Where Next for Fiber Capacity?

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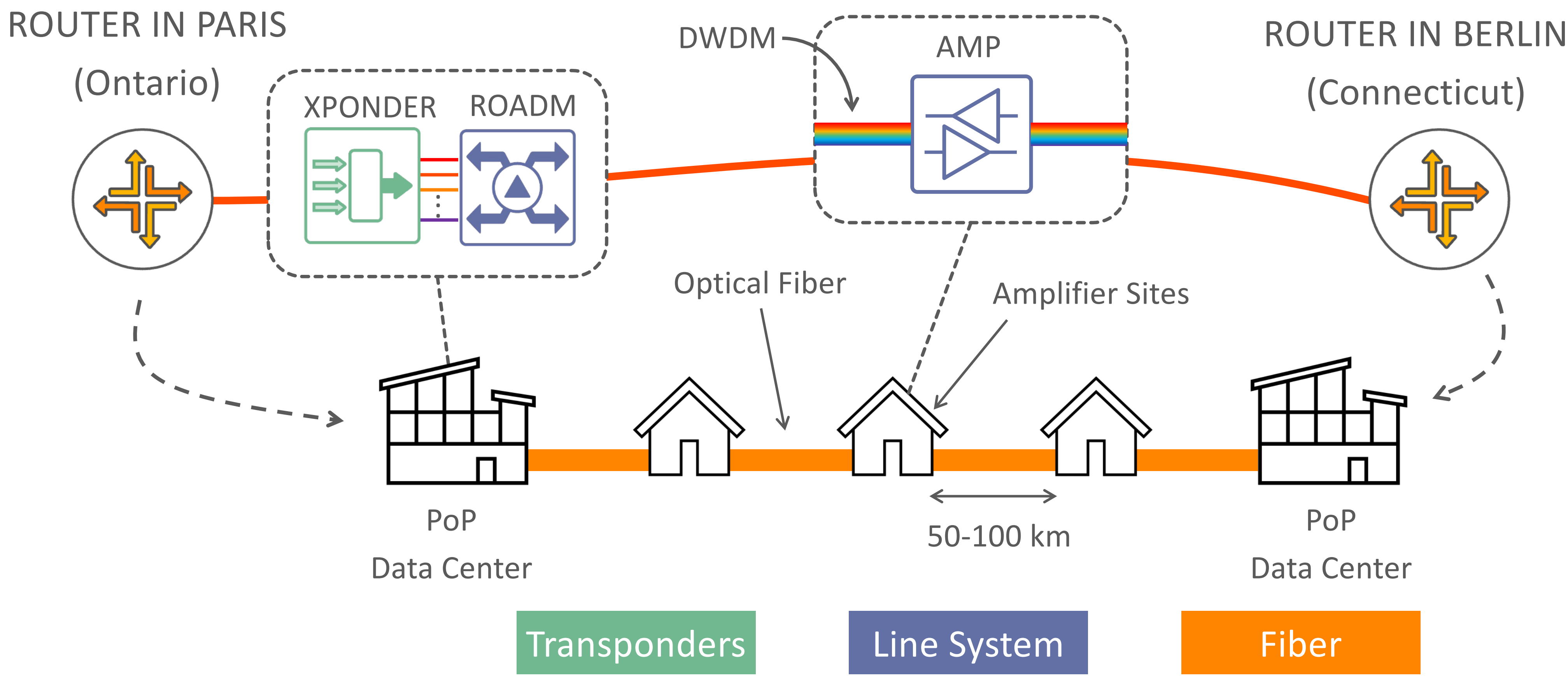
Some Basic Terminology

Please check out NANOG77

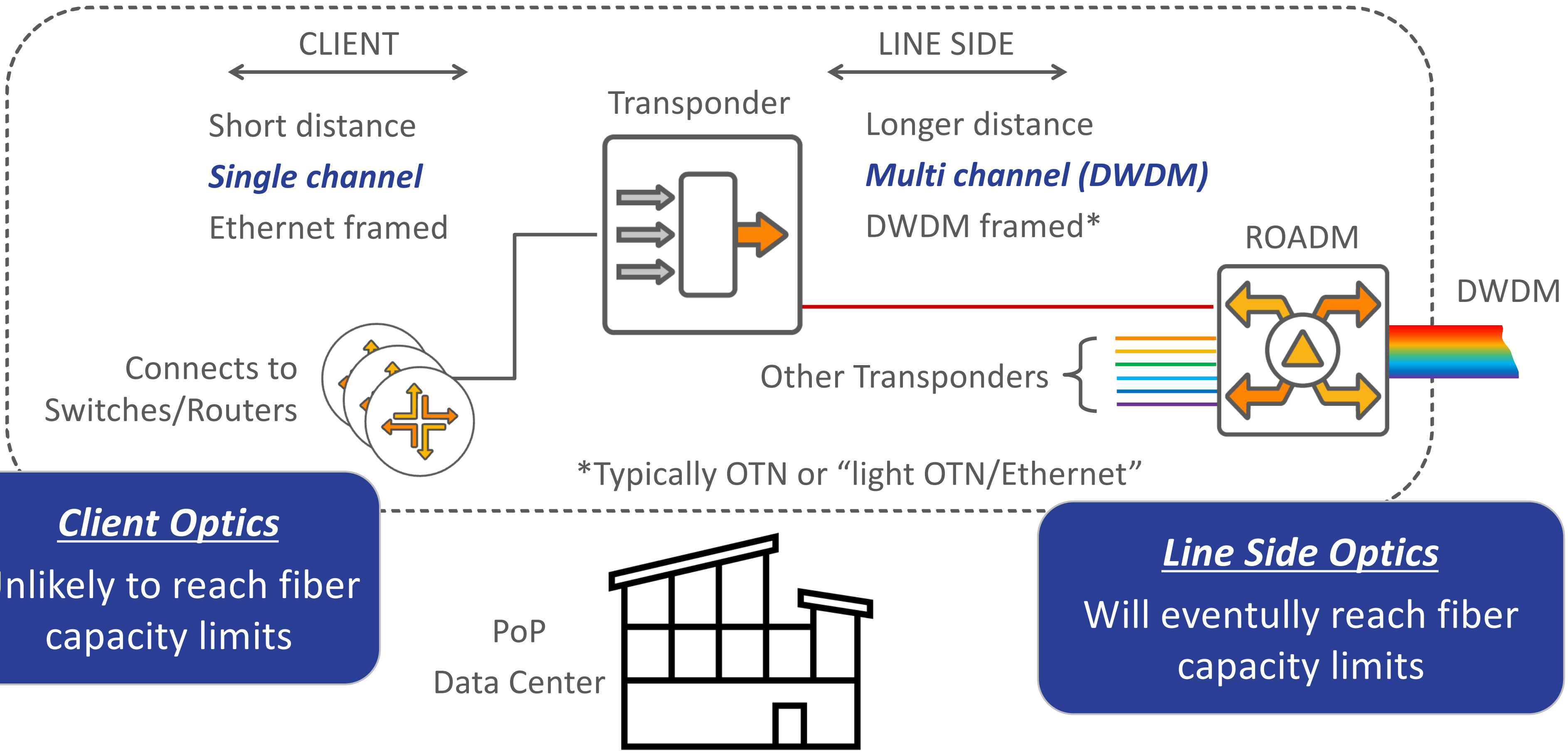
Richard A Steenbergen

"Everything You Always Wanted To Know About Optical"

What is an Optical Network: A Basic Point to Point Example



Client vs Line Side Optics



Client Optics

Unlikely to reach fiber capacity limits

Line Side Optics

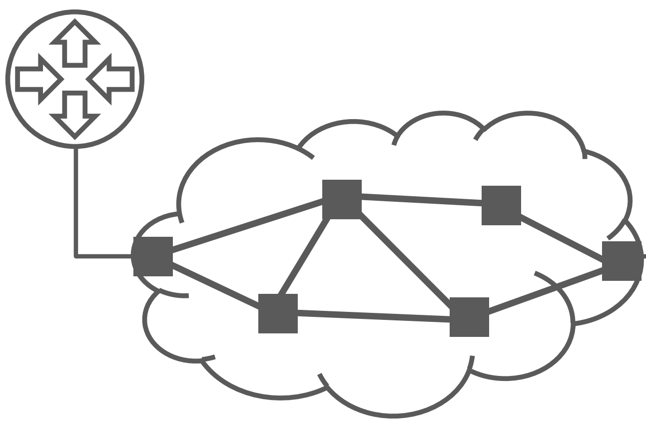
Will eventully reach fiber capacity limits

Why do you care about fiber capacity?

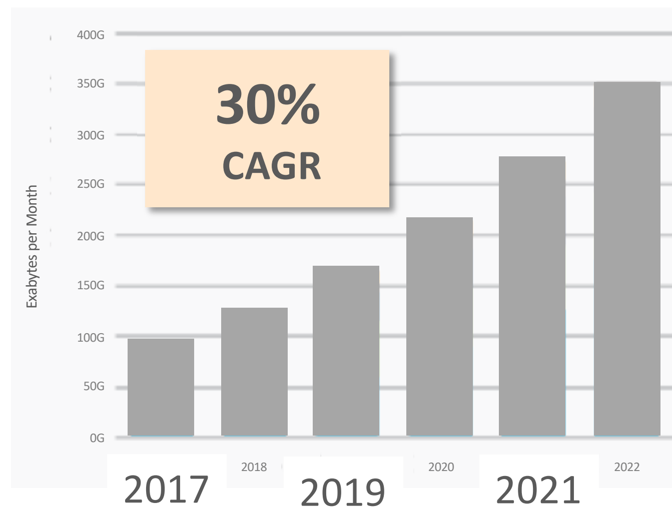
When you draw diagrams like this…

San Francisco

New York



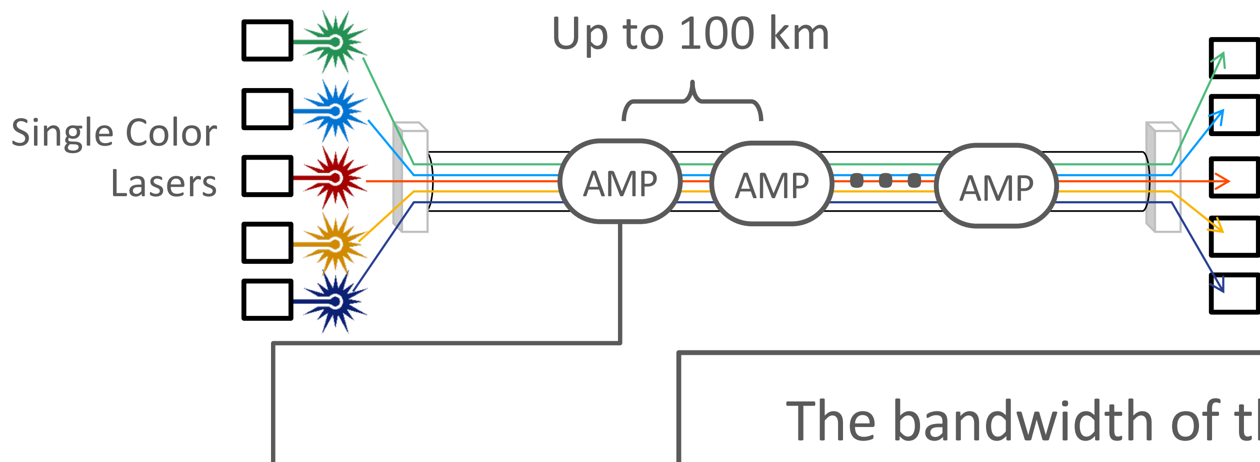
Demand is continuing to rise YoY



- There is another network inside this cloud, based on optical fiber
- Some of these fiber routes are getting “full”

The Role of Optical Amplifiers

Long haul optical links must include ***optical amplifiers***



- Erbium Doped Fiber Amplifiers
- Raman Amplifiers
- C-Band, or C+L Band

The bandwidth of the amplifiers will determine ***how much fiber spectrum we can use***

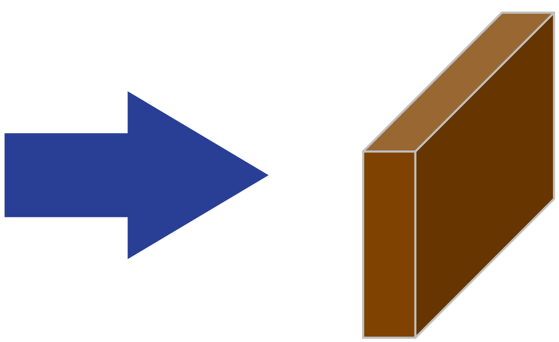
More on this later!

Historically…

We were able to scale total fiber capacity by advances in ***wavelength data rate***, or in ***wavelength multiplexing***,

or both…because…

Fiber capacity = Wavelength data rate x Number of wavelengths



We may be approaching capacity limits in today's optical fiber

So…what are those limits, and what are the options?

Why are we approaching “the limit”?

Are we there yet?

How far away are we?

Prepare to see an equation!

Theoretical capacity limit: Shannon Equation (simplified)

There's a non-linear threshold for signal power

The "bandwidth term"

The "SNR term"

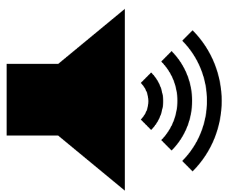
Fiber capacity

$$C = B\log_2\left(1 + \frac{S}{N}\right)$$

Bandwidth	Signal	Noise
How much of the fiber spectrum are we able to use?	How strong is the signal when it arrives at the receiver?	How much noise was added to the signal on its journey?

What is a nonlinear effect?

Imagine you're listening to music and you keep turning up the volume



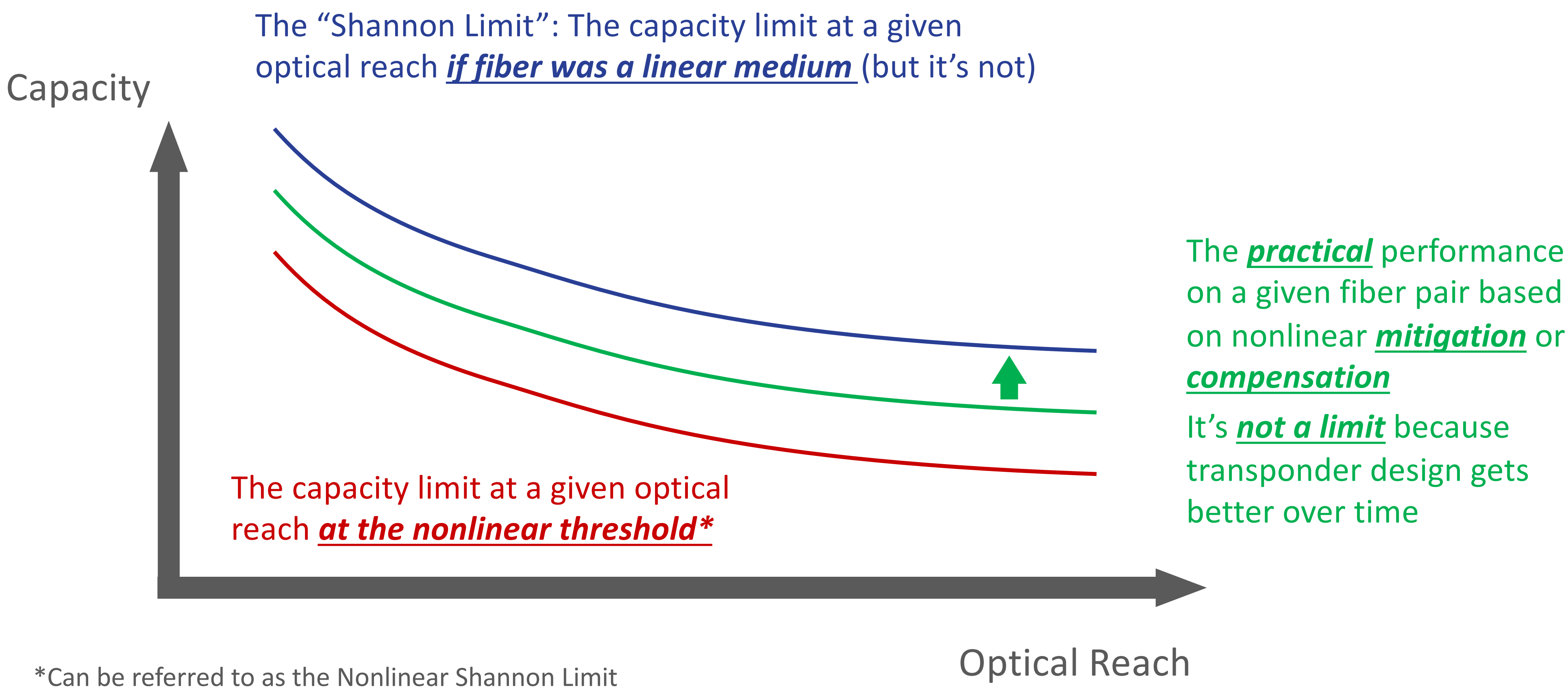
Above a certain volume level the music will become ***distorted***

It's similar with optical fiber – above a certain optical power level the signals will ***distort*** – adding lots of noise!!

There are several nonlinear effects

- Self Phase Modulation
- Cross Phase Modulation
- Four Wave Mixing

The Shannon Limit: It's not a limit, and Shannon was not involved



*Can be referred to as the Nonlinear Shannon Limit

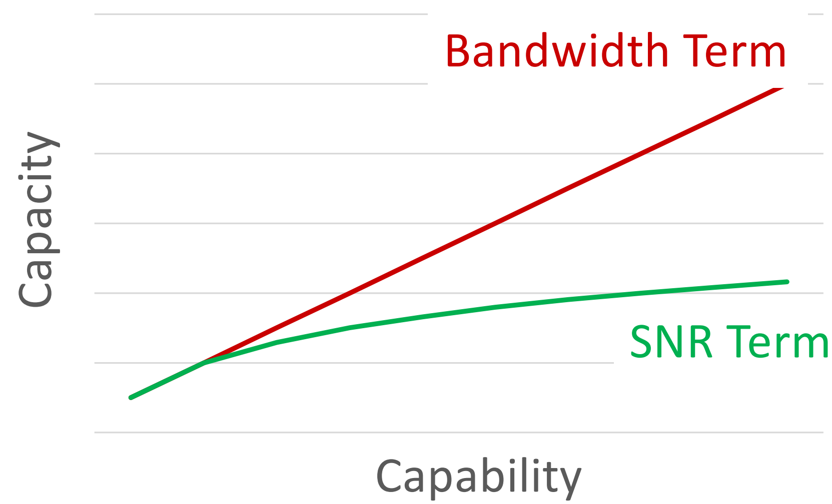
Expanding Capacity: **B** vs **SNR**

The "bandwidth term" — The "SNR term"

Fiber capacity

$$C = B \log_2\left(1 + \frac{S}{N}\right)$$

- If we increase **Bandwidth**, **Capacity** increases linearly
- If we improve **SNR**, **Capacity** increase limited by log function



What have we learned so far?

- Optical fiber is the only medium that allows ultra high capacity over ultra long distances
- We use multiple wavelengths to boost capacity and optical amplifiers, which define bandwidth
- Optical fiber is a nonlinear medium and signals will distort above the nonlinear power threshold
- Every optical fiber pair in the world has a theoretical, nonlinear capacity limit
- We can better understand where to look for capacity increases using the ***Shannon Equation***

Increasing fiber capacity will have an ***operational*** and ***financial*** impact

Let’s see what sort of impact we might experience

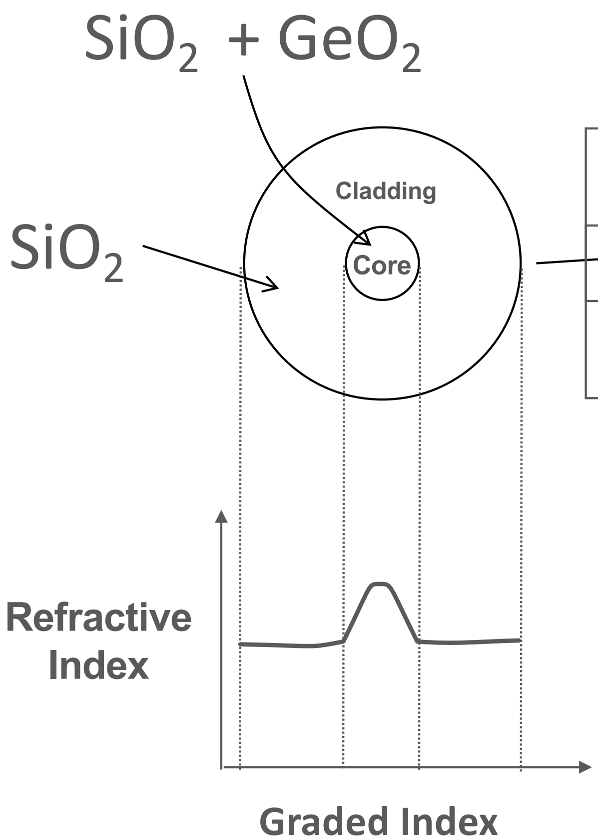
Logical sequence for investment

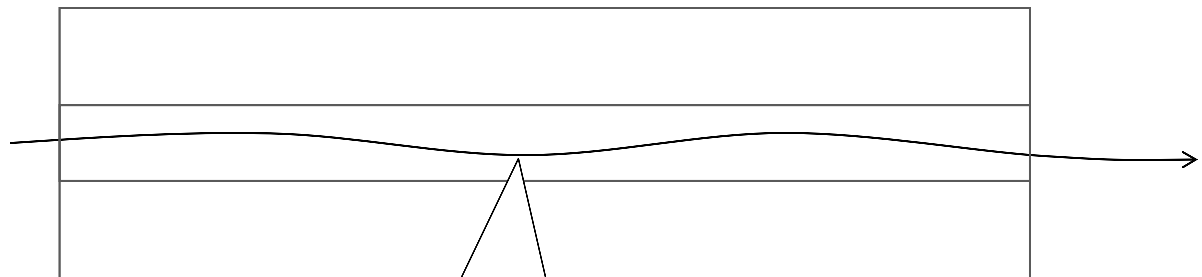
1. Keep the existing fiber and the existing line system (ROADMs, amps)
2. Keep the existing fiber but consider bandwidth upgrades to the line system
3. New fiber and new line systems

The technology evolution of the fiber you have in the ground today

How Does Optical Fibre Work?

Only room for one mode → ***Single mode fiber***

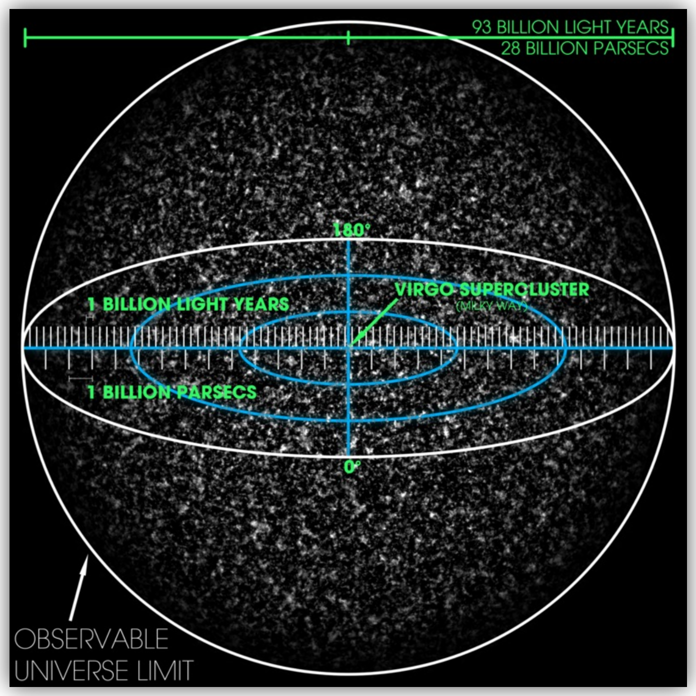




Light is ***guided*** to stay in the core – hence, ***waveguide***

Low Attenuation Is Important

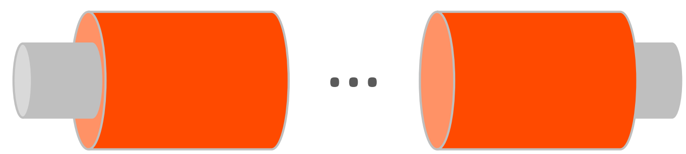
Attenuation: How much of the energy of the signal does the fiber absorb per km?



Assume there are **3.28 x 10^{80}** particles in the observable universe

You have a **single-photon** detector

You have **20 dB/km** loss fiber*



How far before you need to put in more photons than there are particles in the visible universe to get one photon out?

→ **42 km**

*This was the original target set as "low loss fiber" in the late 1960s

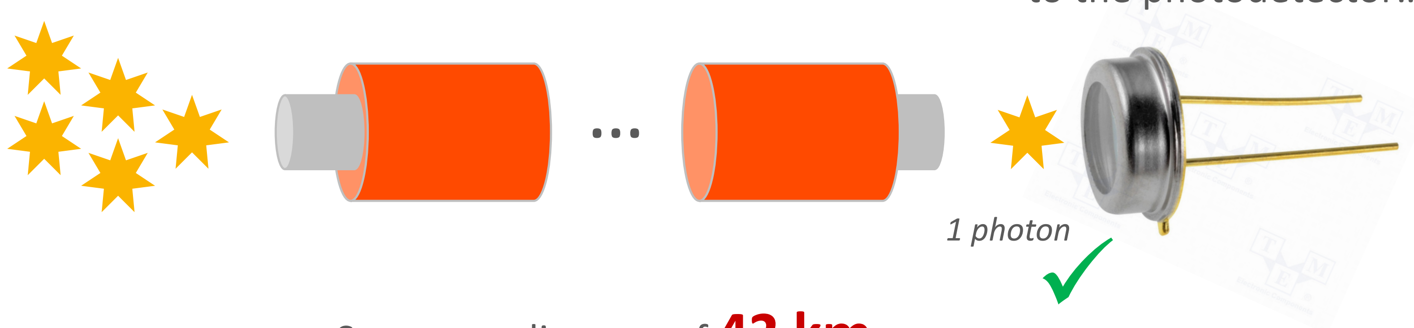
How many photons does today's fiber need?

A typical modulation symbol may contain around
10,000,000,000,000,000,000 photons

We only need to put
5 photons into the fiber

Corning SMF-28 ULL has a loss of
0.17 dB/km

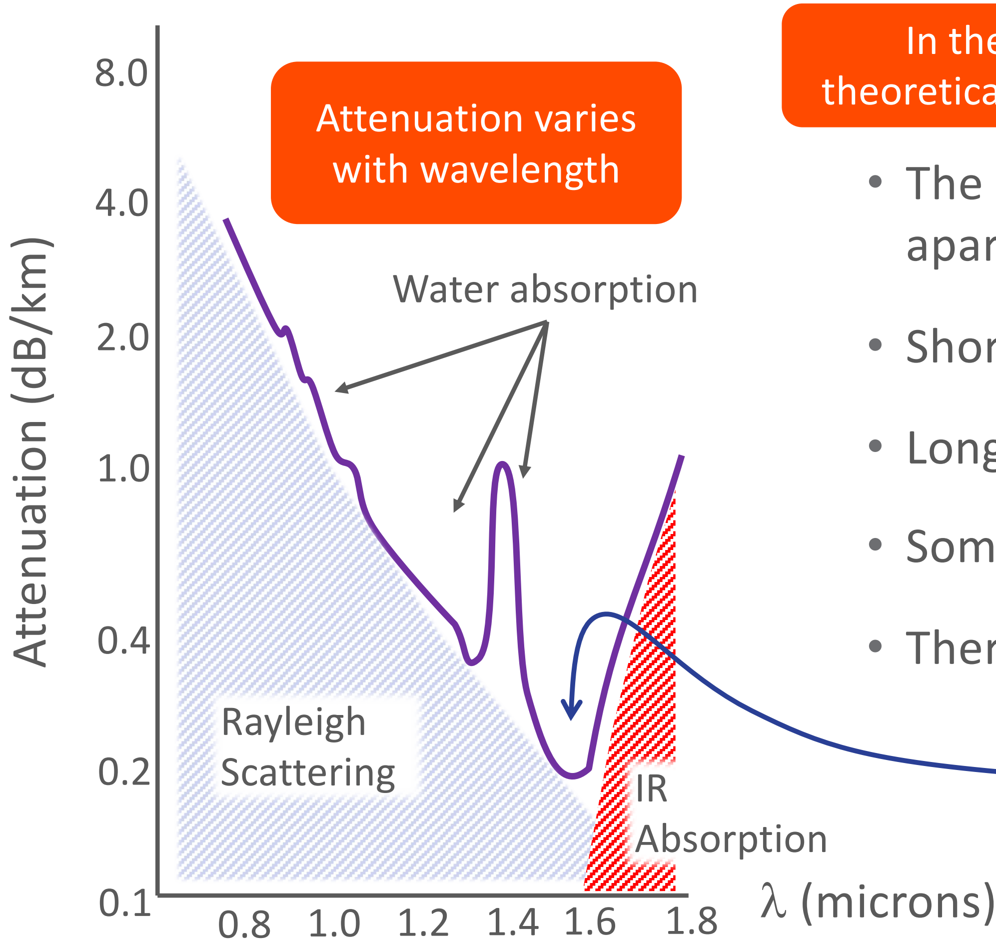
…to get **one photon**
to the photodetector…



So, over a distance of **42 km**…

Typical amp spacing is **100 km**…we'd only need **50 photons**
into the fiber to get **one photon** to the photodetector

Optical Fiber has very low ***attenuation***



In the C&L Bands today we are close to the theoretical minimum attenuation for glass core fiber

- The lower the attenuation, the further apart our amp sites can be
- Shorter wavelengths are scattered
- Longer wavelengths are absorbed
- Some anomalies such as water absorption
- There is a clear "sweet spot" here

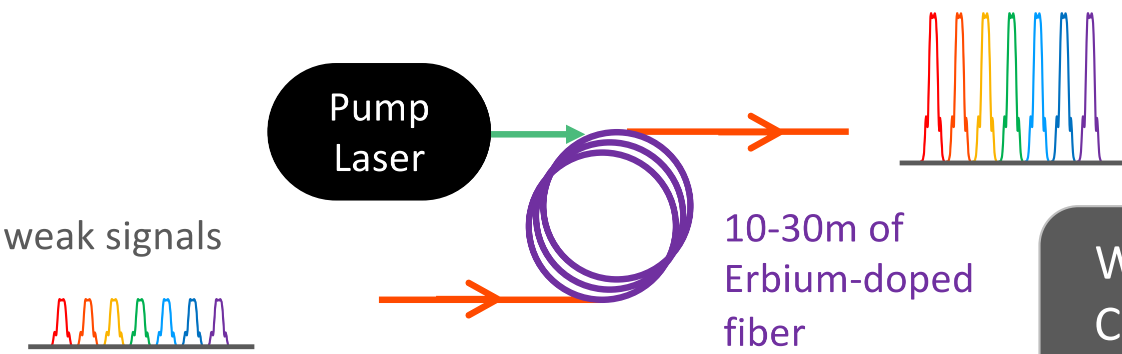
A band from 1.53 to 1.65 microns

We refer to these and the C-Band and L-Band

In long distance transmission we can only use as much of the spectrum as we can ***practically amplify***

Note: In short reach applications we can use much more spectrum. But the higher loss and absolute capacity are usually irrelevant

Erbium Doped Fiber Amplifiers (EDFAs)



We need one EDFA for C-Band and a different EDFA for L-Band

C-Band	L-Band

Conventional C-Band → 3.6 → 4 → 4.8 → 6 THz

"Super" C-Band: 6 THz

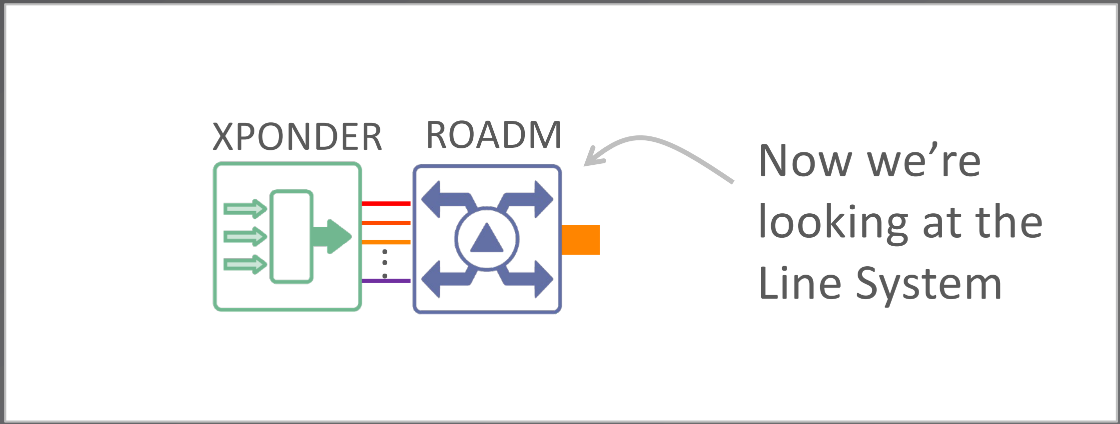
Extended C-Band: 4.8

Super-C and Super-L Bands will give up to 12 THz of amplified bandwidth

There are other optical amplification options

- Raman Amplification
  - Offers low noise, high gain amplification
  - Is more expensive and can be operationally complex
  - Wideband operation beyond C and L bands is possible
  - Can be used in combination with C and/or L-Band EDFAs
- Semiconductor Optical Amplifiers (SOA)
  - Ultra small – similar to laser in size
  - Excellent gain, but higher noise factor
  - Challenging for multi-wavelength operation (crosstalk)
  - Can be used as part of the laser chipset (Photonic Integration)
  - Can operate at any wavelength where we can build a laser
  - Not generally used in external commercial amplifiers for long haul & subsea

Fixed Grid vs Flexible Grid

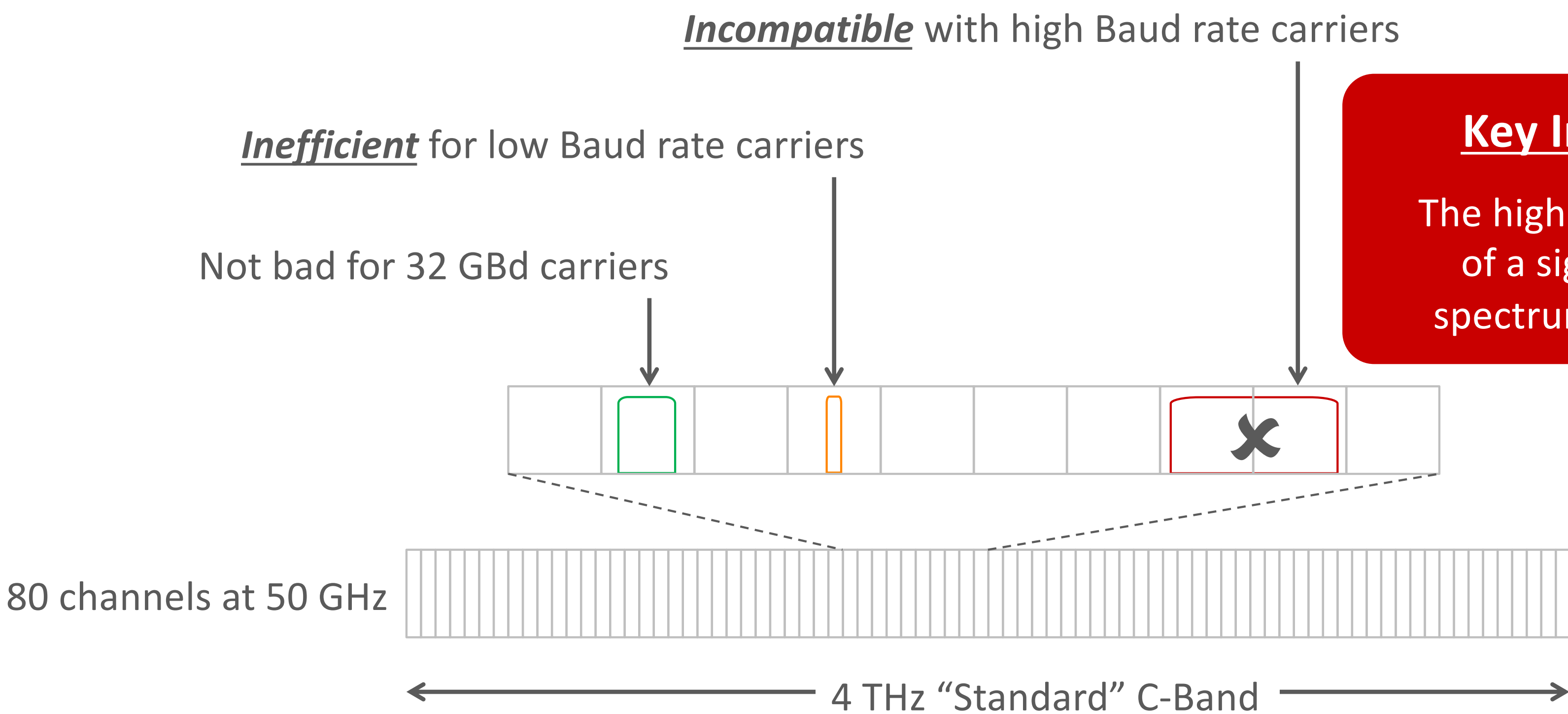


The DWDM Multiplexing Grid: ***Like lanes on a highway***

- How do individual wavelengths share the spectrum?
- From 1995 to 2013 the only commercial approach was Fixed Grid
- Total fiber capacity was limited by the grid spacing
- Grid granularity evolved as better DWDM mux/demux technology became available

	Assume 4 THz C-Band			
Grid Spacing	200 GHz	100 GHz	50 GHz	25 GHz
C-Band Channels	20	40	80	160

Fixed Grid

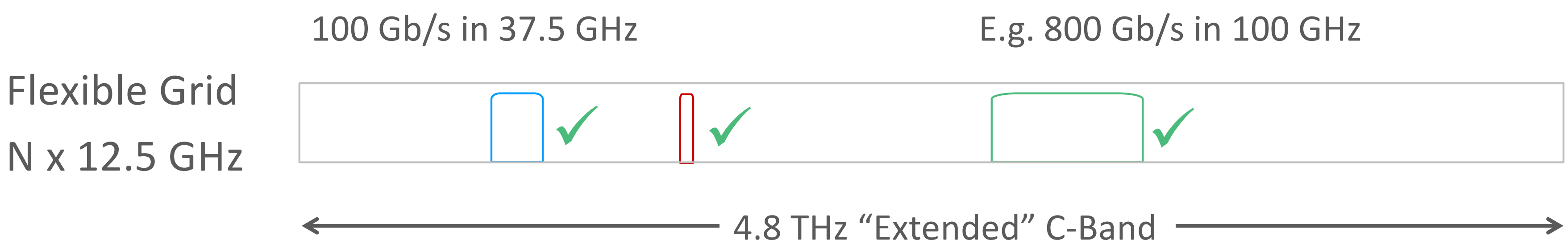


Key Information

The higher the Baud rate of a signal the more spectrum it will occupy

Flex Grid

- With Flexible Grid we throw away the predefined grid settings
- We create flexible sized (N x 12.5 GHz) slots
- Each flexible slot can be rightsized for the wavelength it is transporting



Flexible grid line systems (1) waste less “stranded spectrum” and (2) support high Baud rate signals

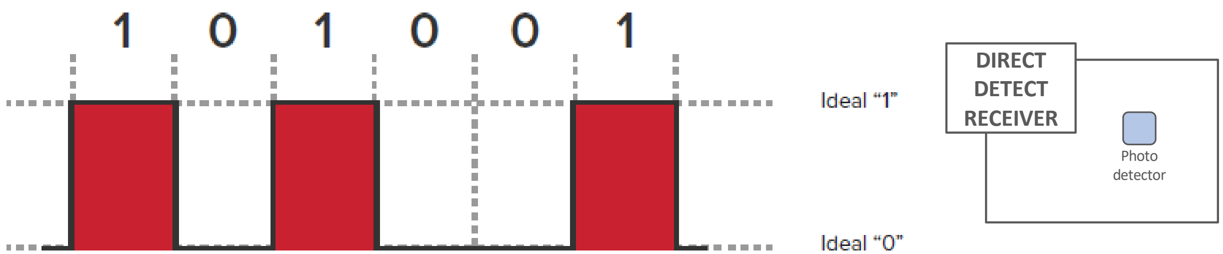
What have we learned about optical fiber capacity?

- Optical fiber acts as a ***waveguide***, trapping the signal inside so it can go further without losing integrity
- A given pair of optical fibers has a ***practical capacity*** that is defined by
  - The low attenuation bandwidth range we can practically amplify
  - The SNR performance of the system – typically limited by nonlinear impairments of the fiber and the internal noise of the modem
- The lowest attenuation part of today's fiber is in the ***C and L-Bands***
- We have to be able to amplify these signals all at once for minimum cost
  - EDFAs, Raman and hybrid EDFA/Raman are the commercial options today
- The wavelength mux grid also affects useable capacity, and the most spectrally efficient option today is ***Flexible Grid***

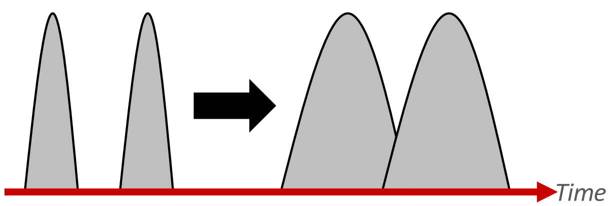
Evolution of Transponders

Before Coherent Transponders: Direct Detect

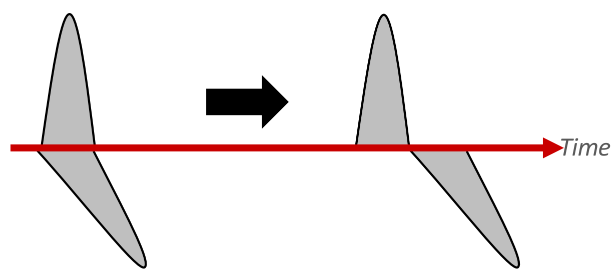
- Simple modulation (OOK, NRZ) and receiver: 2.5Gb/s ->10Gb/s (WDM)



- Challenges scaling beyond 10Gb/s due to dispersion, etc.



Chromatic Dispersion



Polarization Mode Dispersion

These are linear impairments

We can now add to our Fixed Grid table…

	Assume 4 THz C-Band			
Grid Spacing	200 GHz	100 GHz	50 GHz	25 GHz
C-Band Channels	20	40	80	160
C-Band Capacity @10G per channel	200 Gb/s	400 Gb/s	800 Gb/s	1600 Gb/s

- This capacity evolution took place from about 1995* to 2007
- Driven by higher quality wavelength mux components

* 10G transponders were introduced around 1998

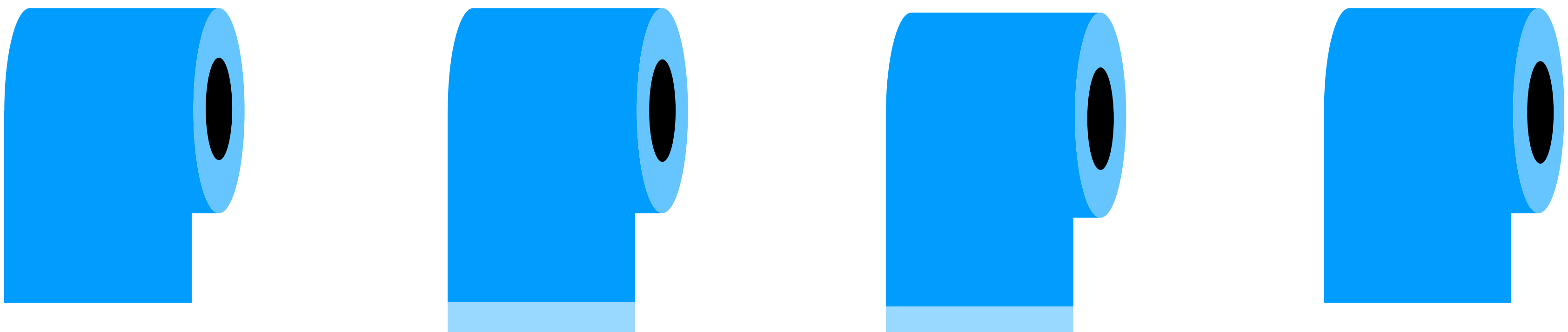
Key Innovation: Coherent Transmission (circa 2009)

- What is "coherent"?

Phase Modulation in Tx	Coherent Detection in Rx	Digital Signal Processing in Tx and Rx
• More tolerant to optical impairments • Ability to carry more bits per symbol	• Linear detector (enables DSP for linear impairments) • Low noise amplification (using local oscillator)	• Linear impairment compensation • Nonlinear impairment compensation • Many other processing options

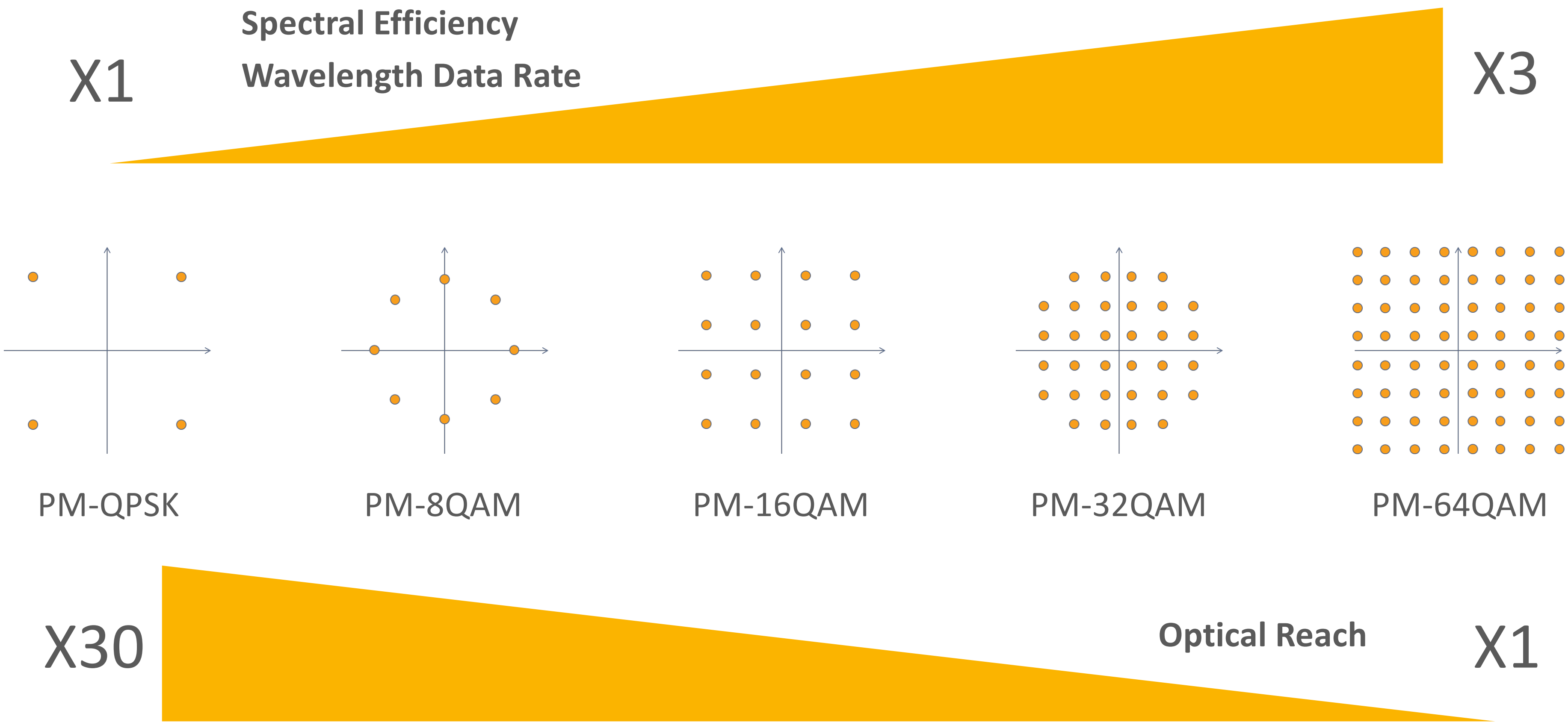
Try this at home: *Phase differences to encode bits*

Symbol 1	Symbol 2	Symbol 3	Symbol 4
1	0	0	1



Let’s assume: In-phase = 1 Out of phase = 0

Higher Order Modulation: Spectral Efficiency and Reach



Five Generations of Coherent Transmission (so far)

1	2	3	4	5
2009 → 2011	**2015**	**2017**	**2019**	**2020**
PM-QPSK	PM-16QAM	PM-32QAM	PM-64QAM	PS-PM-64QAM
32 GBd	32 GBd	56 GBd	68 GBd	100 GBd
40G → 100G	**200G**	**400G**	**600G**	**800G**
8T C-Band	**19.2T Ext C**	**38T Ext C**	**38T Ext C**	**42T Ext C**
65 nm ASIC	28 nm ASIC	28 nm ASIC	16 nm ASIC	7 nm ASIC

C-Band = 4 THz EDFA

Ext C = 4.8 THz EDFA

Other Coherent Transponder Evolutionary Features

- Hybrid Modulations
- Probabilistic Constellation Shaping
- High gain, Soft Decision Forward Error Correction (SD-FEC)
- Nyquist Subcarriers
- Line rate encryption
- Built-in telemetry

These require a separate tutorial ☺

Transponder Performance Evolution

Direct Detection	Coherent Detection
2.5[1] → 10	40 → 100 → 200 → 400 → 600 → 800 → 1600[2]

[1]This was the data rate of the first C-Band transponder at 1550 nm. There were earlier devices at shorter wavelengths and lower data rates.

[2]Transponders at these data rates are likely to ship in the 2023-24 timeframe.

Wavelength data rate

320X increase

C-Band capacity

>200X increase

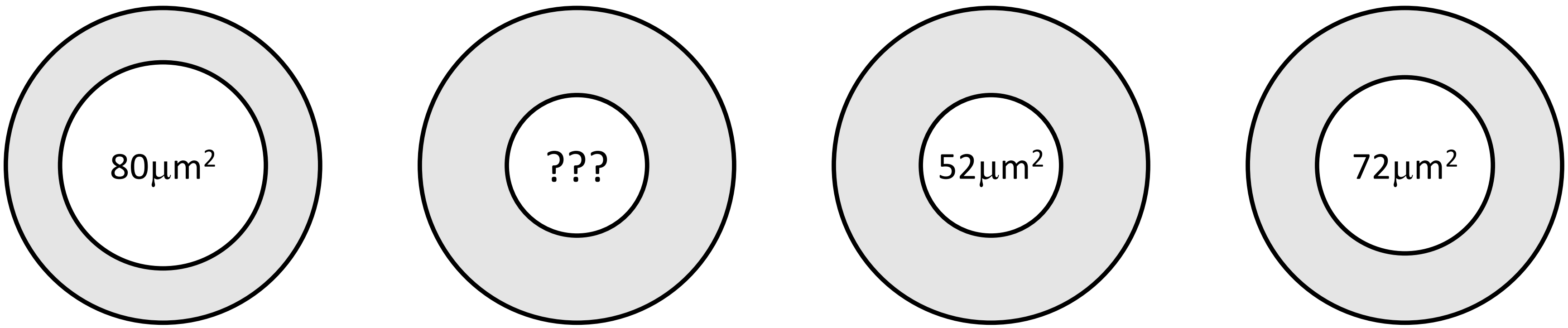
Summary of Transponder Evolution

- Coherent transponders have revolutionized long haul capacity and reach
- The industry is in the 5th generation of coherent optical engines with the 800G generation
- Historically transponder upgrades were the easiest way to increase fiber capacity on existing routes
- Coherent performance is driven by ASIC technology for the DSP
  - We are currently on 7 nm ASICs – next stages are 5 nm and then 3 nm
  - ***Capacity advances are starting to become harder to achieve***
  - Look for ***higher wavelength data rates*** at longer reach for future generations
  - Next step is 1.2 Tb/s or 1.6 Tb/s wavelengths
- Independently we can expect the optical performance of pluggable coherent transponders to make big advances

The interaction between the evolution of optical fiber and the evolution of transponders

Optical Fiber Evolution: *In search of the "perfect" fiber*

1984*	1988*	1996*	1998**
G.652	G.653	G.655	G.655 LEAF

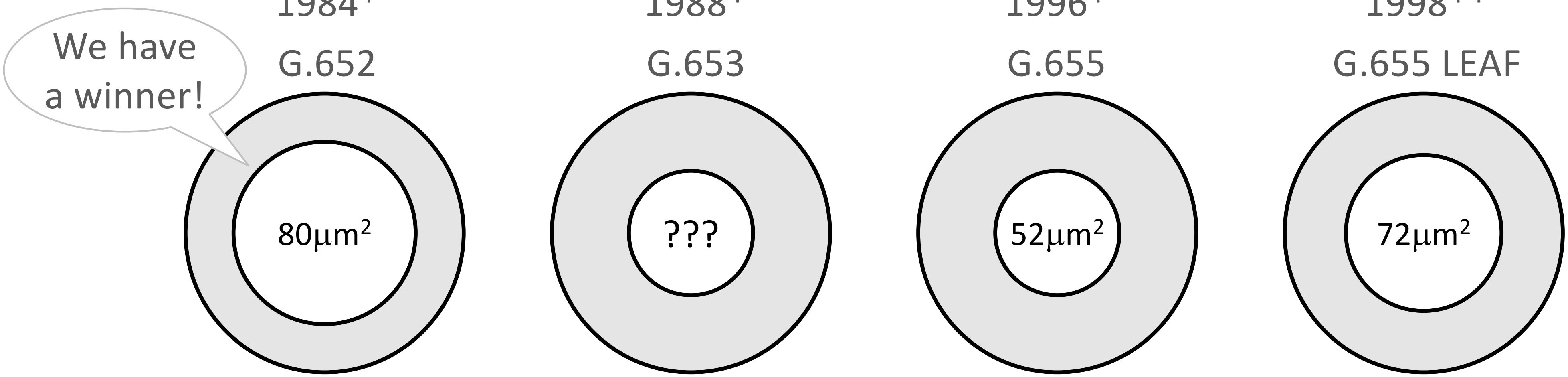


The perfect fiber for single wavelength at 1310 nm	The perfect fiber for single 2.5G wavelength at 1550 nm	The perfect fiber for single 10G wavelength at 1550 nm	The perfect fiber for DWDM 10G at 1550 nm

* Date of first ITU standard for this fiber type

** Date of first LEAF shipments

Which is the best fiber for ***coherent*** transmission?

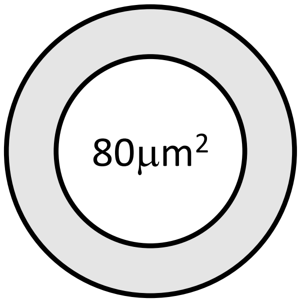


	1984* G.652	1988* G.653	1996* G.655	1998** G.655 LEAF
Effective Area	**HIGH**	**???**	**LOW**	**MEDIUM**
Chromatic Dispersion	**HIGH**	**ZERO**	**MEDIUM**	**MEDIUM**

* Date of first ITU standard for this fiber type

** Date of first LEAF shipments

New, Commercially Available Fiber Types



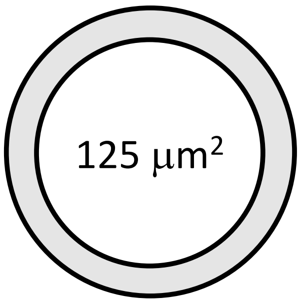
G.652 SMF ULL

Reduced attenuation

<0.16 dB/km

(vs up to 0.25 dB/km for existing G.652 fibers)

Up to 1,000 km at 800 Gb/s



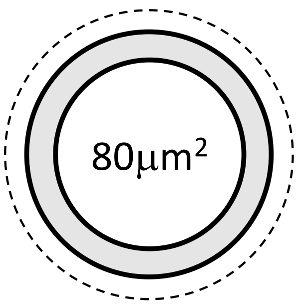
G.654 Large Area

Reduced attenuation

<0.17 dB/km

Reduced nonlinear penalty

Up to 1,600 km at 800 Gb/s



G.657 Reduce Cladding

These fibers are not intended to lead in low attenuation (typically <0.3 dB/km)

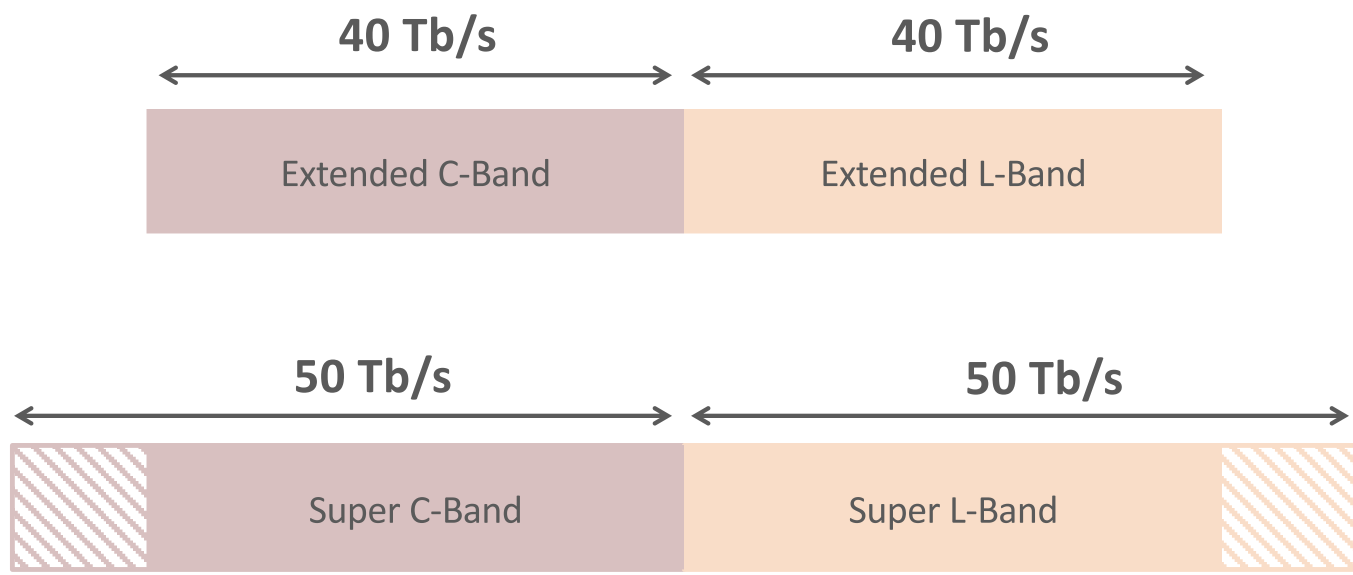
20% reduction in cladding diameter → ***50% increase in fiber pairs per duct***

How far can we push capacity on existing fiber, using existing line systems, and only changing the transponders?

Capacity Limits of Today's Optical Fiber

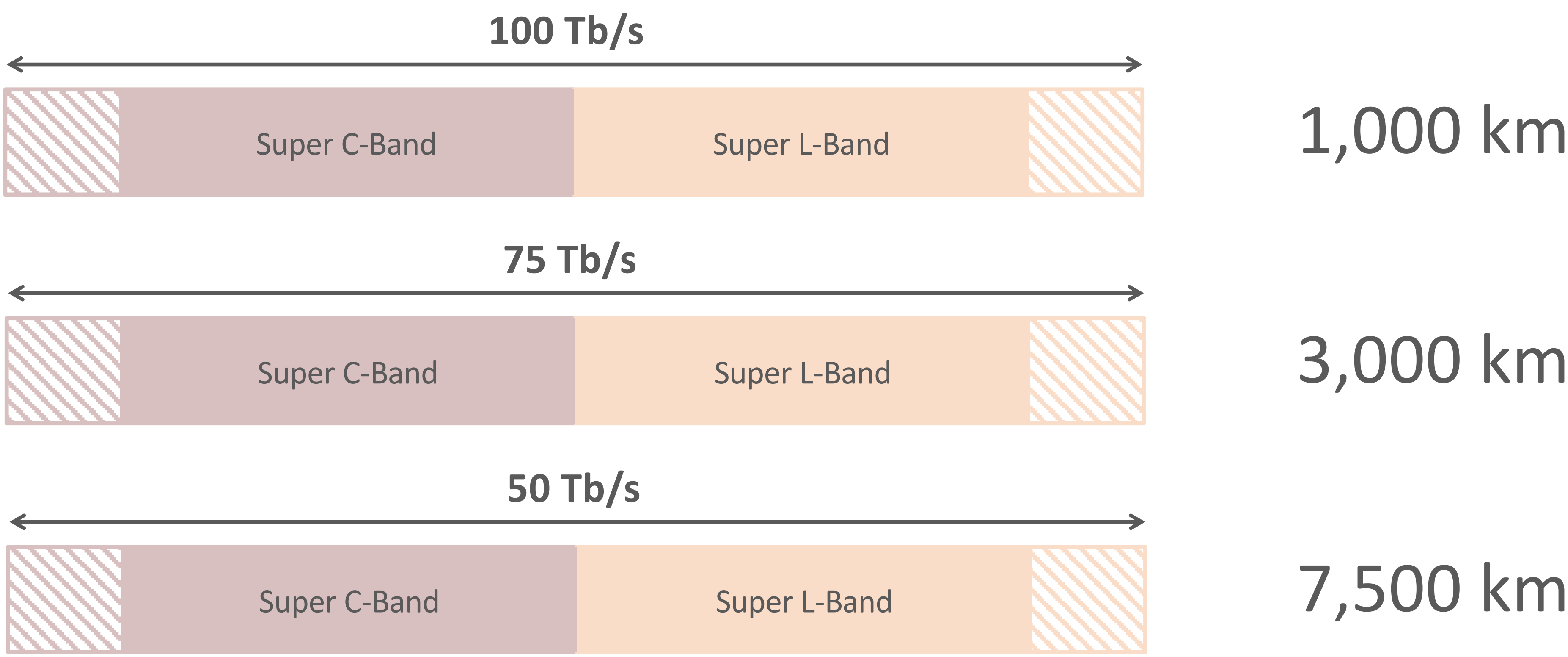
Line systems that are commercially available today

Next gen line systems with enhanced bandwidth



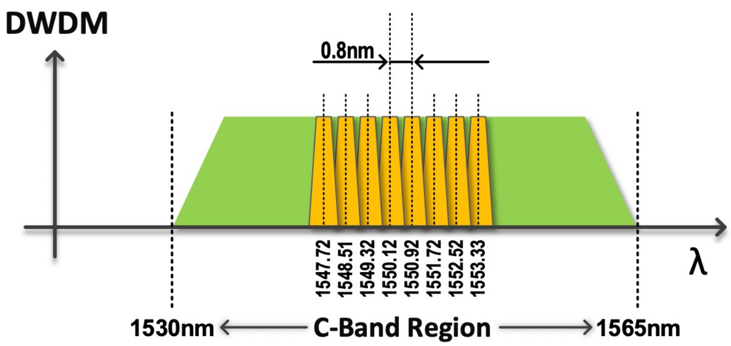
We are getting close to practical limits, but there may still be some "gas left in the tank" in terms of transponder performance

Capacity at Longer Reach

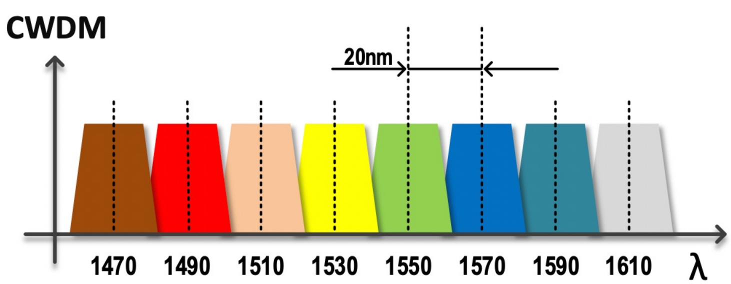


Can we transmit in other wavebands to increase fiber capacity?

Simple answer – yes! But not *easily* for increased capacity



- I've been describing DENSE WDM (**DWDM**)
- We also have COARSE WDM (**CWDM**)



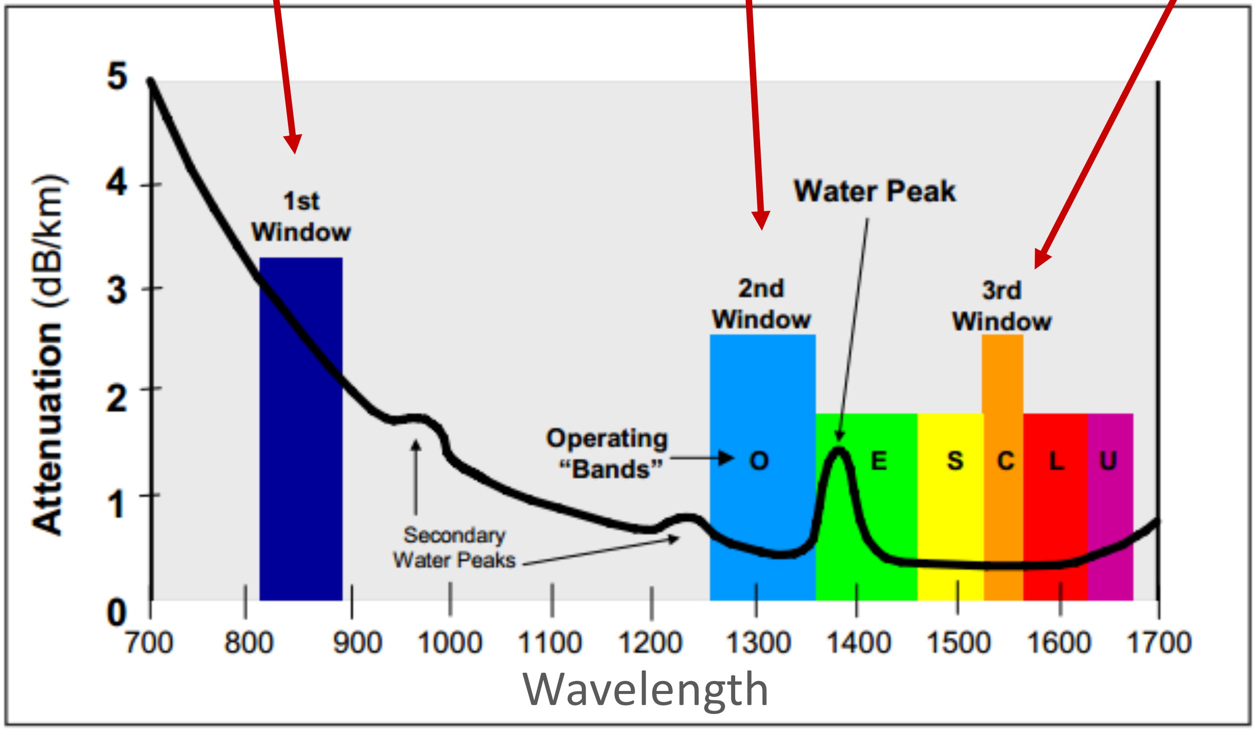
- We use CWDM because it's cheap, not for additional capacity
- Up to 10G per channel, and only a few channels
- Used in unamplified (short reach) applications
- But it's proof we can use other fiber bands

Optical Fiber Wavebands

Then 1300 nm lasers

First we could make 860 nm lasers

Eventually 1550 nm lasers – at the fiber attenuation minimum



Commercial DWDM today operates in the C and/or L Bands

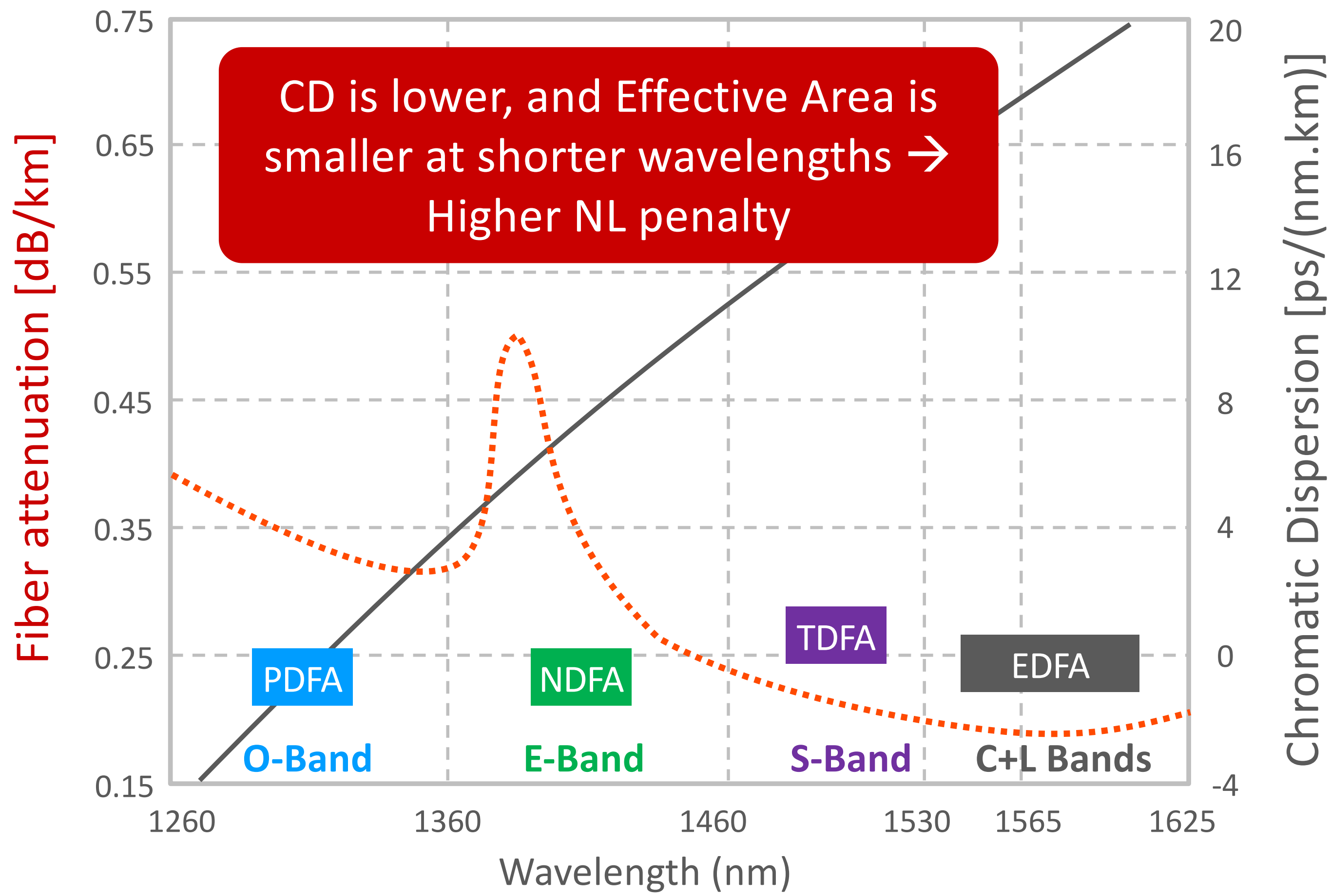
We "solve" for attenuation using amplification

We can certainly amplify in these wavebands…

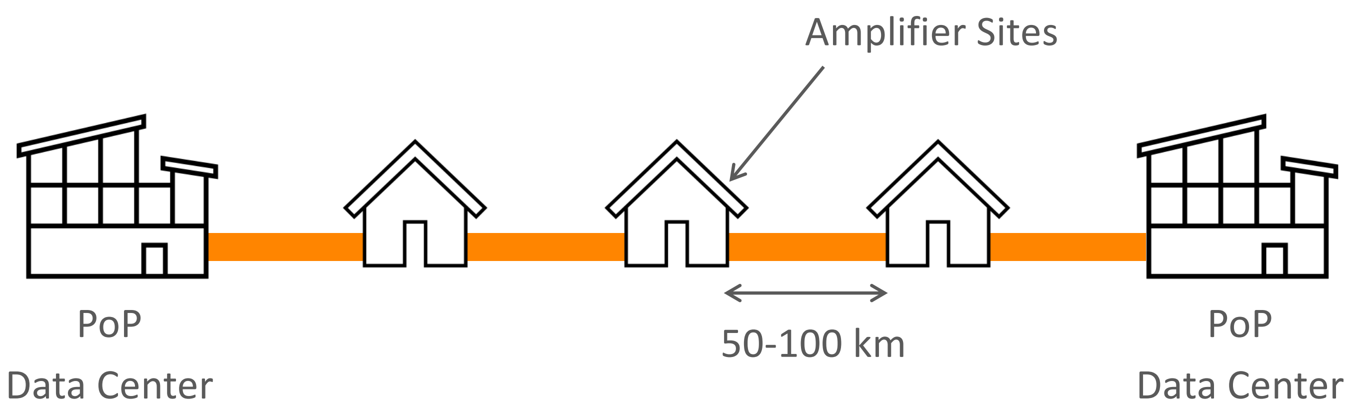
Dopant Element

EDFA	Erbium
TDFA	Thulium
NDFA	Neodymium
PDFA	Praseodymium

These will all cost more per Gb/s than C or L Band amps



Wideband communication is ***challenging*** in LH networks



Optical performance and amp site spacing is set by C+L bands (e.g. attenuation, NL penalties)

Other wavebands have higher attenuation…but the amp site locations are already set

Accept lower optical performance in exchange for more total capacity at higher cost per Gb/s?

For many terrestrial networks there is a simple solution…

- More fiber pairs!

Many operators have installed 1.25” ducts

Historically the limit would be **864** fiber pairs in 1.25”

Today there are **1728**-pair cables for **1.25”** ducts

And **6912**-pair cables for **2”** ducts

What have we learned about fiber so far?

- Minimum fiber attenuation is in C and L-Bands for long haul transmission
  - Could use other bands as well (e.g. O, E, S), but at higher cost per Gb/s/km
  - Wideband transmission is perfect for CWDM
- Fiber design has evolved to match optical transponder capabilities:
  - Longer Wavelengths
  - Multiple Wavelengths
  - Use of Optical Amplifiers
- Good old G.652 SMF in C and L-Bands is a great fiber for modern coherent transmission
- And more fiber pairs are a quick and easy fix for capacity shortage!

Moving away from conventional optical fiber

1: ZBLAN

ZBLAN Fiber

Special mention

- Exotic mix of fluorides
  - This is not Silica glass
- Generally not used for transmission fiber
  - Gratings, gain fiber etc.
- There have been experiments with high bandwidth ZBLAN transmission fiber
  - BUT…it must be made in zero gravity
  - Can we really make tens of millions of km?

Zirconium ***Bismuth*** ***Lanthanum*** ***Aluminum*** ***Sodium***

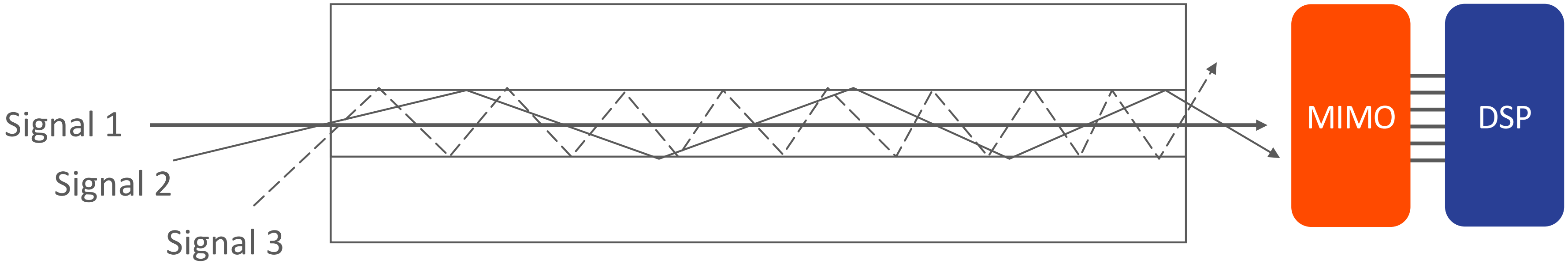
Low probability of commercial adoption

Moving away from conventional optical fiber

2: Few Mode Fiber

Few Mode Fiber

With a wider core, optical fiber will support multiple modes (transmission paths)



We ***could*** use Multiple Input/Multiple Output (MIMO) techniques with a DSP to compensate for modal dispersion

Lots of crosstalk because of Modal Dispersion

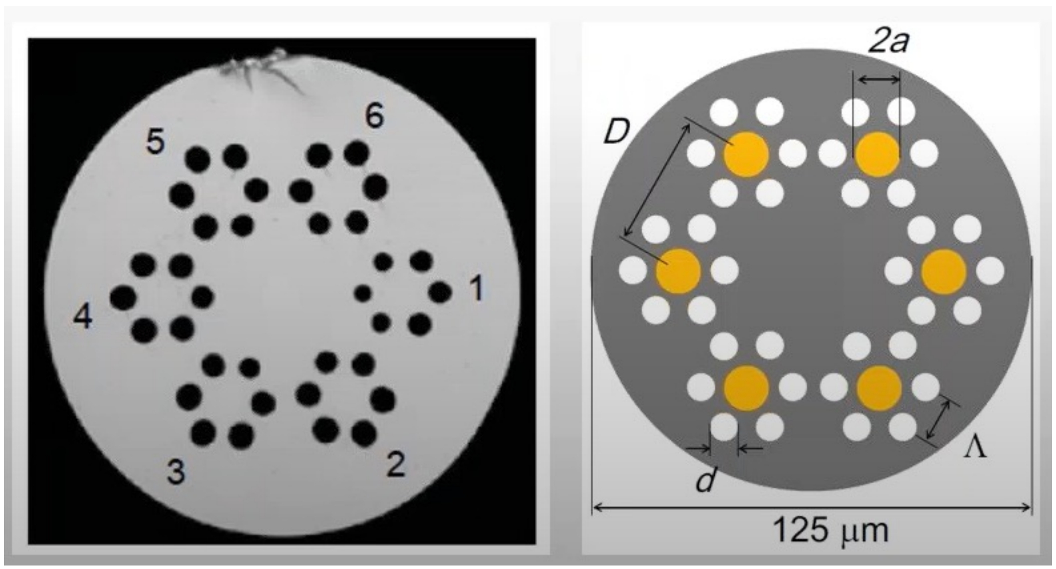
Initial experimental results: 2X – 3X vs C+L systems

But this requires new fiber and new transponders

Moving away from conventional optical fiber

3: Multicore Fiber

What is Multicore Fiber?



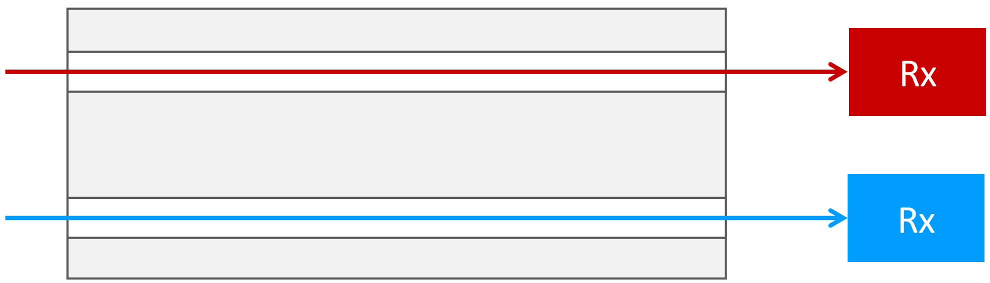
A fiber that is designed to have multiple cores within the same cladding

A form of Space Division Multiplexing (SDM)

Multiplies potential capacity by the number of cores

Uncoupled vs Coupled Cores: Transmit/Receive

Uncoupled: no interaction between cores



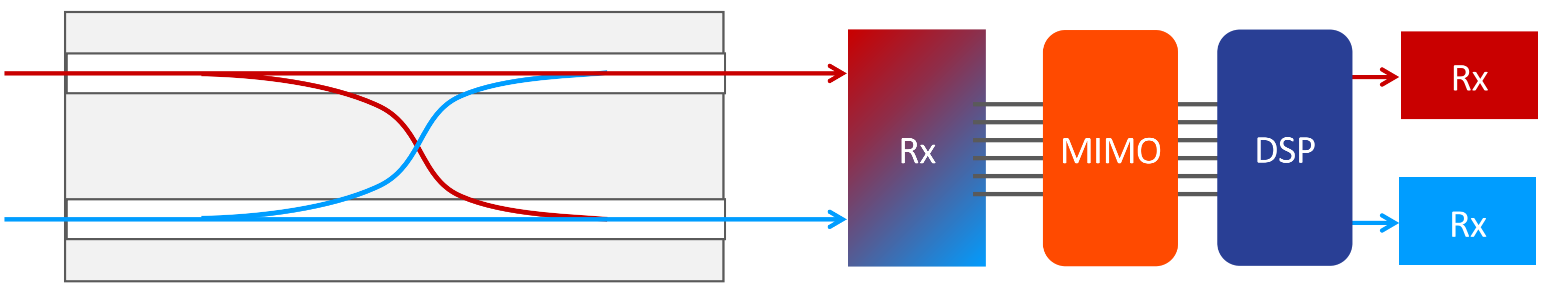
ADVANTAGE TO UNCOUPLED

2-Core and 4-Core fibers

No need for MIMO compensation

Coupled: deliberate crosstalk between cores

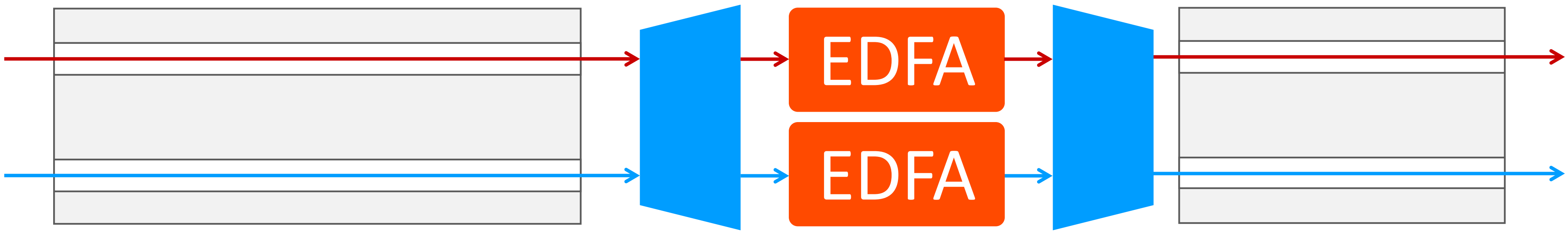
Requires MIMO compensation



Uncoupled vs Coupled Cores: Amplification

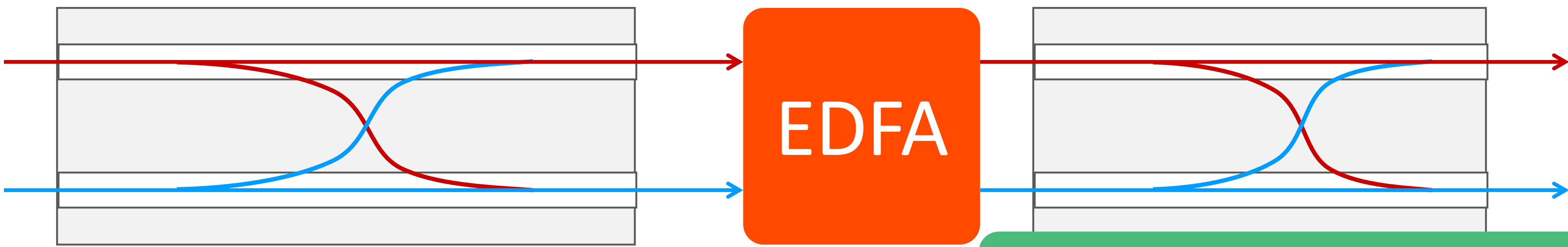
Uncoupled: no interaction between cores

Fan-out/Fan-in and multiple EDFAs



Coupled: deliberate crosstalk between cores

Single EDFAs



ADVANTAGE TO COUPLED

Multicore Fiber: Likely scenarios

- Multicore fiber challenges:
  - Possibly low yields, new connector and splicing infrastructure
- In terrestrial networks
  - There is no practical advantage for MCF unless space in the duct is an issue
  - Large fiber count cables solve the same problem with existing technologies, training, operational methods and other infrastructure
- In subsea networks
  - There may be a use case for 2-core and 4-core, uncoupled MCF to save space in the cable
  - Likely timeframe >3-5 years
- ***There is no change needed to existing transponders for <u>uncoupled</u> MCF***
- Coupled core MCF will require transponder MIMO development
  - This can only happen if there is a use case in ***both terrestrial and subsea***

Moving away from conventional optical fiber

4: Hollow Core Fiber

What have I told you about glass-core optical fiber?

- Optical fiber acts as a ***waveguide***
- ***Single mode*** operation – no modal dispersion
- Attenuation varies with wavelength
  - Today's optical communication is in the ***C-Band*** and ***L-Band***
  - There is so much more potential capacity in optical fiber
- Glass is a ***nonlinear medium*** – a major limiting factor
- Glass core fiber has ***higher latency*** than transmission through air

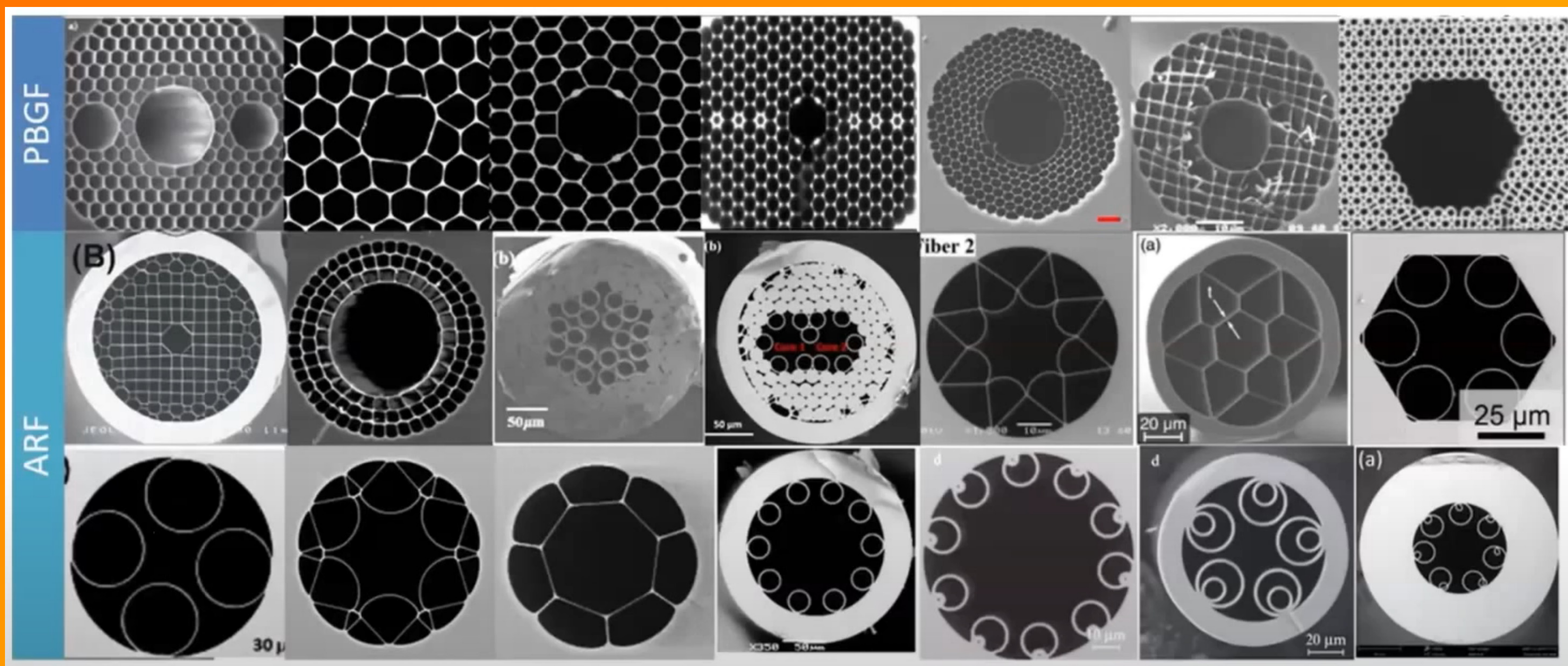
Which means that…

- ***A wider bandwidth waveguide would increase capacity-reach***
- ***A more linear optical waveguide would increase capacity-reach***

- As a ***separate market driver*** (ie. not related to capacity-reach) it would be great to find a waveguide that has ***lower latency*** than glass

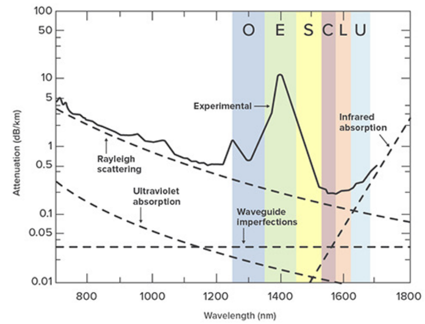
- ***All of these limitations derive from using fiber with a glass core***

Hollow Core Fiber

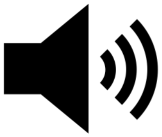


Potential HCF Advantages – Transmission in Air (or vacuum)

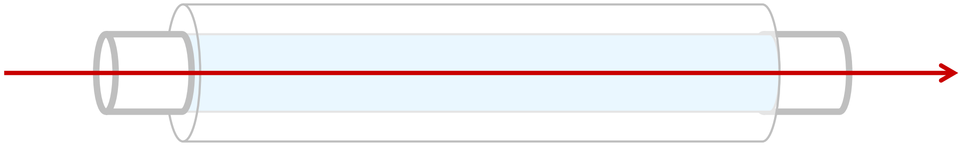
Wideband transmission



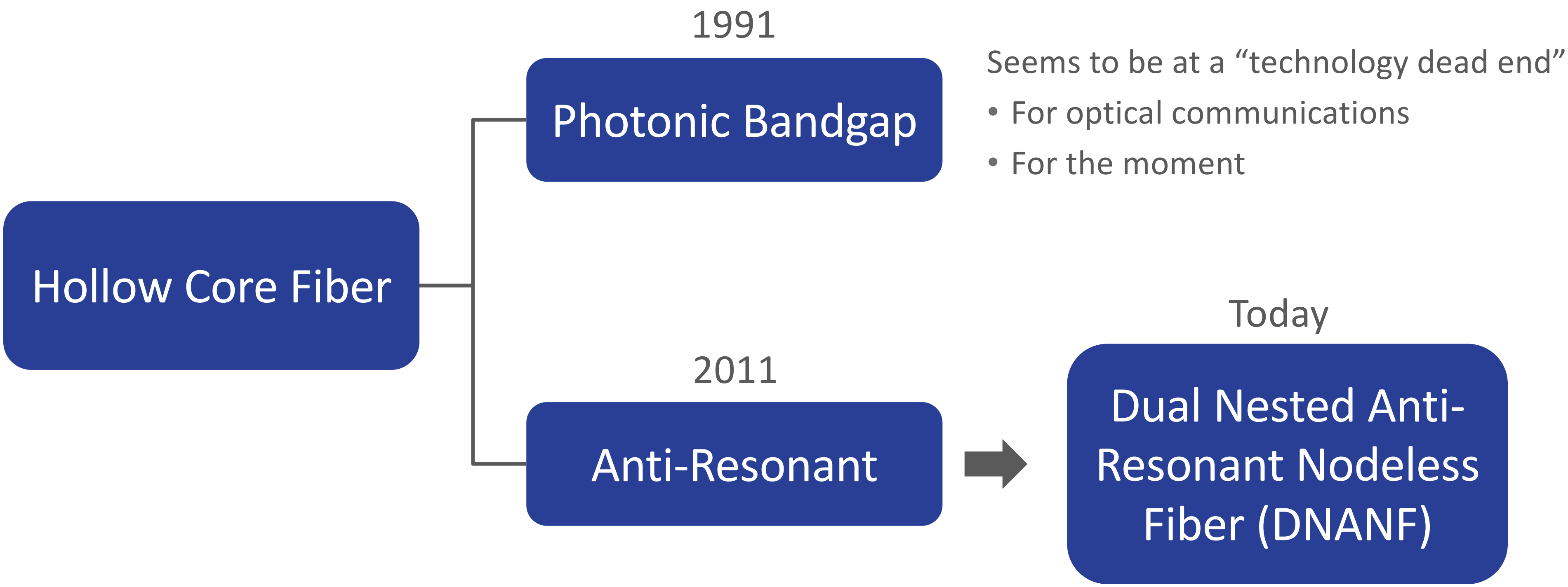
Lower nonlinear effects



Lower latency



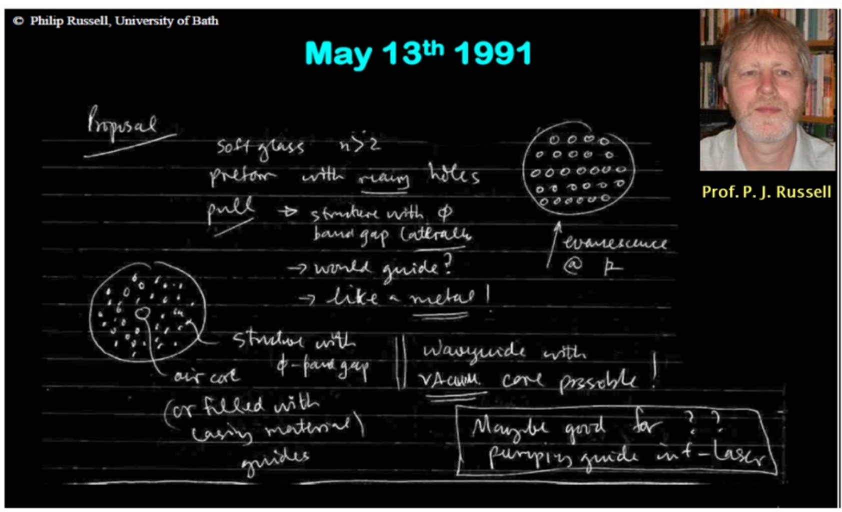
Types of HCF: *How they create the waveguide*

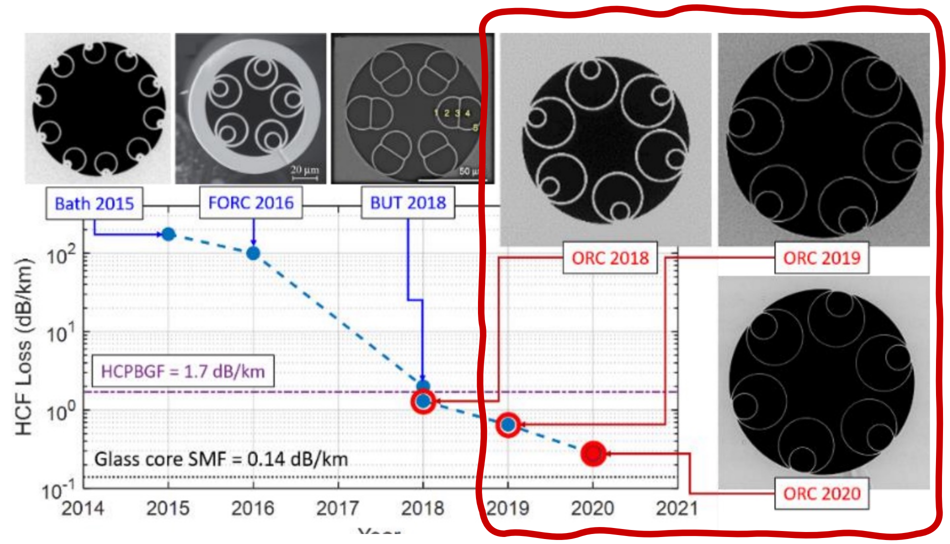


HCF is (mostly) a Great British Invention!!

First HCF proposal in 1991 was Photonic Bandgap

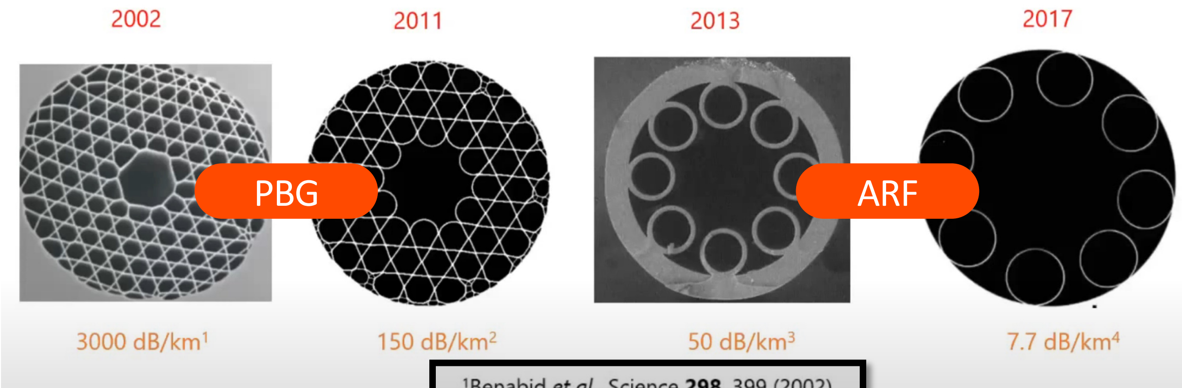
First AR-HCF proposal in 2011 by Dr. AD Pryamikov





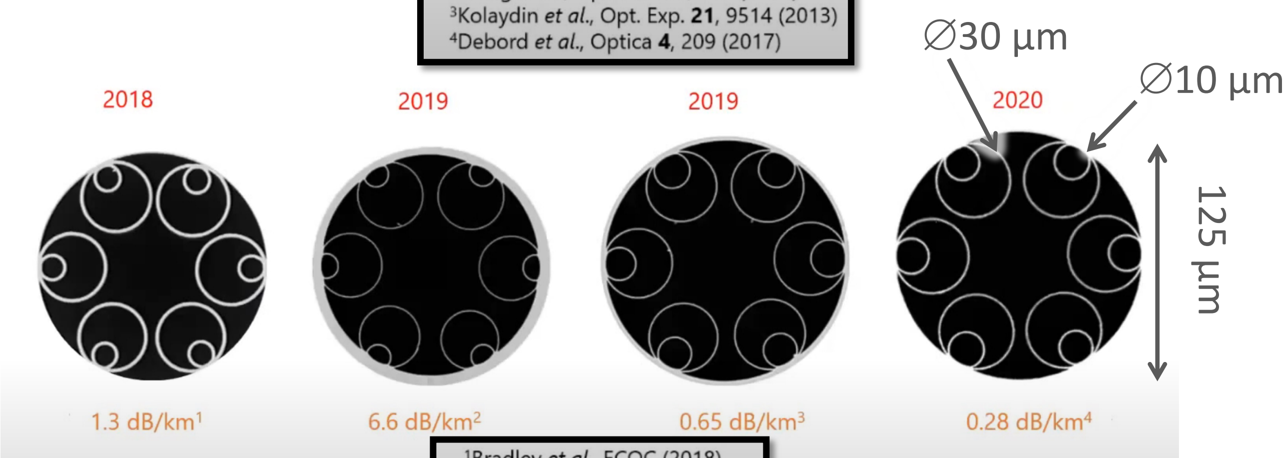
The most recent breakthroughs have been at Southampton University

Another evolutionary view



[1]Benabid *et al.*, Science **298**, 399 (2002)
[2]Wang *et al.*, Opt. Lett **36**, 669 (2011)
[3]Kolaydin *et al.*, Opt. Exp. **21**, 9514 (2013)
[4]Debord *et al.*, Optica **4**, 209 (2017)

PBG → ARF



[1]Bradley *et al.*, ECOC (2018)
[2]Sakr *et al.*, OFC (2019)
[3]Bradley *et al.*, ECOC (2019)
[4]Jaison *et al.*, OFC (2020)

Nested structures

The Big News This Year (Announced at OFC)

LUMENISITY
Connect. Light. Faster.

Press Release

Lumenisity® announces next generation of hollowcore fibre technology with lower loss than standard single-mode fibre

More spectrum = more capacity

DNANF

<0.22 dB per km at 1310 nm

<0.18 dB per km at 1550 nm

vs

SMF-28e+

<0.35 dB per km at 1310 nm

<0.20 dB per km at 1550 nm

SMF-28 ULL

<0.31 dB per km at 1310 nm

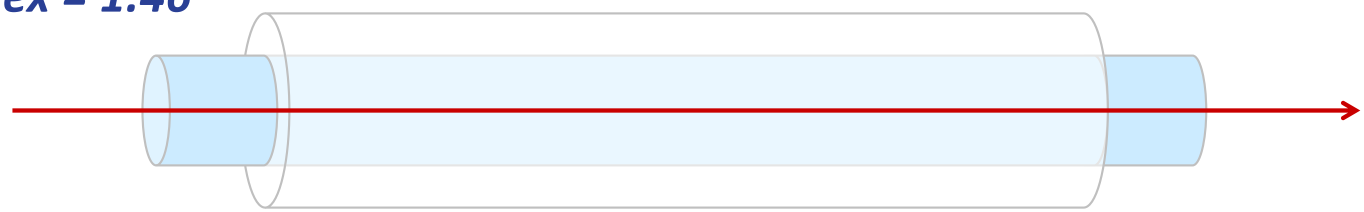
<0.17 dB per km at 1550 nm

Latency: Glass Core vs Air Core

Glass core

Refractive index = 1.46

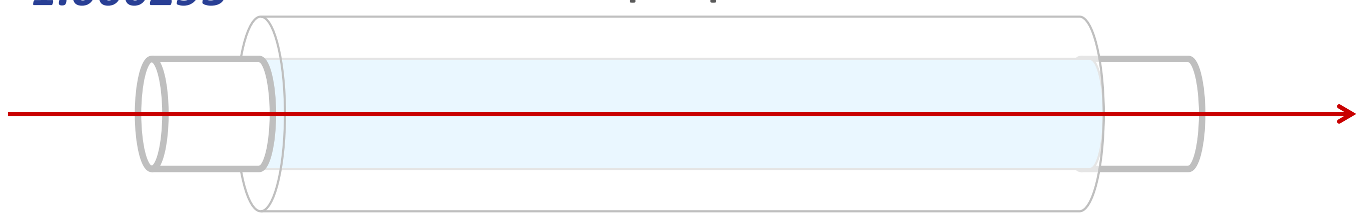
4.897 µs per km



Air core

Refractive index = 1.000293

3.353 µs per km



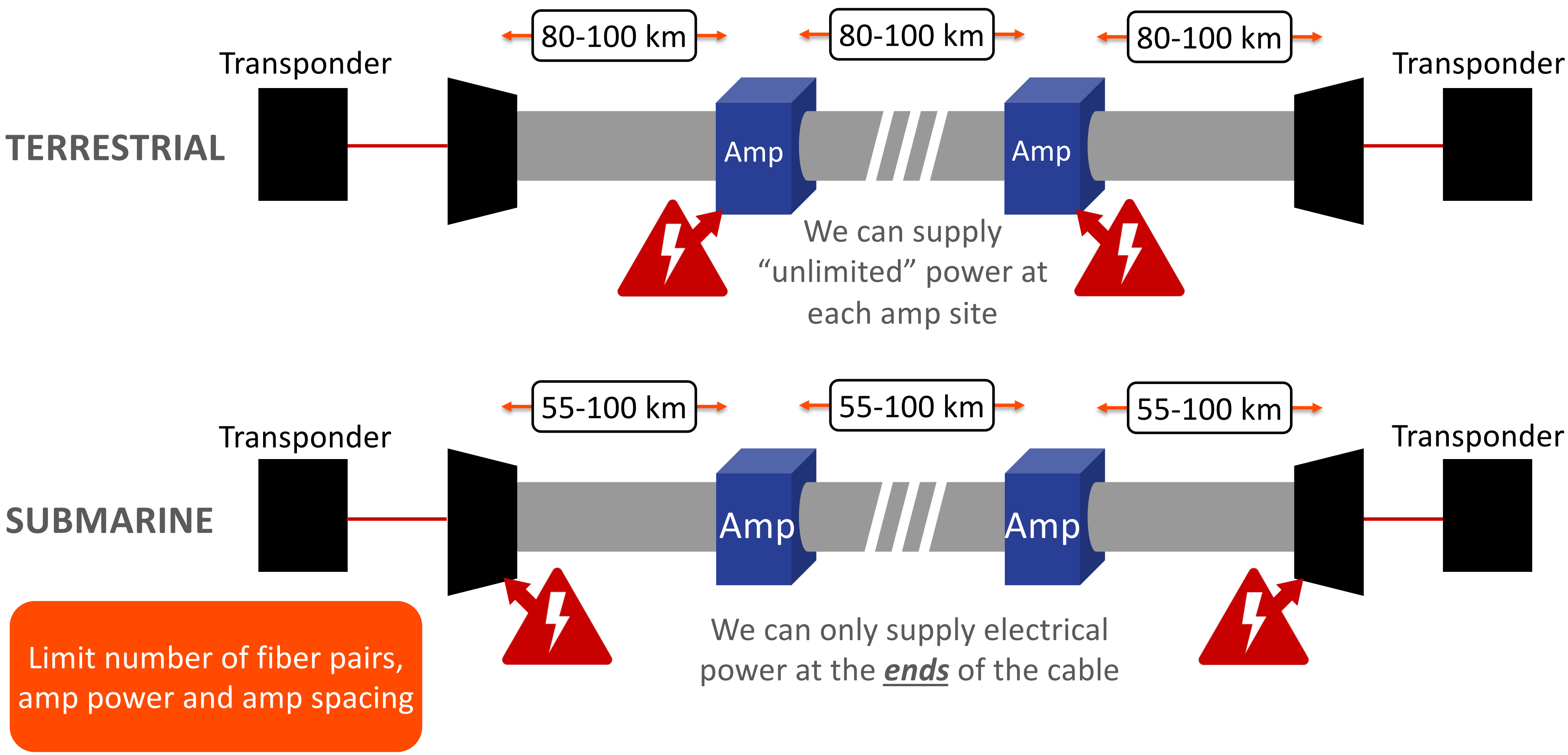
Hollow Core Fiber: Pros, Cons and Likely Scenarios

- Hollow core fiber now offers several advantages over glass core fiber
  - Low latency over a much wider band of wavelengths
  - Lower nonlinear penalty
  - 33% lower propagation latency
- No modifications needed to transponders
- Will it be possible to manufacture these intricate structures?
- If so, how much will it cost?
- Will they be durable in real deployments – including subsea?
- Will existing amplifiers work on HCF?
- How can we repair fibers in the field that may need internal vacuum?

Special Topic:

Submarine Cable Capacity Evolution

Terrestrial vs Submarine Amplification Power Supply



The Capacity Expansion Approach for Subsea Cables

Focus on total cable capacity, not on fiber pair capacity → Wider amp spacing, lower amp power, pump farming, etc.

We refer to this approach as Space Division Multiplexing (SDM)

Before SDM

Max transatlantic cable capacity of about **250 Tb/s**

(Assumes 6th Gen Transponders)

With SDM

Today	Planned	Roadmap
>300 Tb/s	**>500 Tb/s**	**1 Pb/s**
(12 FP)	**(24 FP)**	**(48 FP)**

Is there a Fiber Pair limit in Submarine Cables?

Yes: There are limits to the number of fibers before the industry has to develop a new, wider design

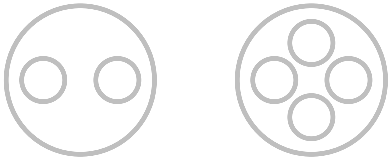
This is non-trival for something with a 25-year engineering life at the bottom of the ocean

Yes: The external diameter of the cable affects the total length that a cable ship can carry in a single load.

Negative impact on deployment economics

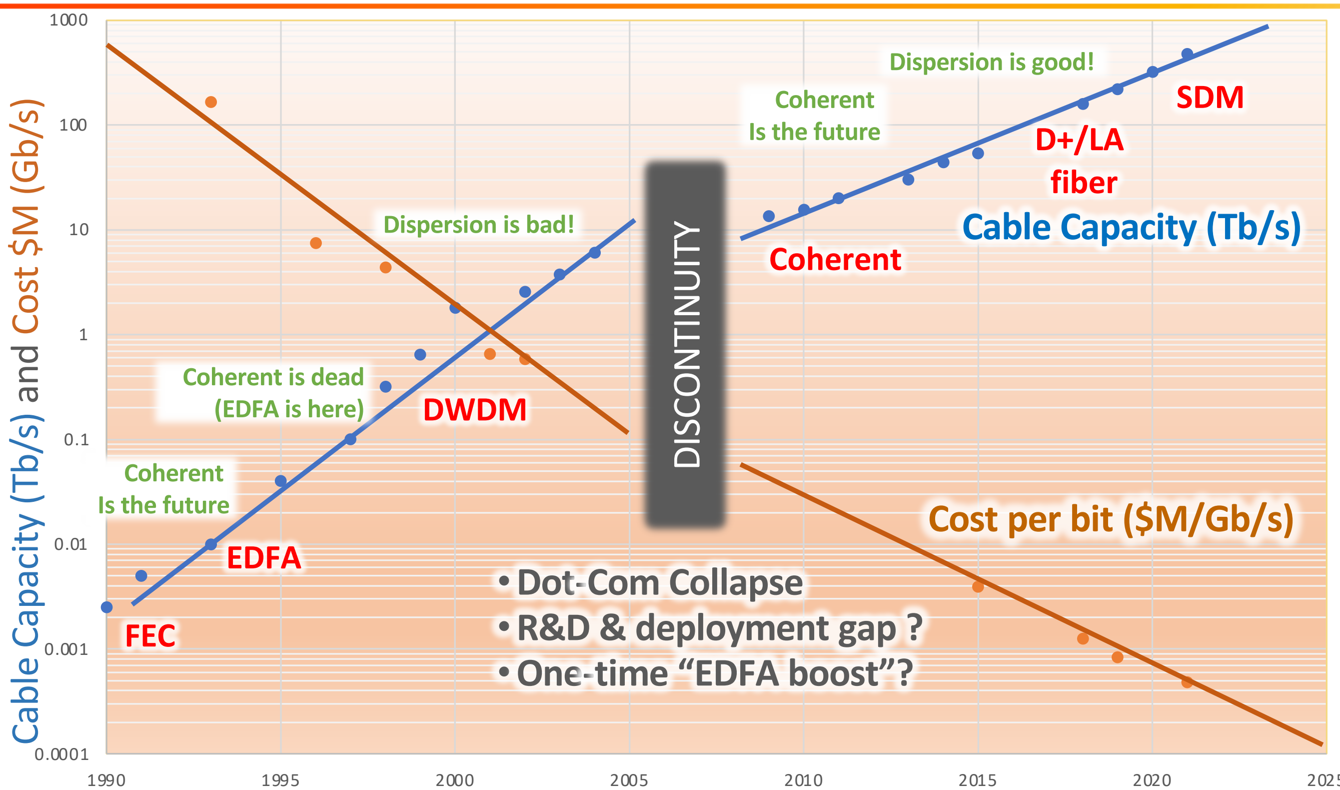
Future Fiber Types in Submarine Cables

- There are no plans for new fiber types in submarine cables for at least 2 years
  - ***Current fiber types will deliver up to 1 Pb/s transatlantic***
- Multicore, uncoupled fiber could be a good next step to save cable space while tracking future SDM cable architectures
  - ***Solving for cable diameter***
- Hollow core fiber is very interesting in submarine deployments because of the potential for higher capacity per fiber and much lower latency
  - ***Potentially solving for fiber pair capacity and latency***



2 and 4-core uncoupled fibers

Neptune's Law for Transatlantic Cables



Enabling Technologies

Conventional Wisdom

Dr. Steve Grubb, Meta

Neptune's Law

Submarine Cable Capacity Doubles Every 2 Years

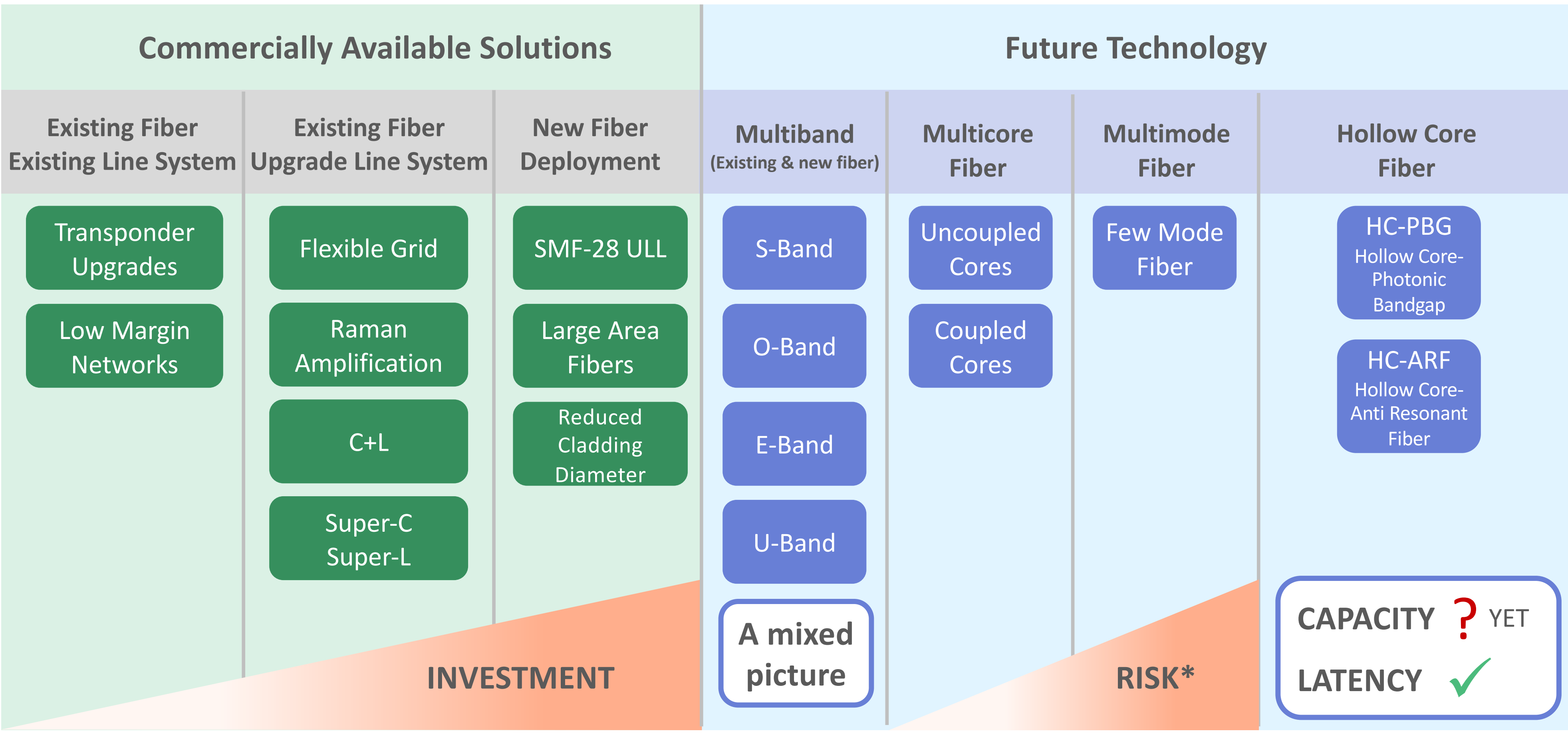
Submarine Cable Cost Per Gb/s Halves Every 3 Years

Summary of Submarine Cable Capacity Evolution

- Historically transatlantic submarine cable capacity has doubled every two years, and the cost per Gb/s has halved every three years (Neptune's Law)
- Until recently the focus was on capacity per fiber pair (FP)
- On the highest quality cables we are starting to reach practical FP capacity limits
- Future transponder generations may deliver higher wavelength data rates, but not that much more ***capacity per fiber pair***
- The focus has shifted to ***capacity per cable*** by compromising on fiber pair capacity and enabling higher fiber count cables – this is called SDM
- SDM has a roadmap to achieve a 1 Pb/s capacity transatlantic cable ***using proven technologies***
- There are practical limits on fiber pair count in submarine cables using today's fibers
- Multicore fiber can solve the problem of increasing cable diameter for "future SDM"
- Hollow core fiber could potentially solve the problem of ***fiber pair capacity*** and ***latency***
  - But there are many challenges for using HCF in both terrestrial and submarine cables

Let’s try to summarize the options…

A Summary Of The Options



*Likelihood of commercial maturity

Thank you!

I'm happy to answer questions if I can…

Geoff Bennett

gbennett@infinera.com