Fiber Optic Communications

Georgia Institute of Technology

Lecture 2

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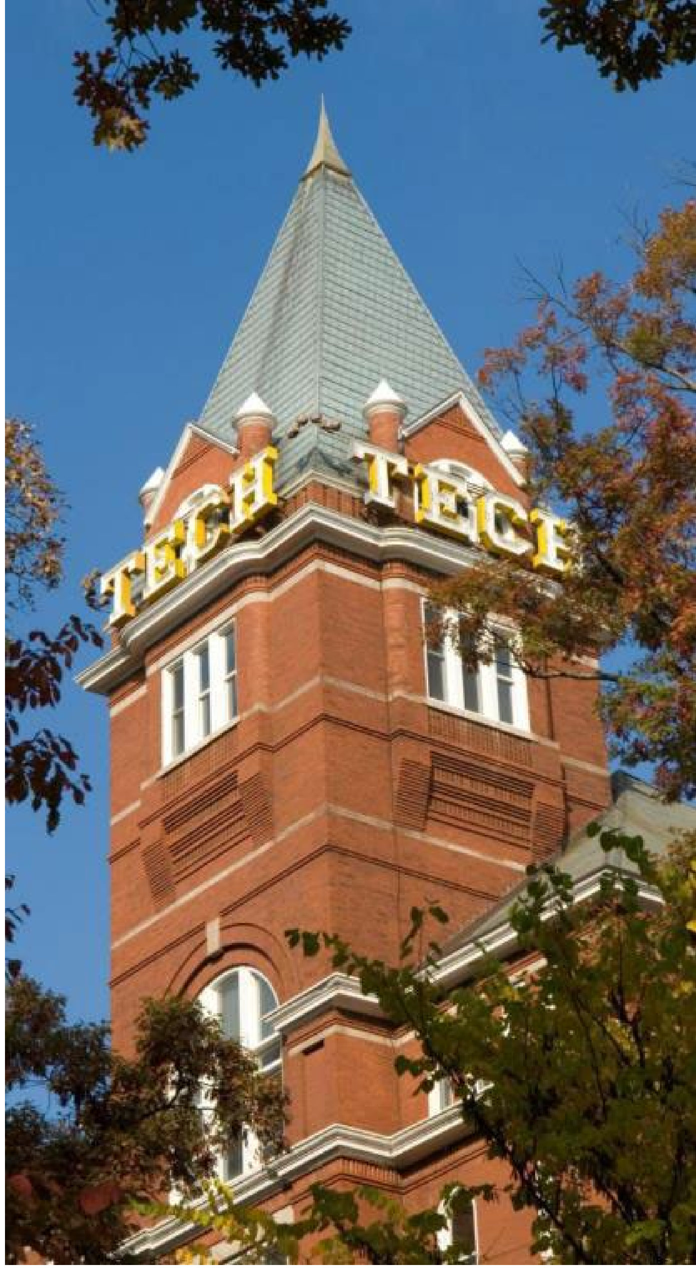
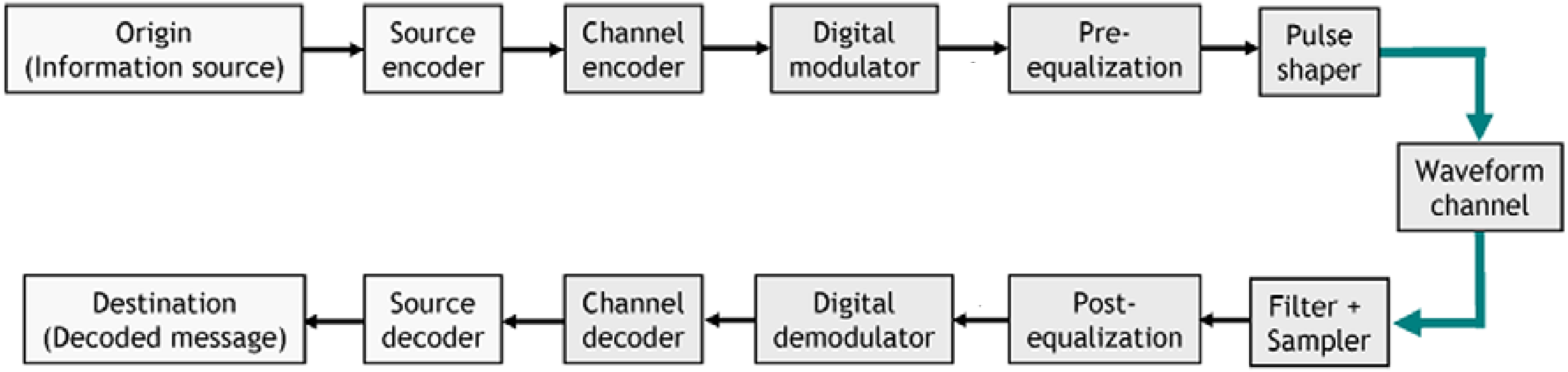
Spring 2026

Fiber Communication System Architecture



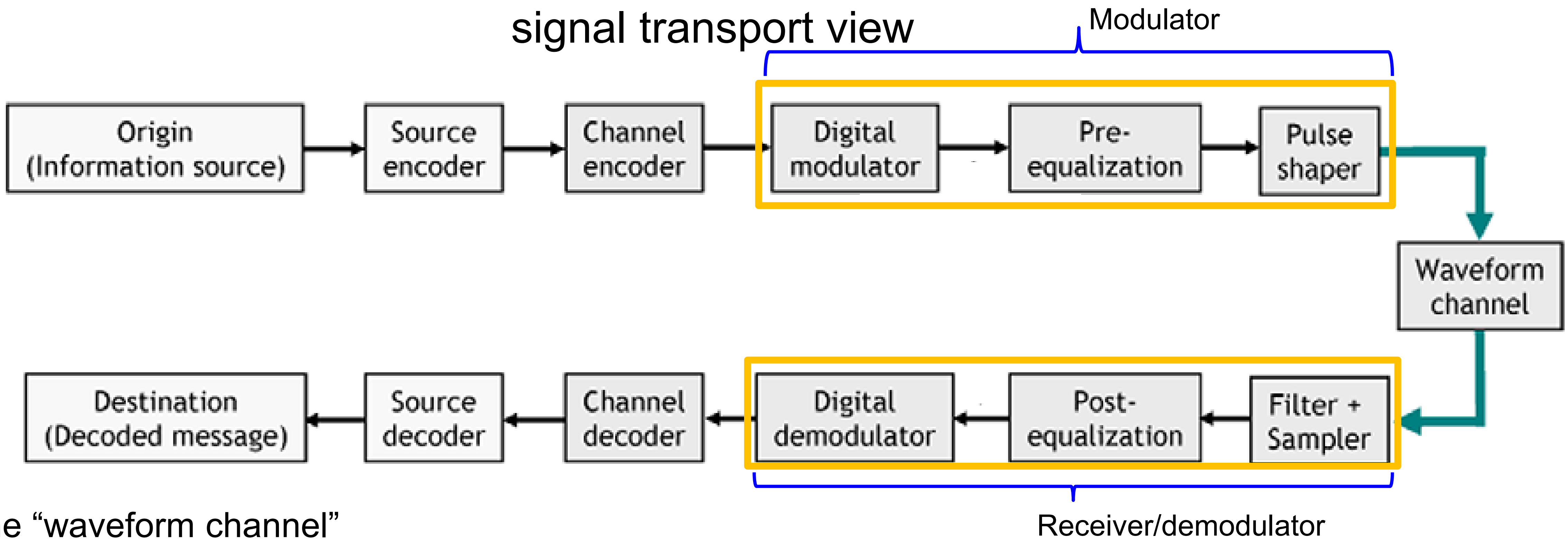
Basic Link Elements

signal transport view



- Source Encoder
  - Data compression, reduce redundancy
- Channel Encoder
  - Code data so that errors can be detected and corrected
  - Forward error correction;
    - Linear block codes; Reed-Solomon for eg.
    - Convolutional codes

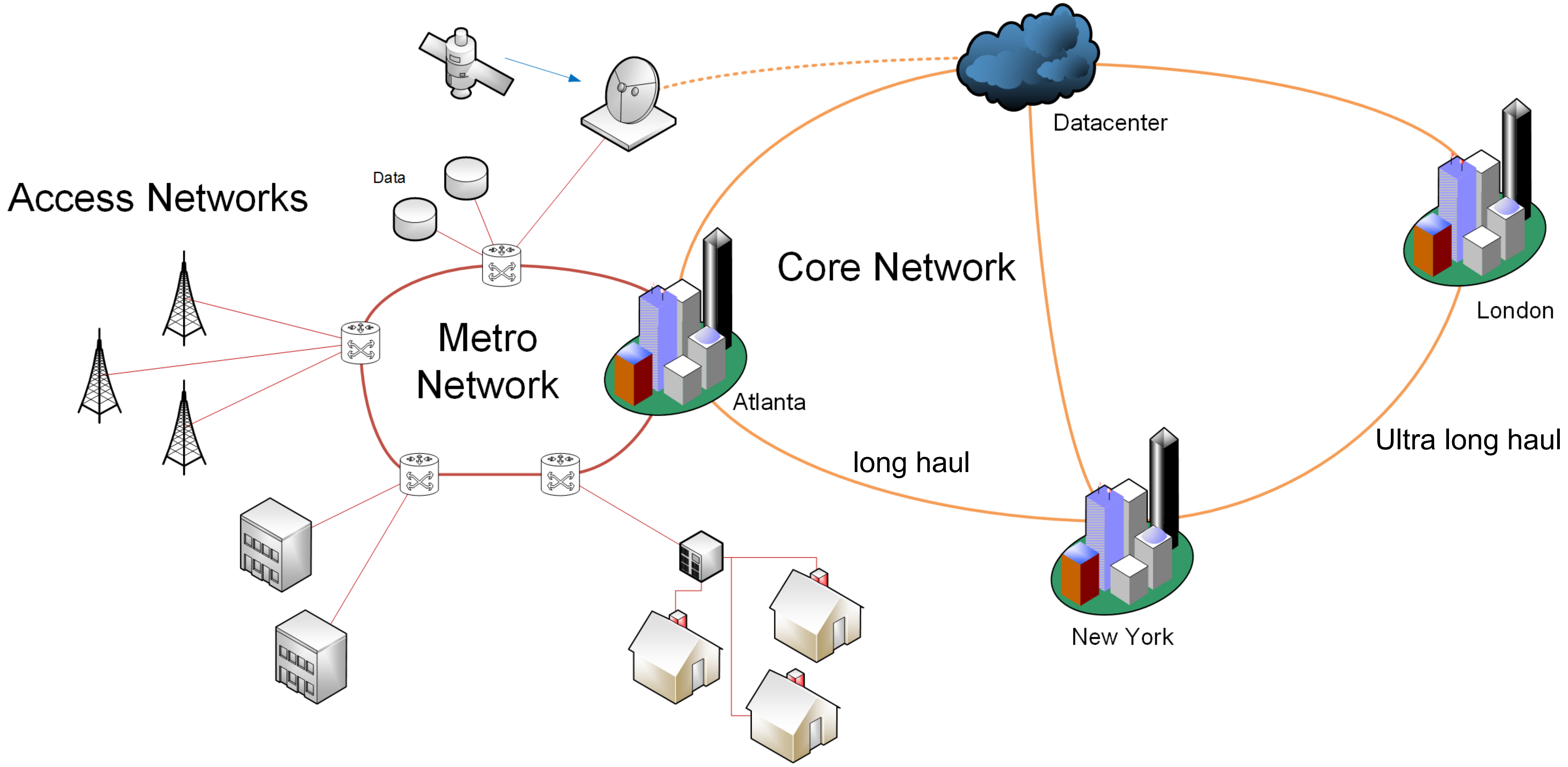
Basic Link Elements



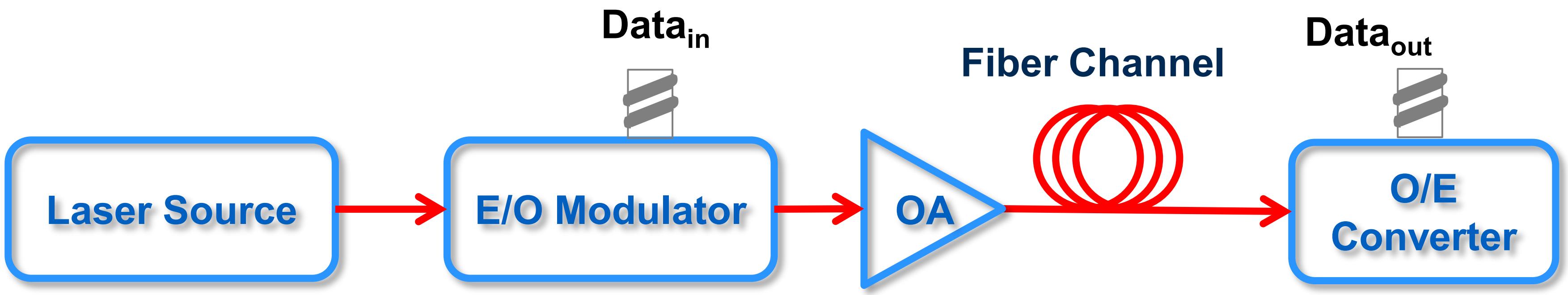
- The "waveform channel"
  - Signal is often viewed as continuous or analog in nature
  - Wired: twisted pair, coaxial cable, optical fiber
  - Wireless: air, vacuum
  - Complex transfer characteristic; loss and phase velocity are both functions of frequency
  - May have nonlinear (wrt intensity) response
  - Shannon examined the additive white Gaussian noise (AWGN) memory less channel

High speed DACs and ADCs together with high thru put ASICs implementing sophisticated DSP have enabled 100G single carrier coherent systems

The Telecommunications Network



Basic Fiber Optic System Building Blocks



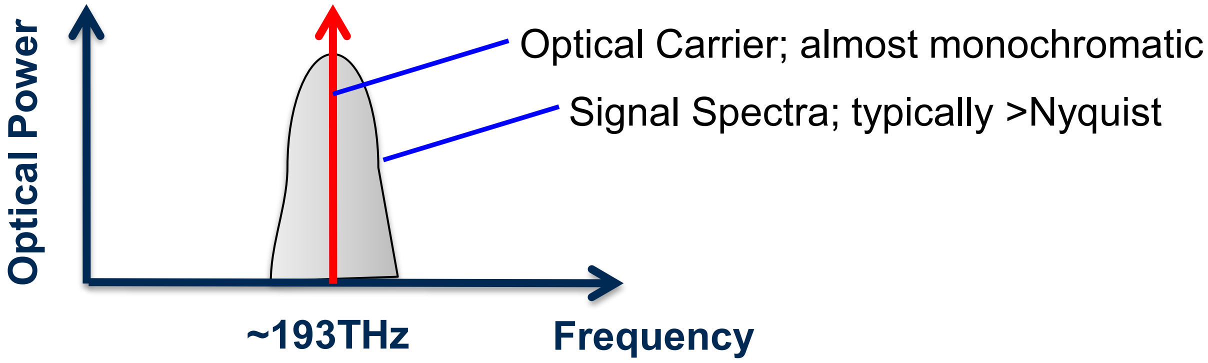
Laser:
Generates optical carrier

E/O Modulator:
Modulates Data onto optical carrier

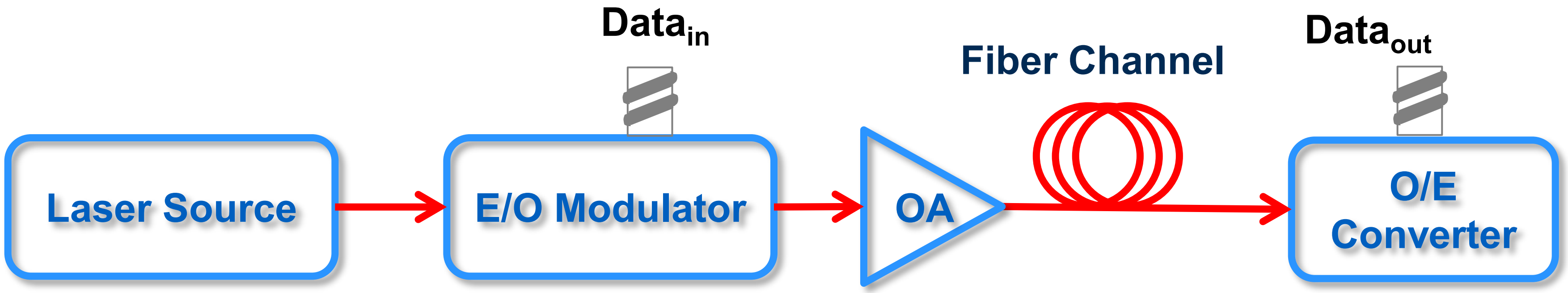
OA:
Optical Amplifier, gain

Optical Fiber

O/E Converter:
Photodiode



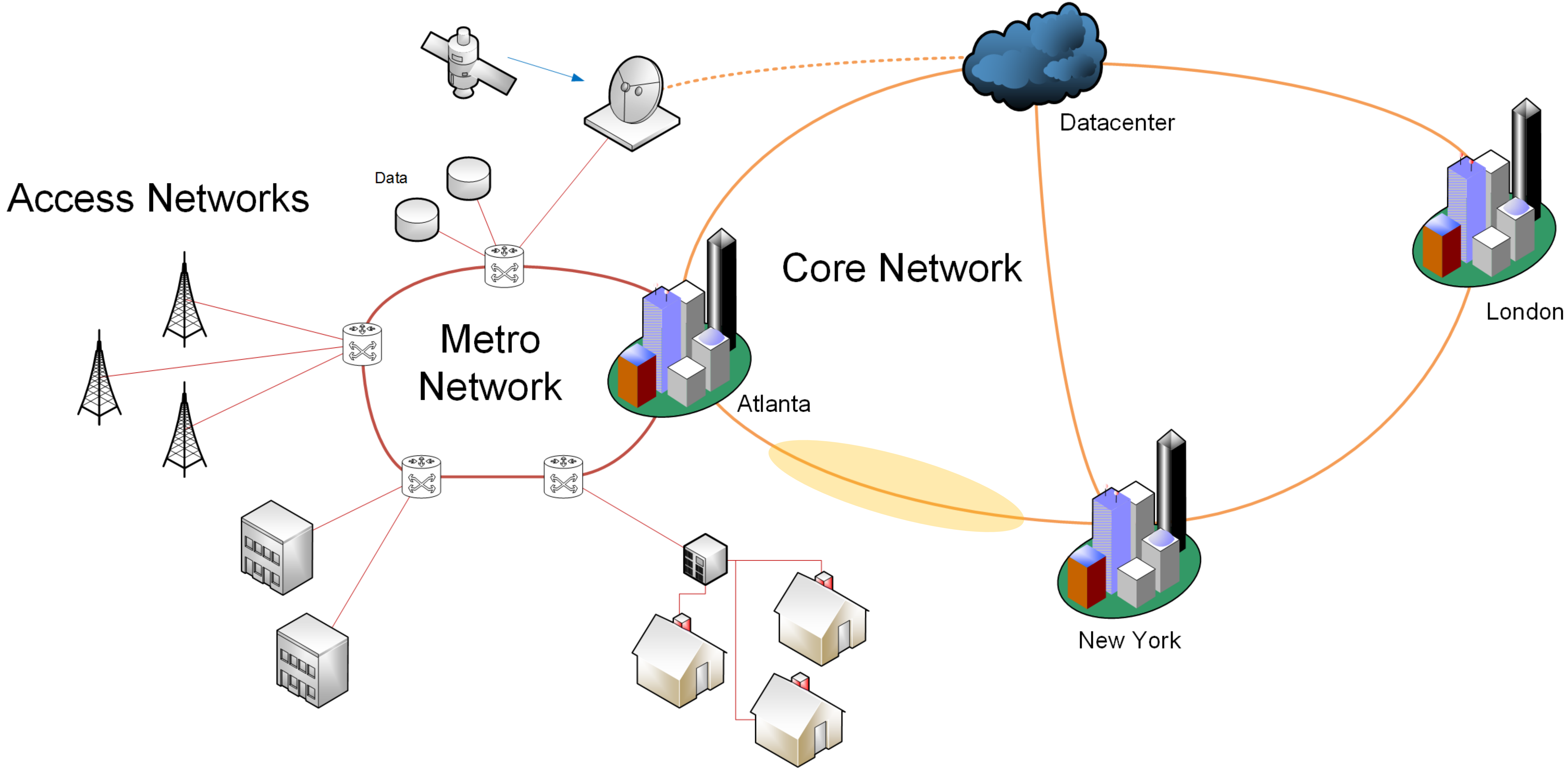
Disciplines Within Fiber Communications



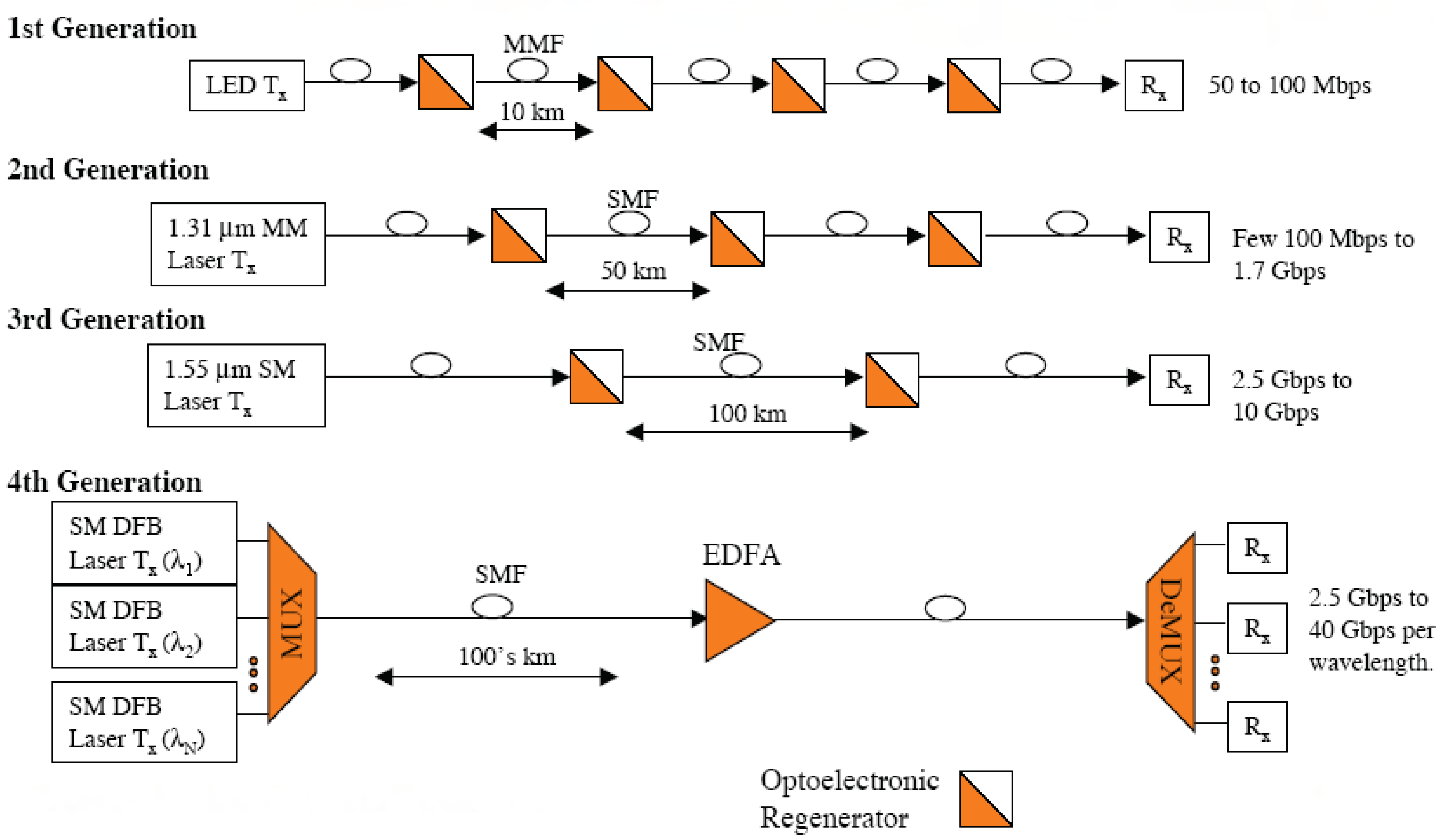
Laser Source	E/O Modulator	OA	Fiber Channel	O/E Converter
Semiconductors Circuits Quantum	Semiconductors Many Materials Control Circuits RF circuits	Optics E&M Quantum	E&M Nonlinear Wave Equation	Circuits Semiconductors DSP

- Fiber communications systems incorporate all disciplines of EE
- Each component is worthy of semester-long study
- Class goal is to understand each component from the system level view
  - how they fit and enable fiber communications
  - why they are chosen
  - how they are analyzed

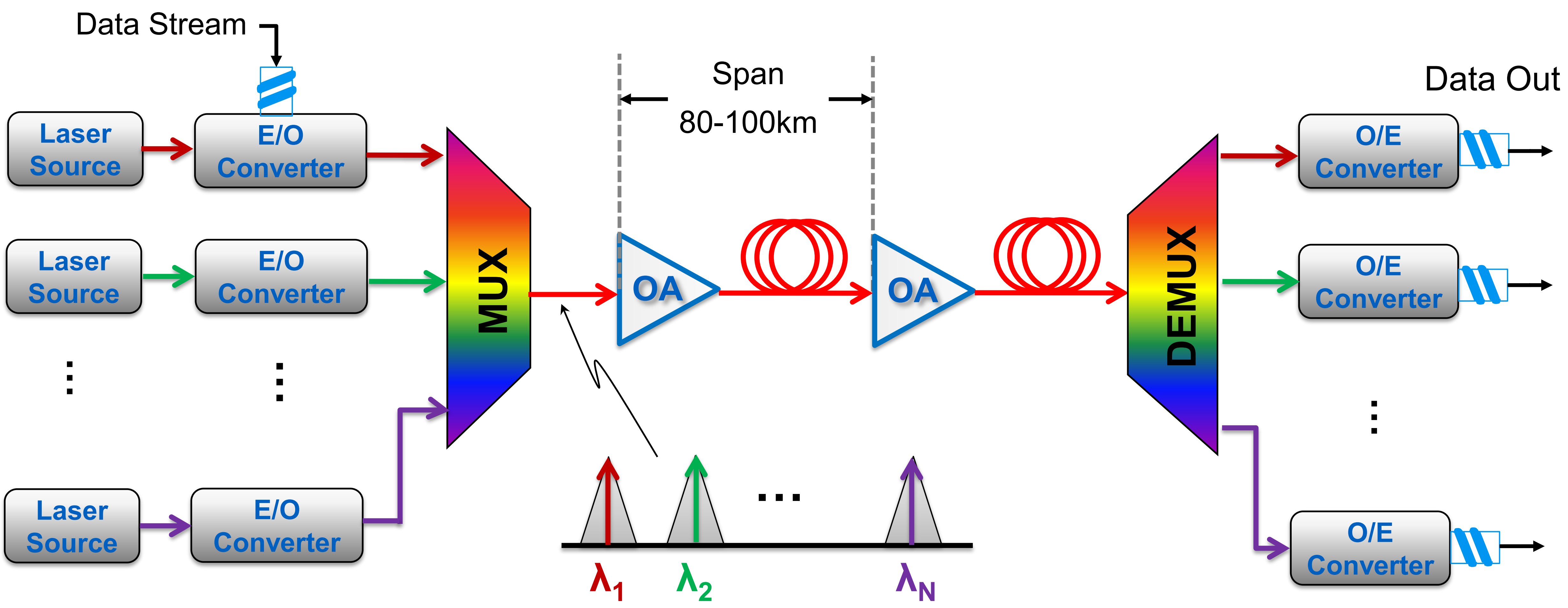
The Telecommunications Network



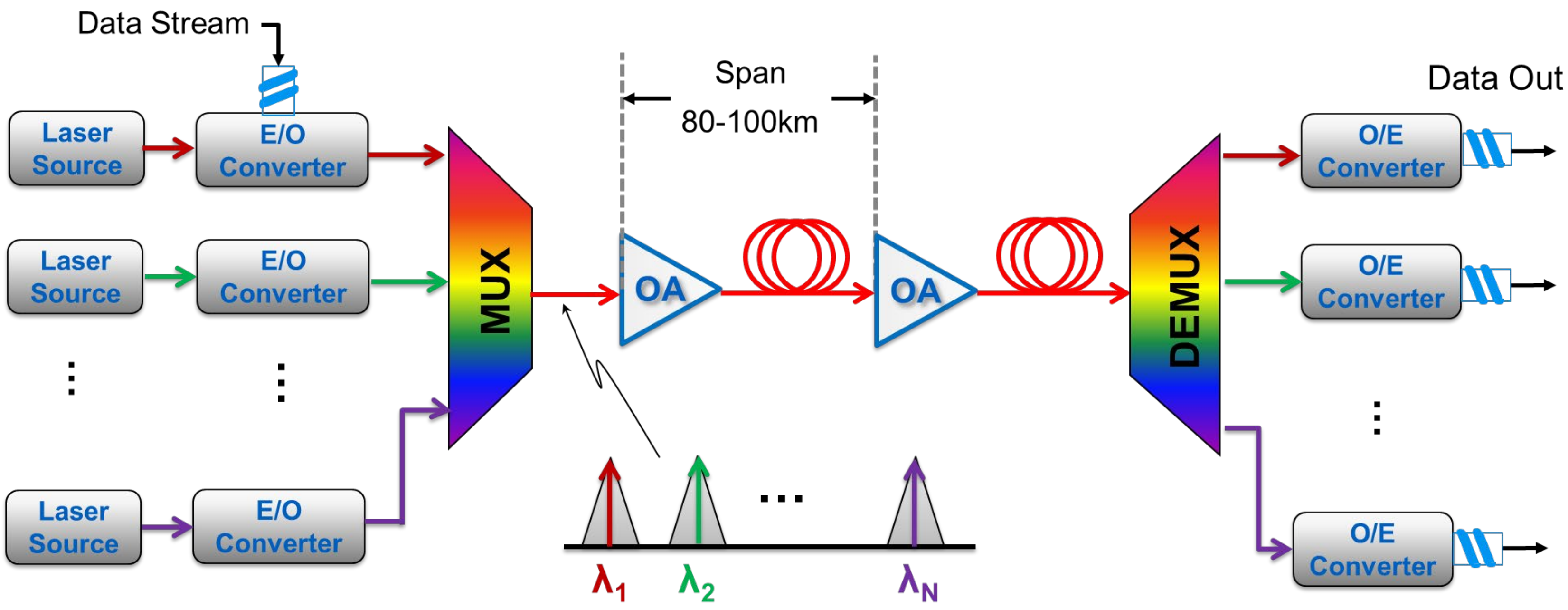
Fiber System Evolution



4^{th} Generation: WDM Long Haul Fiber Networks



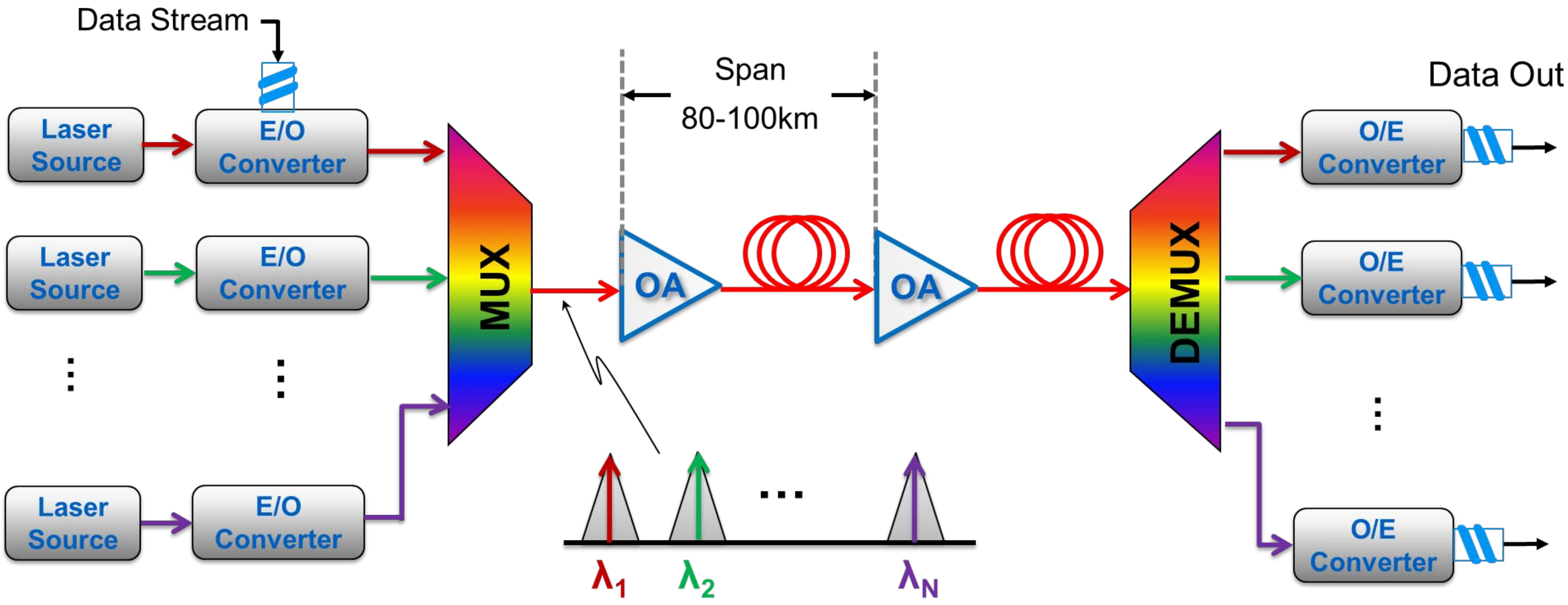
4th Generation Long Haul Networks: Key Technologies



- Narrow Linewidth lasers (<100kHz)
- High-speed (>25Gbaud) signal generation
- High-speed DACs and Linear Amplifiers
- High-speed, efficient (low Vπ) optical modulation
- Optical multiplexing/ demultiplexing

- Quasi linear fiber propagation (gain, reshaping)
- Add/Drop multiplexers/switching
- Digital Coherent High-speed receivers
- Coding: Forward Error Correction
- **Digital signal processing to generate and detect signal**

4^{th} Generation Long Haul Networks: Standard Link Budget

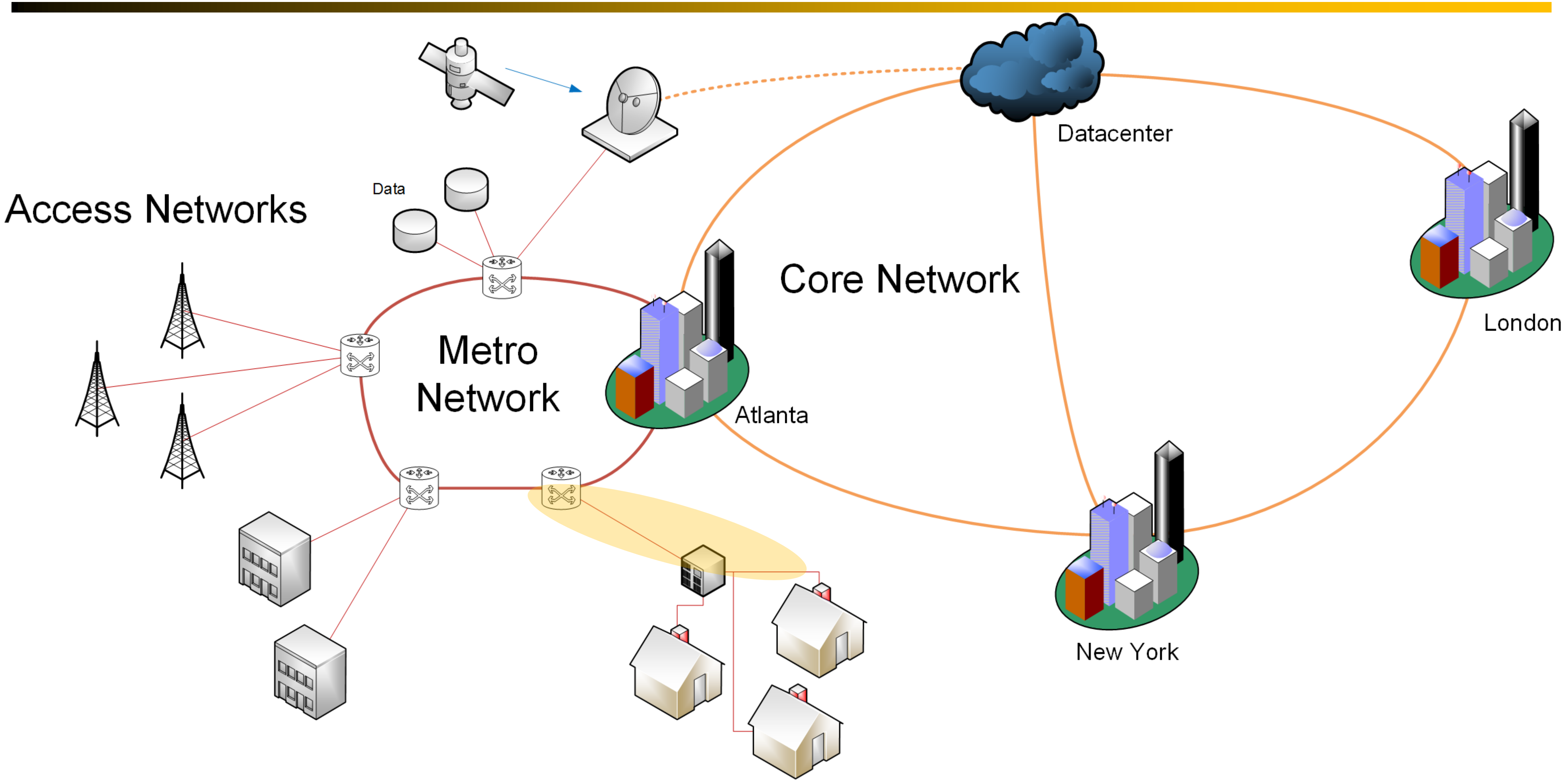


Standard Link Budget Equation

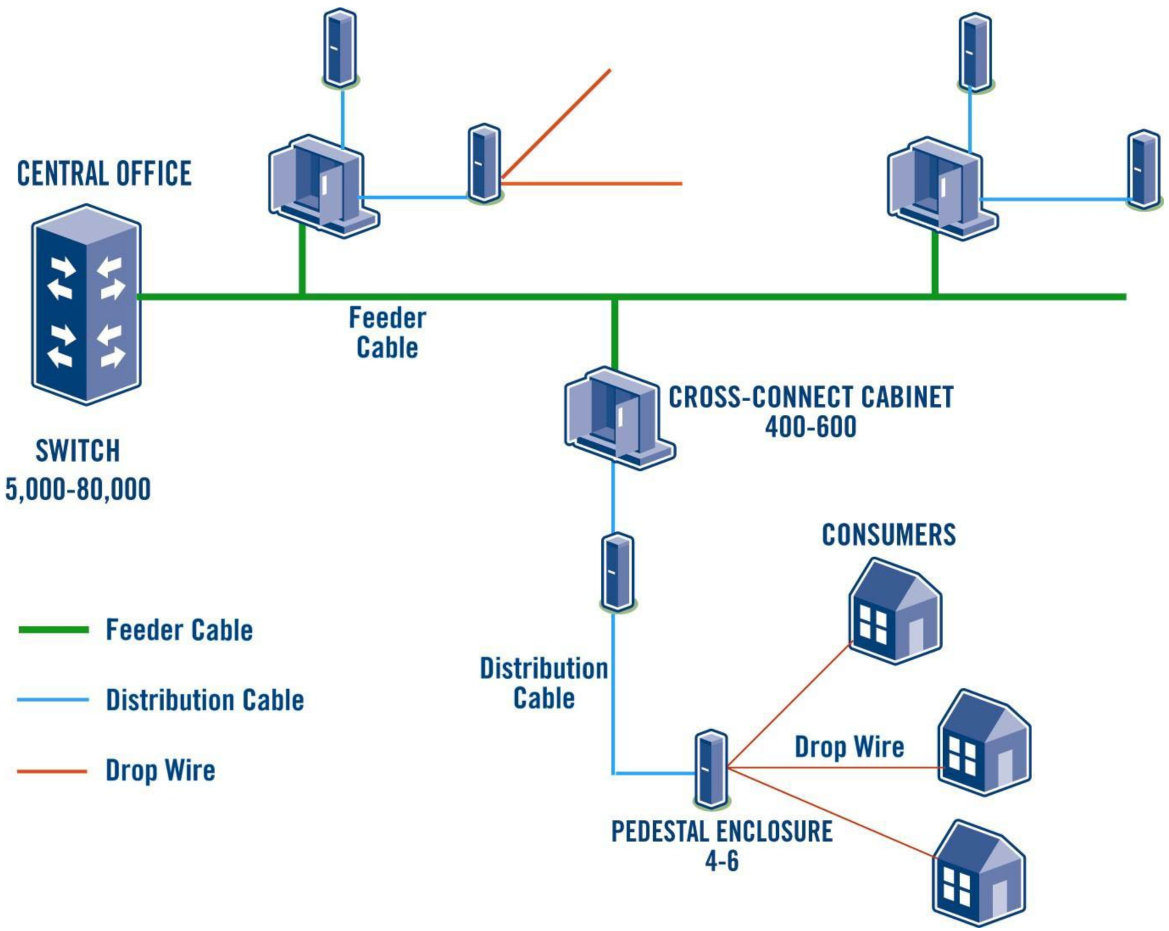
Assuming N identical spans, each with amplifiers with gain that equal the span loss L and noise figure NF, with launch power P_{out}, the resulting SNR can be shown to be:

$$SNR = 58dB + P_{out} - L - NF - 10\log_{10} N$$

The Telecommunications Network

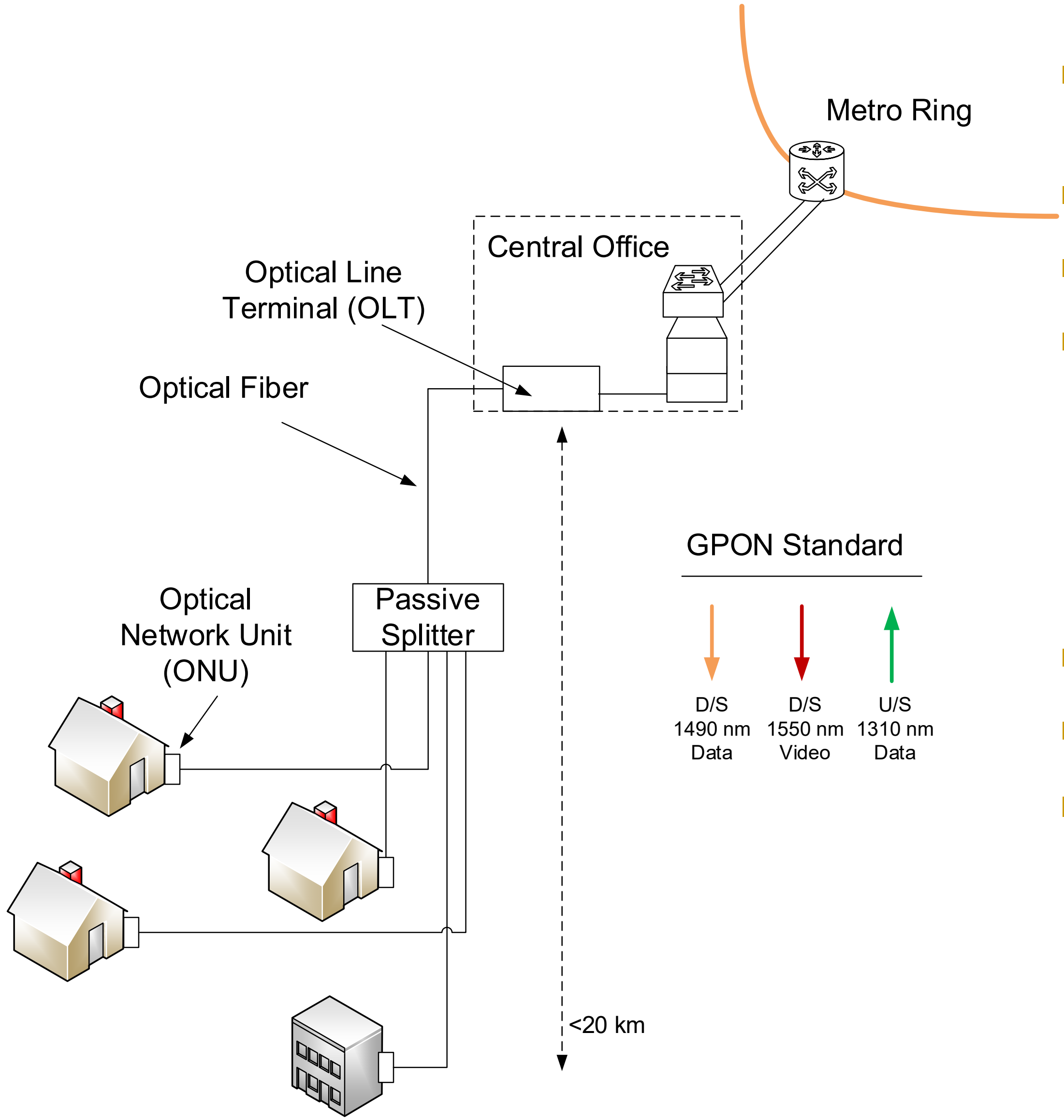


Access Networks



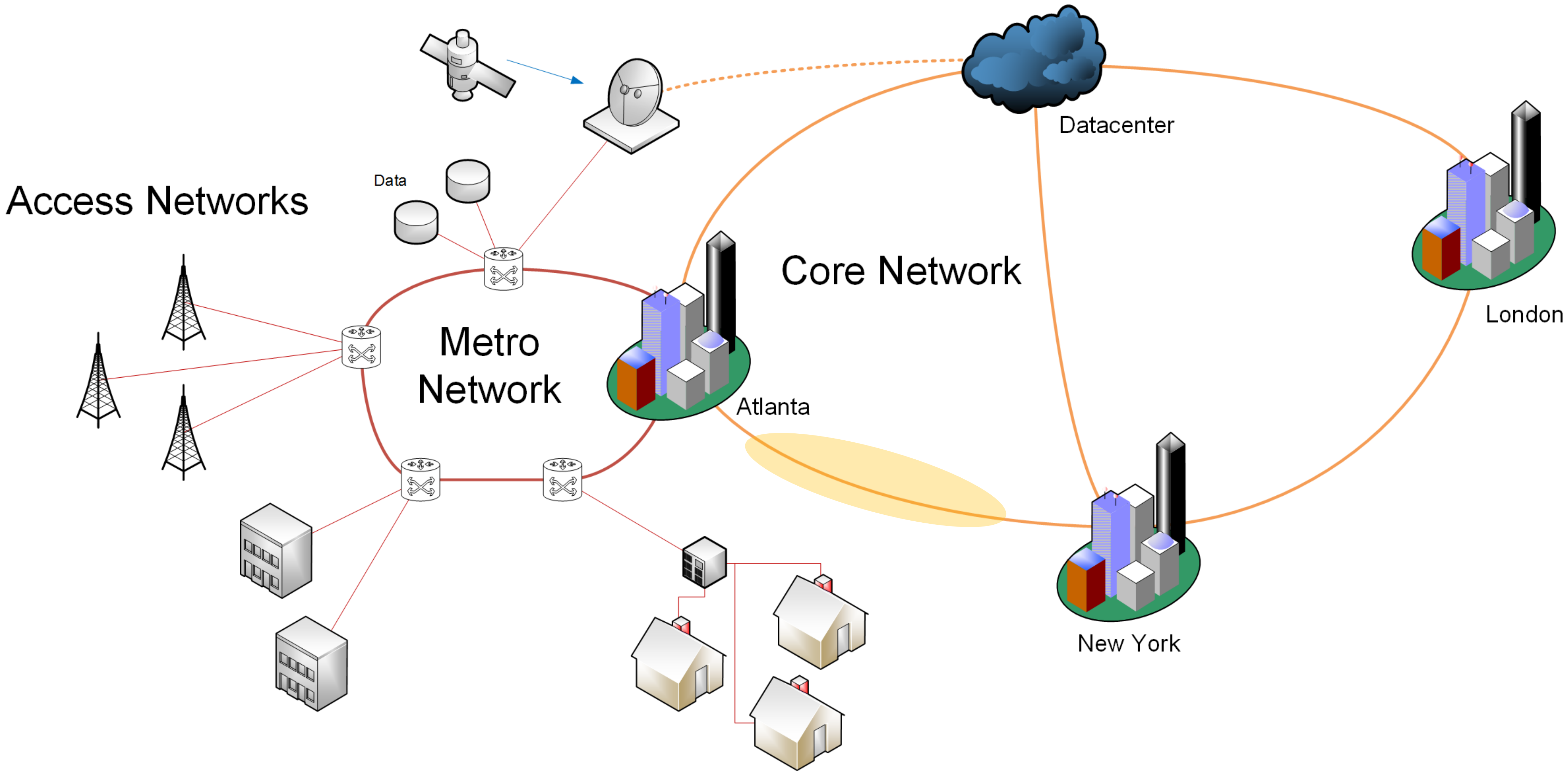
- Access network for typical telephone service
  - Fiber deployments can reach to the distribution cable and the drop wire

Passive Optical Networks (PON)

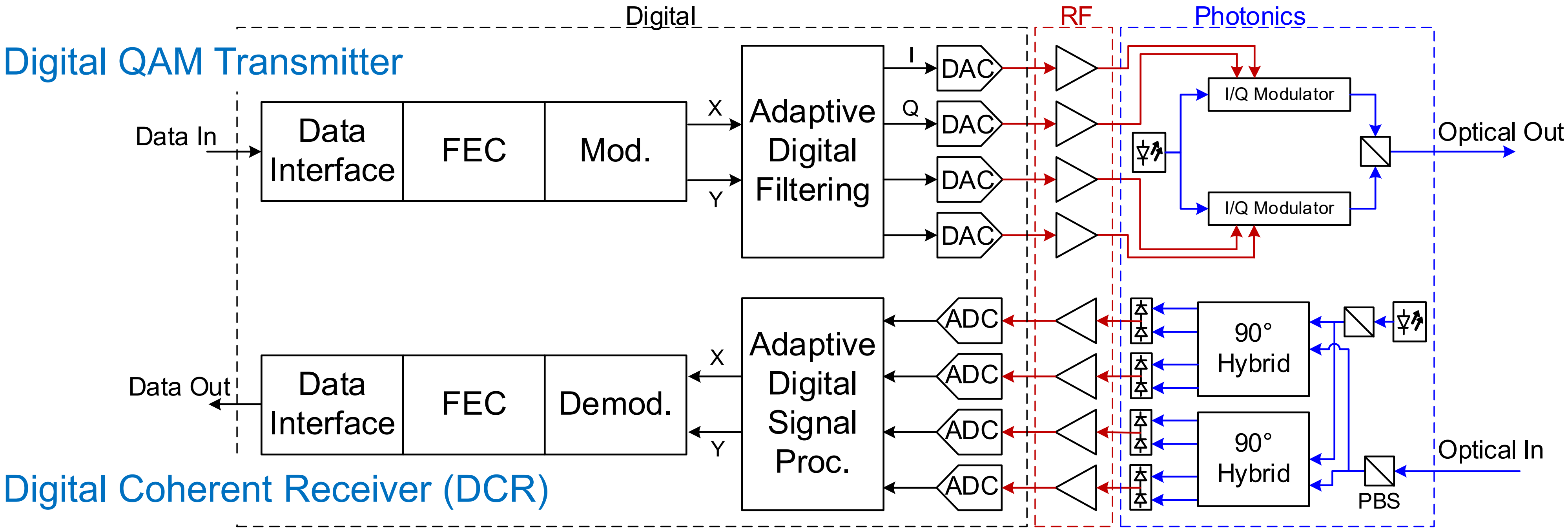


- Passive splitters are typically tiered: 1x2 or 1x4 then 1x32 later in the network
- Central office houses all video content delivery services
- Metro ring equipment likely co-located in CO
- GPON most widely deployed PON system
  - 20M+ ports per year
  - 2.5 Gb/s Down / 1.25 Up
  - Direct detect links
  - RF Video Overlay for broadcast
  - XGS-PON and NG-PON2 upcoming standards
- Fiber on telephone poles or buried
- https://www.itu.int/en/Pages/default.aspx
- coherent passive optical network (CPON)
  - uses coherent transmission, unlike traditional PON systems that use intensity modulation-direct detection (IM-DD)
  - CPON uses advanced modulation formats (QAM) with coherent detection and DSP

The Telecommunications Network

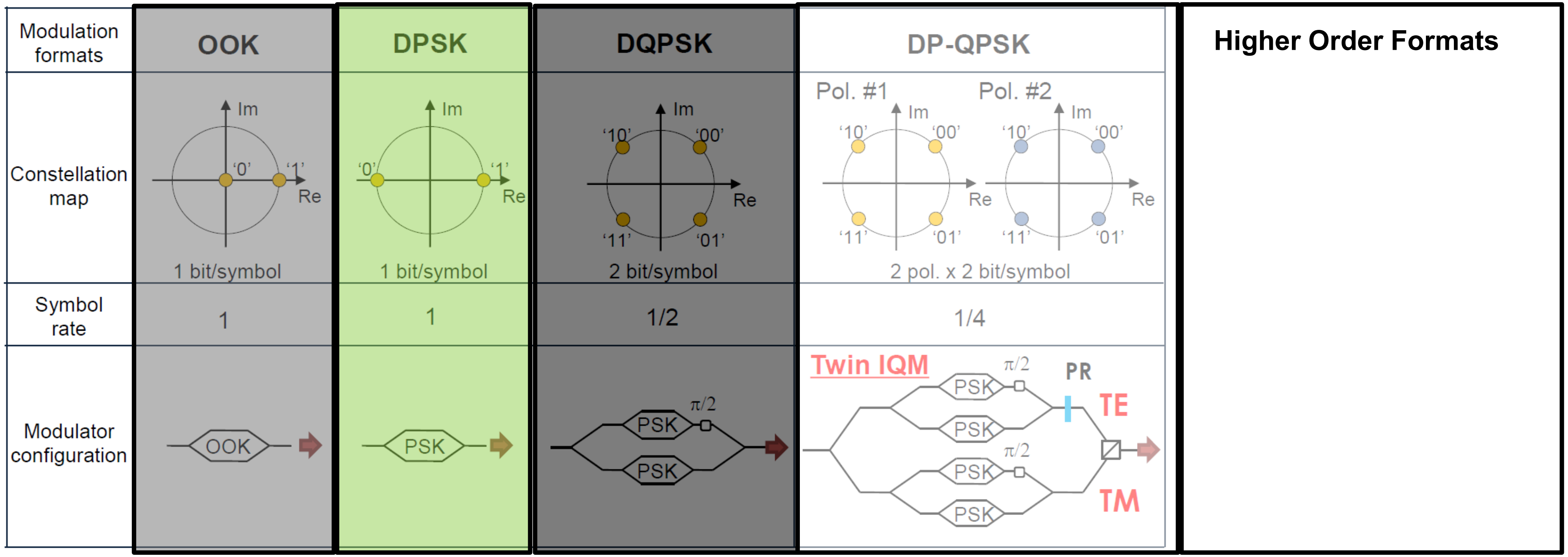


5th Generation: Digital Coherent Receivers



- 5th Generation
  - Higher order modulation with coherent detection
    - Started with QPSK and 112 Gbps for each wavelength
  - Dual-polarization: two separate channels
  - DSP to demodulate signal
- Photonics, RF, and Digital co-design
- OIF(Optical Internetworking Forum): http://www.oiforum.com/public/impagreements.html

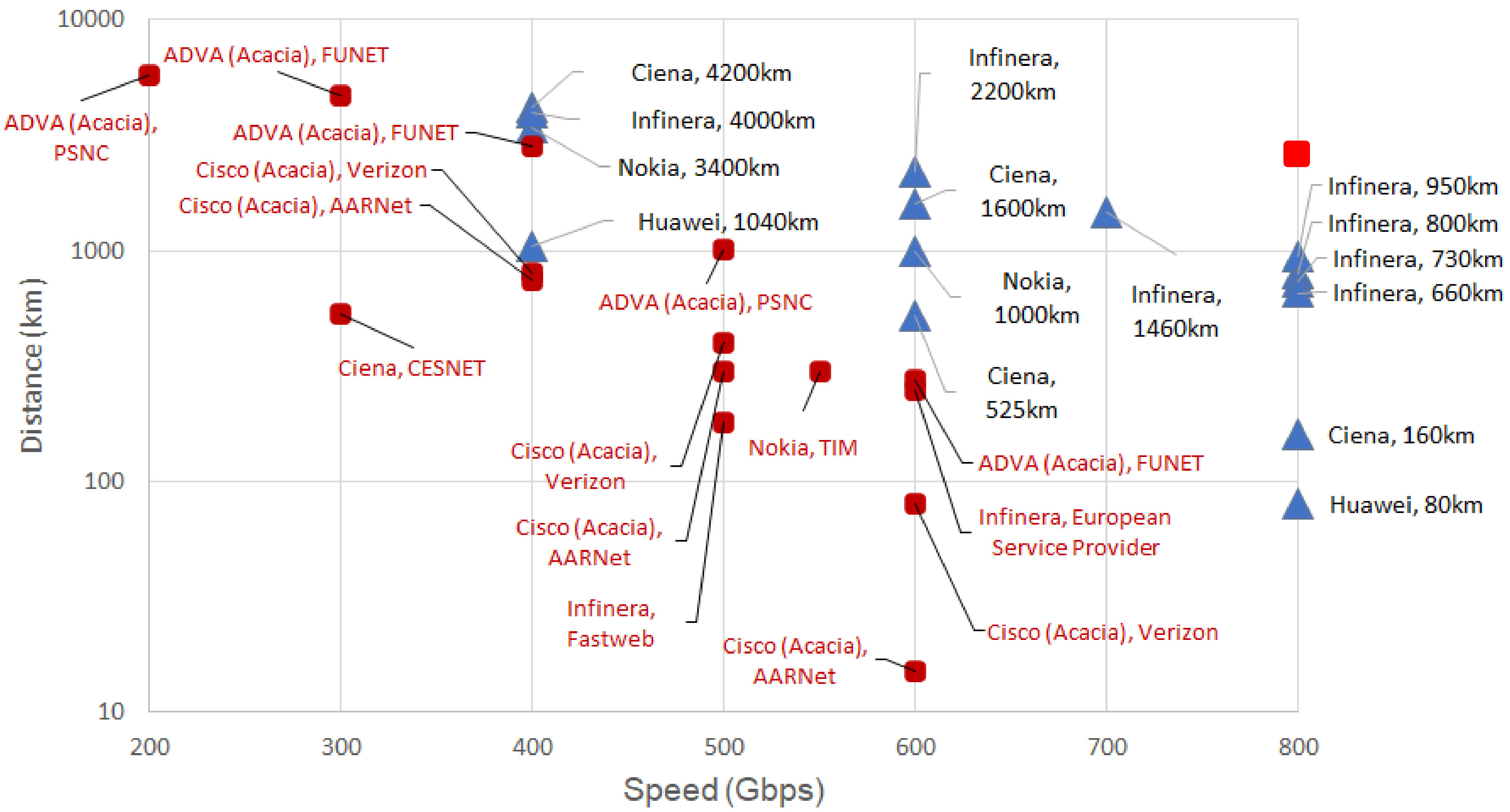
Modulation Options



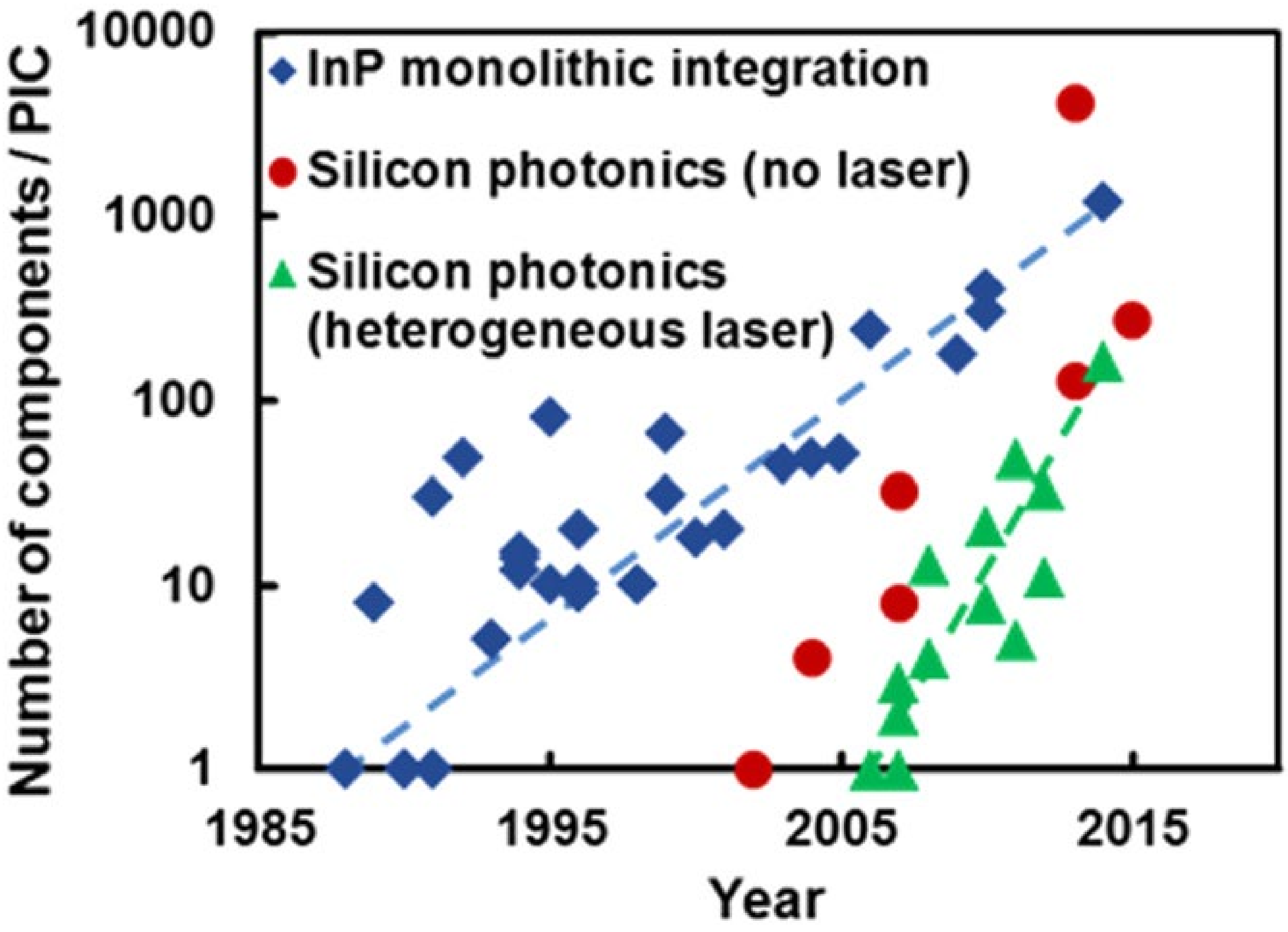
10 Gb/s	10 Gb/s	40 Gb/s	100 Gb/s	>100 Gb/s
"Standard"	"Ultra-Long"	"Metro"	"Metro or Long-Haul"	"Metro or Long-Haul"

“5th Gen Coherent”: Trials and Deployments August 2020

- 5th generation of Coherent systems
  - 800Gbps-capable
  - 90+ Gbaud
  - Dynamically alter baudrate and modulation format
  - 100Gbps to 800Gbps
- 3rd generation coherent (~60-70GBaud): red squares

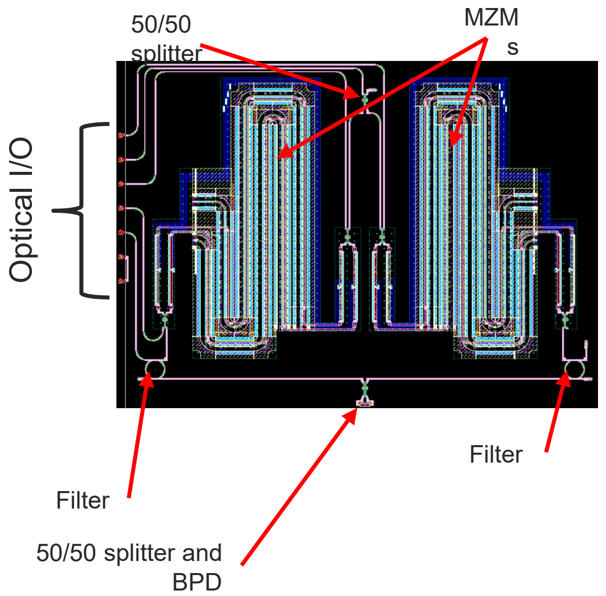


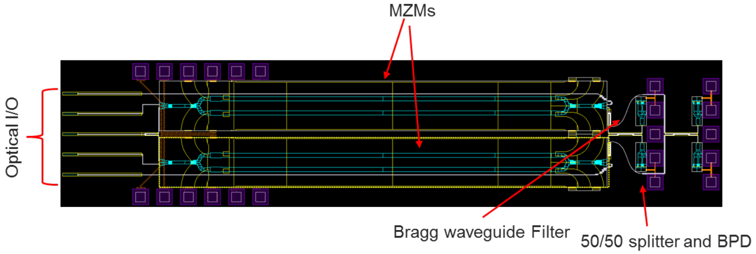
Photonic Integration Trends



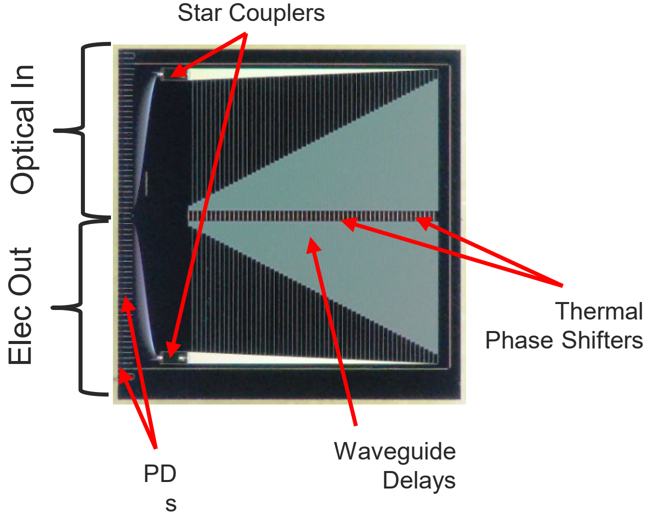
Recent Photonic Integrated Circuit Efforts at GT and GTRI

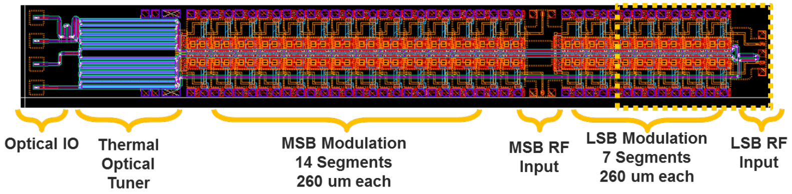
Frequency Conversion



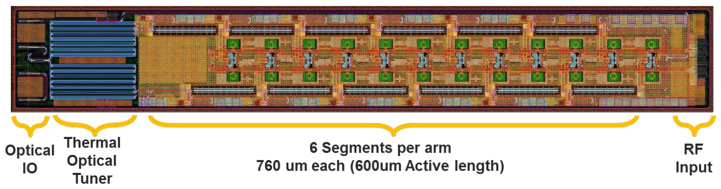


Arrayed Waveguide Grating for Channelization

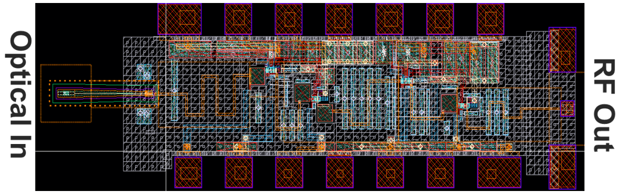




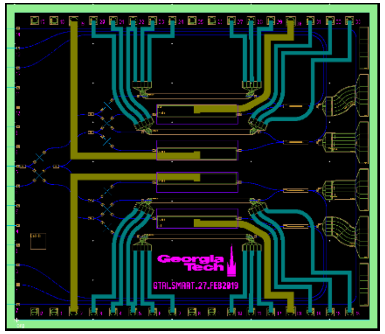
PAM-4 Segmented Modulator

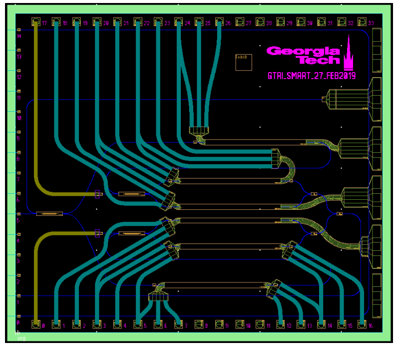


PAM-4 Modulator, Integrated Electronics



90 GHz Photoreceiver

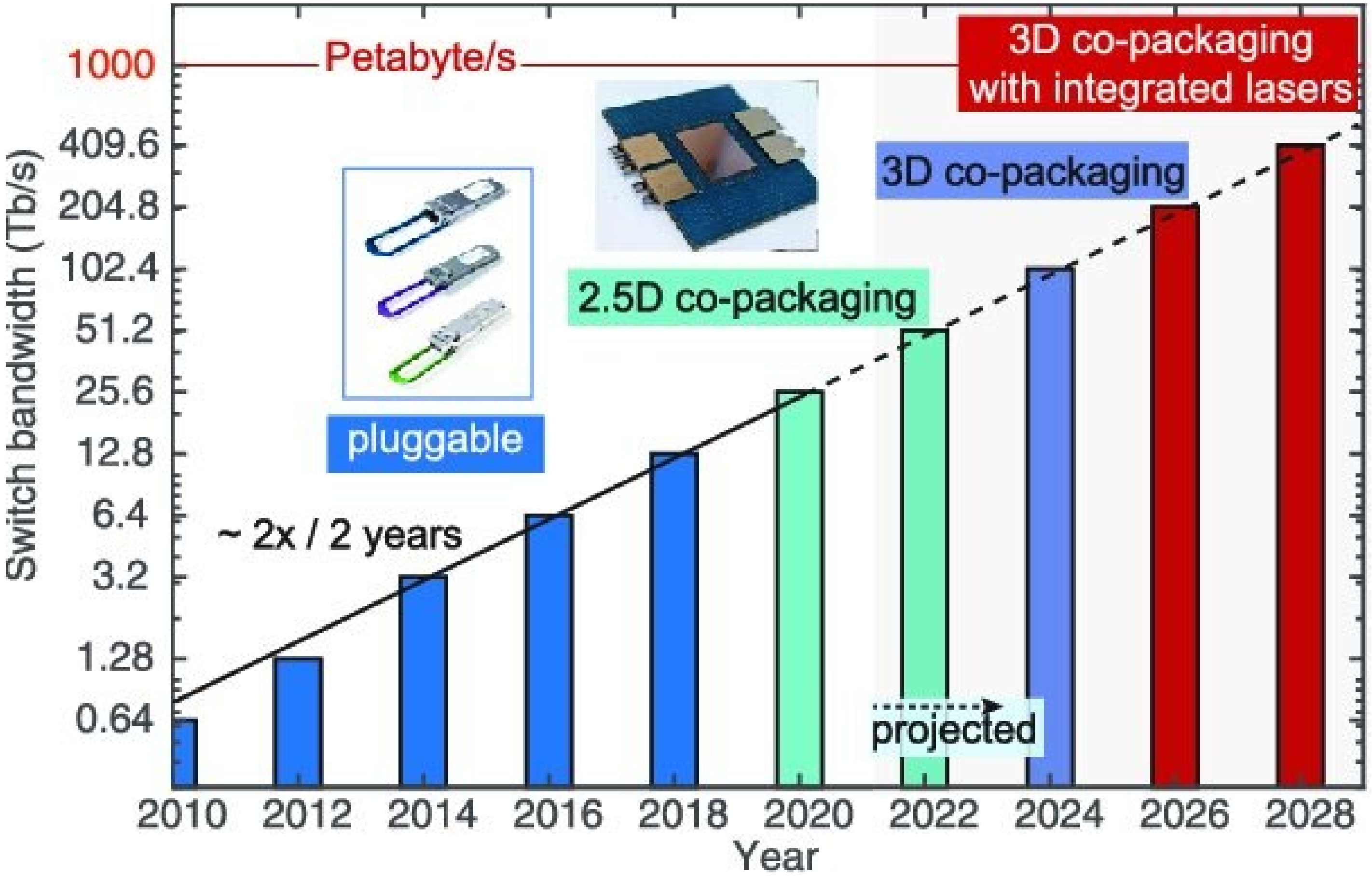




Phased Array Driver

I/Q Modulator

Perspective on the Future of Silicon Photonics and Electronics



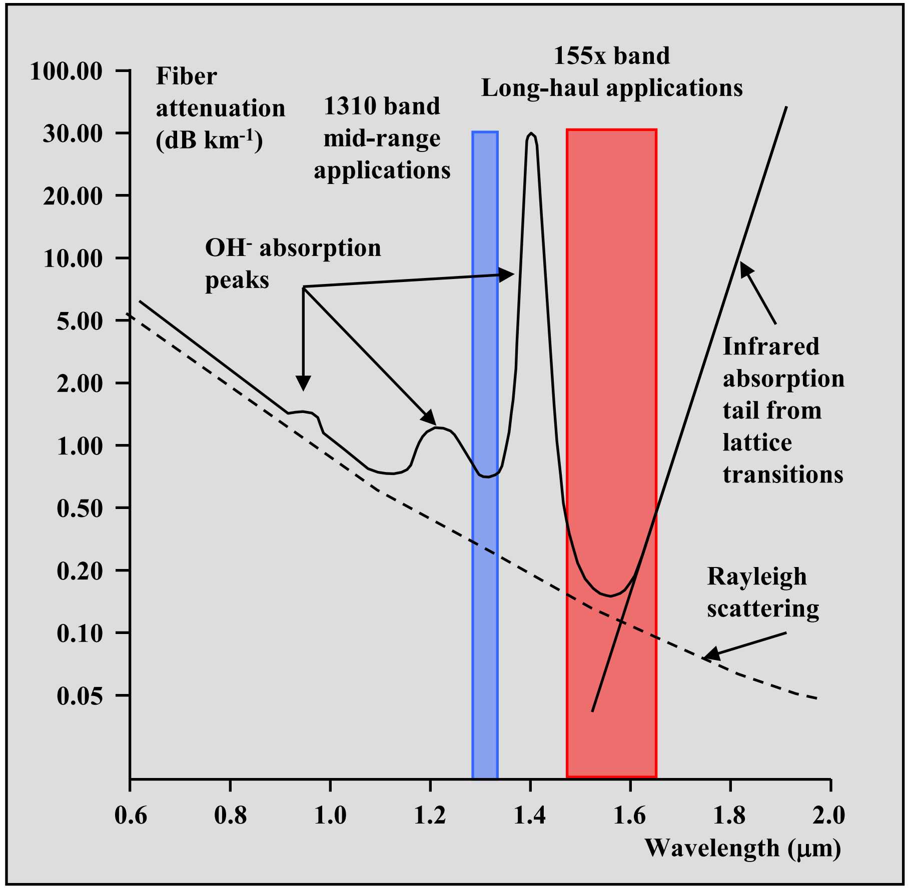
Bowers et al

Applied Physics Letters 118(22):220501, May 2021

DOI: 10.1063/5.0050117

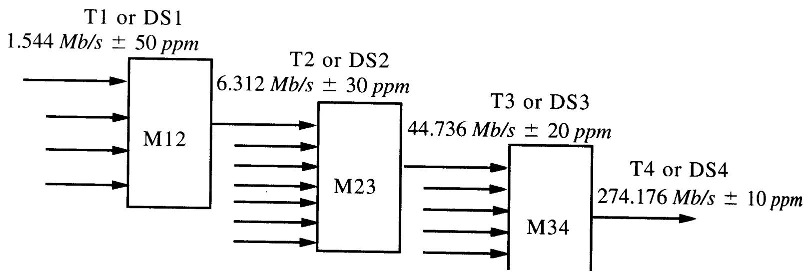
Darpa Picasso

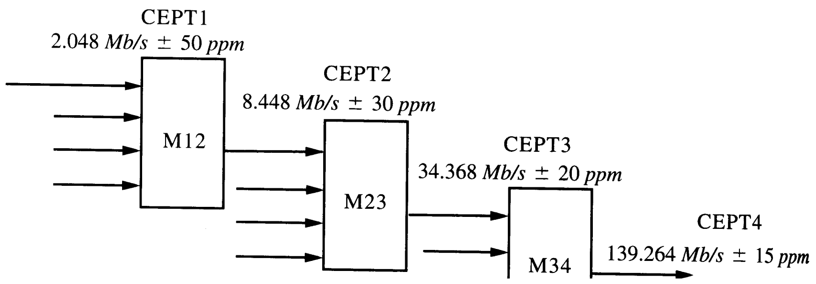
Absorption in Optical Fibers



- Attenuation in the near-infrared is close to the minimum achievable
  - determined by intrinsic properties of glass
  - Rayleigh scattering limited
- Three regions are used for optical communications
  - ~0.8μm and 1.3 and 1.5μm
  - Or just two regions
- Unlikely to find lower loss glass
- 0.25 dB/km @1550nm
  - 100 dB: 1% transmitted after 400km
  - Typical links have 20 to 25dB loss
- Attenuation losses are significantly lower than those in copper cables
  - 10 to 20 dB/km for best coaxial cable
- Fewer repeaters - 2 to 3 km spacing for coax, 30 to >100 km spacing for optical fiber

Telephone Data Rate Hierarchy





CEPT1 also known as E1, is the 2.048 Mbps rate used by European carriers to transmit 30 64 kbps digital channels for voice, plus a 64 kbps signaling channel and a 64 kbps channel for framing and maintenance.

“T1 line”

carries 24 voice channels

1 voice channel is digitized into 64kb/s

64kb/s x 24 = 1.536Mbs

Mb/s with TDM overhead bits

SONET

uses OC-1 as a basic building block

OC-1 = DS3 = 28 T1 (45Mb/s) 51.84 Mb/s

OC-192 = 192 x OC-1 = 9,953 Mb/s (“10G”)

OC-192 = 130,000 voice channels

Full-screen, full-motion video requires 10Mb/s

Channels are aggregated electronically using Time Division Multiplexing TDM

SONET Hierarchy

SONET Name	Name When Transported Optically	SDH Name	Signal Rate (Mb/sec)	User Rate[1] (Mb/sec)
STS-1	OC-1		51.84	49.54
STS-3	OC-3	STM-1	155.52	148.61
STS-12	OC-12	STM-4	622.08	594.43
STS-48	OC-48	STM-16	2,488.32	2,377.73
STS-192	OC-192	STM-64	9,953.80	9,510.91
STS-768	OC-768	STM-256	39,813.12	38,043.65

- SONET: synchronous optical networks; a protocol
  - Strict protocol which allows interoperability between vendors
  - i.e. a midspan meet
- WDM: wavelength division multiplexing; a technology
  - No standard
  - All WDM based systems are essentially proprietary although they generally follow the SONET hierarchy

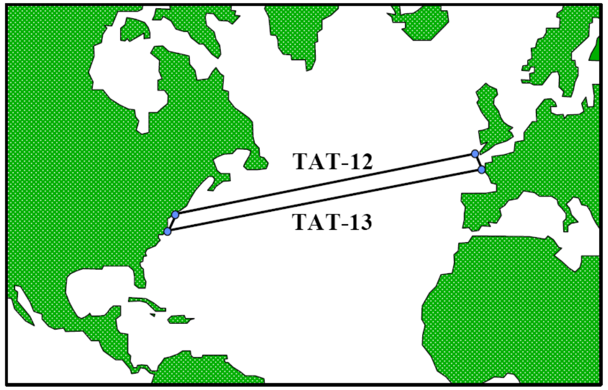
OTN: aka Digital Wrapper

Specifications	OTU1	OTU2	OTU3	OTU4
Line rate (Gbps)	2.666	10.709	43.018	111.809
Payload Rate (Gbps)	2.488	10.037	40.150	104.794
Frame period (µs)	48.971	12.191	3.034	1.167
Frequency accuracy (ppm)	+/- 20	+/- 20	+/- 20	+/- 20
Application	It transports SONET OC-48 or SDH STM 16.	It transports OC-192, STM-64 or WAN PHY for 10GBase-W .	It transports OC-768, STM-256 ot 40 GB ETHERNET.	It transports 100 GB ETHERNET Signal.

- OTN (Optical Transport Network) standard that enables multiplexing of lower rate signals into higher rate links
  - Input signals are the client optical signals
  - Functions include multiplexing, transport, switching, management, supervision, survivability etc.
  - Defined in ITU-T G.709 standard
  - Uses WDM (Wavelength Division Multiplexing) unlike SDH/SONET

TAT

First transatlantic cable: 1858
First telephone:1876

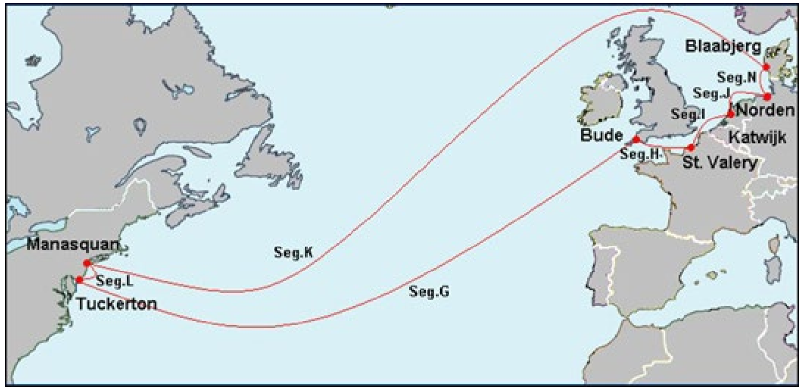


- TAT-8: Transatlantic Telephone (1988)
  - First fiber optic transatlantic cable
  - Eight fibers
  - Capacity of 40,000 telephone calls
  - each pair of fibers carries 560Mb/s.
- TAT-9 and TAT-10 (1992)
  - 80,000 voice circuits
- TAT-11
  - 7,162 km from Manahawkin, New Jersey to a location 600 miles from both Ireland and France where it splits and continues to Swansea, in the U,K, and St. Hilaire in France
- TAT-12/13 (1996)
  - 12,400 km total
  - first to use EDFAs
  - forms a ring of undersea segments connecting stations in Green Hill, Rhode Island; Lands End, England; Penmarch, France; and Shirley, New York.
  - Green Hill to Lands End is 5,913 km long.
  - One segment has 133 EDFAs spaced 45 km
  - Every fiber has a backup for restoration service
- Reference distance
  - Earth circumference 40,075 km (24,901.5 miles)
  - NY to LA ~4000km
  - Atl to Seattle 3500km (2200 miles)
  - NY to London 5572 km (3500 miles)
  - LA to Tokyo ~9,000km

http://www.atlantic-cable.com/

Trans Atlantic Cable systems

System	19xx		cost	circuits	$/circuit
TAT-1	56	C	$49.6M	40	213,996
TAT-2	59	C	42.7M	44	167,308
TAT-3	63	C	50.6M	79	111,027
TAT-4	65	C	50.4M	62	140,238
TAT-5	70	C	70.4M	648	18,773
TAT-6	76	C	197.0M	3,200	10,638
TAT-7	83	C	180.0M	3,821	8,139
TAT-8	88	F	360.0M	6,048	10,285
TAT-9	92	F	406.0M	10,584	6,628
TAT-10	92	F	300.0M	18,144	2,857
TAT-11	93	F	280.0M	18,144	2,667
TAT-12	96	F	378.0M	60,480	1,080
TAT-13	96	F	378.0M	60,480	1,080
Gemini	98	F	520.0M	214,920	371
AC-1	98	F	850.0M	483,840	304
TAT-14	00	F	1500.0M	4x2.5M	<75

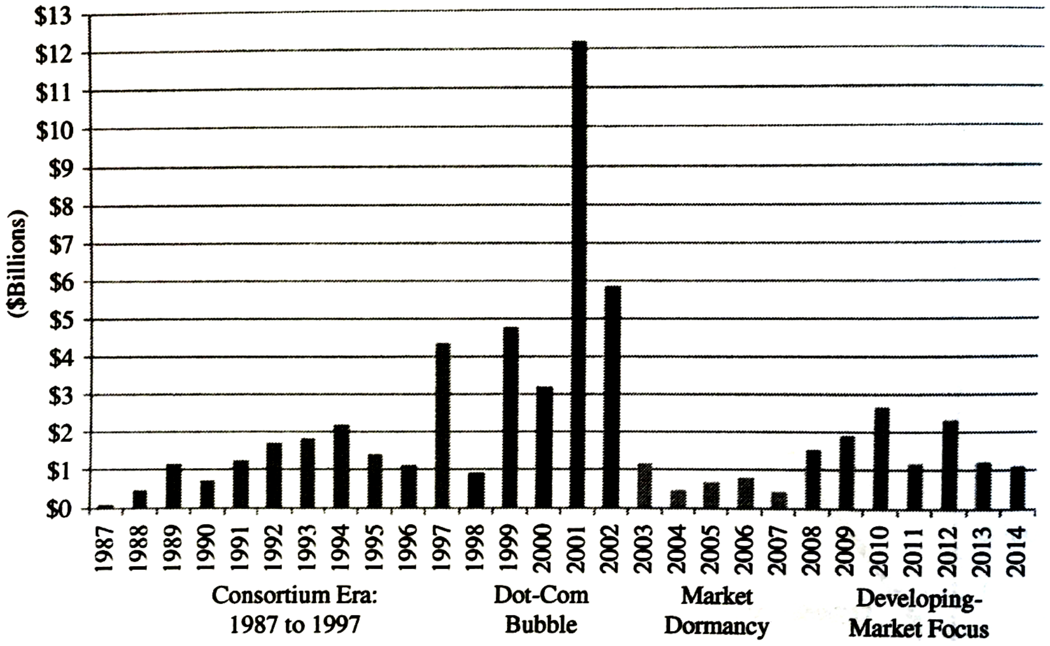


16λ @10Gbps DWDM, 4 fiber pairs
2 active fiber pairs, two backup
Self healing ring (SHR) topology
1.87Tbps total capacity,
Upgraded in 2012 to 40Gbps/λ

Ref: 1) Henning Schulzrinne Columbia University, New York
2) Submarinenetworks.com

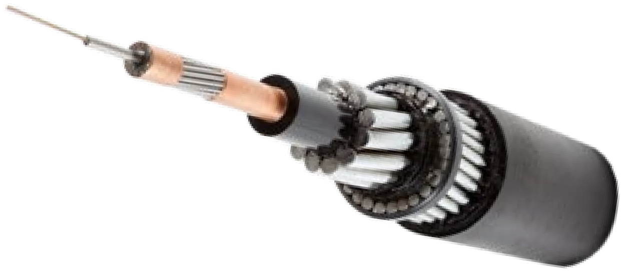
Submarine (aka Subsea) Systems

- EDFA
  - Deployed in 1994 and 95 commissioned in 1996 (decision in 1990) for TAT12-13 and later TPC5, 5Gbps per fiber using single lamda
  - All deployed since have used EDFA
  - All non EDFA systems have been decommissioned
  - WDM in 1999 SEA-ME-WE
  - 2001 100λ@10Gbps
- Telecom bubble burst: same technology until 2007
  - Wholesale restructuring of business
  - Not a single transatlantic cable deployed from 2002 to 2015
- Coherent
  - Deployed in 2010 and 2011 as an upgrade to existing systems
  - Deployed in 2012 as 100x100G on greenfield systems with large +D fiber



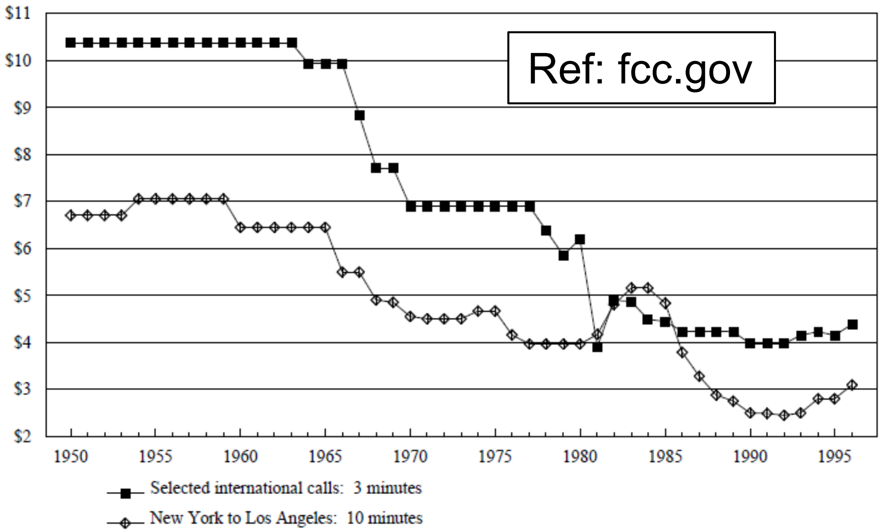
Unity

- Trans-Pacific submarine communications cable between Japan and the United States which was completed in April 2010
- Funded by a consortium; Bharti Airtel, Global Transit, Google, KDDI Corporation, Pacnet and SingTel
- Installation cost ~USD $300 million
- Five fiber pairs, each fiber pair capable of carrying up to 960 Gigabits per second
- 9,620 Km
- Design Capacity:
  - 7.68 Tbps
  - Eight optical fiber pairs, each operating at 96x10 Gbps DWDM
  - Initially 5 fiber pairs “lit”



Economics of TAT systems

- TAT 12 and 13
  - $750M installation in 1996
  - Capacity: 300,000 voice circuits
  - $1 per minute revenue per call (for this part of the link) for 1996 regulated markets
  - Generates $18M per hour (at full capacity)
  - Recovers installation cost in <2 days
  - Remaining income $430M per day (minus operating cost) is profit
  - Allowing for only 10% average capacity still yields good business case
  - Note: limited number of service providers allows non competitive pricing. Competitive pricing would support ~$0.02 per minute



Plane Waves (Review)

- The wave equation for linear media
  - Linear means that the material parameters, ε and μ, do not depend on the field E
  - We have also ignored a term proportional to $\nabla\varepsilon / \varepsilon$
  - The units are Volts/m^3

$$\nabla^2 \vec{E} = \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2}$$

- The solution to the wave equation is (by separation of variables)

$$\psi(r,t) = \psi_o(r)\phi(t) = \psi_o e^{-ik\bullet r} e^{i\omega t} + cc$$

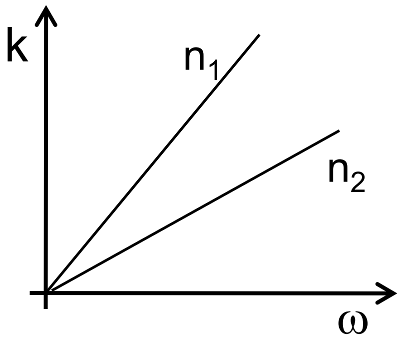
ψ_o is the amplitude

k is the wavevector or spatial frequency [1/cm]

ω is the angular frequency [1/s]

$$|k| = \omega\sqrt{\mu\varepsilon}$$

Plane Wave Dispersion
Slope = n/c



$n_2 < n_1$ and $n \neq n(\omega)$

- There is a relationship between the spatial and angular frequencies and that relationship depends on the properties of the medium
  - Direction of **k** is the direction of propagation
  - Recognizing that $1/\sqrt{\mu_o\varepsilon_o} = c$ lets us write
    $k = \omega/(c/n)$ and $k = 2\pi/(\lambda/n)$
  - Where $n = \sqrt{\varepsilon_r}$