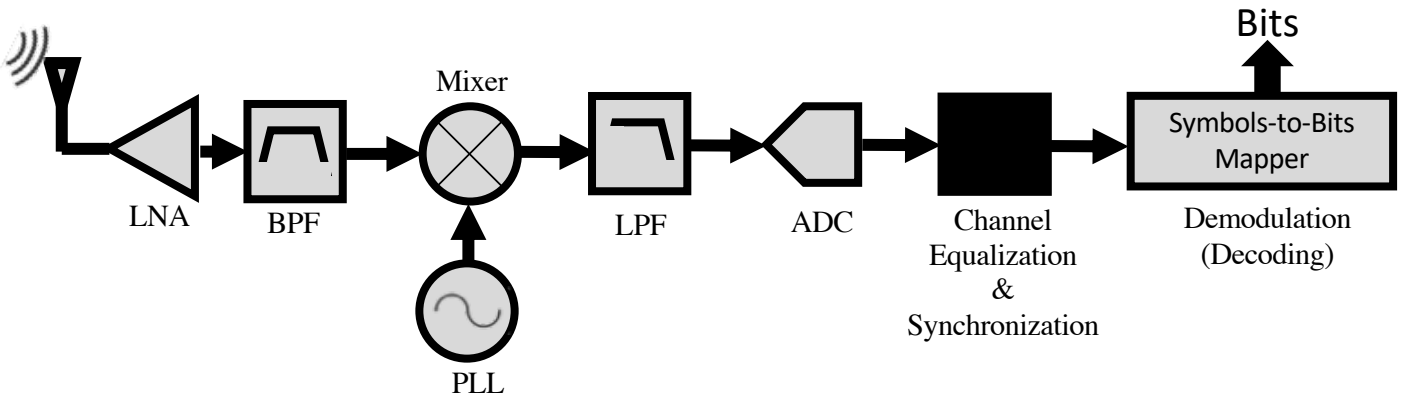


Digital Communication System

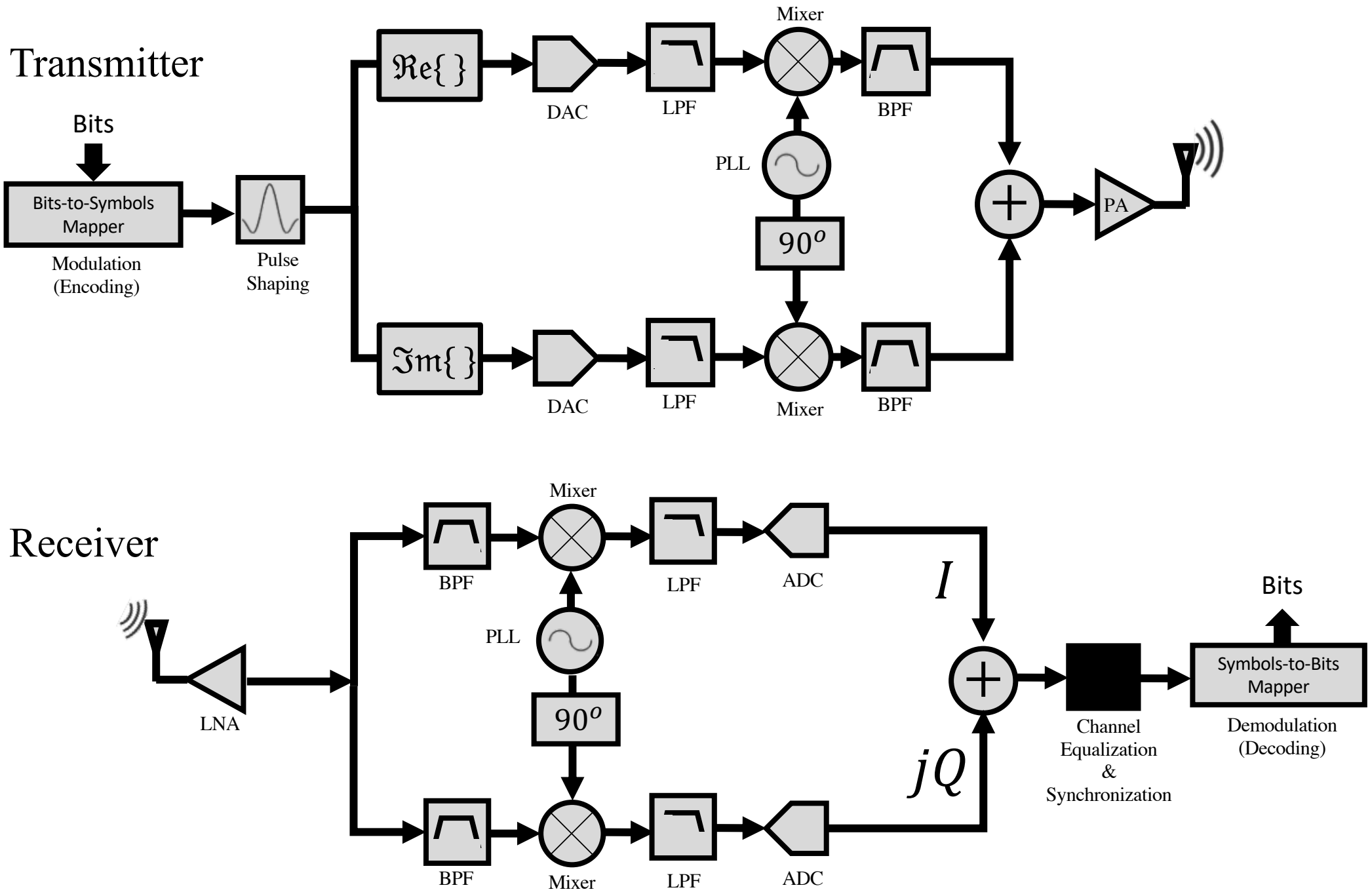
Transmitter



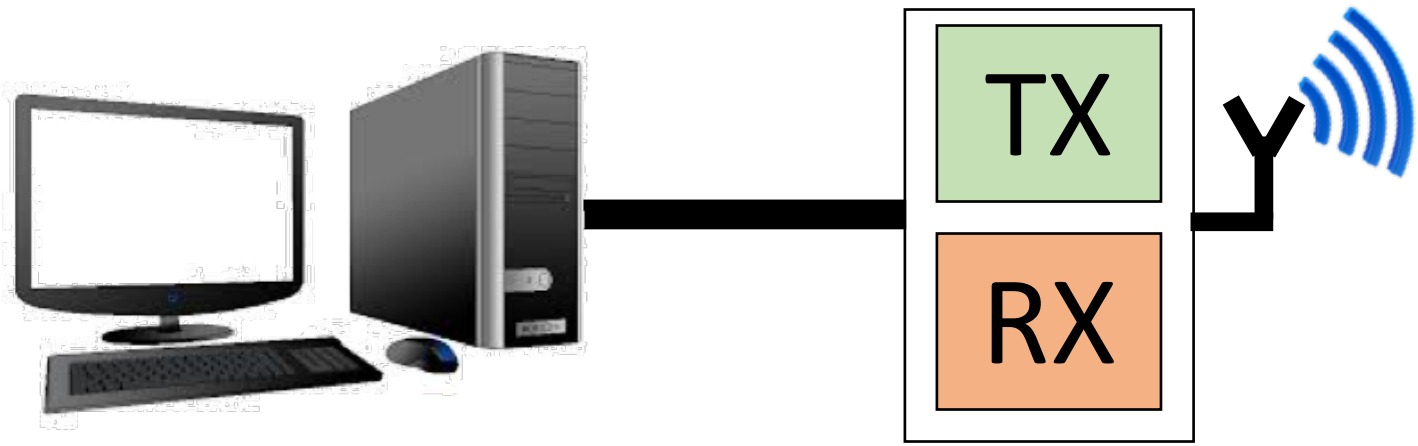
Receiver



Digital Communication System



Software Defined Radio



- Flexible radio frontend with ADC & DAC connected to machine
- Streams digital samples to/from the machine
- Machine controls radio parameters

Software Defined Radio

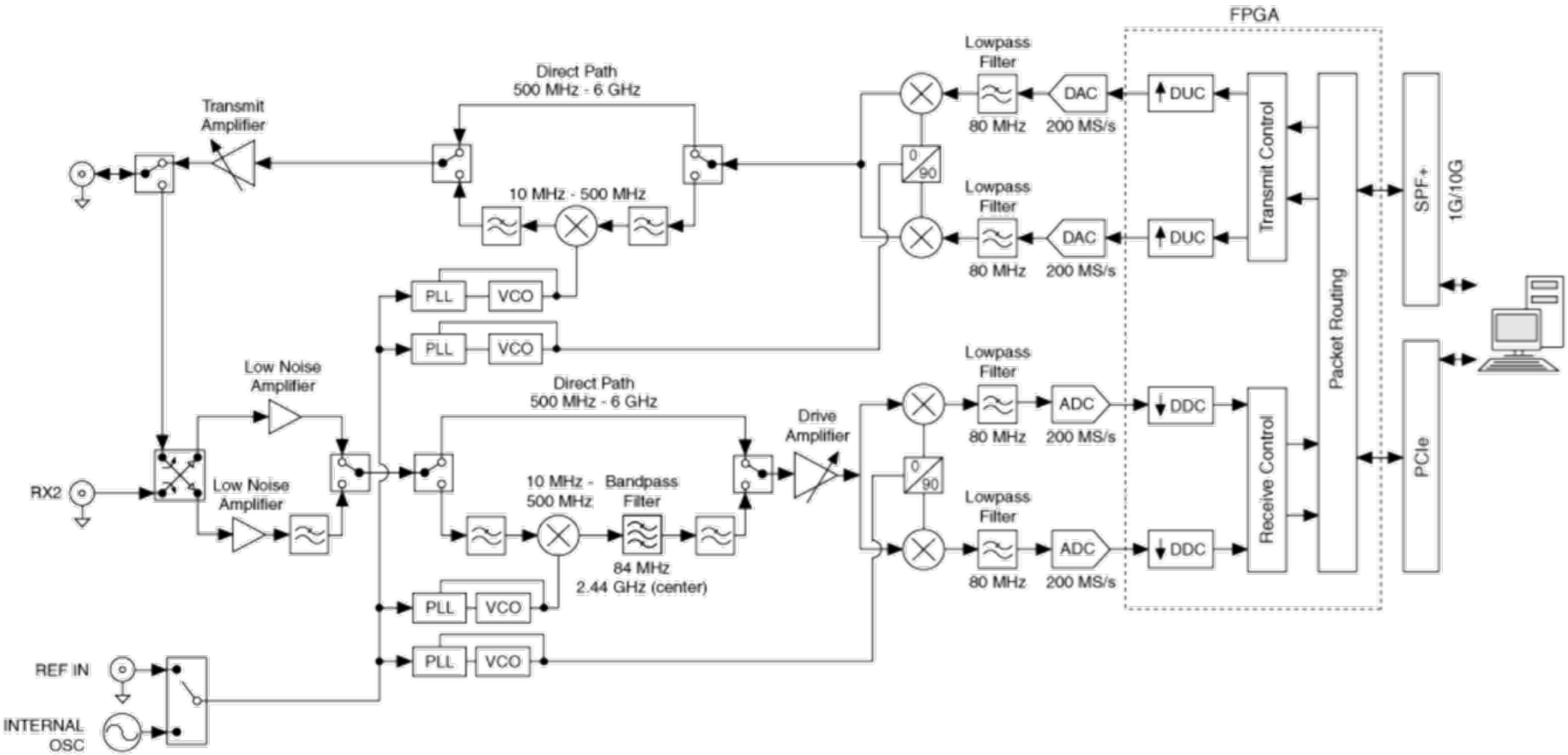
- Can control hardware parameter from software:
  - Change frequency
  - Change bandwidth
  - Change amplifier gain
  - Change the sampling rate
  - …

- Can design all digital processing in software:
  - Filters
  - Modulation
  - Synchronization
  - …

Software Defined Radio

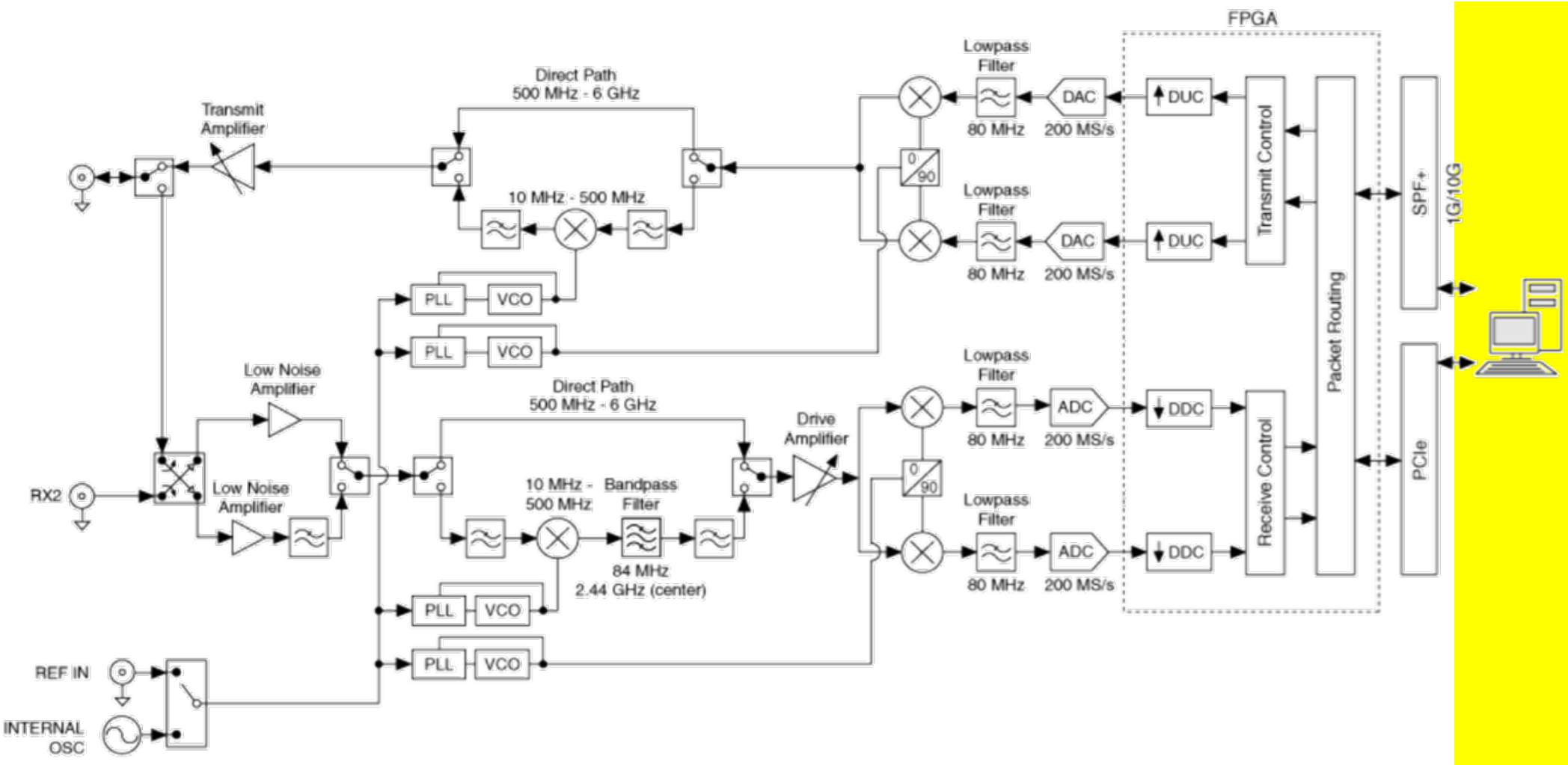
- In this class we will use USRP X310
  - 2 Channels
  - Wide bandwidth up to 160 MHz
  - ADC up to 200 MS/s and DAC up to 400 MS/s
  - Wide frequency range 10MHz- 6GHz

USRP X310 Architecture



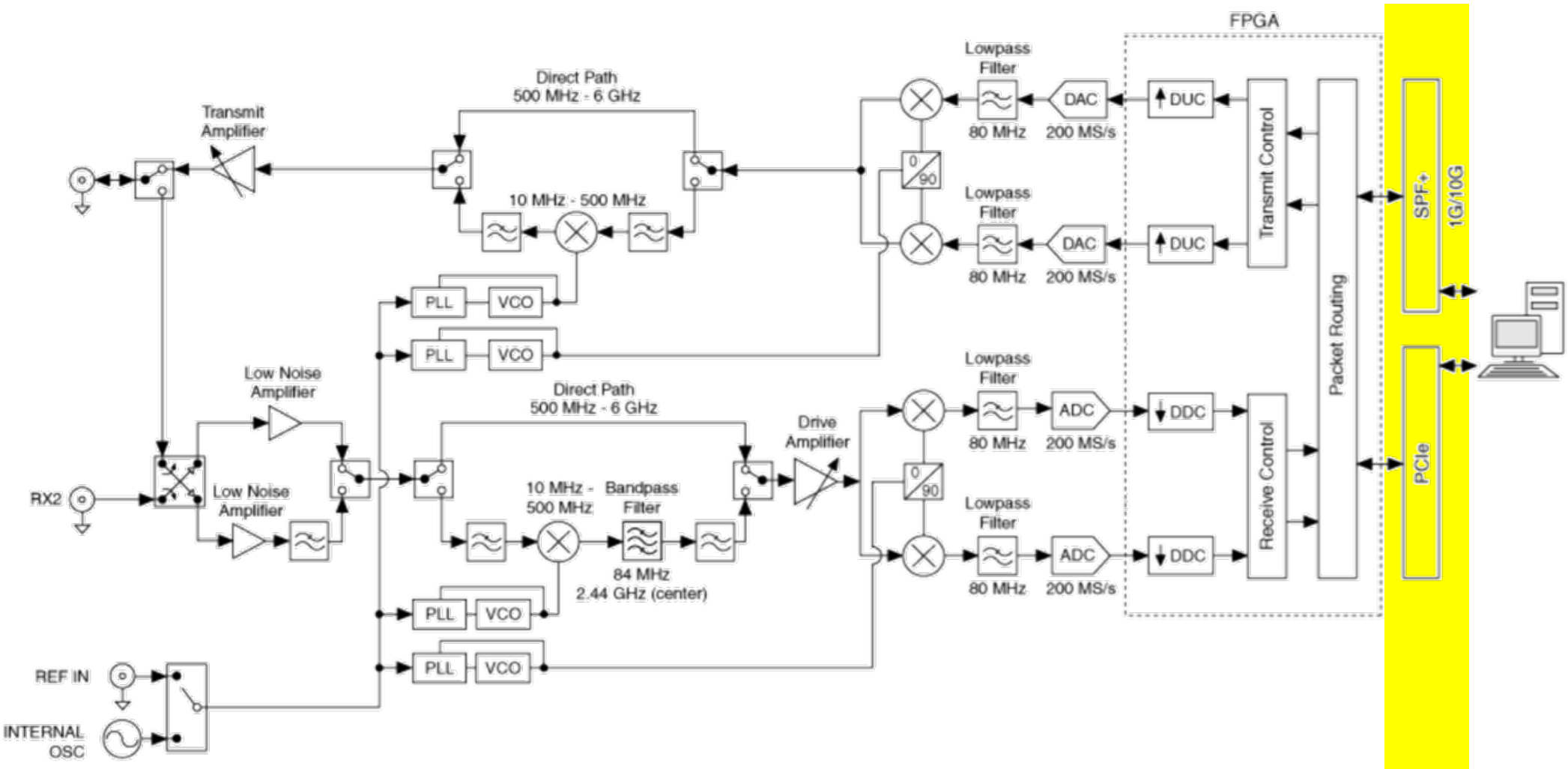
USRP X310 Architecture

Digital Processing (Host)



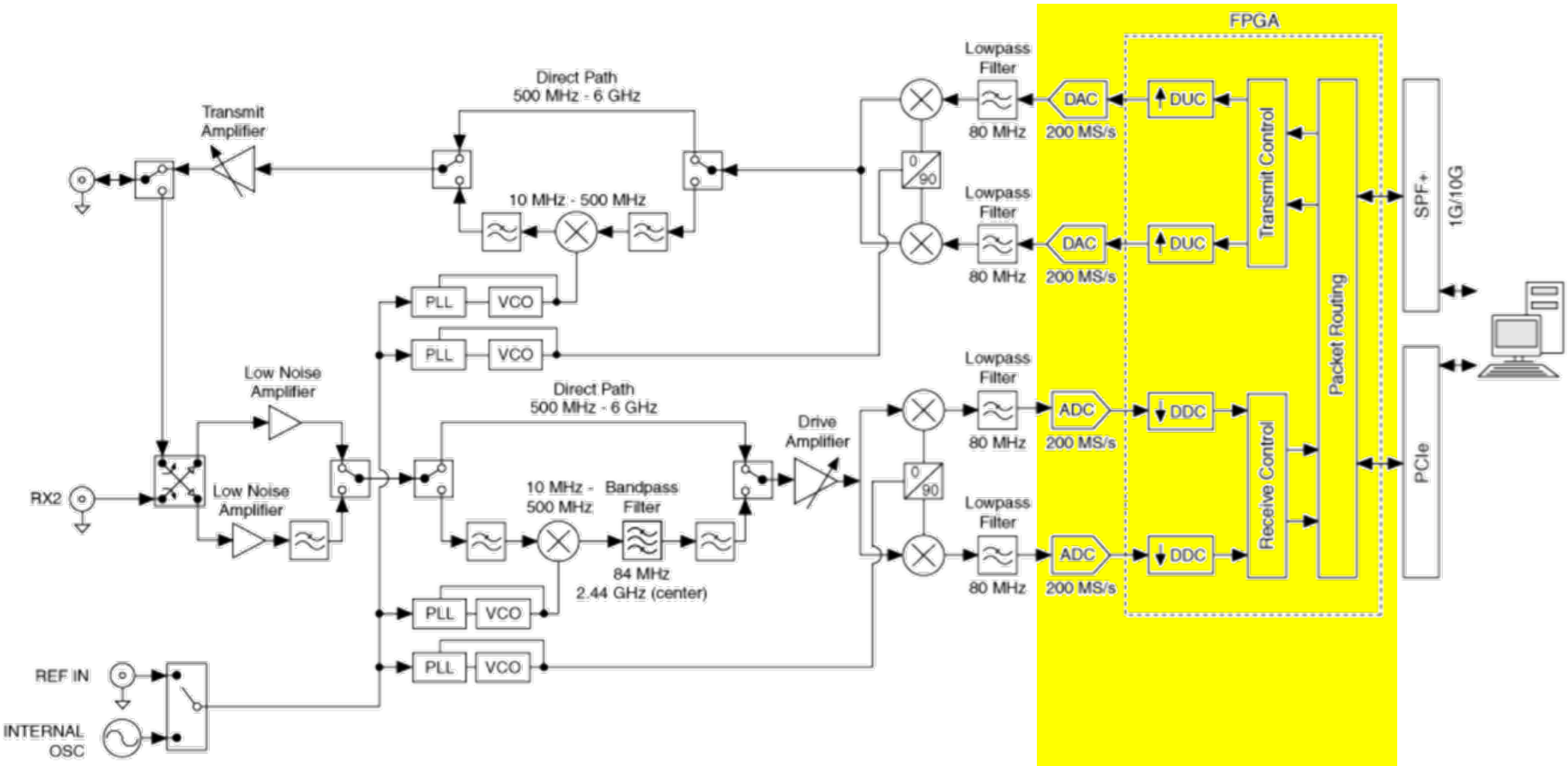
USRP X310 Architecture

Interface



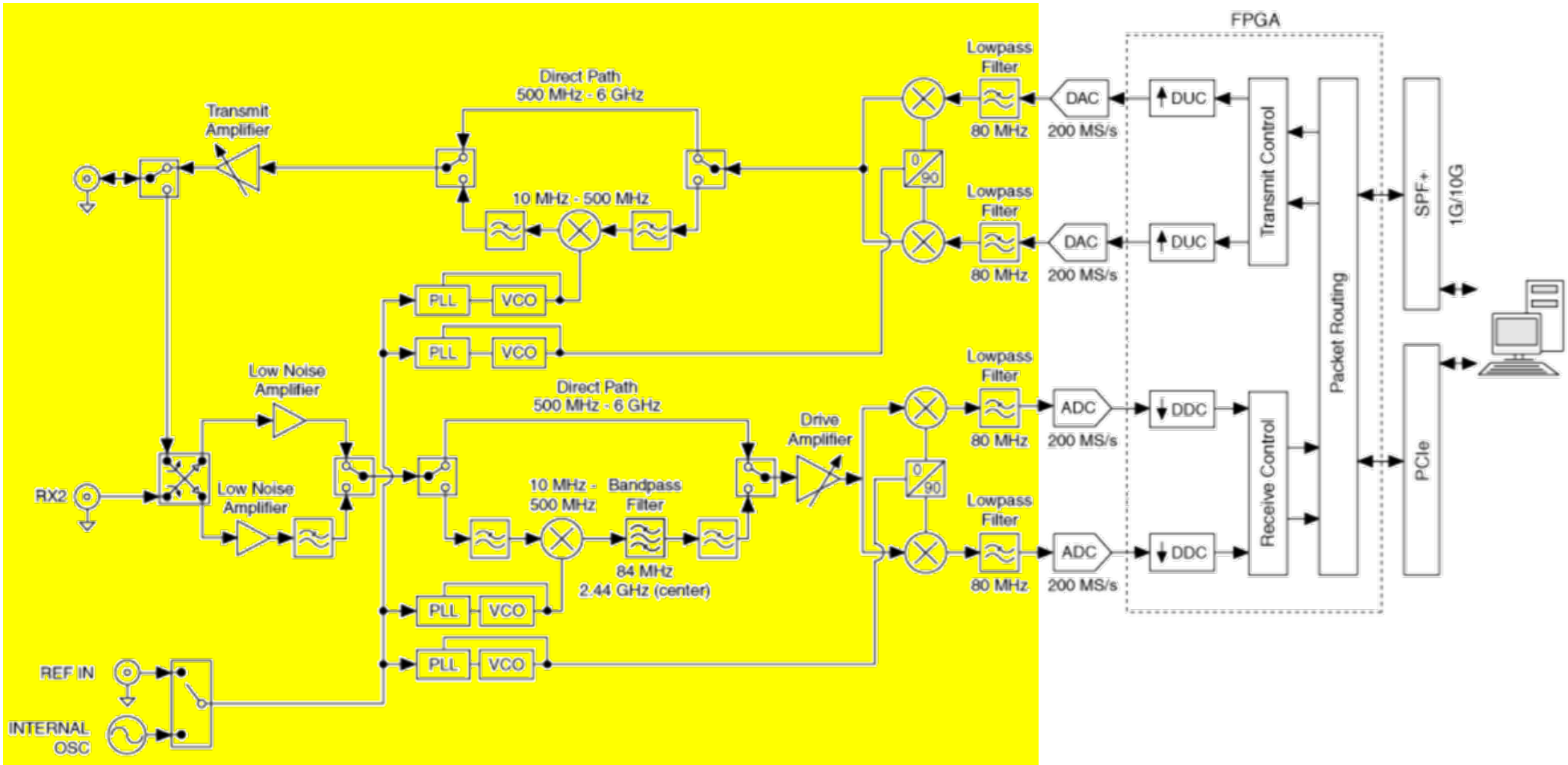
USRP X310 Architecture

Digital Frontend (Main board)



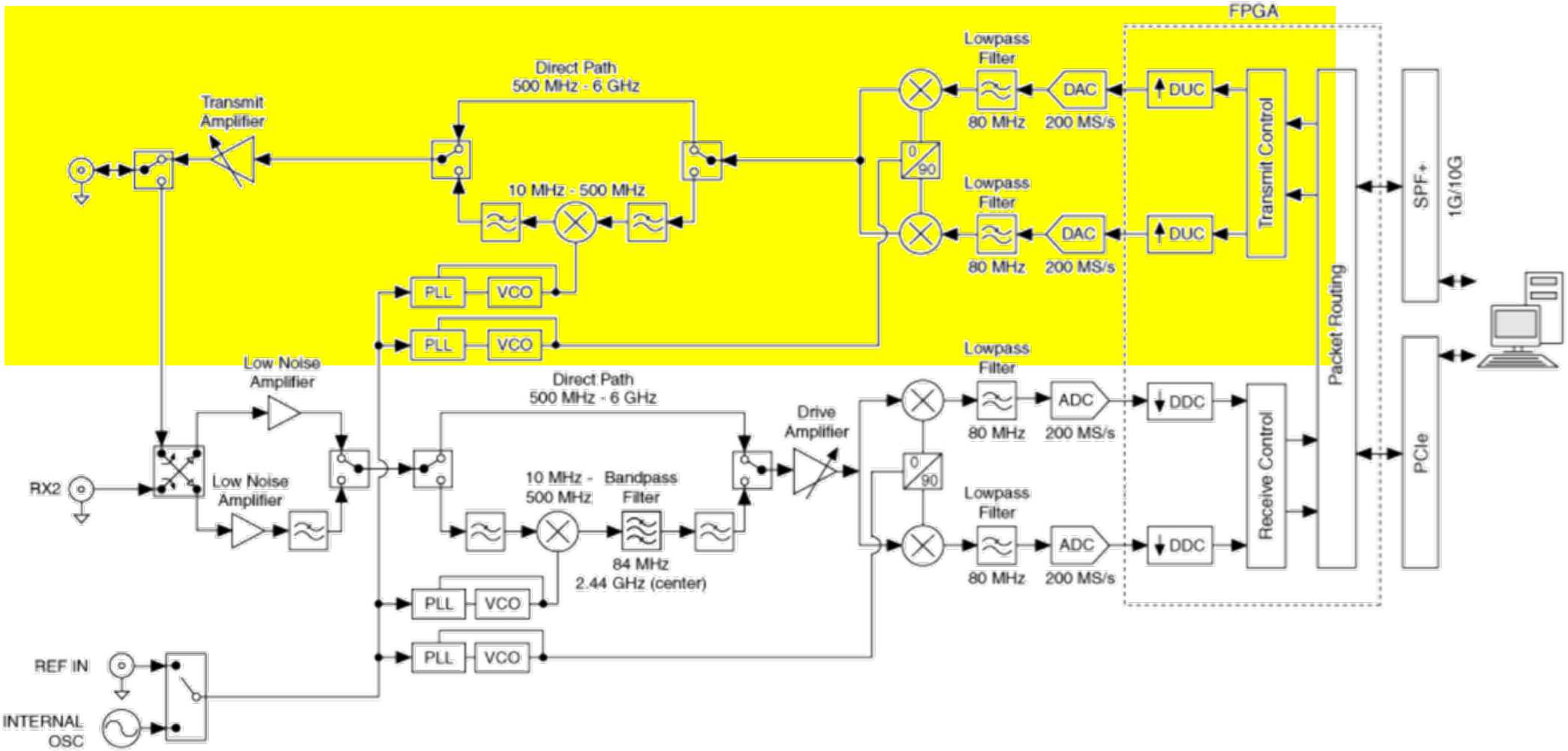
USRP X310 Architecture

RF Frontend (Daughterboard)



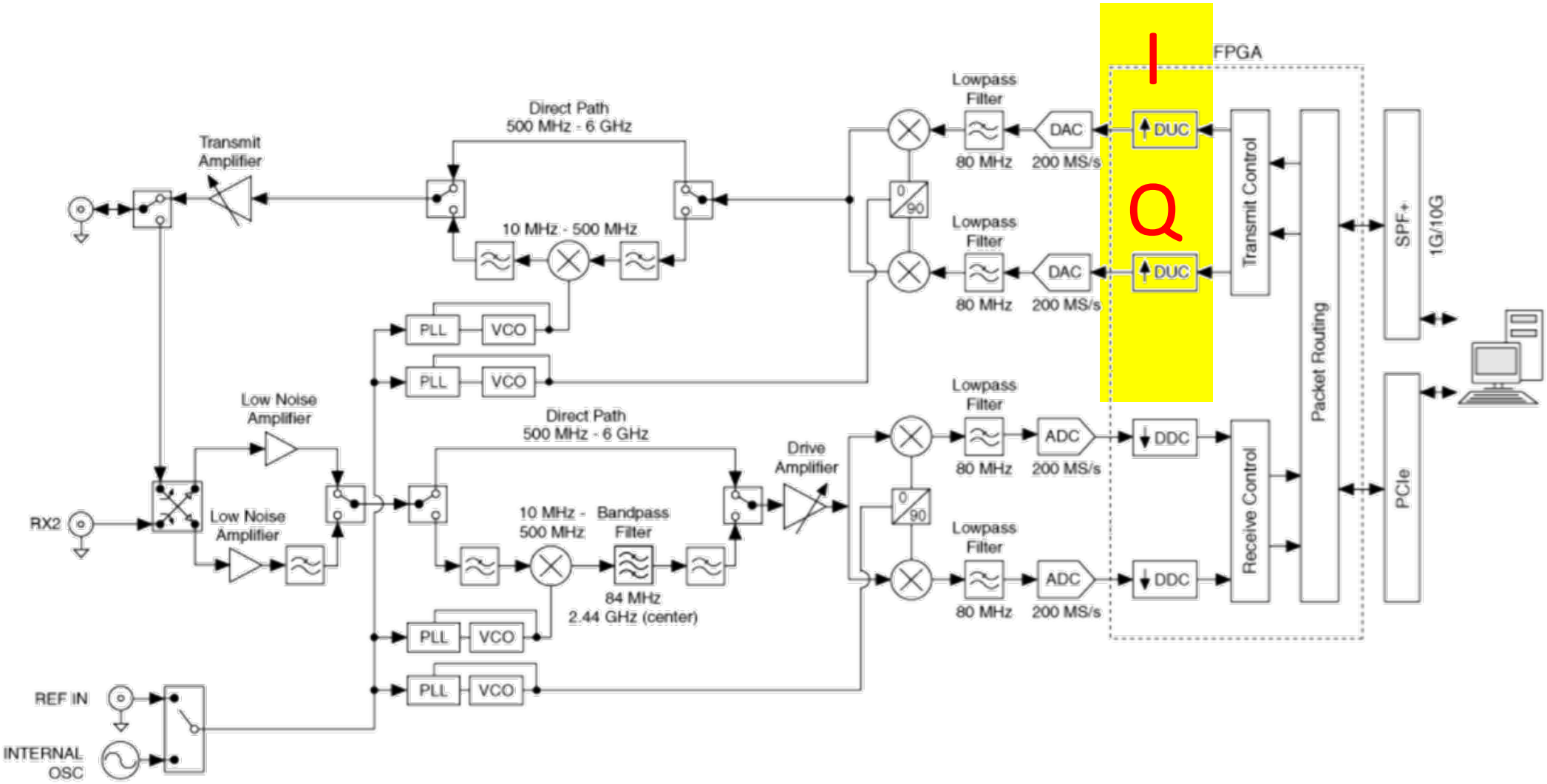
USRP X310 Architecture

Transmitter



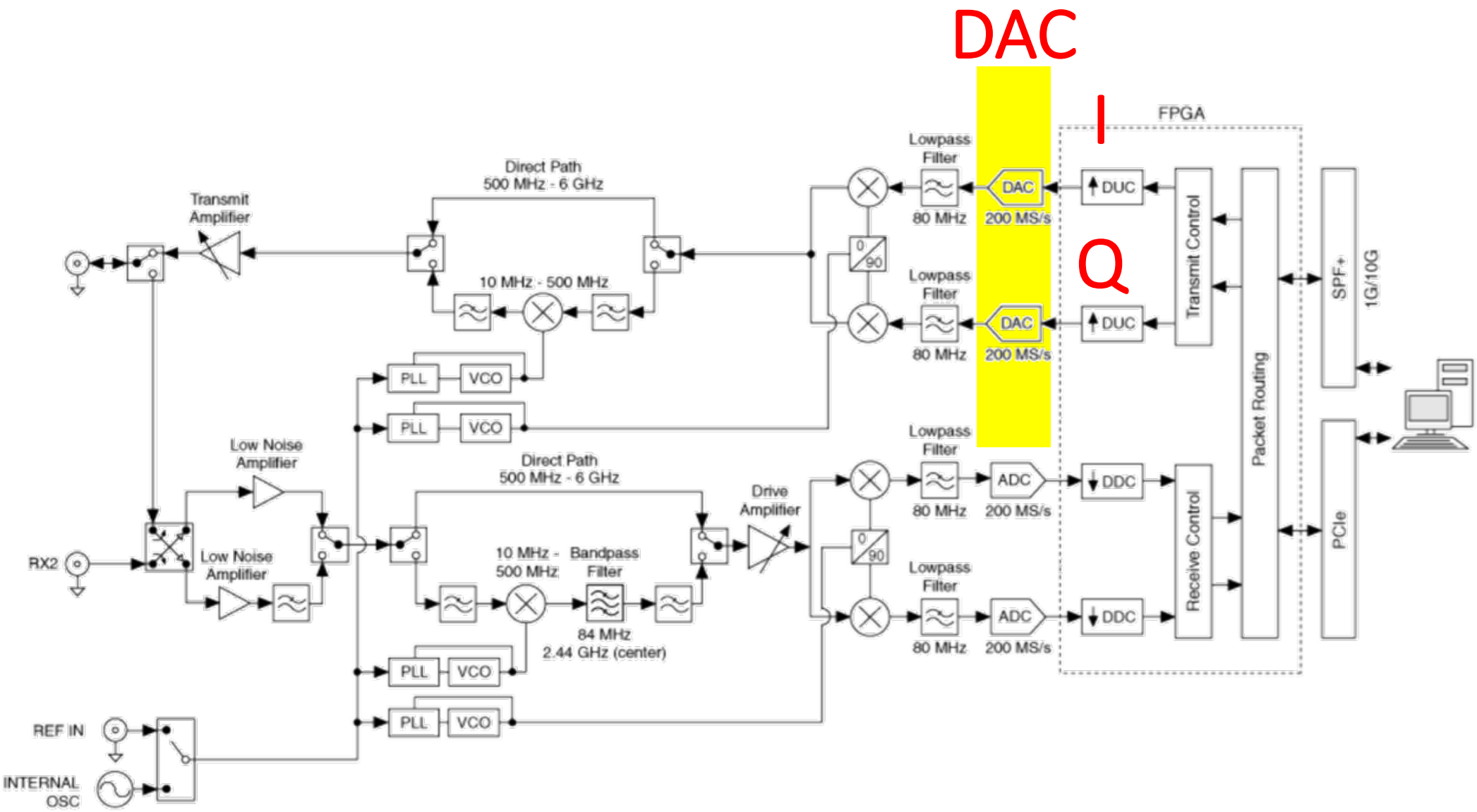
USRP X310 Architecture

Transmitter



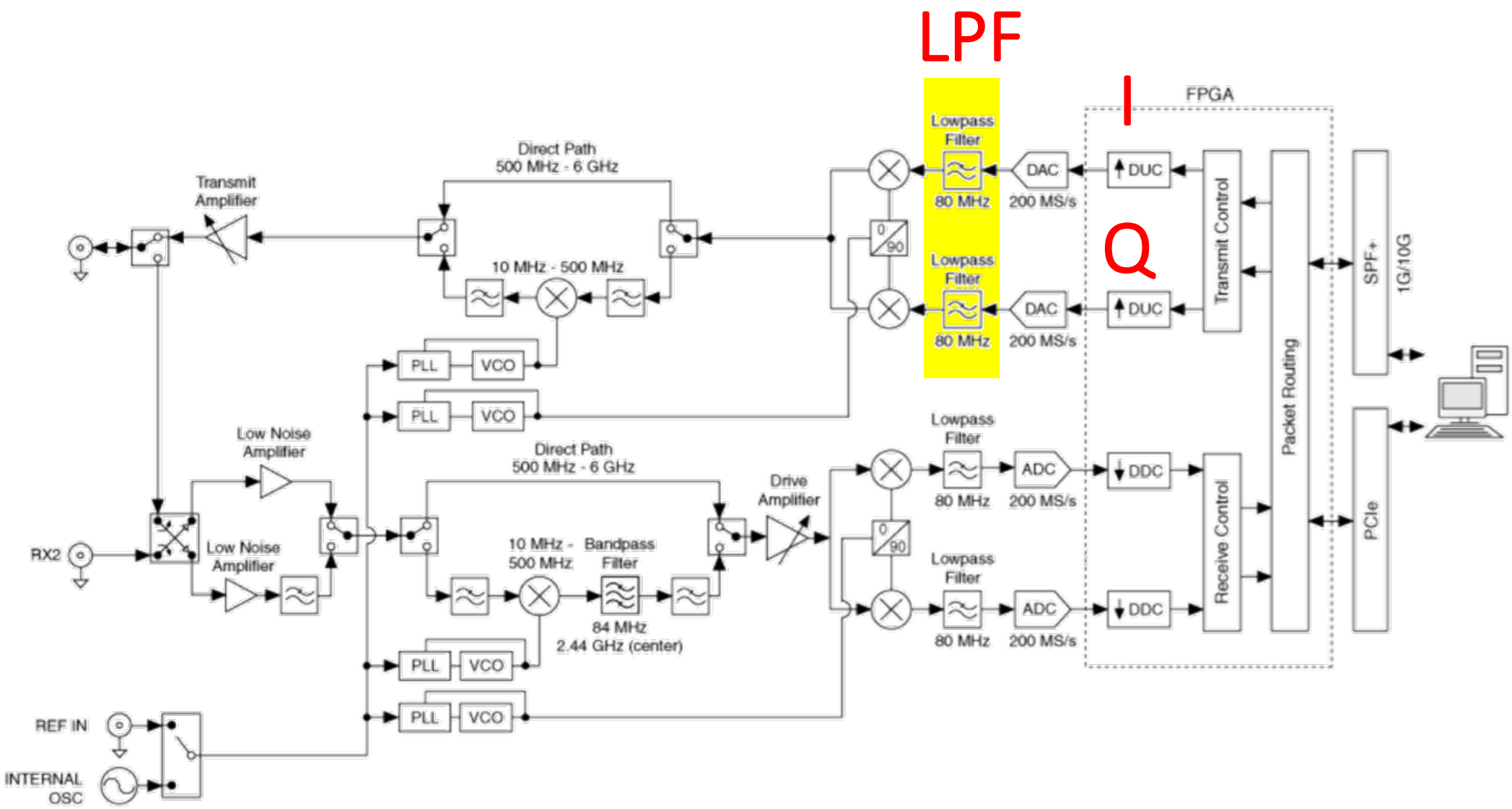
USRP X310 Architecture

Transmitter



USRP X310 Architecture

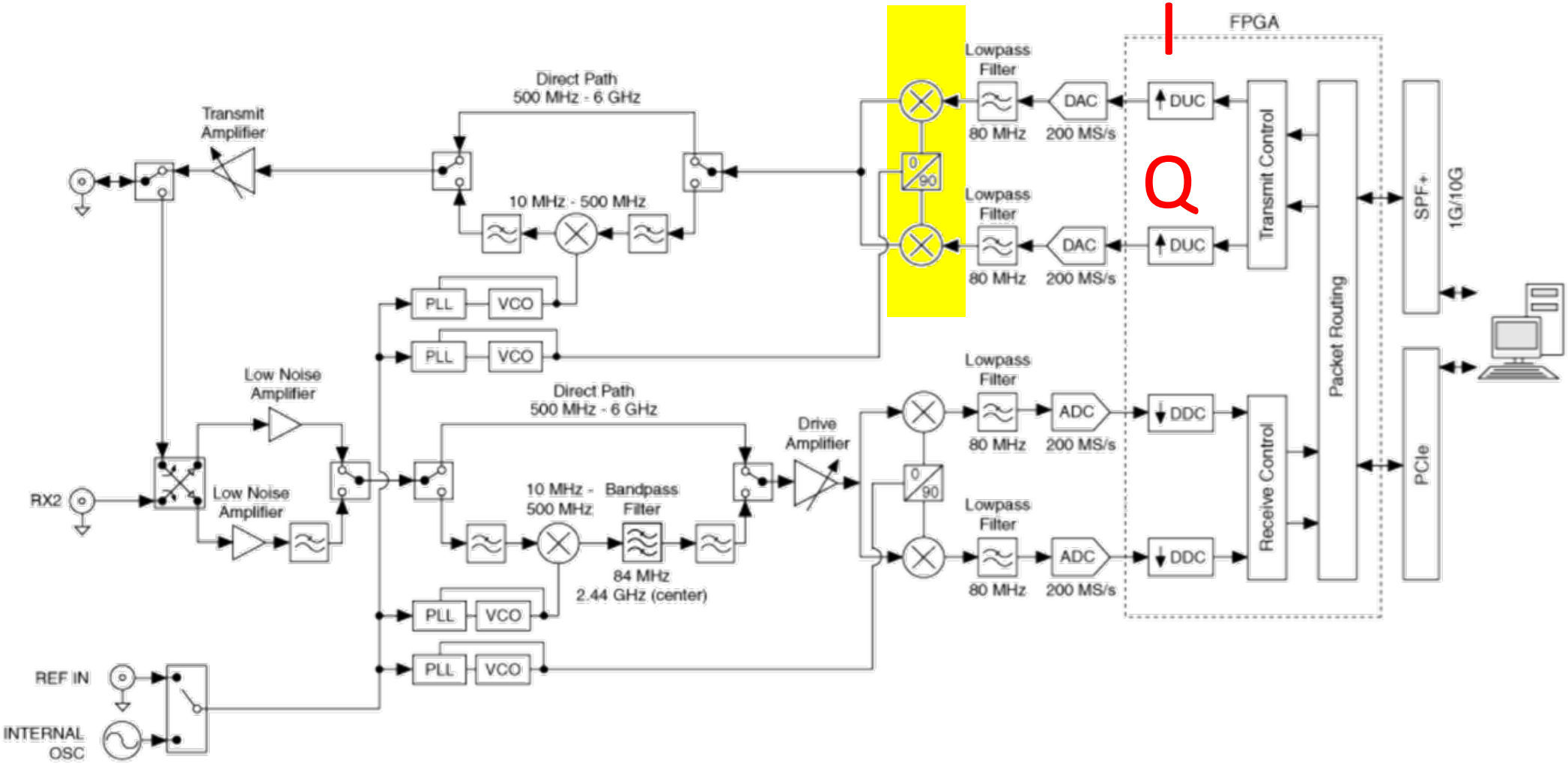
Transmitter



USRP X310 Architecture

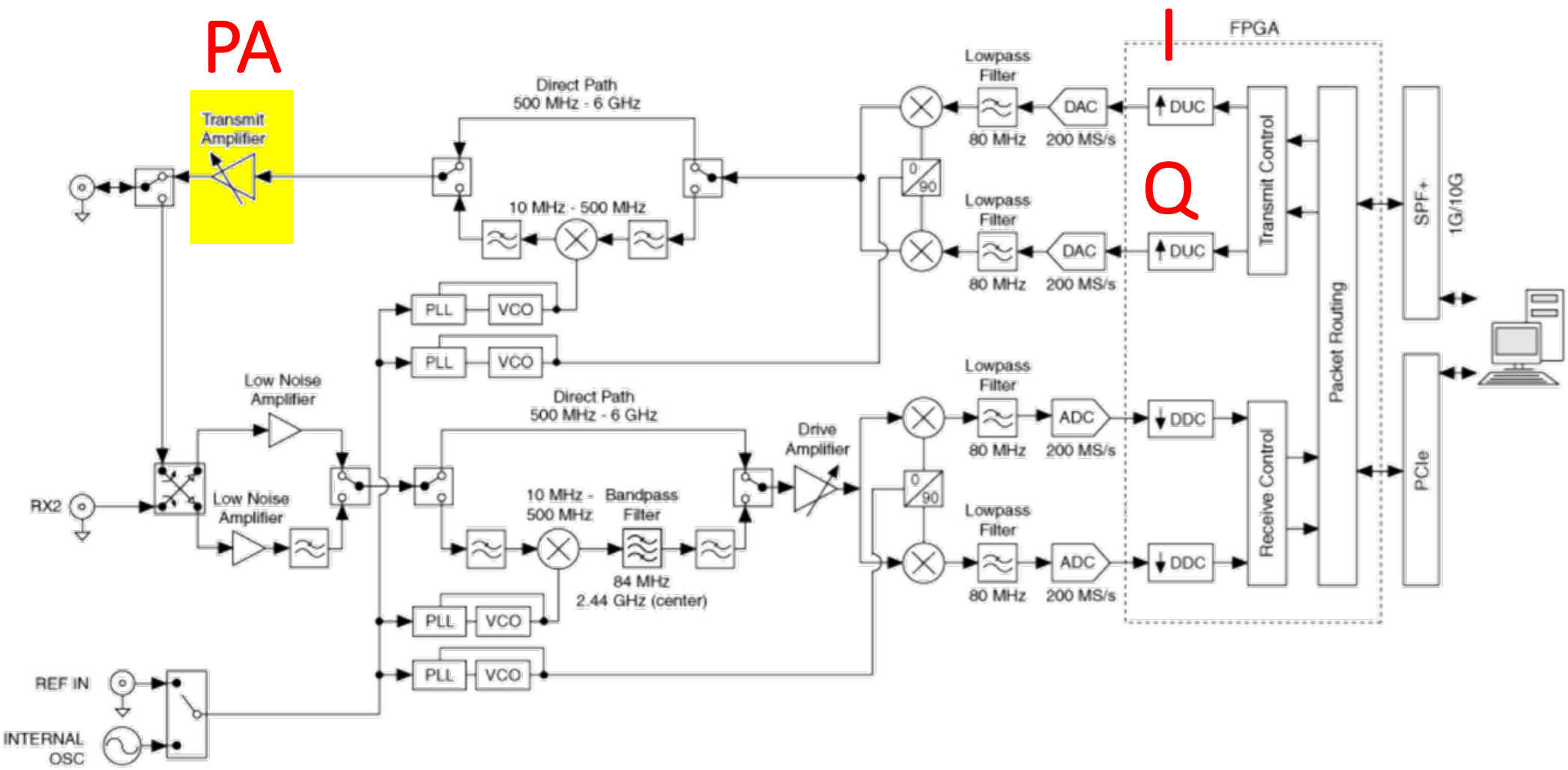
Transmitter

Mixer



USRP X310 Architecture

Transmitter

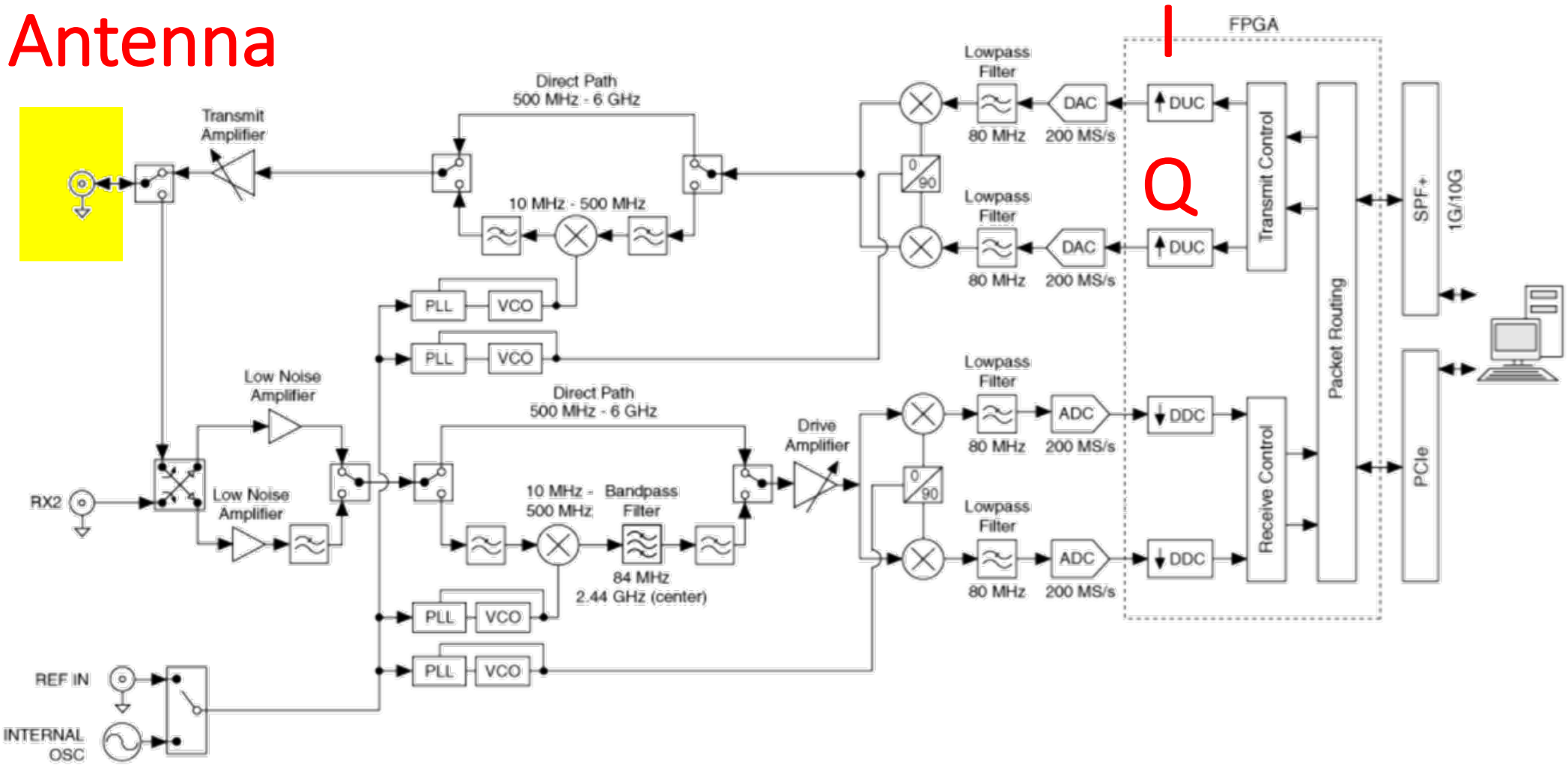


USRP X310 Architecture

Transmitter

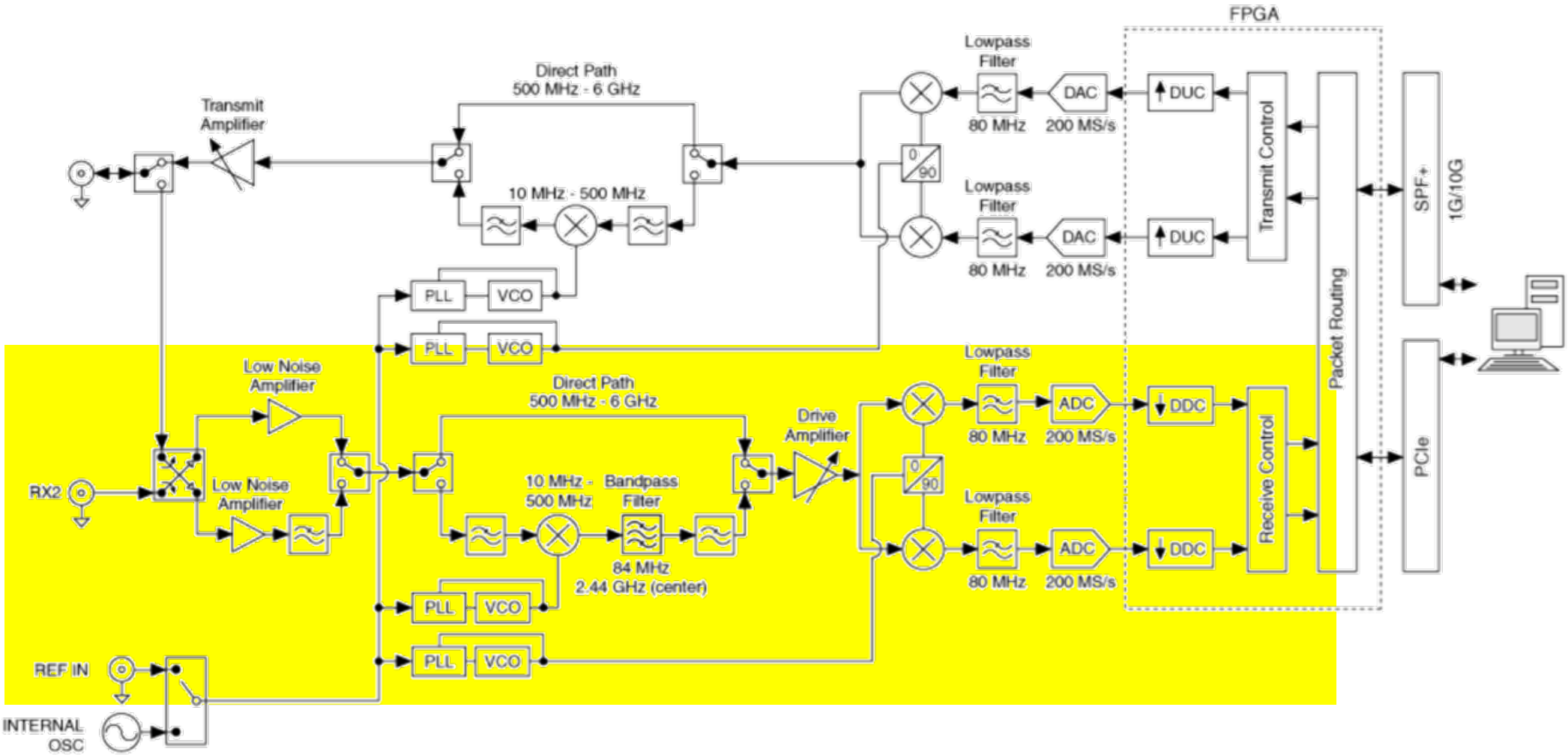
TX/RX

Antenna



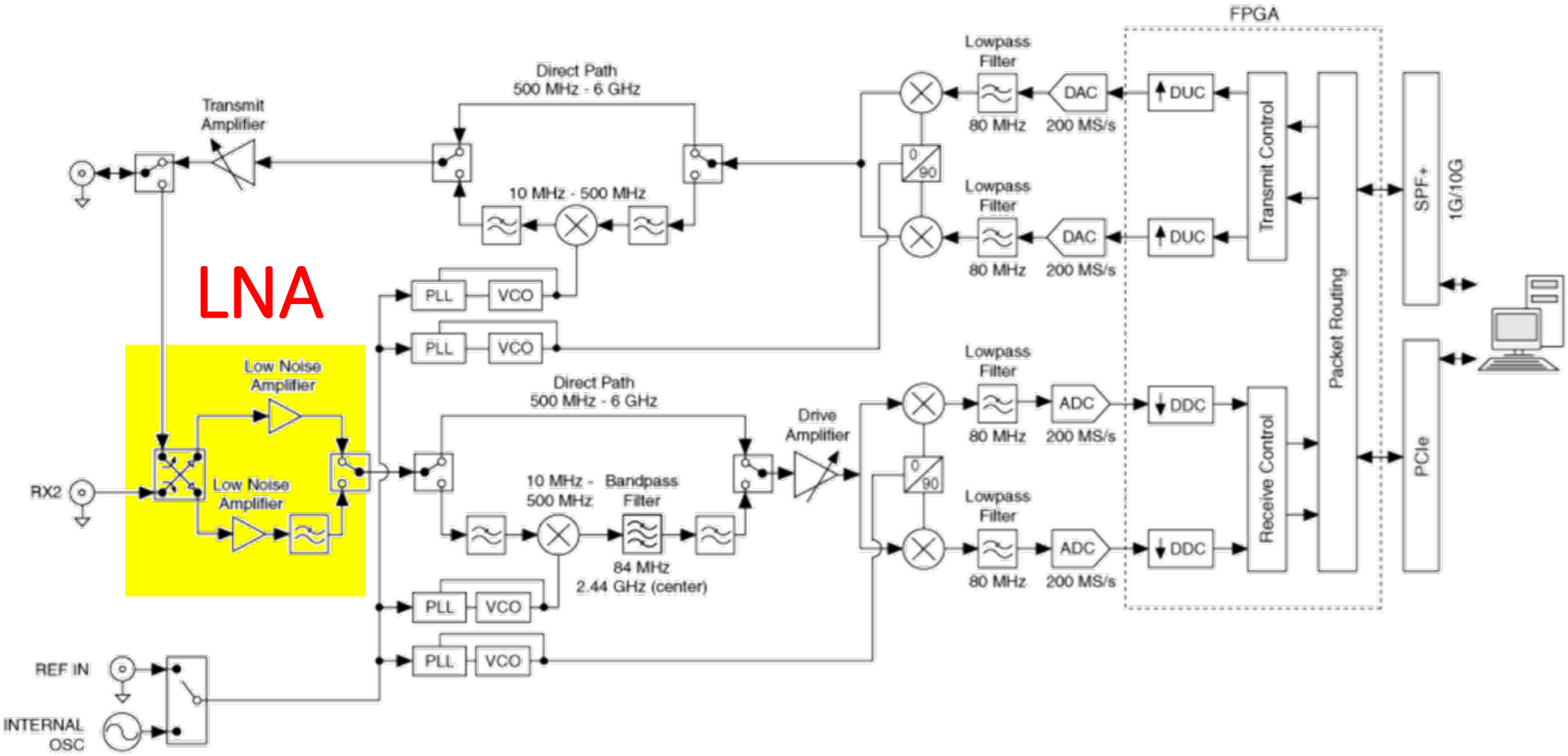
USRP X310 Architecture

Receiver



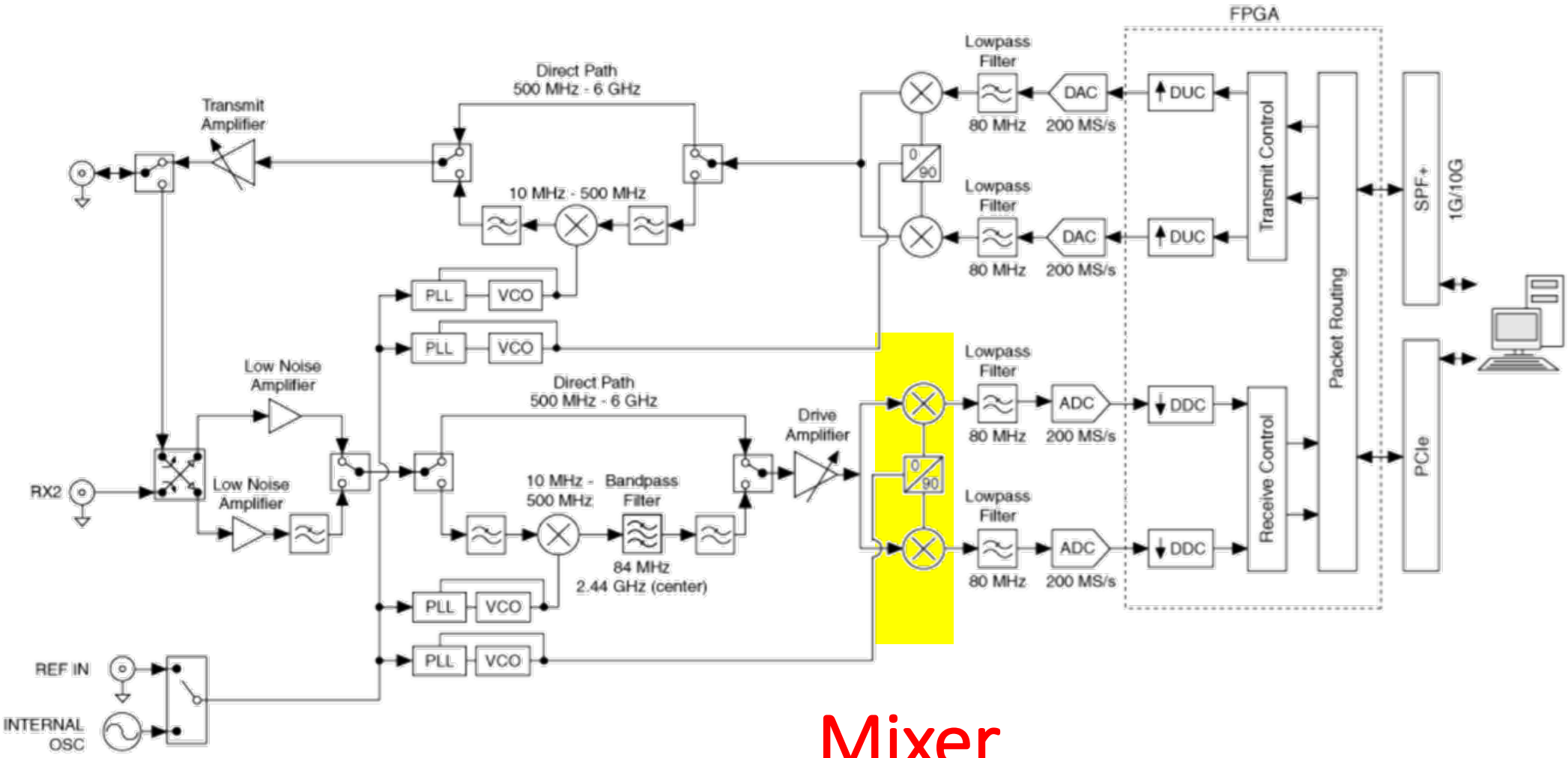
USRP X310 Architecture

Receiver



USRP X310 Architecture

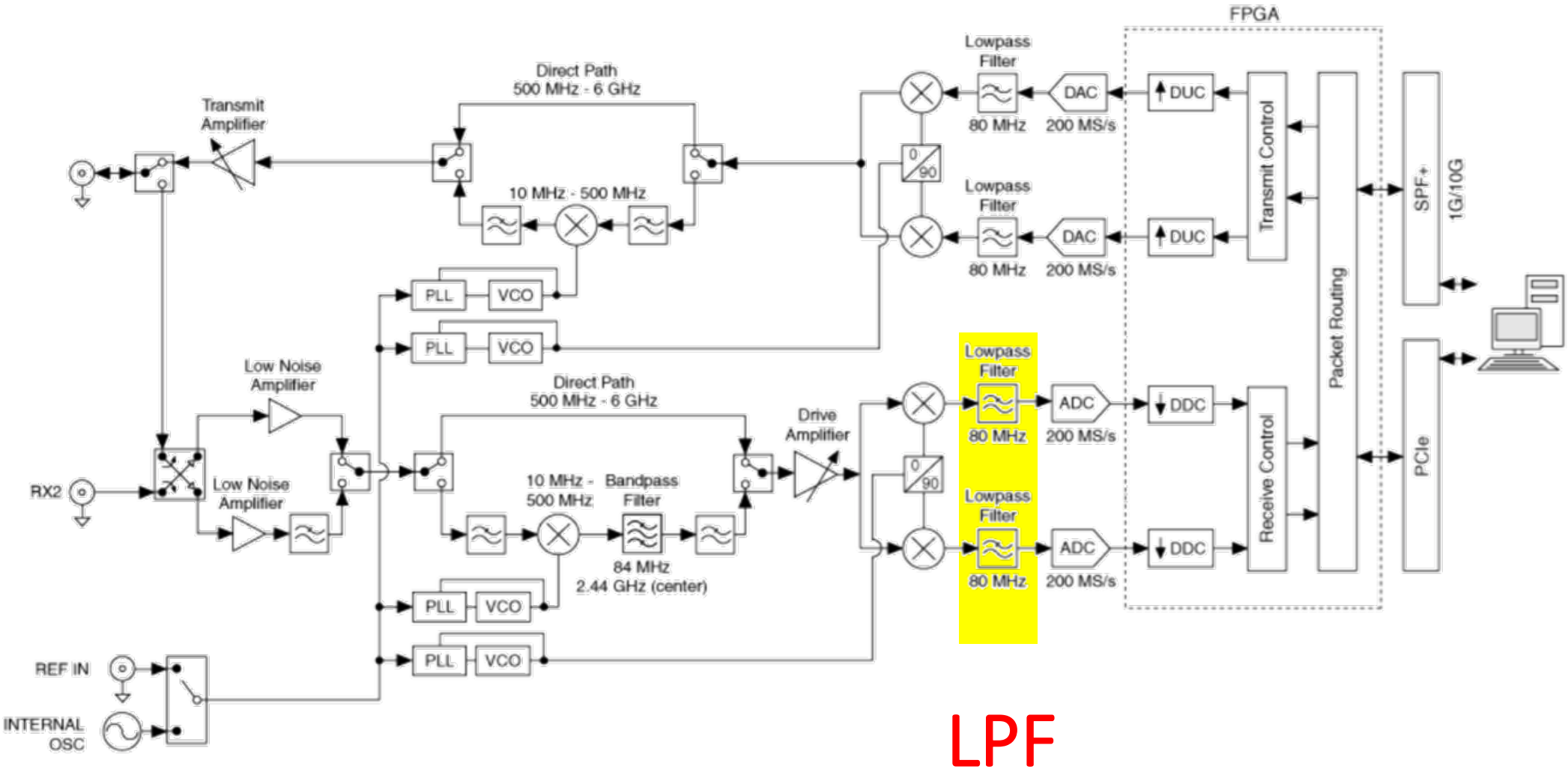
Receiver



Mixer

USRP X310 Architecture

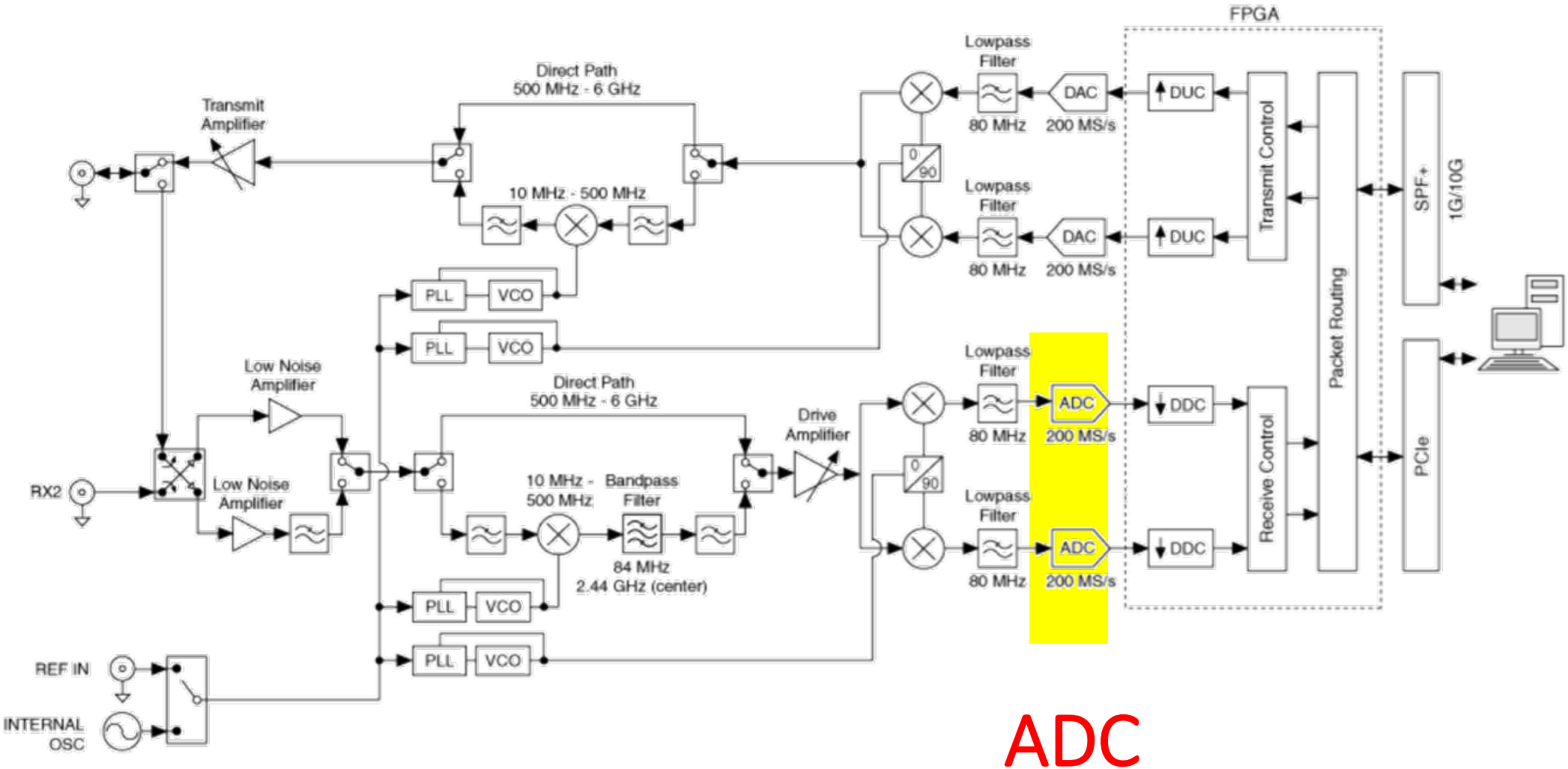
Receiver



LPF

USRP X310 Architecture

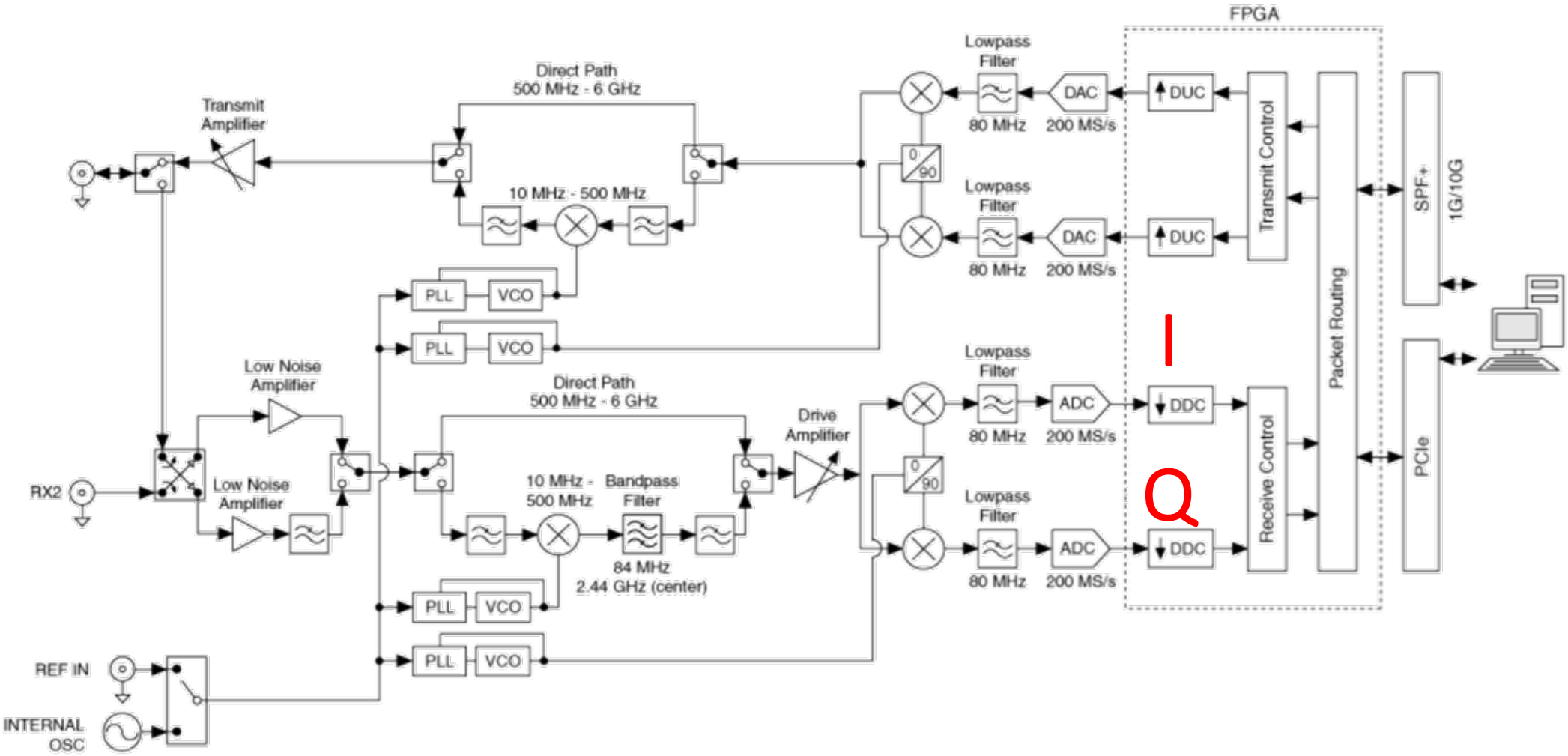
Receiver



ADC

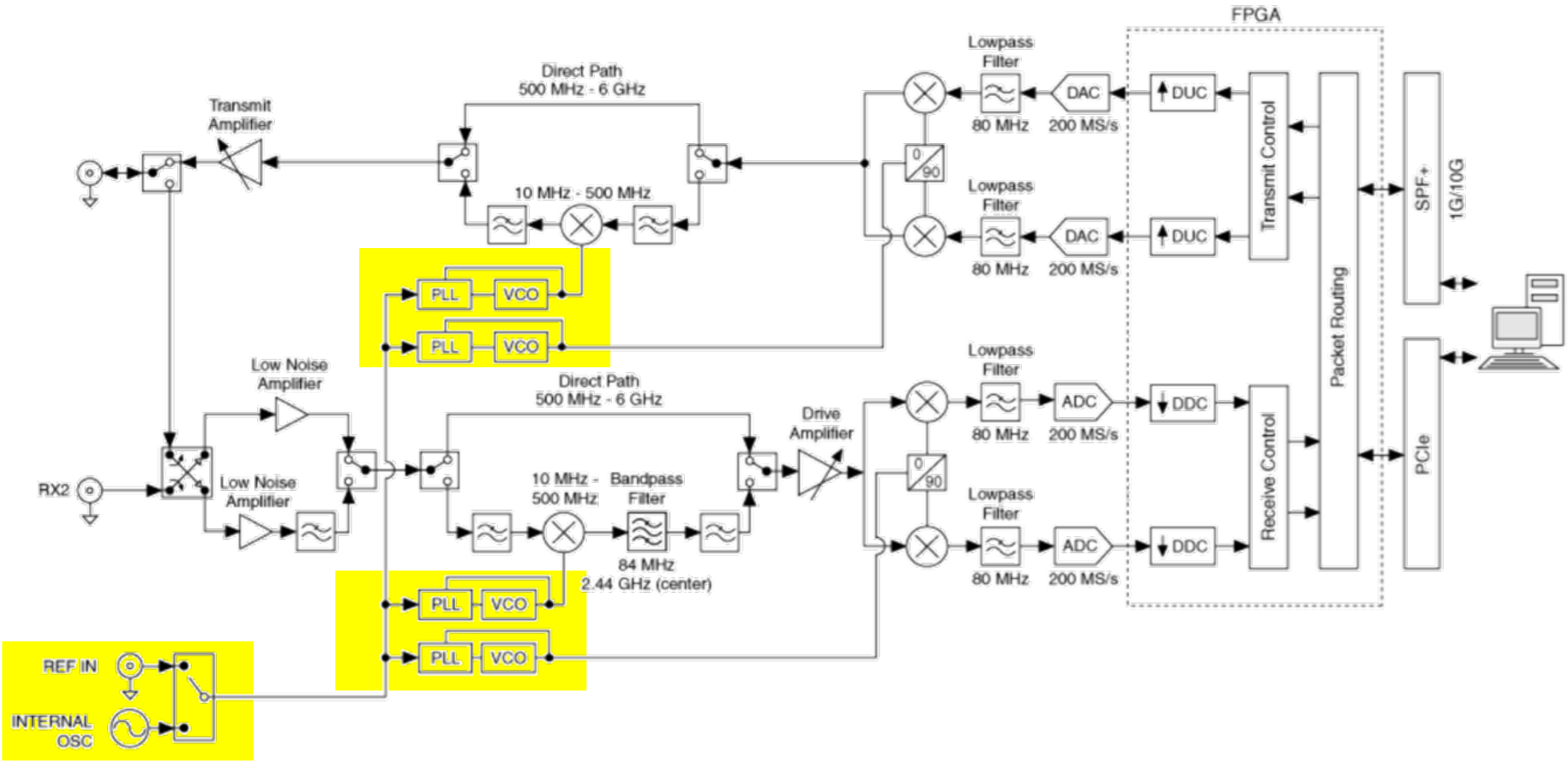
USRP X310 Architecture

Receiver

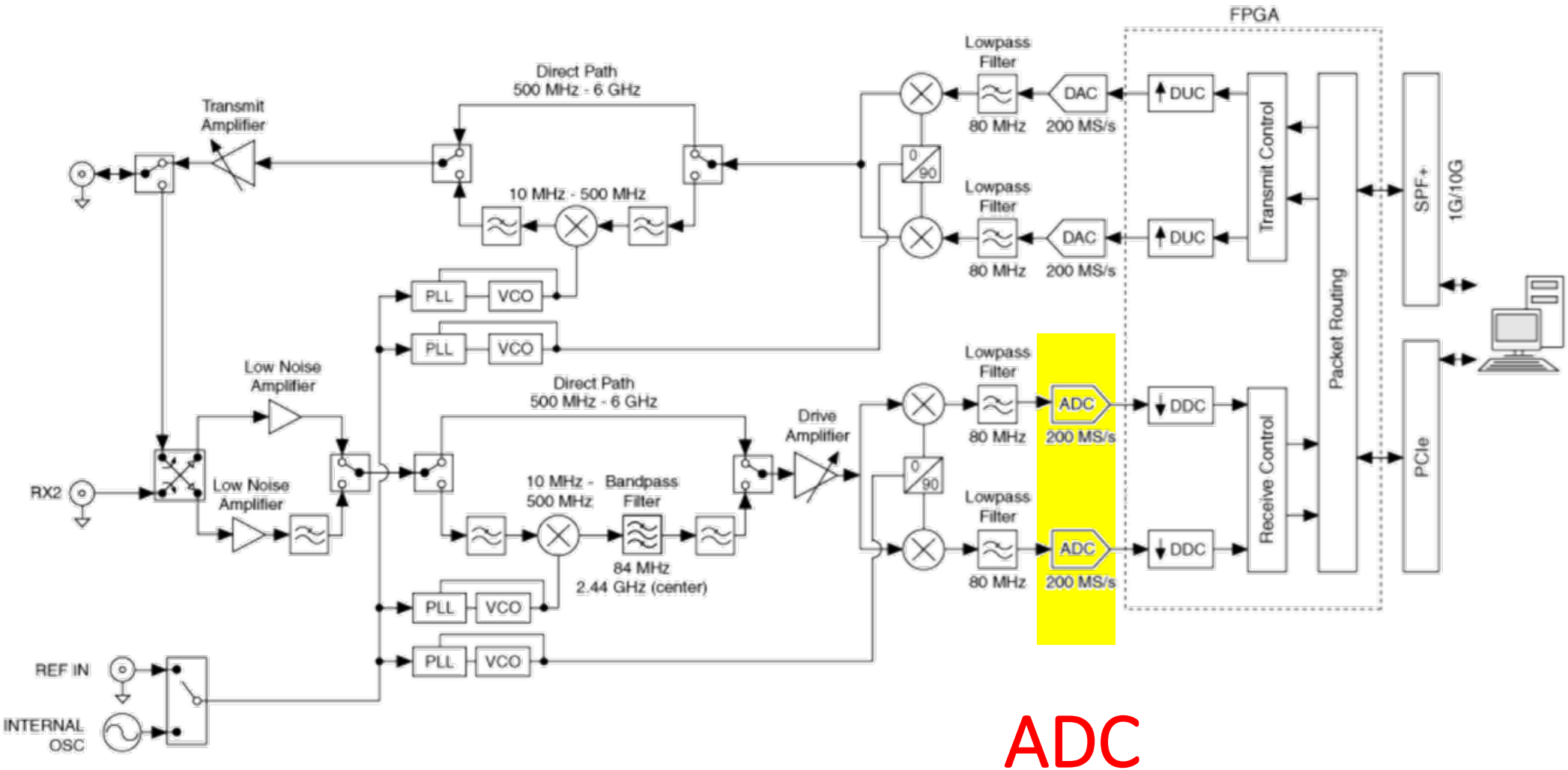


USRP X310 Architecture

Clock

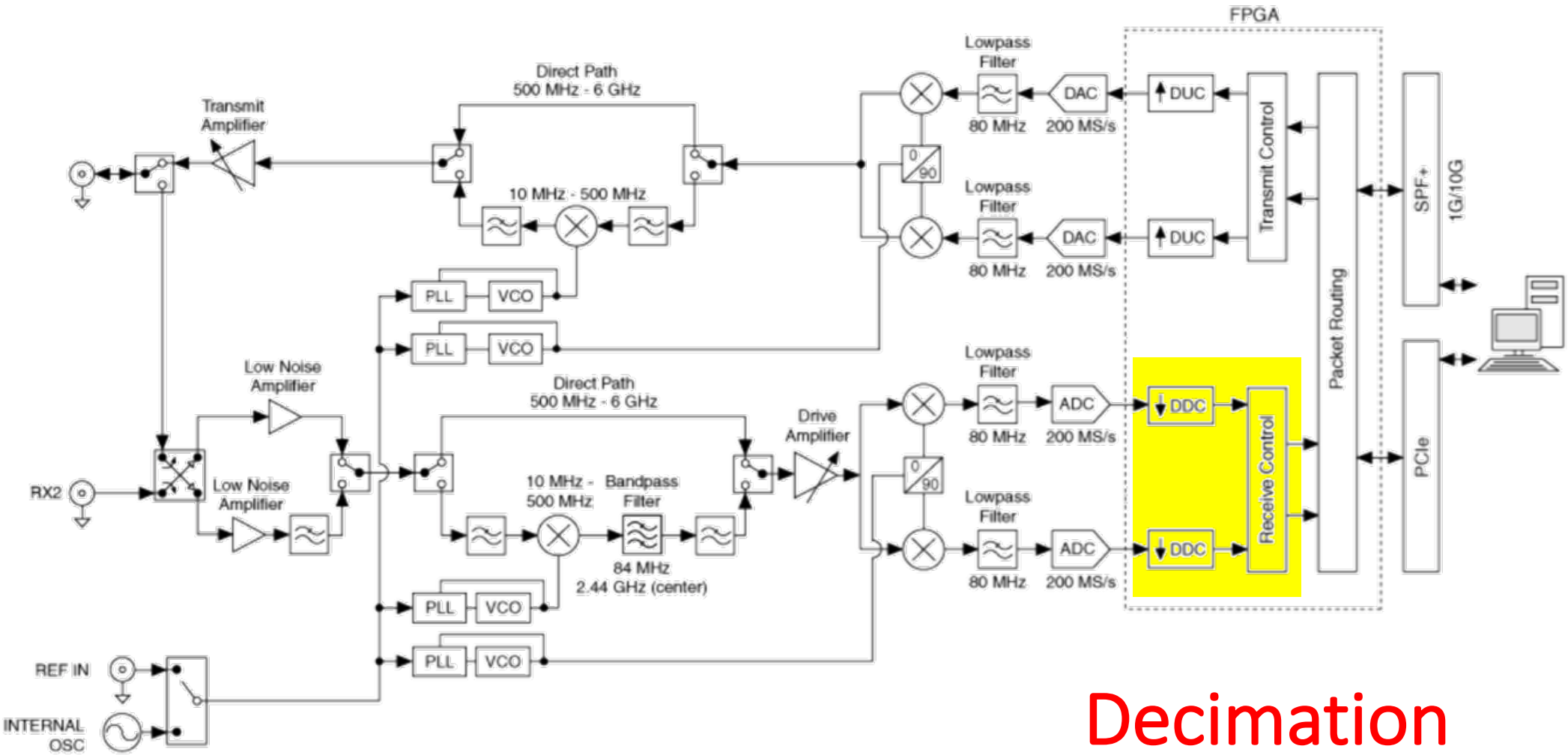


USRP X310 Architecture



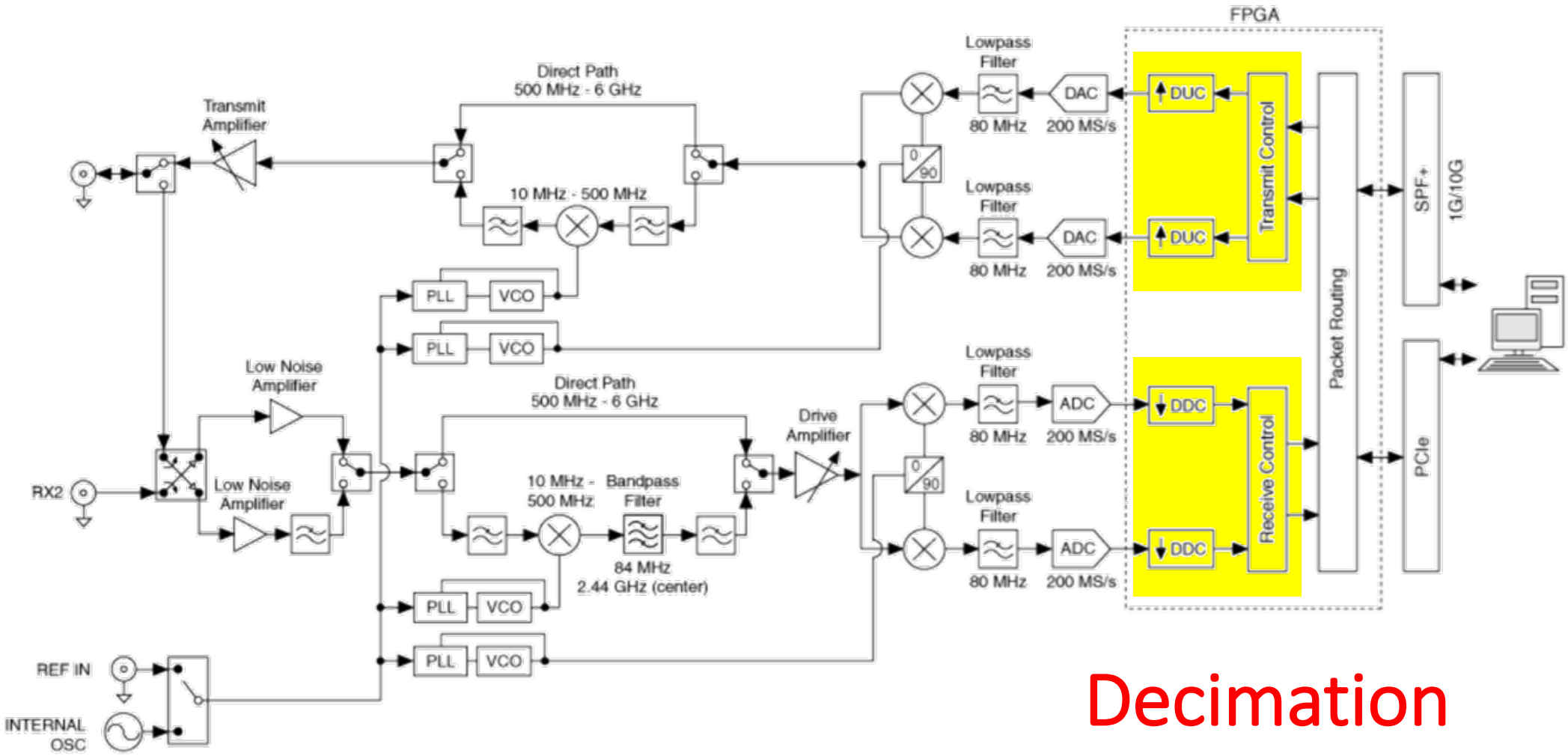
ADC

USRP X310 Architecture



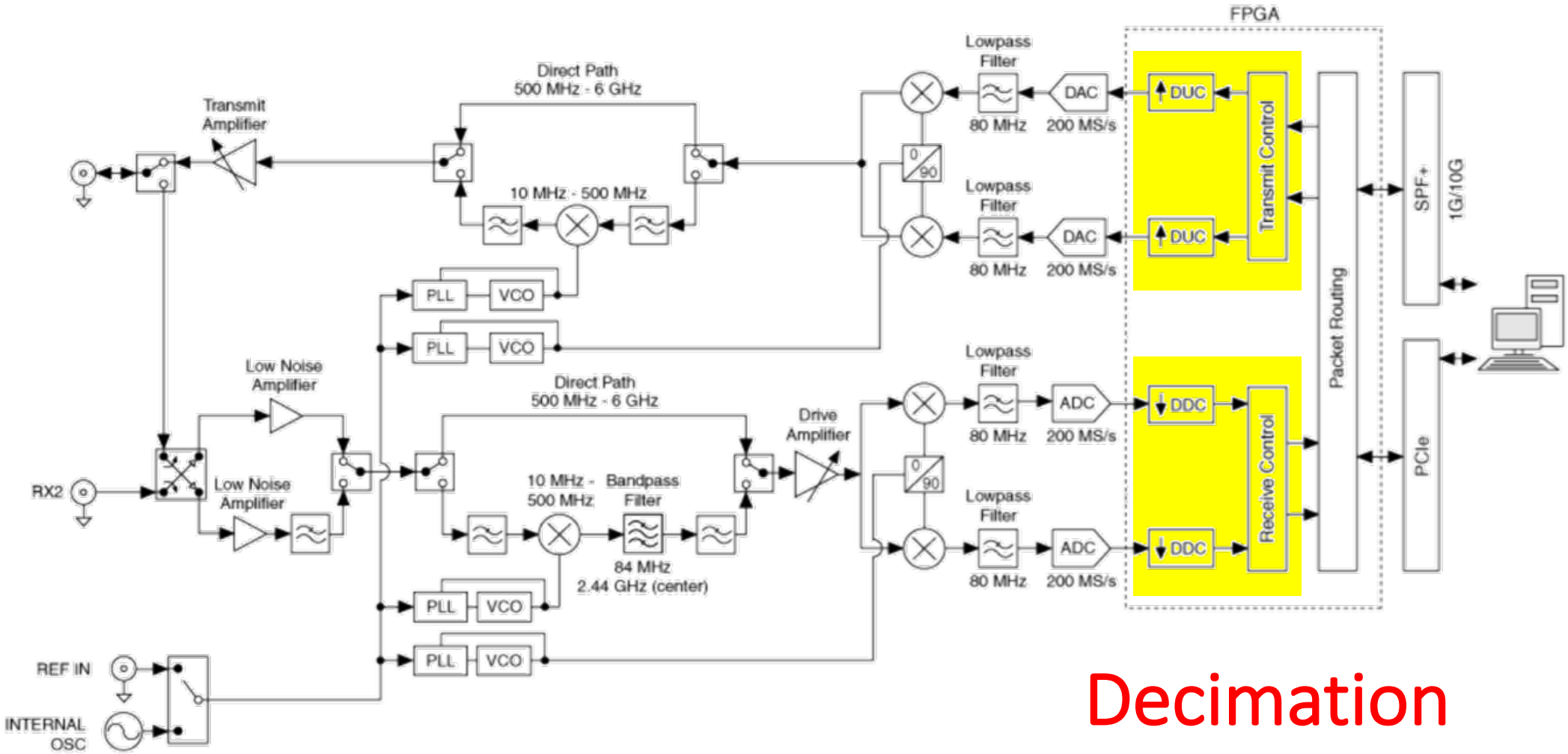
Decimation

USRP X310 Architecture



USRP X310 Architecture

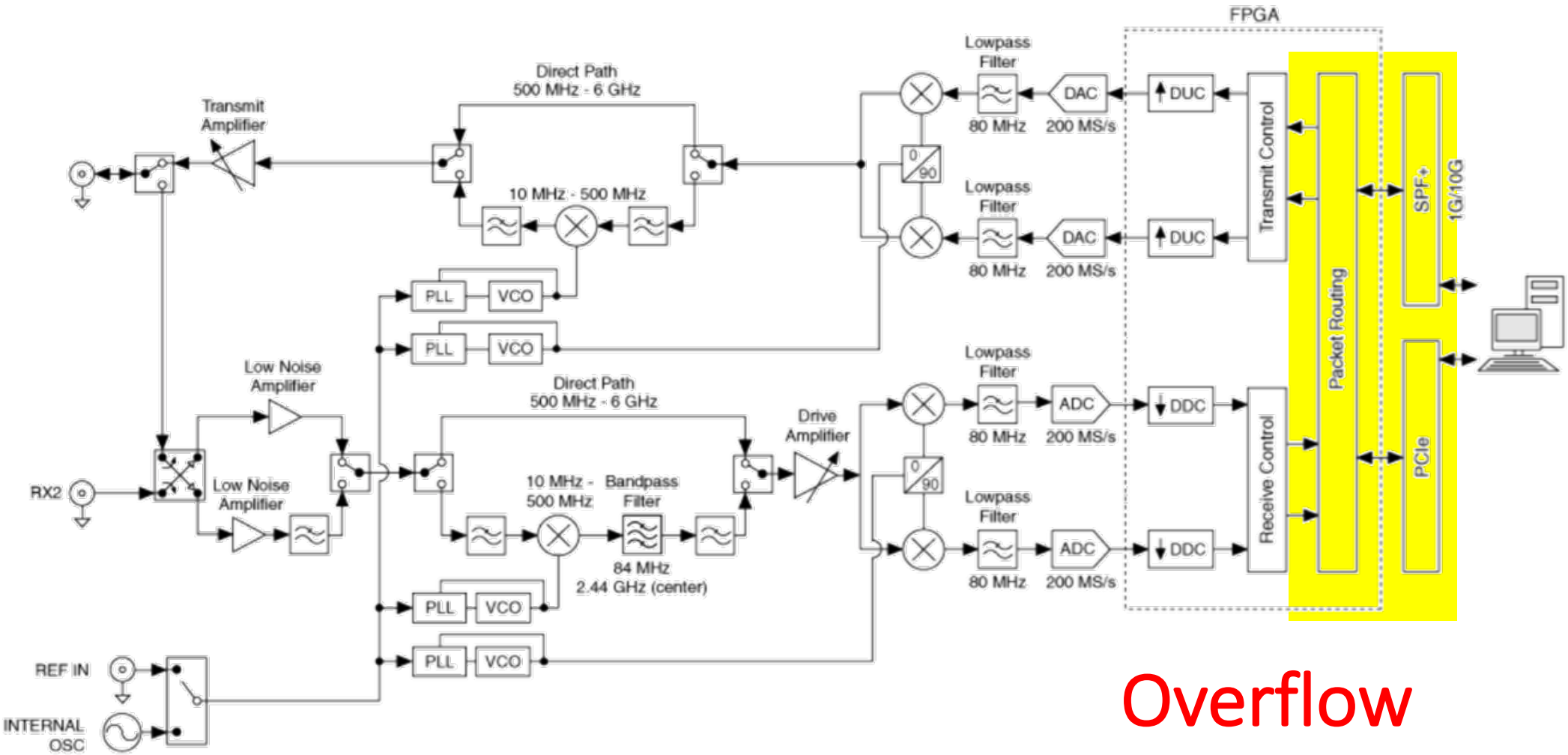
Sampling Rates: Integer divider of 200MS/s
200, 100, 200/3, 50, 40, 200/6, 200/7, 25, …



Decimation

USRP X310 Architecture

Underflow



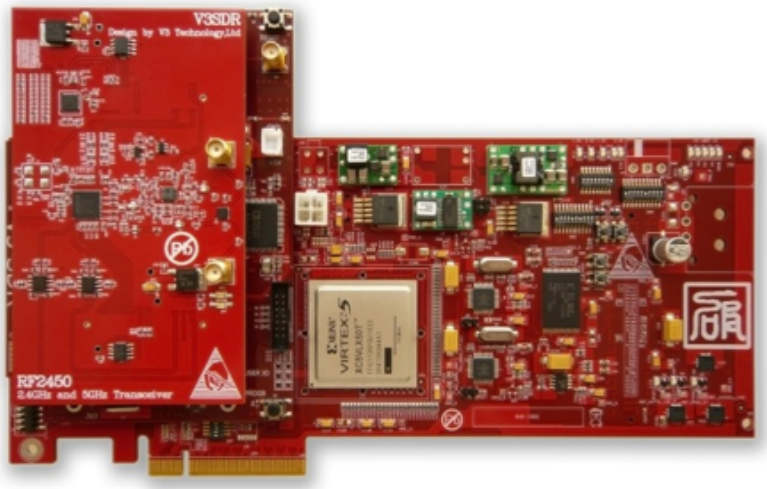
Overflow

Many SDR Platforms

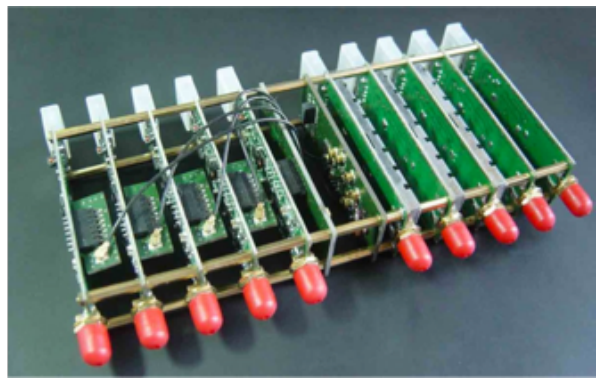
USRP: Universal Software Radio Peripheral (Ettus)

Warp: Wireless Open Access Research Platform (Rice)

SORA: Software-defined Radio (Microsoft)

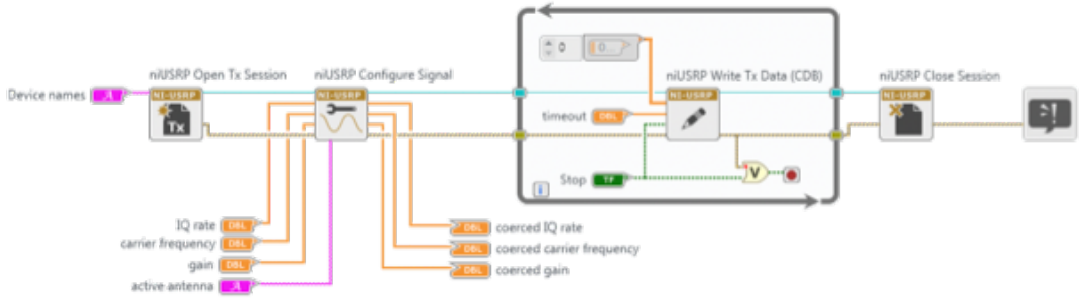


RTL-SDR



USRP SDR Software

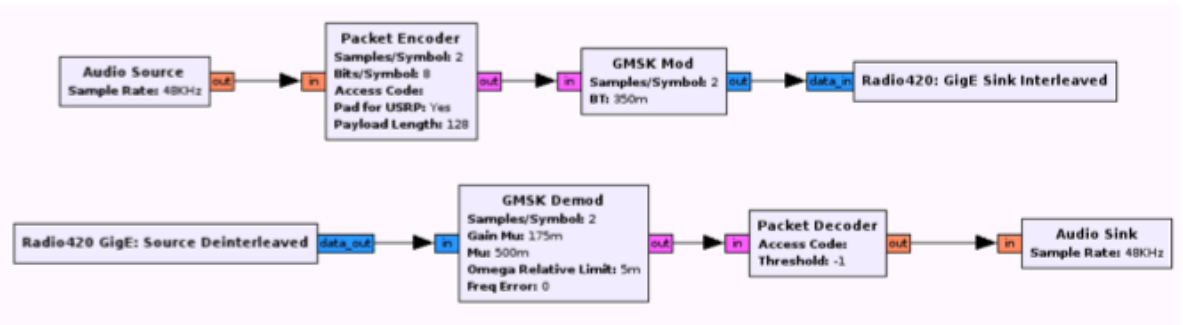
LabView:



GNURadio:

- Open Source
- Python (Flow graph)
- Extensive Library of block (C++)
- Many existing example: 802.11b, DBPSK, …

GRC:



UHD:

- USRP Hardware Driver
- C++
- Integrates with GNURadio

- USRP
  http://www.ettus.com/resource
- GNU Radio
  http://gnuradio.org/redmine/projects/gnuradio/wiki
- Available Signal Processing Blocks
  http://gnuradio.org/doc/doxygen/hierarchy.html
- GNU Radio Mailing List Archives
  http://www.gnu.org/software/gnuradio/mailinglists.html
- USRP Mailing List
  http://lists.ettus.com/pipermail/usrp-users_lists.ettus.com/
- UHD
  http://ettus-apps.sourcerepo.com/redmine/ettus/projects/uhd/wiki

Definitions & Variables

- f_c: Carrier Frequency
- B: Signal Bandwidth
- $s(t)$: Baseband Signal
- $S(f)$: Frequency Spectrum of Baseband Signal
- $\delta(f)$: Impulse Function
- $\circledast$: Convolution Operator
- $I = \Re\mathrm{e}\{s(t)\}$ & $Q = \Im\mathrm{m}\{s(t)\}$
- $(\quad)^*$: Complex Conjugate