OPTI510R: Photonics

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Announcements

- Homework #6 is due today
- Final exam May 1, room 307 (Open book/notes)

Photodetector Noise

Total Noise

The total noise current generated in a photodetector is determined by:

$$I_{tn} = \sqrt{I_{sn}^{2} + I_{jn}^{2}}$$

Noise Equivalent Power (NEP)

Noise Equivalent Power is the amount of incident light power on a photodetector, which generates a photocurrent equal to the noise current. NEP is defined as:

$$NEP = \frac{I_{tn}}{R_{\lambda}}$$

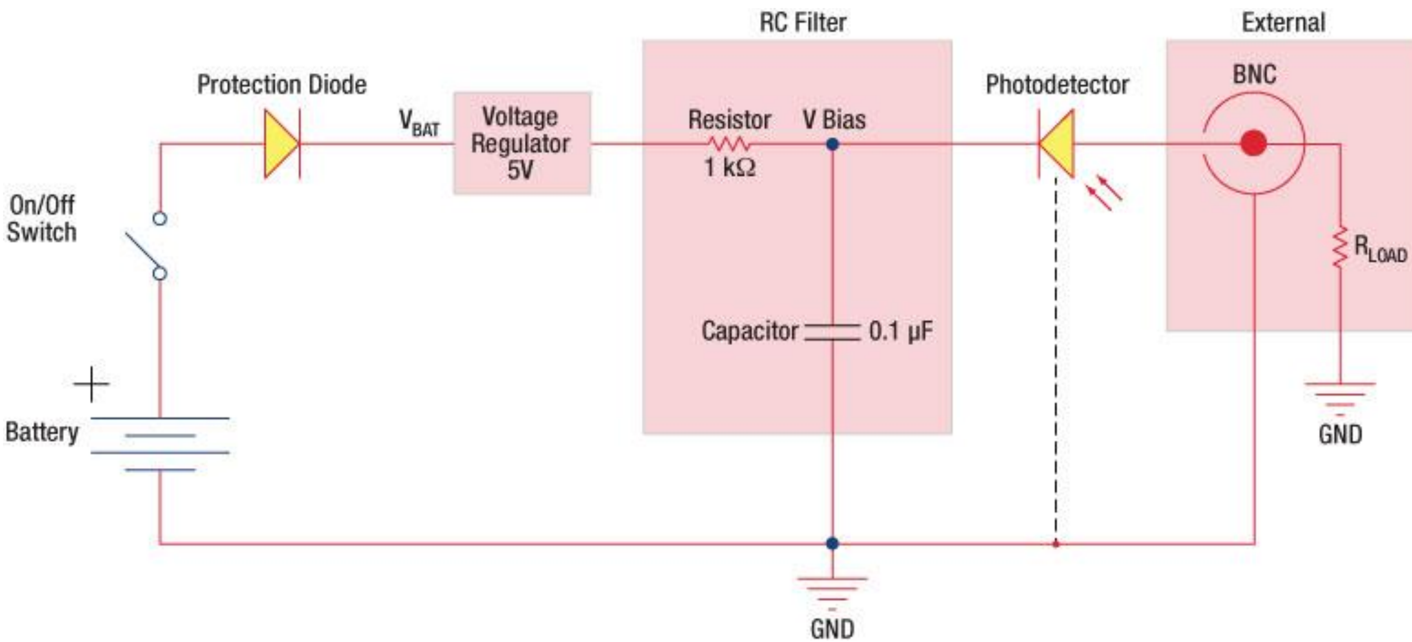
APD example

Item #	APD110C
Detector Type	InGaAs APD
Wavelength Range	900 - 1700 nm
Typical Max Responsivity	9 A/W @ 1500 nm M = 10
Transimpedance Gain	100 kV/A 50 kV/A with 50 Ω Termination
Maximum Conversion Gain	0.9×10^6 V/W
Active Detector Diameter	0.2 mm
CW Saturation Power	4.2 μW
Max Input Power[a]	1 mW
Output Bandwidth (3dB)	DC - 50 MHz
Minimum NEP	0.46 pW/($Hz^{1/2}$)
Electrical Output	BNC, 50 Ω
Max Output Voltage Threshold	3.6 V
DC Offset Electrical Output	<±15 mV
Device Dimensions	2.0" x 3.0" x 1.1" (50.8 mm x 76.2 mm x 27.9 mm)
Power Supply	±12 V @ 200 mA (110/230 VA switchable)

- High-Speed Response up to 1 GHz
- Ultra-High Sensitivity up to 0.9×10^6 V/W
- Wavelength Range of 850 - 1650 nm or 900 - 1700 nm
- SM05 or SM1 Compatible

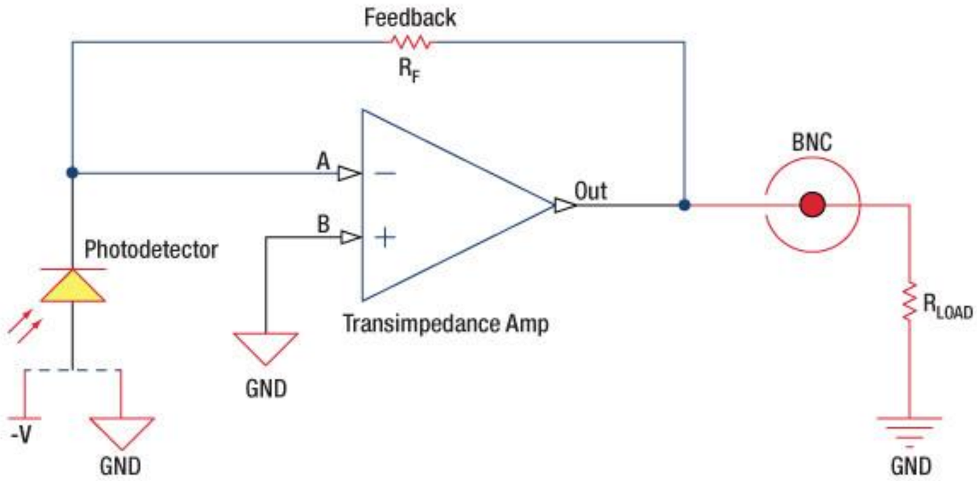
APD110C

Electrical wiring



Reverse biased photodetector

Electrical wiring



Amplified photodetector

Questions for thoughts

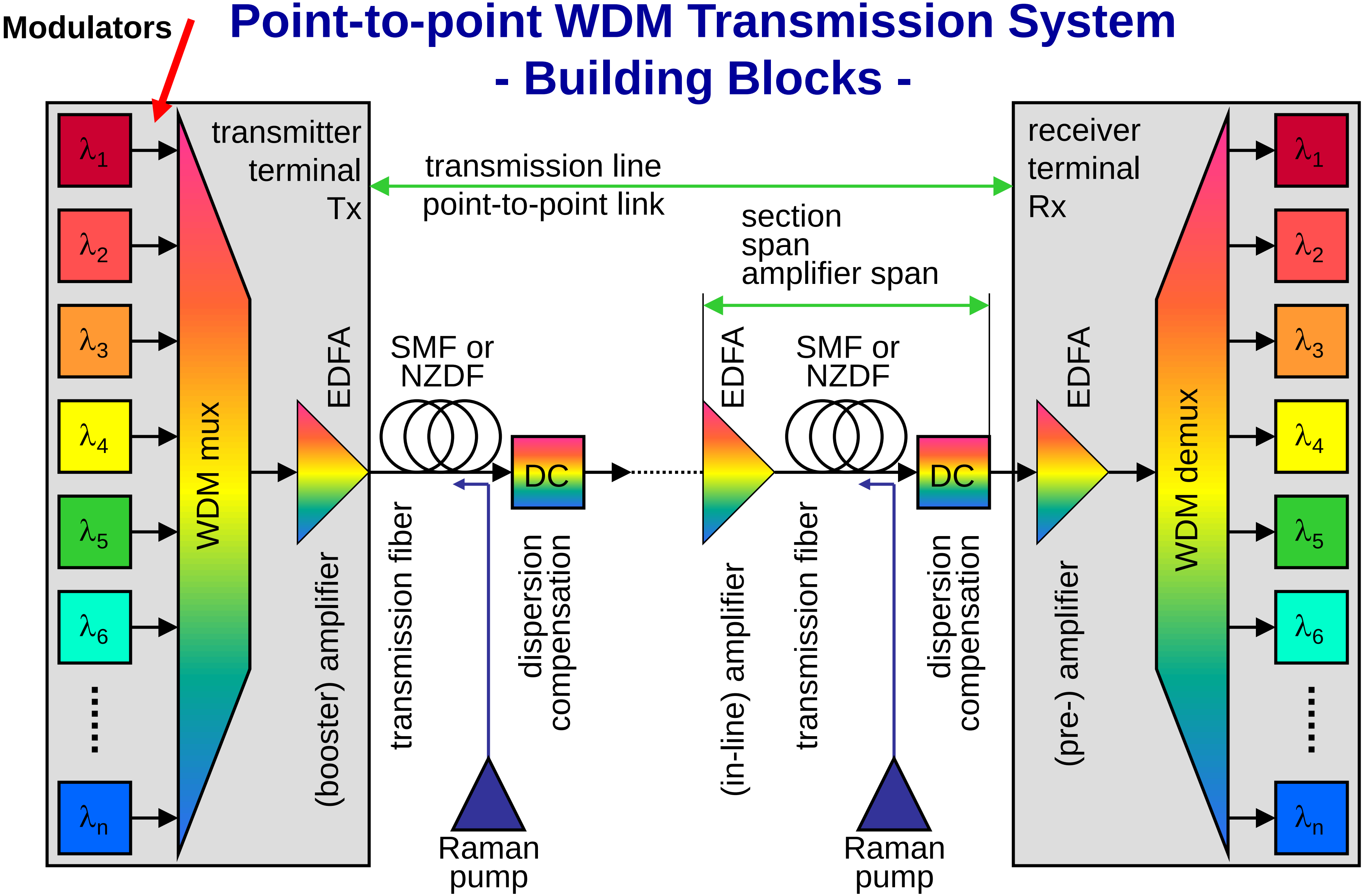
Can we detect a single photon?

Can you come up with a new kind of detector that is faster, more sensitive, and have less noise?

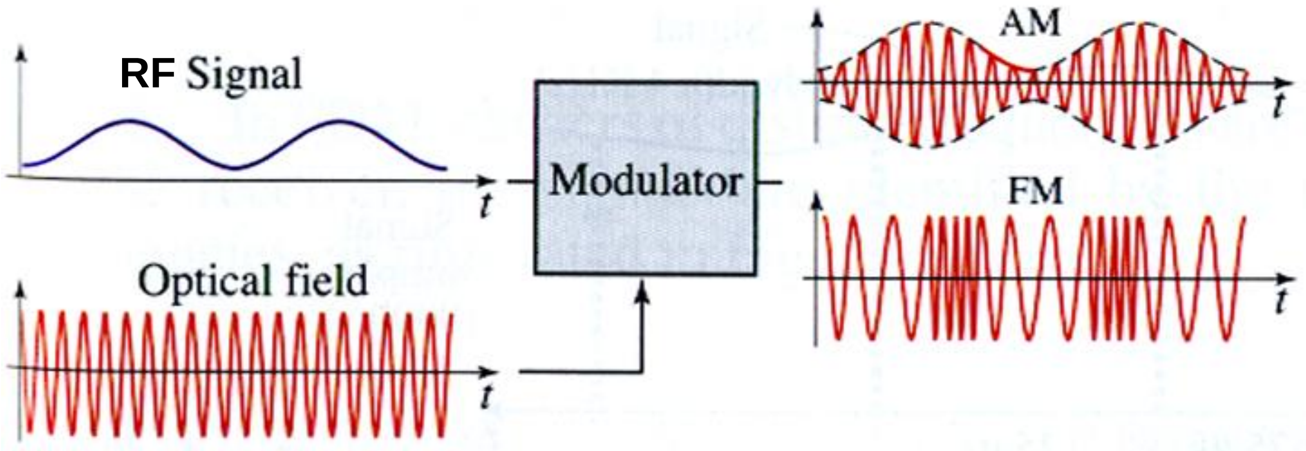
Introduction to Optical Network

- Modulation formats
- Signal multiplexing
  - Time
  - Code
  - Wavelength
- System performance
  - Bit Error Rate
  - Optical signal to noise ratio
  - Eye diagram
- Network architecture, limitation
- CIAN

Point-to-point WDM Transmission System
- Building Blocks -



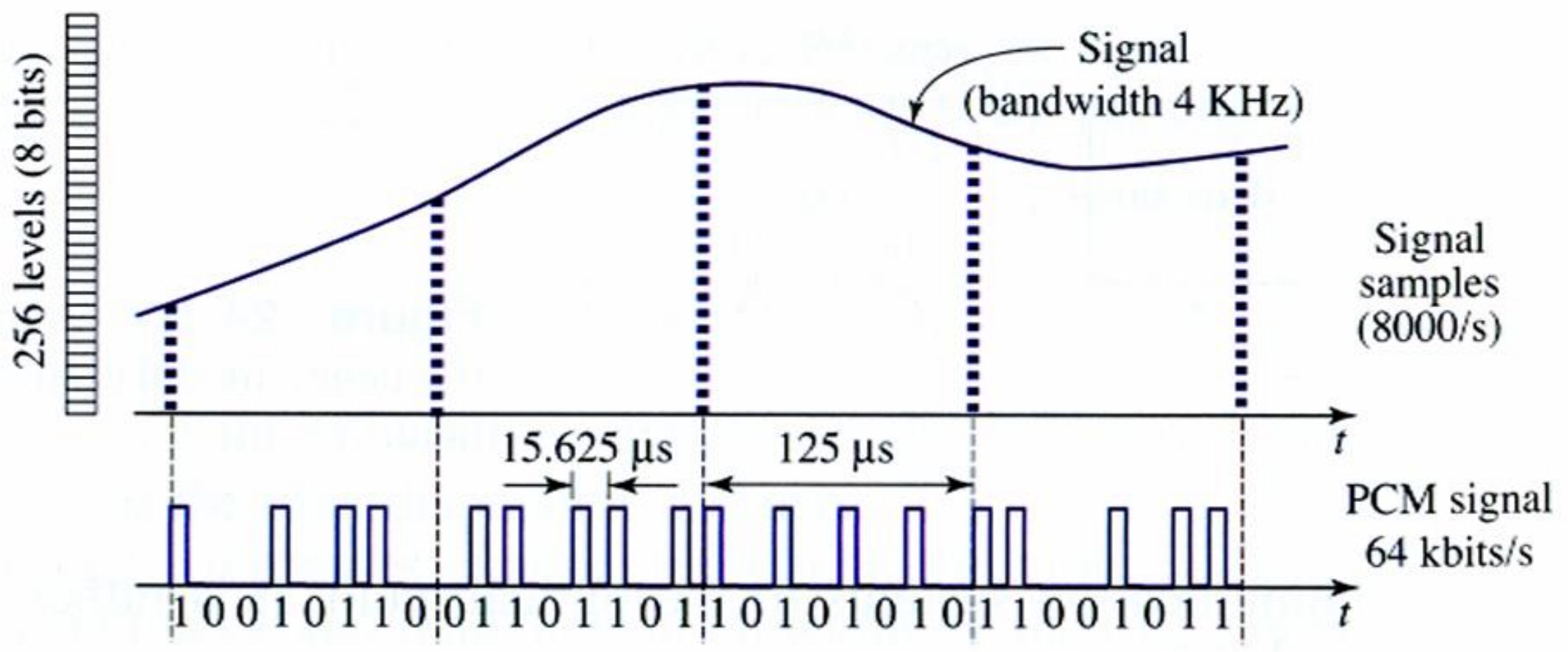
Modulation Schemes



Requirements

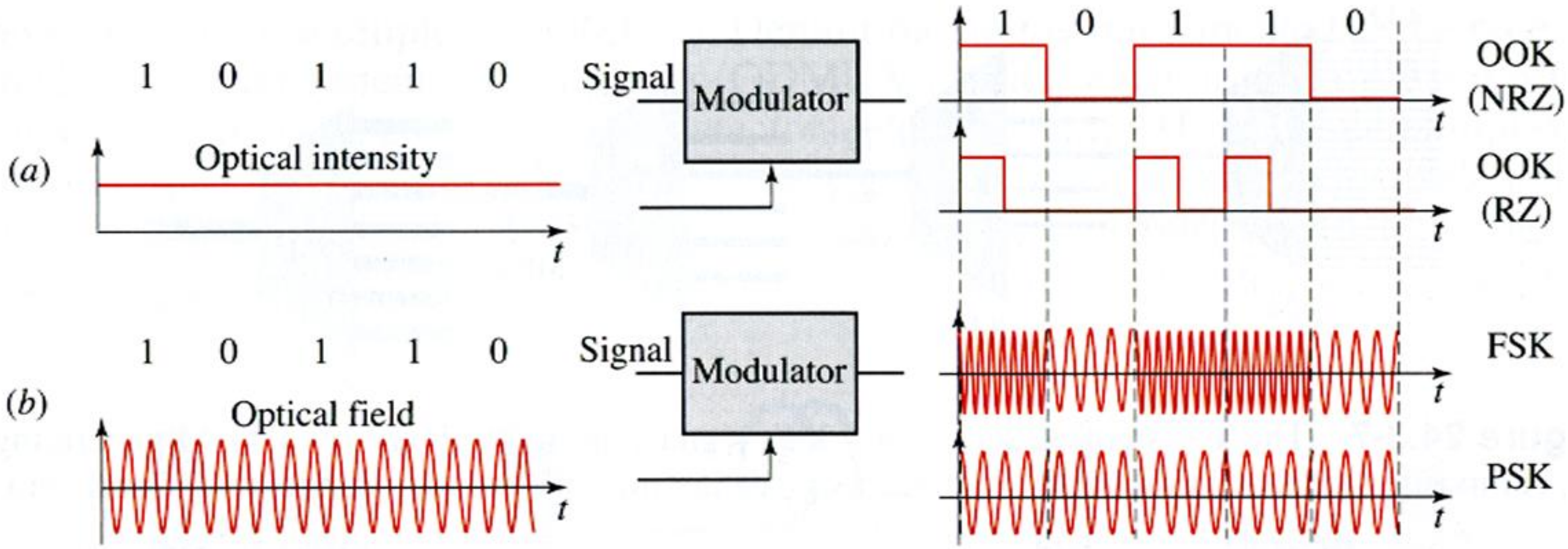
- Source must be stable in amplitude, frequency, phase
- External modulator is often used instead of direct modulation
- Single mode fiber to reduce noise, dispersion effect
- Polarization is monitored
- Receiver must measure amplitude and phase, such as a heterodyne detection system
- Coherent communication system is advantageous for high speed communication systems

Modulation Schemes



Pulse code modulation (PCM) is a modulation format for sampling analog signal. A 4-kHz voice is sampled at $8x10^3$ s^{-1} and 8 bits. Data is transmitted at 64kb/s.

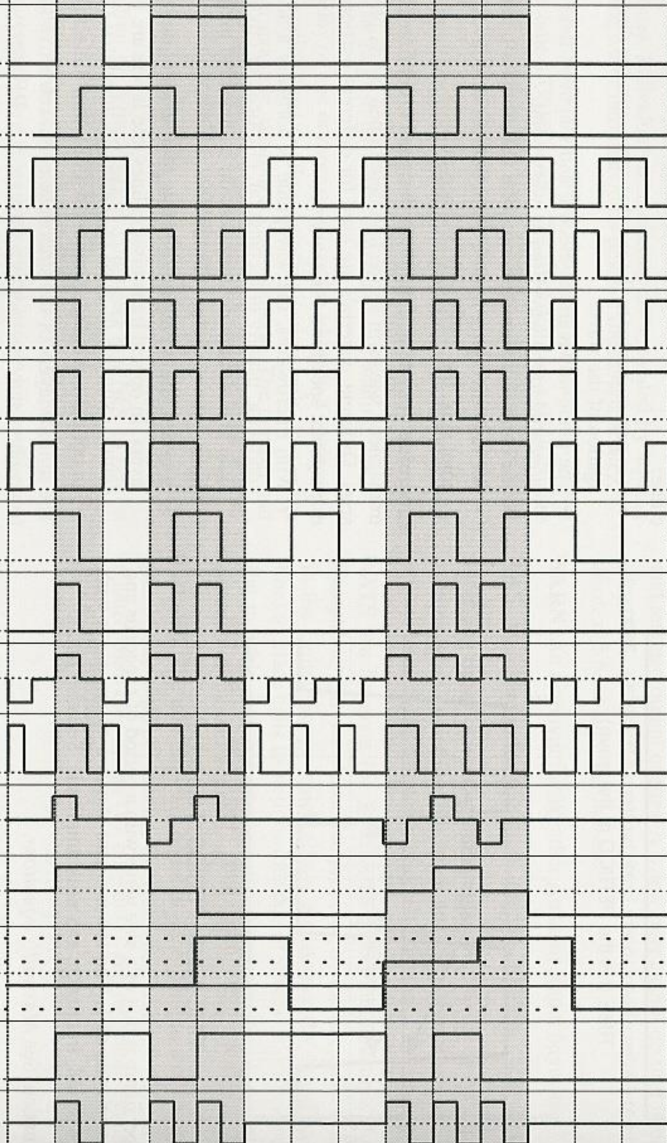
Modulation Formats



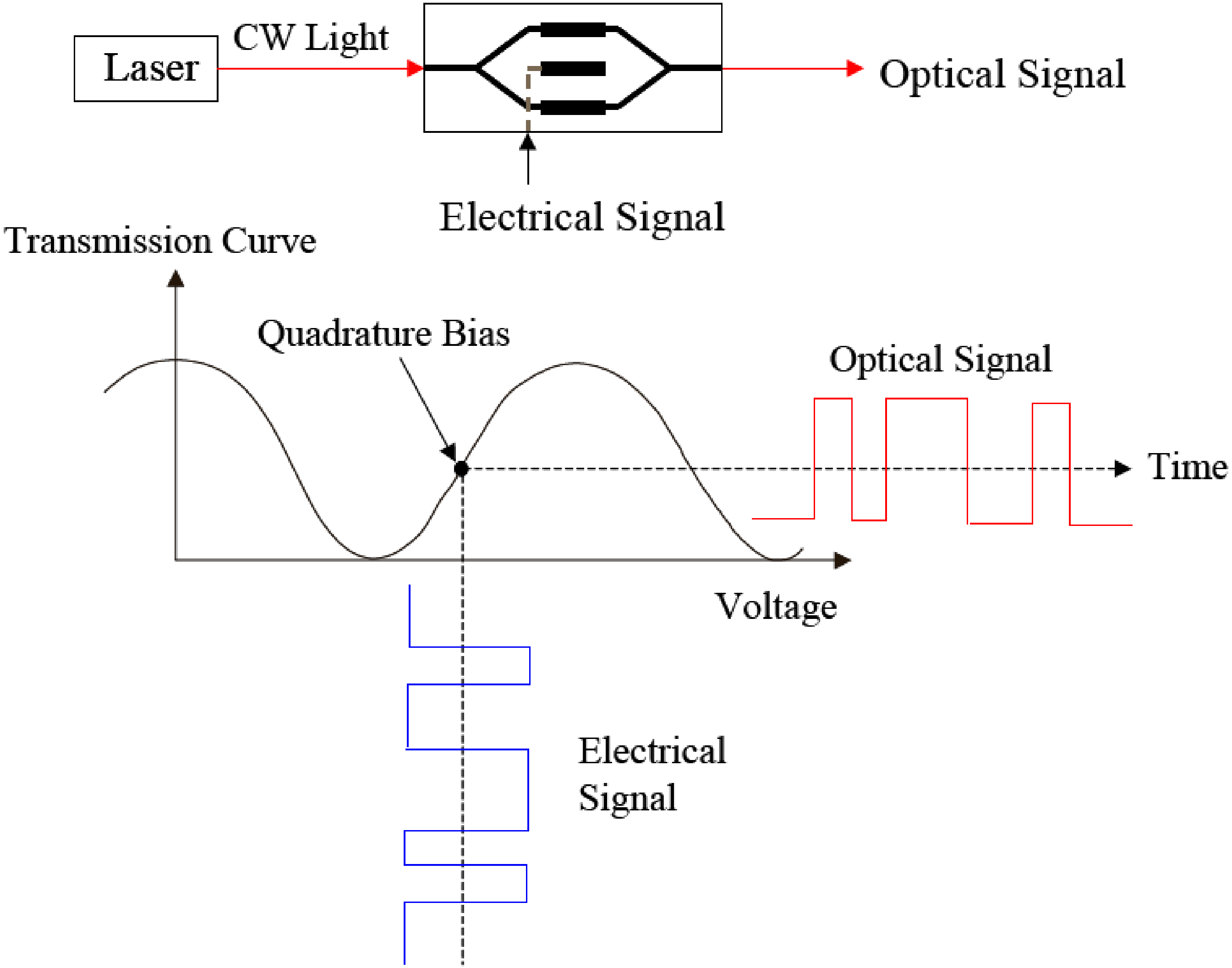
(a) On-Off keying (OOK) intensity modulation
(b) Frequency shift keying (FSK) and phase shift keying (PSK)

Modulation Formats

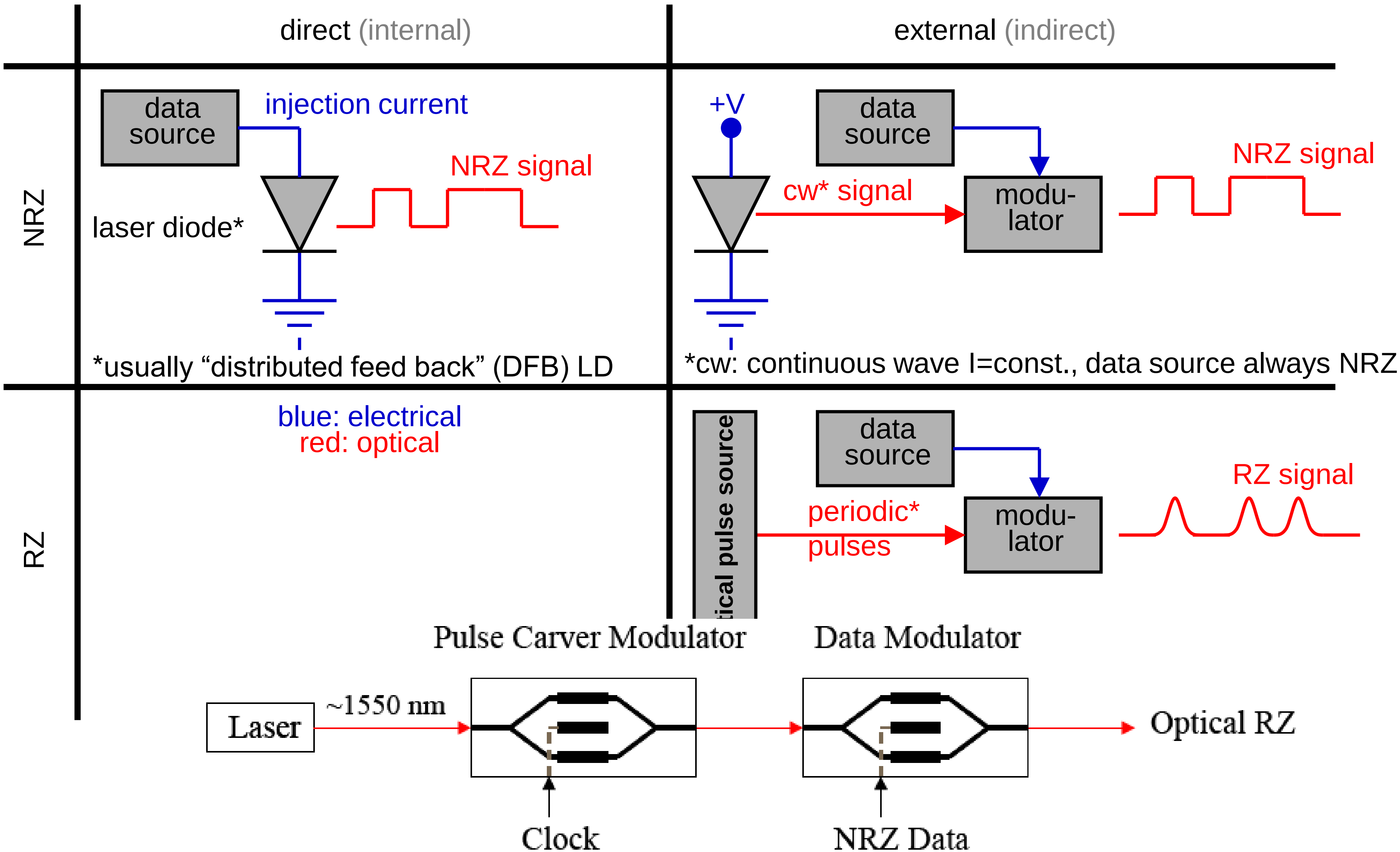
CODE NAME	CODED WAVEFORM	CODING RULE OR ALGORITHM
Binary data	0 1 0 1 1 0 0 0 1 1 1 0 0 0	Source information to be encoded.
NRZ, NRZ-L		Nonreturn to Zero-Level (Basic binary waveform) Waveform is at *one level* while the source data = "1" and is at the *other level* while the source = "0."
NRZ-M, NRZ-I		Nonreturn to Zero-Mark Waveform *changes state* while the source is "1," no change for a "0."
NRZ-S		Nonreturn to Zero-Space Waveform *changes state* while the source is "0," no change for a "1."
Differential Manchester		Differential Manchester Waveform *changes state* at leading edge only when the source = "0," and always *changes state* mid-bit.
BIΦ–L Manchester II		Biphase Level (Manchester II) Mid-bit change from "1 to 0" when the source = "1" and from "0 to 1" when source = "0," transition at leading edge if sucessive source bits same
BIΦ–M		Biphase Mark Transition occurs at the beginning of every bit cell. Source = "1" causes a second transition half a bit period later, source = "0" no second transition.
BIΦ–S		Biphase Space Transition occurs at the beginning of every bit cell. Source = "0" causes a second transition half a bit period later, source = "1" no second transition.
DM Miller		Delay Modulation (Miller Coding) Source = "1" causes a waveform transition at mid bit, source = "0" causes a waveform transition at the start of the bit cell except after source = "1."
RZ		Return to Zero Source = "1" causes a pulse less than 1 bit long, source = "0" is no pulse.
Bipolar RZ		Bipolar Return to Zero Source = "1" causes a pulse less than 1 bit long, source = "0" causes a pulse in the opposite polarity and of the same duration.
Ratio		Ratio Source = "1" causes a pulse approx ⅔ bit long, source = 0 generates a pulse 1/3 bit long.
AMI (T-1)		**Alternate Mark Inversion** Source = "1" causes a pulse, each succeeding pulse of opposite polarity, source = "0" causes no pulse.
MLT-3		**Multilevel** Source = "1" causes change to next available level source = "0" causes no change.
2B1Q		**2B1Q** Source = "00" sets level 1. Source = "01" sets level 2. Source = "10" sets level 4. Source = "11" sets level 3.
Differential NRZ		**Differential NRZ** Source = "1" causes transition at beginning of bit cell source = "0" causes no change.
Dipulse		**Multilevel** Source = "1" causes two pulses of opposite polarity source = "0" causes no change.



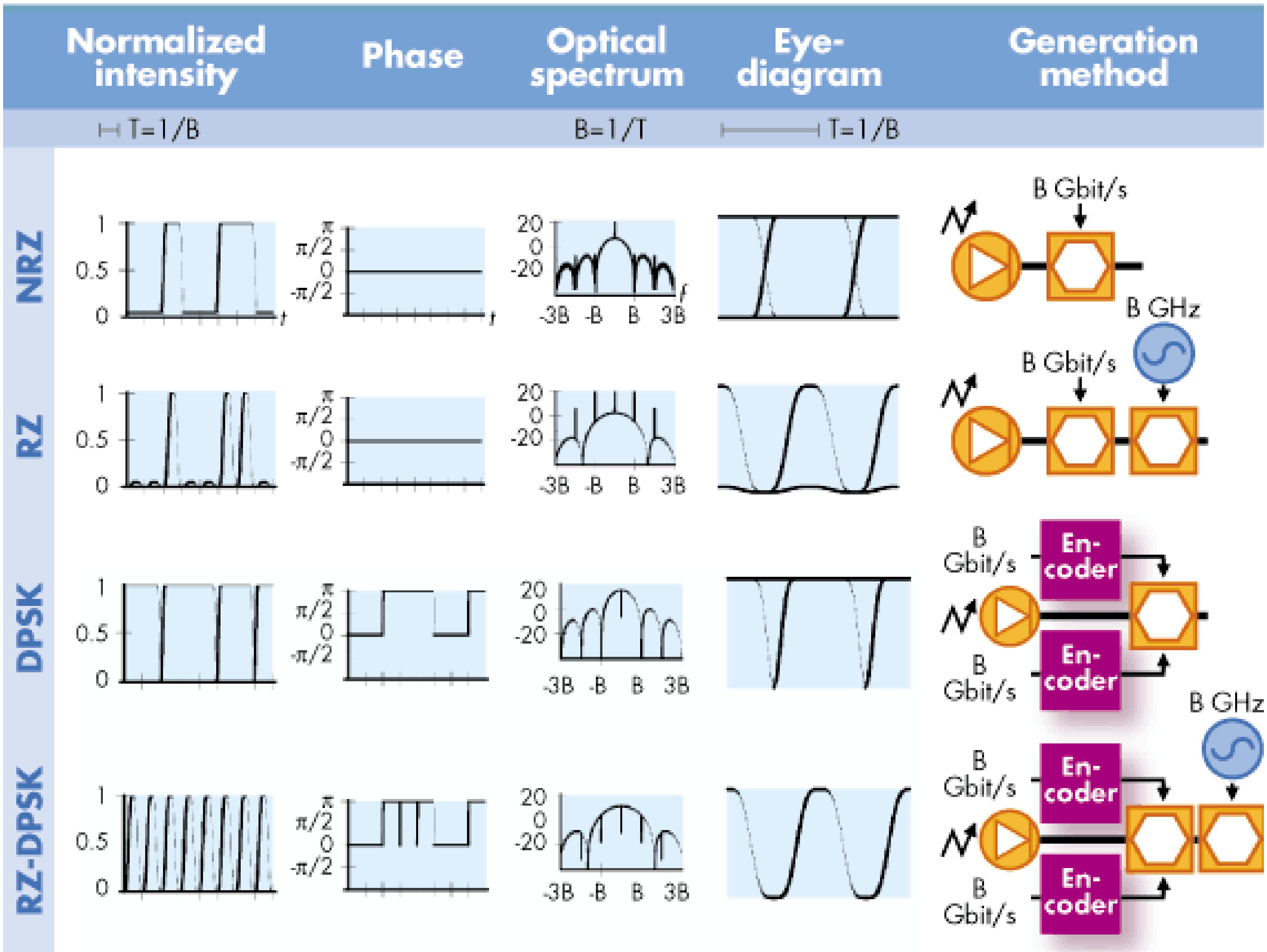
Mach-Zehnder Modulator



Implementation of NRZ and RZ Modulated Signals

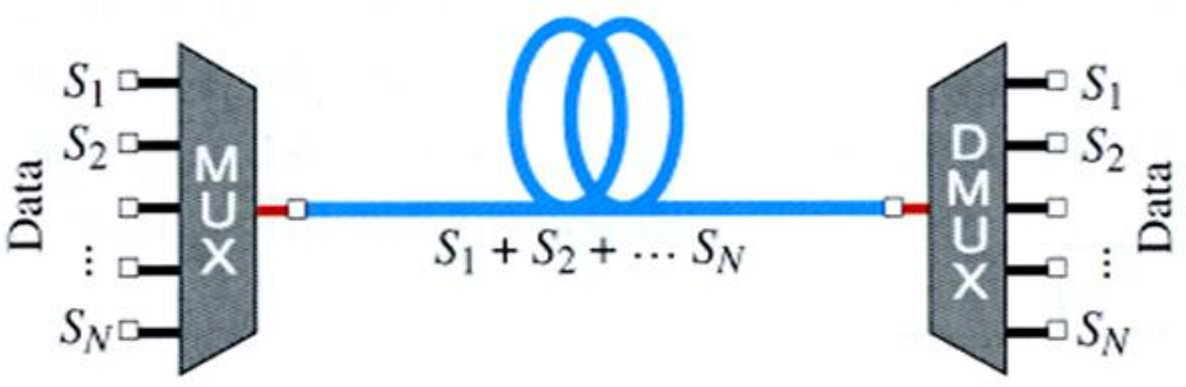


Typical characteristics of four modulation formats



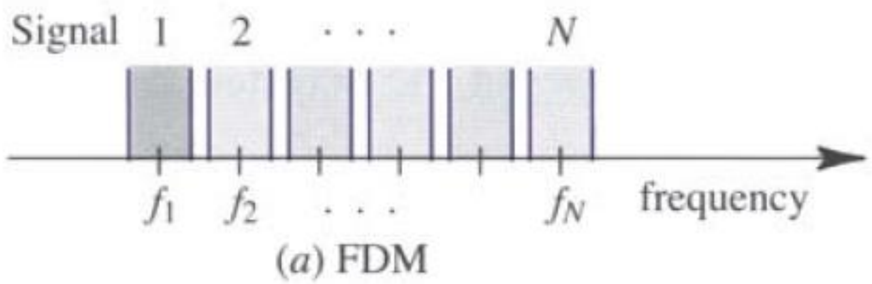
Prof. Norwood

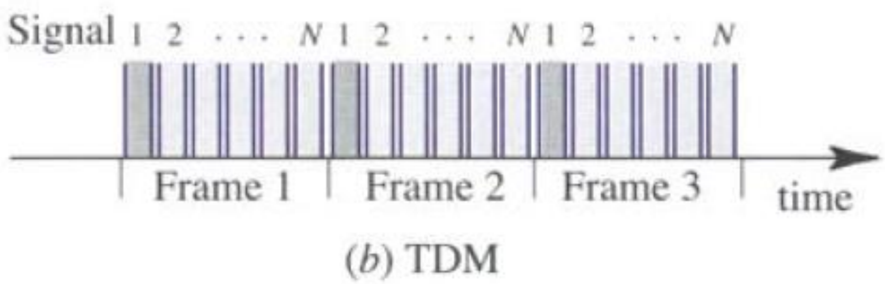
Multiplexing



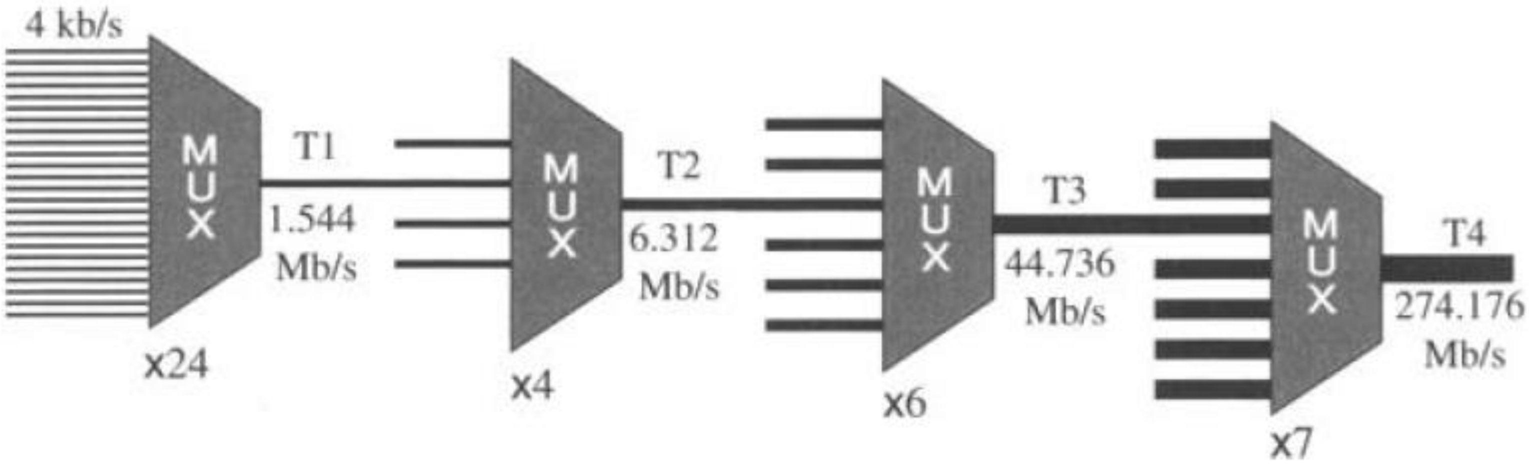
Transmission is often combined (multiplexed).

1) Frequency division multiplexing (FDM)
2) Time division multiplexing (TDM)
3) Code division multiplexing (CDM)





Multiplexing



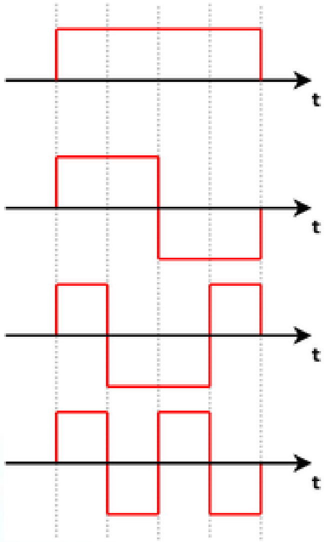
Example of TDM
T system: A set of 24 4-kb/s signals are combined to a T1 at 1.544 Mb/s signal.
A set of T1 is combined to T2 at 6.312 Mb/s.

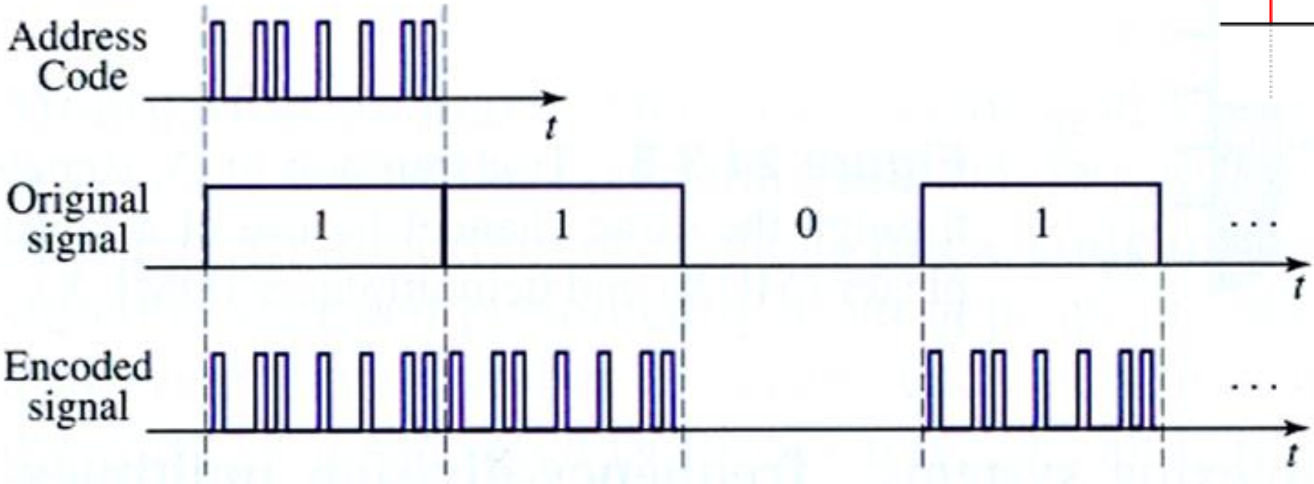
Multiplexing

Code division multiplexing

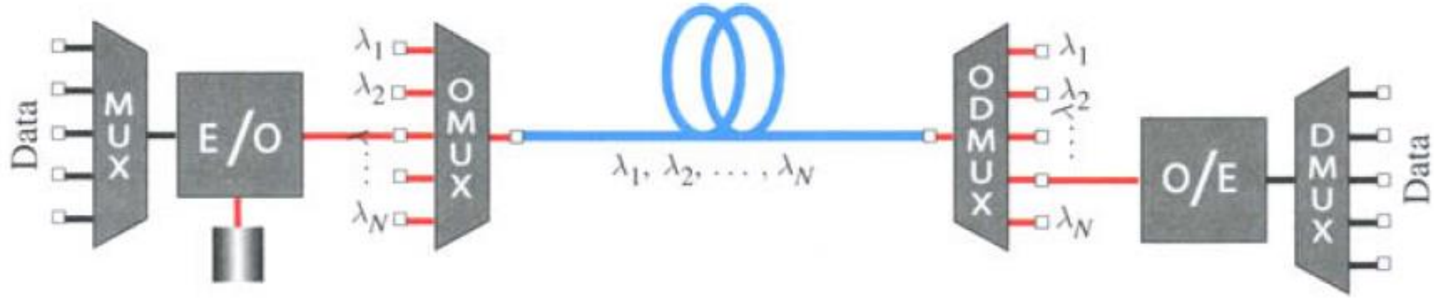
1) Each sender has a code, corresponding to one vector, v, from a group of orthogonal vectors
2) Associate data 0 with –v and 1 with +v
3) Data from all senders are combined and transmitted
4) Data are decoded for each sender using unique vector at receiving end

Example of 4 orthogonal digital signals.

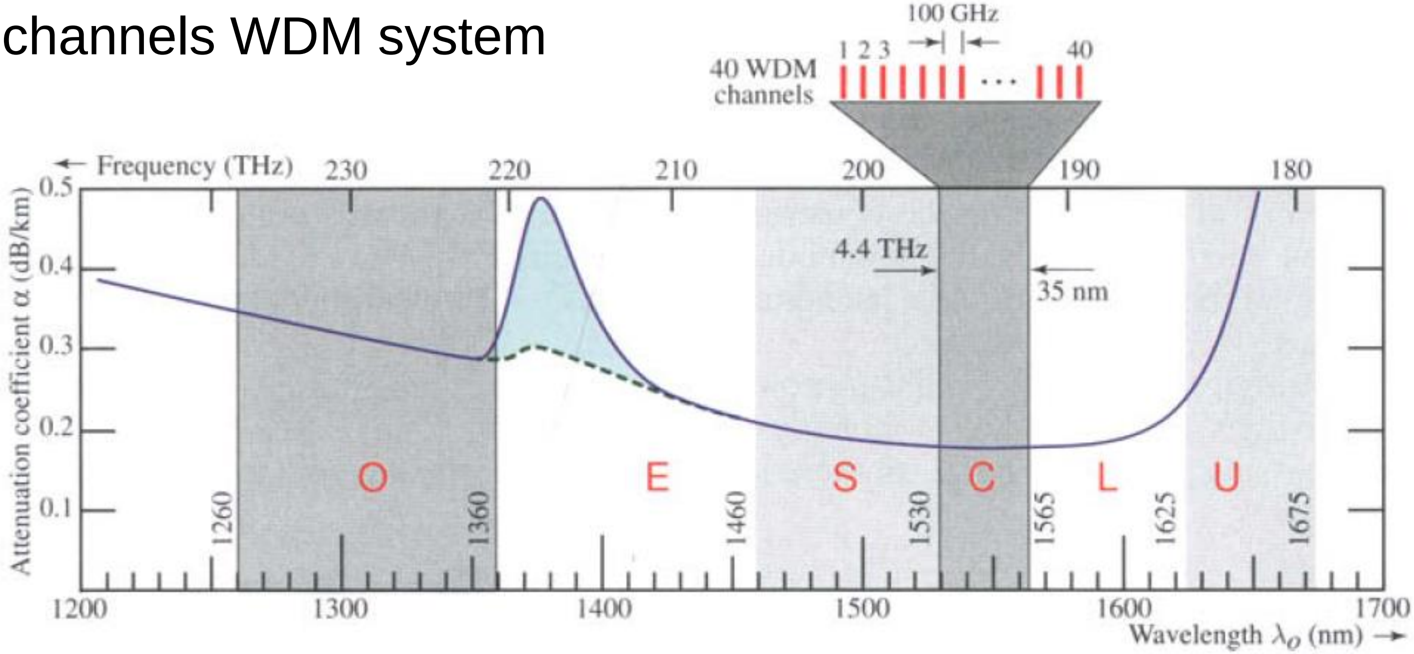




Wavelength Division Multiplexing



40 channels WDM system



Wavelength Division Multiplexing

ITU Frequencies (and Wavelengths) for L- and C-band
(100 GHz spacing, 100 channels)

Frequency (THz)	*Wavelength (nm)*	*Frequency (THz)*	*Wavelength (nm)*
186.00	1611.79	187.50	1598.89
186.10	1610.92	187.60	1598.04
186.20	1610.06	187.70	1597.19
186.30	1609.19	187.80	1596.34
186.40	1608.33	187.90	1595.49
186.50	1607.47	188.00	1594.64
186.60	1606.60	188.10	1593.79
186.70	1605.74	188.20	1592.95
186.80	1604.88	188.30	1592.10
186.90	1604.03	188.40	1591.26
187.00	1603.17	188.50	1590.41
187.10	1602.31	188.60	1589.57
187.20	1601.46	188.70	1588.73
187.30	1600.60	188.80	1587.88
187.40	1599.75	188.90	1587.04

continues

ITU Frequencies and Wavelengths (continued)

Frequency (THz)	*Wavelength (nm)*	*Frequency (THz)*	*Wavelength (nm)*
189.00	1586.20	192.50	1557.36
189.10	1585.36	192.60	1556.55
189.20	1584.53	192.70	1555.75
189.30	1583.69	192.80	1554.94
189.40	1582.85	192.90	1554.13
189.50	1582.02	193.00	1553.33
189.60	1581.18	193.10	1552.52
189.70	1580.35	193.20	1551.72
189.80	1579.52	193.30	1550.92
189.90	1578.69	193.40	1550.12
190.00	1577.86	193.50	1549.32
190.10	1577.03	193.60	1548.51
190.20	1576.20	193.70	1547.72
190.30	1575.37	193.80	1546.92
190.40	1574.54	193.90	1546.12
190.50	1573.71	194.00	1545.32
190.60	1572.89	194.10	1544.53
190.70	1572.06	194.20	1543.73
190.80	1571.24	194.30	1542.94
190.90	1570.42	194.40	1542.14
191.00	1569.59	194.50	1541.35
191.10	1568.77	194.60	1540.56
191.20	1567.95	194.70	1539.77
191.30	1567.13	194.80	1538.98
191.40	1566.31	194.90	1538.19
191.50	1565.50	195.00	1537.40
191.60	1564.68	195.10	1536.61
191.70	1563.86	195.20	1535.82
191.80	1563.05	195.30	1535.04
191.90	1562.23	195.40	1534.25
192.00	1561.42	195.50	1533.47
192.10	1560.61	195.60	1532.68
192.20	1559.79	195.70	1531.90
192.30	1558.98	195.80	1531.12
192.40	1558.17	195.90	1530.33

System Performance

- Important parameters of a digital communication system
  - Bit error rate: BER
  - Optical signal to noise: OSNR
  - Q factor
- All parameters are monitored regularly to track the health of the network
- Parameters are related to each other

Bit Error Rate

Bit error rate (BER): One of the most important ways to determine the quality of a digital transmission system is to measure its Bit Error Rate (BER). BER is calculated by comparing the transmitted sequence of bits to the received bits and counting the number of errors. The ratio of how many bits received in error over the number of total bits received is the BER. This measured ratio is affected by many factors including: signal to noise ratio, distortion, and jitter.

$$BER = N_{err}/N_{bits}$$

For a good system performance $BER < 10^{-12}$

Bit Error Rate

The most obvious method of measuring BER is to brute force send bits through the system and calculate the BER. Since this is a statistical process, the measured BER only approaches the actual BER as the number of bits tested approaches infinity. Fortunately, in most cases we need only to test that the BER is less than a predefined threshold. The number of bits required to accomplish this will only depend on the required confidence level and BER threshold. The confidence level is the percentage of tests that the system's true BER is less than the specified BER. Since we cannot measure an infinite number of bits and it is impossible to predict with certainty when errors will occur, the confidence level will never reach 100%.

To calculate the confidence level (CL), we use the equation:

$$CL = 1 - e^{-N_{bits} * BER}$$

This equation can be rearranged to calculate the number of bits required for a given BER and confidence level (CL):

$$N_{bits} = \frac{-\ln(1-CL)}{BER}$$

Bit Error Rate

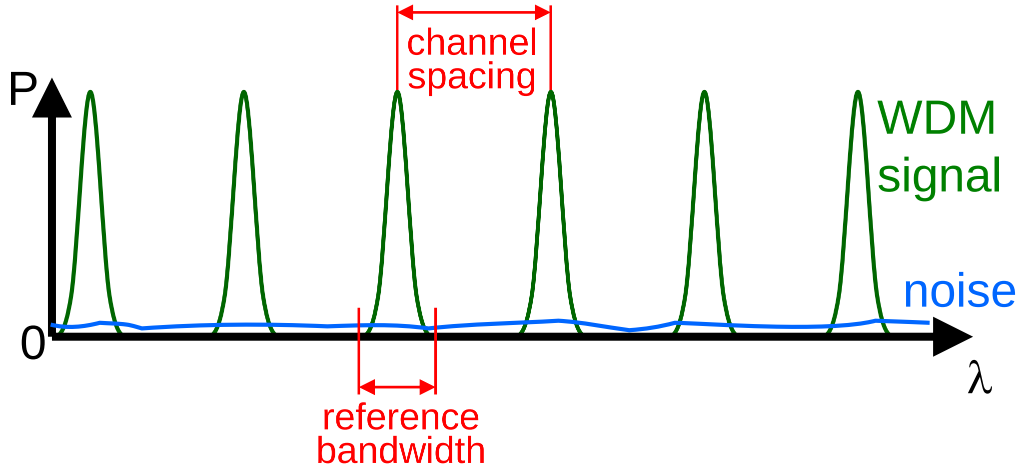
In order to determine the test time required, the number of bits to be tested is simply divided by the data rate

$$Time(seconds) = \frac{-\ln(1-CL)}{f * BER}$$

	STM-256/OC-768 39.81312 GHz	STM-264/OC-192 9.95328 GHz	STM-16/OC-48 2.48832 GHz	STM-4/OC-12 622.08 MHz	STM-1/OC-3 155.52 MHz
10^{-16}	~ 8.7 days	~ 35 days	~ 139 days	~ 2 yrs	~ 8.4 yrs
10^{-15}	~ 21 hrs	~ 3.5 days	~ 30 days	~ 42 days	~ 224 days
10^{-14}	~ 2.1 hrs	~ 8.4 hrs	~ 1.4 days	~ 5.6 days	~ 22.4 days
10^{-13}	~ 12.5 mins	~ 50 mins	~ 3.3 hrs	~ 13 hrs	~ 2.2 days
10^{-12}	~ 1.3 mins	~ 5 mins	~ 20 mins	~ 80 mins	~ 5.35 hrs
10^{-11}	~ 7.5 secs	~ 30 secs	~ 2 mins	~ 8 mins	~ 32 mins

A table of test times at 95% confidence level is given for standard data rates and bit error ratios

OSNR



"The IEC standard defines optical signal-to-noise ratio as the ratio of the signal power at the peak of a channel to the noise power interpolated at the position of the peak and is described by the following equation:

$$OSNR = 10 \times \log \frac{P_i}{N_i} + 10 \times \log \frac{B_m}{B_r}$$

where:

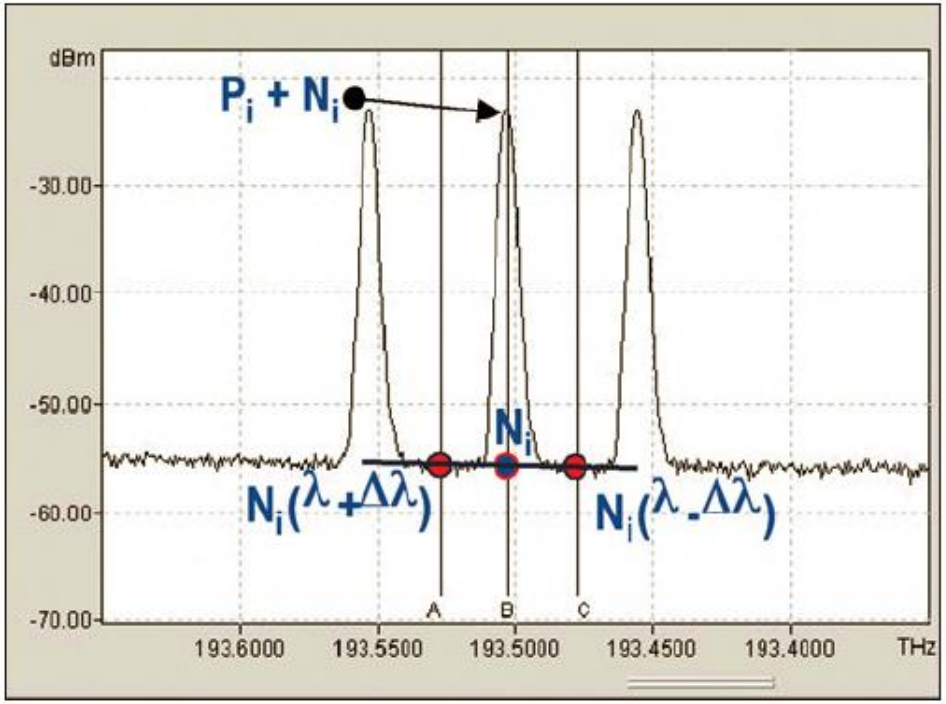
P_i is the optical signal power in watts at the i^{th} channel;

Bm is the resolution bandwith of the measurement;

N_i is the interpolated value of noise power in watts measured in the resolution bandwidth[v] of the measurement (B_m) derived from the noise measured at the mid-channel spacing point[vi];

B_r is the reference optical bandwidth, typically chosen to be 0.1 nm, and the second term of the equation is used to provide an OSNR value that is independent of the instrument's resolution bandwidth (B_m) for the measurement so that results obtained with different instruments can be compared[vii].

OSNR



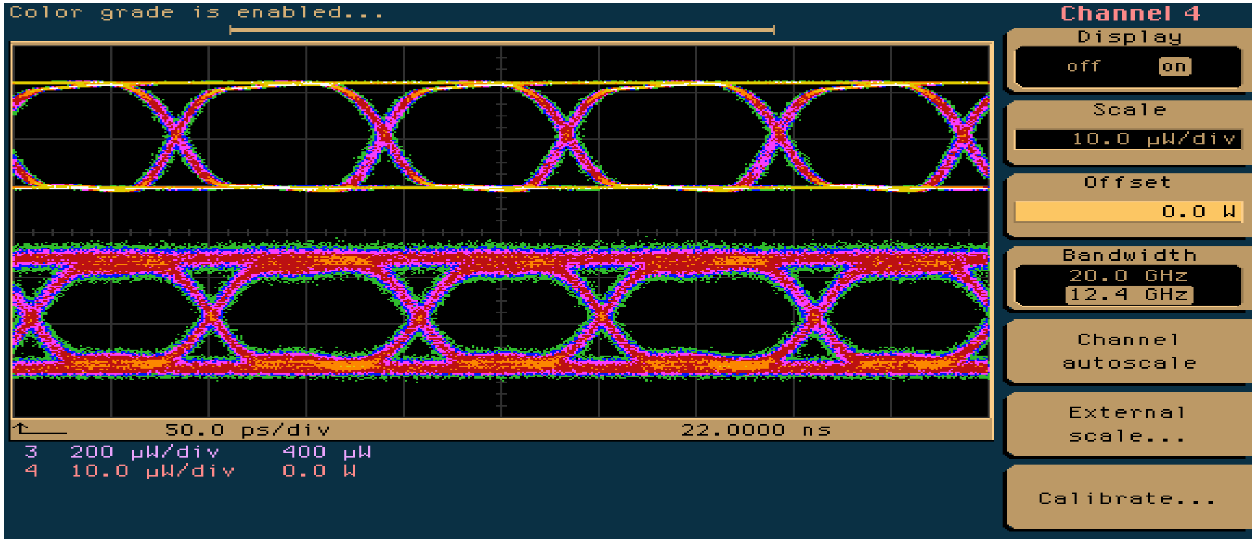
Noise power is usually interpolated at the peak

OSNR can be correlated to the BER. According to IEC 61280-2-7 draft document,

$$BER = \frac{1}{\sqrt{2\pi}} \int_{SNR}^{\infty} dt \exp(-\frac{t^2}{2})$$

Bit Error Testing-Eye diagram

An eye diagram is a common indicator of the quality of signals in high-speed digital transmissions. An oscilloscope generates an eye diagram by overlaying sweeps of different segments of a long data stream driven by a master clock.

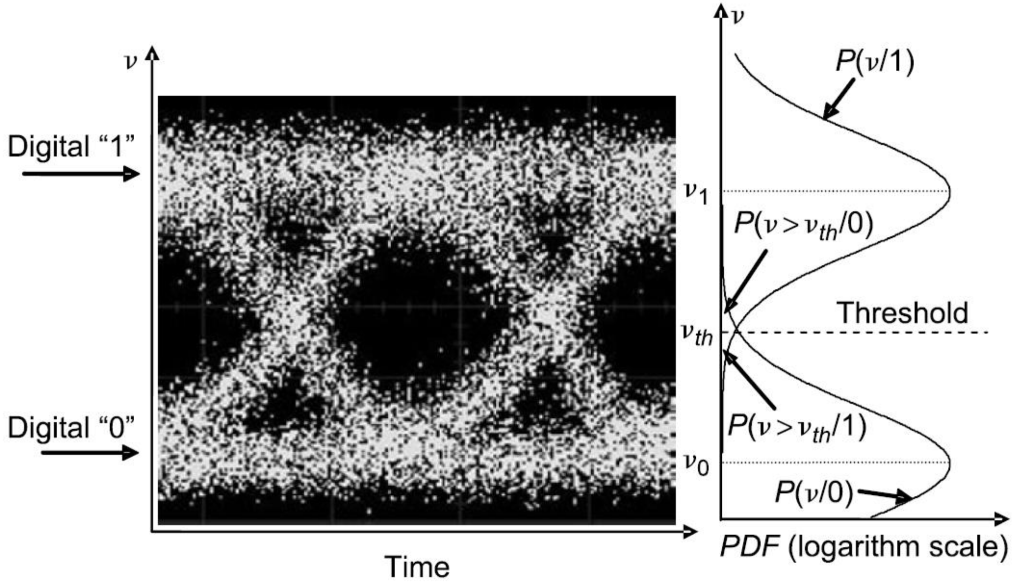


In practical terms this may be achieved by displaying the data waveform on a sampling oscilloscope triggered from the system clock.

Q-factor

The performance of digital fiber-optic transmission systems can be specified using the Q-factor. The Q-factor is the electrical signal-to-noise ratio (SNR) at the input of the decision circuit in the receiver terminal Rx.

For the purpose of calculation, the signal level is interpreted as the difference in the **mean values** ν_0 and ν_1, and the noise level is the sum of the **standard deviations** σ_0 and σ_1 at the sampling time:



$$Q = \frac{\nu_1 - \nu_0}{\sigma_1 + \sigma_0}$$

Q-factor

Bit Error Testing-Eye diagram

BER is a conditional probability of receiving signal *y* while the transmitted signal is *x, P(y/x),* where *x* and y can each be digital 0 or 1. Since the transmitted signal digital states can be either 0 or 1, we can define *P(y/0)* and P(y/1) as the PDFs (probability density function) of the received signal at state *y* while the transmitted signals are 0 and 1, respectively. Suppose that the probability of sending digital 0 and 1 are *P(O)* and *P(1)* and the decision threshold is v_{th}; the BER of the receiver should be:

$$BER = P(0)P(v > v_{th}/0) + P(1)P(v < v_{th}/1)$$

$$P_{Gaussian}(v) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(v - v_m)^2}{2\sigma^2}\right)$$

,If Gaussian noise is assumed

Bit Error Testing-Eye diagram

The probability for the receiver to declare 1 while the transmitter actually sends a 0 is:

$$P(v > v_{th}/0) = \frac{1}{\sigma_0\sqrt{2\pi}}\int_{v_{th}}^{\infty}\exp\left(-\frac{(v-v_0)^2}{2\sigma_0^2}\right)dy = \frac{1}{\sqrt{2\pi}}\int_{Q_0}^{\infty}\exp\left(-\frac{\xi^2}{2}\right)d\xi$$

Where $\xi = (v - v_0)/\sigma_0$, $Q_0 = \frac{v_{th} - v_0}{\sigma_0}$,Q-value or quality factor

Similarly, the probability for the receiver to declare 0 while the transmitter actually sends a 1 is:

$$P(v < v_{th}/1) = \frac{1}{\sigma_1\sqrt{2\pi}}\int_{-\infty}^{v_{th}}\exp\left(-\frac{(v_1-v)^2}{2\sigma_1^2}\right)dy = \frac{1}{\sqrt{2\pi}}\int_{Q_1}^{\infty}\exp\left(-\frac{\xi^2}{2}\right)d\xi$$

$\longrightarrow$

$$BER = \frac{1}{2}P(v > v_{th}/0) + \frac{1}{2}P(v < v_{th}/1)$$

$$= \frac{1}{2\sqrt{2\pi}}\left\{\int_{Q_0}^{\infty}\exp\left(-\frac{\xi^2}{2}\right)d\xi + \int_{Q_1}^{\infty}\exp\left(-\frac{\xi^2}{2}\right)d\xi\right\}$$

,*P(0) = P (1) = 0.5* is assumed

Bit Error Testing-Eye diagram

A widely used mathematical function, the error function, is defined as:

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-y^2)dy$$

And the complementary error function is defined as:

$$erfc(x) = 1 - erf(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty \exp(-y^2)dy$$

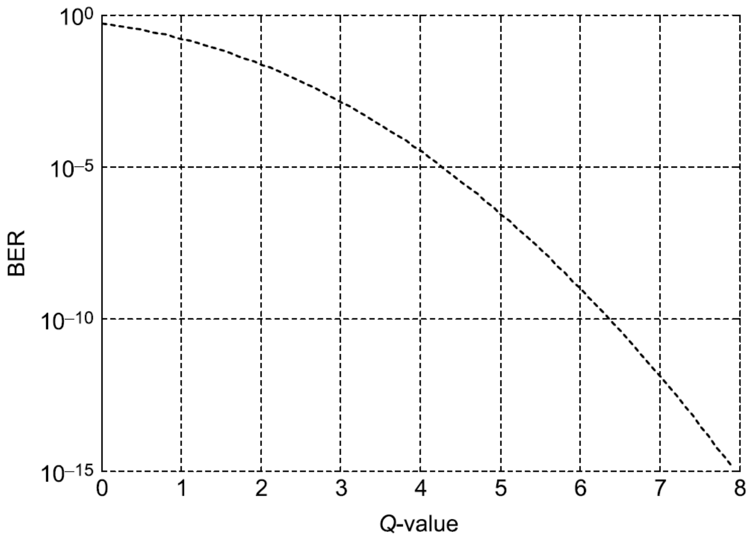
$$\longrightarrow \quad BER = \frac{1}{4}\left\{ erfc\left(\frac{Q_0}{\sqrt{2}}\right) + erfc\left(\frac{Q_1}{\sqrt{2}}\right) \right\}$$

Bit Error Testing-Eye diagram

By symmetry, we can assume $Q_1 = Q_0 = Q$, or $\frac{v_{th} - v_0}{\sigma_0} = \frac{v_1 - v_{th}}{\sigma_1}$

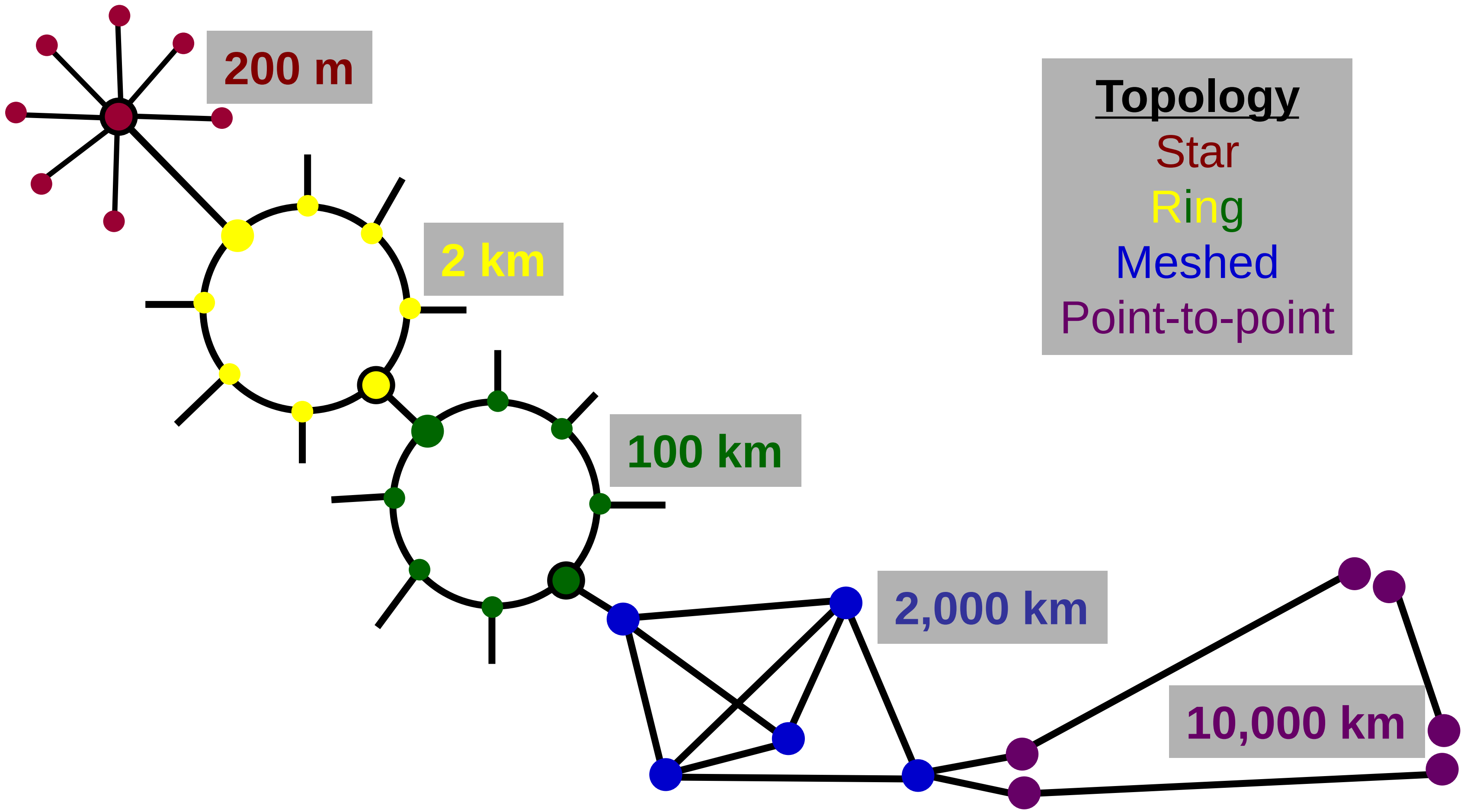
$$\longrightarrow \quad BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right)$$

,where $Q = \frac{v_1 - v_0}{\sigma_1 + \sigma_0}$



BER as the function of the Q-value

Network Topology



Network Topology

- \- From “In-house” to “Submarine” -

In-house
Plastic optical fiber POF
10/100 Mbit/s Ethernet

Campus / LAN
Multimode fiber
100 Mb/s / 1 Gb/s
Ethernet

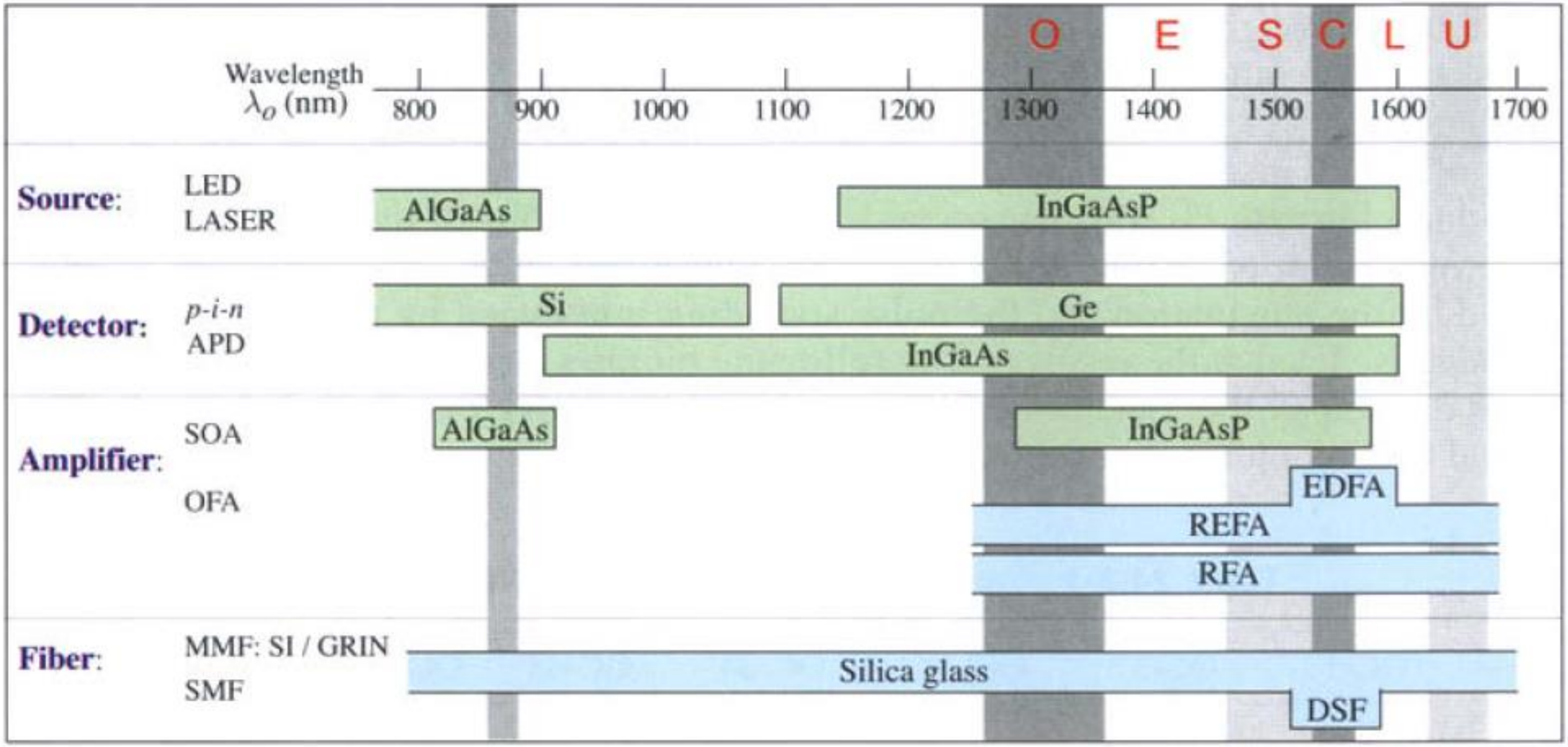
City / MAN
Singlemode fiber
2.5 Gbit/s SONET

National backbone / WAN
Singlemode fiber
N×10 Gbit/s SONET / OTN

Different requirements:
low-cost
flexible
manageable
reliable

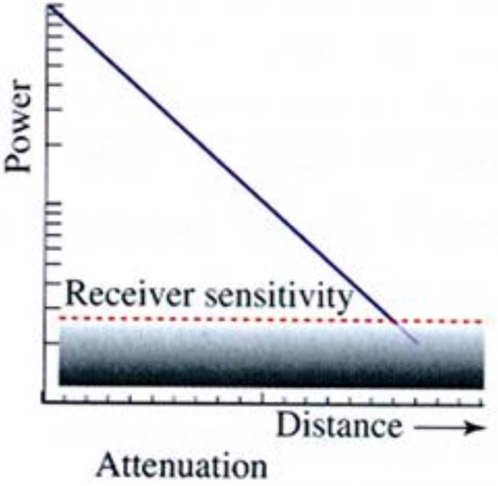
Global / submarine
Singlemode fiber
N×10 Gbit/s
SONET / OTN

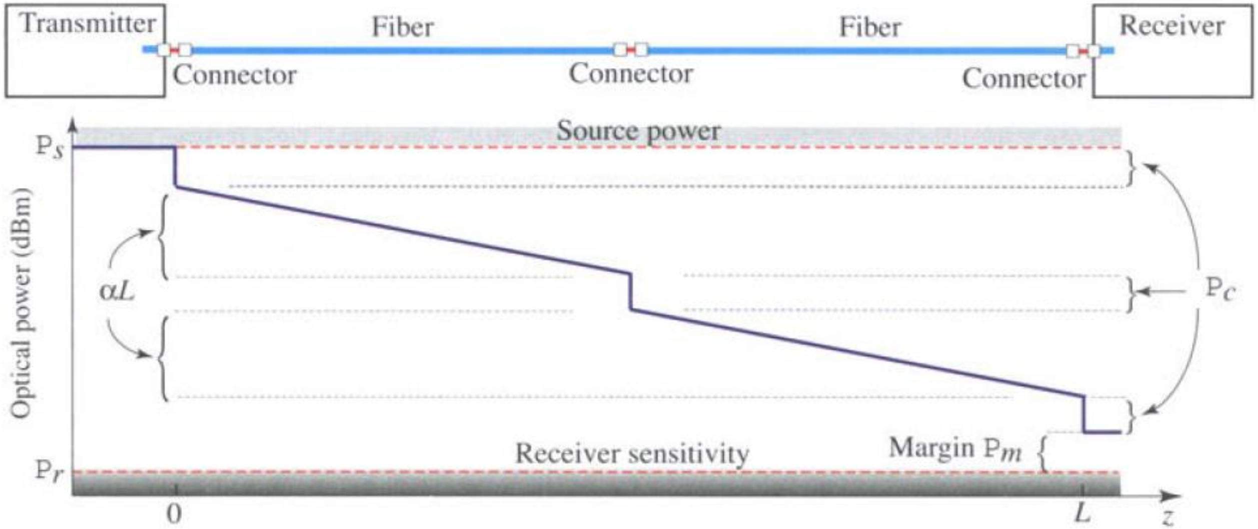
Network Technologies



Limitation factors

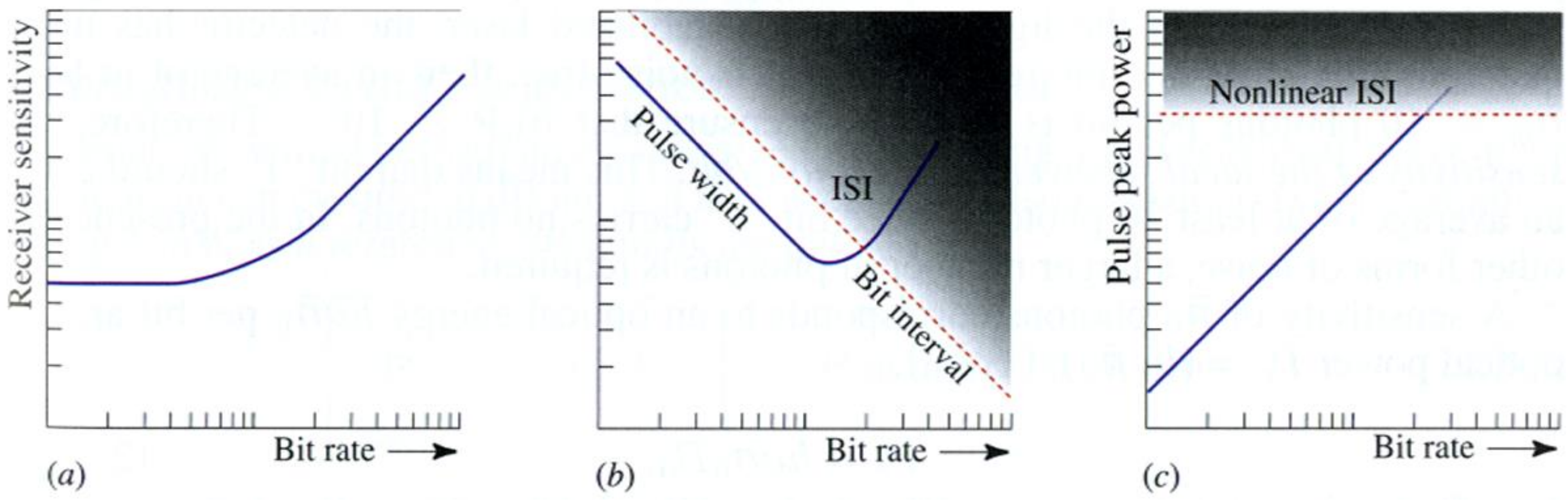
- ➢ Fiber loss
- ➢ Dispersion
- ➢ Nonlinear effects





Limitation factors

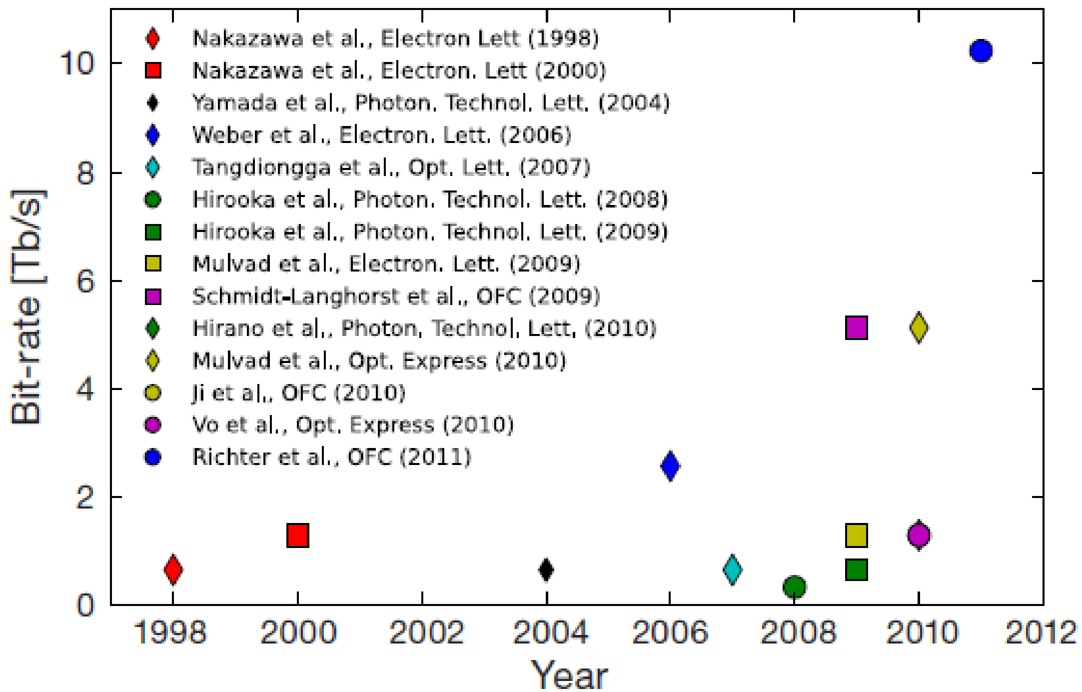
1. At higher bit rate, transmission is more sensitive to attenuation. For a fixed power, higher bit rate means fewer photons per bit and more photon noise.
2. At higher bit rate, pulse is shorter and spectrum is wider. Dispersion, and nonlinear effects such as intersymbol interference (ISI) become important.
3. At fixed number of photon per bit, higher bit rate means greater optical power.



ISI: Intersymbol interference

State-of-the-art

[Single channel bit-rate research: The last 25 years]



Research was first focused on increasing the bit rate of 640 Gbaud signals via polarization multiplexing and high efficiency modulation formats. The current record for single channel bit-rate is a remarkable 10.2 Tbit/s for a polarization multiplexed 1.28 Tbaud quadrature amplitude modulation signal.

OPN Optics & Photonics News

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State-of-the-art

OPTICAL COMMUNICATIONS

Integrated combs drive extreme data rates

A chip-based optical frequency comb source has now been successfully used to send 661 Tbit s^{-1} over 9.6 km of multicore fibre, bringing considerable savings in the energy consumption and size of data transmission equipment.

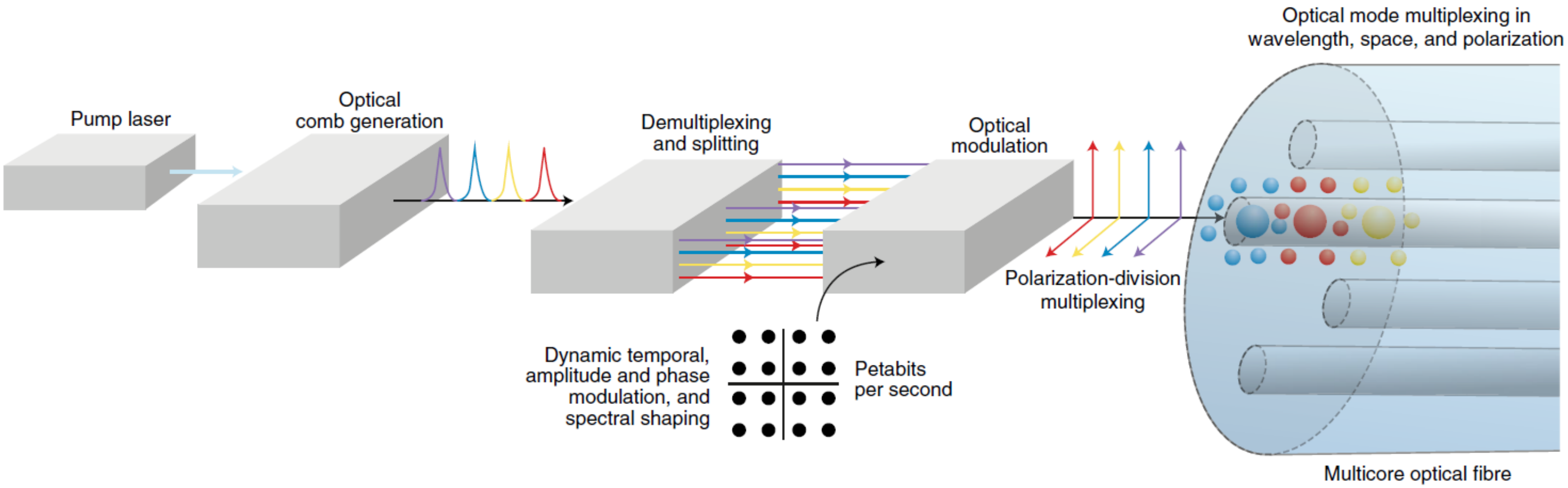


Fig. 1 | Generating extreme transmission data rates with a single chip-scale optical frequency comb source. An optical frequency comb generator is coherently modulated by terabits of data channels in time, frequency and phase, and parallel multiplexed or bundled into a superchannel on a multicore optical fibre using WDM, PDM, SDM and MDM techniques.

nature photonics LETTERS
https://doi.org/10.1038/s41566-018-0205-5

Single-source chip-based frequency comb enabling extreme parallel data transmission

CIAN: Developing Integrated opto-electronics technology for future Internet

Industry Partners

Vision

<u>Vision</u>: A transformed Internet that would enable end-user access to emerging real time, on-demand, network services at data-rates up to 100Gbps, anywhere at anytime, at low cost and with high energy efficiency

Anytime/ Anywhere:
Converged wire-line and wireless service aware networking
[C1-2, C1-3, C1-6]

Low Cost:
Integrated OE chips, integrated end-to-end platform, minimization of OEOs
[C1-1, C1-2, C2-1, C2-2, C2-3]

On-Demand:
Dynamic intelligent Hybrid switched networking, BW on demand [C1-1, C1-2, C1-5, C1-6]

Energy optimization activity in all thrusts and WGs, integrated OE chips [C1-2, C1-4, C2-3, C3-1, C3-2]

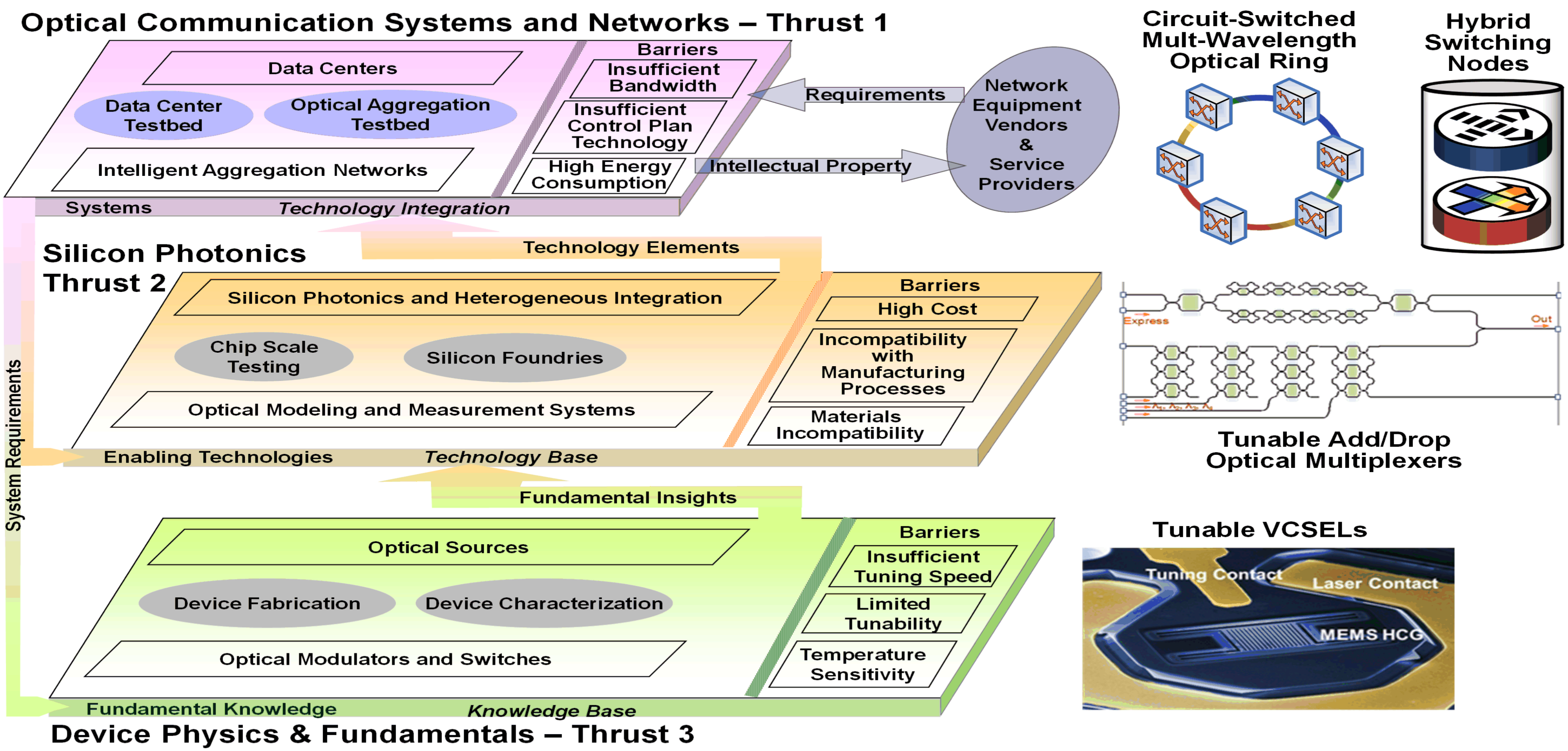
100 Gbps:
High capacity Hybrid optical/electronic systems, 100+ Gbps hosts [C1-1, C1-2, C1-7]

Real-Time:
Low latency end-to-end optical connections, fast switching of very high data rate flows, minimizing OEOs
[C1-3, C1-5, C1-6]

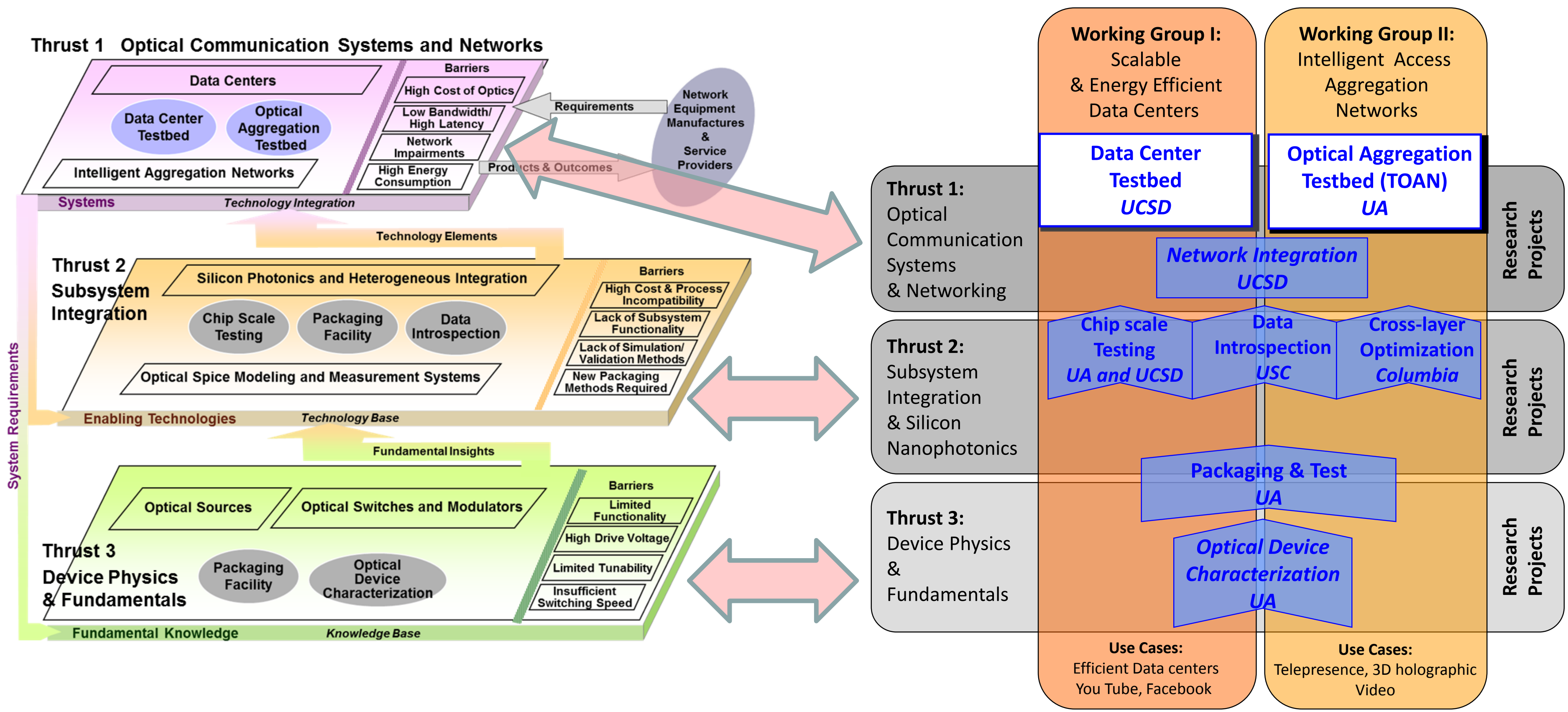
<u>Mission</u>: Create integrated optoelectronic technologies for access aggregation and data centers to overcome the existing network bottlenecks

Validate and achieve CIAN vision by working with SAB and our industry partners: Google, Cisco, Facebook,…

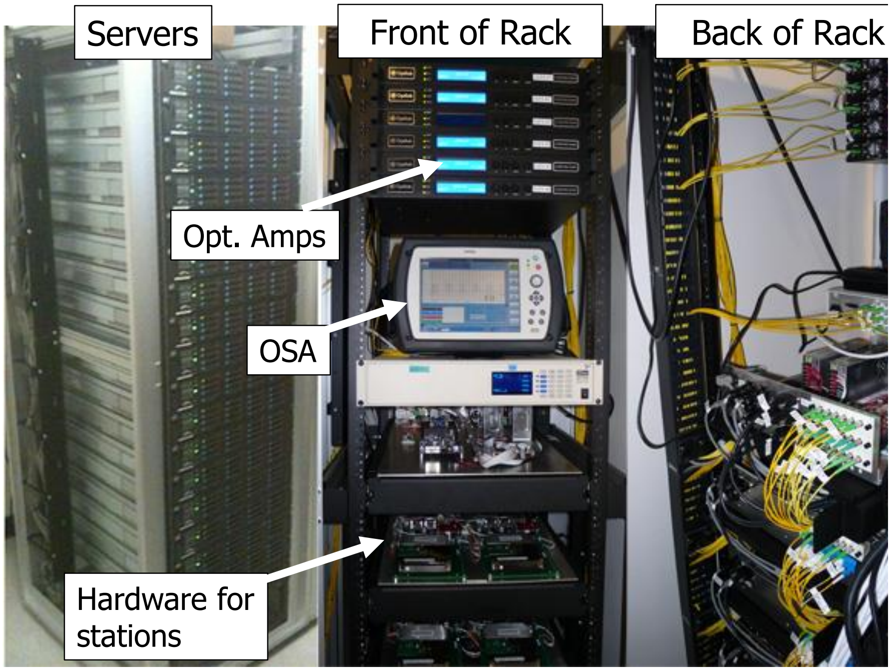
Strategic Research Plan



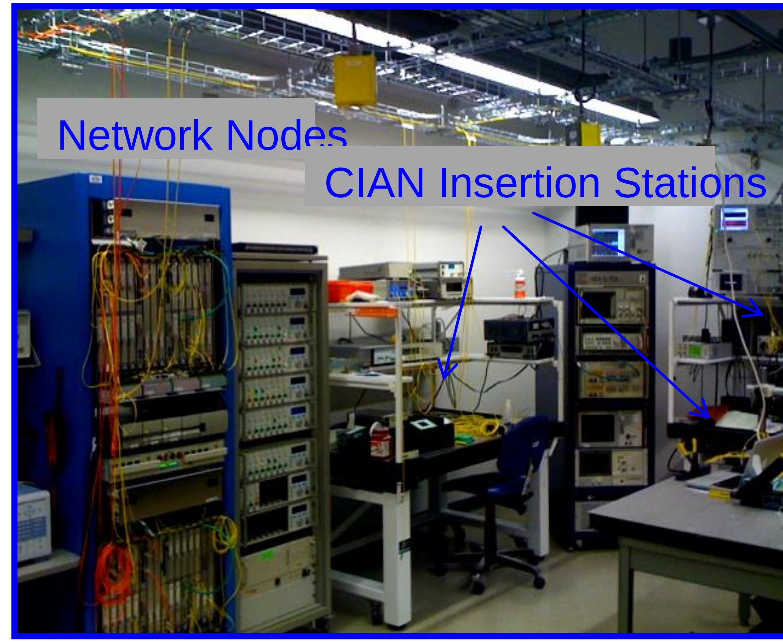
Working Groups (WG) integrate research across 3 thrusts



Testbeds



Data Center Network



Aggregation Network

- MORDIA (24 servers)
- Chip-scale testing and insertion from Sandia, Columbia/Cornell
- Wavelength translation through parametric processing