

Optical Links for TDAQ

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(CERN EP-LBC)

Outline

- Fundamental concepts
- Physical devices
- Applications
 - CERN Versatile Link PLUS
- Installation / Commissioning

Safety first!

- Class 1
 - Safe
- Class 1M
 - Safe if not magnified
- Class 2
 - Visible light, triggers blink reflex
safe $\leq 0.25\text{s}$ (e.g. laser pointers)
- Class 2M
 - Same as 2, if not magnified
- Class 3R
 - Low risk of injury, limit direct exposure
(typical tx)
- Class 3B
 - Do not look directly (CD, DVD)
- Class 4
 - Permanent eye damage, skin burns,
may light flammable materials



Why optical fibers (vs. copper)

PROs

- Cheap material (silica)
- High rates (Tb/s)
- Low weight
- Low material budget
- Long range (1000s Km)
- No interference
- Improving technology

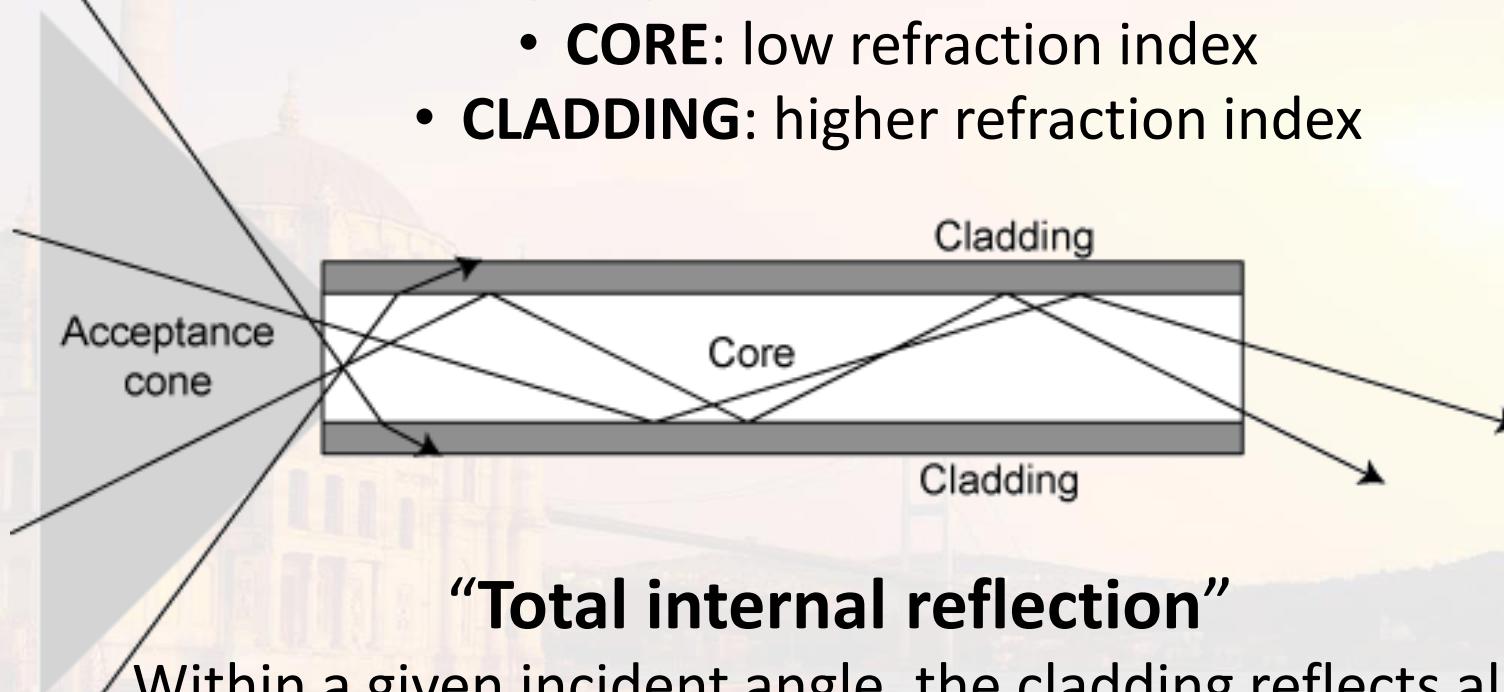
CONS

- Expensive technology
- System complexity
- Mechanical fragility
- Installation complexity
- Termination complexity

How optical fibers work

Essentially, a light guide with a two layer structure

- **CORE:** low refraction index
- **CLADDING:** higher refraction index

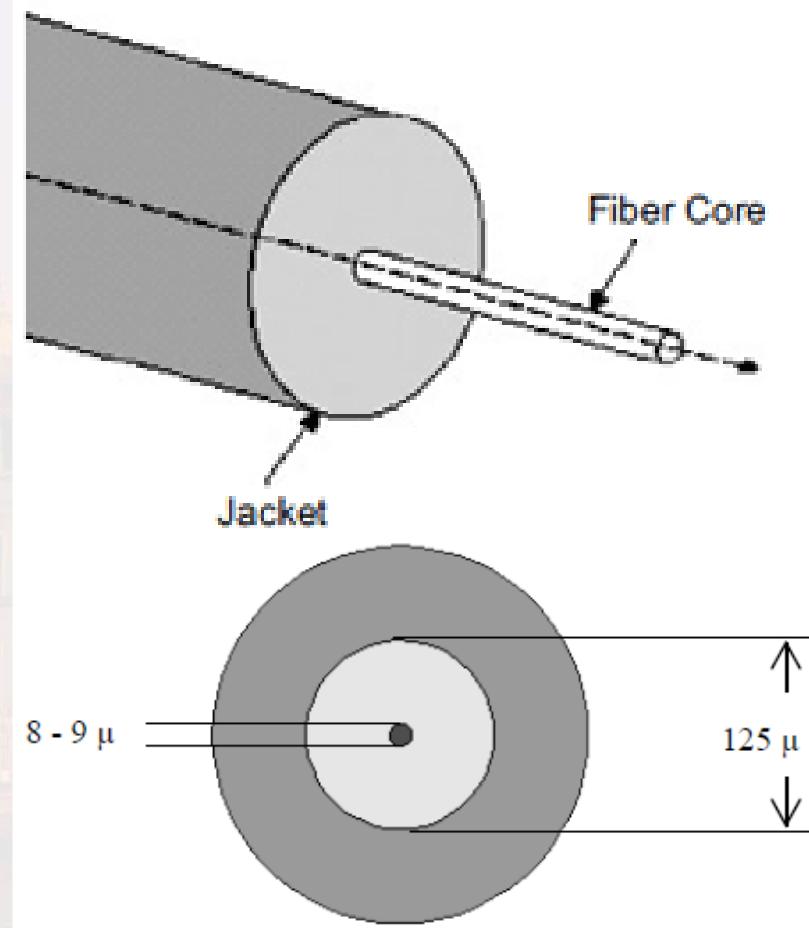


“Total internal reflection”

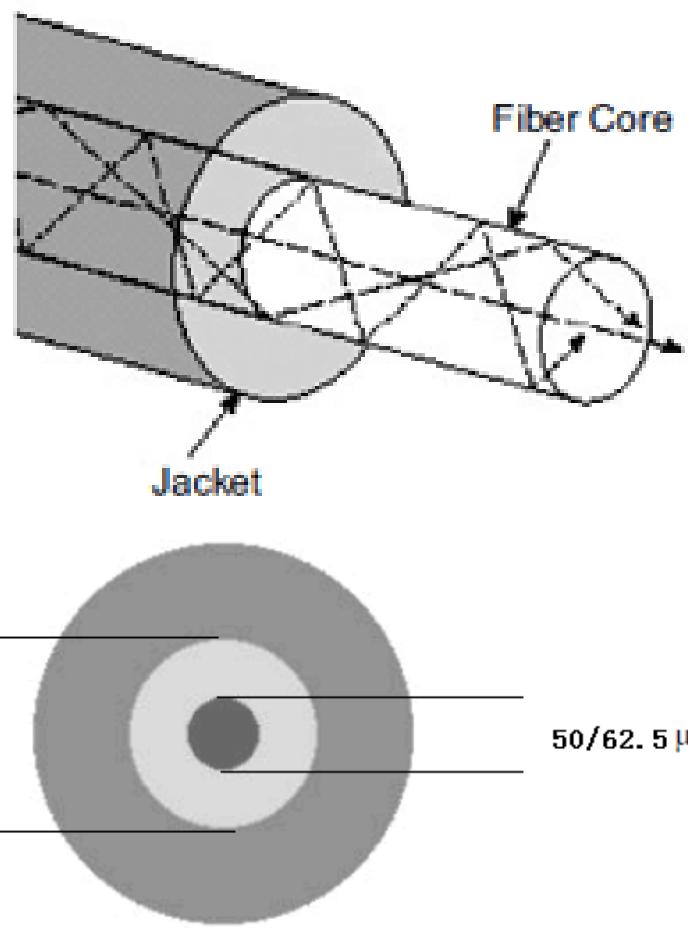
Within a given incident angle, the cladding reflects all light back into the core

“Single-Mode” vs. “Multi-Mode”

Single-Mode Fiber (SMF)

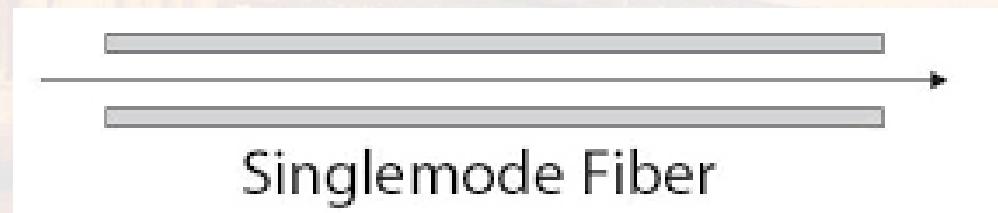


Multi-Mode Fiber (MMF)



Single-Mode fiber (SMF)

- Smaller core diameter (8-10 μm)
- Higher bandwidth and longer range
- No “modal dispersion” (frequently used for WDM)
 - ~80 Km unamplified
 - 1000s of Km amplified
- Very expensive and precise laser transmitters

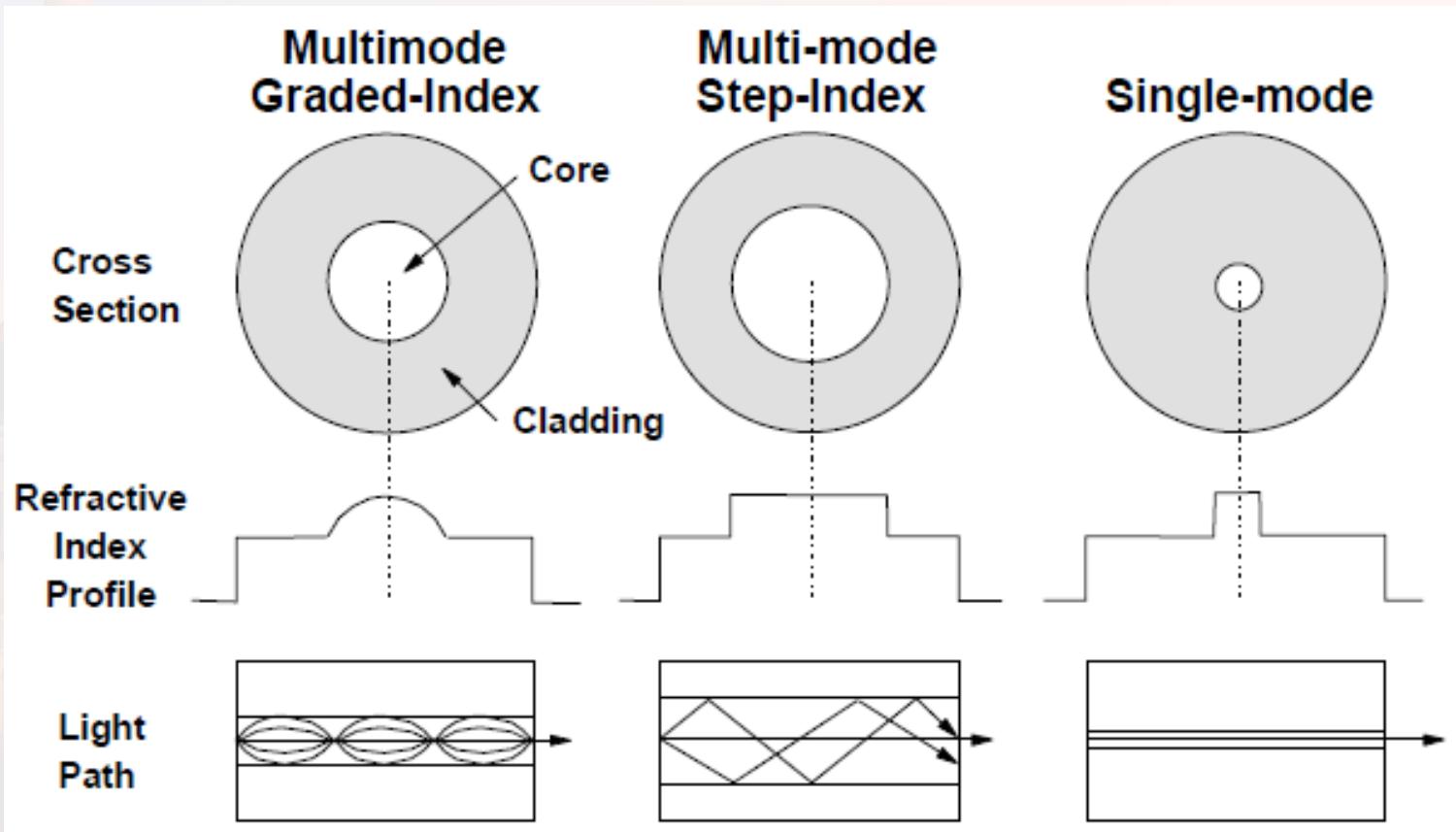


Multi-Mode Fiber (MMF)

- Much wider core ($\sim 50 \mu\text{m}$)
- Much more forgiving wrt light quality & alignment
- Attenuation influenced by “modal dispersion”
 - Multiple propagation modes allowed in the light guide
 - Range limited to hundreds of meters
 - Less on graded-index wrt step-index fibers
- Light sources are considerably cheaper



Graded-index vs. Step-index fiber



OM3 vs. OM4

OM3

- <3.5 dB/Km @850nm
- EMB: 2000 MHz x km
- 1000m @ 1 Gb/s
- 300m @ 10 Gb/s
- 100m @ 100 Gb/s

OM4

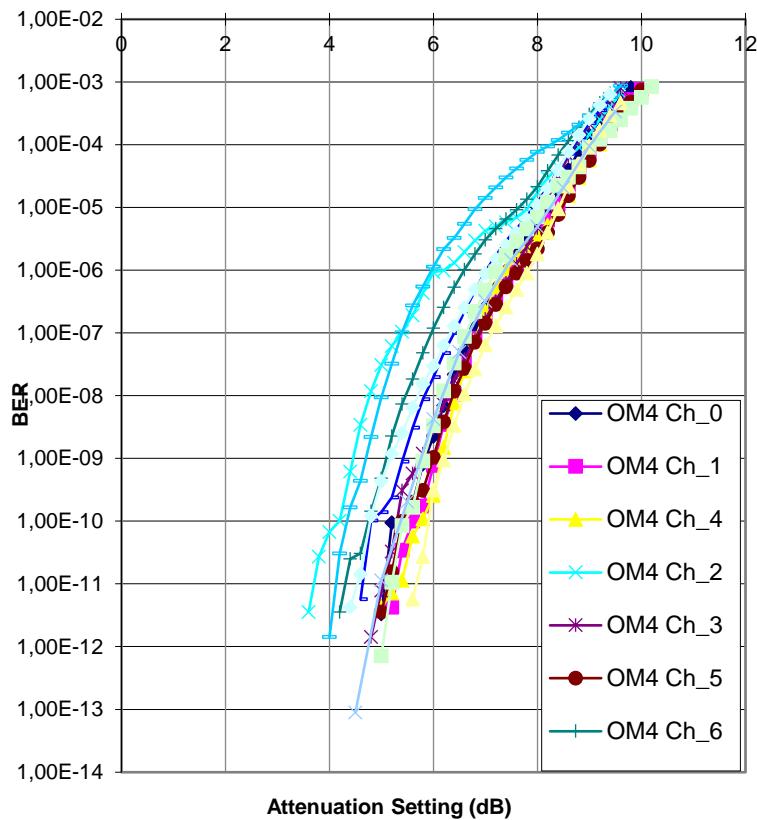
- <3.0 dB/Km @850nm
- EMB: 4700 MHz x km
- 1000m @ 1 Gb/s
- 500m @ 10 Gb/s
- 150m @ 100 Gb/s
- Higher cost



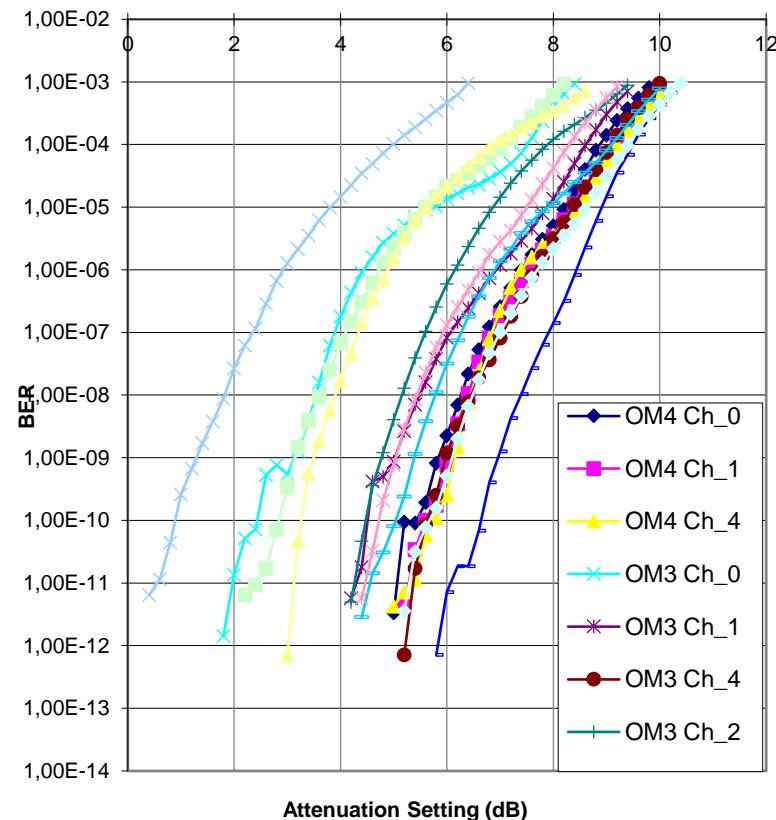
EMB = Effective Modal Bandwidth = max data rate at a given distance (constant) and λ
only accounts for modal dispersion, not BER

OM3 vs. OM4 Bit Error Ratio (BER)

BERT vs. Attenuation - OM4 10G



BERT vs. Attenuation - OM3 10G



<https://indico.cern.ch/event/297003>

21/06/2023

ISOTDAQ 2023 - Optical Links for TDAQ

Ethernet: BER < 10^{-12}

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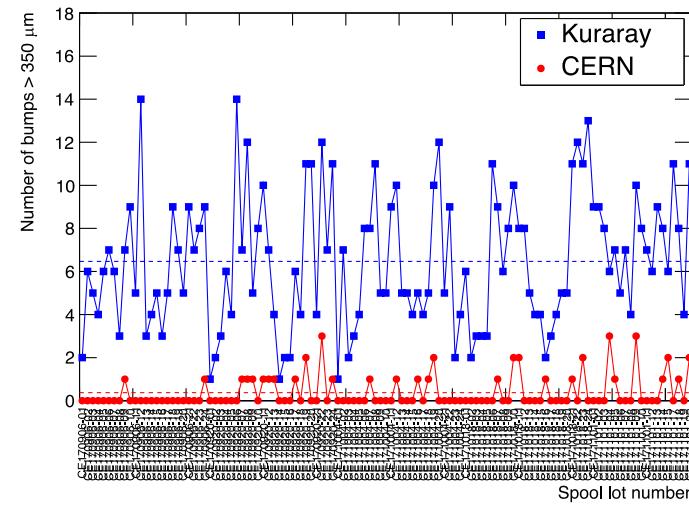
Chromatic Mode Dispersion (CMD)

- Dispersion spreads out pulse shapes
- Different wavelengths (colors) propagate in a non vacuum at different speeds
- CMD is worse at higher data rates (f^2)



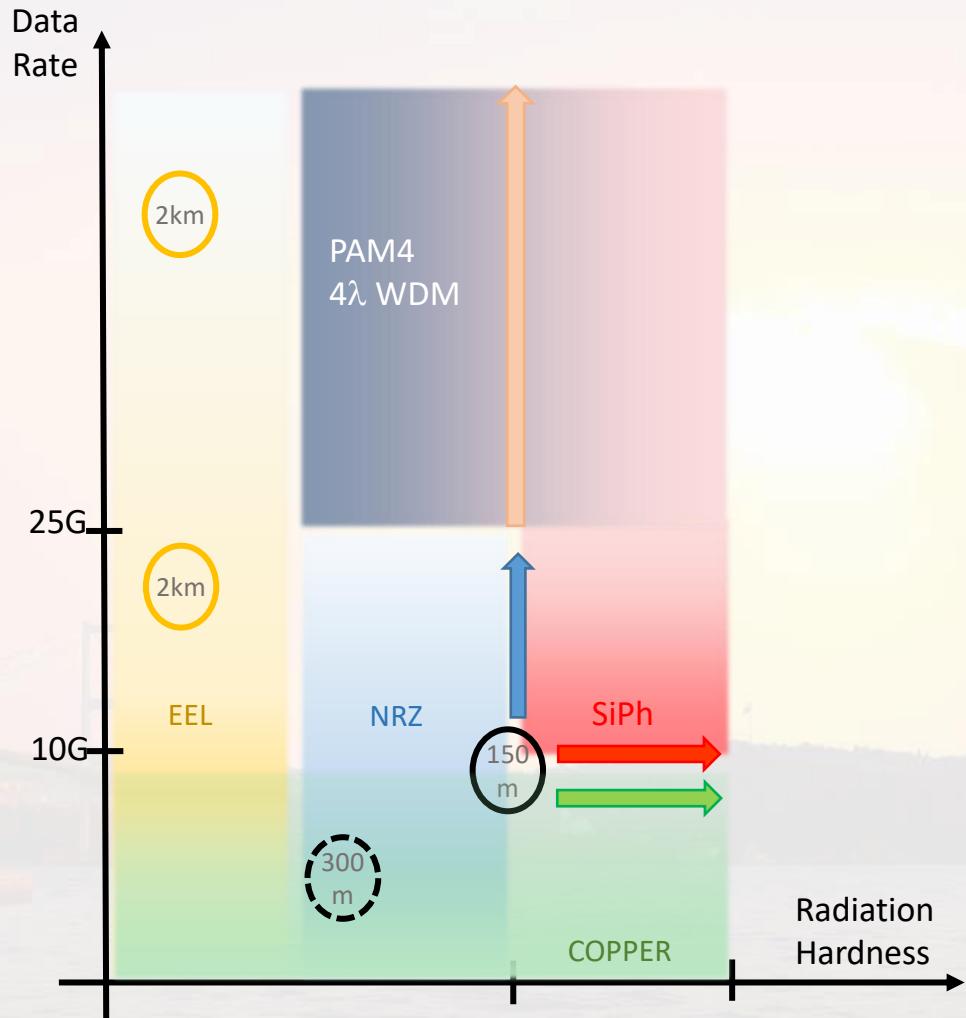
Polarization Mode Dispersion (PMD)

- Real optical fibers are not perfectly cylindrical
- Light with different polarization propagates at different speeds

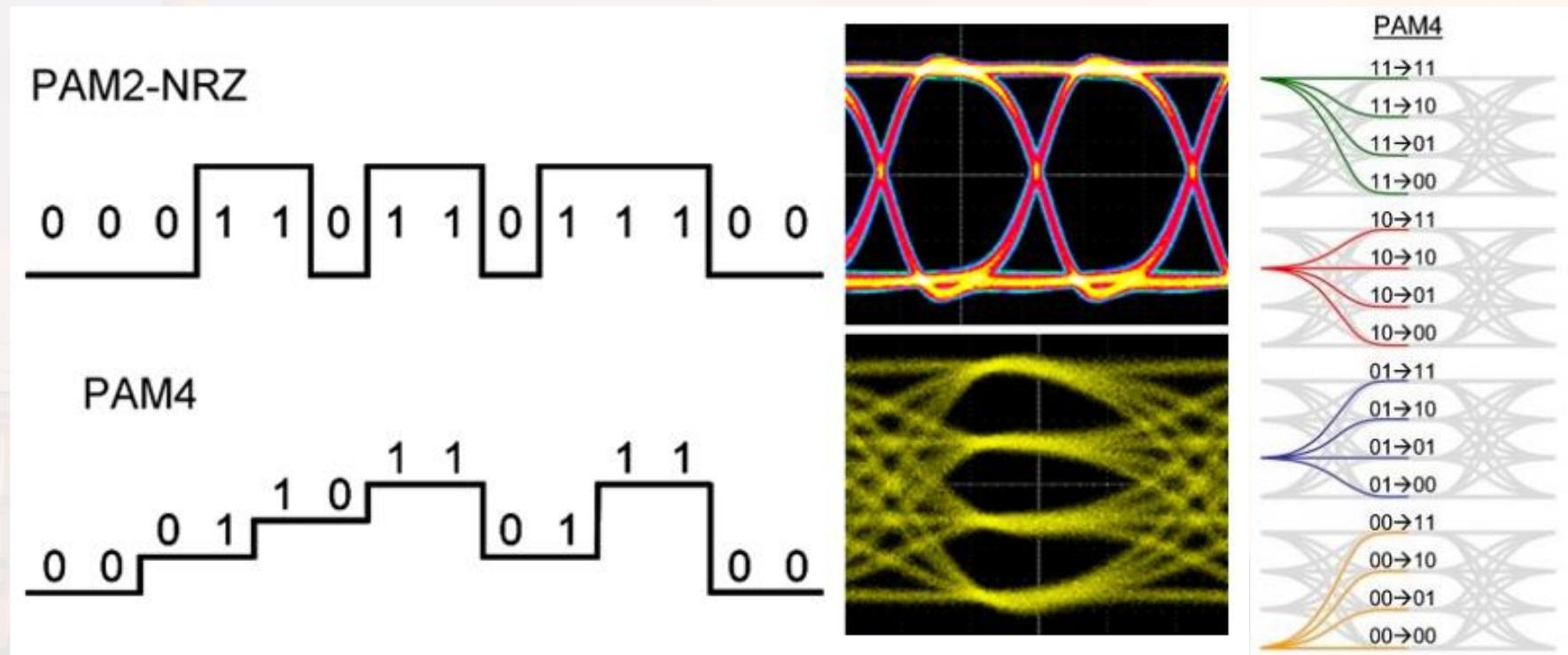


Modulation

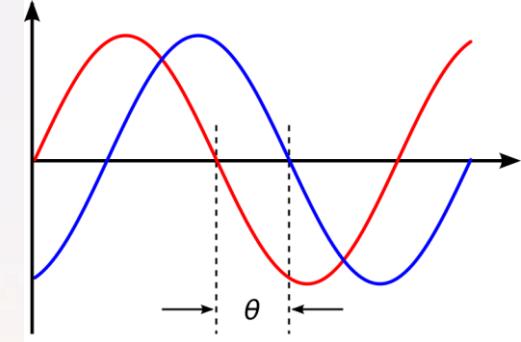
- The simplest form of modulation is called “IM-DD”
 - Which stands for “Intensity Modulation with Direct Detection”
 - Also called “Amplitude Shift Keying” (ASK)
 - The most common version is “NRZ”, or “Non-Return to Zero”
 - “Direct Detect” means only a photodiode is needed to RX
- Historically, fiber optic systems were purely NRZ based
 - All 10G and below optical technology is based around NRZ
- How to go beyond NRZ?
 - More fibers in parallel
 - DWDM over a single fiber
 - Polarization Division Multiplexing (PDM)
 - ASK with more amplitudes
 - Modulate the “phase” of the signal over time (PSK)



Amplitude Shift Keying (ASK)



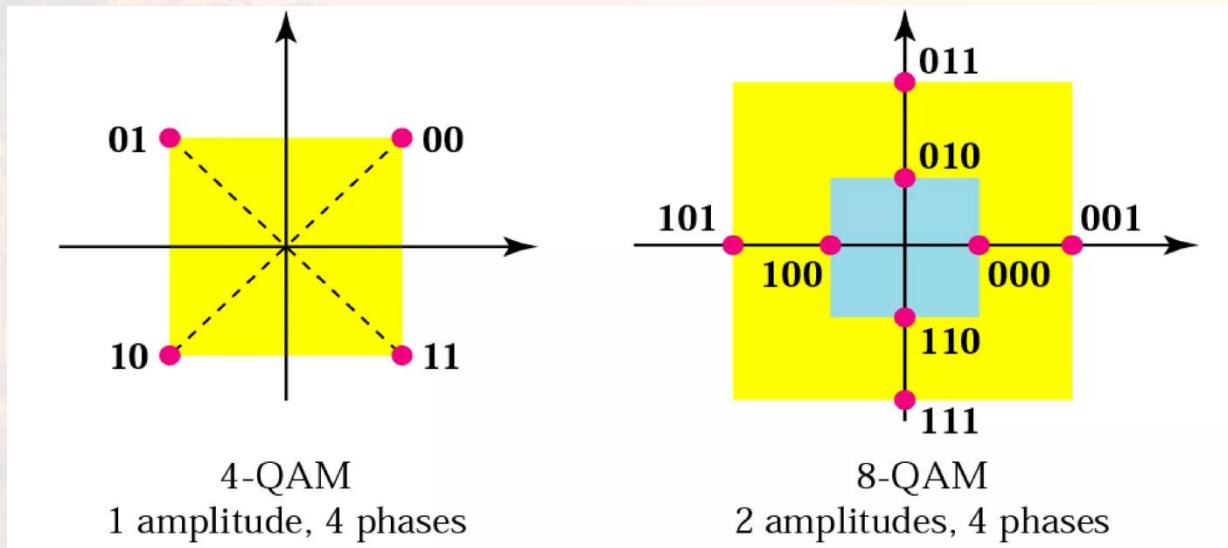
Phase Shift Keying (PSK)



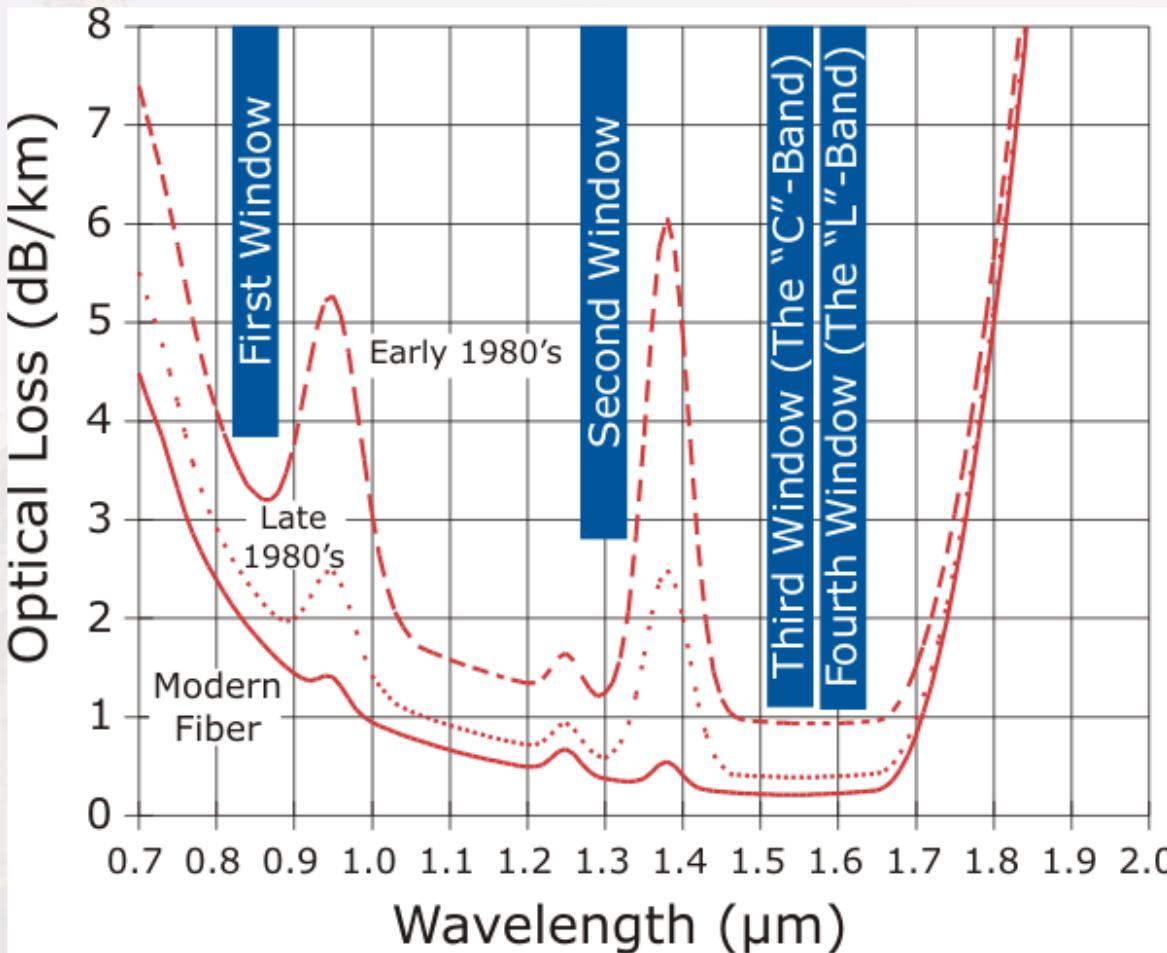
- Receiver tracks phase change in analog optical signal (“phase coherence”)
 - Dedicated oscillator on receive side of channel
 - Difference between reference and received signal to compute phase
 - Requires digital signal processing (“DSP”) on the receiver
 - Expensive, power-hungry, hard to integrate
 - Chromatic Dispersion Equalization to compensate for CMD
 - Also marketed as “coherent optics”

Quadrature Amplitude Modulation (QAM)

- Combine ASK and PSK
 - Multiple amplitude-modulated carriers
 - Carriers have different phase (e.g. sine and cosine)
- Heavy digital signal processing required



Optical fiber transmission bands

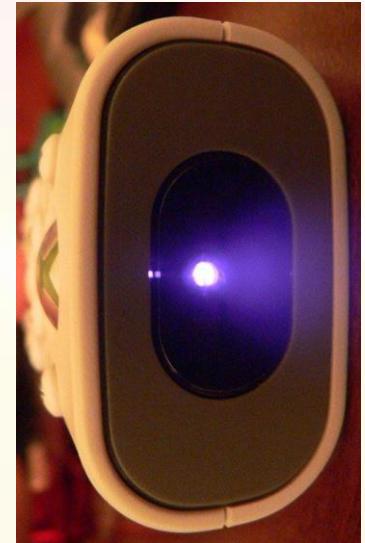


OM3, OM4, OM5 are usually specced for 850-953 nm.

O band ("second window") is mainly used for high-speed Ethernet transmission and Passive-Optical Network (PON) systems.

Optical fiber transmission bands

- “First Window” – 850 nm
 - Highest attenuation, “short range” $O(100\text{ m})$
- “Second Window” – 1310 nm
 - “O-band”, kilometer range
- “Third Window” – 1550 nm
 - “C-band”, “Conventional band”, long-reach DWDM
- “Fourth Window” – 1590 nm
 - “L-band”, “Long band”
- The human eye can only see between 390 – 750nm
 - One trick to check for light in a fiber is to hold it up to your camera phone



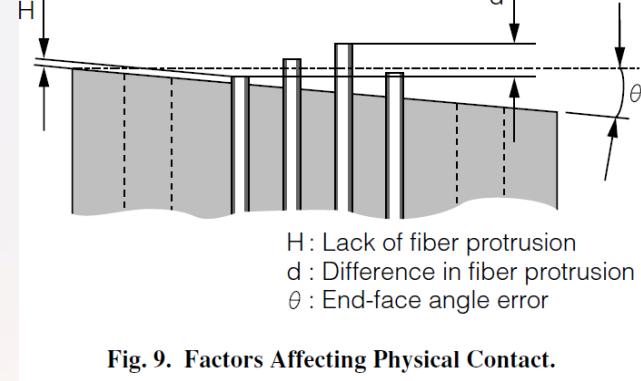
Optical attenuation

- As light propagates in a fiber, its intensity decreases
 - Scattered by defects in the glass
 - Absorbed by impurities and converted to heat
- Attenuation is measured in “Decibels” ($10 \times \log_{10}(A/B)$)
 - $1/10 = 90\% \text{ loss} = -10 \text{ dB}$
 - $1/100 = 99\% \text{ loss} = -20 \text{ dB}$
- Optical power often expressed in “dBm”
 - $0.5 \text{ mW} = -3 \text{ dBm}$
 - $1 \text{ mW} = 0 \text{ dBm}$
 - $2 \text{ mW} = 3 \text{ dBm}$
 - $100 \text{ mW} = 20 \text{ dBm}$
- Combining losses/gains expressed in dB = addition

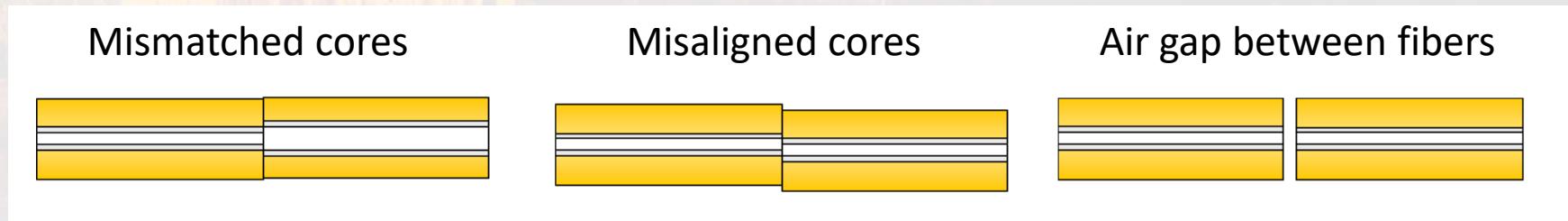
Other causes for attenuation

- Insertion loss
- Return loss
- Bending loss
- Environmental contamination
- Radiation induced “darkening”

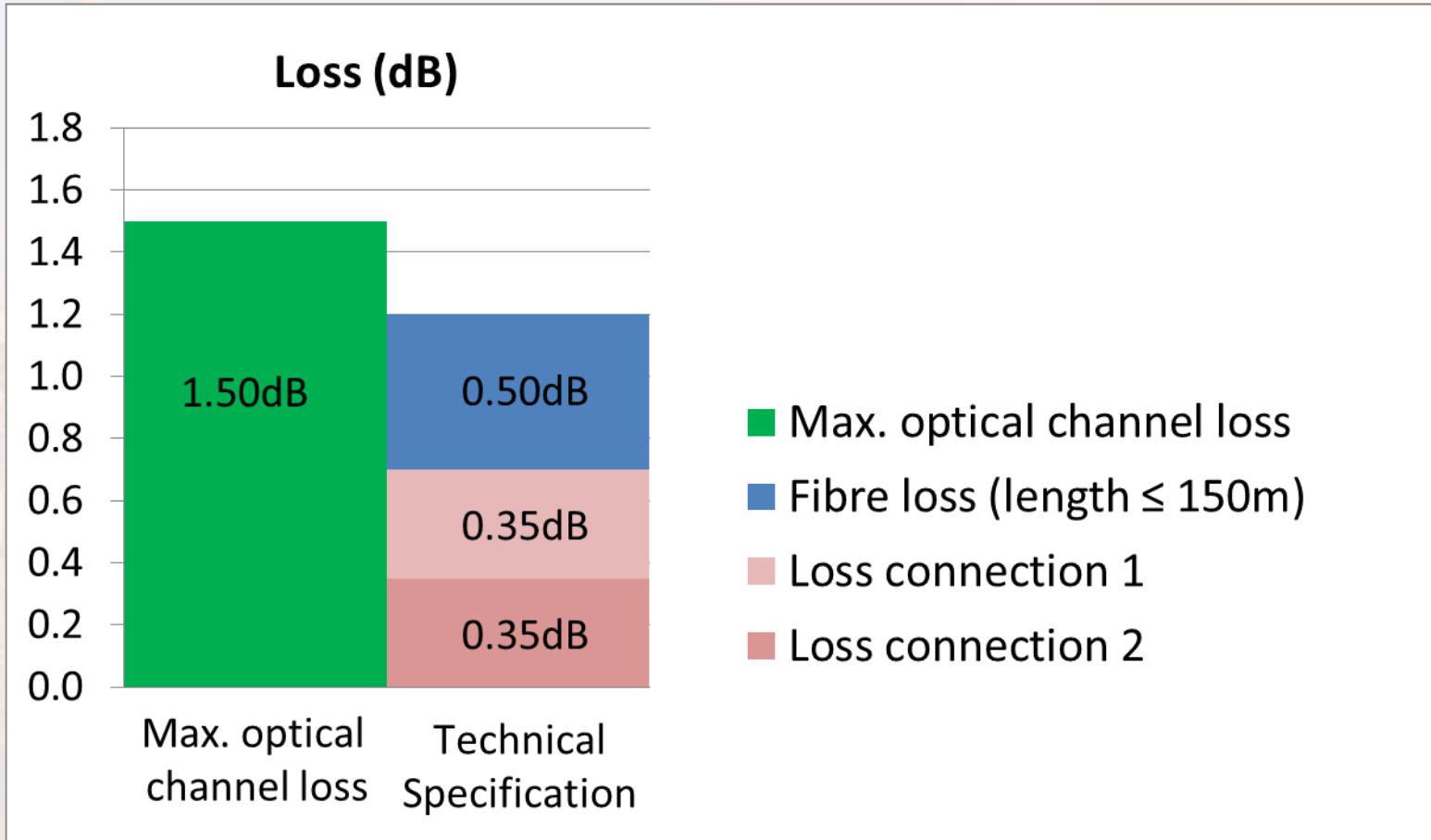
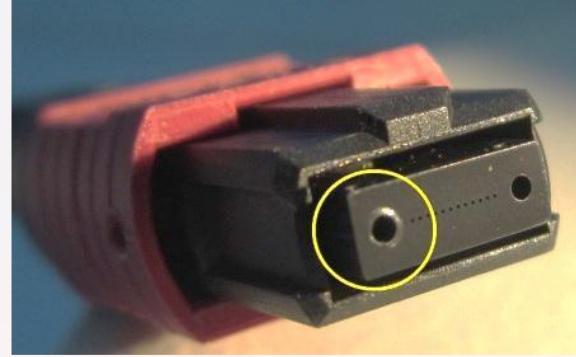
Insertion loss



- Number and quality of connectors and splices
- Standard < 0.60 dB (typ. 0.20 dB)
- «Elite» < 0.35 dB (typ. 0.10 dB)
- 40G OM3: 1.5dB total connector loss budget
- 40G OM4: 1.0dB total connector loss budget



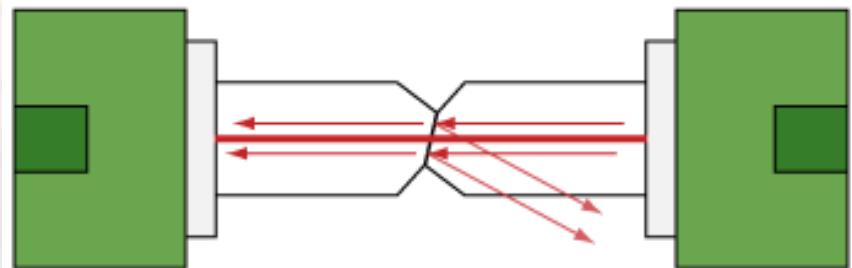
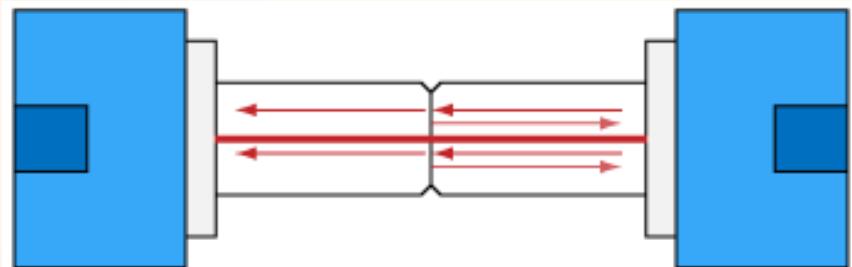
Connector loss budget



$$\text{ORL(dB)} = 10 \log_{10} \frac{P_i}{P_r}$$

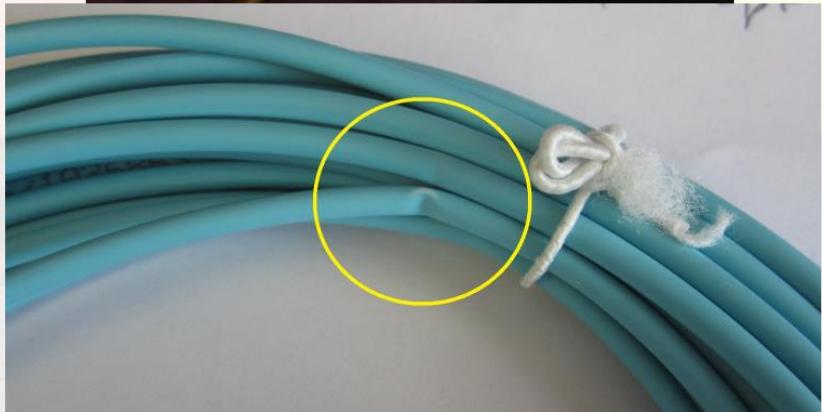
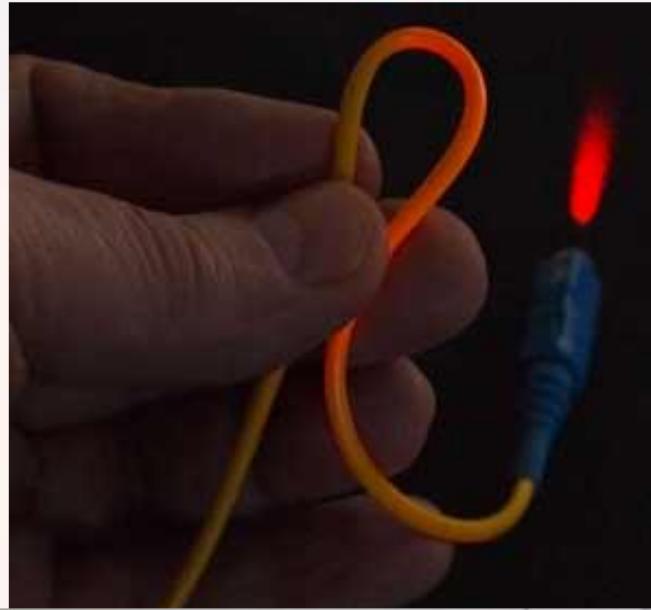
Return loss

- Incident / reflected power [dB]
- (Ultra) Physical Contact (UPC) blue
 - ($< -30 \text{ dB}$) $< -55 \text{ dB}$ ORL
- Angled Physical Contact (APC) green
 - 8° angle
 - $< -65 \text{ dB}$ ORL
 - For high-power emitters
- Are incompatible!



Bending loss

- Total internal reflection depends on critical angle
- Small bend radius causes light leaks
- Bend-insensitive fibers exist
 - Higher n cladding
 - Short range (patch panels)
- Exceeding the safe bend radius (kinking) physically damages the fiber

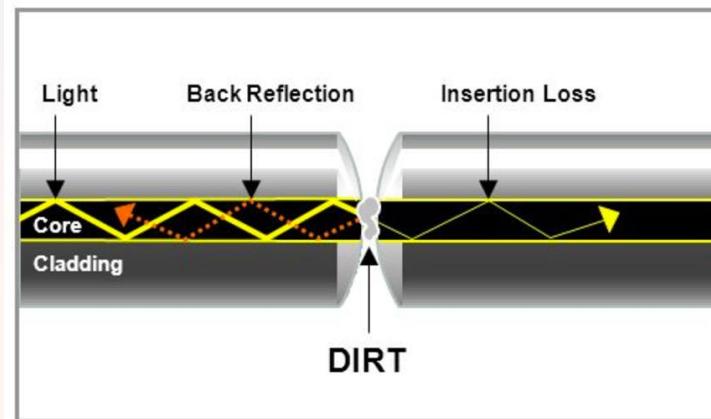


Dirt induced loss

- A μm speck of dust can completely (or partially) cover the core
- Insertion force can dent the optical interface
- Don't leave fibers exposed
- Clean **both sides** before mating
 - Cleaning cassettes
 - Insertable tape rolls

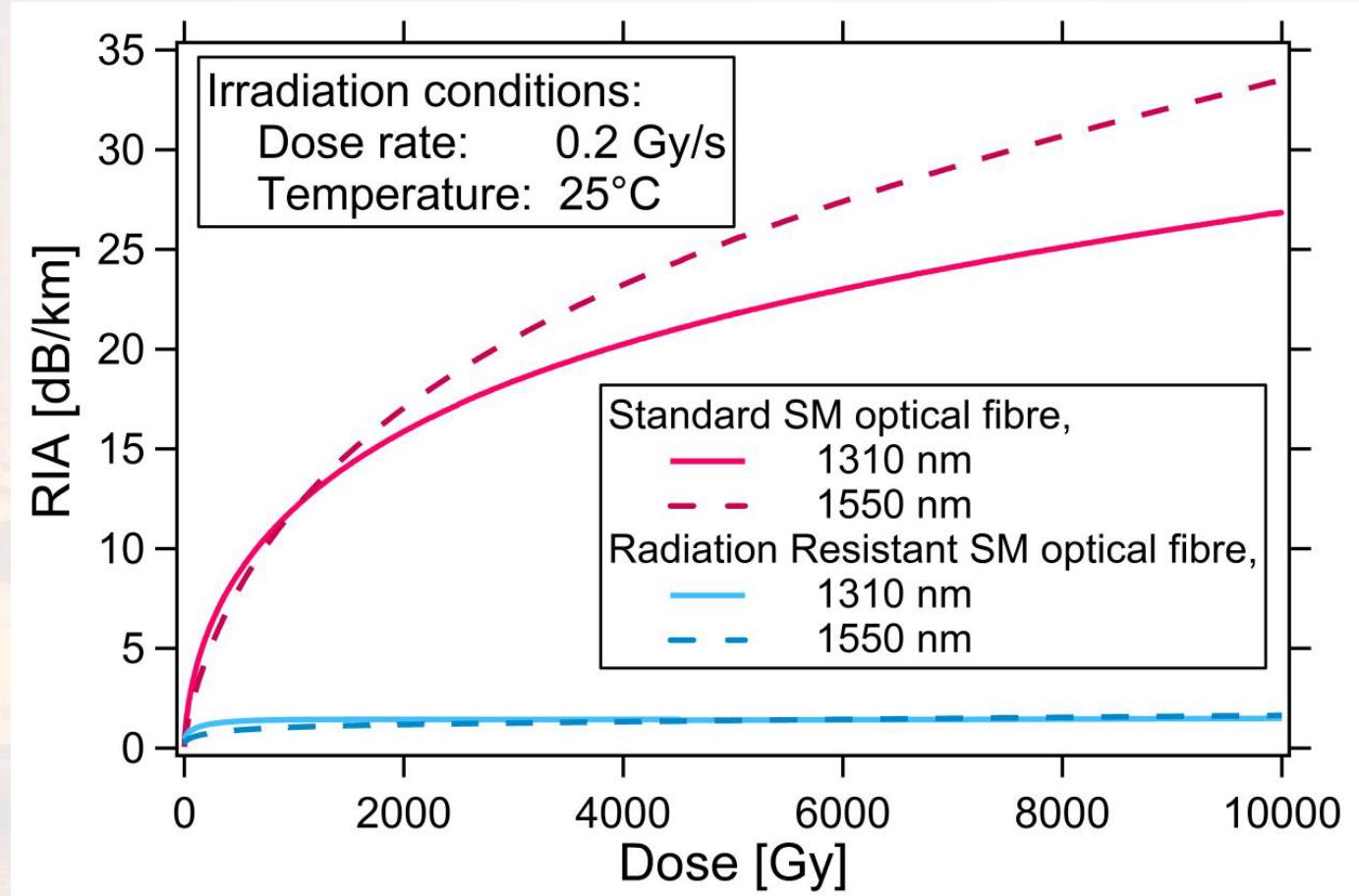


Optical fiber visual inspection



Radiation induced loss

Use rad-hard fibers with special doping and manufacturing processes



Other definitions

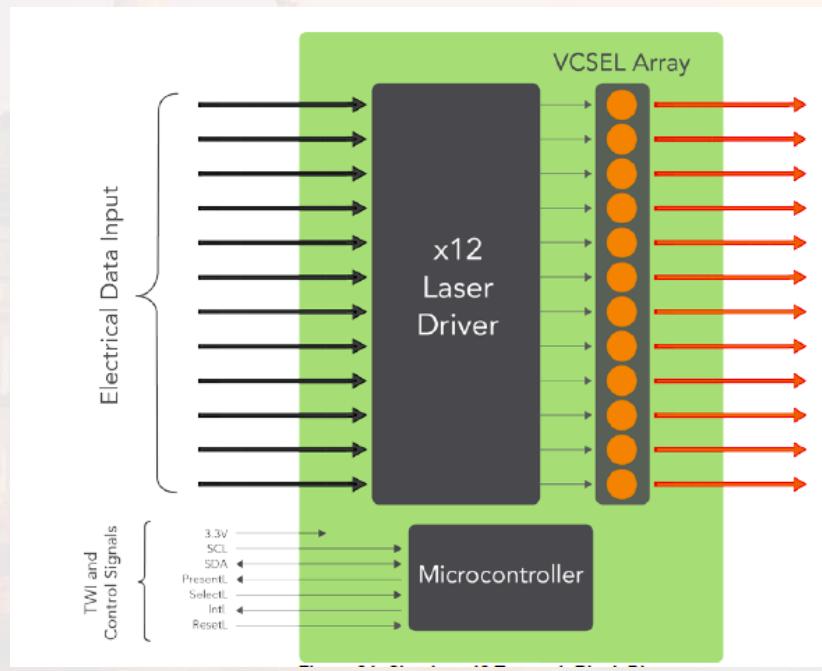
- Transmitter launch power
 - dBm power @ λ
- Optical Modulation Amplitude (OMA)
 - $OMA = P_1 - P_0$
- Extinction ratio
 - $r_e = \frac{P_1}{P_0}$
- Receiver sensitivity
 - Min. received power @ BER target
- Dynamic range
 - (Worst-case max input power - Sensitivity)

Outline

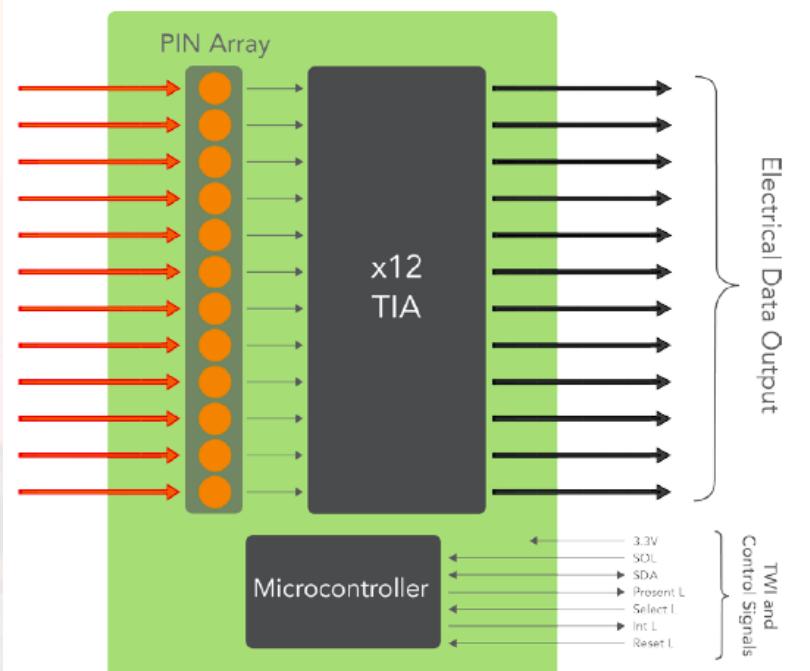
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Vertical-Cavity Surface-Emitting Laser (VCSEL)

Tx

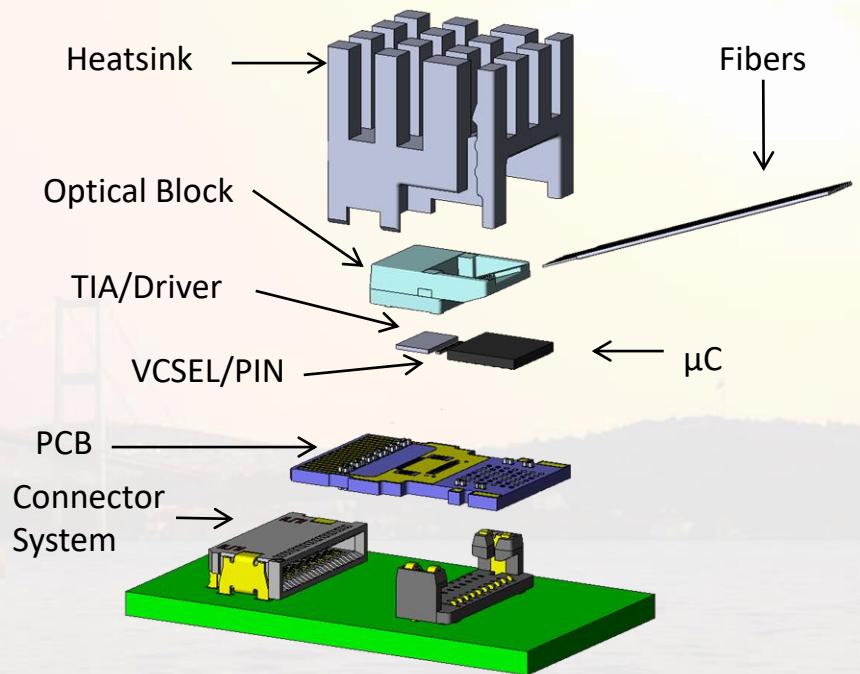
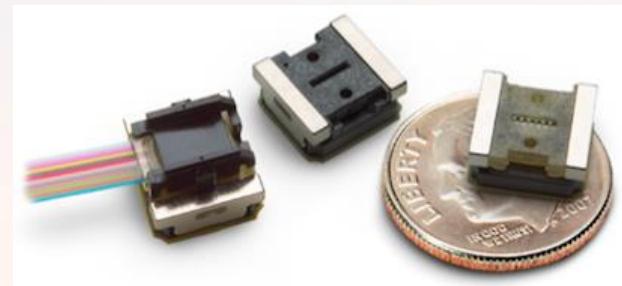


Rx



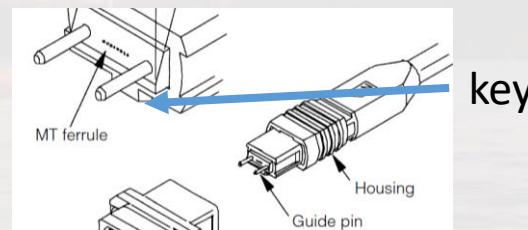
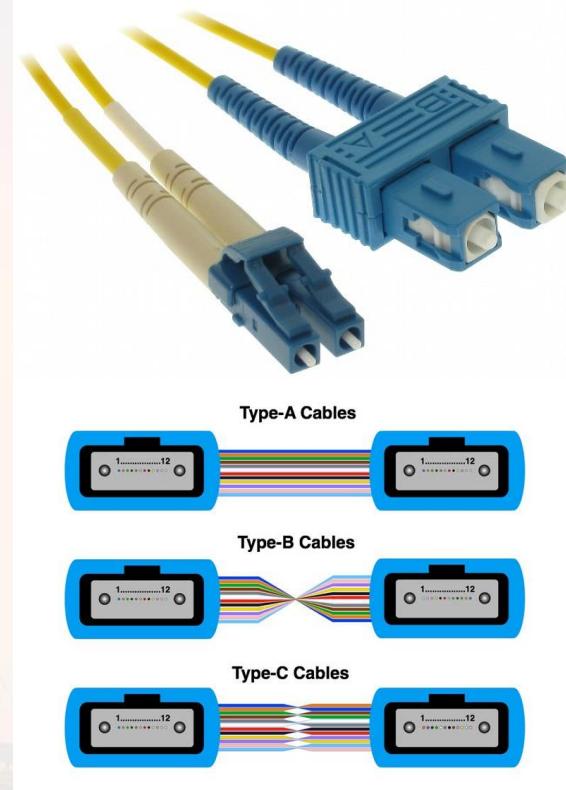
VCSEL optical engine assembly

- Can be integrated with other circuitry
- Can be packed in dense 1D and 2D arrays
- Can be tested pre-dicing
- High quantum efficiency -> low power
- Good optical coupling via MO interfaces
(e.g. PRIZM® LightTurn®)

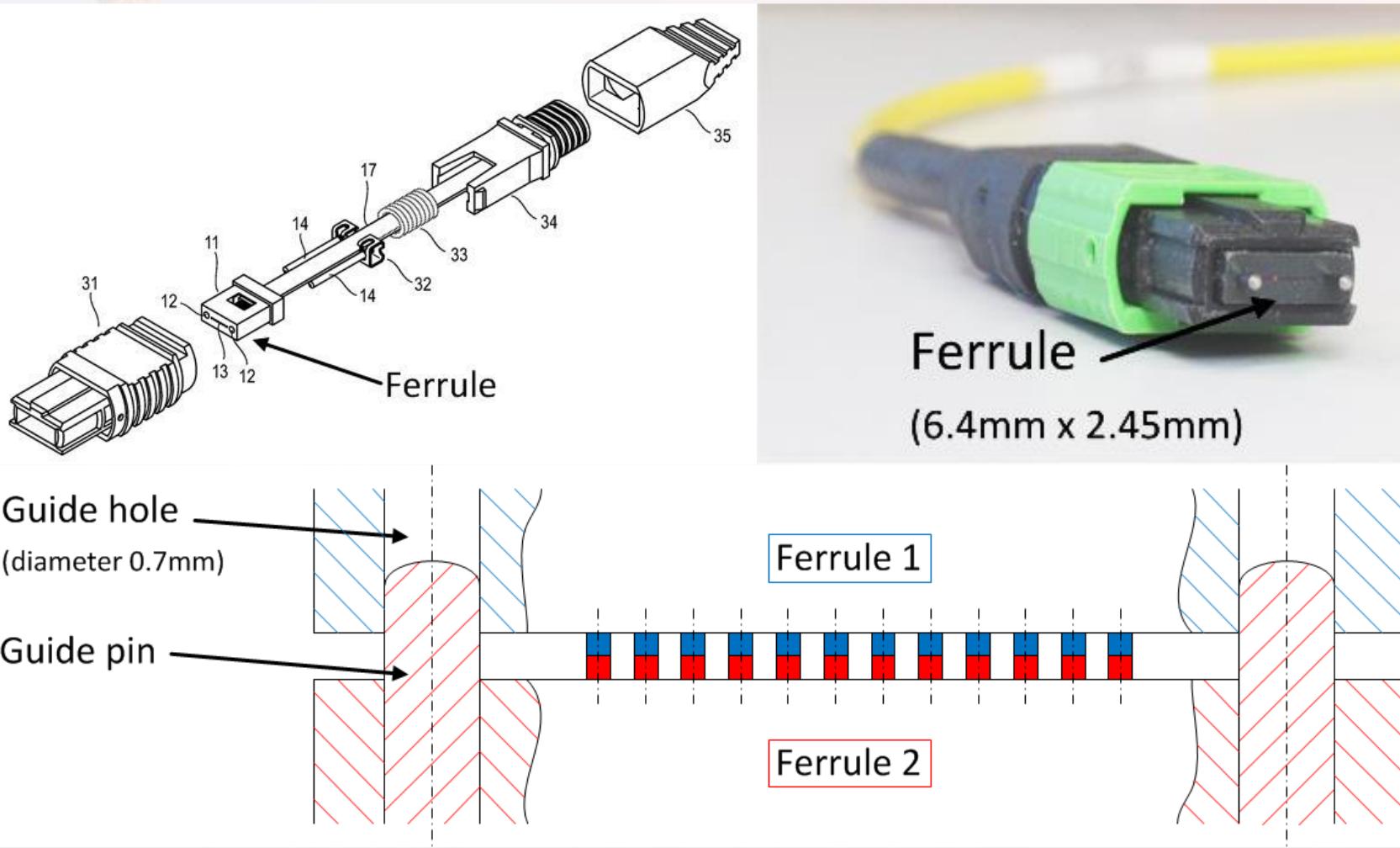


Optical connector assemblies

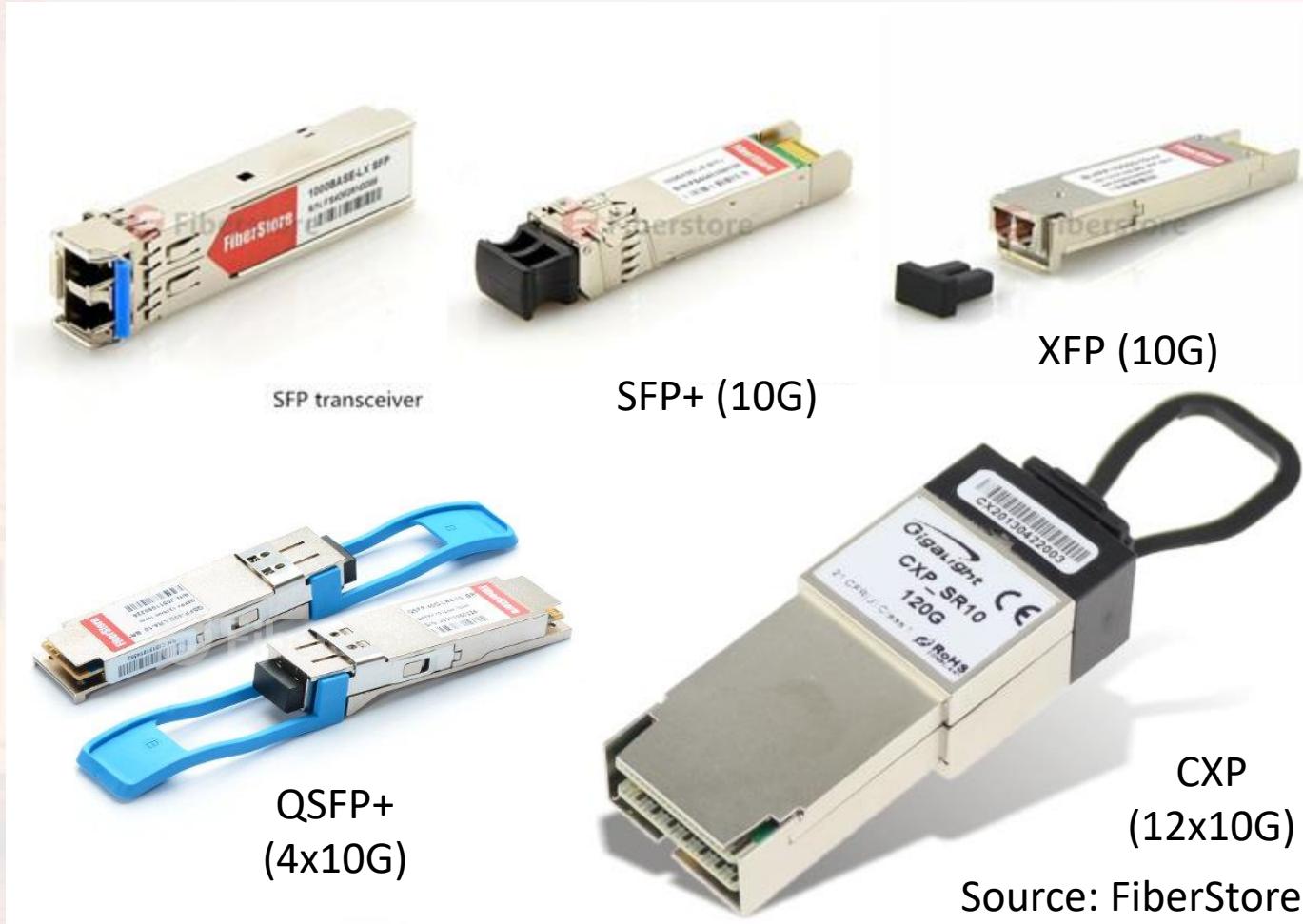
- Form factors
 - SC (x1, x2, obsolete)
 - LC (x1, x2)
 - MPO (12, 16, 24, 32, 48)
 - MTP (high-quality MPO)
- Polarity
 - Straight (A)
 - Crossover (B)
 - Flipped-pairs (C)
- Gender
 - Male
 - Female



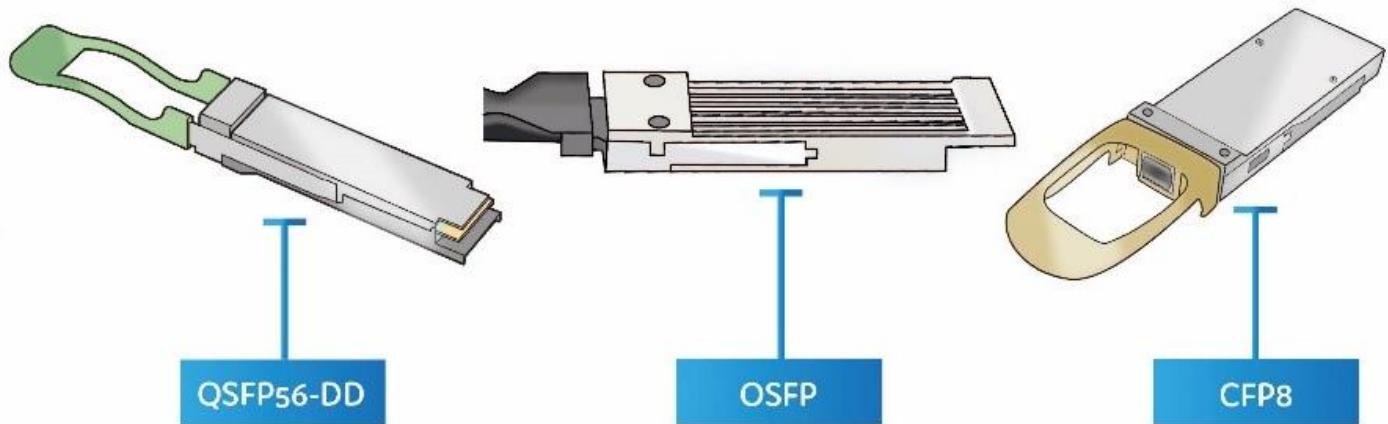
MTP/MPO optical assembly



Pluggable form factors (“slow”)



Pluggable form factors (“fast”)

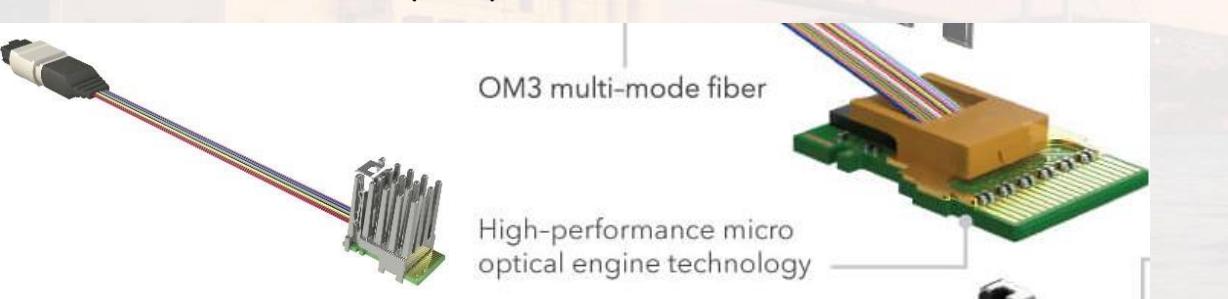


Power consumption:	max 12W	max 15W	max 24W
Backward compatibility with QSFP+, QSFP28 and QSFP56:	yes	Through adapter	No
Size:	Similar to QSFP28	Slightly bigger than a QSFP28	Slightly smaller than CFP2
Thermal management:	Indirect	Direct	Indirect

Proprietary packages (high density)

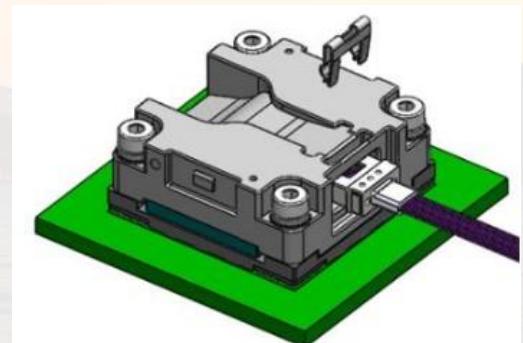
Samtec FireFly ECUO

- 70m OM3 850nm
- 12 simplex or 4 duplex
- Ribbon MPO-12 or MPO-24
- 3.3V (+1.8V si duplex 28G)
- 14 / 25 / 28 Gb/s
- 240mm² footprint
- T12 | R12 | B04 variants (14G)
- B04 variant (28G)



III-VI Finisar BOA

- 70m OM4 850nm (possible 70m OM3)
- 12 duplex
- MT-24 connector (no ribbon)
- 6W (2.5V + 3.3V rails)
- 25Gb/s
- 625mm² footprint
- CFP MSA slow control interface



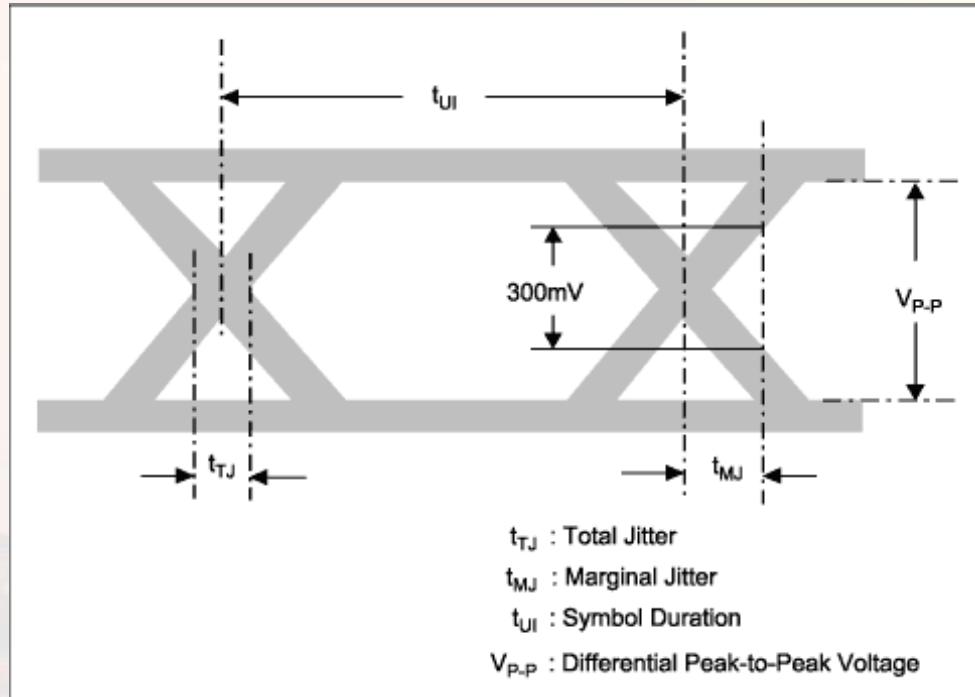
Active Optical Cables (AOC)

- Great for point to point connections, when length is known in advance
- Handled (almost) like a copper cable, no optical connector or cleanliness related problems
- Cheaper than discrete optics
- Available in “Octopus” breakouts



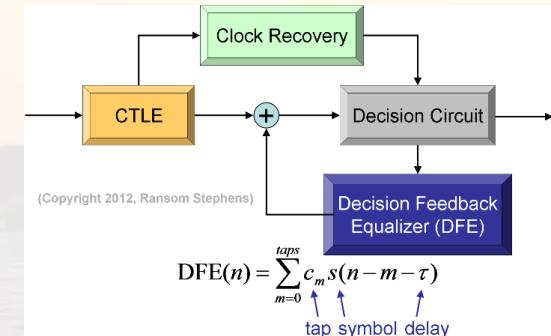
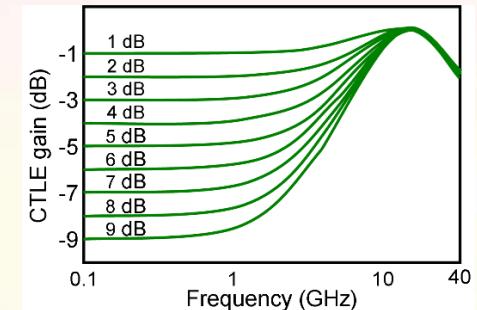
Eye diagram

- $I \rightarrow V$ (trans-impedance amplifier)
- Superimpose all possible binary transitions
- Quickly quantify noise and inter-symbol interference (ISI) effects
- Many standards mandate minimal eye parameters



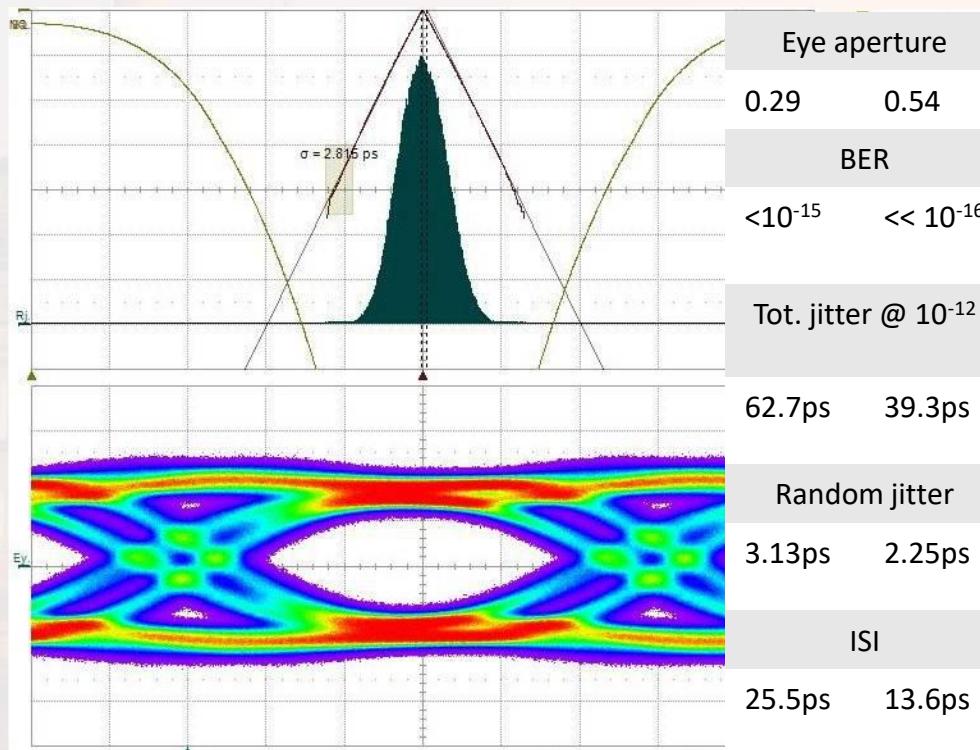
Signal optimization techniques

- Pre-emphasis (already used at 10G)
- Tx FFE (Feed Forward Equalization)
 - Emphasis of high-speed content to combat frequency dependent attenuation in channel
- Rx CTLE (Continuous Time Linear Equalization)
 - De-emphasizes low frequency, peak at Nyquist, filters off high frequency
- Rx CDR (Clock and Data recovery)
 - Used together with CTLE or other equalization
- Rx DFE (Decision Feedback Equalization)
 - Non-linear, feedback from decision circuit
 - Power hungry...
- Wave Division Multiplexing
- PAM4 Modulation (56G and up)

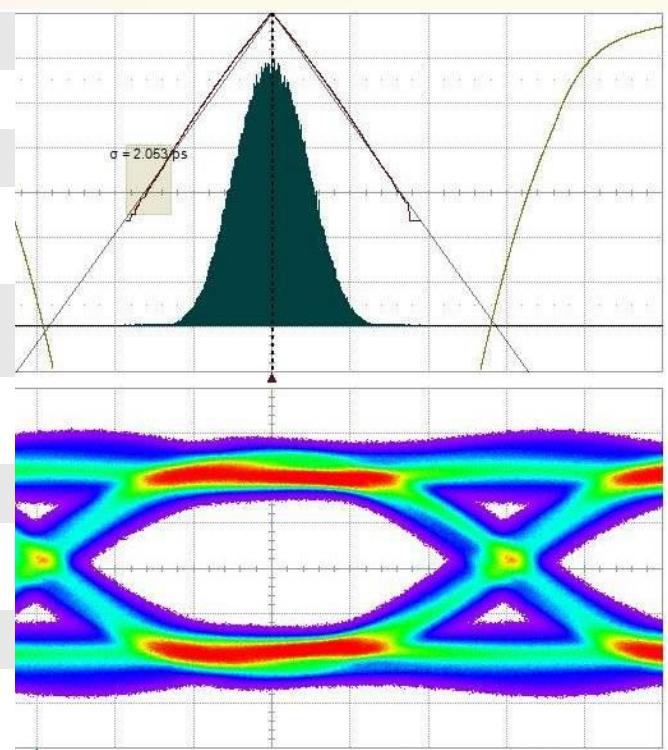


Example: 10GBASE-R

No de-emphasis nor
equalization on optical drivers



With de-emphasis and
equalization



<https://indico.cern.ch/event/297003/>

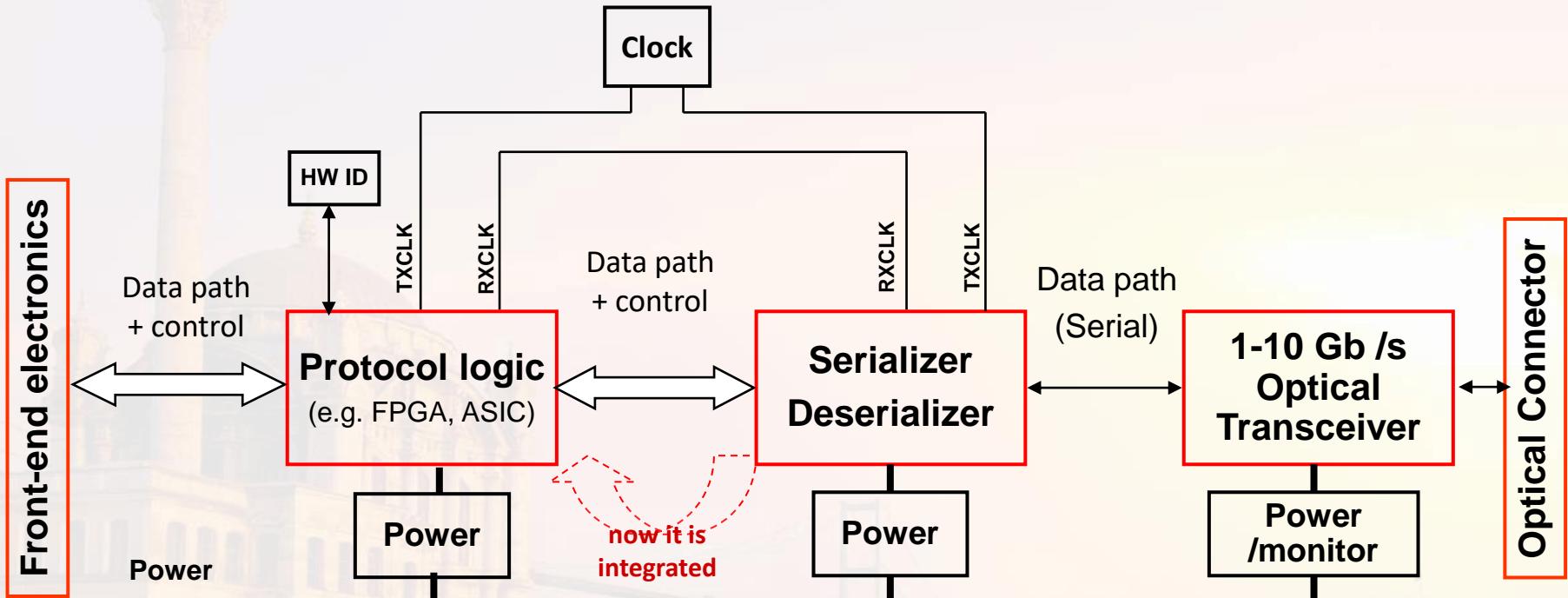
Forward Error Correction (FEC)

- Insert “redundant” information before transmission
- Receiver can detect if errors occurred, and where
- Receiver can computationally fix errors, up to a design limit dependent on the algorithm
- 1st generation FEC (Reed-Solomon)
 - 6% overhead for ~6 dB BER gain
- 2nd generation FEC (EFEC)
 - 7% overhead for 8~9 dB BER gain
- 3rd generation FEC (SD-FEC)
 - 20-25% overhead for 10~11 dB BER gain
- FEC is now **mandatory** in most high speed standards, like 100GbE and beyond

Outline

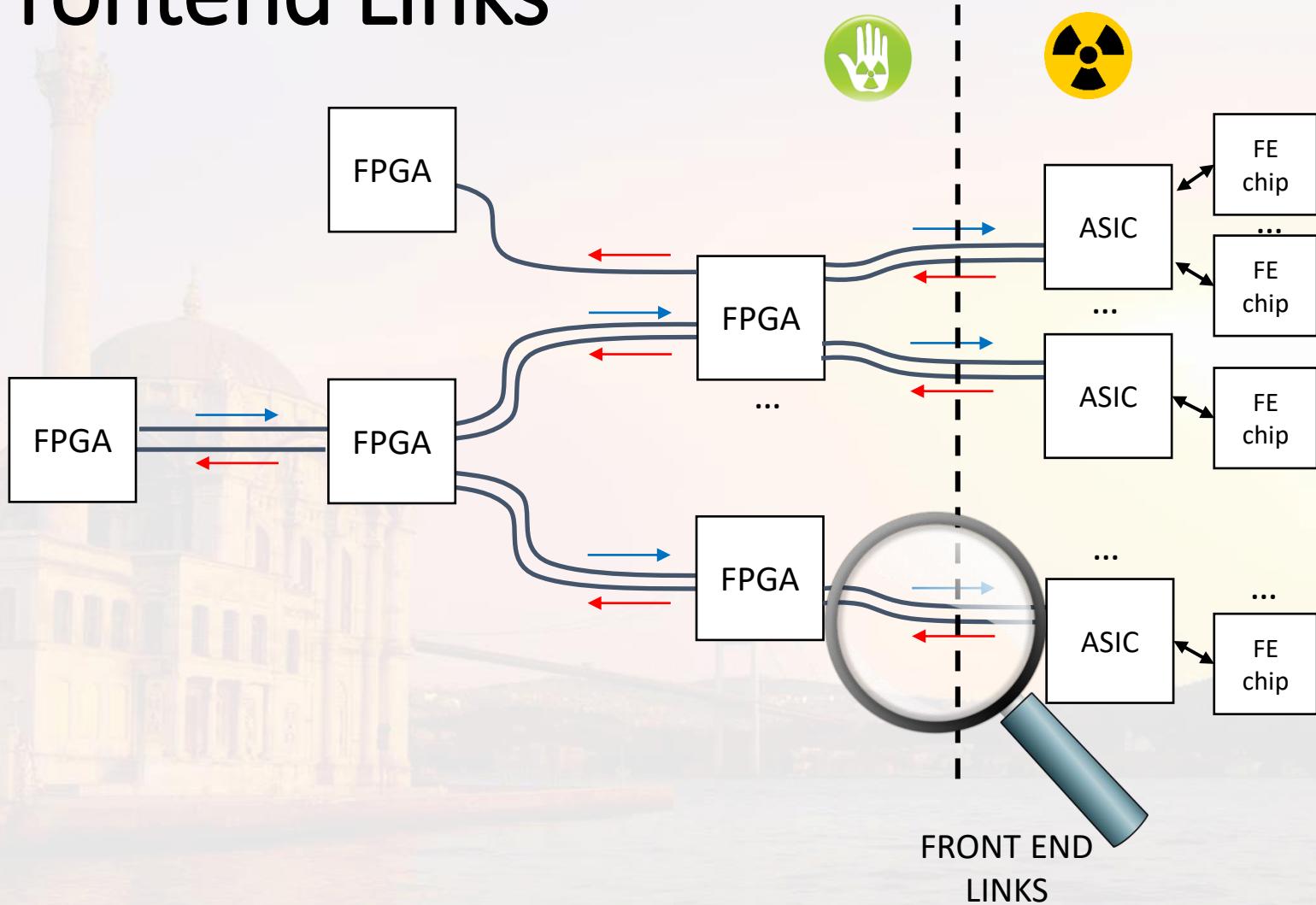
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System integration



- FIFO like parallel interface
- Simplex, half-duplex, or duplex
- Physical Coding (e.g. 8B/10B)
- Link Control, Data Framing,
- Flow Control
- Error Detection
- E/O conversion

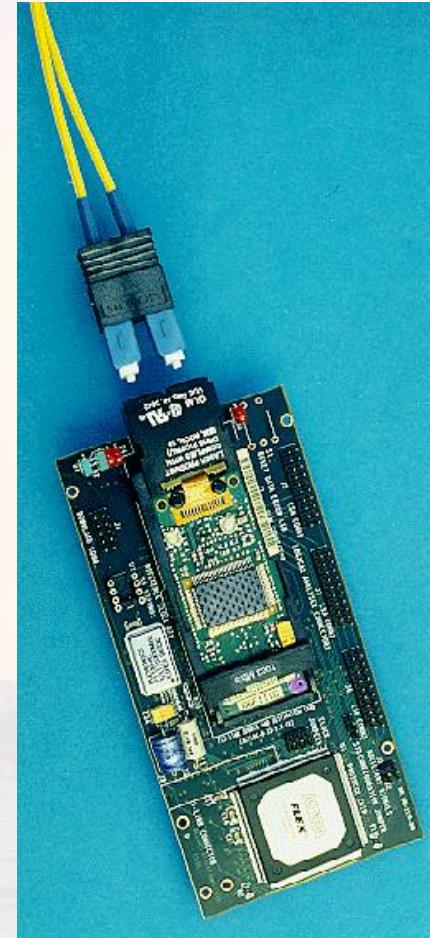
Frontend Links



Frontend Links: S-LINK



- Defined in 1995
- Duplex
- PCI interface
- 32-bit: ≤ 132 MB/s
- 8-bit: ≤ 64 MB/s
- Dual SC
- MMF
 - 50/125: 2 km
 - 62.5/125: 0.7 km
- OPB: 0.25 dB

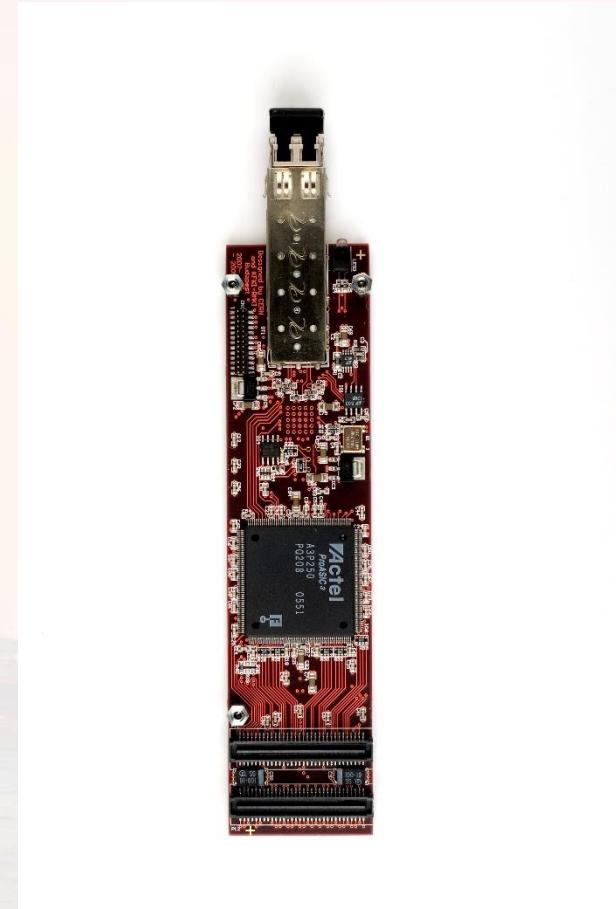


<http://cern.ch/HSI/s-link>

Frontend Links: DDL



- Defined in 1997
- Duplex
- PCI Interface (RORC)
- 2.125 Gb/s (max. 2.5 Gb/s)
- 850 nm
- MMF: 50 μ m or 65 μ m
- Up to 500m



Frontend Links: Versatile Link

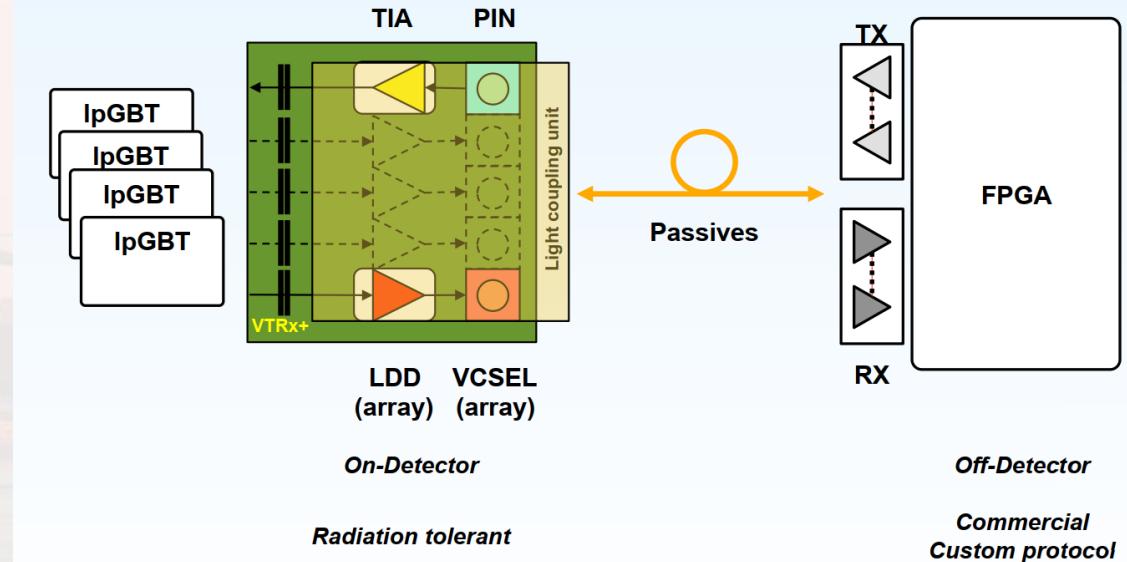
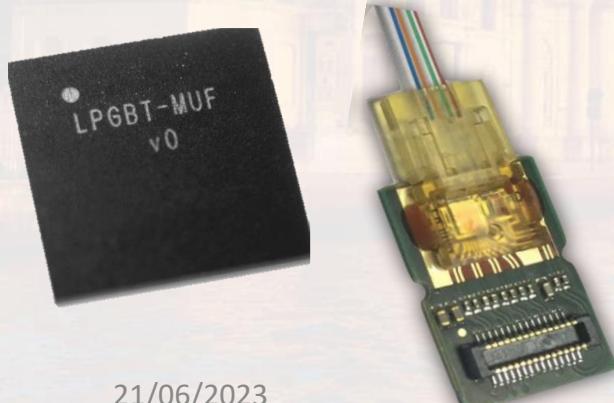
<https://espace.cern.ch/project-versatile-link/public/default.aspx>

- **3.2 Gbit/s or 4.48 Gbits/s** user bandwidth
- Optional FEC
- SFP-like form factor
- Deterministic latency in both directions
- Radiation hard – qualified for:
 - 1 MRad total dose
 - 5e14 neq/cm²
- FE interface: 10 to 40 E-links: SLVS based with 320, 160 or 80 Mbit/s
- “Low”-power
 - <1.5W, 2.2W Worst-case



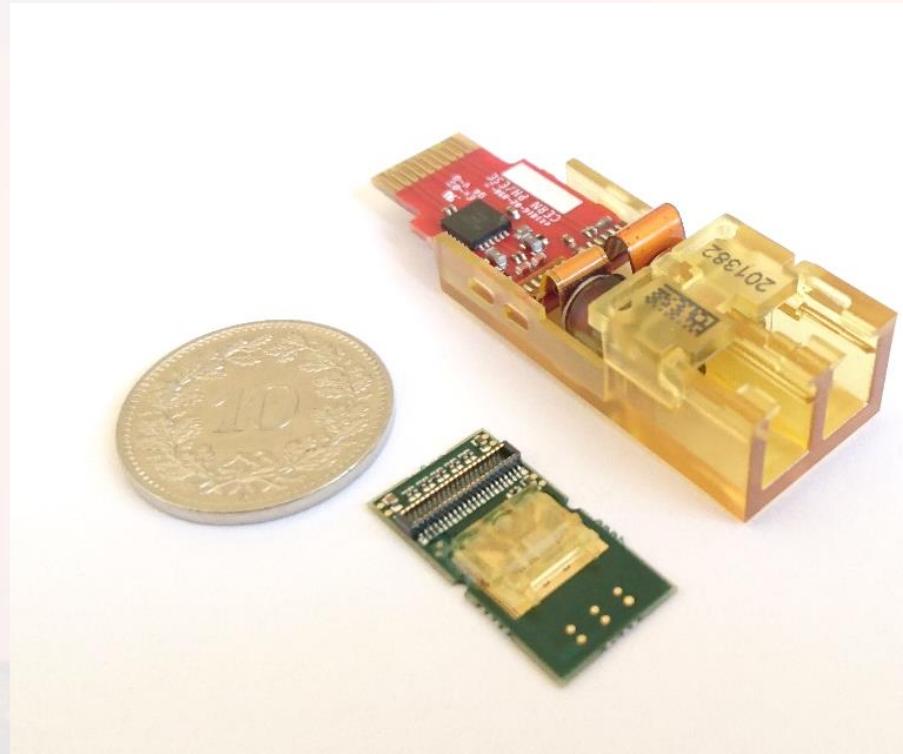
Frontend Links for LHC Phase-2 upgrades

- Two partner projects
 - **IpGBT** Chipset & protocol development: SerDes, LDD, TIA, FPGA core
 - **Versatile Link + Optical Link**: Custom module, fibre plant, commercial module
- Asymmetric Data-rates
 - 5 or 10 Gb/s upstream (out of detector)
 - 2.5 Gb/s downstream
- Environment
 - 1 MGy, 3×10^{15} neq/cm²
 - -35 to +60 °C



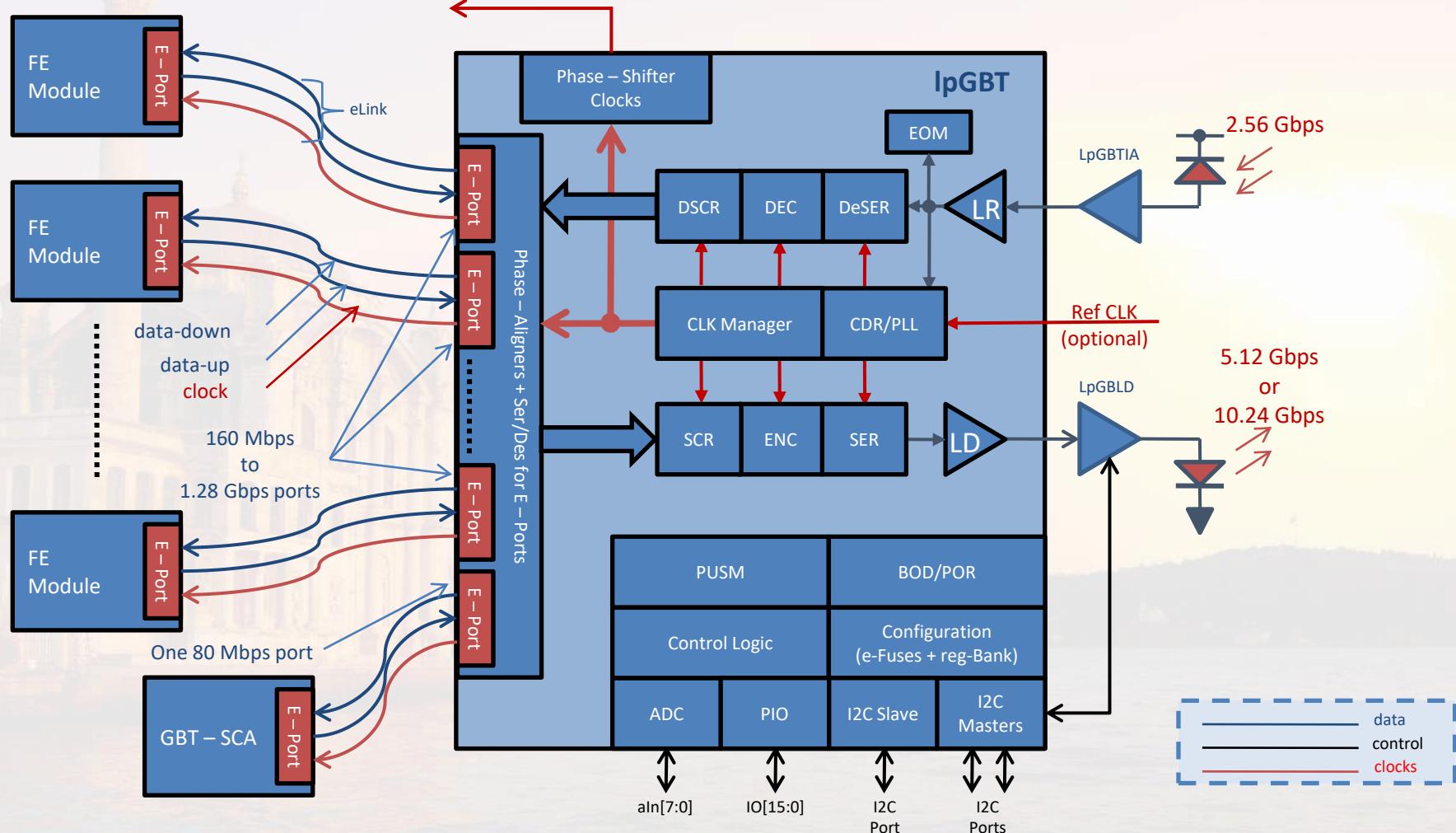
Versatile Link Plus – VTRX+

- Miniaturized and pluggable
 - Electrical connector
 - Optical pigtail
- Up to 4Tx+1Rx configuration
 - configurable by channel masking
- Tx
 - 1x4 850 nm VCSEL array
 - 5 and 10 Gb/s
- Rx
 - InGaAs photodiode
 - 2.5 Gb/s
- For harsh environment
 - Temperature: -35°C to +60°C
 - Total dose: 1 MGy
 - Total fluence up to 1×10^{15} n/cm² and 1×10^{15} hadrons/cm²
- Recovered clock jitter
 - ~ 5ps rms
- Fixed and Deterministic Latency
 - 1ps precision when Tlink is used



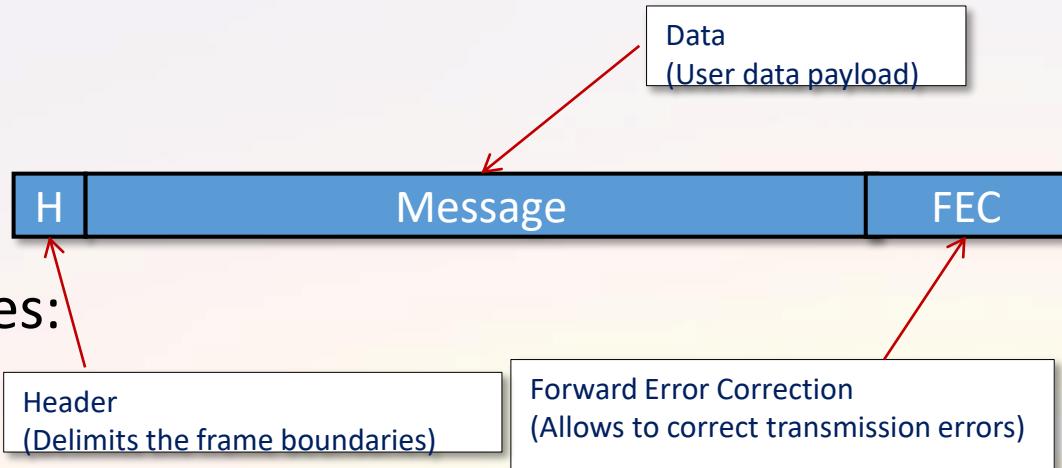
LpGBT system block diagram

<https://espace.cern.ch/GBT-Project/LpGBT>



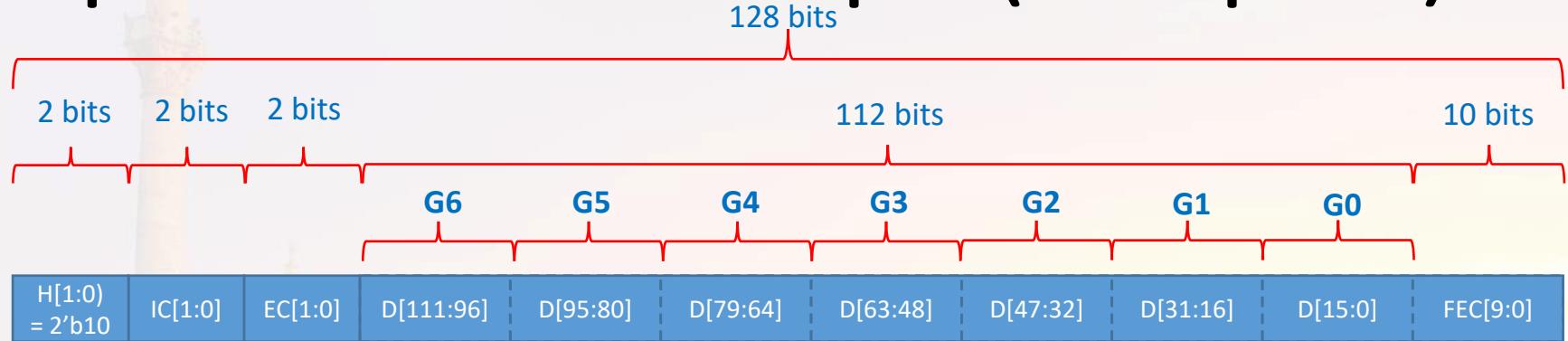
LpGBT uplink

- The LpGBT supports the following uplink data rates:
 - 5.12 / 10.24 Gbps
- Data is transmitted as a frame composed of:
 - Header
 - The data field
 - A forward error correction field:
FEC5 / FEC12
- The data field is scrambled to allow for CDR operation at no [additional] bandwidth penalty



	uplink			
	5.12 Gbps		10.24 Gbps	
Frame [bits]	FEC5	FEC12	FEC5	FEC12
Header [bits]	128		256	
Data [bits]	116	102	232	204
FEC [bits]	10	24	20	48
Correction [bits]	5	12	10	24
Efficiency	91%	80%	91%	80%

IpGBT e-links example (5G uplink)

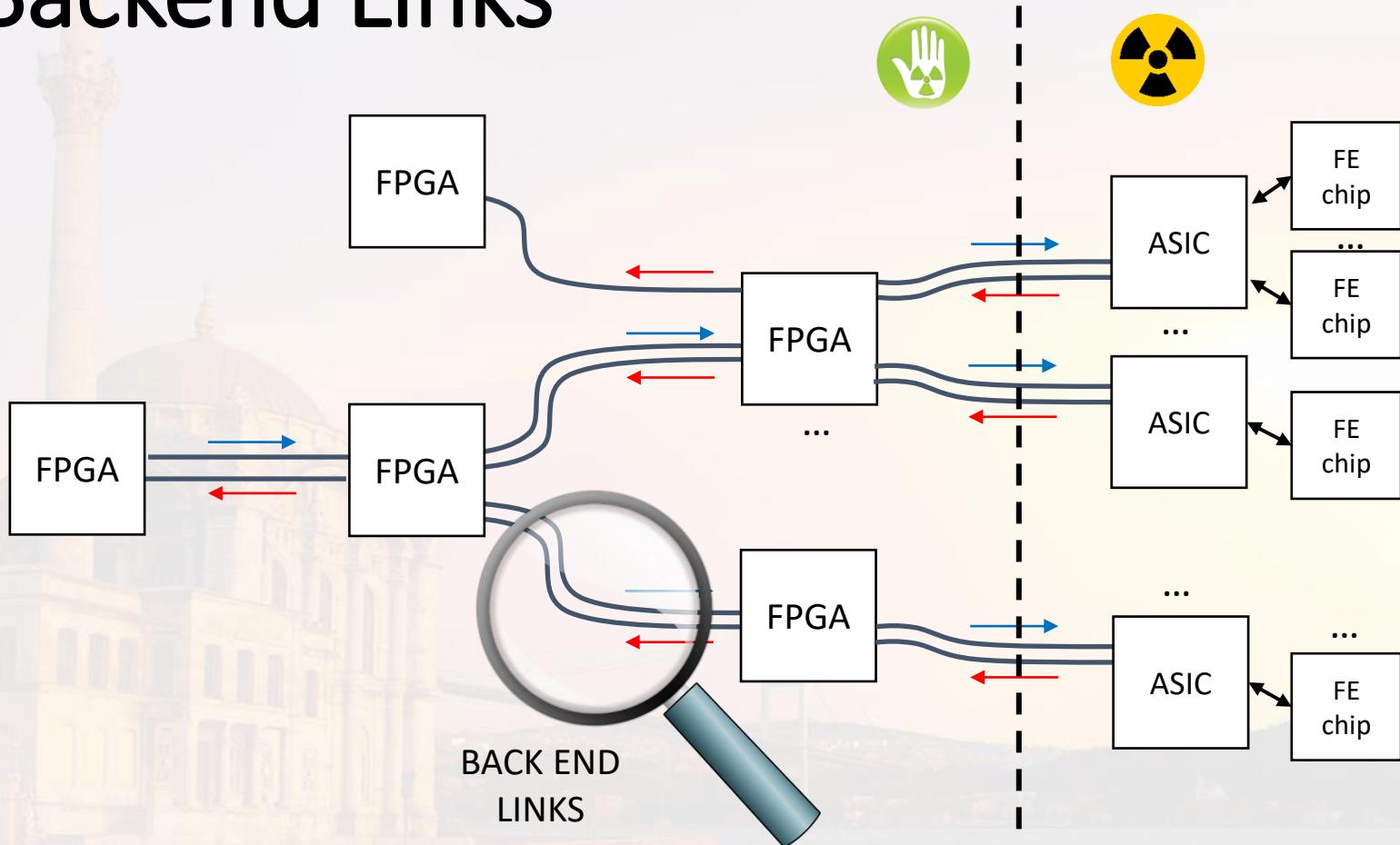


Frame	Function	I/O Group
FRMUP[9:0]	FEC[9:0]	
FRMUP[25:10]	Data[15:0]	0
FRMUP[41:26]	Data[31:16]	1
FRMUP[57:42]	Data[47:32]	2
FRMUP[73:58]	Data[63:48]	3
FRMUP[89:74]	Data[79:64]	4
FRMUP[105:90]	Data[95:80]	5
FRMUP[121:106]	Data[111:96]	6
FRMUP[123:122]	EC[1:0]	EC
FRMUP[125:124]	IC[1:0]	
FRMUP[127:126]	H[1:0] = 2'b10	HFH[1:0] = 2'b10

- 7 groups of 4 input e-Ports
Number of data ports:
- 28 eLinks @ 160 Mbps
 - 14 eLinks @ 320 Mbps
 - 7 eLinks @ 640 Mbps

Note: This is how you will see the uplink frame after it has been processed by the IpGBT-FPGA receiver but not how it is actually transmitted by the IpGBT ...

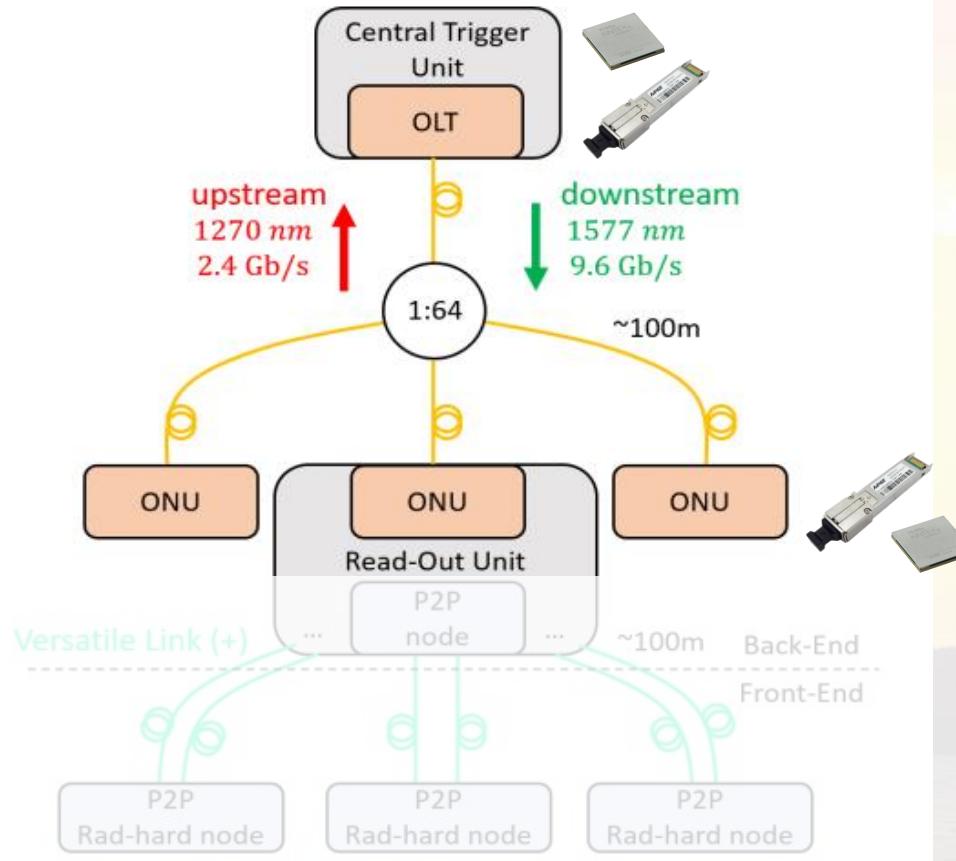
Backend Links



Backend Links – TTC-PON

https://gitlab.cern.ch/TTC-PON/official_release

- Based on ITU XG-PON Fiber-to-the-Home technology
 - Upstream/downstream wavelength multiplexed
 - Commercial components
 - Custom protocol tailored to our specifications
- Point2MultiPoint
 - Split-ratio - 1:64
- Payload (including FEC):
 - Downstream Data-rate=9.6Gb/s
 - Upstream Data-rate=2.4Gbps shared between ONUs
- ONU recovered clock jitter - $\sim 5\text{ps rms}$
- Latency (active components)
 - Fixed and deterministic
 - Downstream - $\sim 100\text{ns}$
 - Upstream - $\sim \text{Number_ONU} \times 125\text{ns}$
- Complete monitoring



Backend Links – 10-25 Gbps

- Timing or DAQ links
- Based on COTS
 - No multiplexing
 - Commercial components
 - Custom protocol tailored to our specifications
- Point2Point
- Payload:
 - 10-25 Gbps
- Recovered clock jitter
 - When proper PLL used ~ 2ps rms
- Fixed and Deterministic Latency
 - 1ps precision when TCLink IP is used on bidirectional links



High Performance Fixed latency
Jitter Attenuators



Mid/High range FPGAs + TCLink IP



MM Minipods 12x10-25Gbps, 100m



MM Firefly 12x10-25Gbps, 100m



MM/SM SFP28 1x25Gbps, 100m-20km

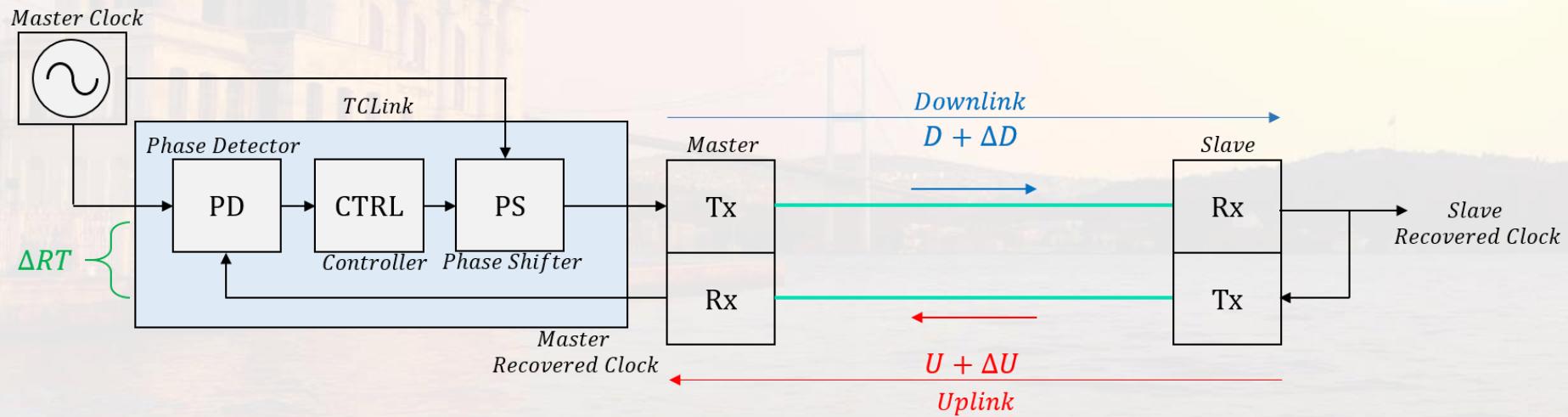


MM/SM SFP28 4x25Gbps, 100m-20km

TCLink

<https://gitlab.cern.ch/HPTD/tclink>

- The TCLink is a protocol-agnostic FPGA core designed to mitigate long-term phase variations in high-speed optical links
 - Protocol-agnostic but already integrated with IpGBT
 - Specific to Ultrascale+ FPGAs



Outline

- Fundamental concepts
- Physical devices
- Applications
 - CERN Versatile Link PLUS
- Installation / Commissioning

Optical Power Meter (Light meter)

- Actually two devices
 - Optical reference
 - Receiver module
- Measures the “brightness” of the signal [dBm] or [mW]
- Automated (re)-calibration
 - Measure either absolute power or relative loss
- MPO polarity detection
- Scan one entire MPO bundle at once

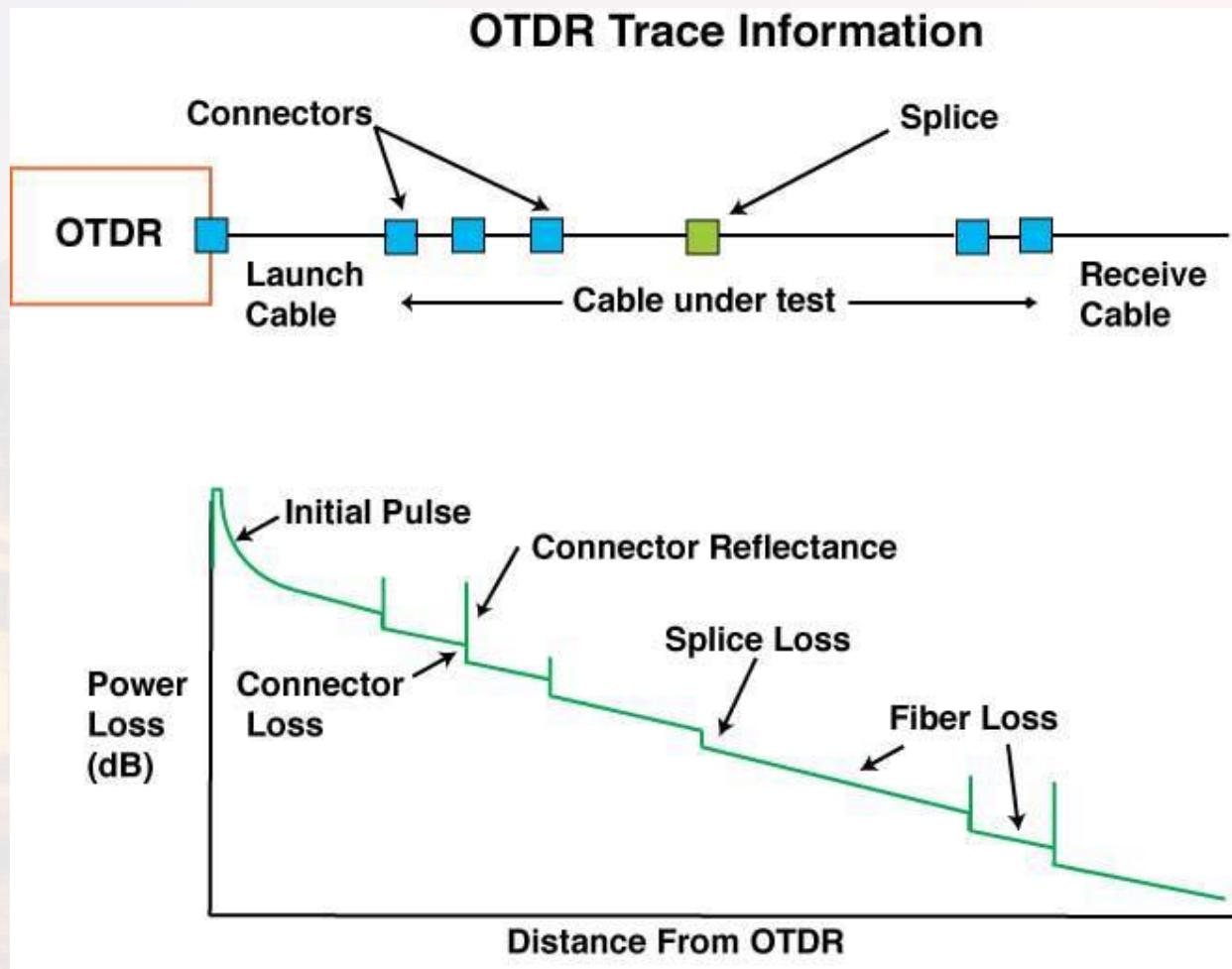


Optical Time-Domain Reflectometer (OTDR)

- Indispensable tool to test fiber installations
- Inject a train of light pulses in fiber strand
- Analyze light that is reflected back
- Characterize fiber path
 - Locations of fiber splices
 - Locations of fiber breaks
 - (As distance from probe)
 - Overall attenuation of fiber

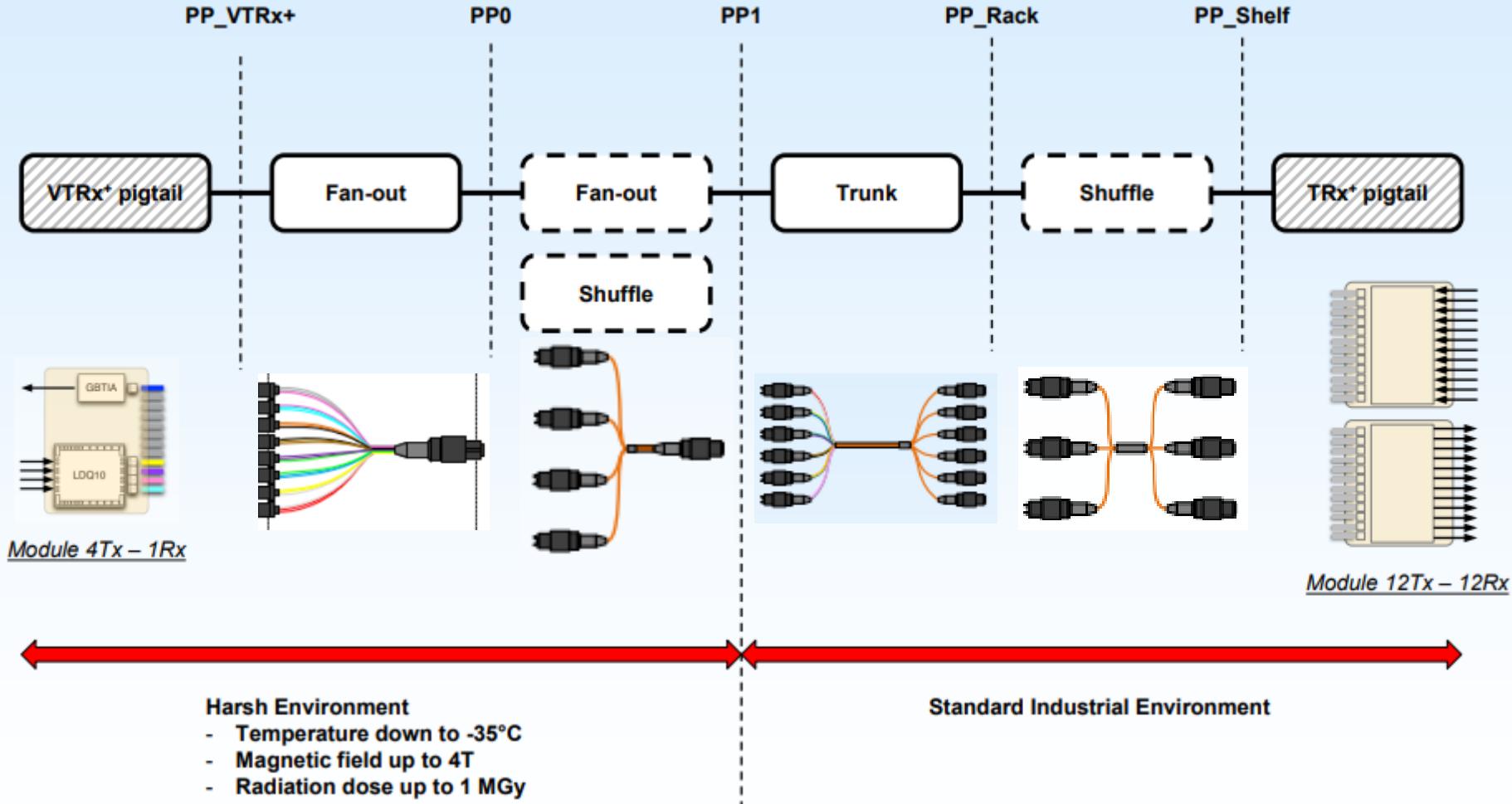


OTDR output diagram

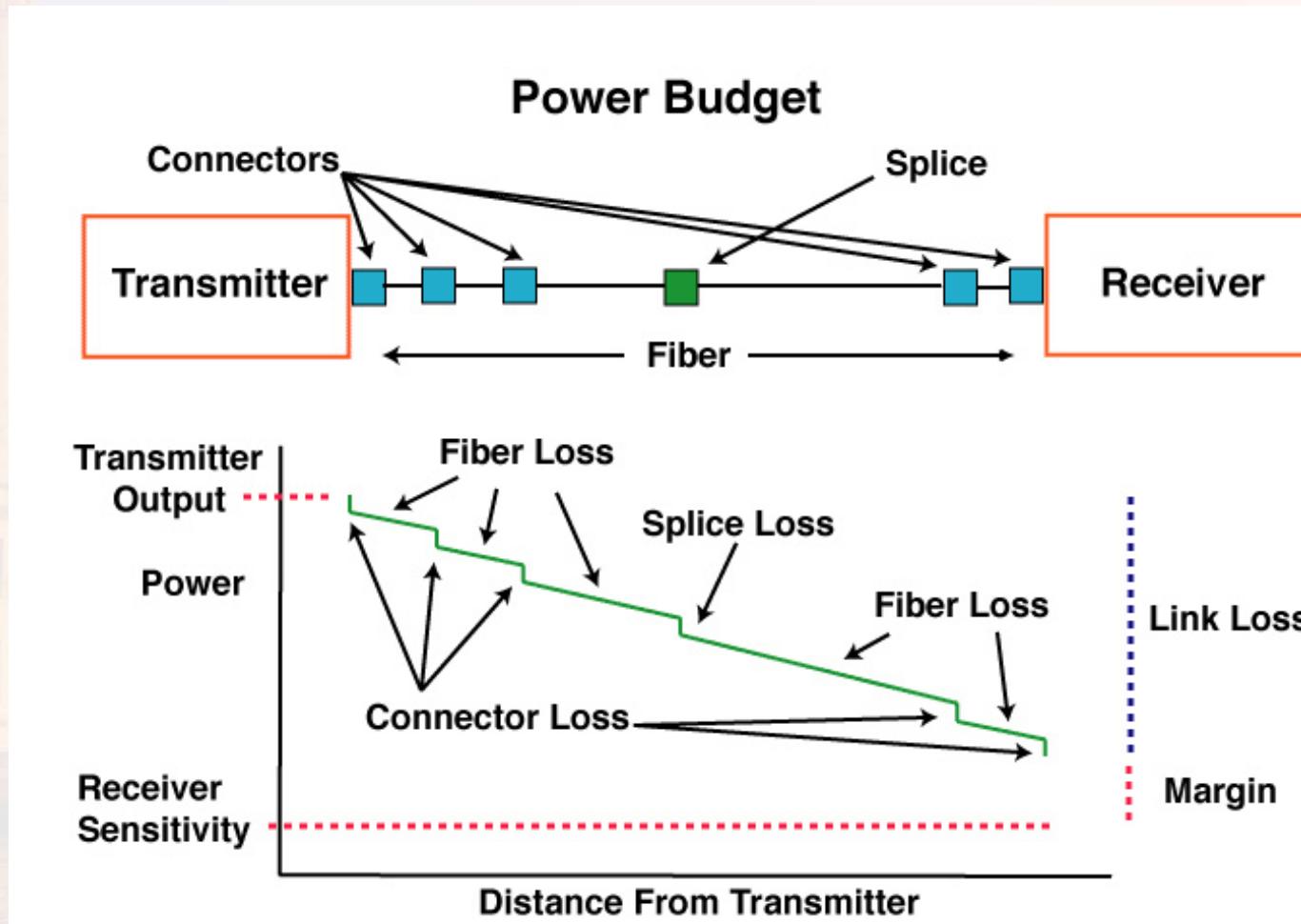


Cabling Plant

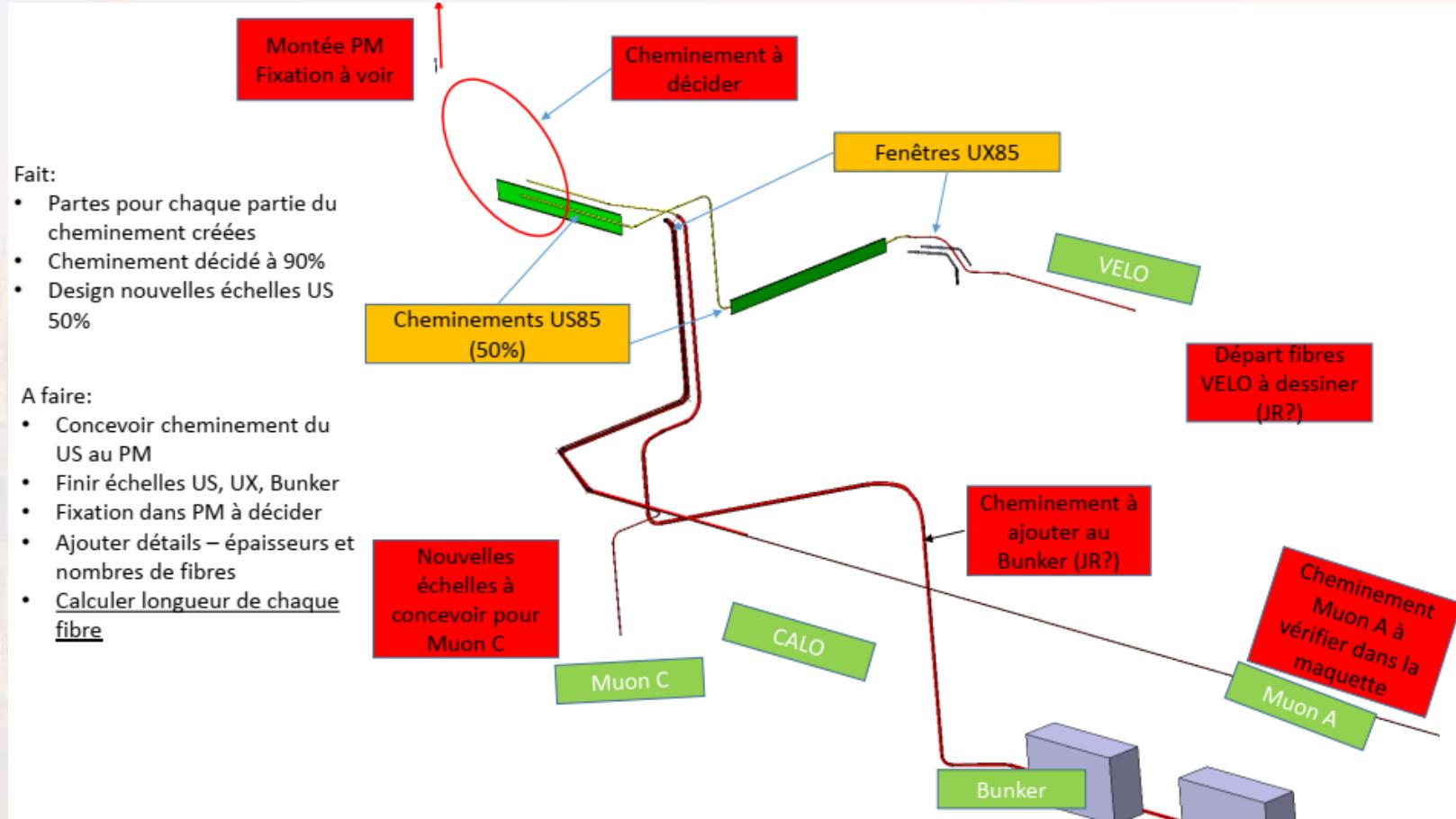
- Up to 150m, up to 5 breakpoints (VL+)
- The shorter the length and the fewer the breakpoints, the better the power margin



Plan your optical budget...



...plan your cable paths...



...plan your cabling and spares...

Custom SQL query returning 101 rows ([hide](#))

```
1 select trunk_name, trunk_fiber, trunk_mpo_port, trunk_mpo_fiber, pcie40_name, pcie40_mpo_port,
       pcie40_mpo_fiber, pcie40_link_dir, pcie40_link_number, sd_name, notes from fibers order by trunk_name,
       trunk_fiber limit 101
```

[Format SQL](#)[Run SQL](#)

This data as [json](#), [CSV](#)

trunk_name	trunk_fiber	trunk_mpo_port	trunk_mpo_fiber	pcie40_name	pcie40_mpo_port	pcie40_mpo_fiber	pcie40_link_dir	pcie40_link_number	sd_nar
220-01	1	1	1	CASOL011	1	1	Rx	0	EC00_
220-01	2	1	2	CASOL011	2	1	Tx	0	EC00_
220-01	3	1	3	CASOL011	1	2	Rx	1	EC01_
220-01	4	1	4	CASOL011	2	2	Tx	1	EC01_
220-01	5	1	5	CASOL011	1	3	Rx	2	EC02_
220-01	6	1	6	CASOL011	2	3	Tx	2	EC02_
220-01	7	1	7	CASOL011	1	4	Rx	3	EC03_
220-01	8	1	8	CASOL011	2	4	Tx	3	EC03_
220-01	9	1	9	CASOL011	1	5	Rx	4	EC04_
220-01	10	1	10	CASOL011	2	5	Tx	4	EC04_

...and monitor your links

