Fiber Optic Communications

Lecture 1

Stephen E. Ralph

Spring 2026
CoC 53

34694	ECE 6543 A	Fiber Optic Networks	M,W 0800-0915	College of Computing	53

ECE 6543

Meeting Time and Place:

M-W 8:00-9:15pm

Instructor:

Stephen E. Ralph

Office: TSRB 505

Office Hours: by appointment

Email: stephen.ralph@ece.gatech.edu

Phone: 404.894.5268

Course objectives:

This course will provide a framework to understand the performance and design aspects of fiber-optic communications networks, components and technologies and the impact on network and Data Center architectures

Course Prerequisite:

Graduate standing. An undergraduate understanding of optics, electromagnetics and semiconductor devices is expected.

Course Material

- Text: Shiva Kumar and M. Jamal Deen, Fiber Optic Communications: Fundamentals and Applications ISBN: 978-0-470-51867-0
- References
  - Agrawal, Fiber-Optic Communication Systems
  - Proakis, Digital Communications
  - Barry, Lee and Messerschmitt, Digital Communications
- Homework
  - One assignment per two weeks, 5-8 problems, all problems completed in class on board, random person per problem
- Course Credit: 3-0-3 semester hours
- Grading:
  - Class participation and HW 20%
  - Exams 1 and 2: 20%
  - Project and presentation: 20%
  - Final: 20%
- Cell Phones: No Cell Phones allowed
- Honor Code: The Institute Student Honor Code is printed in the Georgia Tech General Catalog. http://www.honor.gatech.edu/
- Disability Services
  - (404)894-2563 or http://disabilityservices.gatech.edu/

Kumar and Deen

Fiber Optic Communications

Optical Interconnects

1) Drivers of Optical Interconnect in Data Centers

- **Bandwidth Growth**: AI/ML workloads and cloud services demand **400G** → **800G** → **1.6T** links
- **Energy Efficiency**: Optical links reduce power compared to copper at high speeds and long reaches
- **Latency & Density**: Optics enable low-latency, high-density interconnects for rack-to-rack and chip-to-chip

2) Key Technologies

a) Pluggable Optics

- **Current Standard**: QSFP-DD and OSFP modules dominate for 400G/800G Ethernet
- **Trend**: Moving toward **Linear Drive Optics (LDO)** to eliminate DSP in optics, reducing power and cost

b) Co-Packaged Optics (CPO)

- **Concept:** Integrating optics with switch ASICs to overcome electrical I/O bottlenecks
- **Status:** Early deployments expected around 2026–2027 for 51.2T switches
- **Challenges:** Thermal management, reliability, and interoperability

c) Silicon Photonics

- **Role:** Enables integration of lasers, modulators, and detectors on CMOS-compatible platforms
- **Advances:** PAM4 modulation at 100G per lane; work on coherent optics for >1 km reaches

d) Optical Engines

- **Linear Optics:** Simplified architectures for short-reach links
- **Coherent Engines:** Used for DCI (Data Center Interconnect) beyond 10 km, now moving to 400ZR/800ZR standards

3) **Modulation & Encoding**

- **PAM4:** Dominant for 400G/800G short-reach links
- **Coherent QPSK/16QAM:** For long-haul and metro DCI
- **Future:** Probable shift to probabilistic constellation shaping (PCS) for coherent links

4) **Packaging & Integration Trends**

- **Flip-chip bonding for photonic ICs**
- **Heterogeneous integration:** III-V lasers bonded to silicon photonics
- **Polymer waveguides for board-level optical routing**

5) **Challenges**

- **Power Consumption:** Even optics must meet strict energy budgets (<10 pJ/bit)
- **Thermal Management:** Especially for CPO and high-density optics
- **Cost & Yield:** Silicon photonics still faces yield challenges at scale

6) **Emerging Directions**

- **Optical Circuit Switching (OCS)** for AI clusters.
- **On-board optics** as an intermediate step before full CPO.
- **Integrated lasers** on silicon photonics for true monolithic solutions

Recent Literature

1) Co-Packaged Optics (CPO)

- **Wenchao Tian et al.**, “Progress in Research on Co-Packaged Optics”, *Micromachines*, 2024
  - Comprehensive review of CPO with VCSEL/silicon photonics, exploring 2D/2.5D/3D packaging, challenges, and future outlook in data-intensive environments. [mdpi.com], [pdfs.seman...cholar.org]
- **Min Tan et al., “Co-packaged optics (CPO): status, challenges, and solutions”, Frontiers in Optoelectronics, 2023**
  - Perspective paper analyzing bandwidth–power benefits of CPO, focusing on silicon photonics integration by major players (Intel, `Broadcom, IBM). [link.springer.com]
- **Tian et al., “Photonic Integrated Circuits: Research Advances and Challenges in Interconnection and Packaging Technologies”, Photonics, 2025**
  - Detailed review of silicon photonics packaging techniques, including fiber-to-chip coupling and co-packaged optics applications. [mdpi.com]
- **Eric Maniloff, “Design Tradeoffs for Coherent Pluggable Optics at 800G and Beyond”, OFC 2024 Technical Digest, 2024**
  - Technical paper discussing coherent optics scaling to 800 Gb/s in pluggable modules, analyzing trade-offs for different applications. [opg.optica.org]

2) Pluggable & Coherent Optics

- **Heavy Reading (Sterling Perrin), “Coherent Pluggable Optics: A 2023 Heavy Reading Survey” – Industry white paper**
  - Insights from operator surveys on 400 G/800 G coherent pluggables, IPoDWDM adoption, and roadmap benchmarking. [infinera.b...dfocus.com]
- **Sterling Perrin, “Coherent Optics at 400G, 800G, and Beyond”, Heavy Reading White Paper (2021)**
  - Foundational overview of coherent optics evolution in compact pluggables and embedded architectures. [cisco.com]
- **Sterling Perrin (Omdia), “Migrating to 800G coherent pluggable optics”, 2025**
  - Market analysis summarizing CSPs' planned deployments and timing for 800 G coherent optics. [lightreading.com]

Recent Literature

3) Silicon Photonics & Integrated Interconnects

- **Intel Labs,** "Intel Presents Latest Integrated Photonics Developments at 2024 Optical Fiber Conference", 2024
  - Highlights include a quantum-dot laser integrated with 300 mm silicon photonics and a packaged OCI chiplet for compute interconnects. [community.intel.com]
- **Columbia Univ. & Intel,** "Silicon Photonics Chip I/O for Ultra High-Bandwidth and Energy-Efficient Die-to-Die Connectivity", IEEE CICC 2024.
  - Introduces a DWDM SiPh transceiver targeting 2 Tbps/mm and sub-pJ/bit die-to-die links. [lightwave....lumbia.edu]

4) Market & Technical Trends

- **Introl blog "Fiber Optics for Data Centers: the state of the art in 2025", Apr 2026.**
  - Market insights on 800 G/1.6 T transceiver adoption, silicon photonics CPO in NVIDIA, and Google's optical circuit switching demos. [introl.com]
- **IDTechEx report via Signal Integrity Journal,** "Co-Packaged Optics (2025–2035): Technologies, Market, and Forecasts", May 2025.
  - Covers migration trajectory from pluggable → on-board → CPO, forecasting $1.2 B market by 2035. [signalinte...ournal.com

Important Dates

Monday	Jan 19	Martin Luther King Day
Tuesday	Feb 2	**Project outline due**
Weds	Feb 11	**Exam 1**
Wednesday	March 8	**Exam 2**
Mon-Fri	March 23- 27	Spring Break
Friday	April 6	Written **Project due**
Tuesday	April 27	**Final Class Day**
Friday	May 1	**Final** 8:00am to 10:50 am

Exam dates may shift plus or minus a lecture or two
Do not plan to be away

2025 Calendar United States

- Jan 1 New Year's Day
- Jan 19 Martin Luther King Jr. Day
- Feb 14 Valentine's Day
- Feb 16 Presidents' Day
- Mar 17 St. Patrick's Day
- Apr 5 Easter Sunday
- Apr 6 Easter Monday
- Apr 15 Tax Day
- May 10 Mother's Day
- May 25 Memorial Day
- Jun 14 Flag Day

January

Su	Mo	Tu	We	Th	Fr	Sa
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
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February

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March

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April

Su	Mo	Tu	We	Th	Fr	Sa
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May

Su	Mo	Tu	We	Th	Fr	Sa
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June

Su	Mo	Tu	We	Th	Fr	Sa
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30				

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SPIE Photonics West Jan 20-22

OFC: March 15-19

Silicon Photonics: April 13-15

CLEO 2026: May 17-21

Verification of participation Jan 27

https://www.timeanddate.com/calendar/?country=1

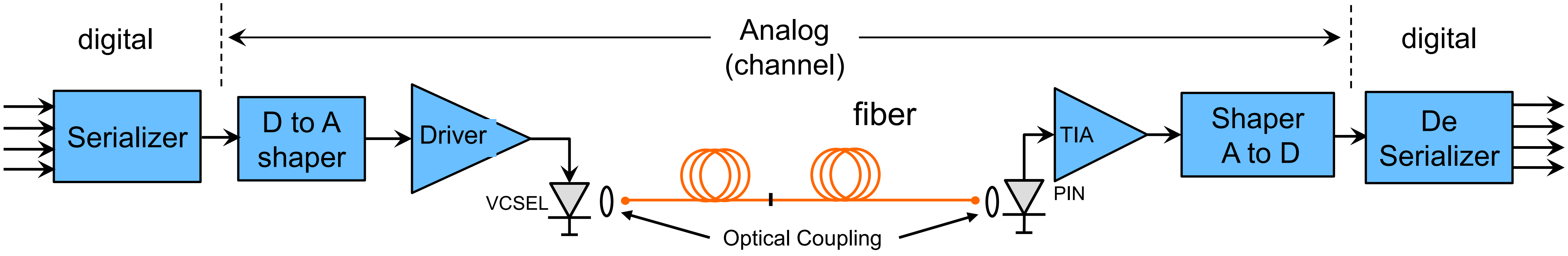
Homework 1

- Review basic E&M, Chapter 1 Kumar and Deen (31 pages)
  - Plane waves, relationships between wavelength, velocity, k-vector
  - Phase and group velocity, physical meaning and mathematical definition
  - Problems 1.9, 1.15

- Read Journal articles
  - Khoe; Lightwave Technology, Selec. Topics Quant. Elec, 2000
  - O'Mahony; Future Optical Networks, JLT V24, 2006

- Read Kumar and Deen Chapter 2.1 to 2.3

Impairments: Direct Modulation and Direct Detect



Tx
- Limited transmitter bandwidth
- Tx nonlinearity
- Driver and VCSEL
  - Finite extinction ratio (ER)

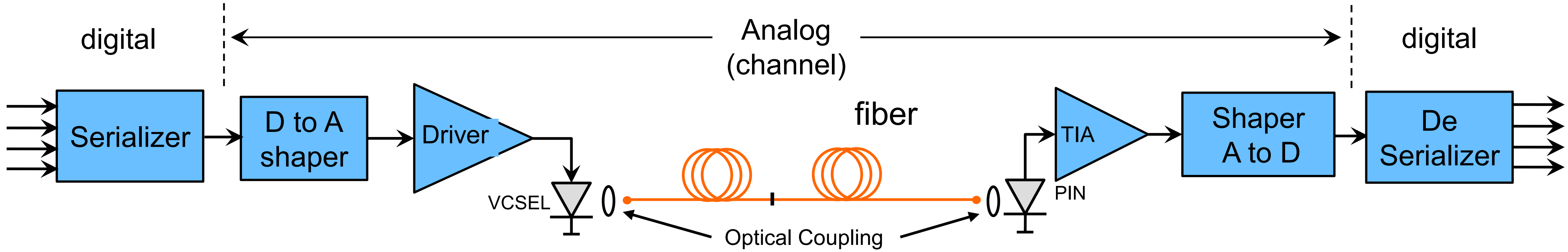
Fiber
- Attenuation
  - connector losses
- Chromatic Dispersion (CD)
  - Real signals have finite spectral content
- Modal dispersion (DMD)
- Multi-Path Interference (MPI)

Rx
- Limited receiver bandwidth
- Rx nonlinearity
- Baseline Wander
  - AC-coupling induces pattern dependent "dc" point

<u>Two most common optical links:</u>

VCSELs and MMF (short reach)
DFBs and SMF (long reach)

Noise: Direct Modulation and Direct Detect



Tx

- Electronic Noise
- Laser Relative Intensity Noise (RIN)
  - Random amplitude fluctuations at the output of VCSEL
- Multimode laser sources contribute to other noise effects

Fiber

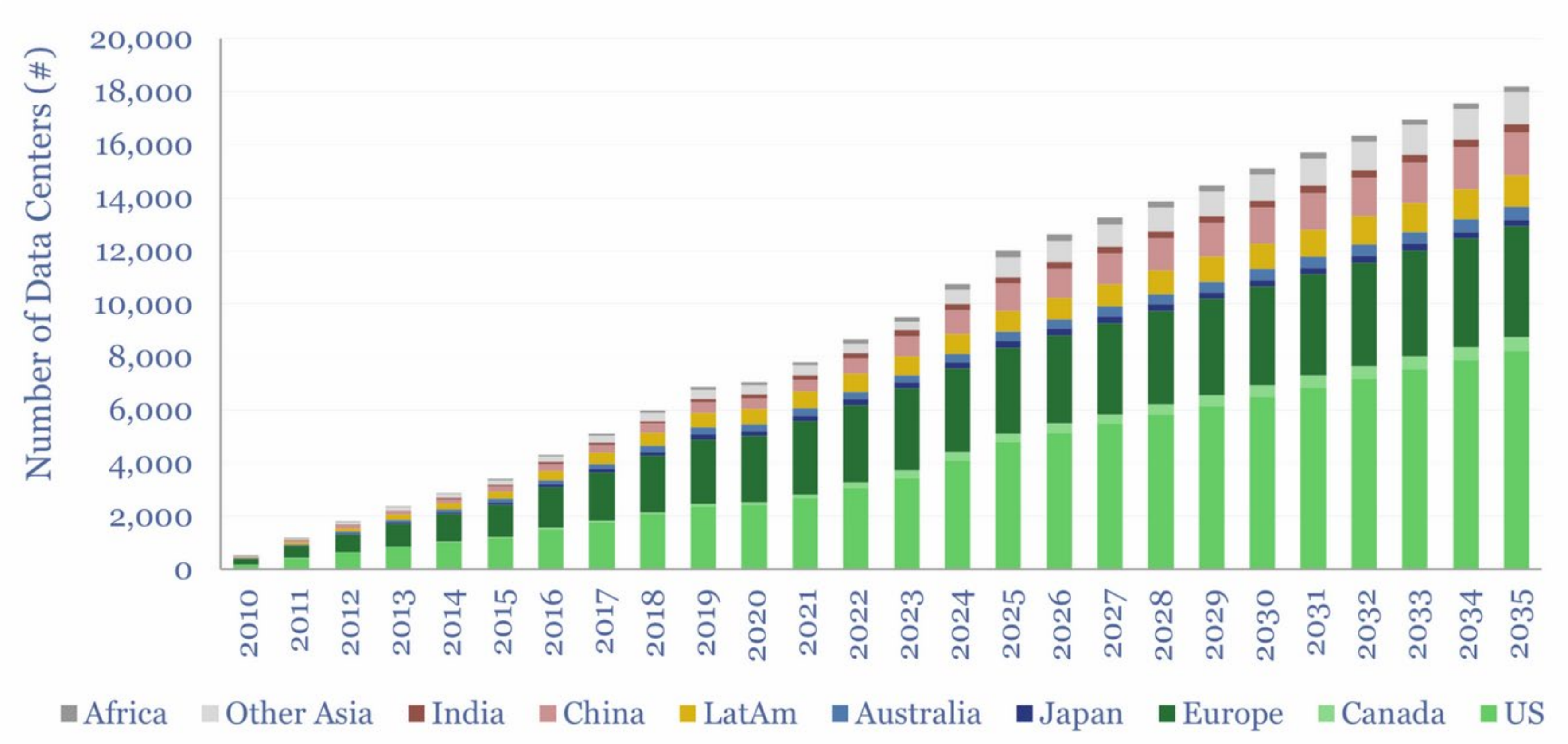
- In Multimode fiber some mechanisms induce noise
  - Mode partition noise (MPN)
    - Different fiber modes have different group velocity and multimode lasers have varying power among the laser modes resulting in timing noise
  - Modal noise (MN)
    - Different fiber modes have different attenuation (fiber DMA or connectors) resulting in amplitude noise

Rx

- Receiver noise
  - Thermal noise
  - Shot noise
- Jitter
  - Timing noise
- All noise is evaluated at the receiver

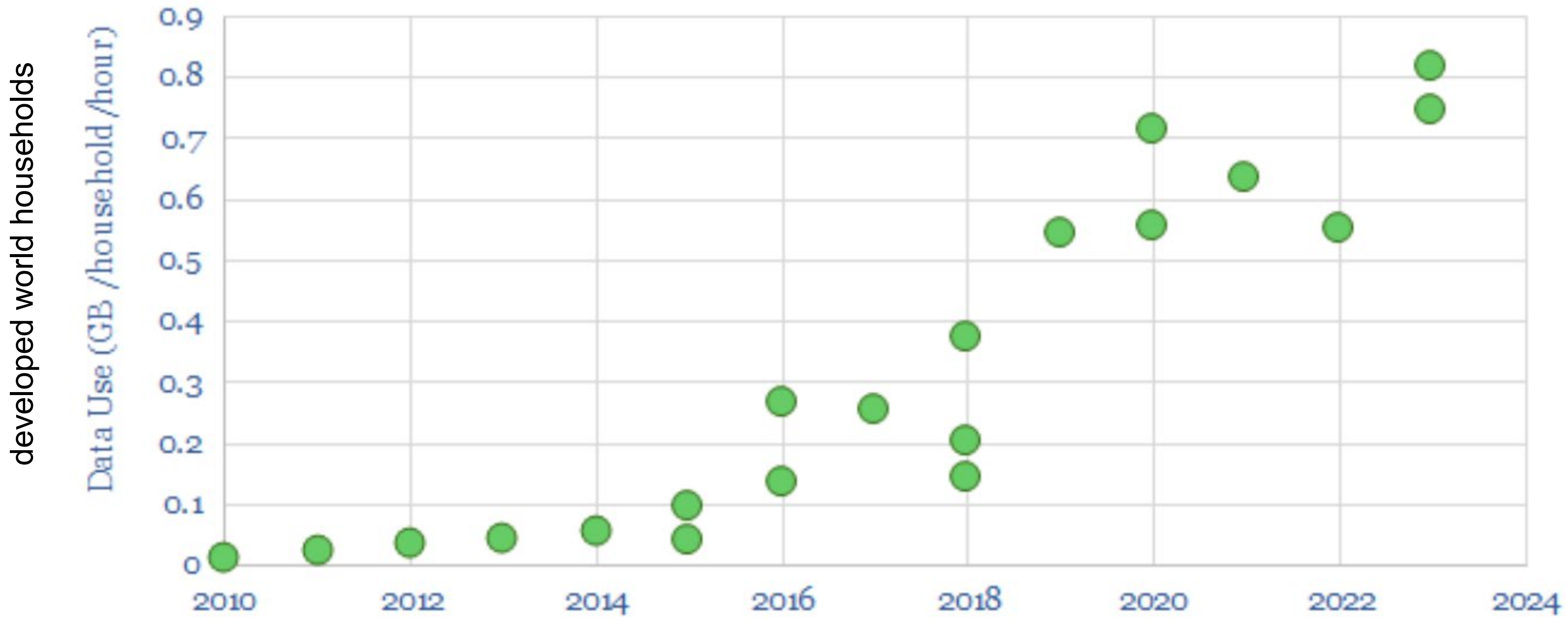
Industry Drivers and History

Data Centers



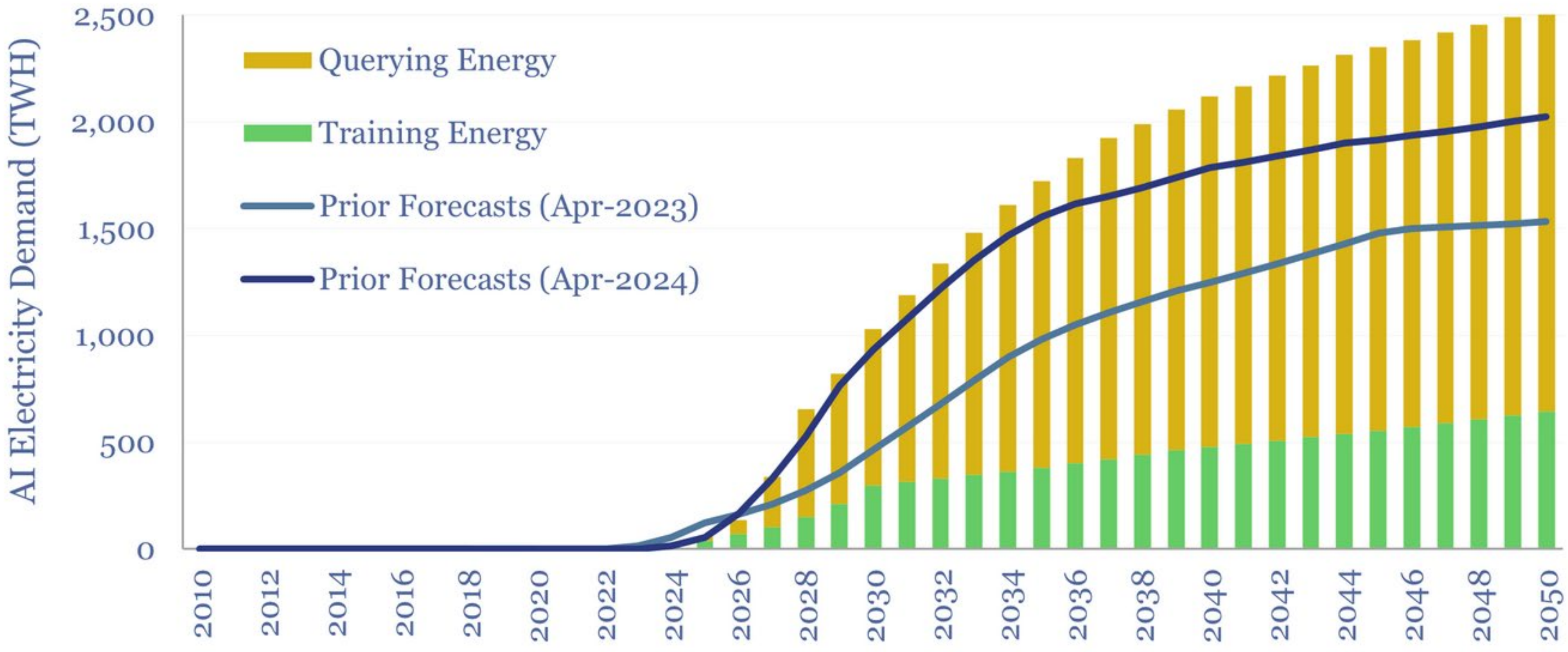
https://thundersaidenergy.com/downloads/internet-energy-consumpion-data-models-forecasts/

Internet traffic



- ***Internet traffic*** has been rising at a CAGR of 30%

Data Centers

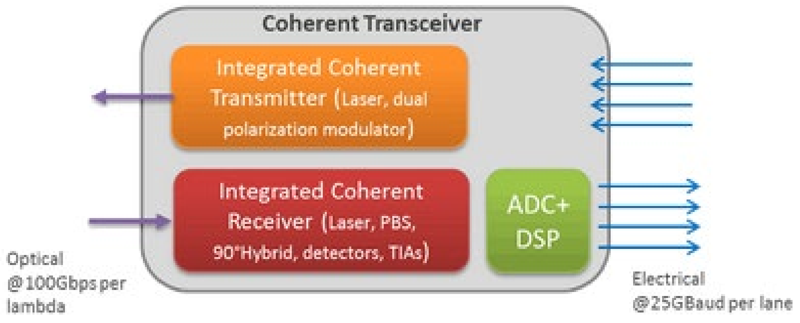


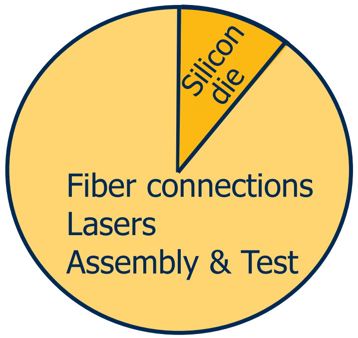
Estimate is that the internet accounted for 850 TWH of global electricity in 2024, which is 2.7% of all global electricity

Integrated Photonics – The Next Big Thing ~~in Telecom~~

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	CAGR
200G/400G Si photonics transceivers	$ 0	$ 0	$ 5	$ 21	$ 68	$ 142	$ 179	$ 257	$ 424	$ 559	95,9%
100G Si photonics transceivers	$ 191	$ 251	$ 475	$ 651	$ 900	$1 278	$1 448	$1 884	$2 401	$3 169	37,3%
40G Si photonics transceivers	$ 11	$ 9	$ 12	$ 9	$ 4	$ 0	$ 0	$ 0	$ 0	$ 0	0,0%

https://www.fibre-systems.com/news/analysis-opinion/silicon-photonics-beyond-hype-cycle





Silicon photonic circuit cost breakdown

- Integrated photonic systems are deployed for telecom
  - DSP inside the module
  - InP or Silicon Photonics with external laser
- Companies: Ciena, ~~Infinera~~, Acacia Communications, Neophotonics, Skorpios, IBM, HP, Intel, others
- Silicon photonics has progressed to a point roughly equivalent to silicon electronics circa 1980
  - 100's of individual photonic devices per die
- Viable commercialization depends on adaption of the silicon electronics fabless model for photonics
  - Development and validation of simulation tools: co-design tools for jointly optimizing photonic and electronic subsystems
  - Availability of photonic device foundries
  - Development of efficient assembly and test methods
    These infrastructure elements are advancing rapidly
  - System design
  - Signal processing (DSP) and co-simulation
  - Component design and Packaging

Data Scale

IP Traffic Term	Equivalent	How much is that?
1 Petabyte	1,000 Terabytes or 250,000 DVDs	**100 Petabytes** The amount of data produced in a single minute by the new particle collider at CERN. **400 Terabytes** A digital library of all books ever written in any language
1 Exabyte	1,000 Petabytes or 250 million DVDs	**5 Exabytes** A transcript of all words ever spoken **100 Exabytes** A video recording of the all the meetings that took place last year across the world **150 Exabytes** The amount of data that has traversed the Internet since its creation **175 Exabytes** The amount of data that will cross the Internet in 2010 alone
1 Zettabyte	1,000 Exabytes or 250 billion DVDs	**66 Zettabytes** The amount of visual information conveyed from the eyes to the brain of the entire human race in a single year
1 Yottabyte	1,000 Zettabytes or 250 trillion DVDs	**20 Yottabytes** A holographic snapshot of the earth's surface

Frame Rate (Hz)	24		48		60		120 (3D)	
Color Depth (bits)	24	48	24	48	24	48	24	48
Full HD 1080p (Gb/s)	1.19	2.39	2.39	4.78	2.99	5.97	5.97	11.94
Quad HD 2160p (Gb/s)	4.78	9.56	9.56	19.11	11.94	23.89	23.89	47.78

RAW Video Bit Rates

Data Scale

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Frame rate	24Hz		48Hz		60Hz		120Hz (3D)	
HDR Increase (color depth)	24	48	24	48	24	48	24	48
Today: Full HD 1080p	1.19 Gbps	2.39 Gbps	2.39 Gbps	4.78 Gbps	2.99 Gbps	5.97 Gbps	5.97 Gbps	11.94 Gbps
Tomorrow : Quad HD 2160p	4.78 Gbps	9.56 Gbps	9.56 Gbps	19.11 Gbps	11.94 Gbps	23.89 Gbps	23.89 Gbps	47.78 Gbps

Ultra High Definition TV

- 4k television 3840 x 2160
- Uncompressed signal requires:
  - 4 Gbps: 24Hz w/ 24bit
  - 45-68 Mbps compressed
  - Higher(lossy) compression 17 Mbps
- 8k television 7680 x 4320
  - with 22.2 channel audio
- Uncompressed signal requires:
  - 10Gbps: 24Hz w/ 24bit
  - 100Gbps: 120Hz w/ 48bit color
  - 100-500Mbps compressed

Resolution	Compressed Bit Rate (Mb/s)	Lossy, e.g. YouTube (Mb/s)
2160p	35 – 45	17.3
1440p	10	8.6
1080p	8	2.6
720p	5	1.5
480p	2.5	0.8
360p	1	0.4

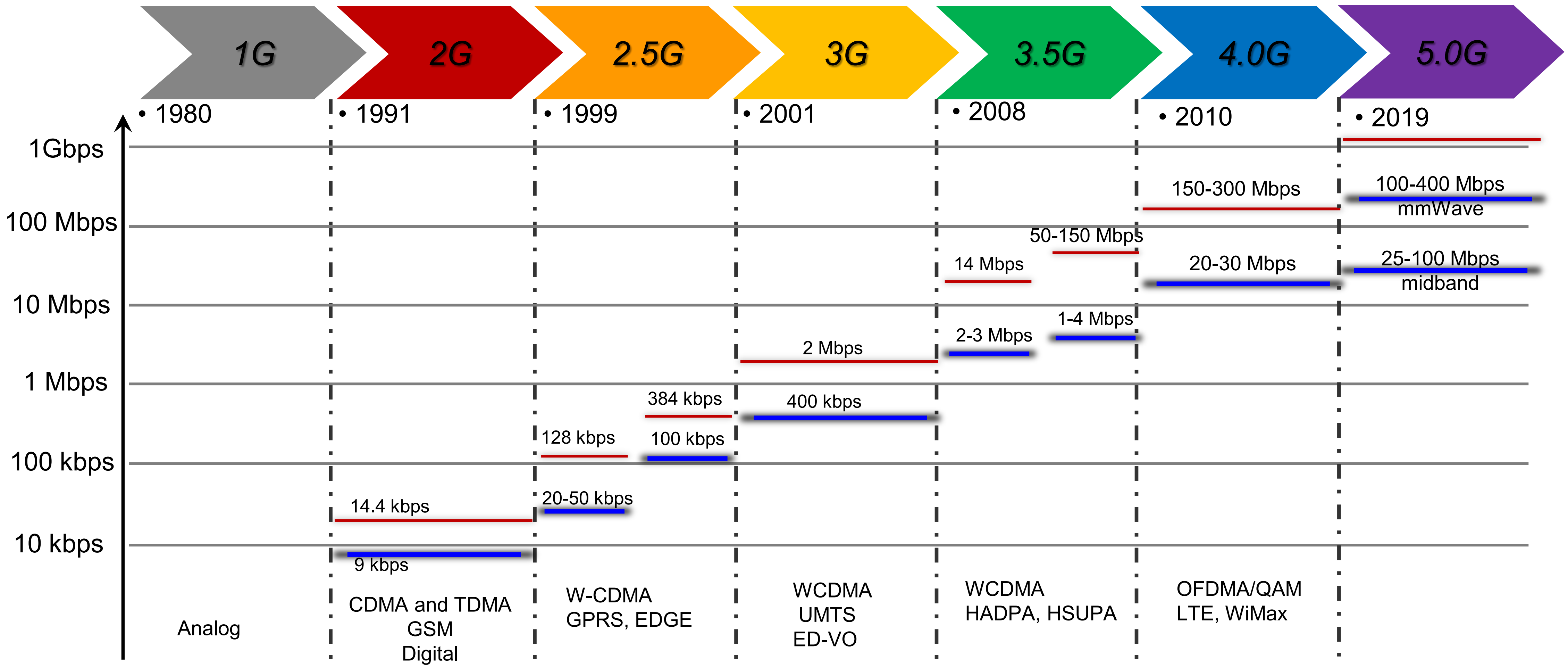
data rate = color depth × vertical resolution × horizontal resolution × refresh frequency

Gigabit-class broadband

- Gigabit Internet
  - Google
    - Google Fiber
    - $70 a month for 1G
  - ComCast
    - GigabitPro 2-gig; point to point fiber that leverages commercial grade equipment
    - Customers must live within one-third of a mile of its fiber network
    - 2-gigabit service in metro Atlanta at $299 a month, Installation fees that up to $1,000
  - ATT
    - Gigapower
    - 1 gigabit per second. Minimum $120/month for 1Gbps and $90/month for 100Mbps

- Underlying technology is GPON (or variant)
    - GPON: Gigabit Passive Optical Network
    - Tree topology with typically two levels; 1:64
    - Variants include use of multiple wavelengths: WDM
- Support for
  - 4K televisions
  - Download HD movies in seconds

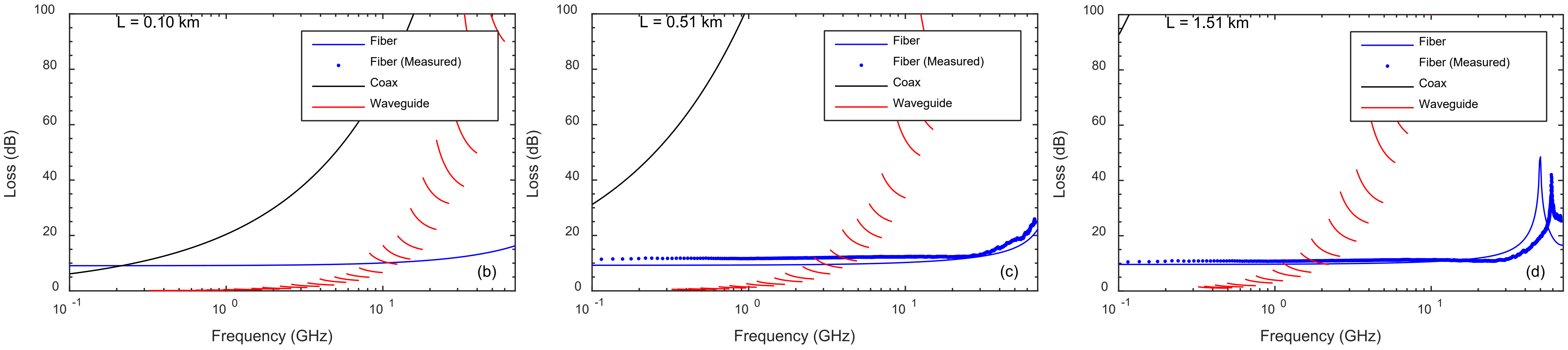
Mobile BroadBand Evolution



GSM: Global System for Mobile Communications
GPRS: General Packet Radio Service
EDGE: Enhanced Data Rates for GSM Evolution
EV-DO: Evolution Data Optimized
HSDPA: High-Speed Downlink Packet Access
HSUPA: High-Speed Up Packet Access
LTE: Long Term Evolution

TDMA: Time Division Multiple Access
W-CDMA: Wideband Code Division Multiple Access
TD-SCDMA: Time Division Synchronous Code Division Multiple Access

Why Use Photons for Communications?

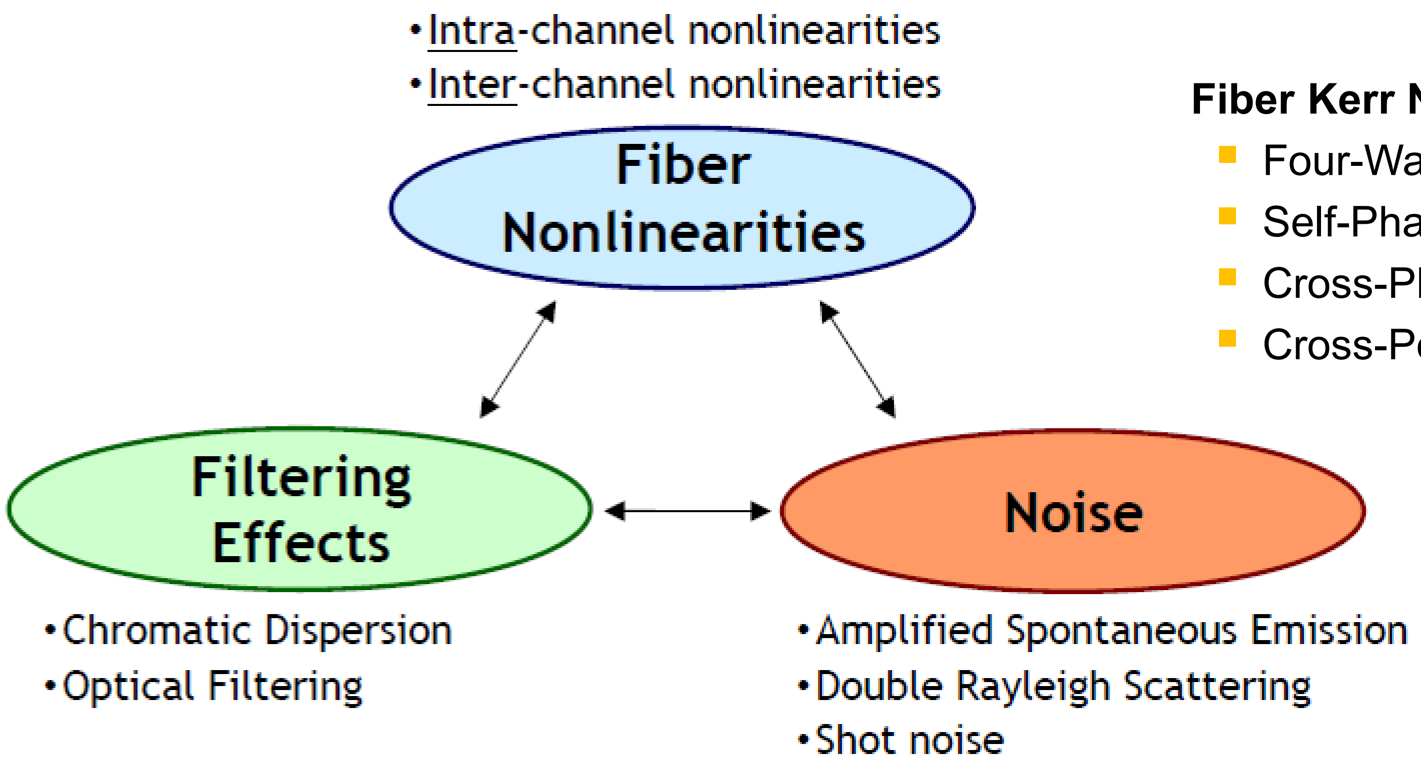


Comparison of analytical RF loss for fiber (blue), coaxial cabling (black), and RF waveguide (red) across a range of link distances from 100m to 1.5 km. For distances of 0.5 km, 1.5 km measurements were made of fiber link –shown as blue dots

- Disadvantages
  - Requires new transport media infrastructure
  - Fiber is more challenging to connect
- Electrical –Optical –Electrical –Conversion
  - Consumes power
  - Requires additional space
- Expensive

- Electrical channels have 10’s of GHz bandwidth

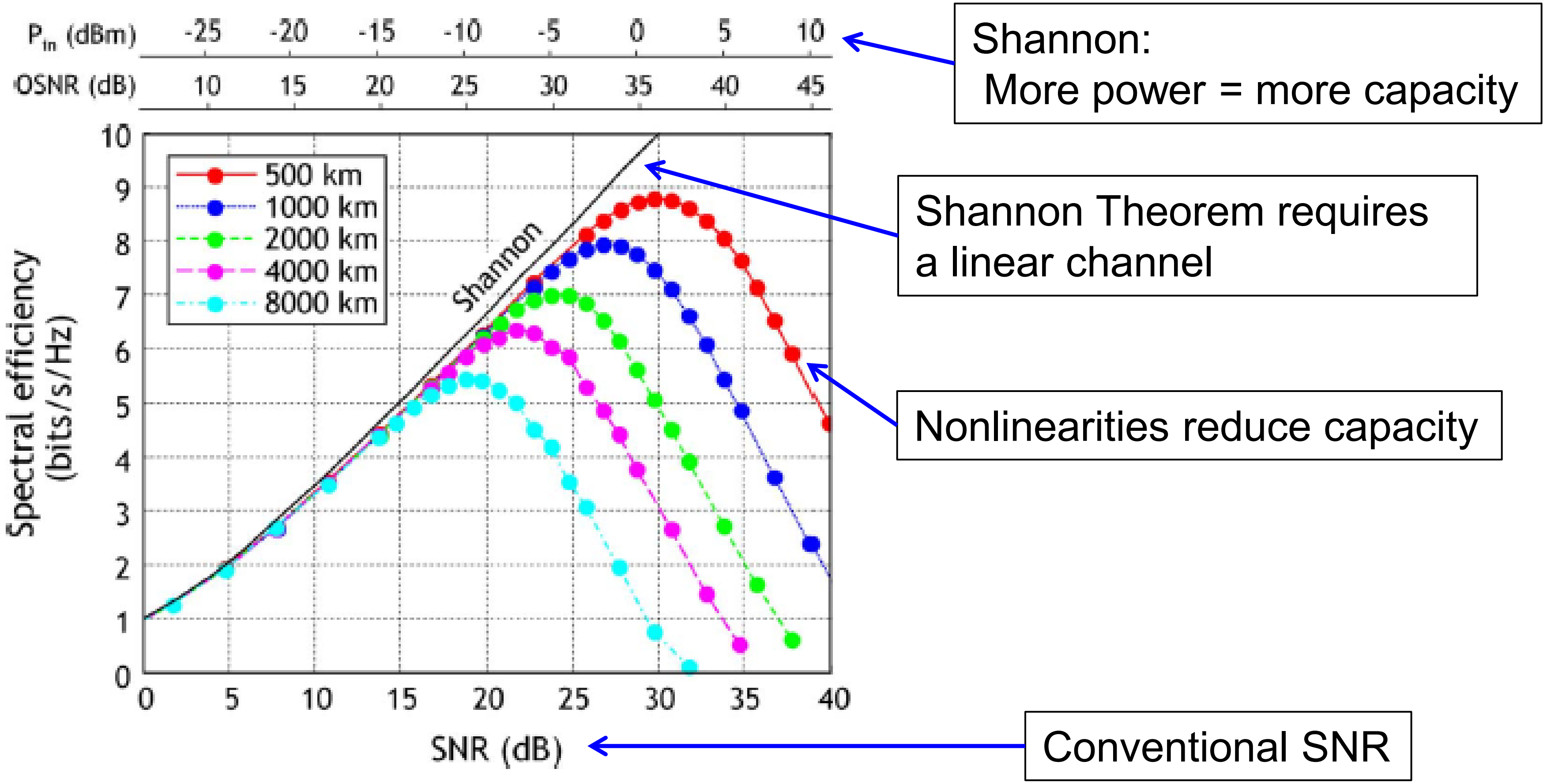
Physical Mechanisms



Fiber Kerr Nonlinearities
- Four-Wave Mixing
- Self-Phase Modulation
- Cross-Phase Modulation
- Cross-Pol Modulation

- Three phenomena are at play **simultaneously during propagation**
  - Each physical effect influences the other
  - Some phenomena are deterministic while others are stochastic
  - Nonlinear transmission over fibers is not simply a transfer function i.e. the channel is not described by simple additive noise

Nonlinear Fiber Channel



- Fiber capacity limited by signal-signal nonlinear impairments
- No dispersion compensation, 16 constellation rings

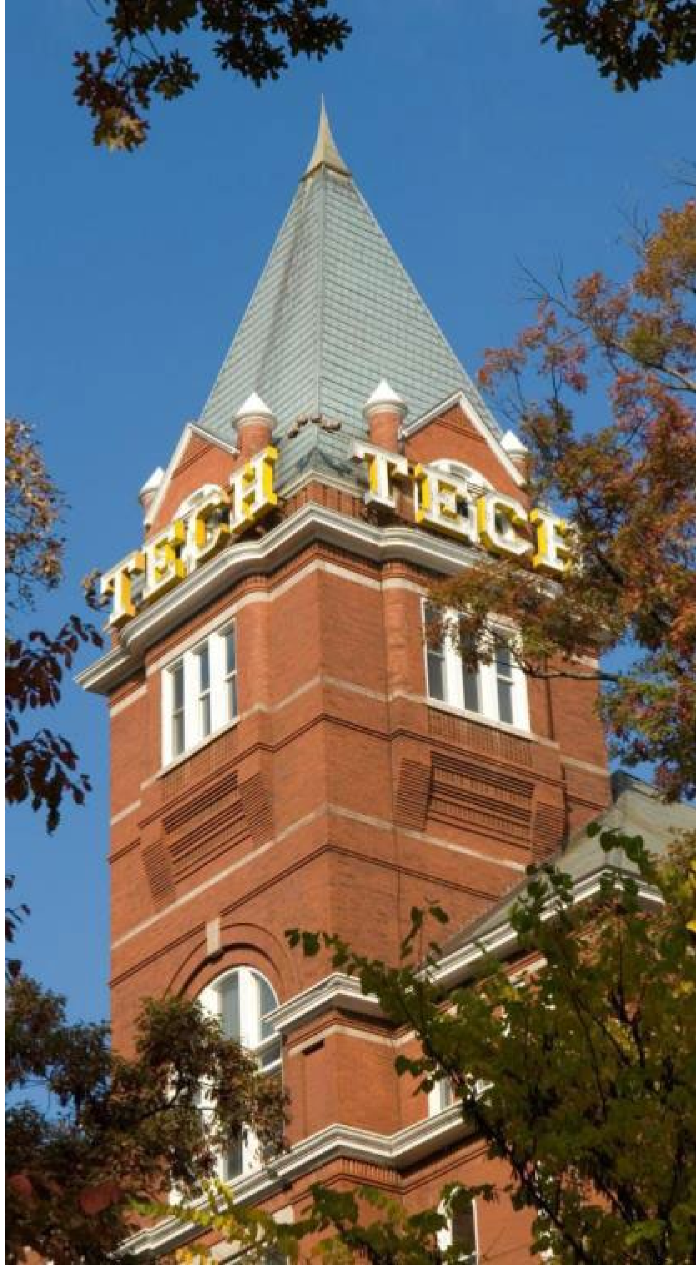
R.-J. Essiambre, et al., "Capacity Limits of Optical Fiber Networks," *Journ. of Lightwave Technol.*, Vol. 28, No. 4, Feb 2010

Progress in Lightwave Transmission Capacity

- Technologies for high-capacity systems
  - optical sources and **integration**
  - modulators/ **modulation formats and DSP**
  - **high-speed electronics** and ICs (central to deployment, increasingly important/challenging >10Gb/s)
  - optical filters, multiplexers/demultiplexers
  - optical add/drops, reconfigurable optical add drop multiplexer (ROADM)
  - discrete and distributed optical amplifiers with static and dynamic optical gain equalization filters
  - fibers and fiber properties
    - absorption
    - chromatic dispersion
    - nonlinearities
    - polarization mode dispersion
  - static and dynamic dispersion compensators (electrical and optical)
  - dispersion management techniques
  - receivers and integration
  - **coherent receivers and DSP**

A .R. Chraplyvy and R. W. Tkach, "Terabit/second transmission experiments," IEEE J. Quantum Electron. **34,** pp. 2103-2108, 1998.

Fiber Optic Technology and the Information Revolution: A Brief History

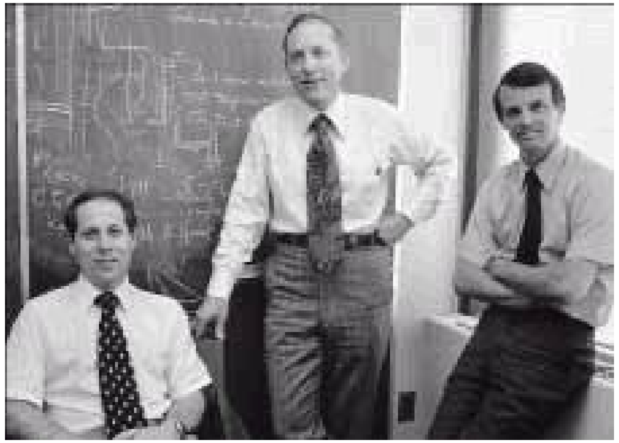


Fiber Optic Technology and the Information Revolution: A Brief History

- The **LASER**
  - 1959 – Gordon Gould, Columbia. Decades in patent dispute with Maiman
  - 1960 – Theodore Maiman, working at the Hughes Research Laboratories in Malibu, California, produced the first operating laser
  - 1962 – The first *laser diode* was demonstrated by Robert N. Hall
- **Fiber Optic Network**
  - 1965, First Fiber-Optic Data Transmission System, Manfred Börner, Telefunken Research Labs
- **Low-Loss Fiber**
  - 1965 - Low-loss fiber theory, Charles Kao, Standard Telephones and Cables (Nobel Prize in 2009)
  - 1972 – Don Keck of Corning Glass demonstrates 20 dB/km
  - 1977 – MasaharuHoriguchi, Nippon Telegraph and Telephone, demonstrates 0.2 dB/km
- The **Erbium-Doped Fiber Amplifier (EDFA)**
  - 1980s – H. J. Shaw and Michel Digonnet, Stanford University
  - 1987 – Commercially viable EDFA, Univ. of Southampton and ATT

Low-Loss Optical Fiber

- Attenuation is characterized on a logarithmic scale
  - Attenuation (dB)= 10 log(P1/P2), -10dB = 10%transmission, -3dB = 50%
- Conventional window glass is not very transparent
- Initial attempts at fiber production yielded 1000 dB/km
- 1966 Charles Kao and George Hockham at Standard Telecommunications Labs(then Nortel) determined attenuation of glass was largely caused by the presence of impurity metal ions, such as iron, copper, vanadium, and chromium



- 1970 Don Keck, Robert Maurer, and Peter Schultz at Corning Glass demonstrated fiber loss of 20 dB/km
  - 1975 4 dB/km
  - 1976 0.5 dB/km
  - 1979 0.2 dB/km
  - 10km @ 0.2 dB/km yields 63% transmission
  - Lowest loss requires reduction of hydroxyl ions
  - Low loss optical window is between 1.3 μm and 1.55 μm

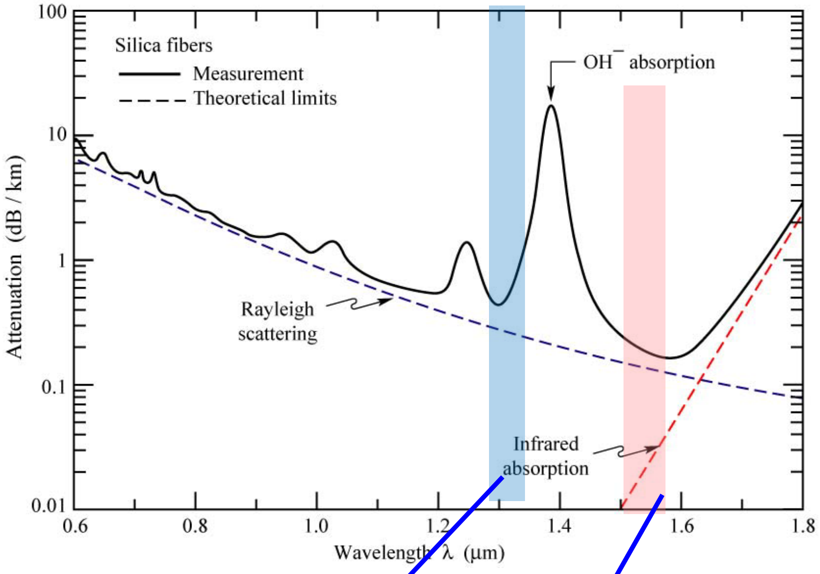
Glass Purity

Fiber Optic Communications Requires Very High Purity Glass

Window Glass	1 inch (~3 cm)
Optical Quality Glass	10 feet (~3 m)
Optical Fiber	9 miles (~14 km)

Propagation Distance Needed to Reduce the Transmitted Light Power by 50% (3 dB)

Attenuation in Glass



"**O-Band**" near 1300 nm
~0.5 dB/km

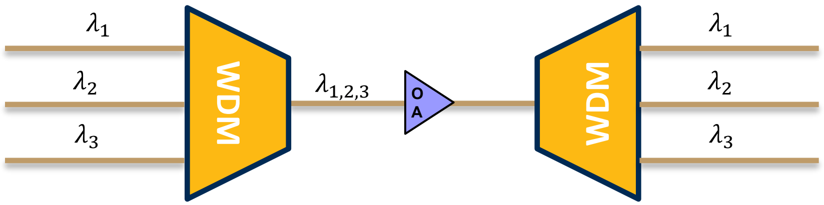
"**C-Band**" near 1500 nm
~0.2 dB/km

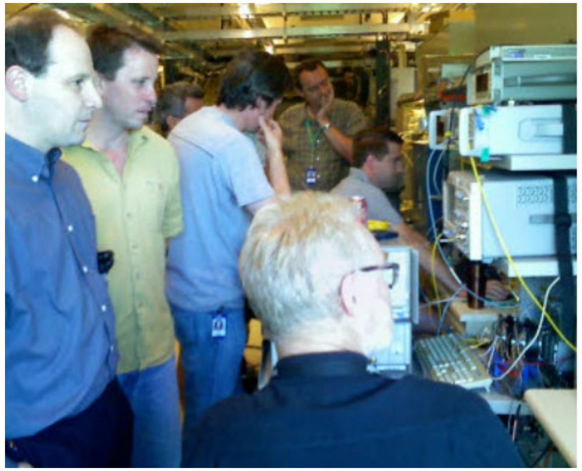
Medium	Propagation Distance for 3 dB
MegaPhase 230 Series RF @10GHz	4.2 meters
MegaPhase 520 Series RF @50GHz	0.6 meters
Optical Fiber	9 miles

- 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
- Carrier frequency ~200THz compared to cellular wireless systems (2 GHz)
- New Fiber Bandwidth 40THz
  - ~300nm; supports a pulse width of 0.011 ps
- 0.25 dB/km @1550nm
  - 100 dB: 1% transmitted after 400km
  - Typical links have 20 to 25dB loss
- Total available channels(analog) 40THz/4.0kHz = 100 billion
- The entire population of the Earth could be on the phone on a single fiber at the same time! Instead of an IP address you could have a wavelength or frequency permanently assigned
- Fiber has been manufactured worldwide at a rate of 2000 miles per hour

Fiber Optic Technology and the Information Revolution: A Brief History

- 1990s, Telecom exponential growth
  - Massive Infrastructure building
  - Wavelength Division Multiplexing (WDM) Technology





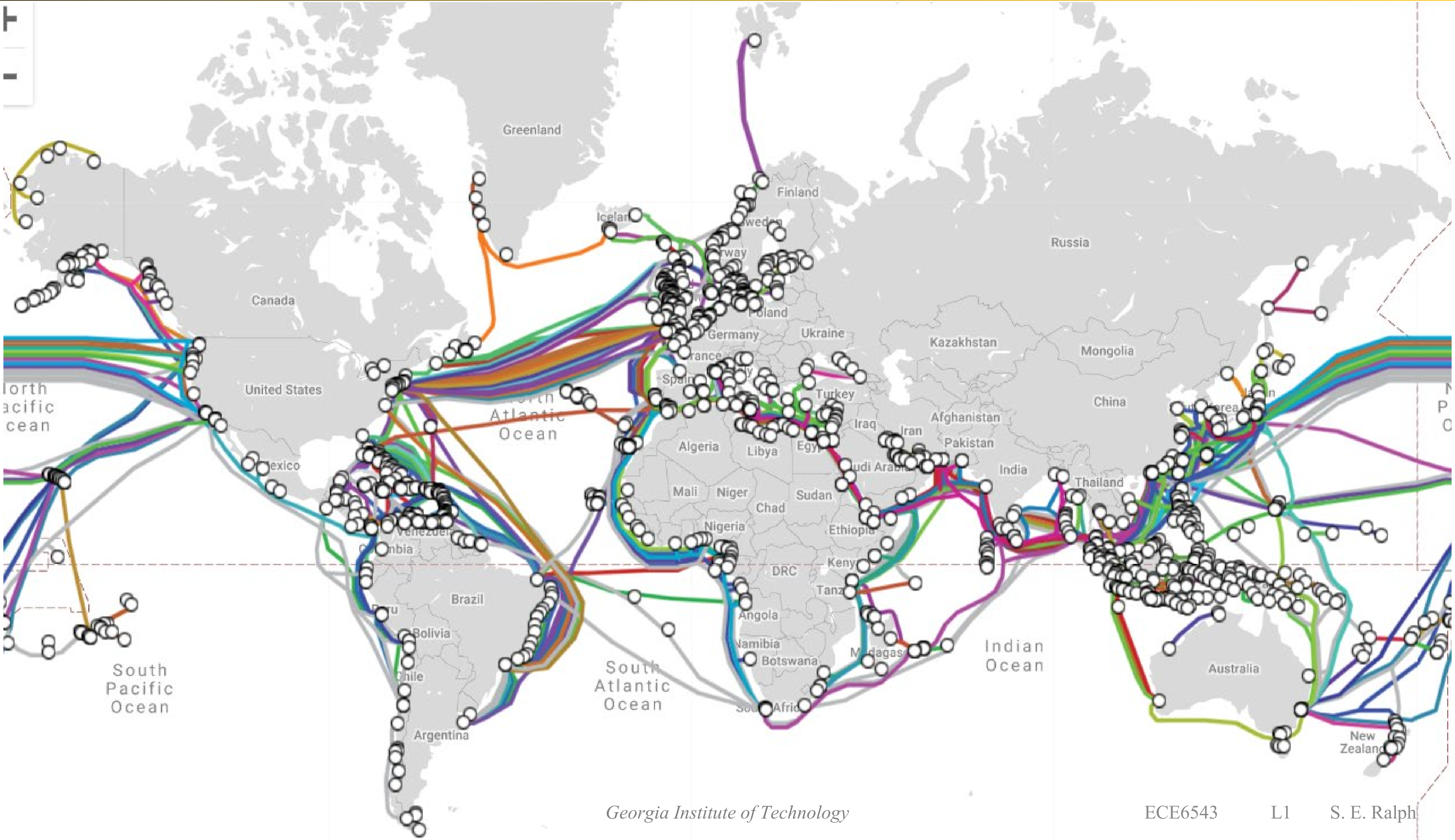
The team, led by Dino DiPerna (far left), watches in anticipation as testing of the first coherent 40G chip begins.

(Picture from our Ottawa R&D labs in 2005.)

- 2001-2002, Telecom crash due to overbuilding, vapor-IPOs
- 2009, Photonic Digital Coherent Receiver
  - Youtube/Netflix finally overran unused bandwidth from 2001
  - Complex modulations (beyond on off keying) required to get more capacity out of existing infrastructure

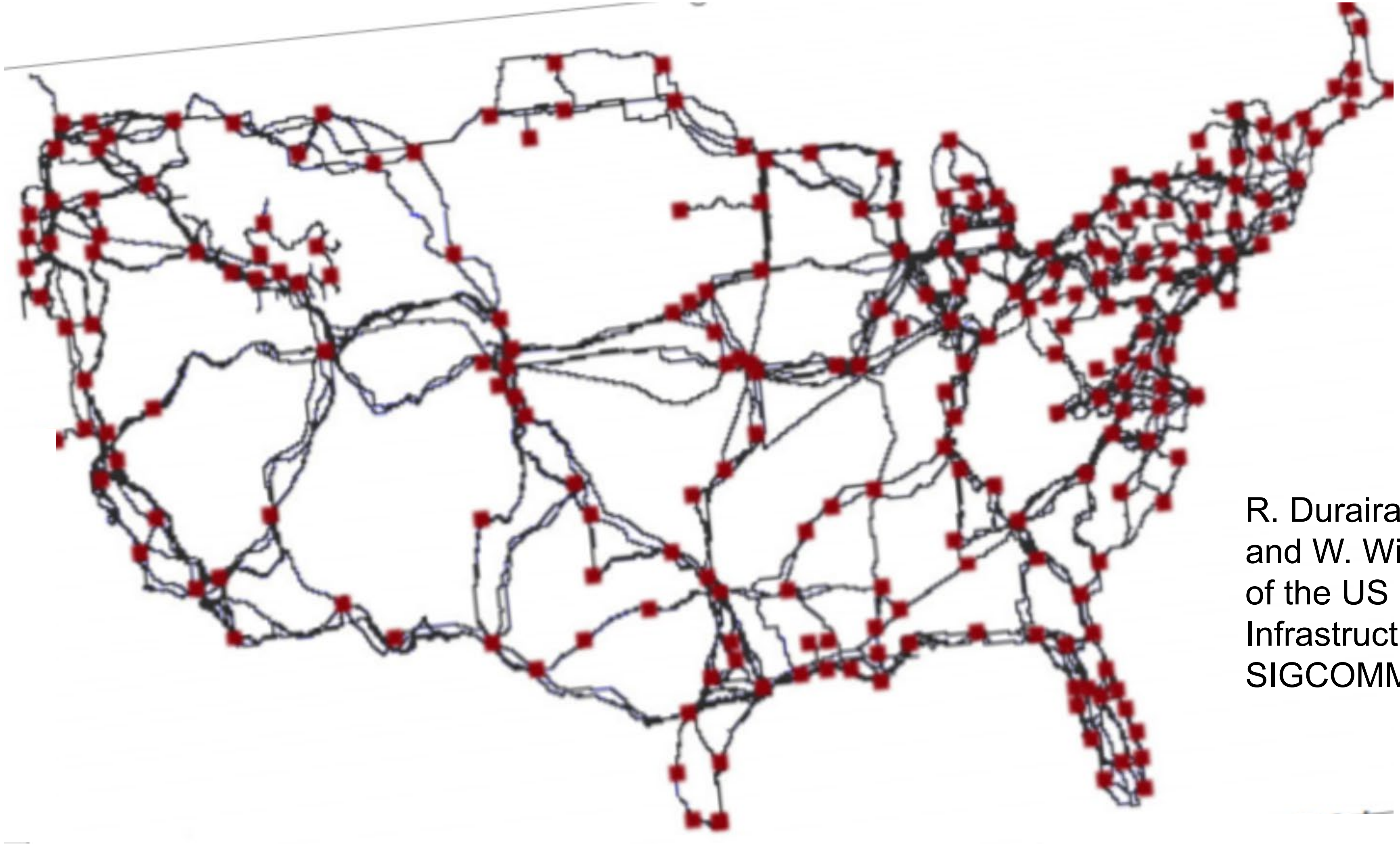
https://www.ciena.com/insights/articles/Coherent-optical-turns-10-Heres-how-it-was-made-prx.html

Undersea Fiber Optic Cables



Terrestrial Fiber Networks in Europe

Terrestrial Fiber Networks in United States



R. Durairajan, P. Barford, J. Sommers and W. Willinger. "InterTubes: A Study of the US Long-haul Fiber-optic Infrastructure", In Proceedings of ACM SIGCOMM, August 2015

Some Terminology

- Decibels (dB): relative measure
  - X dB is $10^{-X/10}$ in linear dimension e.g. 3 dB Attenuation = $10^{-.3} = 0.501$
  - For optical channels we always measure/quantify **power**
    - The power ratio represents loss or gain
    - Warning: in the electrical domain we use both voltage and power ratios
- Decibels milliwatt (dBm): Decibel referenced to a milliwatt
  - Y mW is $10 \times \log_{10}(Y)$ in dBm, X dBm is $10^{X/10}$ in mW
  - 0 dBm = 1mW, 17dBm = 50mW

dBm used for output power and receive sensitivity (Absolute Value)

dB used for power gain or loss (Relative Value)

Some Terminology

- Wavelength (λ): typically nanometers, 10^{-9} m (nm)
  - 300nm (blue) to 700nm (red) is visible
  - In fiber optics primarily use 850, 1310, & 1550nm
- Frequency (ν or f): Typically TeraHertz, 10^{12} cycles per second (THz)
  - Wavelength x frequency = Speed of light $\Rightarrow \lambda \times \nu = c$
  - 1550nm =>193 THz
- Energy (E): Typically electron volts (eV)
  - $E = h\,\nu$
  - h is Planck's constant
- Momentum (p)
  - $p = h\,k/2\pi = h\,\nu/c = h/\lambda$
  - k= wavevector

Some more terminology

- Attenuation = Loss of power in dB/km
  - The decrease in light intensity as it propagates

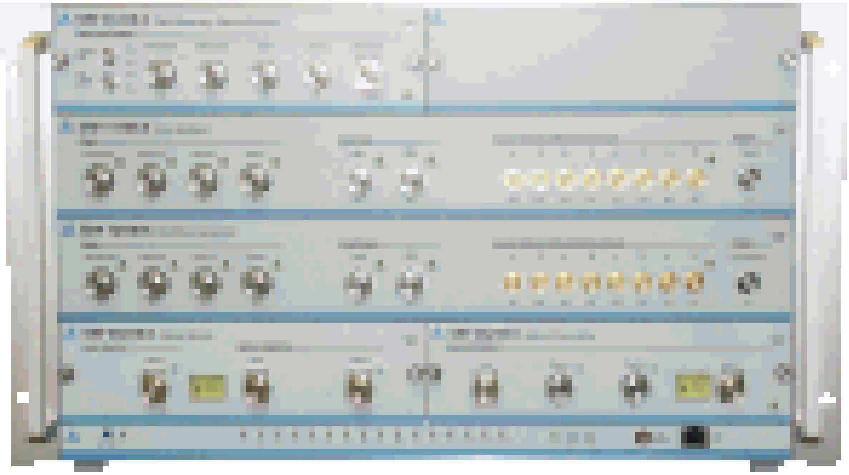
- ITU Grid
  - Standard set of wavelengths used in fiber optic communications
  - Unit GHz, e.g. 400GHz, 200GHz, 100GHz, 50GHz, 37.5GHz
  - Note: 100Gbps is readily transmitted within a 50GHz channel

- Optical Signal to Noise Ratio (OSNR)
  - Ratio of <u>optical</u> signal power to optical noise power
  - Bandwidth of optical signal must be specified
    - Typically 0.1nm

- Optical Supervisory Channel (OSC) = Management channel

Bit Error Ratio (BER)

- BER is a key objective of the Optical System Design
  - BER = # of Bit Errors / # of Bits Counted
  - Goal: detect bits with a BER < BER threshold Rx
  - Typical minimum acceptable rate is 10^{-12}



- Forward error correction provides 4-10 dB of effective coding gain
  - Forward error correction corrects a 10^{-3} error ratio to 10^{-15}
- Often (erroneously) called the Bit Error Rate
- Make the distinction between “raw” BER and “corrected” BER

Spectral Efficiency

- Capacity of an optical communications channel
  - maximum bit rate that can be transmitted without error
  - for a given noise, bandwidth and power
  - for a given noise N, average received signal power S. Both S and N are measured over bandwidth B

$$C = Blog_2\left(1 + \frac{S}{N}\right)$$

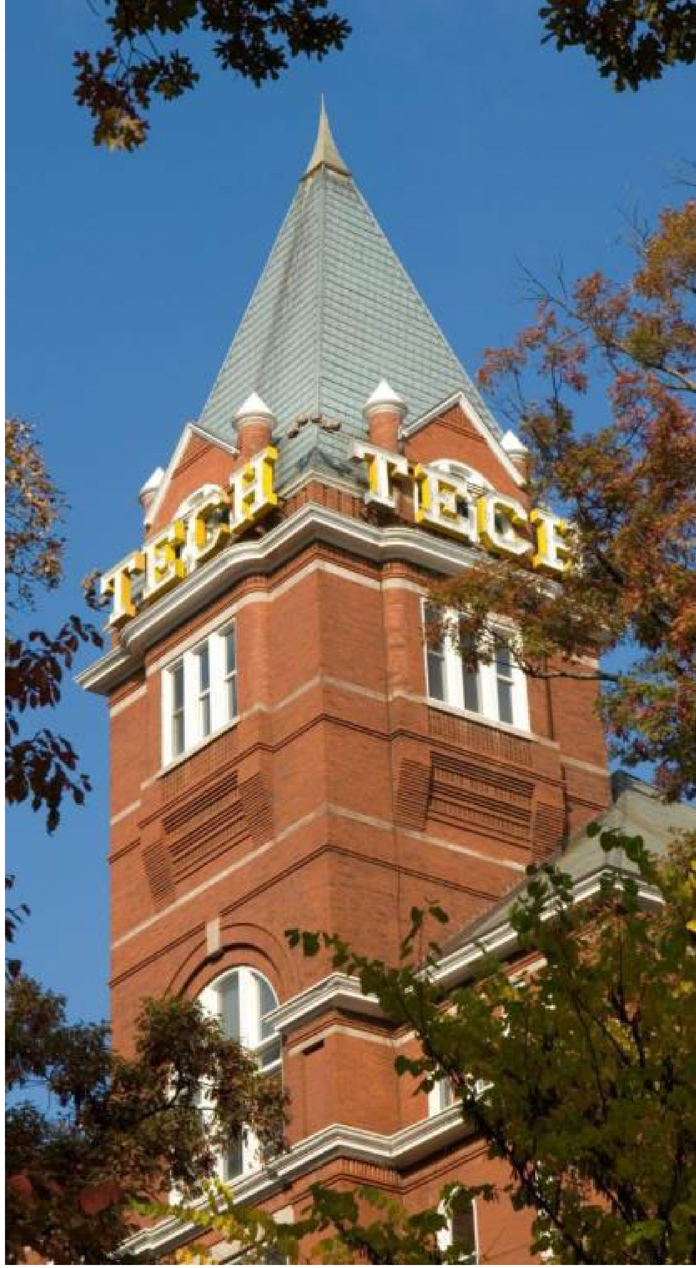
- Capacity will depend on
  - Modulation
  - coding

- High spectral efficiency is important for backbone systems
- For a WDM (Wavelength Division Multiplexed) optical communications system

$$Spectral\ Efficiency = \frac{Capacity\ Per\ Channel}{Channel\ Spacing} = \frac{C}{\Delta f}\left[\frac{b/s}{Hz}\right]$$

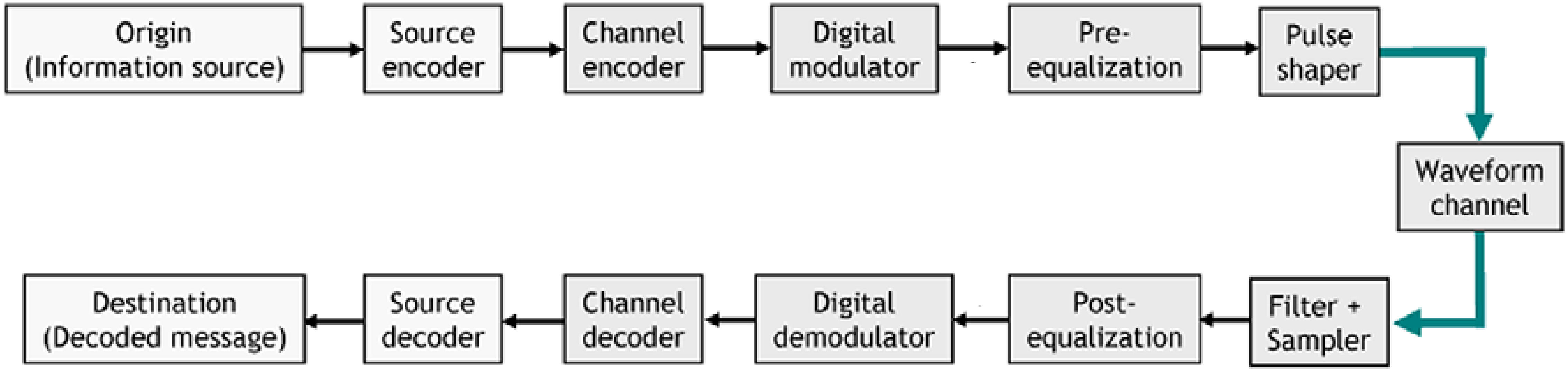
Per channel spacing, not spectral occupancy

Fiber Communication System Architecture



Basic Link Elements

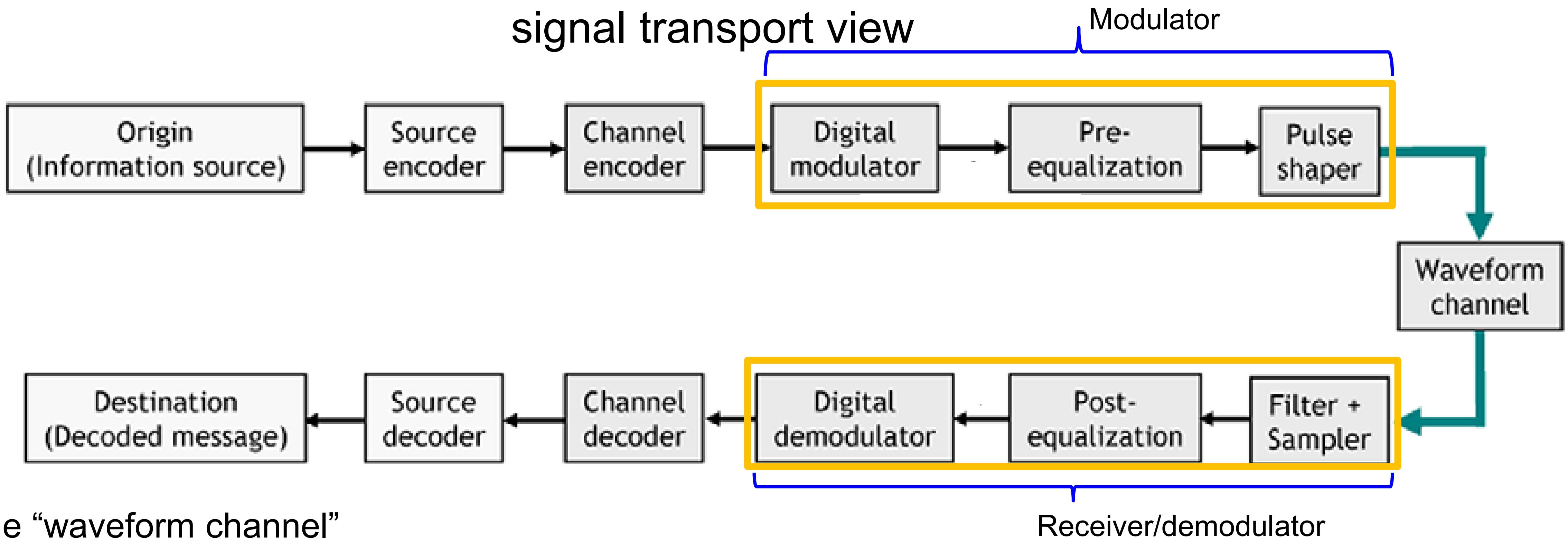
signal transport view



- 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

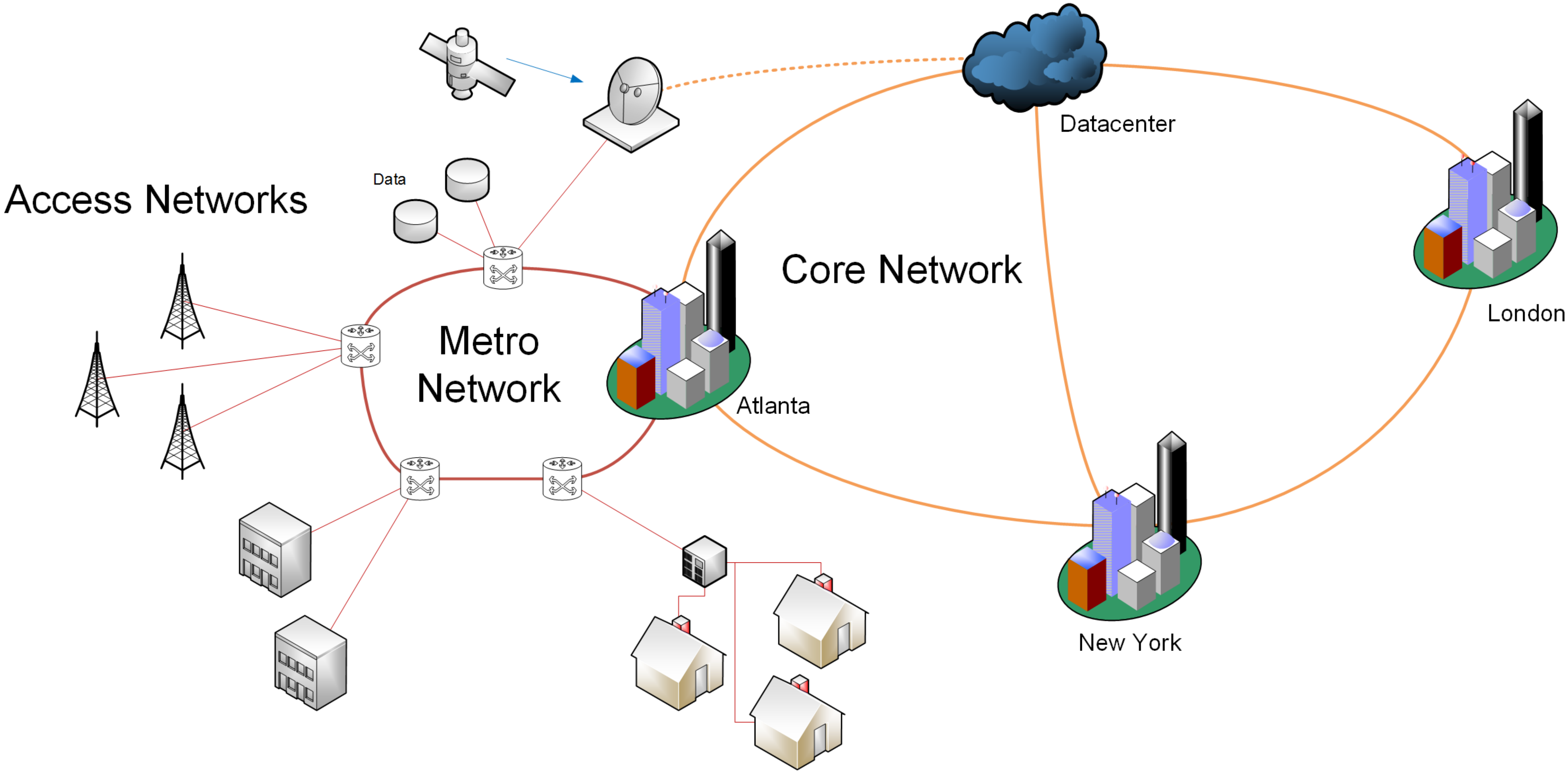
signal transport view



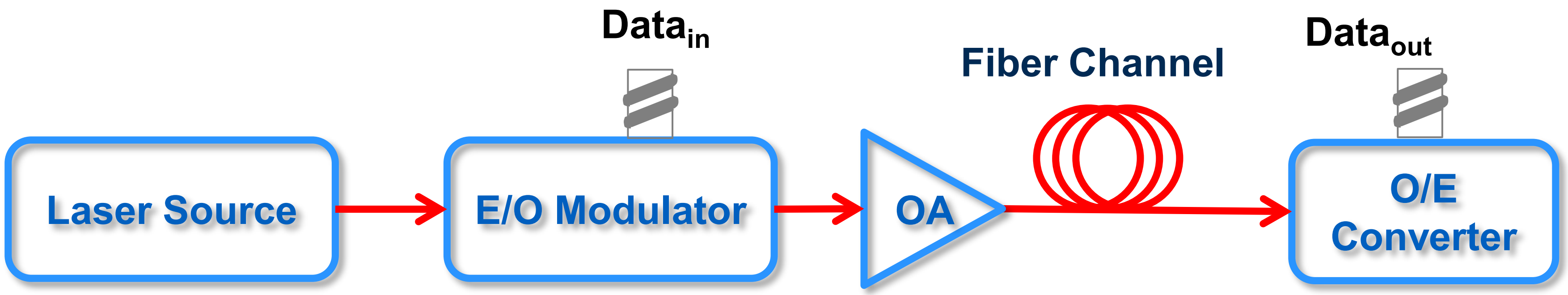
- The "waveform channel"
  - Signal is often viewed as continuous or analog in nature
  - Wired: twisted pair, coaxial cable, optical fiber
  - Wireless: air, vacuum
  - Complex transfer characteristic; loss and phase velocity are both functions of frequency
  - May have nonlinear (wrt intensity) response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



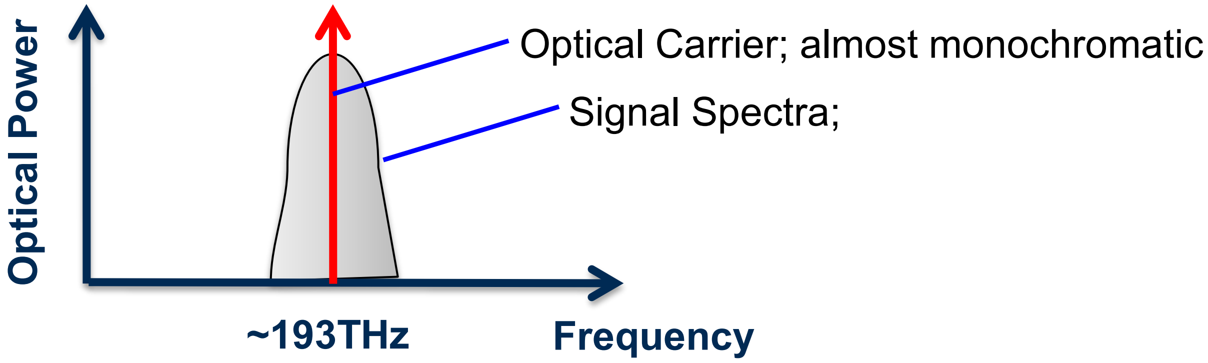
Laser:
Generates optical carrier

E/O Modulator:
Modulates Data onto optical carrier

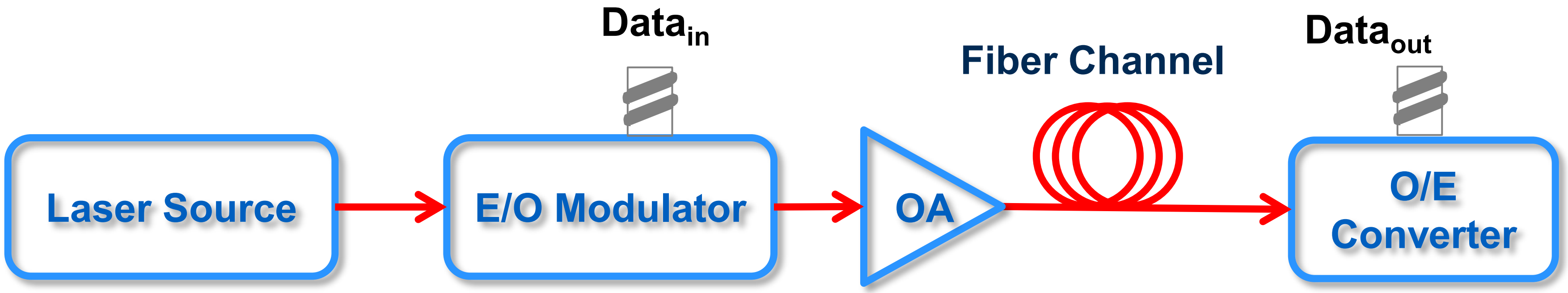
OA:
Optical Amplifier, gain

Optical Fiber

O/E Converter:
Photodiode



Disciplines Within Fiber Communications



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

- 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