Advanced Modulation Formats

[EENGM0003]

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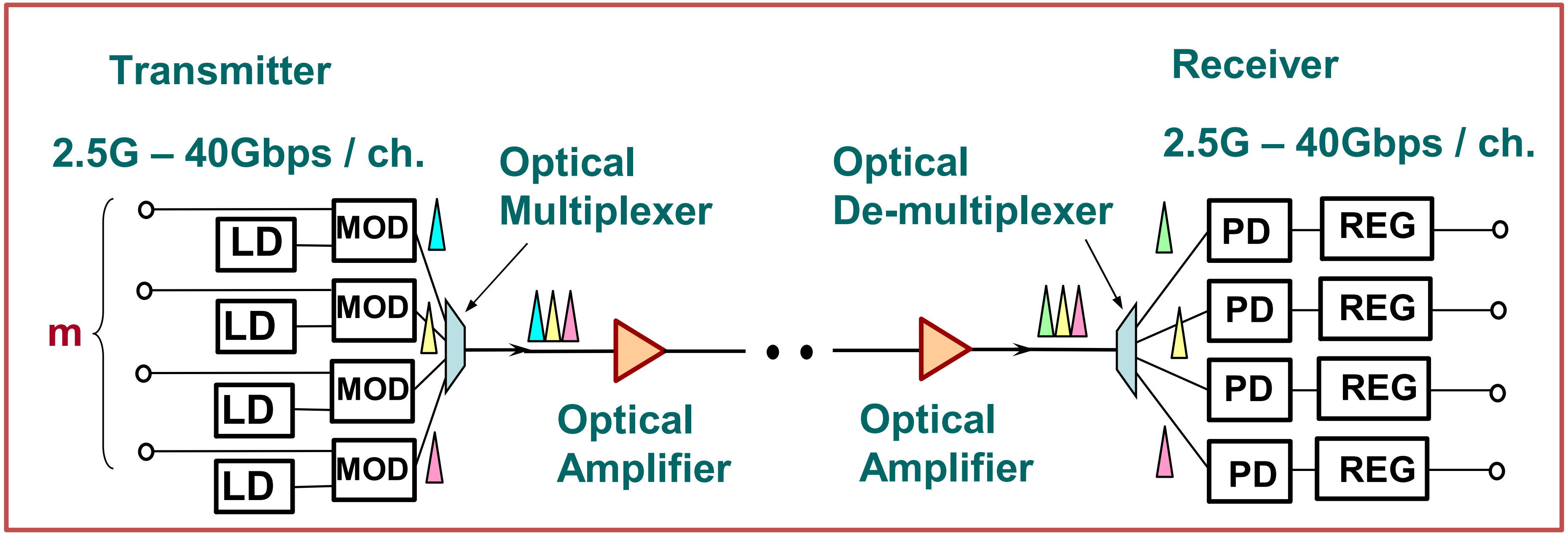
Background

Coherent detection had been intensively researched before 90s.

- Improve system sensitivity of optical transmission systems

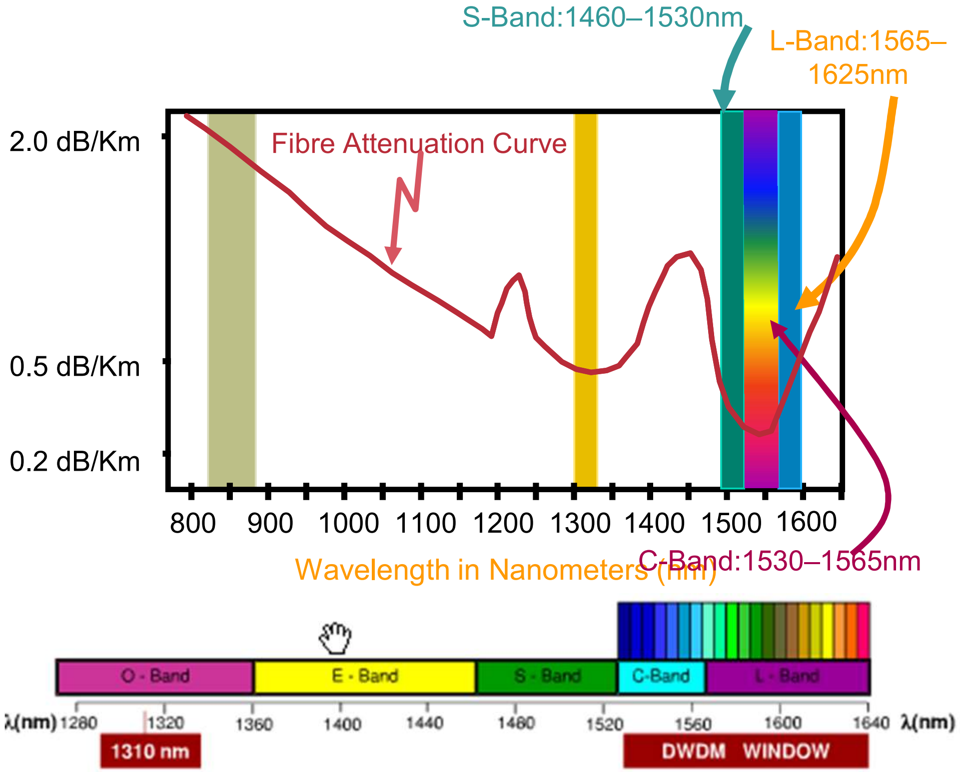
EDFA technology make WDM system with direct detection a big success.

-CWDM to DWDM, transmission capacity experienced great growth.



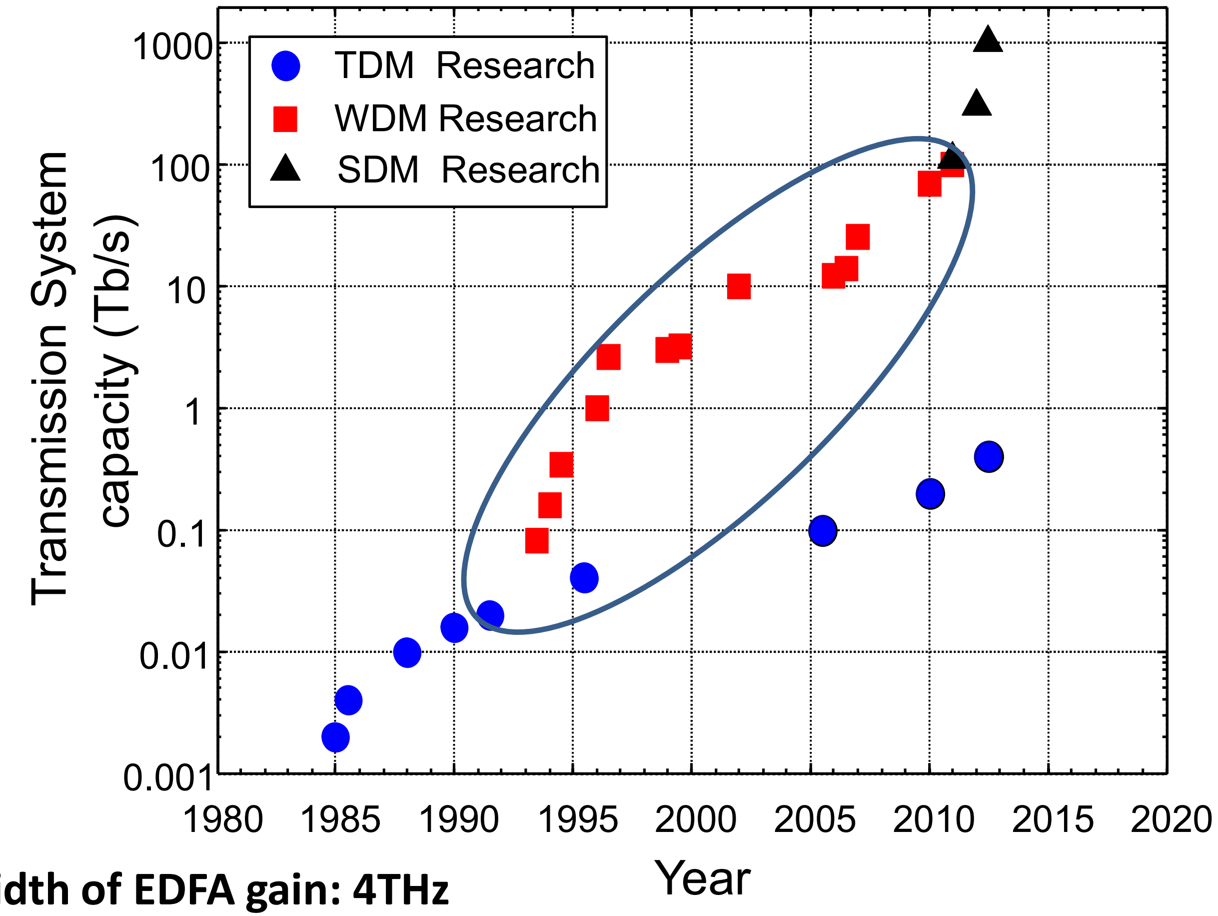
Current deployed DWDM systems: Bitrate/ch: up to 100Gbit/s
Channel space: 50GHz Channel number: 160ch (C+L band).

Background –Limitation of DWDM with direct detection



- Limitation bandwidth in fiber: C+L band
- Channel bandwidths increase with high baud rate signal.
- Dispersion, CD, PMD effect get severe for high bit rate signals.

Available Optical Capacity per Fiber



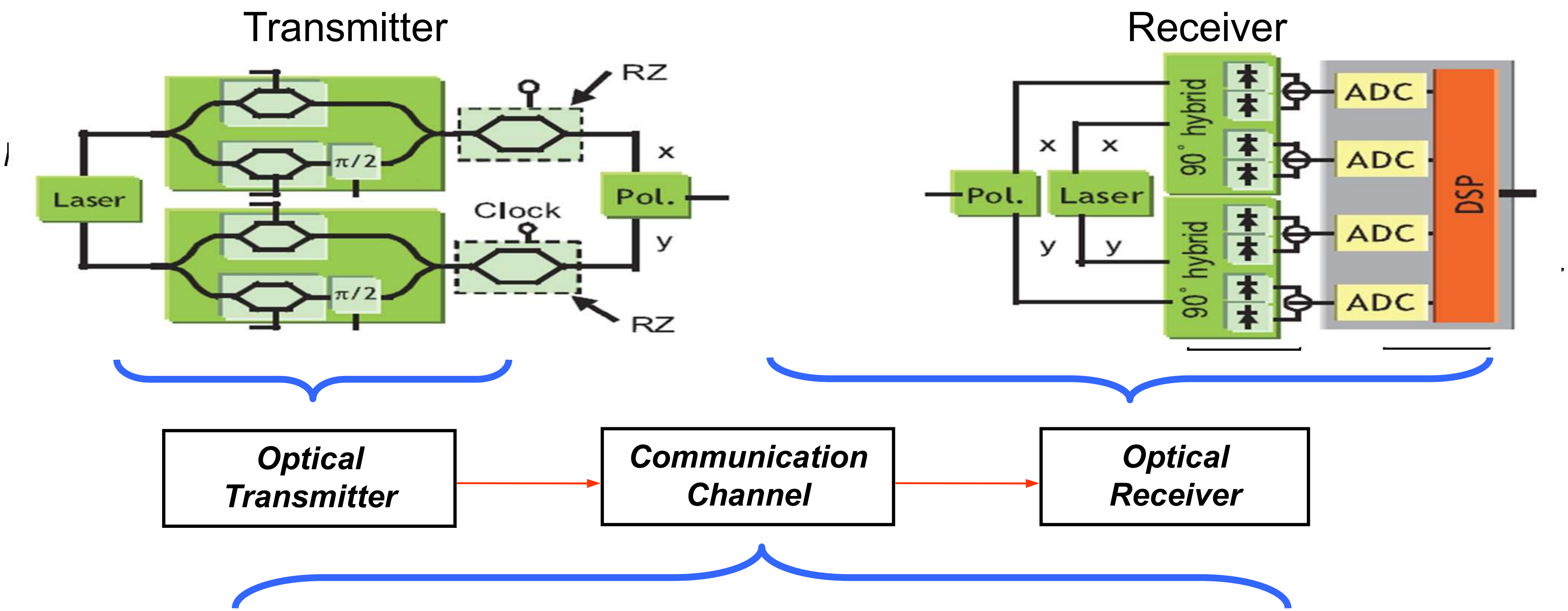
- ✓ **Total bandwidth of EDFA gain: 4THz**
- ✓ **Spectral Efficiency: >10bit/s/Hz**
- ✓ **Total capacity: 40Tbit/s/Fiber in a few years**

Courtesy of R.-J. Essiambre and R. W. Tkach

Two key enabling technologies

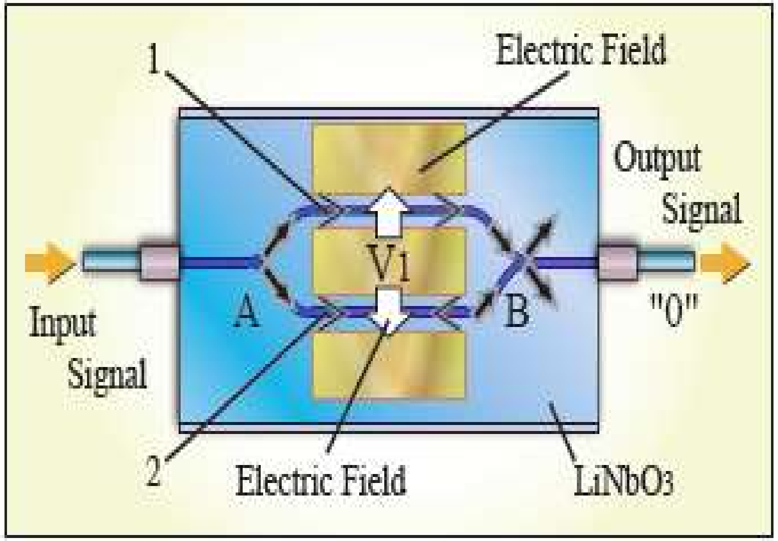
- Advanced modulation formats:
  - Encoding data on other dimensions, such as phase, polarization, not just intensity
  - Improve spectrum efficiency
- Coherent detection
  - Full information of optical fields
- Digital Signal Processing
  - DSP based linear and nonlinear compensation
    - CD
    - PMD, Distortion
  - Pulse shaping or Spectrum squeezing

Advanced modulation formats + Digital Signal Processing

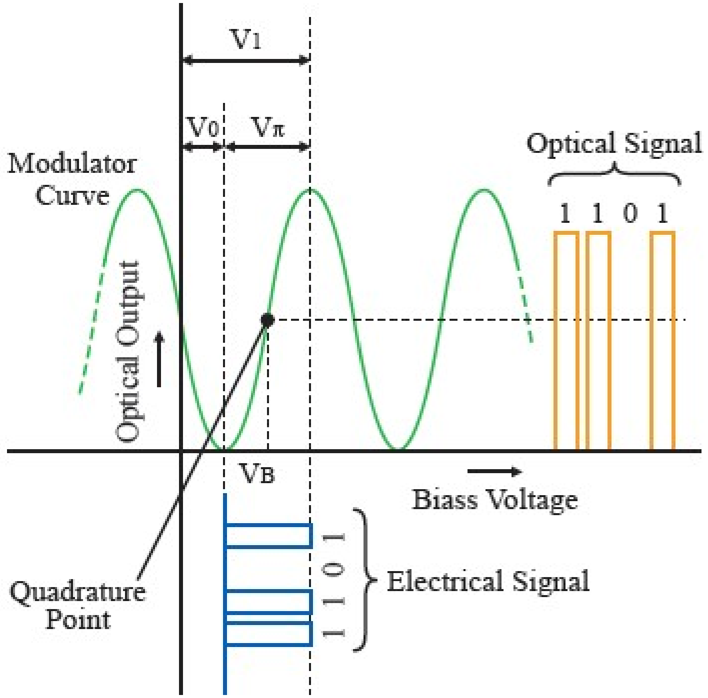


- Free space or Deepspace (between satellites)
- Optical Fiber

Transmitter-Optical Intensity modulator

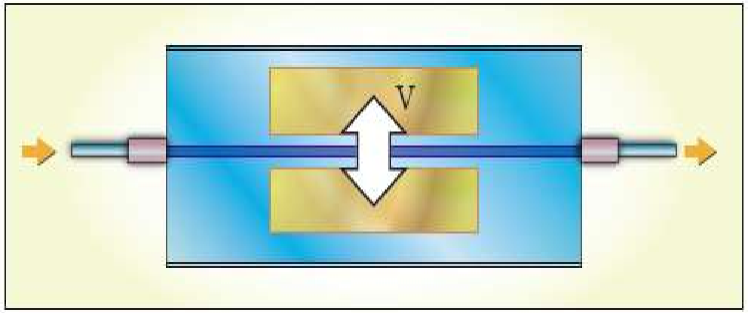


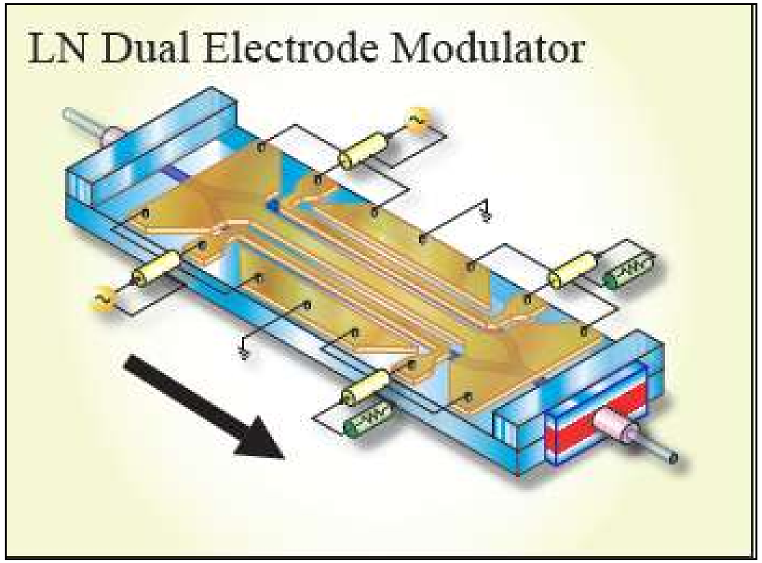
Bias at Quad point:



$$E_{out} = E_{in}(t) * \cos\left(\frac{\Delta\varphi_{MZM}(t)}{2}\right)$$
$$= E_{in}(t) \bullet \cos\left(\frac{u(t)}{2Vpi}\pi\right)$$

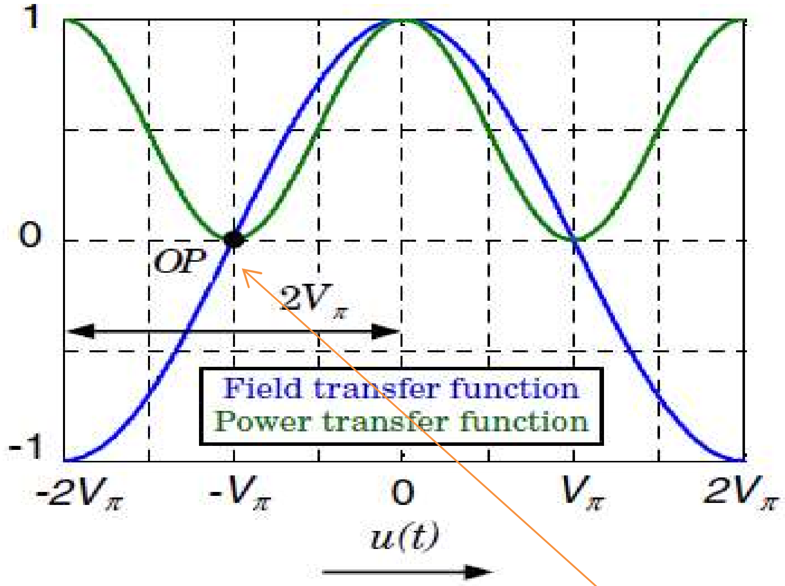
Transmitter-Optical Phase modulator





$$E_{out} = E_{in}(t) * e^{j\frac{u(t)}{V_{pi}}\pi}$$

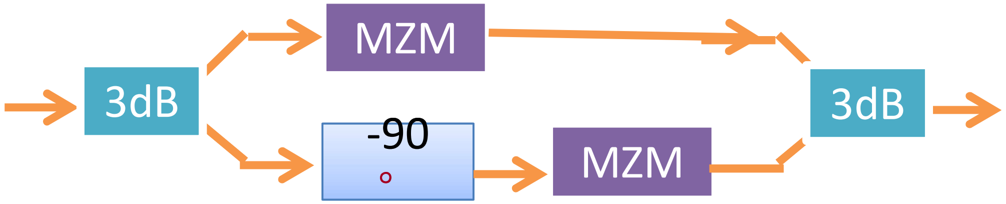
Bias at null Point, Intensity Modulator can be used for binary phase modulation



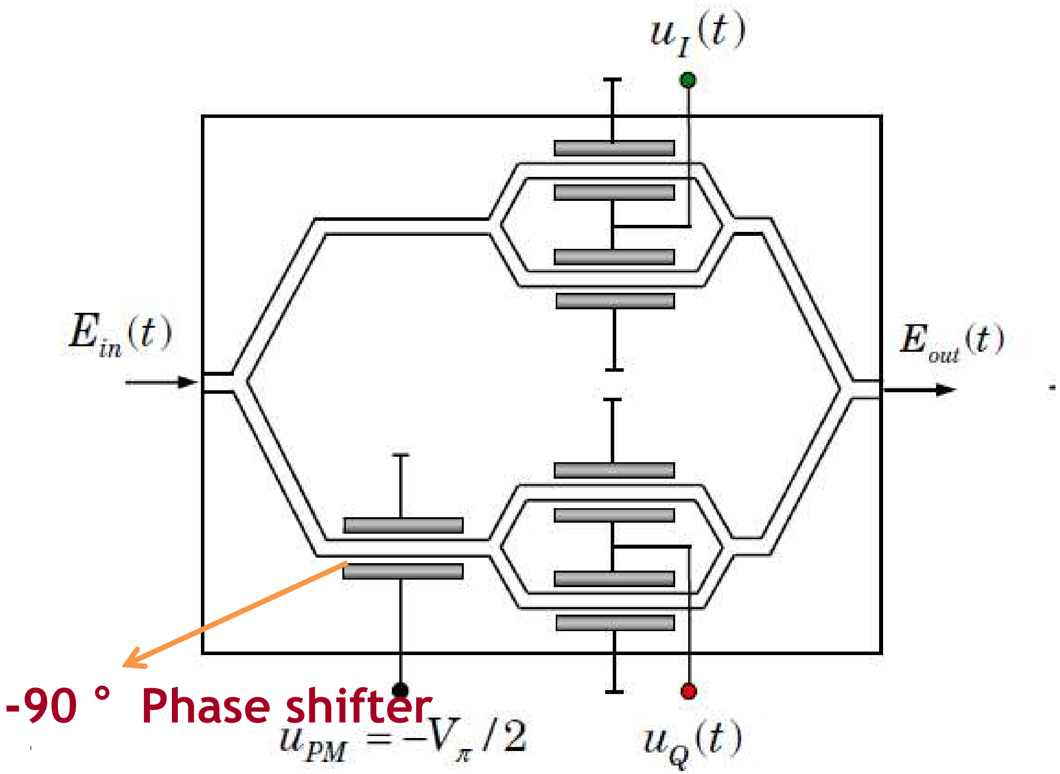
$$E_{out} = E_{in}(t) * \cos(\frac{\Delta\varphi_{MZM}(t)}{2}) = E_{in}(t) \bullet \cos(\frac{u(t)}{2V_{pi}}\pi)$$

Phase skip occurs when driven signal cross Null point

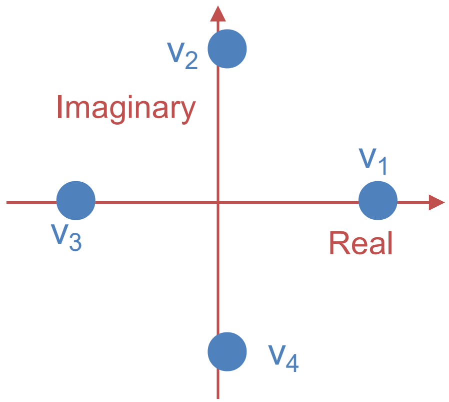
Transmitter-IQ modulator



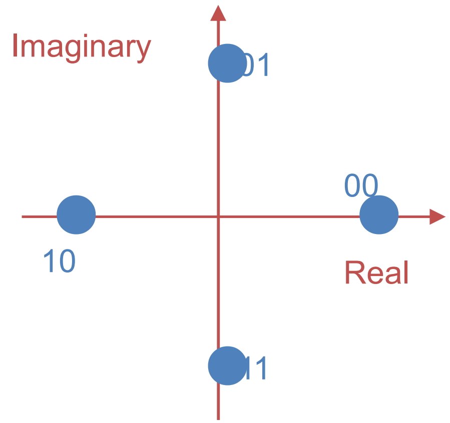
$$\frac{E_{out}(t)}{E_{in}(t)} = \frac{1}{2}\cos\left(\frac{\Delta\varphi_I(t)}{2}\right) + j\frac{1}{2}\cos\left(\frac{\Delta\varphi_Q(t)}{2}\right)$$

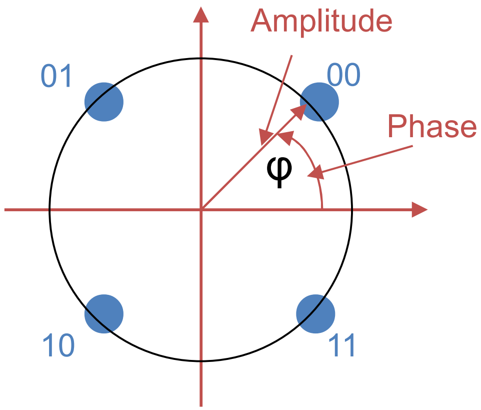


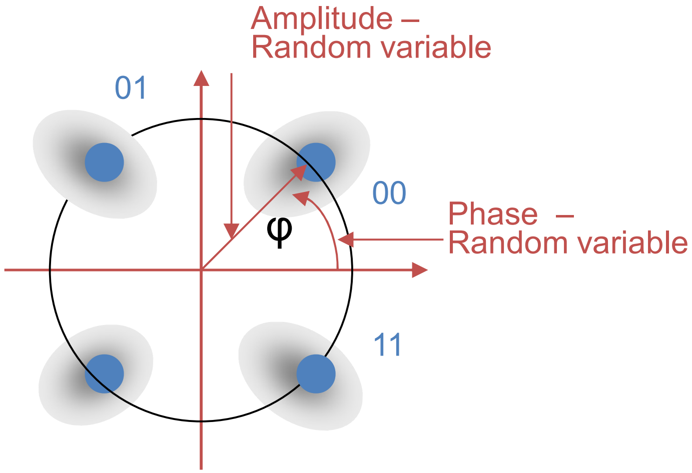
Multi-Phase Modulation



Voltage	Symbol
1+ j 0	00
0 + j	01
-1+ j 0	10
0 - j	11



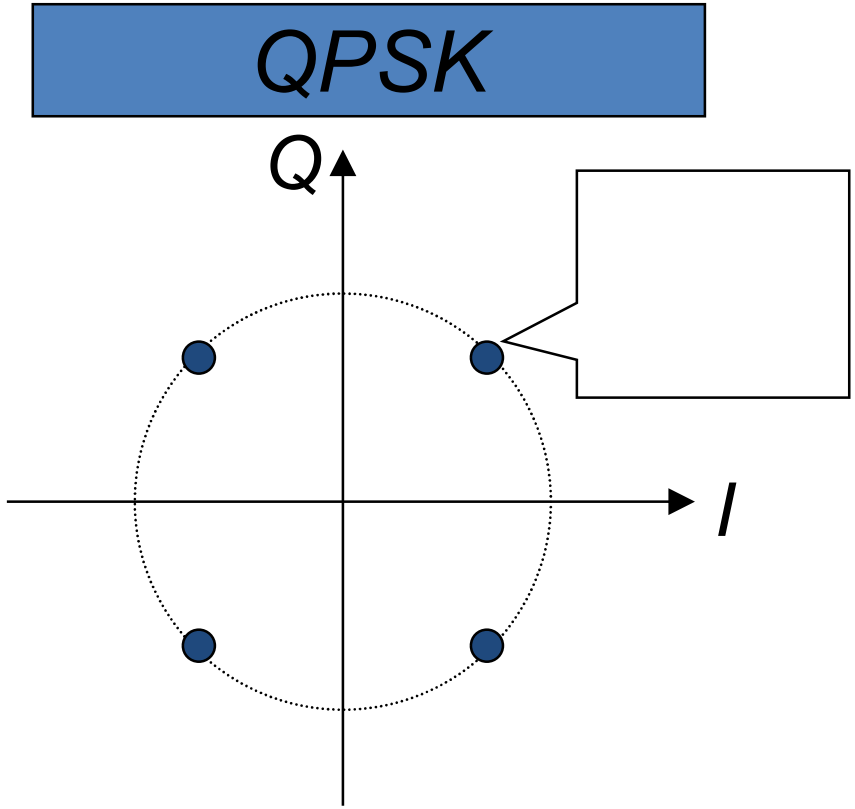




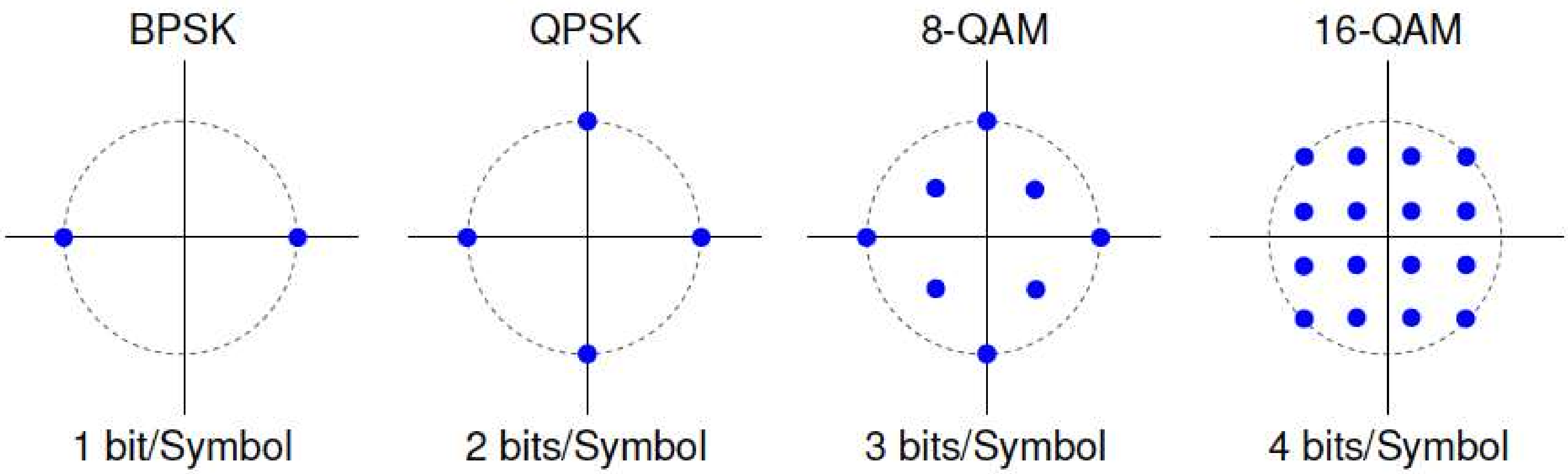
Constellation map

$(a_k + jb_k)$ is plotted on I(real)-Q(imaginary) plane

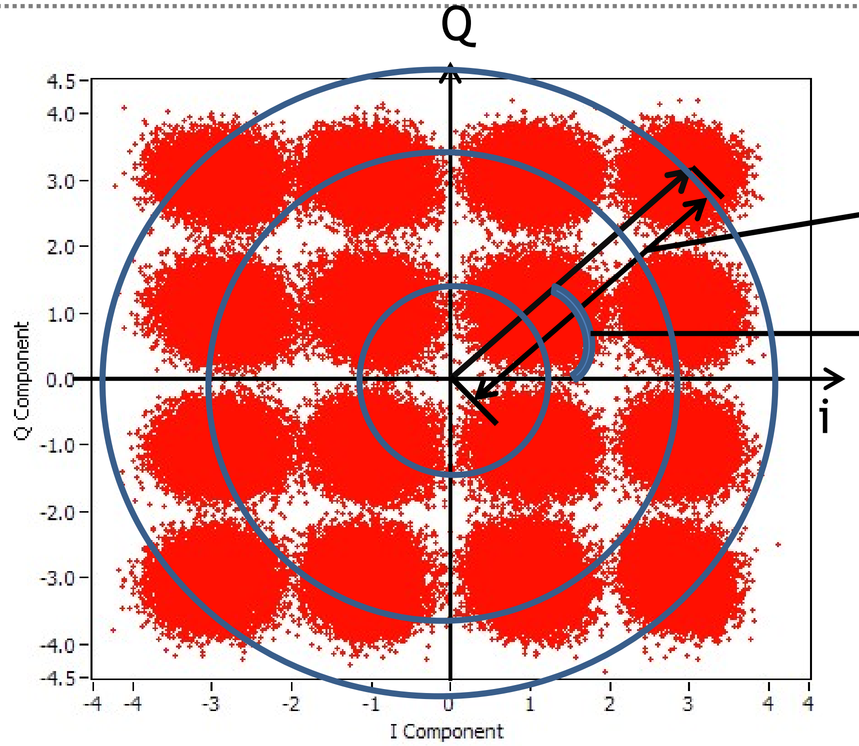
data		a_k	b_k
00	π/4	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$
01	3π /4	$-\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$
11	5π /4	$-\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$
10	7π /4	$\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$



Example of constellations



Constellation diagram



I: In-phase Q: Quadrature phase

$a_{IQM}(t)$: Amplitude moudulation

$\psi_{IQM}(t)$: Phase moudulation

QAM: Quadrature Amplitude modulation

16QAM signal: 16 point, 4 bit/symbol

28 Gbaud/s Pol-Mux 16QAM signal:
224GBit/s at 50GHz Channel grid, with spectral efficiency: 4.2 b/s/Hz

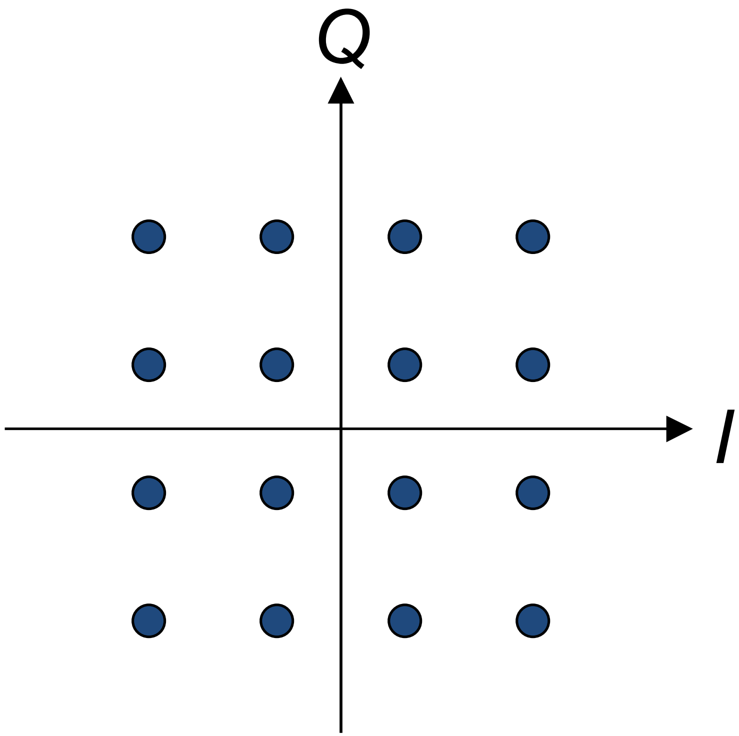
For High-order modulation, a symbol represent several bit information.

→ M bit information need 2^M status

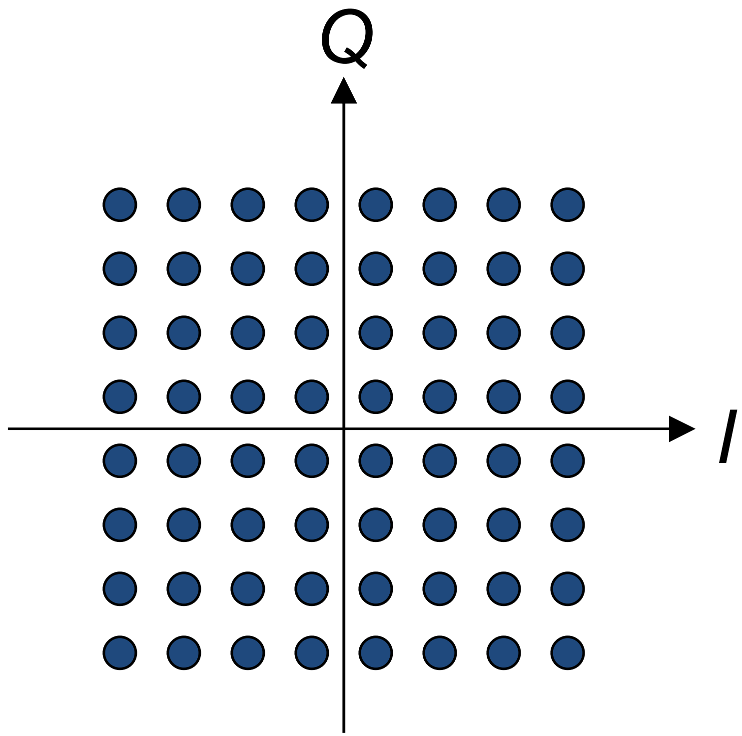
$$\{b_{1k}, b_{2k}, \bullet\bullet\bullet, b_{mk}\} \rightarrow b_k$$

Quadrature Amplitude Modulation(QAM)

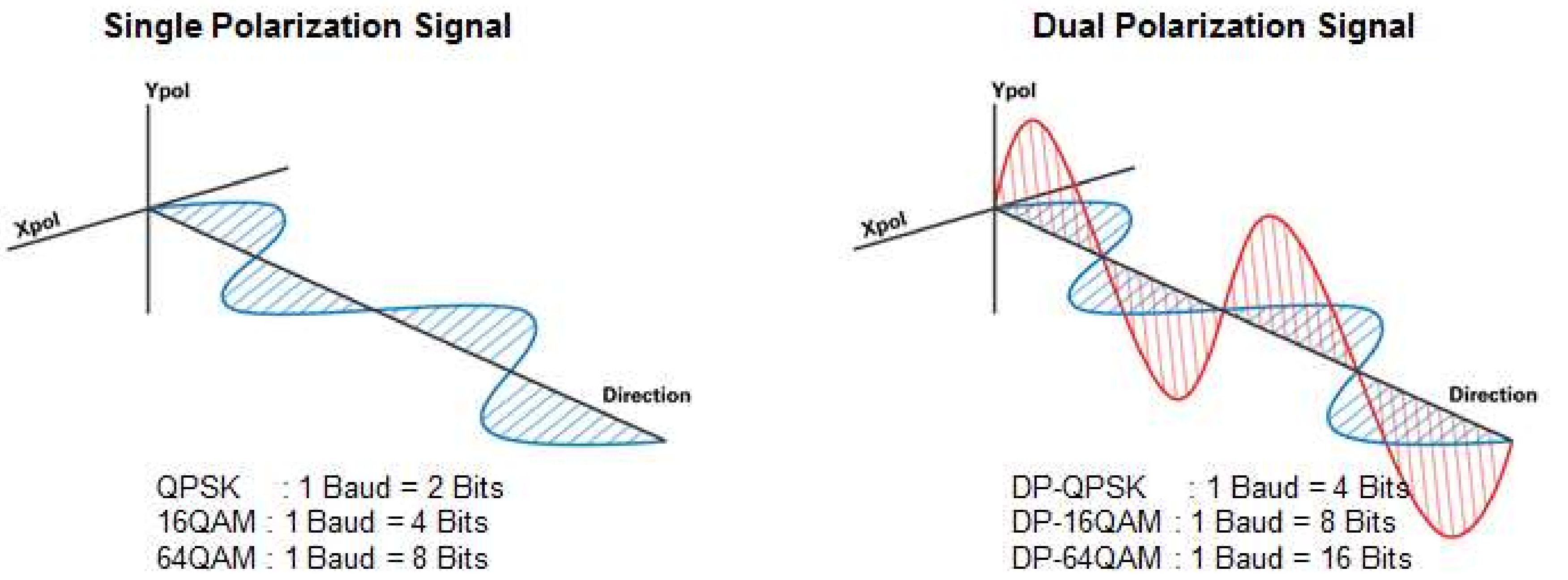
16QAM



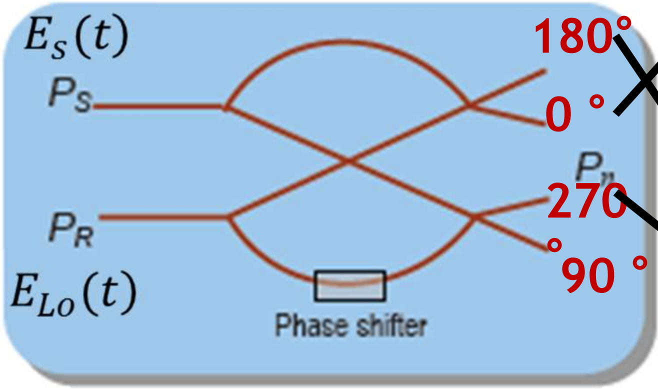
64QAM



Polarization Multiplexing



Receiver -90° Hybrid



$$\begin{bmatrix} E_{out\,1}(t) \\ E_{out\,2}(t) \\ E_{out\,3}(t) \\ E_{out\,4}(t) \end{bmatrix} = \frac{1}{2} \bullet \begin{bmatrix} e^{j\psi_{11}} & e^{j\psi_{12}} \\ e^{j\psi_{21}} & j \bullet e^{j\psi_{22}} \\ e^{j\psi_{31}} & -e^{j\psi_{32}} \\ e^{j\psi_{41}} & -j \bullet e^{j\psi_{42}} \end{bmatrix} \bullet \begin{bmatrix} E_s(t) \\ E_{Lo}(t) \end{bmatrix}$$

Where $\psi_{11} - \psi_{12} = \psi_{21} - \psi_{22} = \psi_{31} - \psi_{32} = \psi_{41} - \psi_{42} = 0$

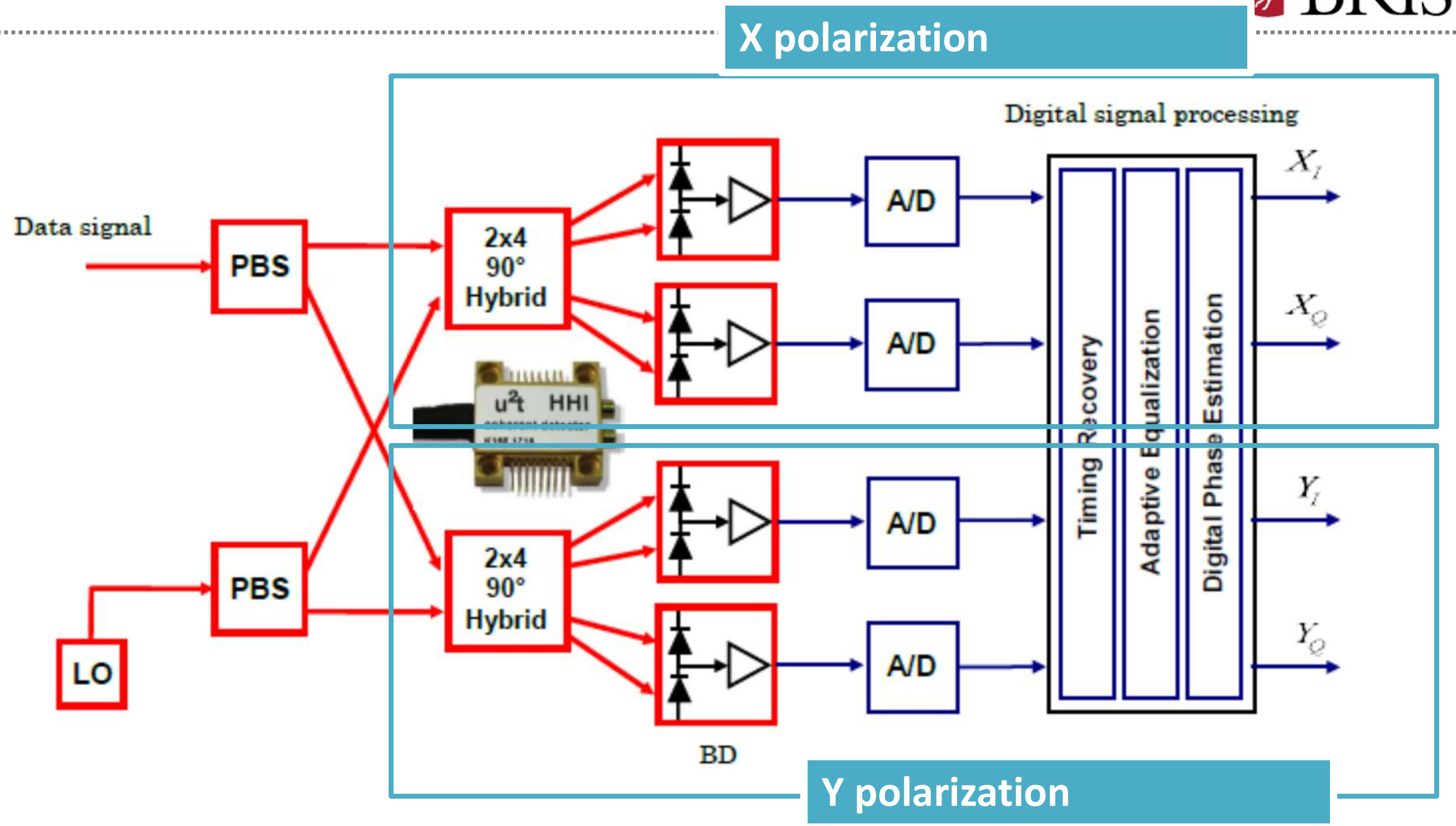
$$I_1 = R|E_1|^2 = \frac{1}{4}R(E_s^2 + E_{LO}^2 + 2E_sE_{LO}\cos((\omega_s - \omega_{LO})t + \varphi_s(t) + \varphi_{LO}(t))\Big)$$

$$I_3 = R|E_3|^2 = \frac{1}{4}R(E_s^2 + E_{LO}^2 - 2E_sE_{LO}\cos((\omega_s - \omega_{LO})t + \varphi_s(t) + \varphi_{LO}(t))\Big)$$

$$I_1 - I_3 = E_sE_{LO}\cos((\omega_s - \omega_{LO})t + \varphi_s(t) + \varphi_{LO}(t)))$$ → I signal

$$I_2 - I_4 = E_sE_{LO}\sin((\omega_s - \omega_{LO})t + \varphi_s(t) + \varphi_{LO}(t)))$$ → Q signal

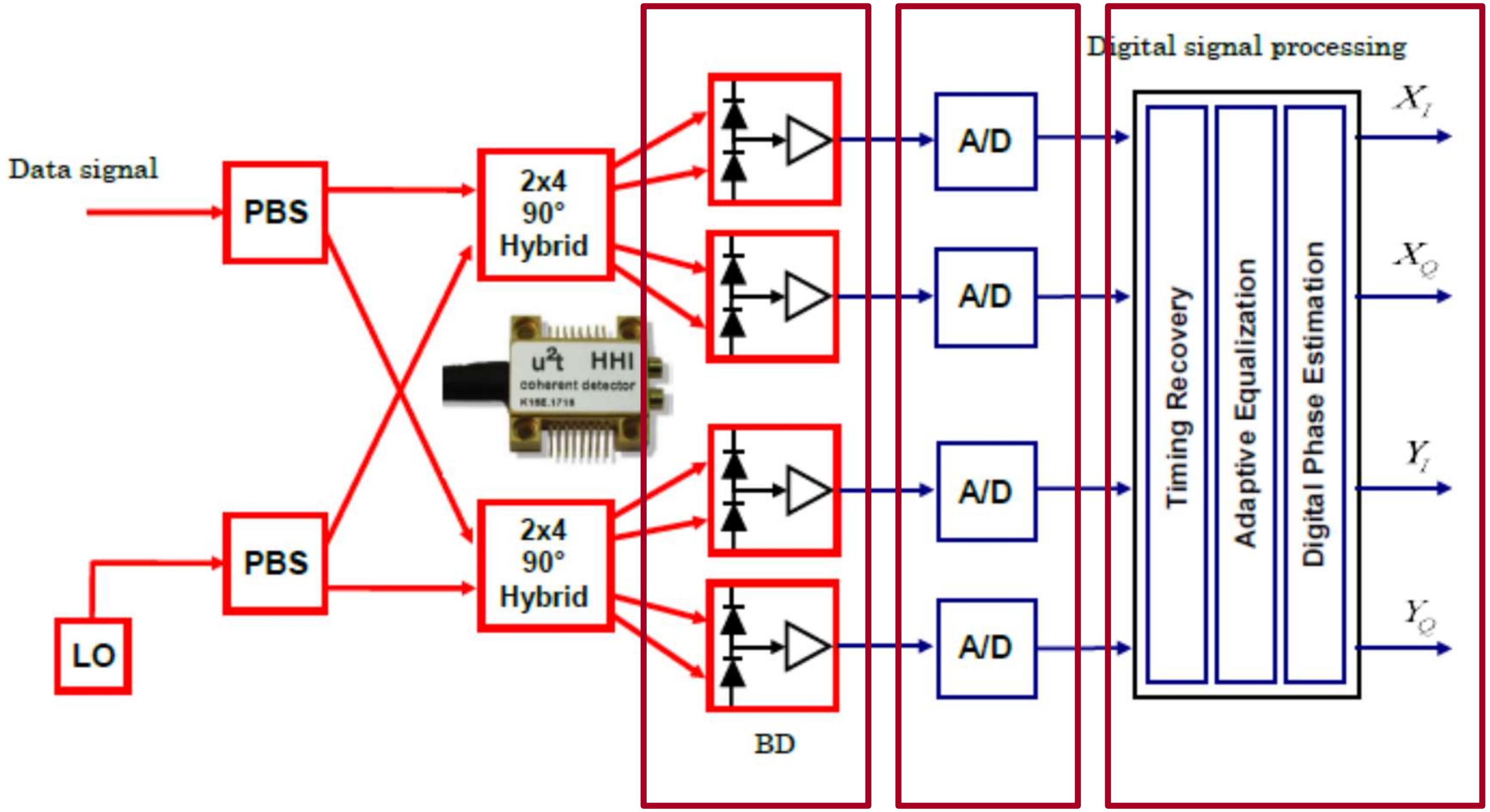
Phase-Diversity Receiver



Homodyne Synchronous detection

- ☐ **Polarization Diversity and Polarization De-multiplexing**
- ☐ **Adaptive electronic distortion equalization**
- ☐ **Digital signal processing**

Phase-diversity Receiver

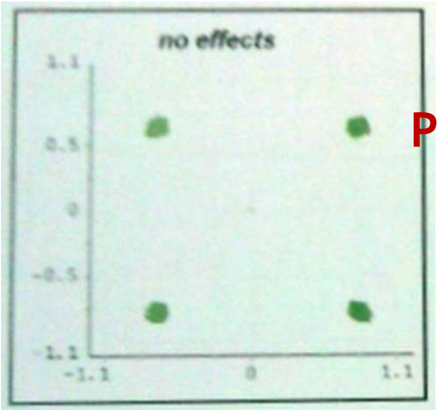


Homodyne Synchronous detection

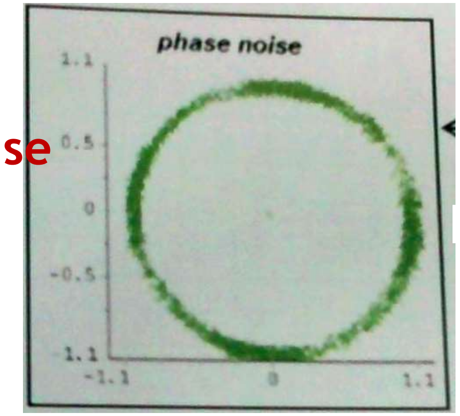
- Polarization Diversity and Polarization De-multiplexing
- adaptive electronic distortion equalization
- digital signal processing

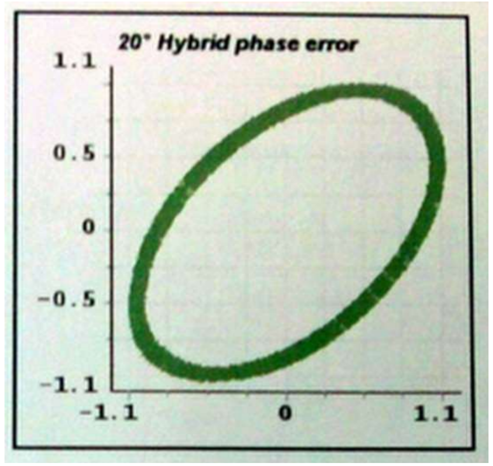
Receiver -typical impairments

Hybrid Phase Error



Phase Noise

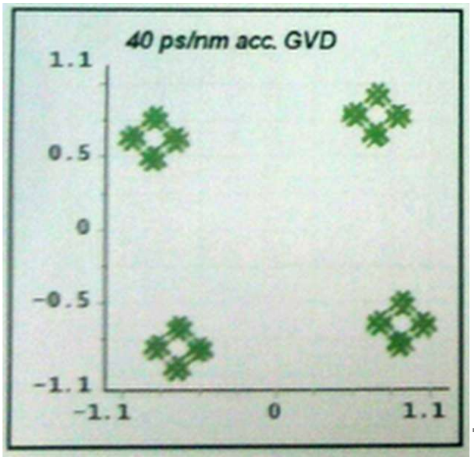


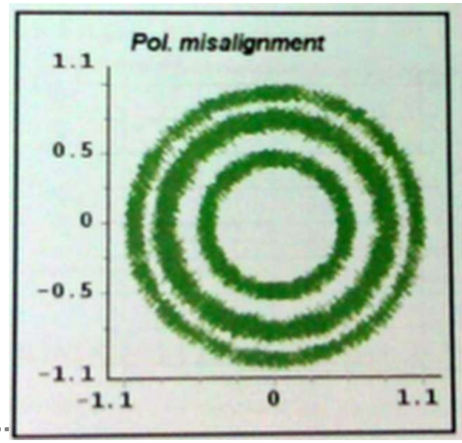


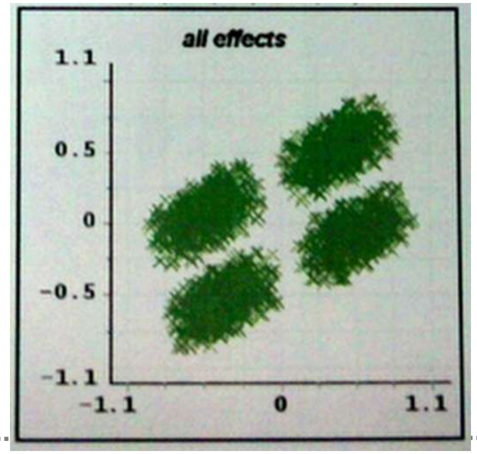
Chromatic Dispersion

Polarization Xtalk

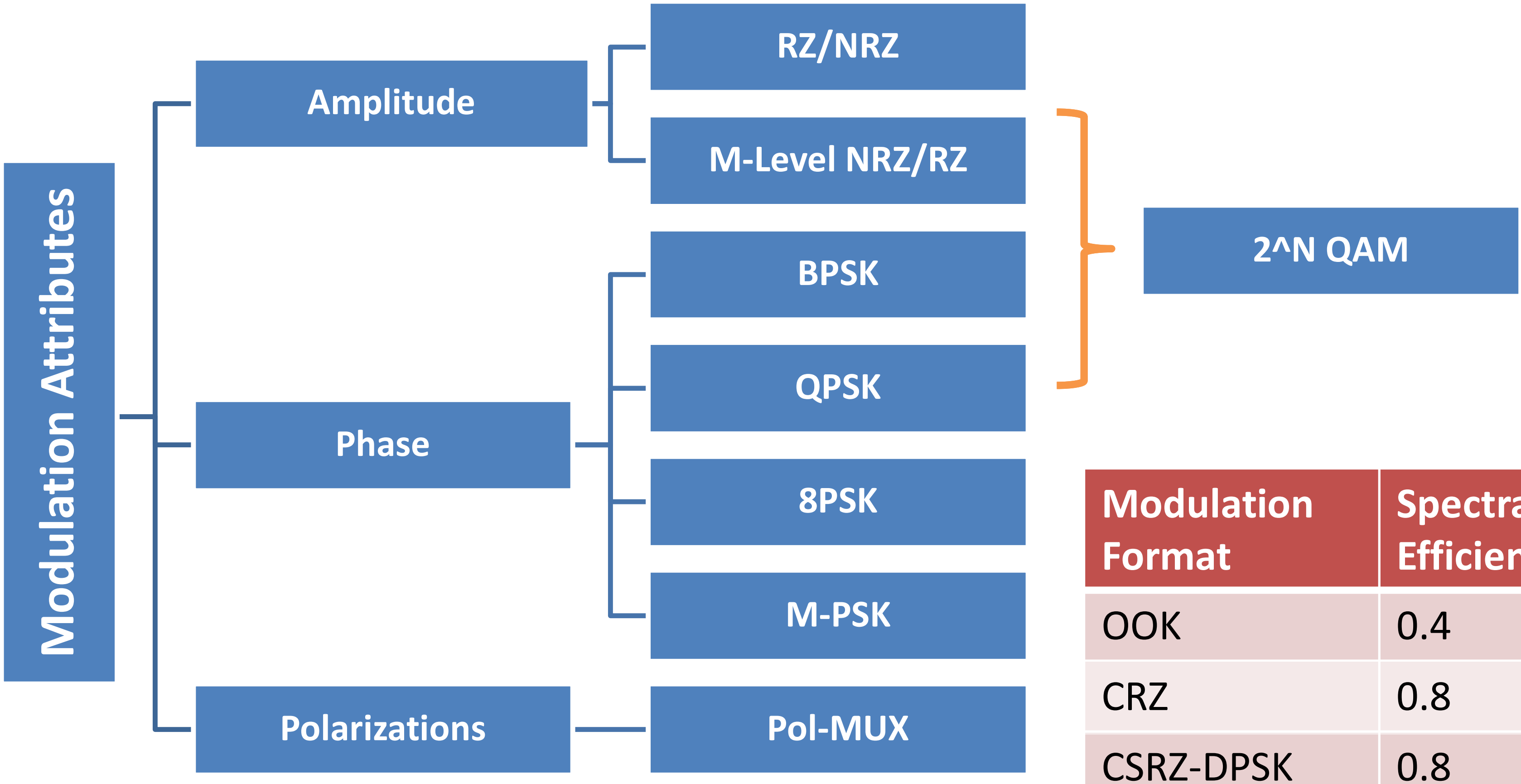
All Effects







Transmitter-Optical Modulation Format

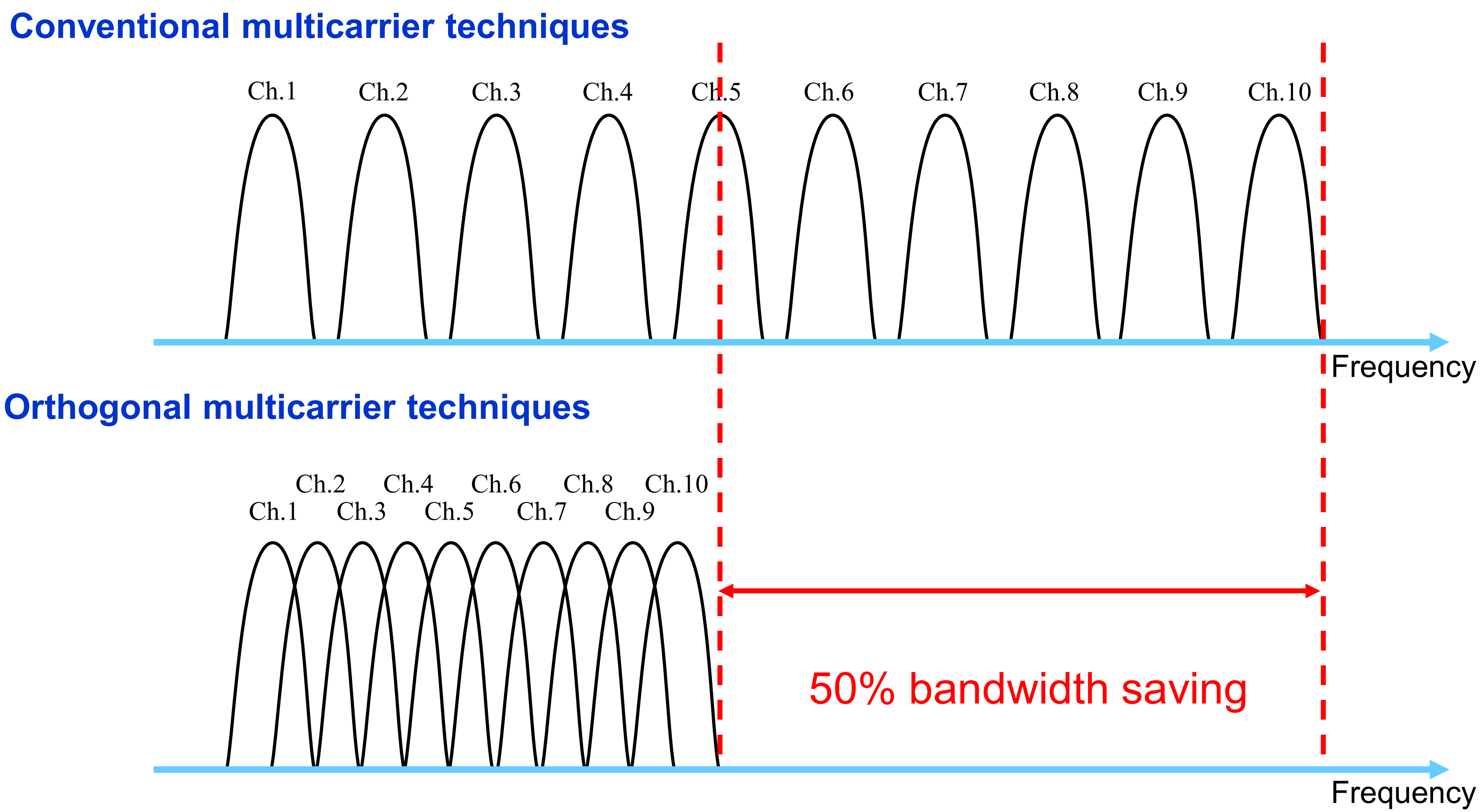


Modulation Format	Spectral Efficiency
OOK	0.4
CRZ	0.8
CSRZ-DPSK	0.8
NRZ-QPSK	1.05
CSRZ-DQPSK	1.6(pol-Mux)
QPSK	2.6(pol-Mux)
16QAM	4.2(pol-Mux)

With high-order modulation format, the spectral efficiency can be improved.

Alternative Solution

- Optical Orthogonal Frequency Division Multiplexing

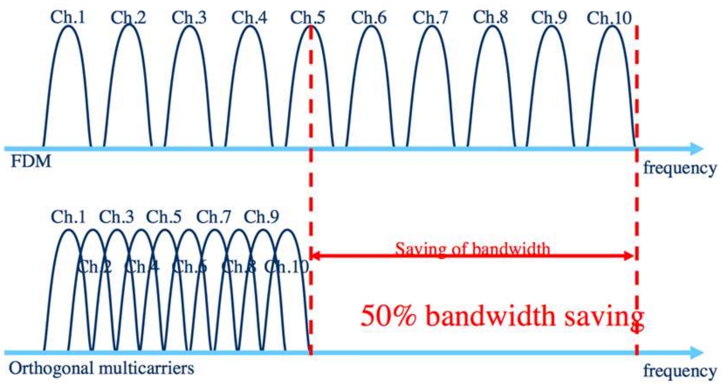


Orthogonal Carriers

- The OFDM carriers are orthogonal, their frequencies being fs, 2fs, 3fs,...

$$\frac{2}{T}\int_{KT}^{(k+1)T} \sin(mf_s\, t).\sin(nf_s\, t).dt = \begin{cases} 1, \text{ if } m=n \\ 0, \text{ if } m\neq n \end{cases}$$

- Complex exponentials of limited duration used in practice
  - Their duration equals OFDM's symbol time(T)
- The orthogonality is met if: fs=1/T



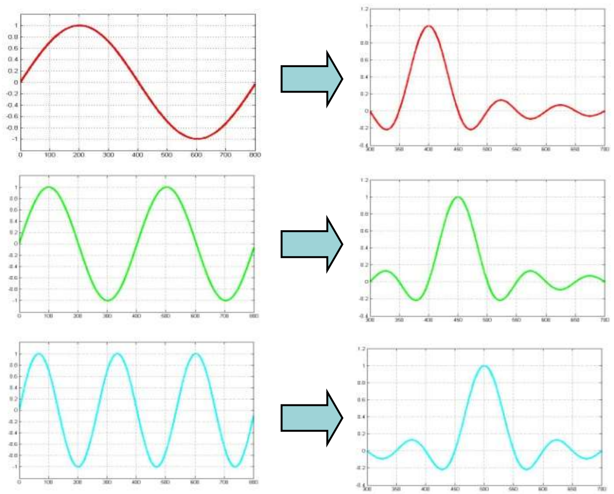
Optical Orthogonal Frequency Division Multiplexing
Basic Principles

Single subcarriers

1st SC

2nd SC

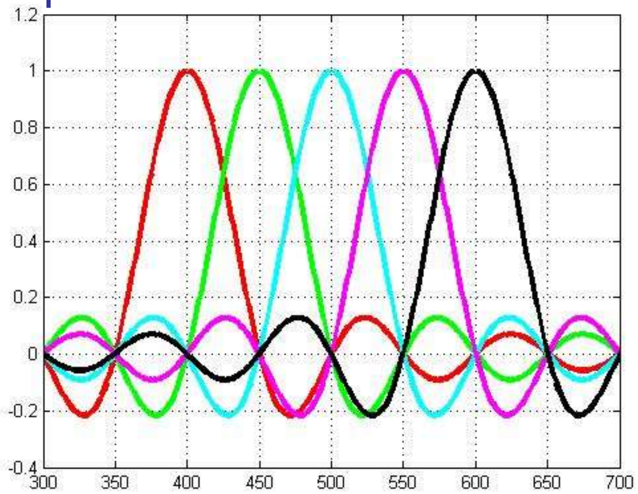
3rd SC



Time Domain
(Sine wave within symbol period, zero elsewhere)

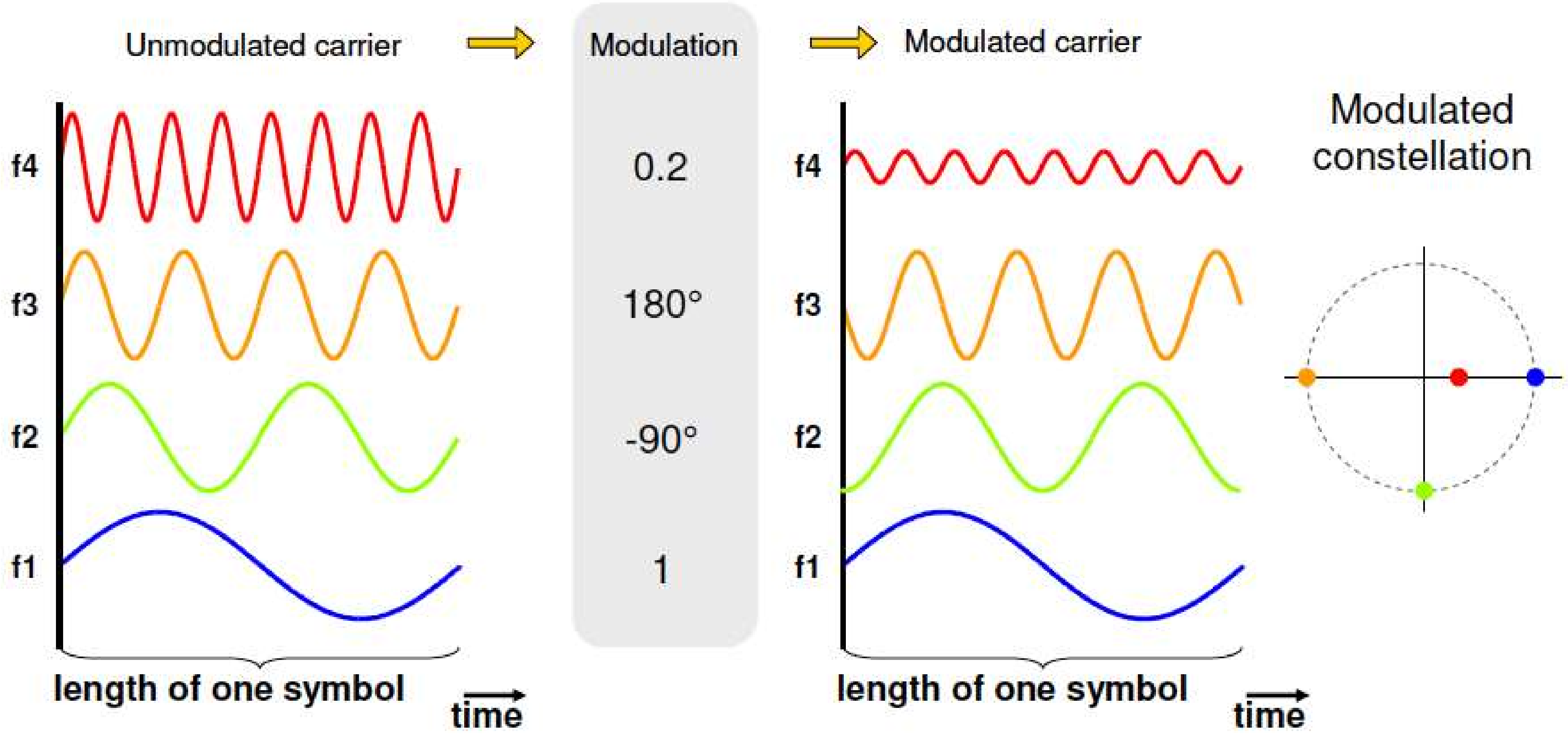
Frequency Domain
(Sinx/x function, peak at subcarrier frequency)

Overlayed Subcarrier Spectra

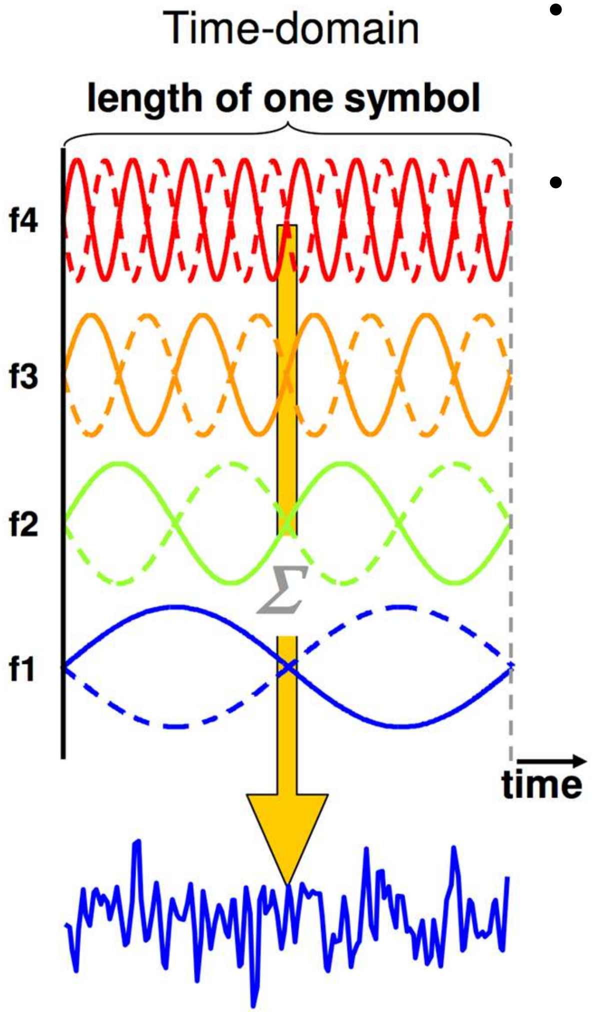


O-OFDM Principles

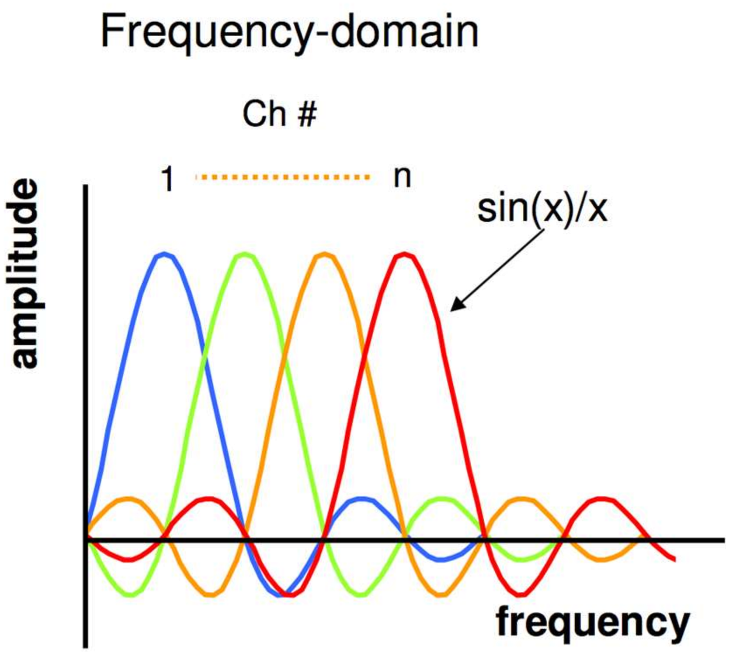
- The subcarriers of the O-OFDM signal can be modulated in phase and amplitude



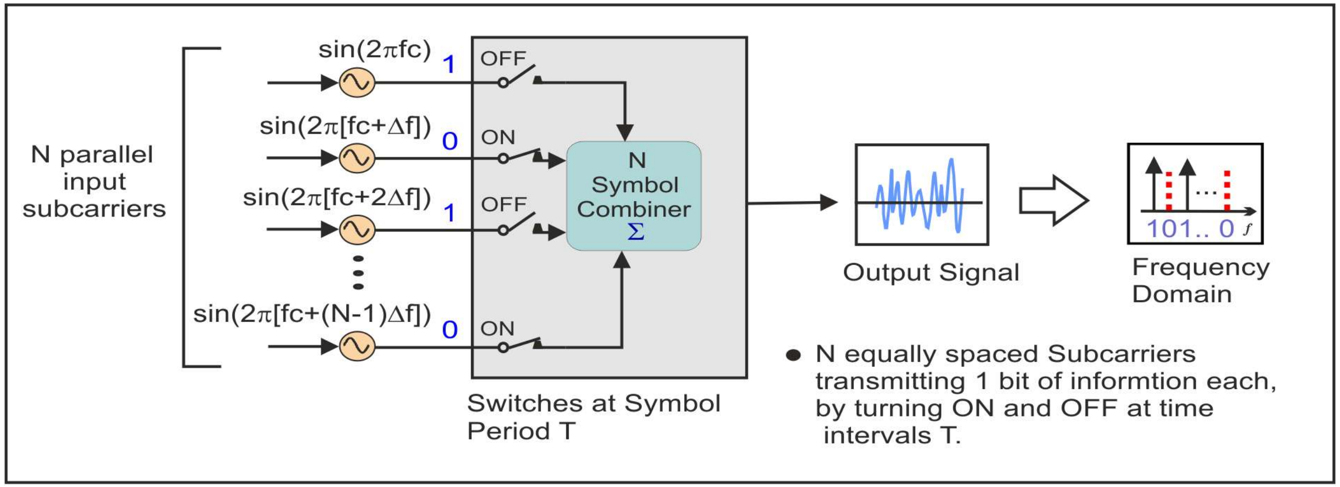
OFDM Transmission Concept



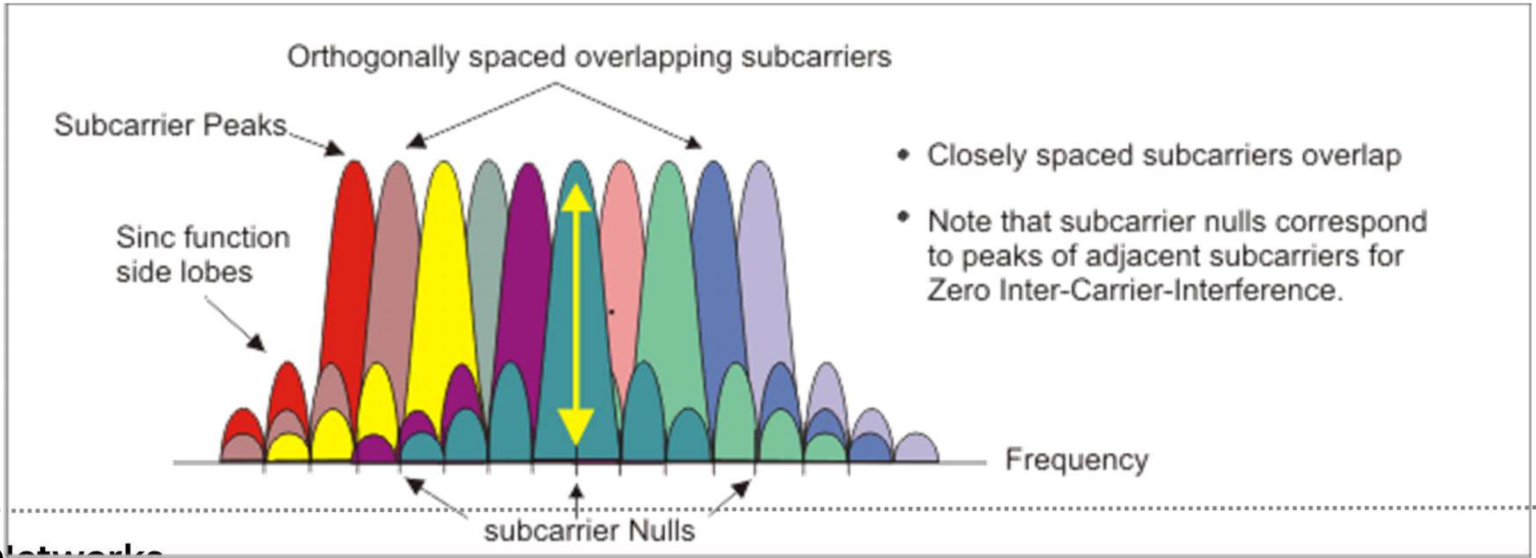
- Main idea: split data stream into N parallel streams of reduced data rate and transmit each on a separate subcarrier
- When the subcarriers have appropriate spacing to satisfy orthogonality, their spectra will overlap.



Generation of OFDM signals

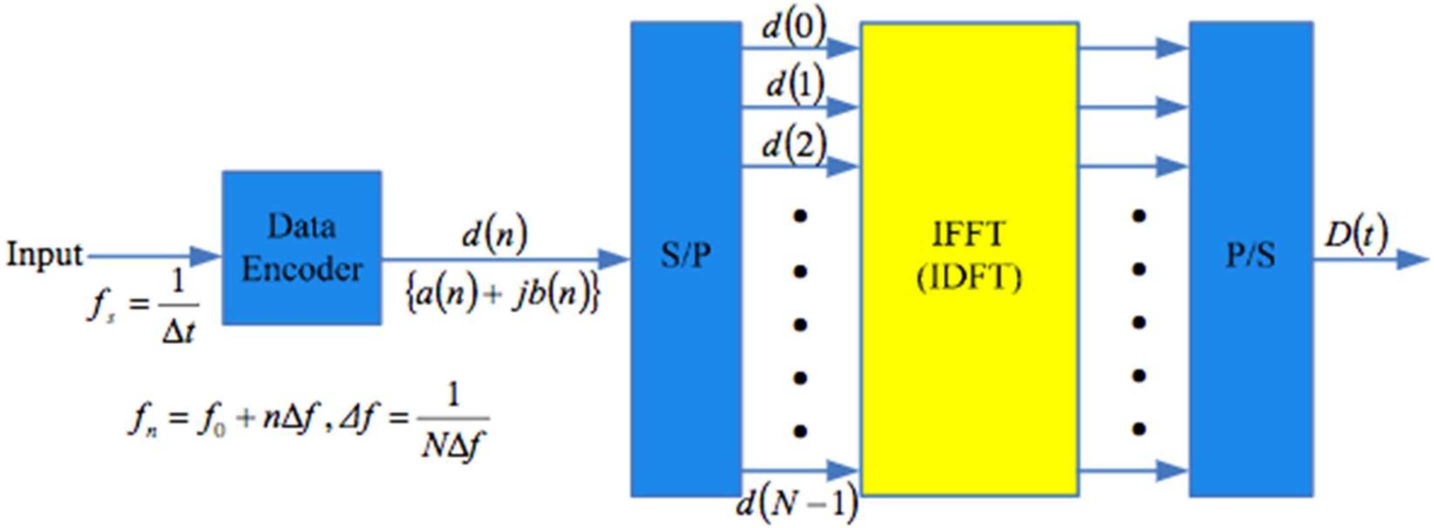


Simple OFDM Generation



OFDM Signal Frequency Spectra

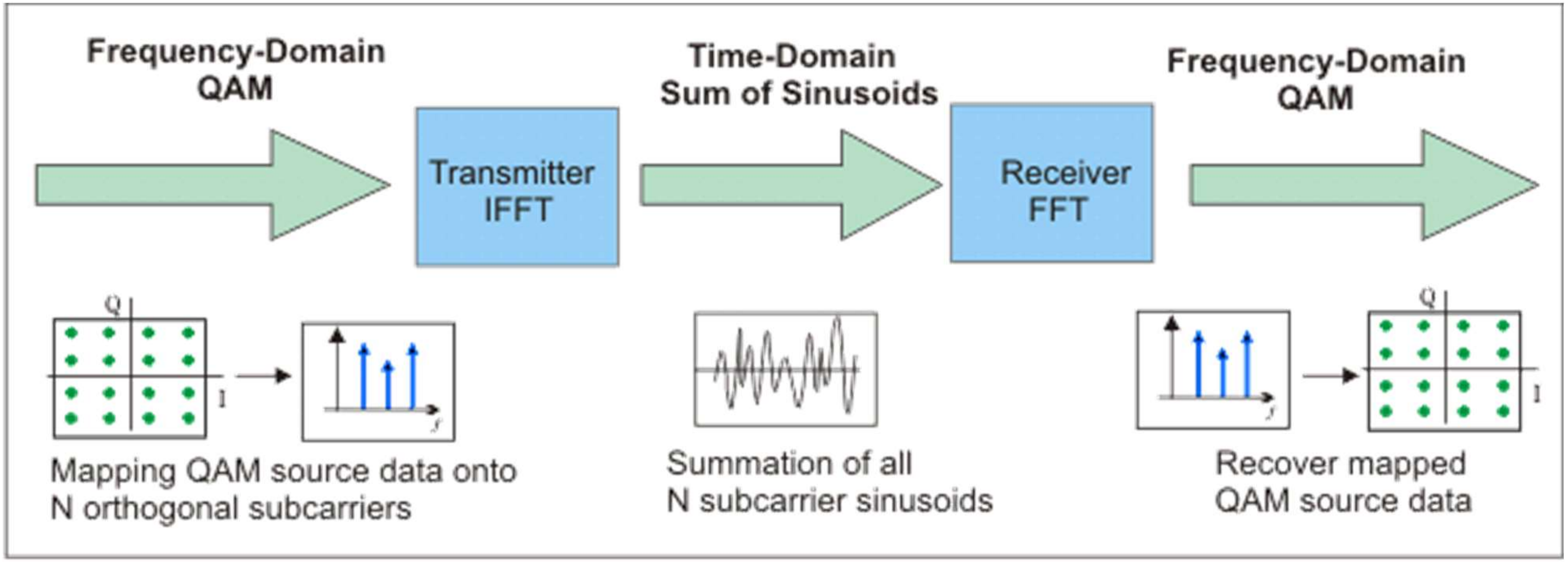
Digital OFDM generation



$IDFT(IFFT)$:

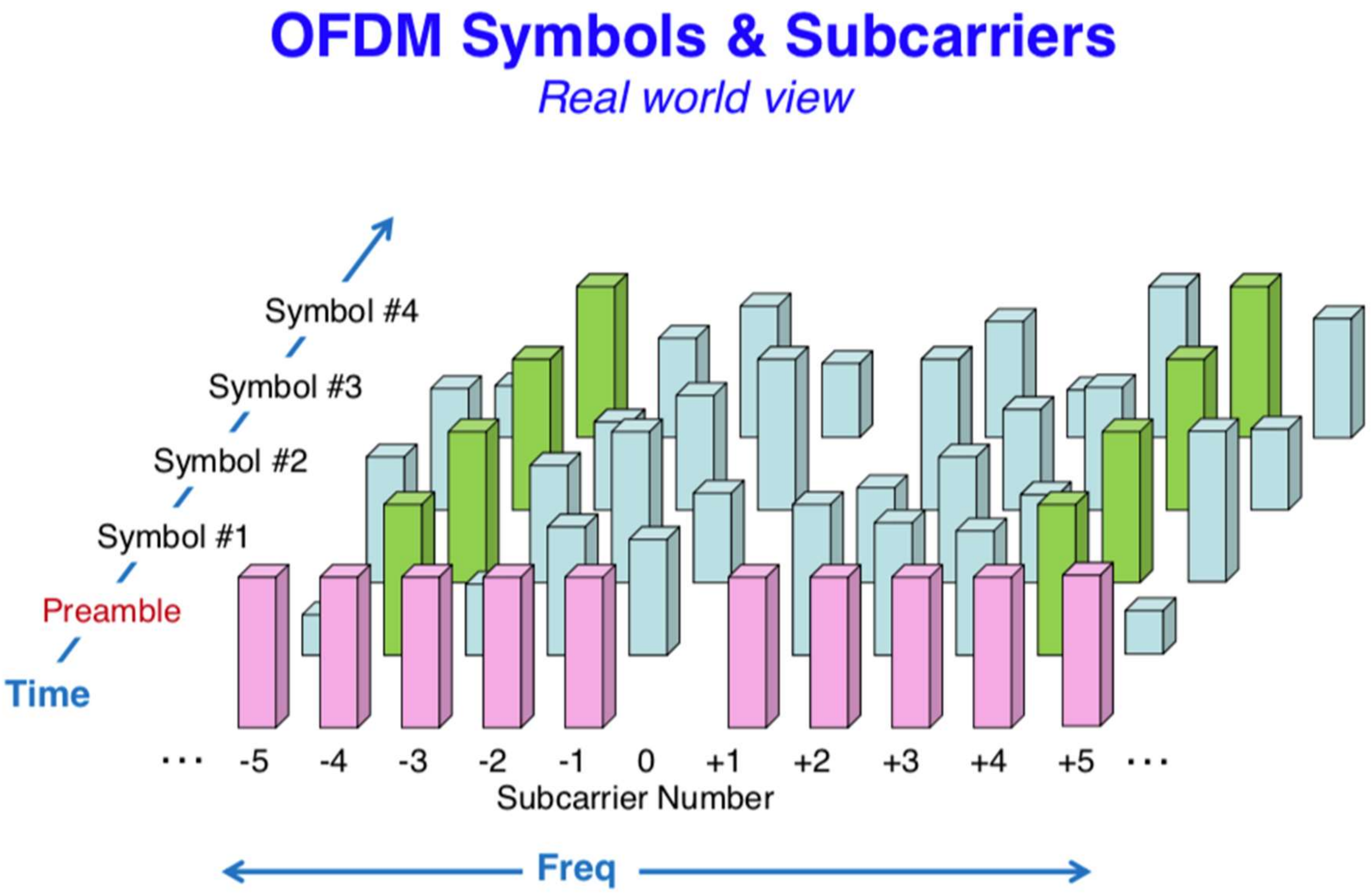
$$x(n) = \frac{1}{N}\sum_{k=0}^{N-1} X(k) \cdot e^{j\left(\frac{2\pi}{N}\right)nk} \quad (n = 0,1,\ldots,N-1)$$

Principle of OFDM system

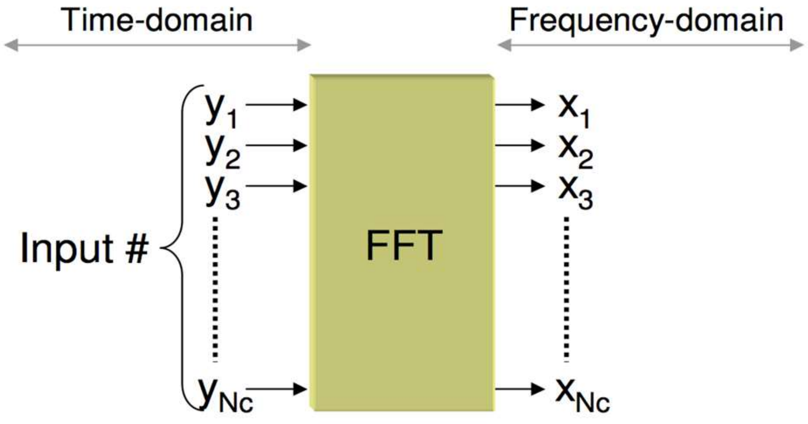


Simplified OFDM System Block Diagram

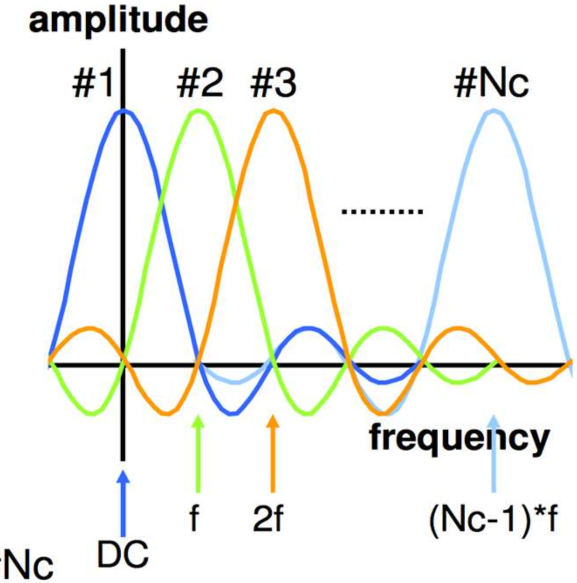
OFDM Symbols & Subcarriers



Detection of OFDM signals with FFT (DFT)



$$\mathbf{x} = \mathbf{F}\mathbf{y}$$



$$\begin{array}{ccccc} \text{Sub-carrier: \#1} & \text{\#2} & \text{\#3} & & \text{\#Nc} \end{array}$$

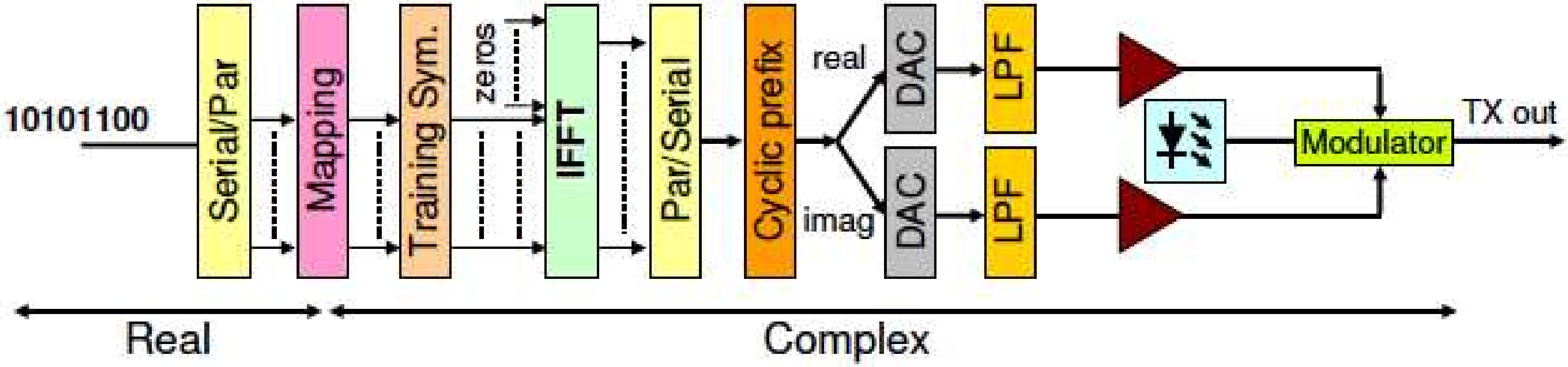
$$\mathbf{x} = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & W^{1} & W^{2} & \cdots & W^{(N_c-1)} \\ 1 & W^{2} & W^{4} & \cdots & W^{2(N_c-1)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & W^{(N_c-1)} & W^{2(N_c-1)} & \cdots & W^{(N_c-1)^2} \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_{N_c} \end{bmatrix}$$

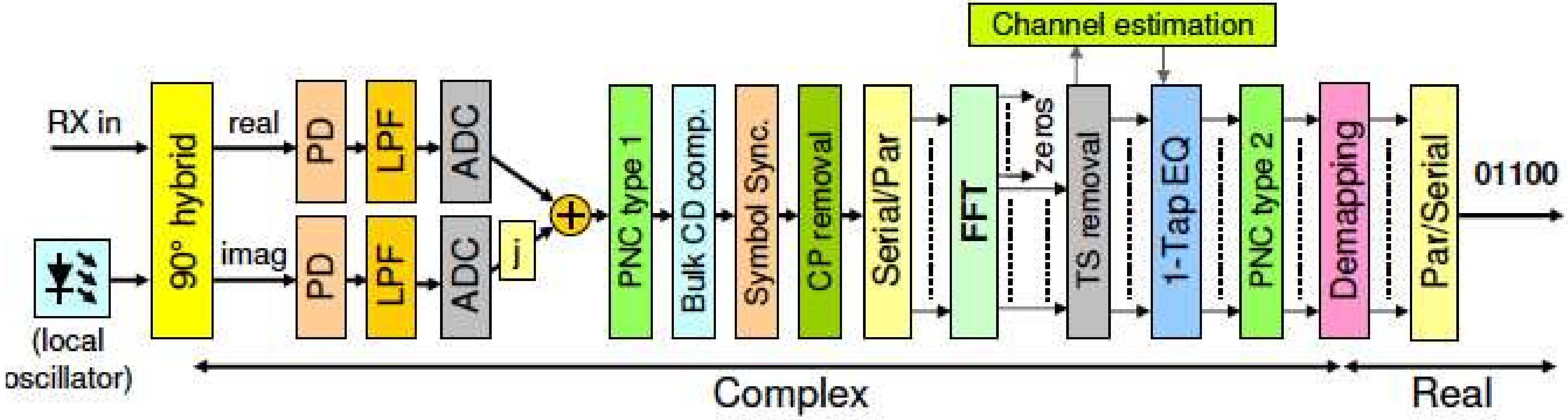
$$\left(W = \exp(-j\,\tfrac{2\pi}{Nc}) \right)$$

$DFT(FFT)$:

$$X(k) = \sum_{n=0}^{N-1} x(n) \cdot e^{-j\left(\frac{2\pi}{N}\right)nk} \quad (k = 0,1,\ldots,N-1)$$

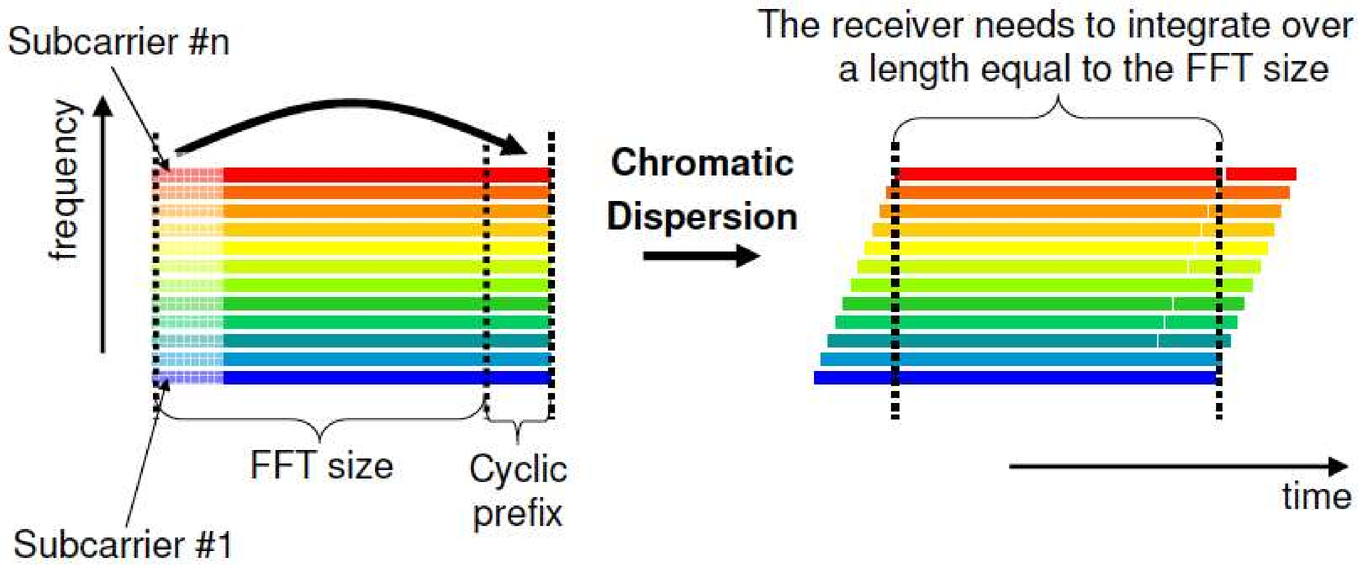
O-OFDM Transmitter and Receiver





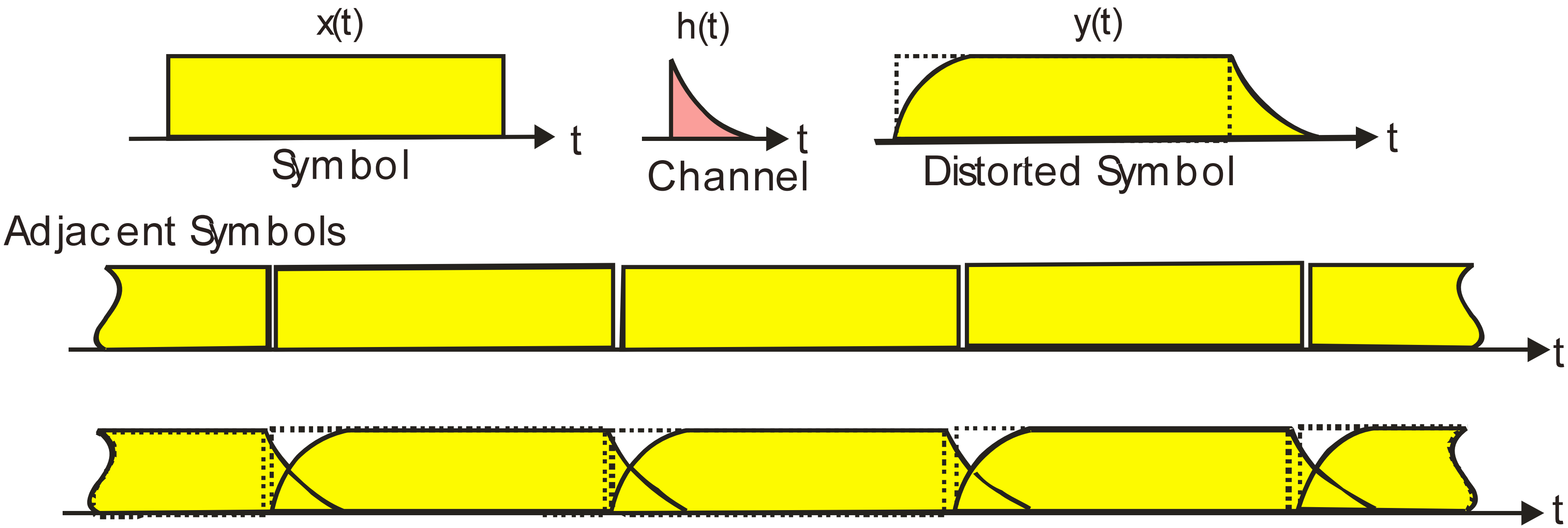
CP (Cyclic Prefix) Overhead

- A cyclic prefix is required to prevent power leakage from neighboring OFDM symbols
  - Chromatic dispersion and PMD cause the subcarriers to drift relatively to each other.
- With cyclic prefix the OFDM symbol is extended by copy-pasting the beginning of the symbol to the end (or vice versa)

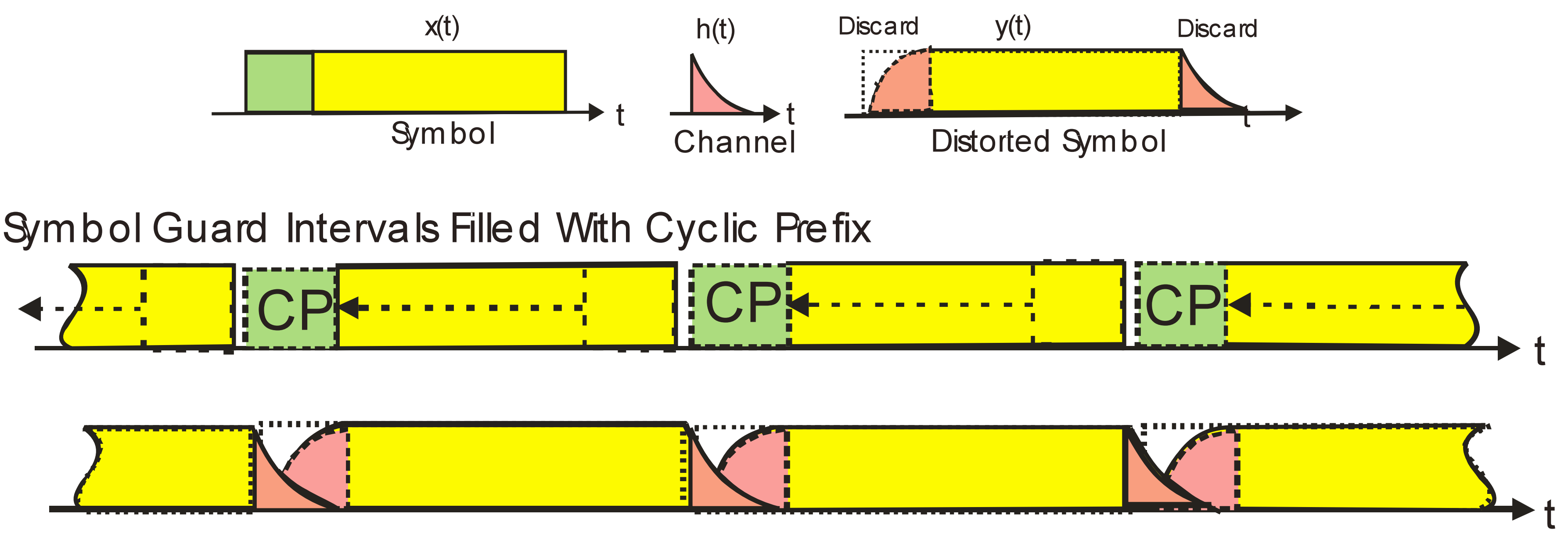


Nokia Siemens Networks

Adjacent Symbol Interference (ASI)
Symbol Smearing Due to Channel

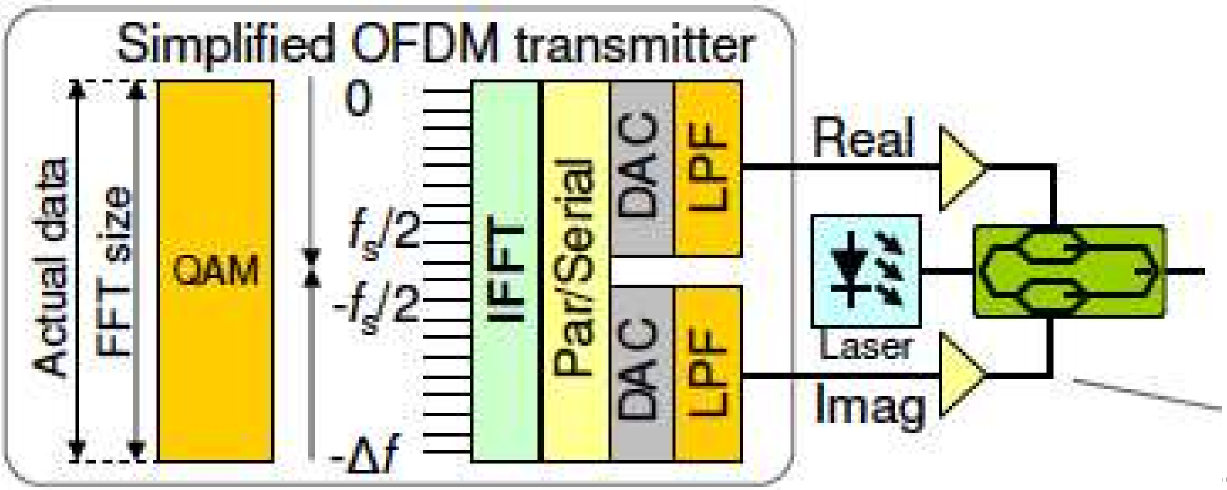


Cyclic Prefix Inserted in Guard Interval to Suppress Adjacent Channel Interference



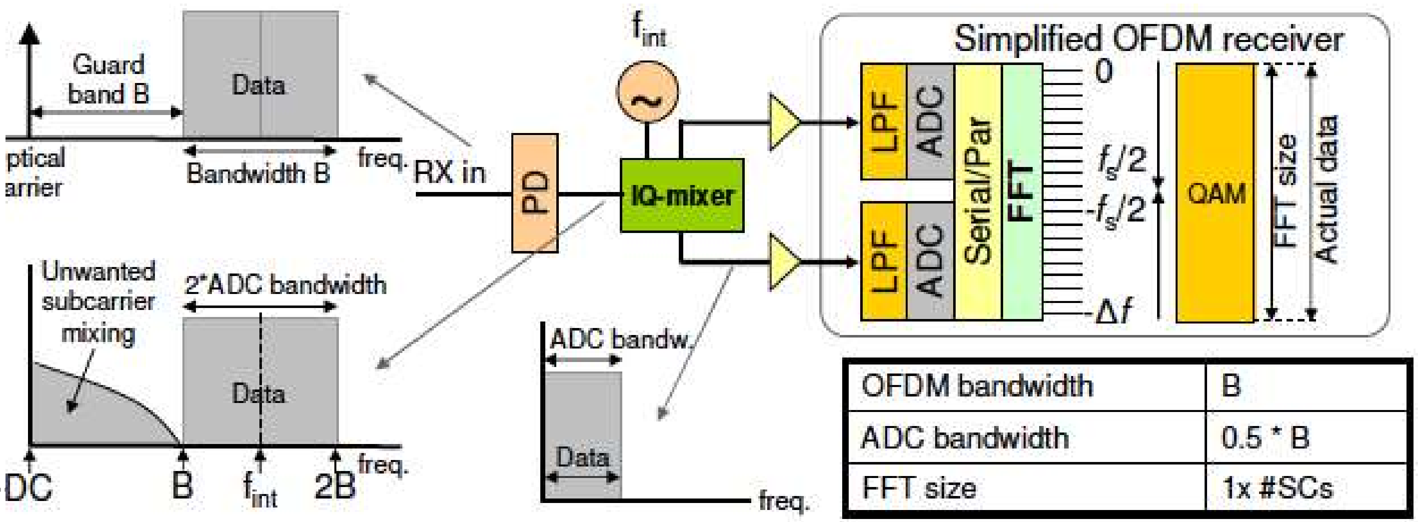
Modulation of an O-OFDM signal

- Realization of Optical OFDM with IQ MZM
  - Two DACs are used to convert the real and imaginary part of the OFDM signal from the digital to the analogue domain.
  - Subsequently an optical IQ MZM is used to directly modulate the complex OFDM signal into the optical carrier.



Demodulation of an O-OFDM signal

- Demodulation of Optical OFDM with IQ Mixer
- In this implementation down-conversion is performed by an electrical IQ mixer
- In essence this implementation is the reverse of the transmitter using the electrical IQ mixer



OFDM bandwidth	B
ADC bandwidth	0.5 * B
FFT size	1x #SCs

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Summary

- Advanced modulation formats
  - QAM
  - OFDM
- Coherent detection technologies
- Digital signal processing