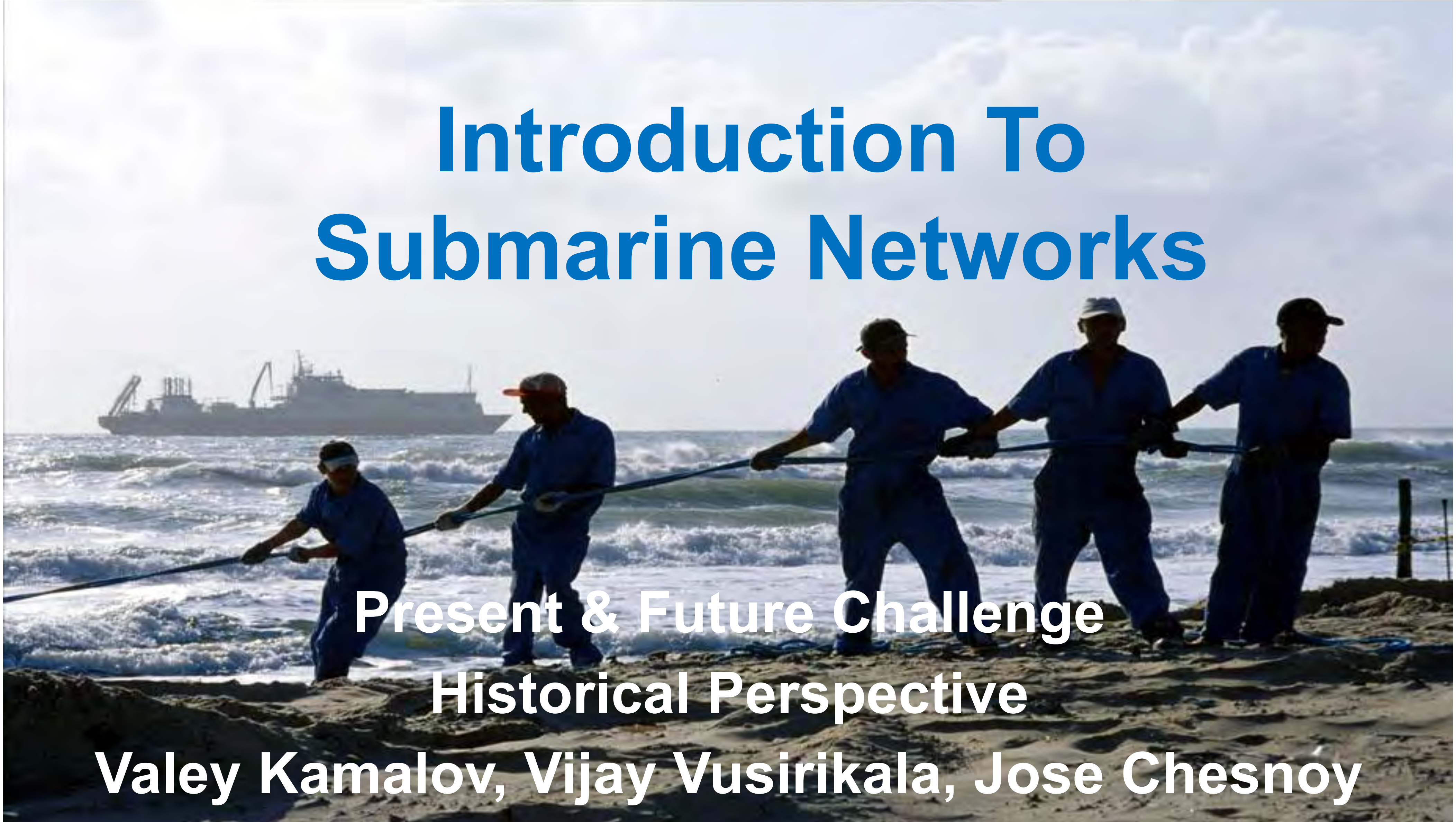


Introduction To Submarine Networks

Present & Future Challenge

Historical Perspective

Valey Kamalov, Vijay Vusirikala, Jose Chesnoy

Monday, August 5, 2019

Welcome from Google and OSA
lecture # 1-1. Valey Kamalov. Introduction to Submarine Networks
lecture # 2. Raynald Leconte. Cable ships and Marine equipment
lecture # 1-2. Vijay Vusirikala. Introduction to Submarine Networks
lecture # 4-1. Jean Christophe Antona. Optical transmission
lecture # 10-1. Michael François. System Planning
Roundtable 1. “Evolution of submarine networks and technology”, Lead: Elizabeth Rivera Hartling

Outline

9:00-10:15

- ► Foreword to Subsea OFC, Valey
- ► What is a submarine Network, Valey
- ► Flying over 150 years of submarine cable technology, Valey

1:30-2:30

- ► Modern networking: Life of a packet / Social Networks, Vijay
- ► Google and Google Cloud global network, Vijay
- ► Reaching the physical limit, Vijay
- ► What's next, Vijay

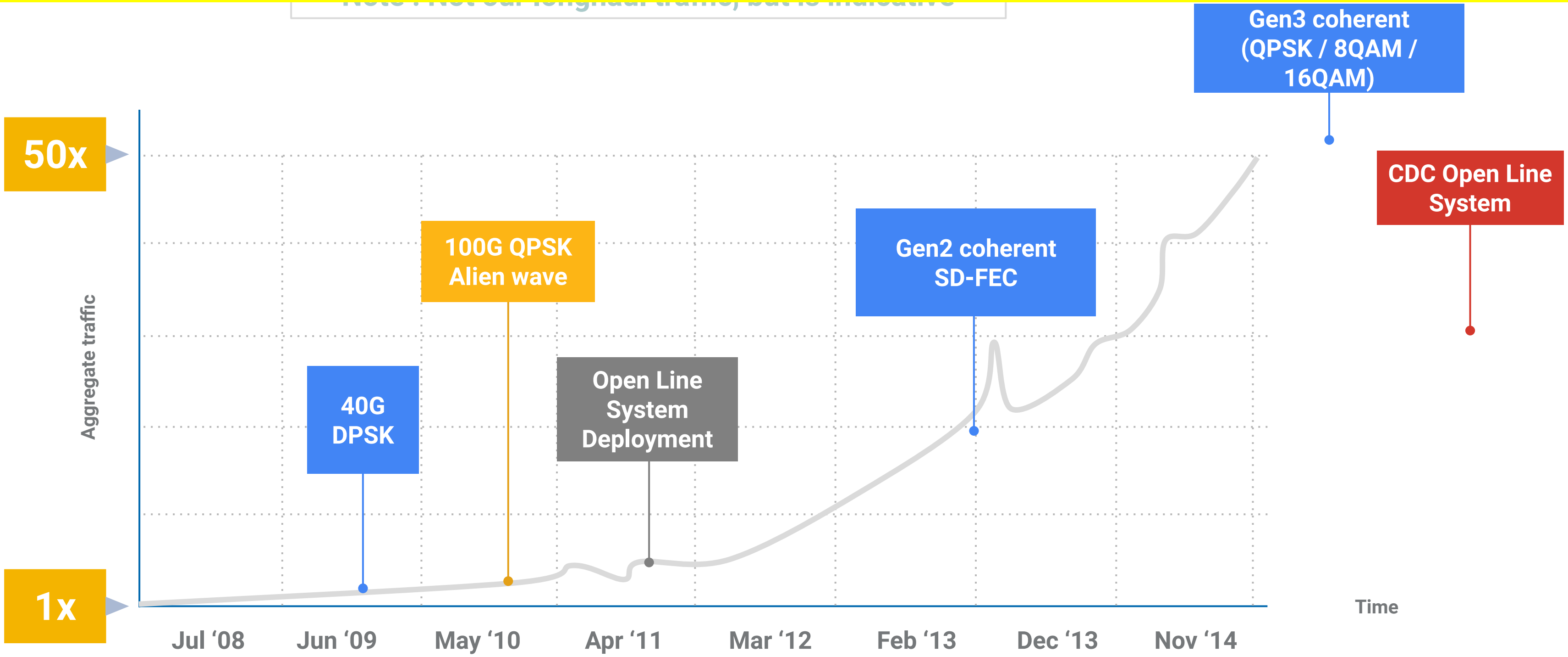
Foreword to Subsea OFC Innovation School 2019

- Math is required in 2020
  - *If I were again beginning my studies, I would follow the advice of Plato and start with mathematics (**Galileo Galilei**)*
- Spirit of innovation is desirable
  - *1st Trans-Atlantic Cable Adventure 1858 (lots of math involved)*
  - *Sputnik 1957 (and Sputnik moment), Apollo 1969 …………..*
- Worldwide tech talent gap is large
  - *A Star Is Born, Map of our students homeland*
  - *Young people need opportunities*
  - *Subsea industry needs young people, this school is to make you interested to join*

Subsea OFC 2019 Students

Information Revolution

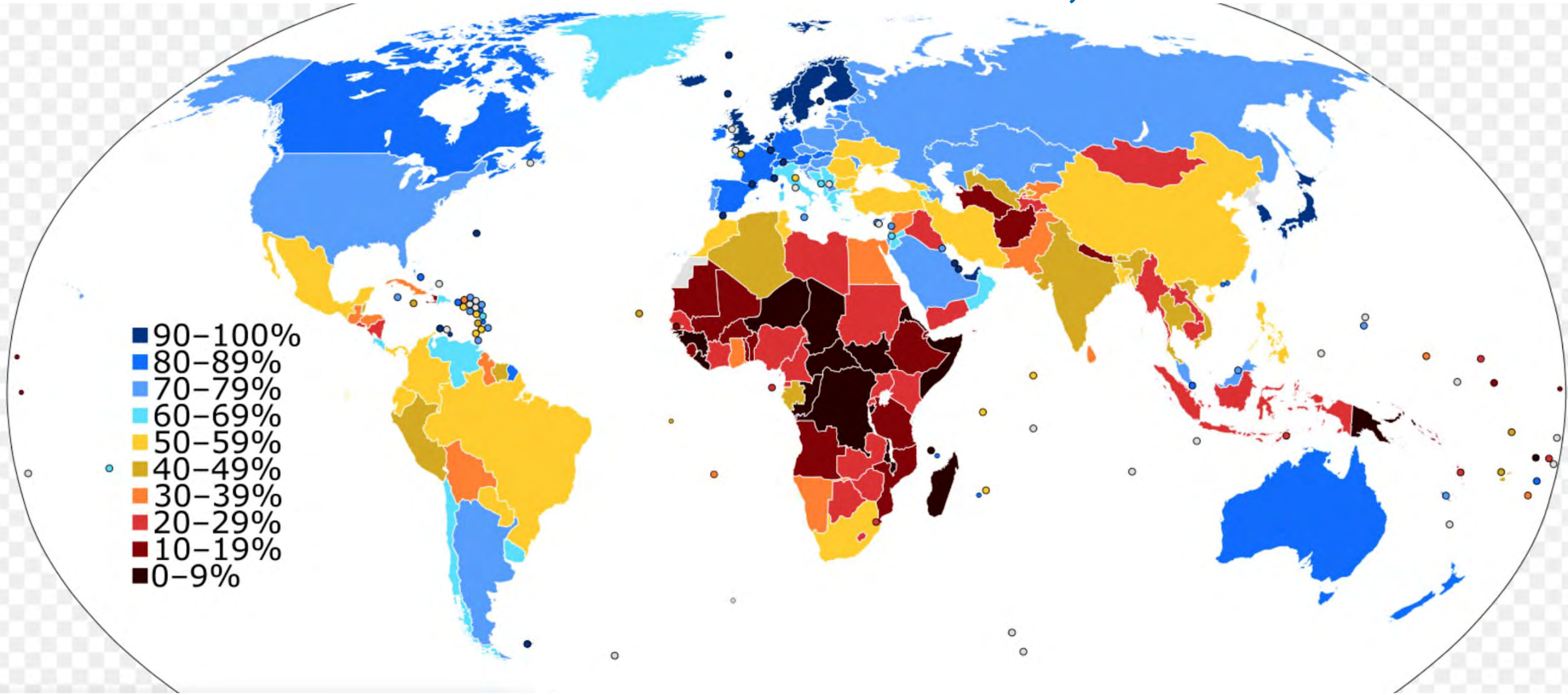
- The information revolution led us to the age of the internet
- Optical communication networks play a key role in delivering massive amounts of data

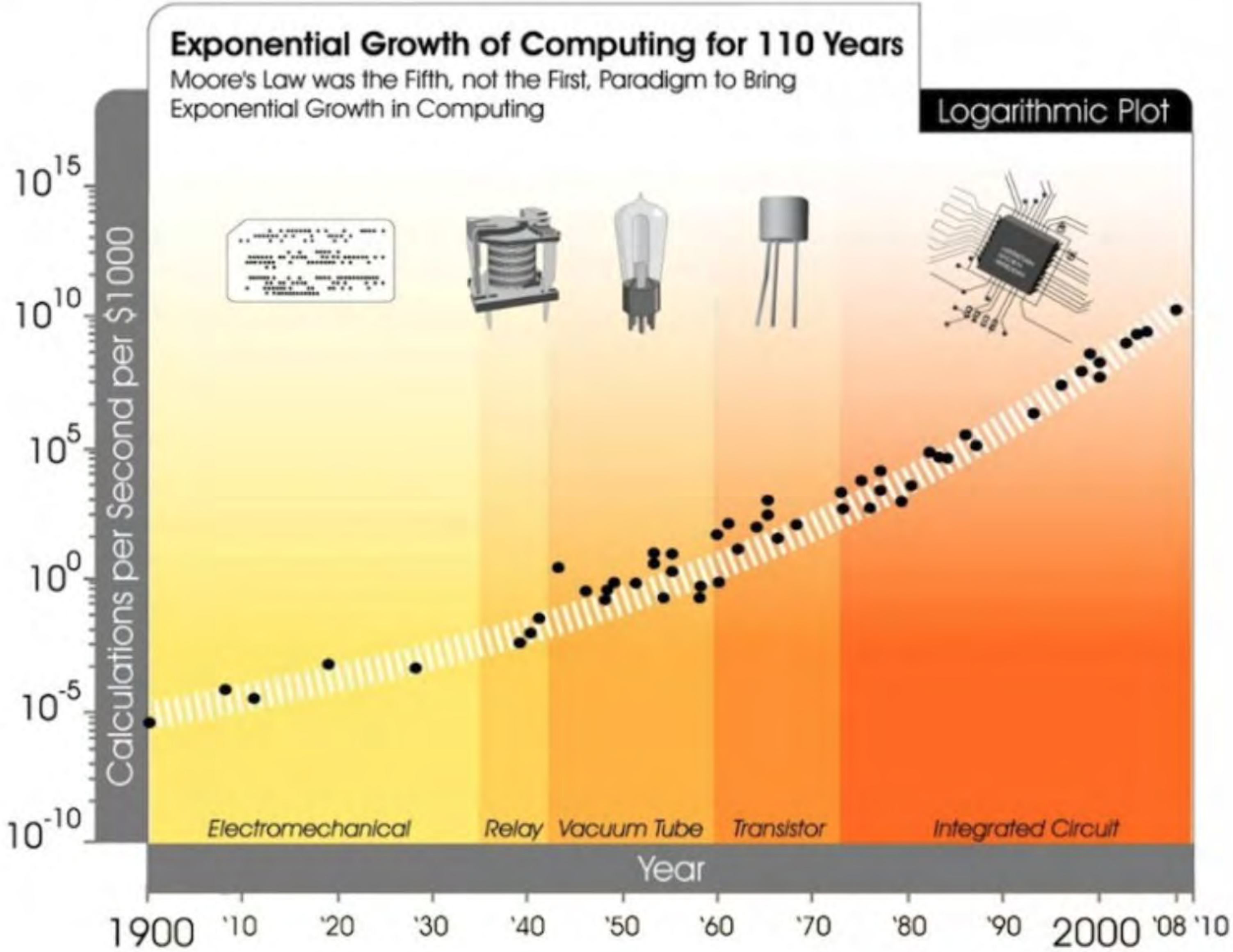


Further Growth Is Imminent

- The internet will continue to expand due to user population growth and internet penetration
  - *Previously inaccessible geographical regions in Africa and Asia will come online*
- Network growth will only be accelerated by improvements in integrated circuits
  - *Nielsen's law of internet bandwidth states: A high-end user's connection speed* ***grows by 50% per year.***
  - *Nielsen's Law of Internet Bandwidth has held true throughout a 36-year period. That doesn't necessarily mean that it will continue to be true for the next several decades, but it's certainly likely*

Internet Penetration Finland >90%, Africa <40%





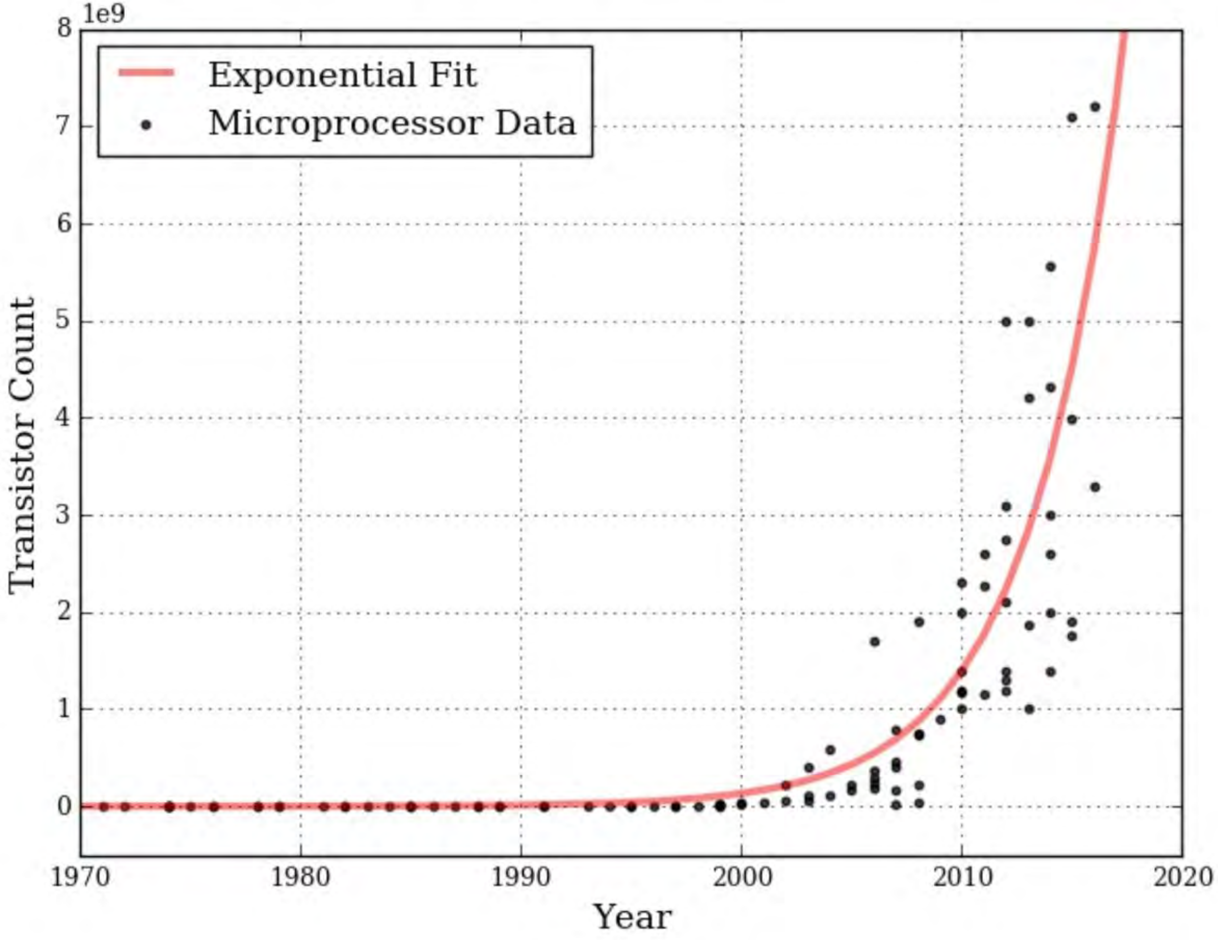
Kurzweil: evolutionary progress is exponential because of positive feedback (2001 essay entitled "The Law of Accelerating Returns")

Challenges in Subsea Communication Industry

Challenge 1: continue exponential push (more fibers or more cables?)

Challenge 2: add developing countries on the digital train (too expensive to build and maintain)

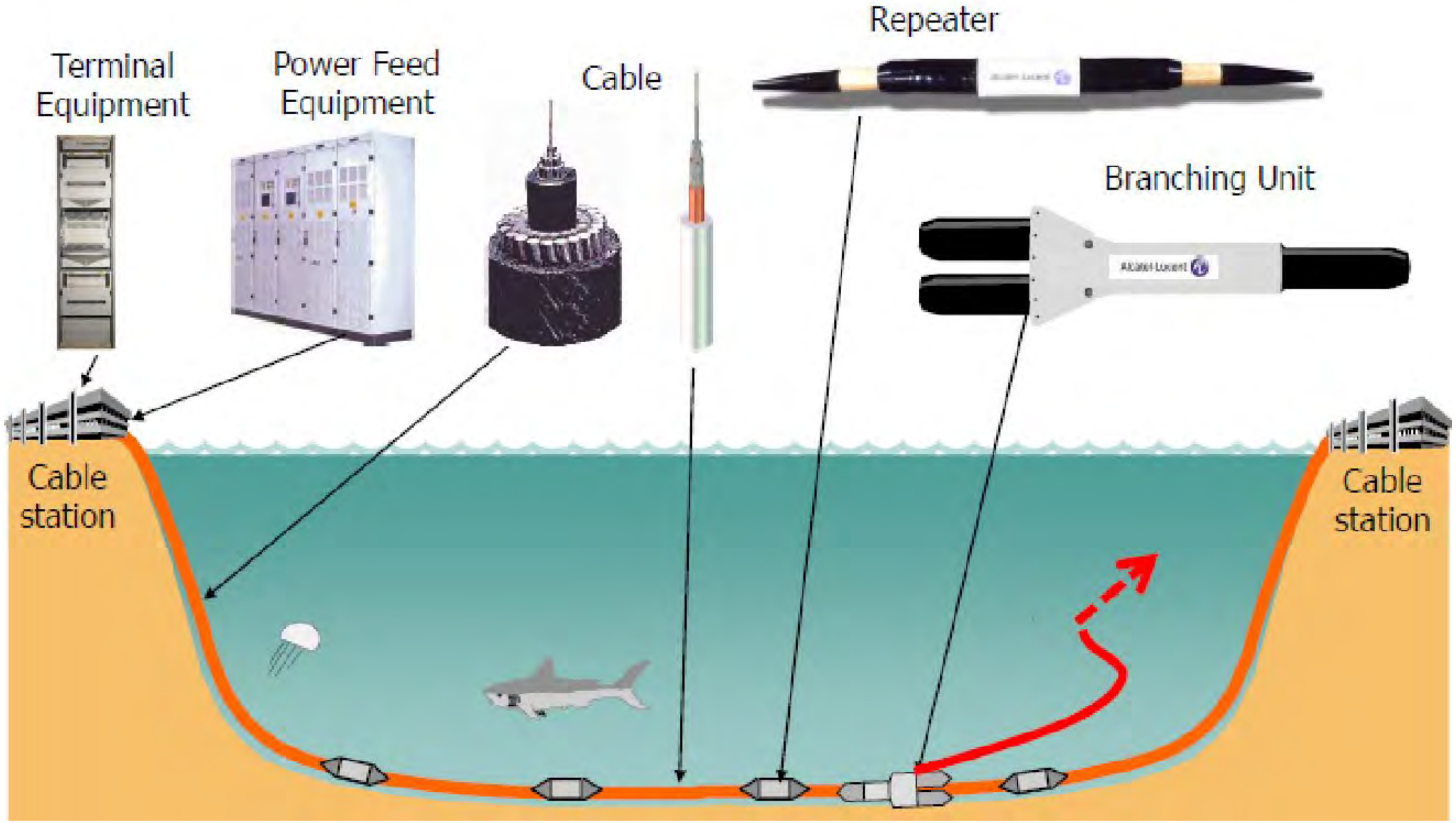
Number of transistors on the chip



What is a submarine Network

- Basic configurations
- Marine operations
- Submerged equipment
- Networks

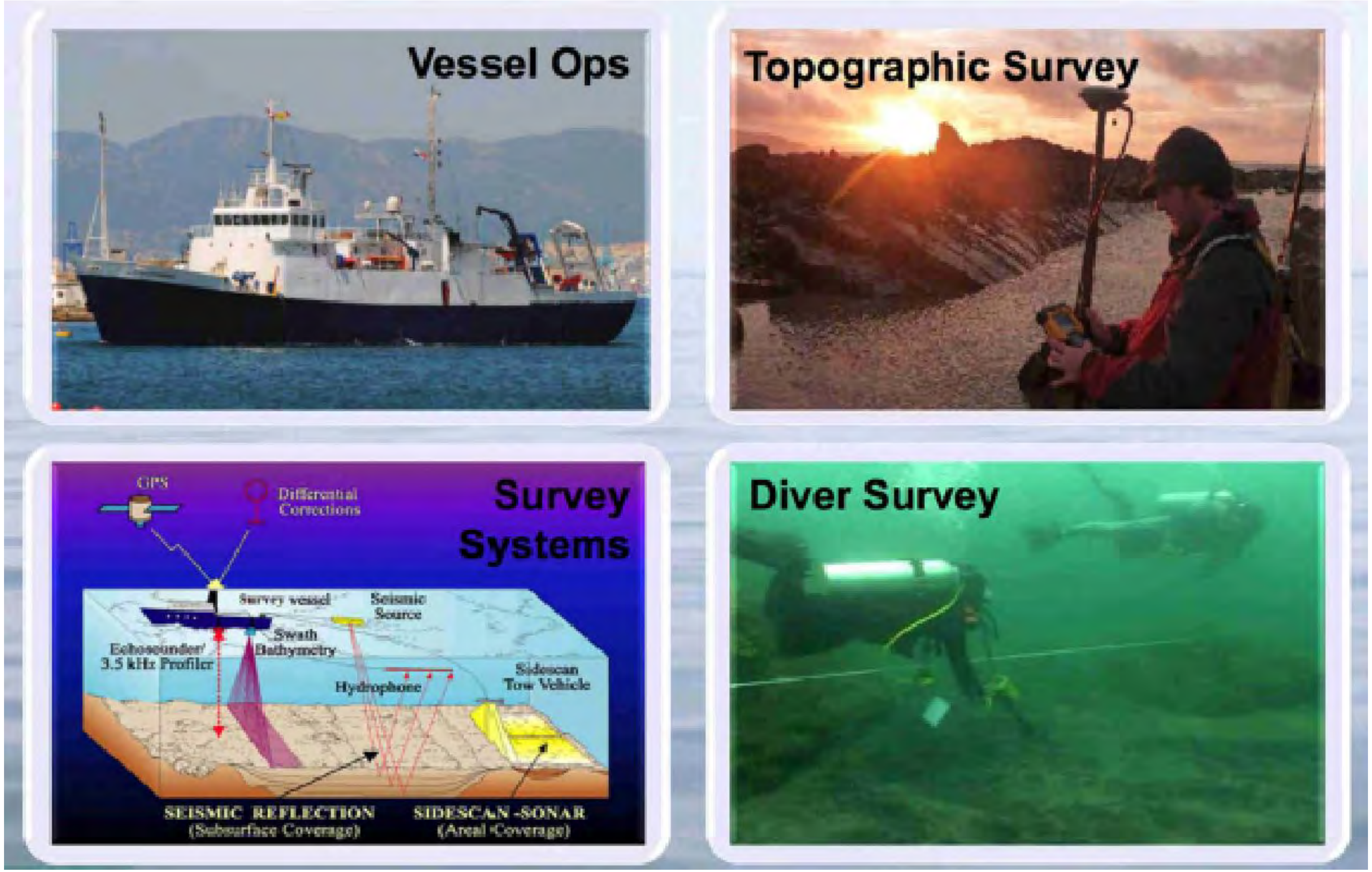
What is a submarine network/ basic configurations



What is a submarine network/ marine operations

- Large part of Cable cost
- Present along lifetime
  - Survey
  - Installation
  - maintenance

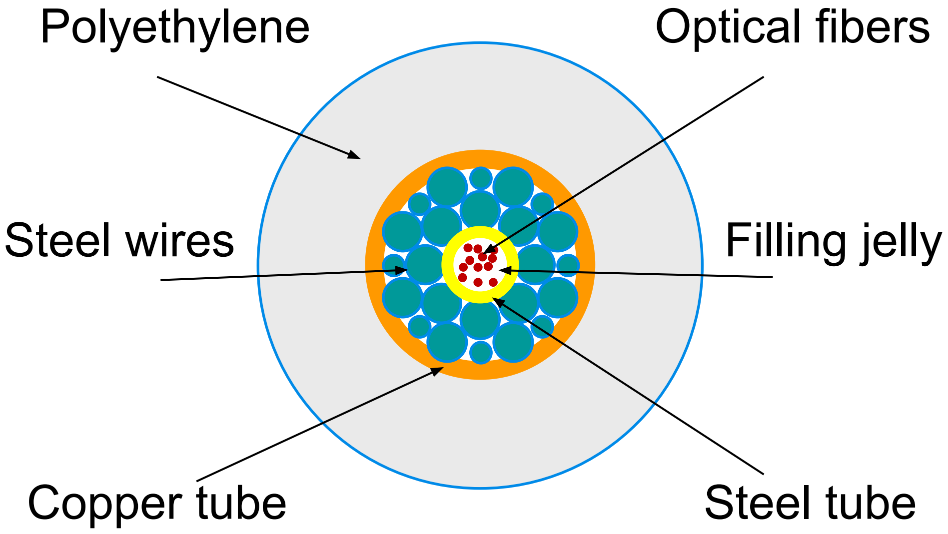
Marine operations: Survey



Marine operations: Installation

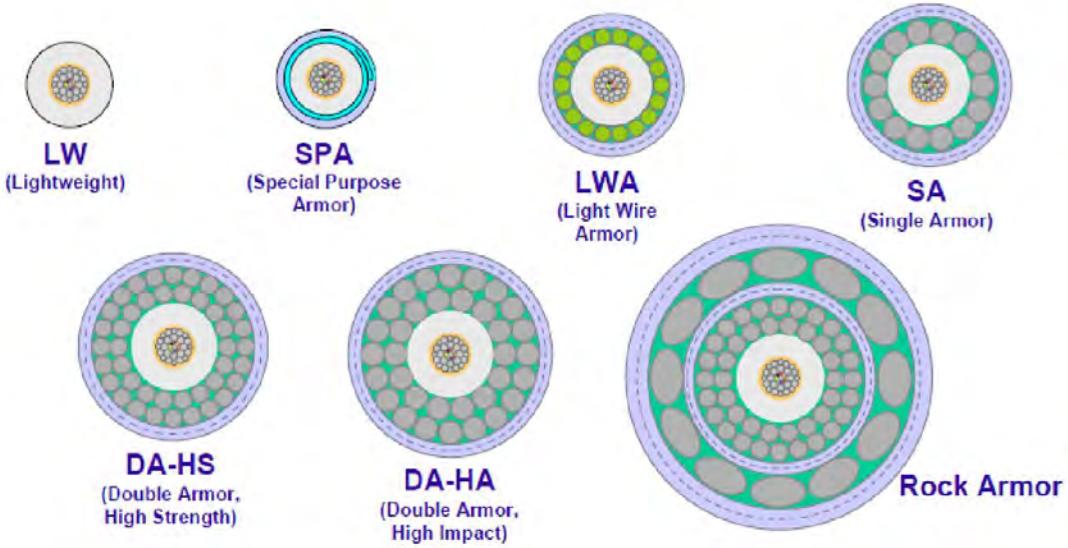
Marine Operations: maintenance & repair

What is a submarine network/ Cable



- **Function**
  - Protect the optical fiber
  - Power repeaters
- **Properties**
  - Optical
  - Mechanical strength
  - Pressure
  - Abrasion
  - Voltage
  - Chemical
  - H_2O barrier
  - H_2 barrier
  - Design life 25 years

What is a submarine network/ Cable



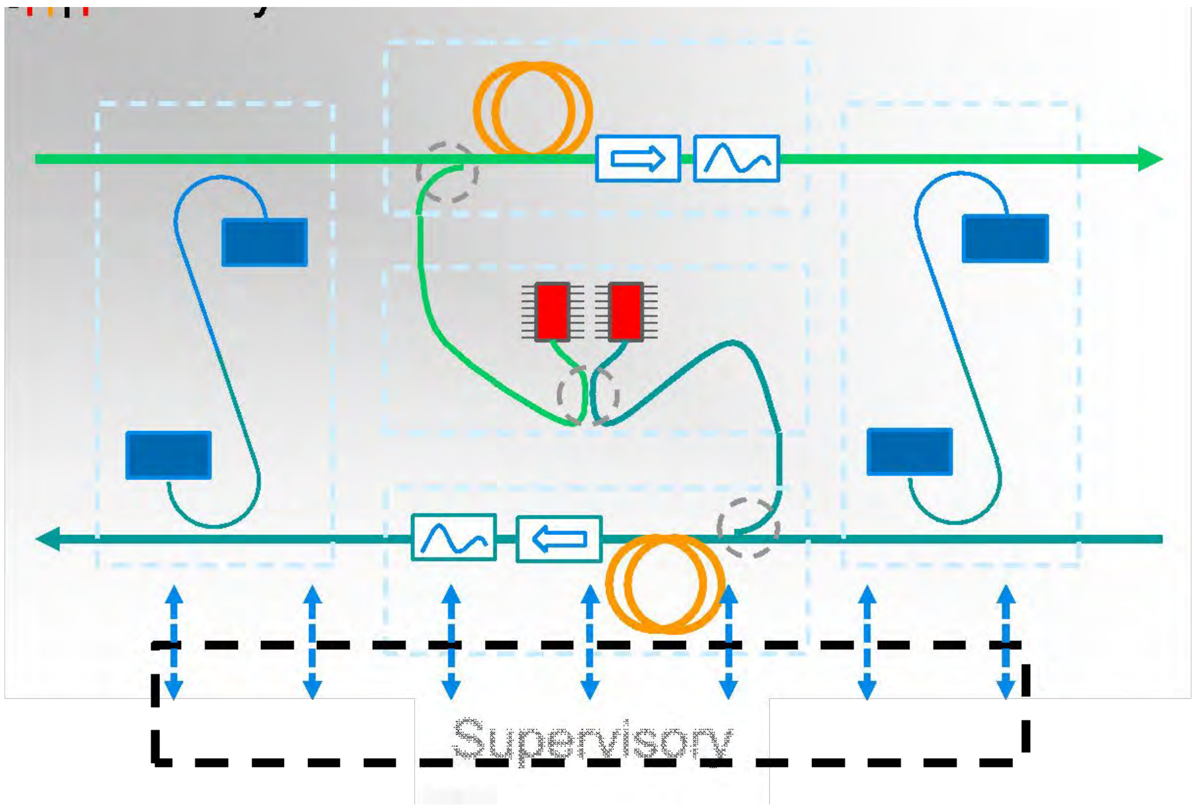
- All types based on the deep sea cable (Light Weight / LW)

What is a submarine network/ Repeater

- Function
  - Amplify optical signal
  - After attenuation through fiber
- Properties
  - Optical
  - Mechanical
  - Pressure
  - Voltage
  - Water ingress with difficulty of mobile fiber penetrators
- Active equipment
  - Semiconductor Optical pump lasers
  - Specific qualification/redundancy for 25 years design life

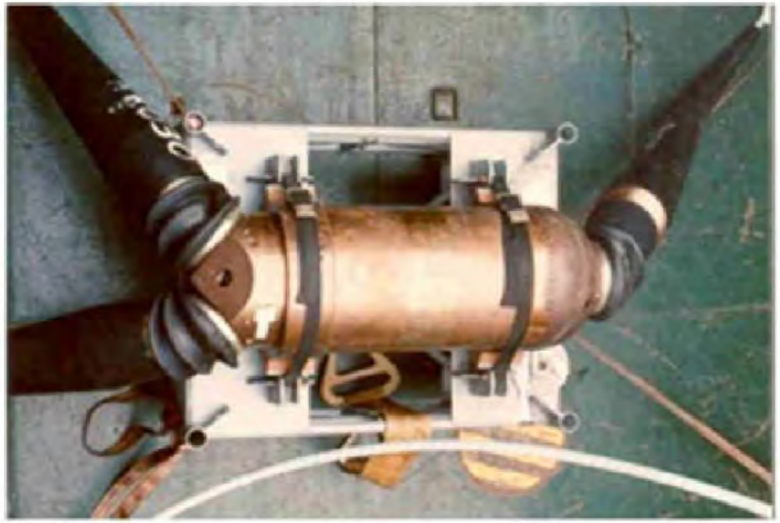
What is a submarine network/ Repeater

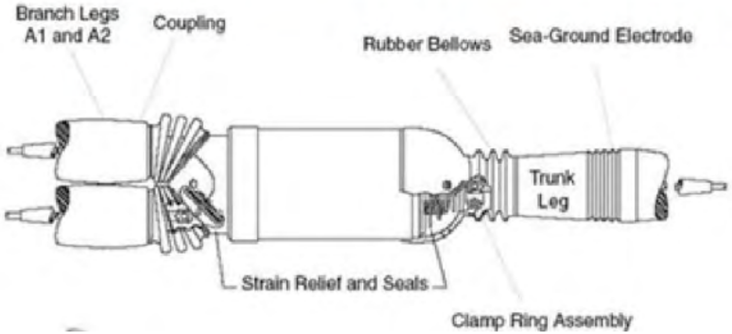
- **EDFA (Erbium Doped Fiber Amplifier)**



- EDFA Introduced in 1994
- Few change since…
  - Transparent
  - Enabling WDM
  - Reliable
- Ongoing evolution
  - Higher power
  - Pump « farming »
  - C + L band (?)
  - Raman (?)
  - SOA(?)

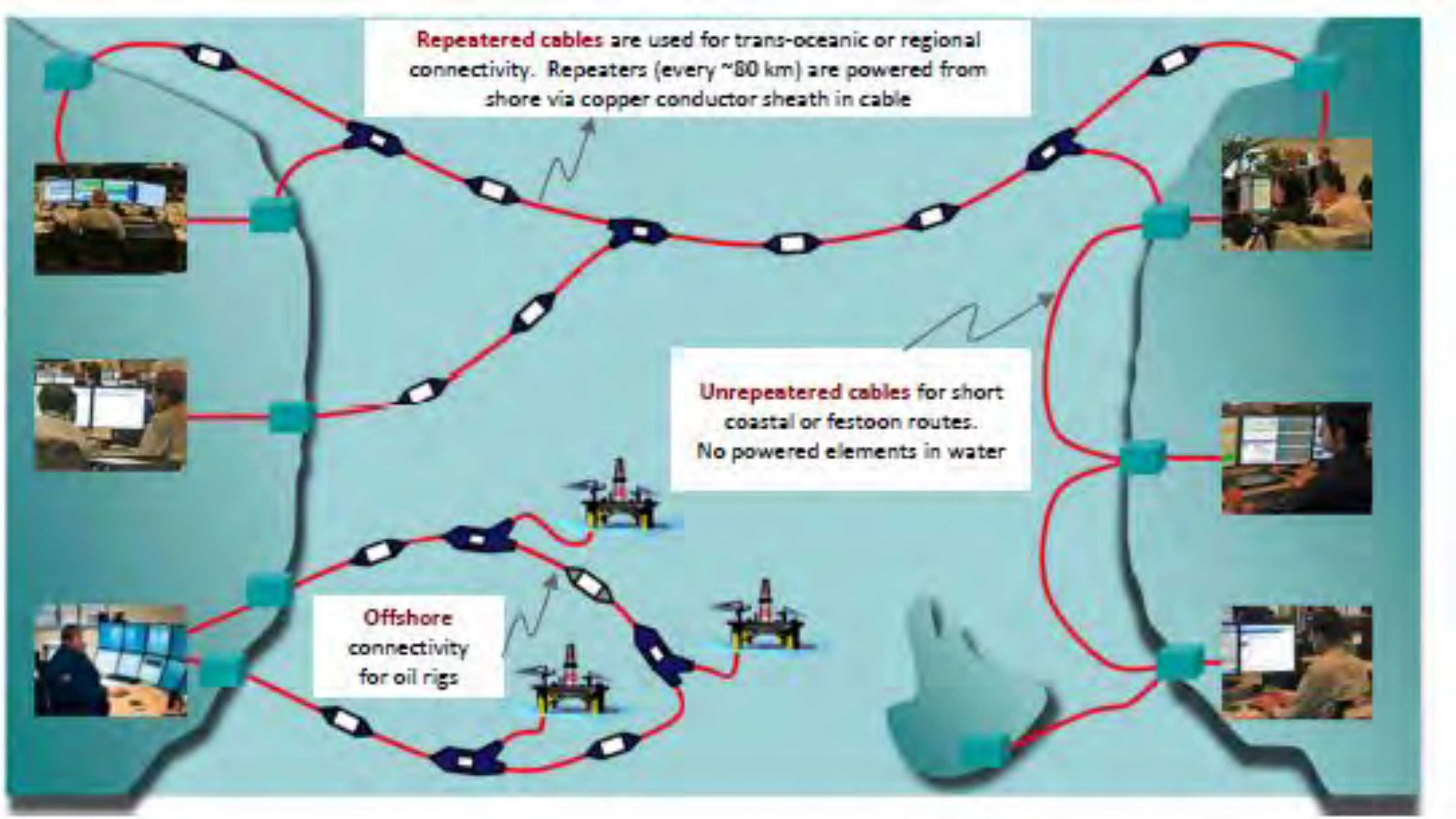
What is a submarine network/ Branching Unit (BU)





- ▶ Function
  - Split fiber path between 3 directions
- ▶ Properties (similar to repeater)
  - Optical
  - Mechanical
  - Pressure
  - Voltage
  - Water ingress with difficulty of mobile fiber penetrators
- ▶ Active equipment
  - Modern BU switch wavelengths and fibers
  - The more complex wet plant equipment

What is a submarine network/ basic configurations



Repeatered cables are used for trans-oceanic or regional connectivity. Repeaters (every ~80 km) are powered from shore via copper conductor sheath in cable

Unrepeatered cables for short coastal or festoon routes. No powered elements in water

Offshore connectivity for oil rigs

Permits

Large capital investment

- Each cable is a Large capital investment
- Complexity requires long lifetime
  - Modern cables are often designed for 25 years of service
  - Successful installation
  - Operation
  - Repairs
- All above depend on the system architecture and component reliability
- Solid project management is the key to success

Experience of several generations of engineers

- Lecturers bring you real life expertize
  - Subsea cable design
  - Installation
  - Maintenance in the harsh environment
- Lecturers are top experts in the field, recognized globally. I want to sincerely thank Lecturers of this School who spent considerable time to prepare, and to share their knowledge and expertise
  - Establish friendship and mentorship Lecturer - Student

Summer School Subsea OFC 2019

- School is intended to help the next generation of researchers and engineers who wants to change the world of subsea communications
- Could we find better and cheaper conductors compared to copper, which has been used since 1858? Could we find materials with better isolation properties than polyethylene, which was discovered almost a century ago?
- We have much more to do: the cost of submarine cables is unbearable for developing countries. Cable repair takes weeks. We lay cables at about the same speed as HMS “Agamemnon” did in 1858.

Innovations based on knowledge

- New ideas keep coming from the information transport community
  - Shannon / 32 y.o.
- We transport an order of magnitude more bits than just five years ago
  - We encode information into phase, polarization, and amplitude of electro-magnetic wave.
- Michael Faraday would be proud of us knowing that we send over 10,000,000,000,000 bits every second across the Atlantic Ocean in a single strand of fiber.
- We would leave in awe Sir William Thomson (known as Lord Kelvin), who was the scientific leader of an 1858 endeavor

The Uniqueness 1

- The **SubOptic community** is unique in that it has to care about environmental impacts
- AND the safety of cables
- AND the safety of data
- AND maintain a fleet capable of overcoming the challenges of the high seas
- AND solve the multi-dimensional problems of submarine projects and complexity of project management

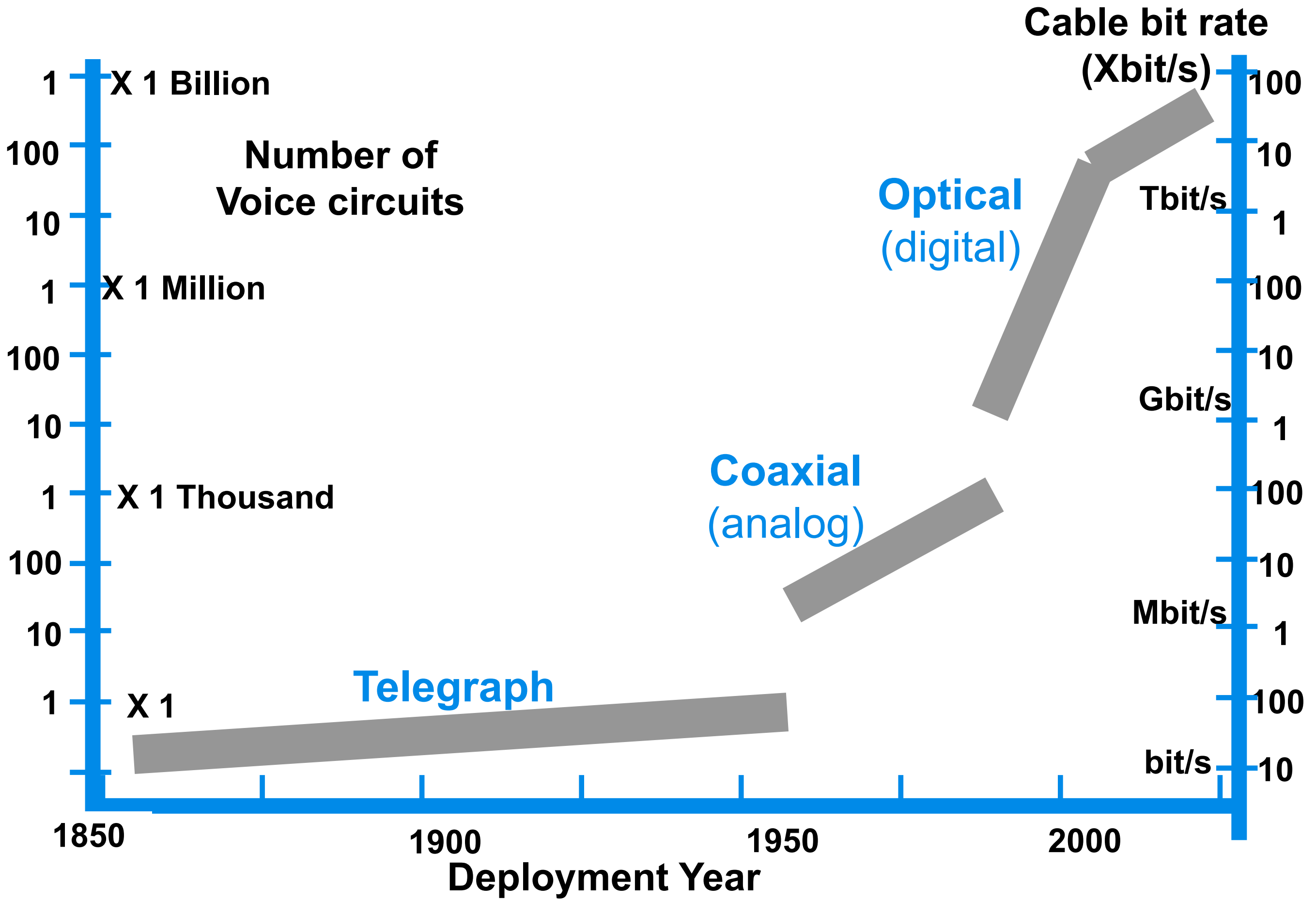
The Uniqueness 2

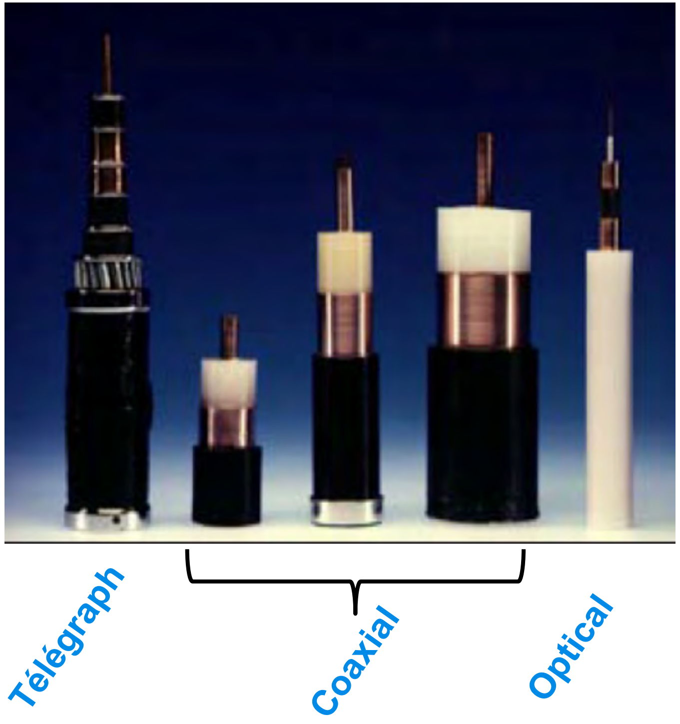
- The uniqueness of this engineering marvels is a combination of
  - information science,
  - nonlinear optics,
  - electrical engineering,
  - material science,
  - engineering practices,
  - project management,
  - marine expertise,
  - high reliability standard
- Undersea fiber communication systems will continue to serve society (with important contributions from the SubseaOFC2019 students?)

Outline.

- What is a submarine Network
- The endless race for capacity
- Life of a packet / Social Networks
- Flying over 150 years of submarine cable technology
  - Era of telegraphs
  - Era of Coaxial
  - Advent of fiber optics
- Basics of optical communications
- Reaching the physical limit
- What’s next

Flying over 150 years of submarine cable technology





Source: G Fouchard Elsevier 2015

150 years of submarine cable: telegraphic cable

The Great Eastern laying a cable 1866
(Original painting in ASN in Greenwich)

- USA connected to England in 1858
  - 1 word per minute…and lasting 20 days....Not reliable at all
- Blue book in UK in 1861
  - Opening the telegraphic era
  - 25 cables in the Atlantic from 1858 to 1928
- Epics of Great Eastern !!!!!
- Fortune of Telcon in UK
  - Telcon becoming later STC still presently integrated in ASN

150 years of submarine cable: coaxial cable

- With TAT-1: Coaxial cables won definitely against radio
- USA thus entered the game
  - AT&T took the lead of TAT-2
  - TAT-2 target to transport 3kHz voice channels
  - AT&T Invented consortiums: 1st construction & maintenance agreement
  - AT&T Invented the IRU: easy to share capacity between cable users
  - AT&T invented the model of « specification and inspection »
    - Permitting design in USA while production and lay was still European
- From years 1960’ all telegraphic cables were abandoned
  - With the transistor, wideband coaxial cables reached 40 MHz
  - In 20 years, STC and Alcatel built 250 000 km cables and 1000 repeaters

150 years of submarine cable: the advent of Optics

- Radiocommunication had not said its final word!!!!!!
- April 6th 1965 Launch of Early Bird:
  - the the first communication satellite
- All countries equipped with their satellite earth stations from 1965

- During this « dark » time, coaxial cable technology stagnated
  - The common view in 1970 was that submarine cables are dead
- But submarine cables were saved by optical fibers!!!
  - Terrestrial radio-satellite stations all decommissioned before 2000 !
  - The idea that satellite can do better that submarine cables survived !

150 years of submarine cable: the advent of Optics

- What made possible optical cables
  - Invention of silica optical fibers: 1966 by KC.Kao (Nobel prize)
  - Simultaneous invention of the semiconductor laser by R.Hall (1962)
  - New competition of satellite telecommunications (Intelsat 1 in 1965/4 years in service)
  - Fast optical technology development
- In years 1960’s:
  - Multimode fibers at 850 nm
  - single mode fibers at 1300 nm, then 1500 nm
- Key demonstration in 1970 with optical fibers
  - 20dB/km fiber + GaAs room temperature laser

150 years of submarine cable: the advent of optics

- First demonstration of regenerated optical cables
  - Demonstrator (2 repeaters) Antibes-Port Grimaud : 1984
  - First optical transoceanic **TAT-8** & TPC-3 in 1987 (1300nm 280 Mbit/s)
  - Second generation transoceanic TAT-9 in 1989 (1500nm 560Mbit/s)
- Modern cables came with optical amplification
  - Fiber amplifiers EDFA demonstration in 1986 (E.Desurvire)
  - First EDFA transoceanic cable **TAT-12/13** in 1996 (5 Gbit/s)
- Then the capacity of optical cables increased by X2 every year
  - 250 Tbit/s with TA DUNANT Cable
- Low latency Satellite Communication - new competition cycle is coming

SpaceX(Elon Musk) 4,425 satellites with 24Tbit/s bandwidth

Compare to 2,000 Tbit/s international capacity today = 1% will be AFTER SpaceX is accomplished

new LEO satellites are designed for 5 years service (vs 25 years cables)

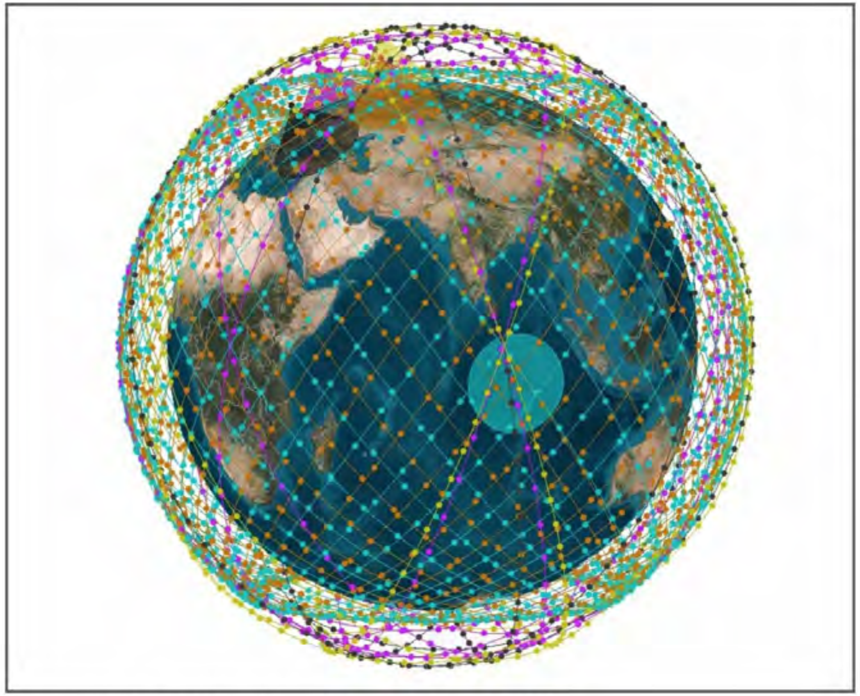


Figure 2.- SpaceX 4,425 satellites constellation

System characteristics

- 4,425 Satellites in 83 planes. Inclined orbits + polar orbits.

- User links @ Ku-band, gateway links @Ka-band
- Optical crosslinks between satellites
- Digital payload with beam steering and shaping capabilities

- Medium size satellites 386 kg, in house designed.
- Target first launch 2019 (~170 Falcon 9 launches for full constellation deployment)
- Beginning of service 2020

Image credit: SpaceX

Epilogue of historical survey: Believe in the future

- Submarine cables are enabling the today Internet
  - Thanks to optical fiber and optical amplifiers
- Remember:
  - In 1920: submarine cables were challenged by radiocommunications
    - And could have disappeared in 1930
  - In 1980: submarine cables were challenged by satellites….
    - And could have disappeared in 1990
  - In 2019: submarine cables carry >99% of the intercontinental Internet traffic
    - Satellites are still nice for television distribution and communication in the deserts….
- Submarine cables wait for their next challenger…

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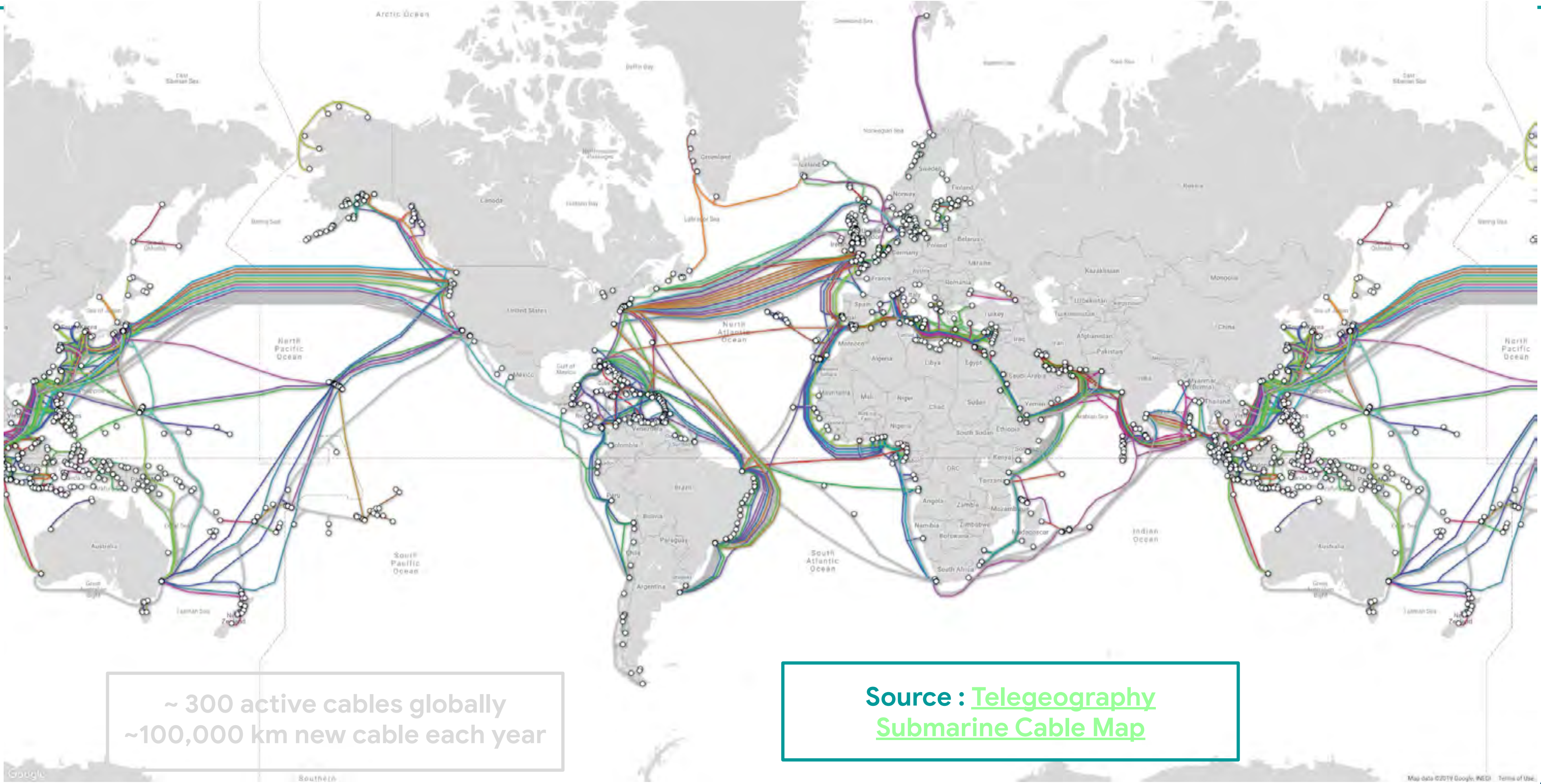
- ► Google and Google Cloud global network, Vijay
- ► Reaching the physical limit, Vijay
- ► What’s next, Vijay

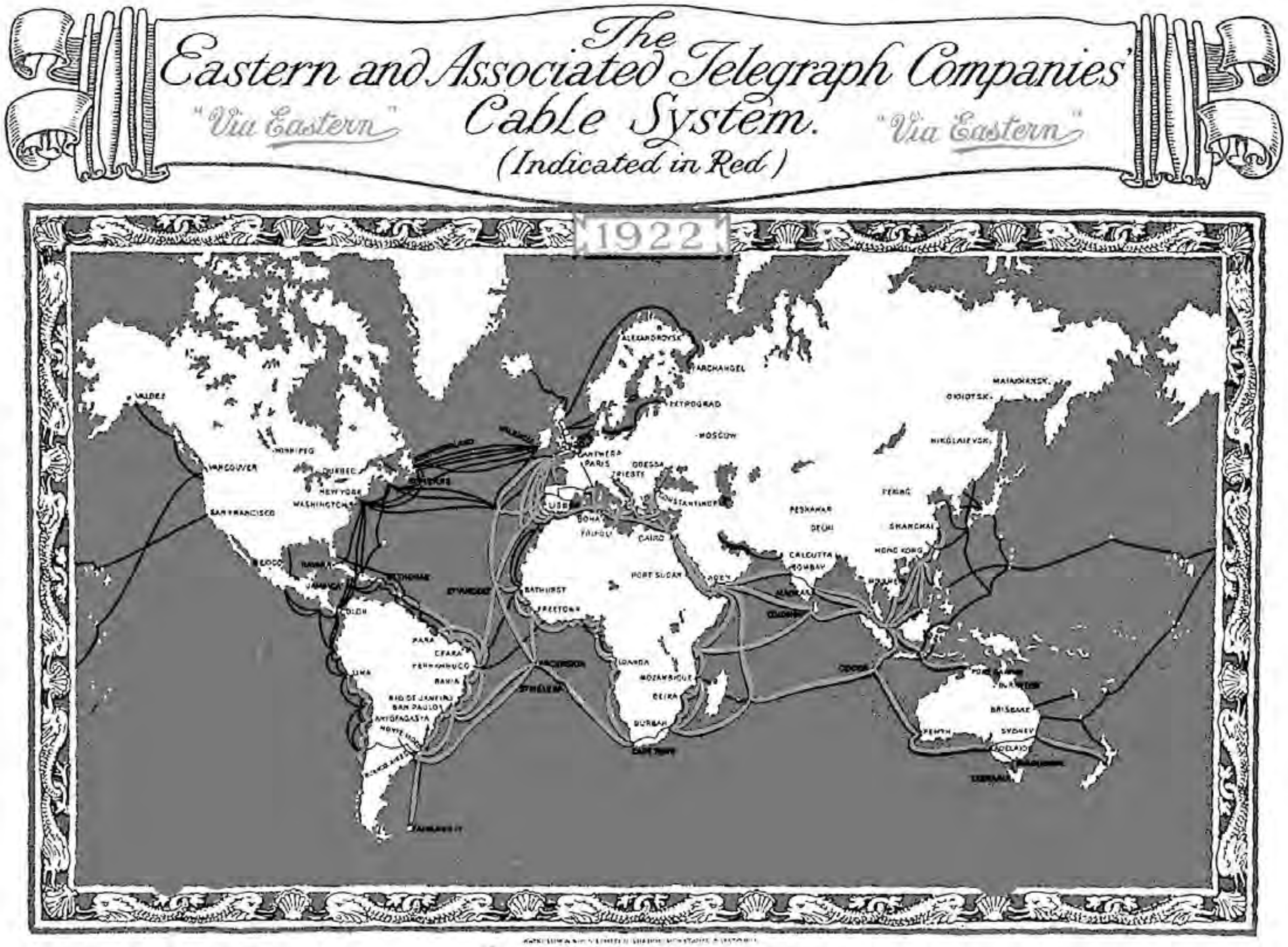
The endless race for capacity: Global networks today



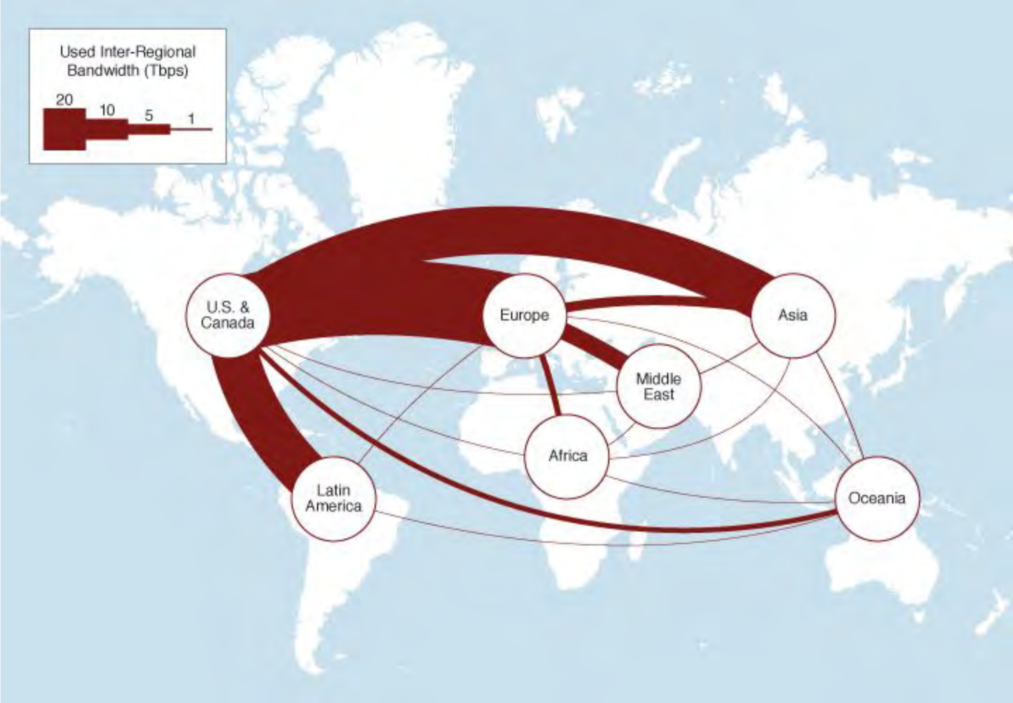
~ 300 active cables globally
~100,000 km new cable each year

Source : Telegeography Submarine Cable Map

The endless race for capacity: 100 Years Ago !!!



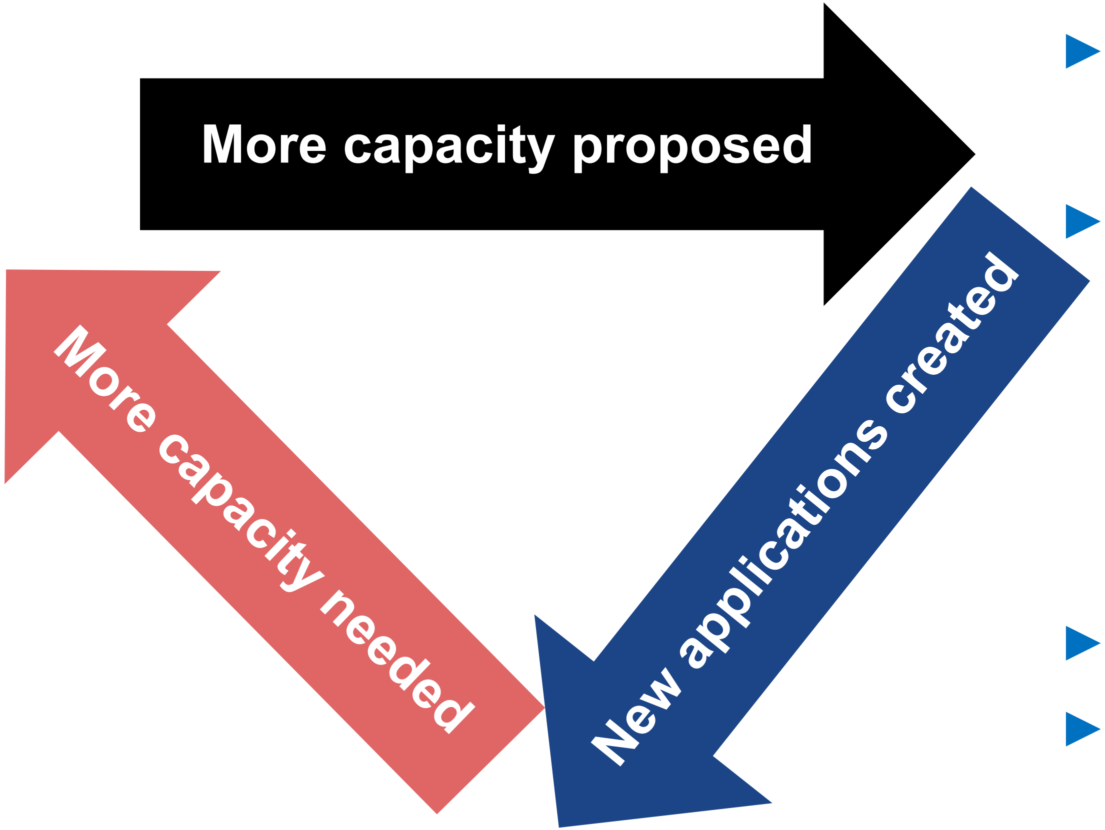
Population (GDP) Gravity Models and Data center Overlay



Source : Telegeography

- Capacity needs have traditionally followed population and GDP gravity models (user facing networks)
- Overlaid on this are datacenter connectivity trunks, if DCs are located in remote locations

The endless race for capacity: the virtuous cycle



- Capacity availability
  - Fueled by demand
- Demand
  - Fueled by available capacity

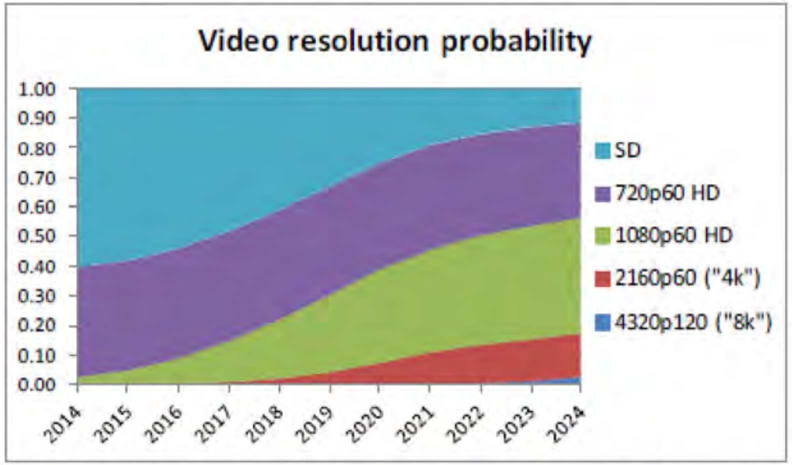
- Perpetual motion…
- Never denied since 150 years

Outline

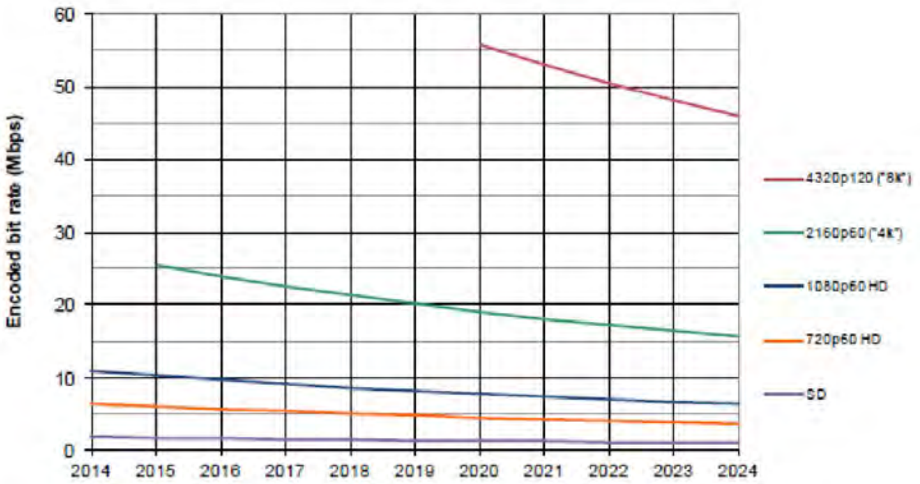
- What is a submarine Network
- The endless race for capacity
- Life of a packet / Social Networks
  - Needs for more traffic
  - Google and Google Cloud Global Network
- Flying over 150 years of submarine cable technology
- Basics of optical communications
- Reaching the physical limit
- Zoom on upgrades
- From Telcos to OTTs
- What next

Lifetime of a packet - Social Networks

- Video demand quality: increasing video stream bit
- Slow progress of video compression



Stream resolution distribution forecast t

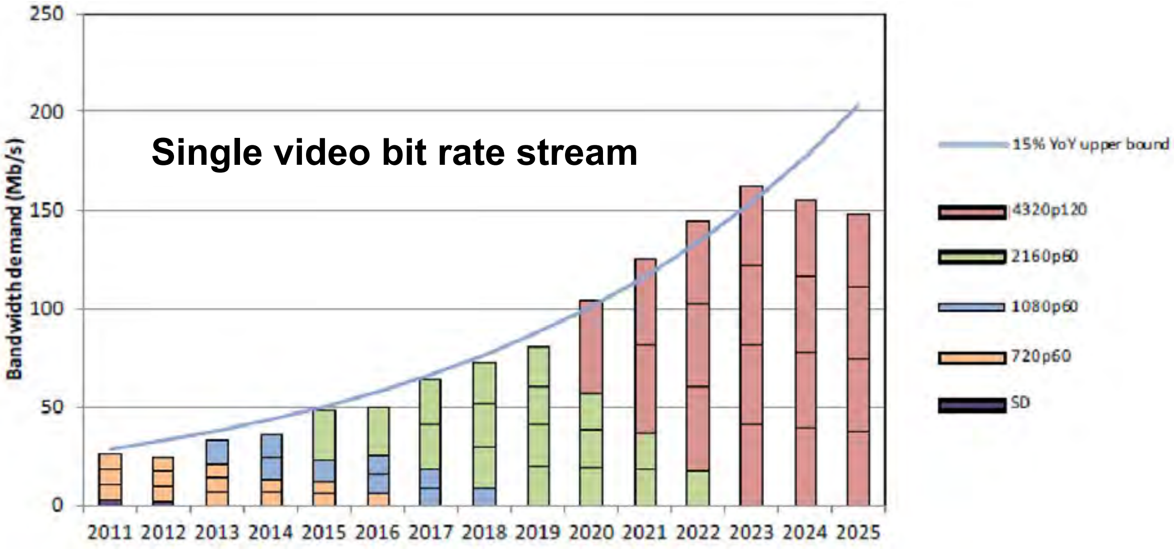


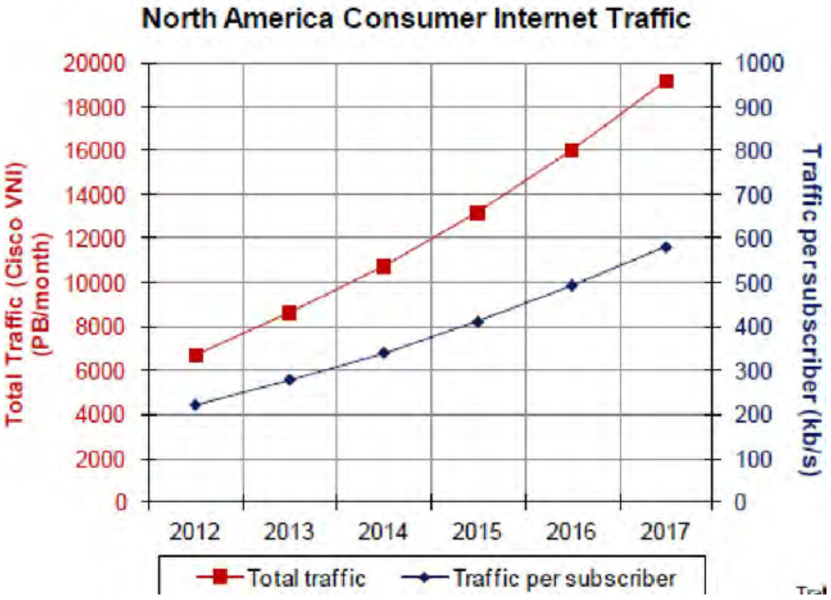
Encoded video bit rate forecast

Source Alcatel-Lucent 2014

Lifetime of a packet - Social Networks

- The video bit rate stream increases
  - Illustrating low impact of improved compression
- In addition the traffic grows due to increasing time per user

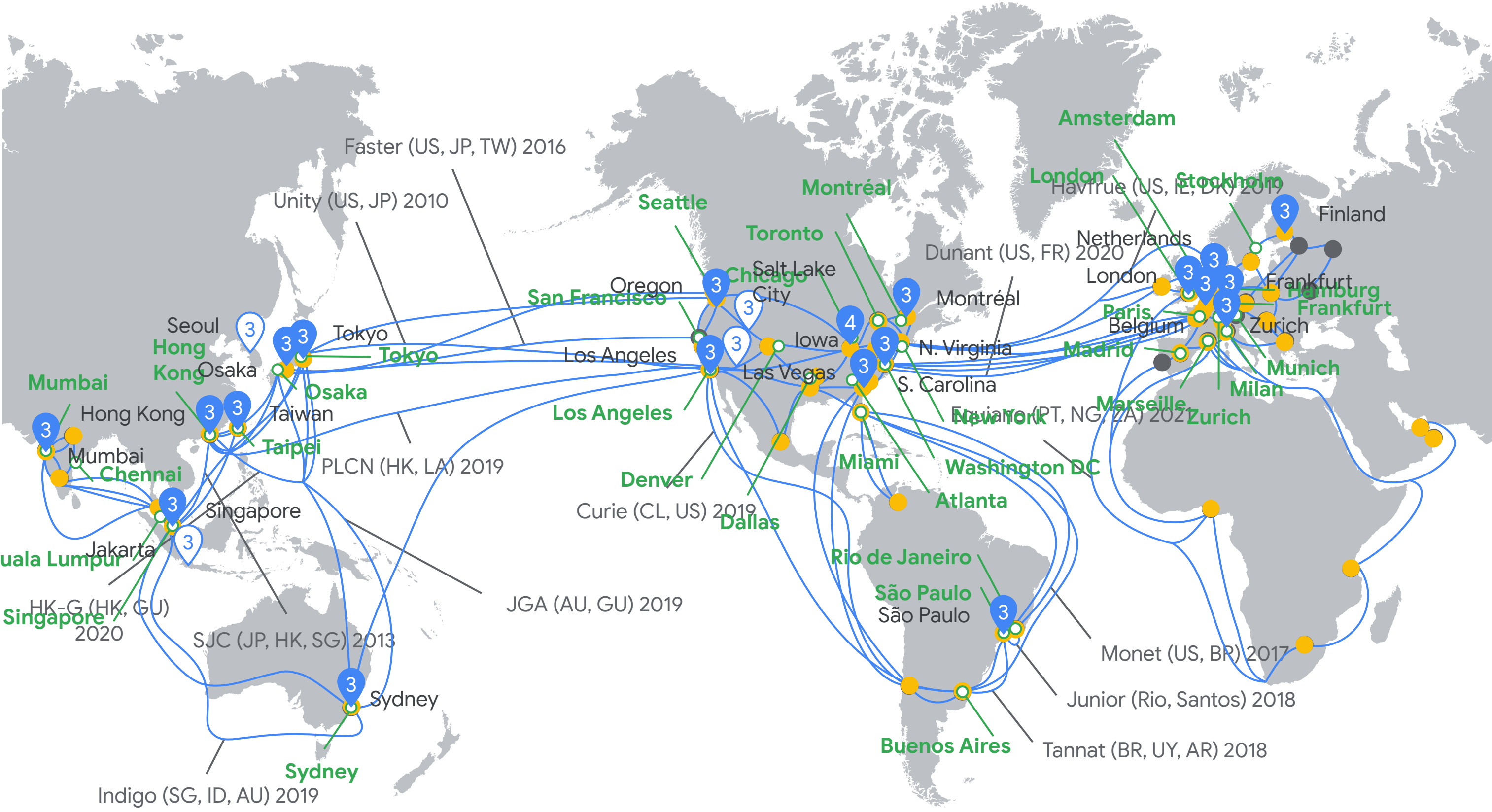




Google Cloud Platform

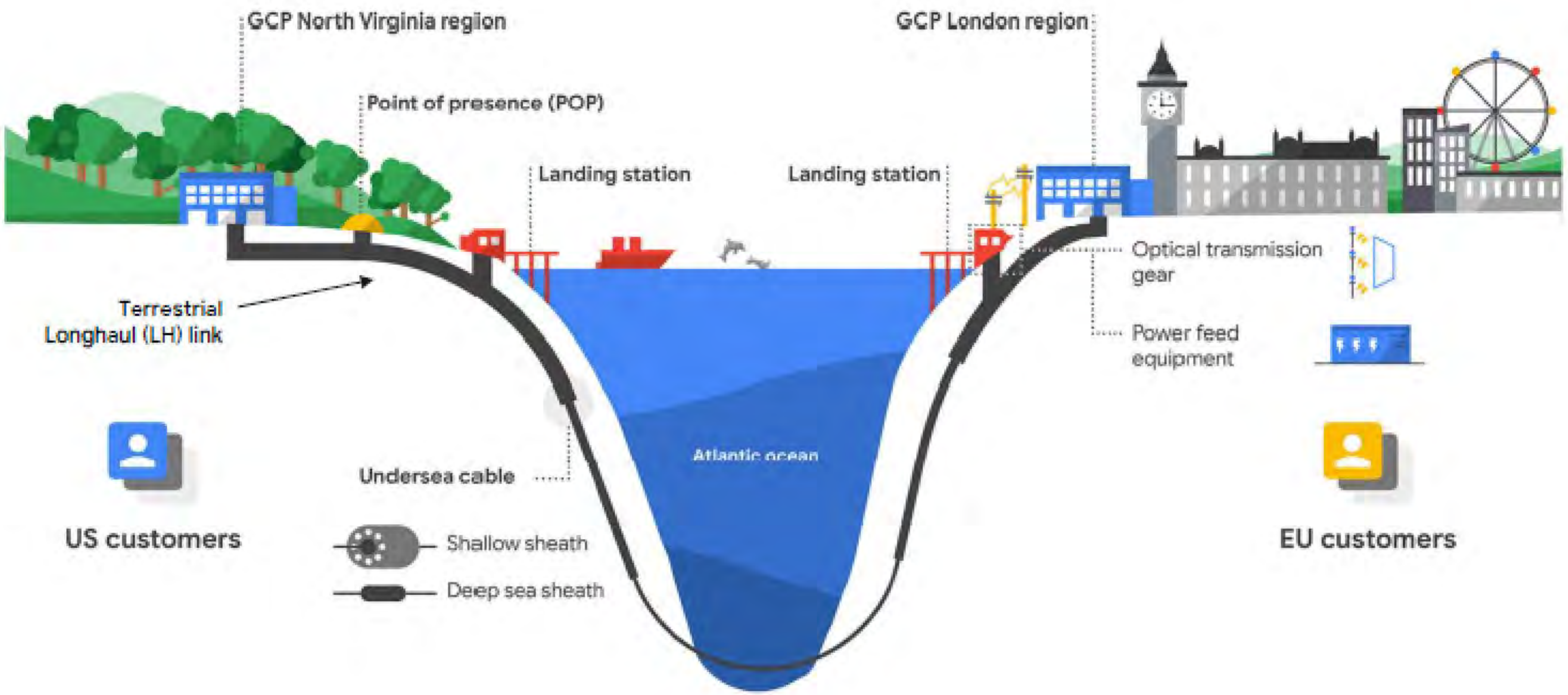
Our global infrastructure

- Current regions and number of zones
- Future regions and number of zones
- ● Edge points of presence
- ● CDN nodes
- Network
- ○ Dedicated Interconnect

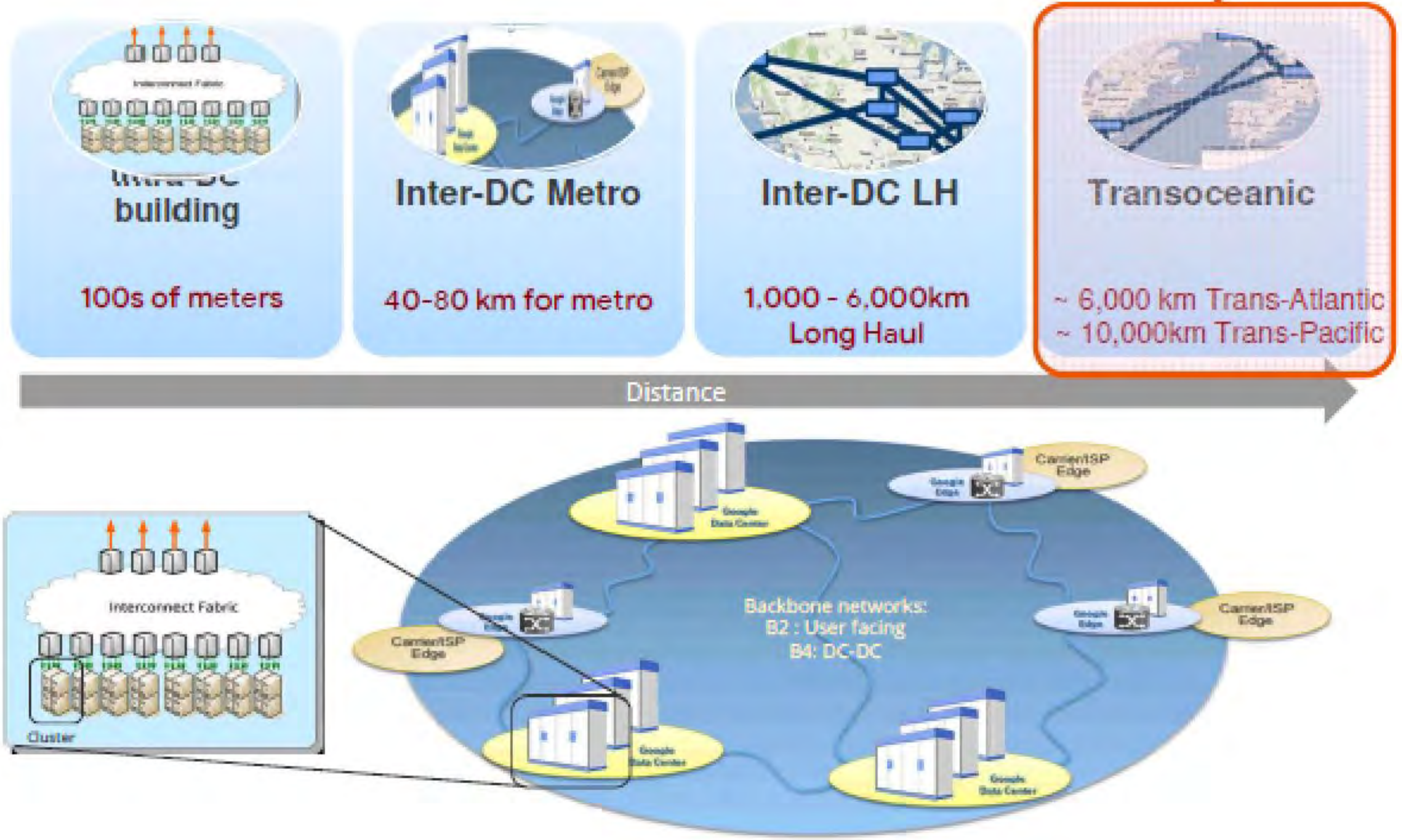


Google Cloud

Google Subsea network- High level Overview



Google Optical Transport network Overview



Focus for today

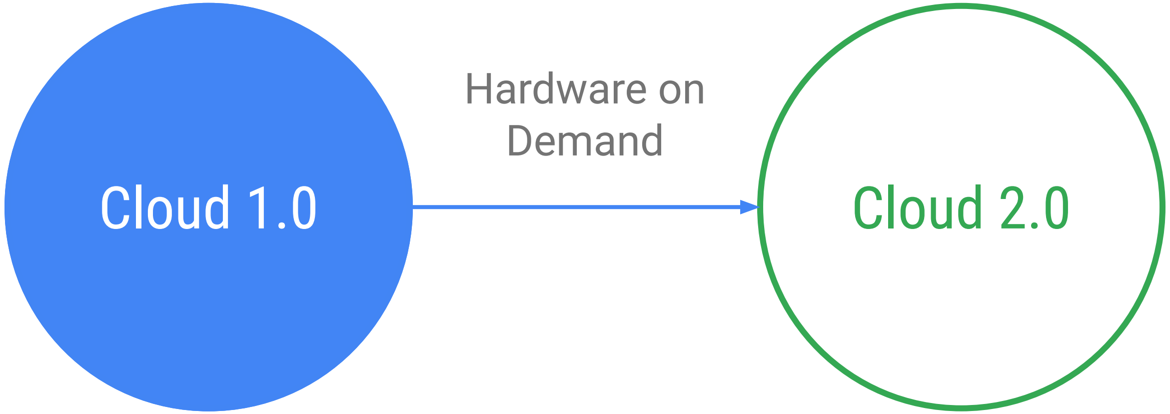
Hyperscaler Datacenters

Cloud: The Last Decade, around 2000

Cloud 1.0

Virtualization delivers capex savings to enterprise DCs

Cloud: Now



Public cloud frees enterprise from private HW infrastructure

Scheduling, virtual servers, fast growth

The Third Wave of Cloud

Serverless compute, actionable intelligence, and machine learning

Google DeepMind Challenge GO Match
Enable Start-ups, Cat recognition, voice recognition

The Third Wave of Cloud

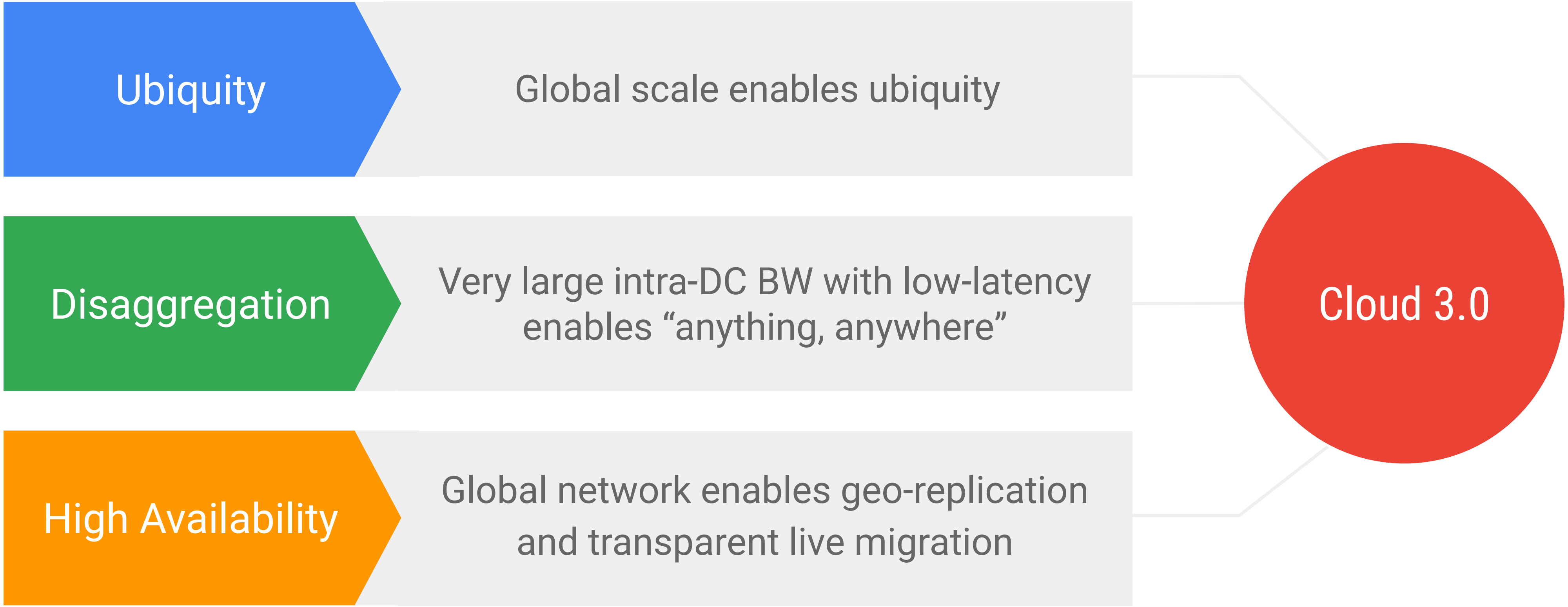
Cloud 1.0

Cloud 2.0

Cloud 3.0

Networking enables Cloud 3.0

Step Function in Networking and Cloud 3.0



Ubiquity	Global scale enables ubiquity
Disaggregation	Very large intra-DC BW with low-latency enables "anything, anywhere"
High Availability	Global network enables geo-replication and transparent live migration

Cloud 3.0

Outline

- What is a submarine Network
- The endless race for capacity
- Life of a packet / Social Networks
- Flying over 150 years of submarine cable technology
- Basics of optical communications
  - Back to basics
  - The optical fiber
  - Optical communication
  - Modulation formats
- Reaching the physical limit
- What’s next

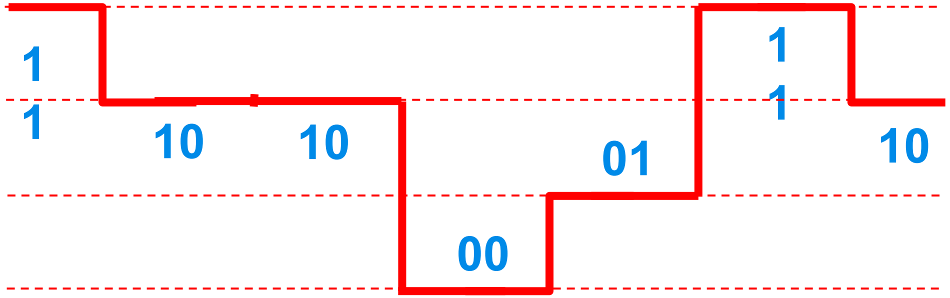
Optical communications: Back to Basics

Digital communications

- Basics of communication is simple:
  - modulation of signal at the transmitter between 0 and 1

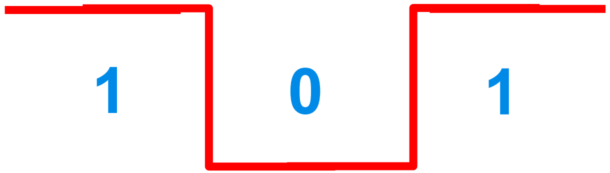
1 bit = 2 levels

- Multilevel by grouping several elementary bits together

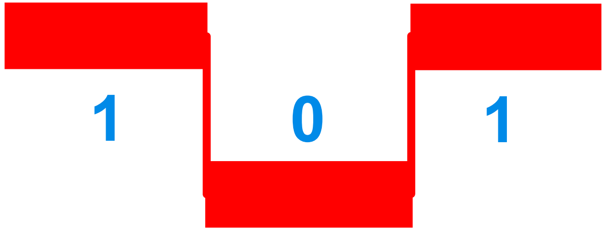


2 bits = 4 levels
(2 x 2 levels)

Optical communications: Back to Basics

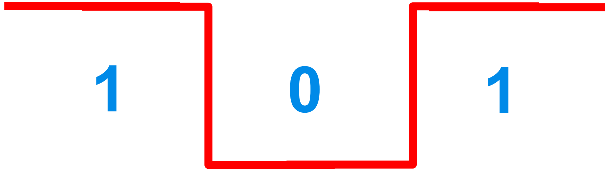


Transmission (noise added)



- Modulation at the transmitter
  - Coding in 1 bit (2 levels illustrated)
- Detection in the receiver

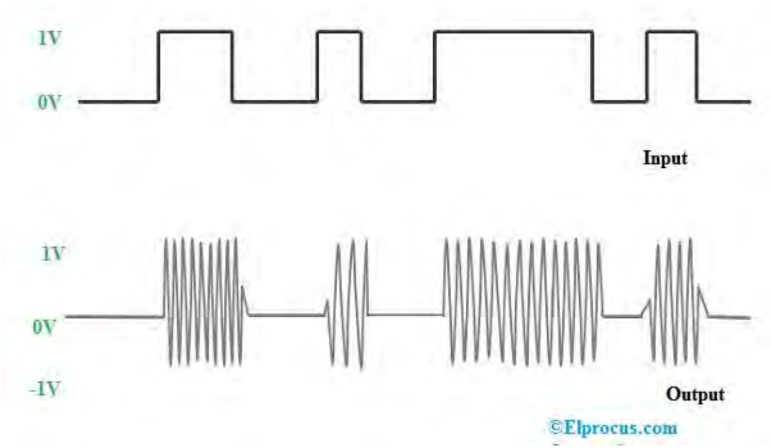
Decision

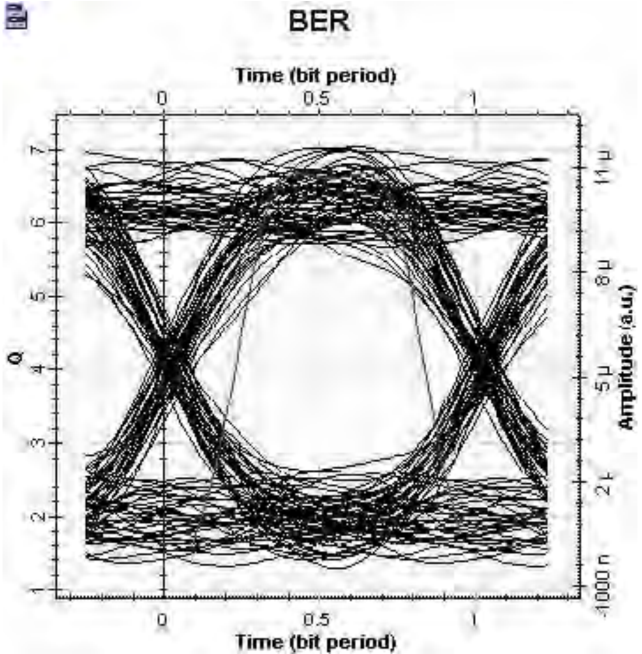


After transmission and decision, the signal is said « regenerated » With a residual Bit Error Rate (BER)

Optical communications: Back to Basics

- In optical fibers: signal coded on a electromagnetic lightwave
  - The more simple coding is Intensity Modulation (IM)
    - On Off Keying (switching the light On or Off)
  - Decision is done by Direct Detection (DD)
  - During 20 years IM/DD was the unique solution

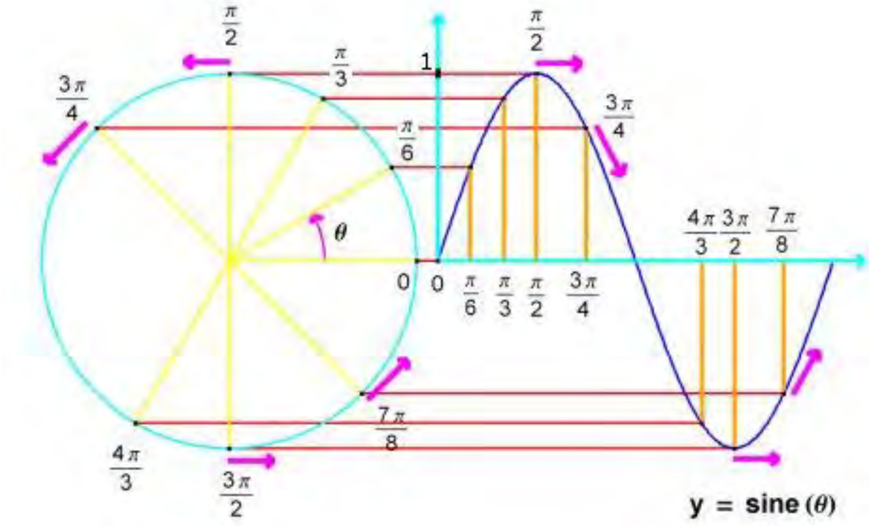


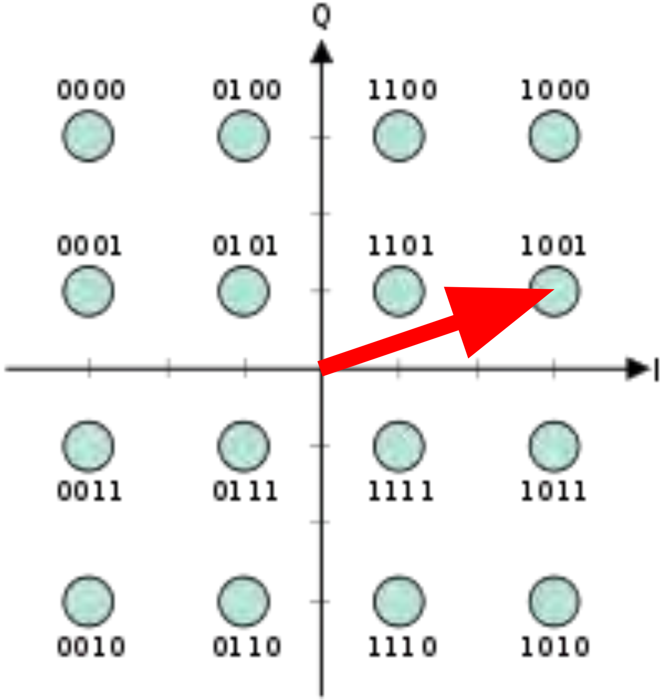


Optical communications: Back to Basics

- An optical signal is also an electromagnetic lightwave
  - Information can be carried by field amplitude (light intensity)
    + optical phase (that can be represented by a vector on a circle)

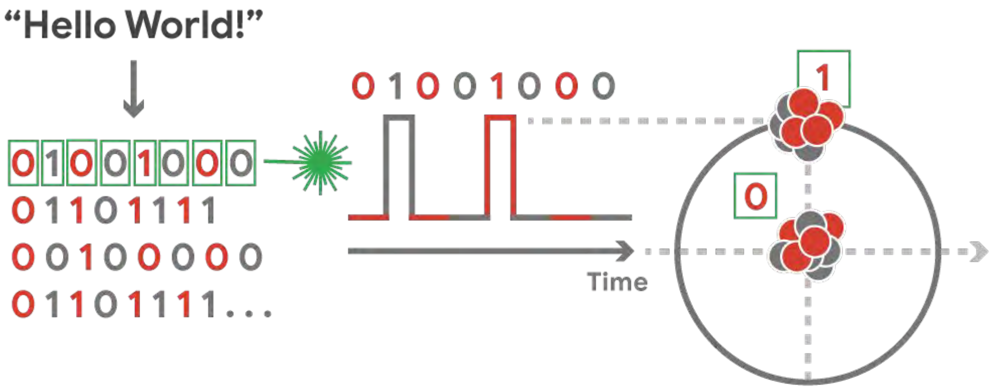
Phase information represented on a circle





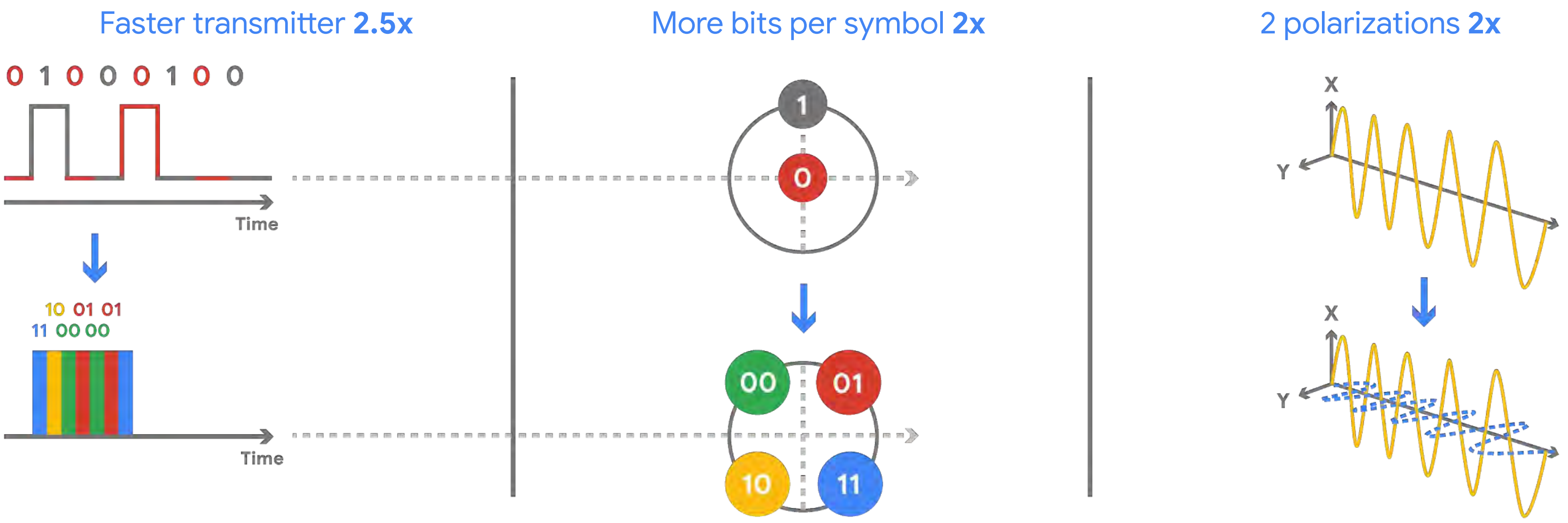
The path from 10G to 100G: a 10x story

Legacy IMDD: 10 Gb/s per laser



The path from 10G to 100G: a 10x story

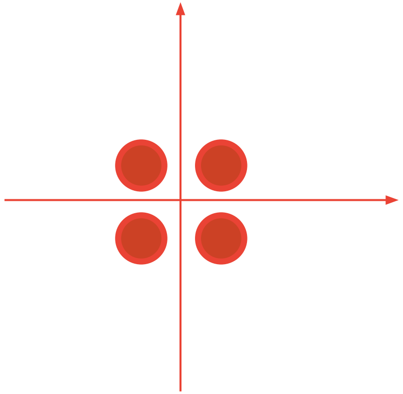
10x capacity increase: 100 Gb/s per laser



The next 10x : From 100G to 1T per carrier

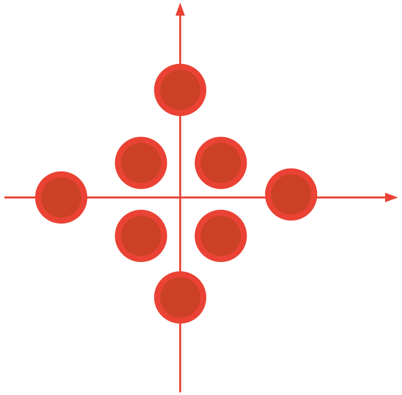
Evolution of Digital Modulation

QPSK



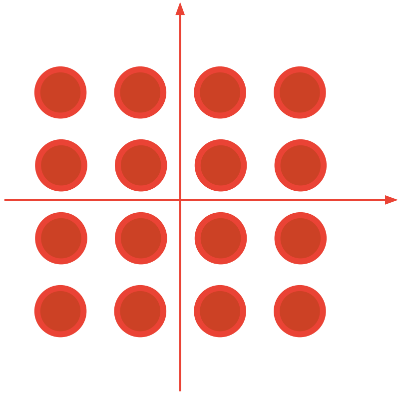
2 bit/symbol/pol

8-QAM



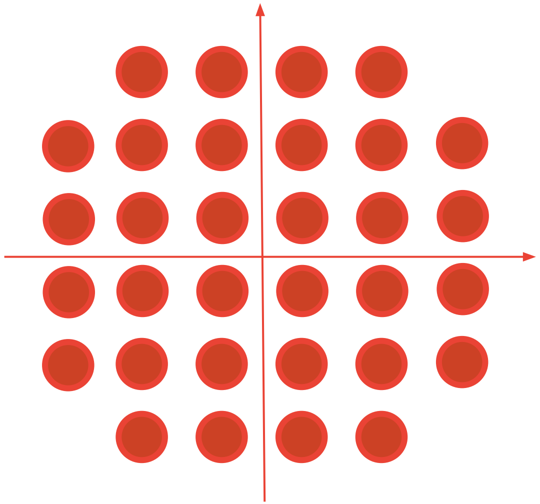
3 bit/symbol/pol

16-QAM



4 bit/symbol/pol

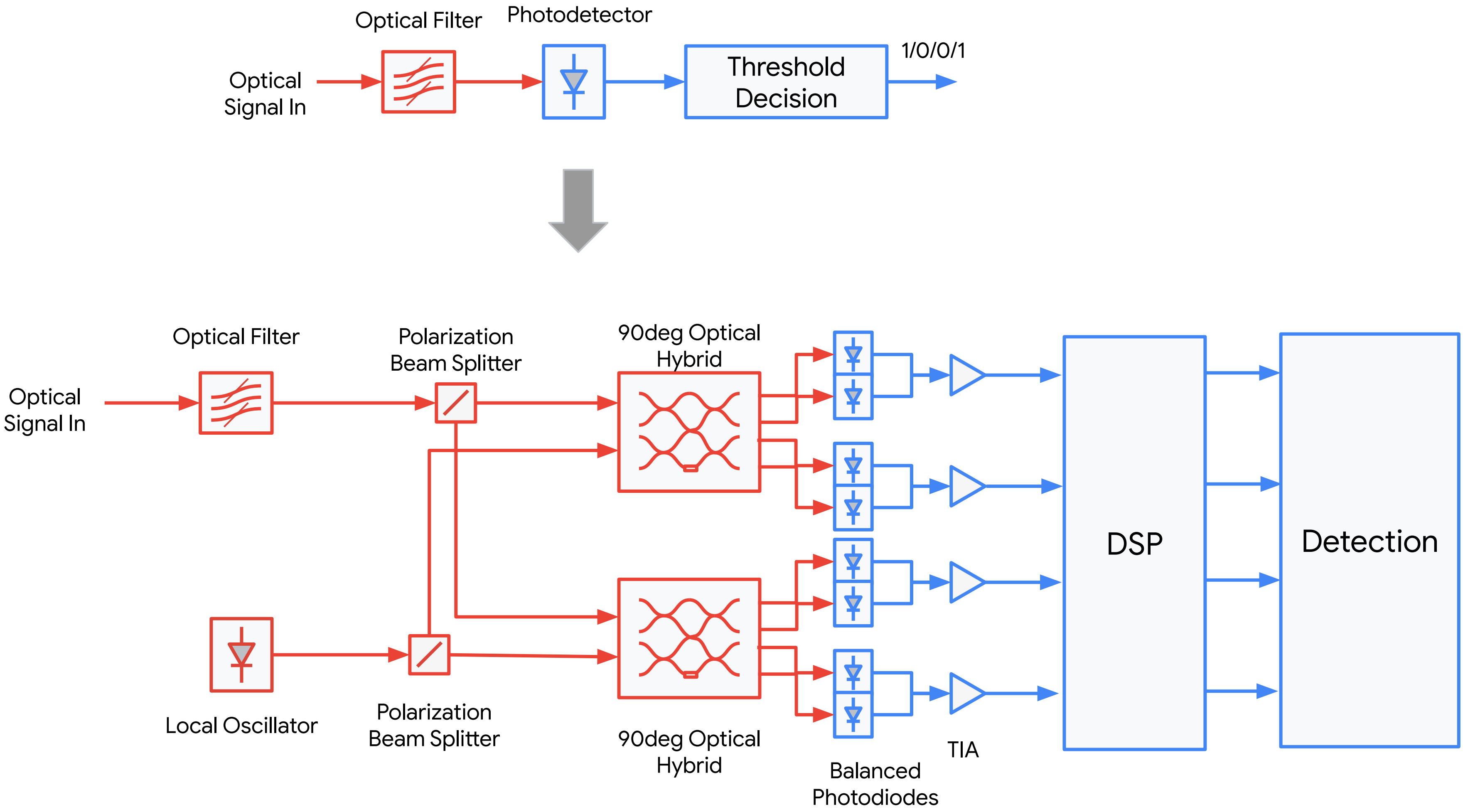
32-QAM



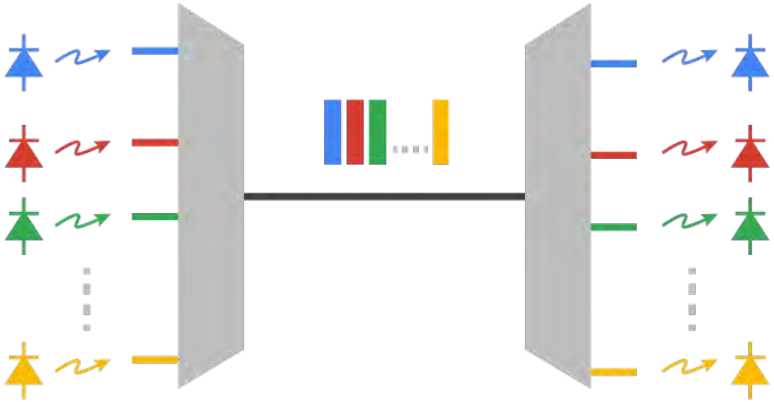
5 bit/symbol/pol

Refer and use material from Nancy's slides of the NetInfra Training
Keep it light (MAX 4 SLIDES)

But comes with complexity ....



Wavelength Division Multiplexing: Scaling Fiber Capacity



- In fiber optic systems we have
    - **THz of low loss** fiber spectrum
    - **THz of amplification** bandwidth
- We can use such a wideband by **multiplexing / demultiplexing multiple TX/RX pairs at different wavelengths** (colors)
- This technique is called **Wavelength Division Multiplexing (WDM)**
- In this way we can squeeze linearly scale the capacity of our system going from hundreds of **Gbps** of **capacity per channel** to **Tbps** of **fiber capacity**

Back to basics: Cable Capacity

Cable capacity =

(Spectral Density) X (Fiber Bandwidth) X (No. Fiber Pairs)

- ► Spectral density (bits/s per Hz)
  - Has increased rapidly by increasing channel bit rate
- ► Fiber bandwidth
  - Determined by the Erbium spectrum of EDFA
- ► No. of Fiber Pairs
  - Number of fiber pair was typically 4FP to 6FP, Max 8FP
  - With DUNANT 12FP TA cable, SDM enabled 12/16/24FP cables

Outline

- What is a submarine Network
- The endless race for capacity
- Life of a packet / Social Networks
- Flying over 150 years of submarine cable technology
- Basics of optical communications
- Reaching the physical limit
  - Physical limit (Shannon)
- What’s next

Scaling Subsea Capacity - Shannon's Playground

$$C = B \log_2(1 + \text{SNR})$$

↑ **Channel capacity**

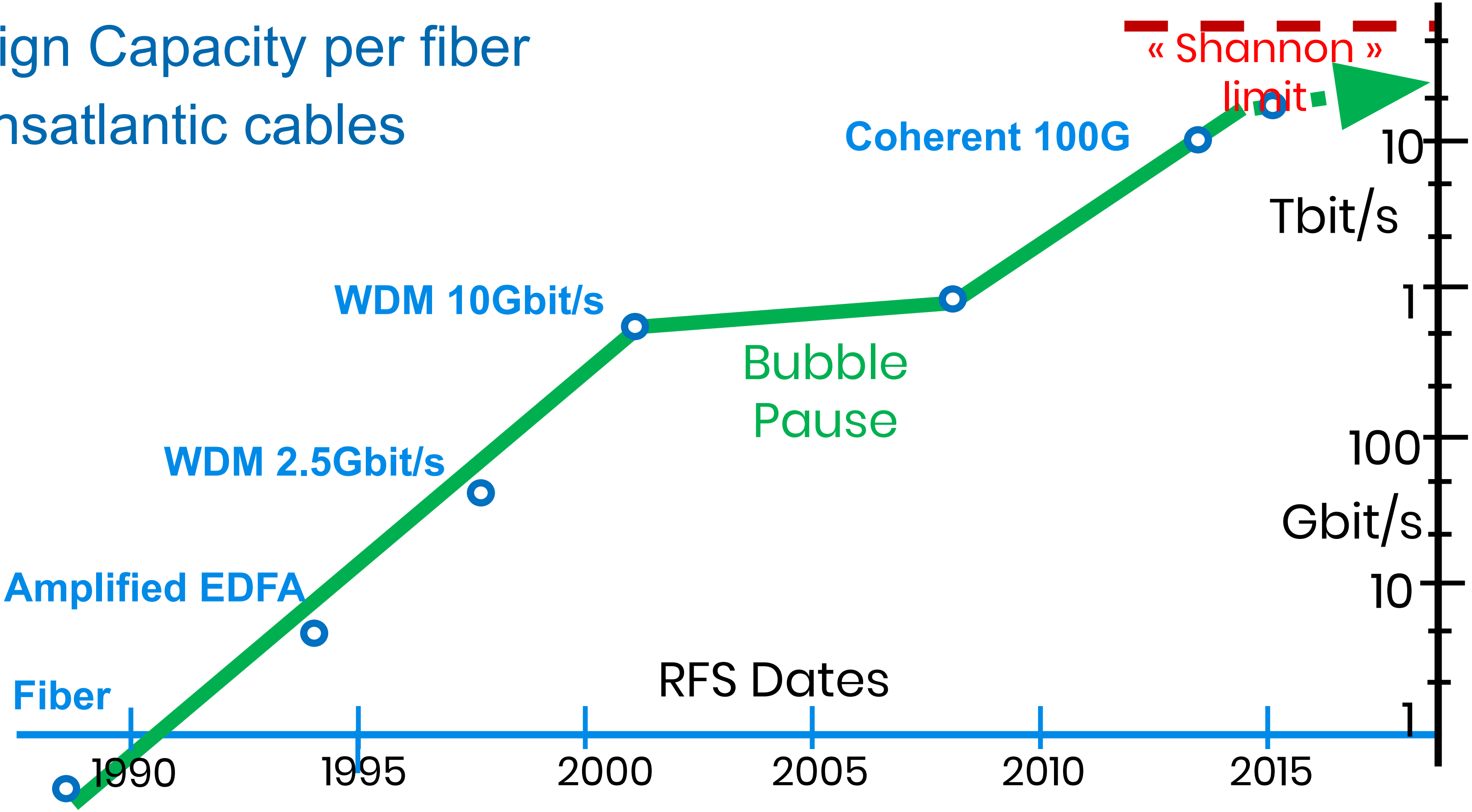
↑ **Bandwidth**

↑ **Signal to noise ratio**

- **Two knobs** to play with
  - **Signal-to-Noise Ratio**
  - **Total** System **Bandwidth** (whole cable, i.e. multiple FPs)
- For **power limited** systems like subsea systems, it is **more effective to scale** the total system **bandwidth** (linear with capacity), rather **than** optimizing the **SNR** (log with capacity)
- More B = **more fibers**
- Higher SNR = more power, more repeaters, better quality fibers

Reaching the physical limit: Shannon Limit

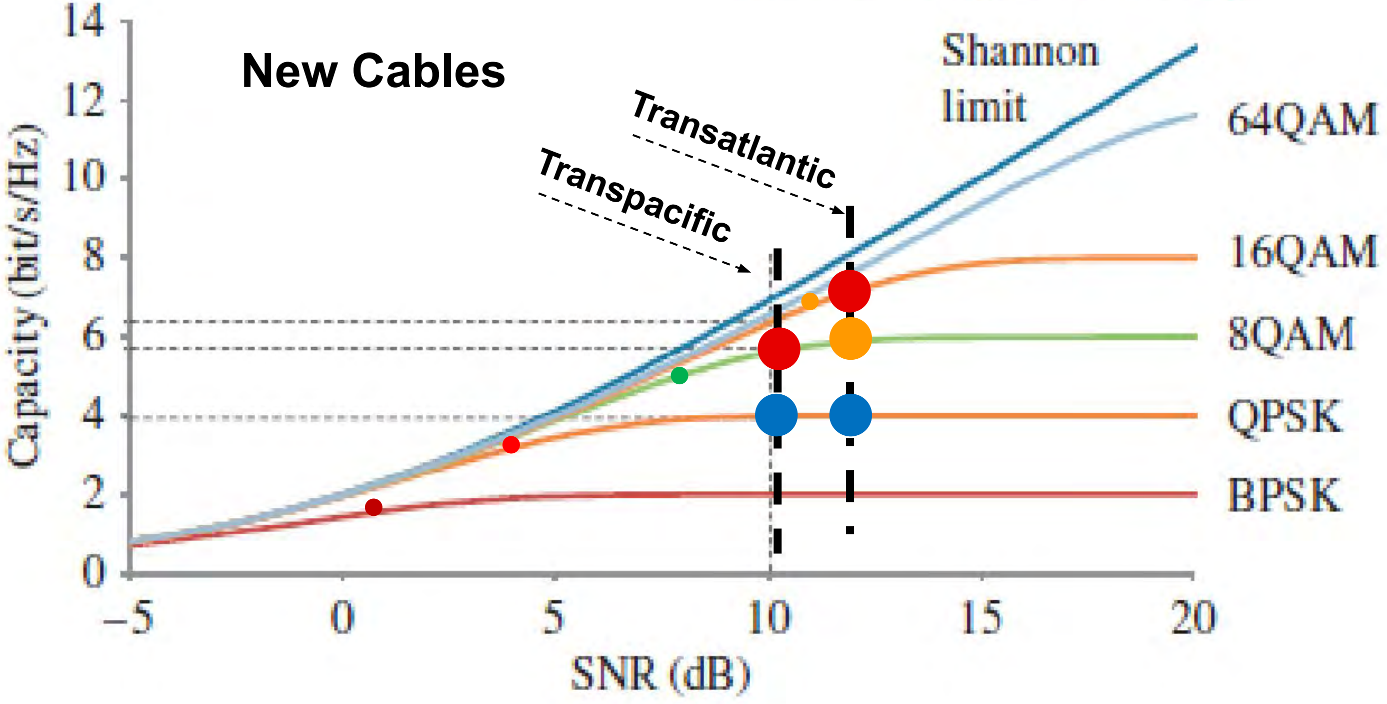
- Design Capacity per fiber for transatlantic cables



Reaching the physical limit: Shannon Limit

- Shannon limit

$$C = B.\log(1 + SNR)$$



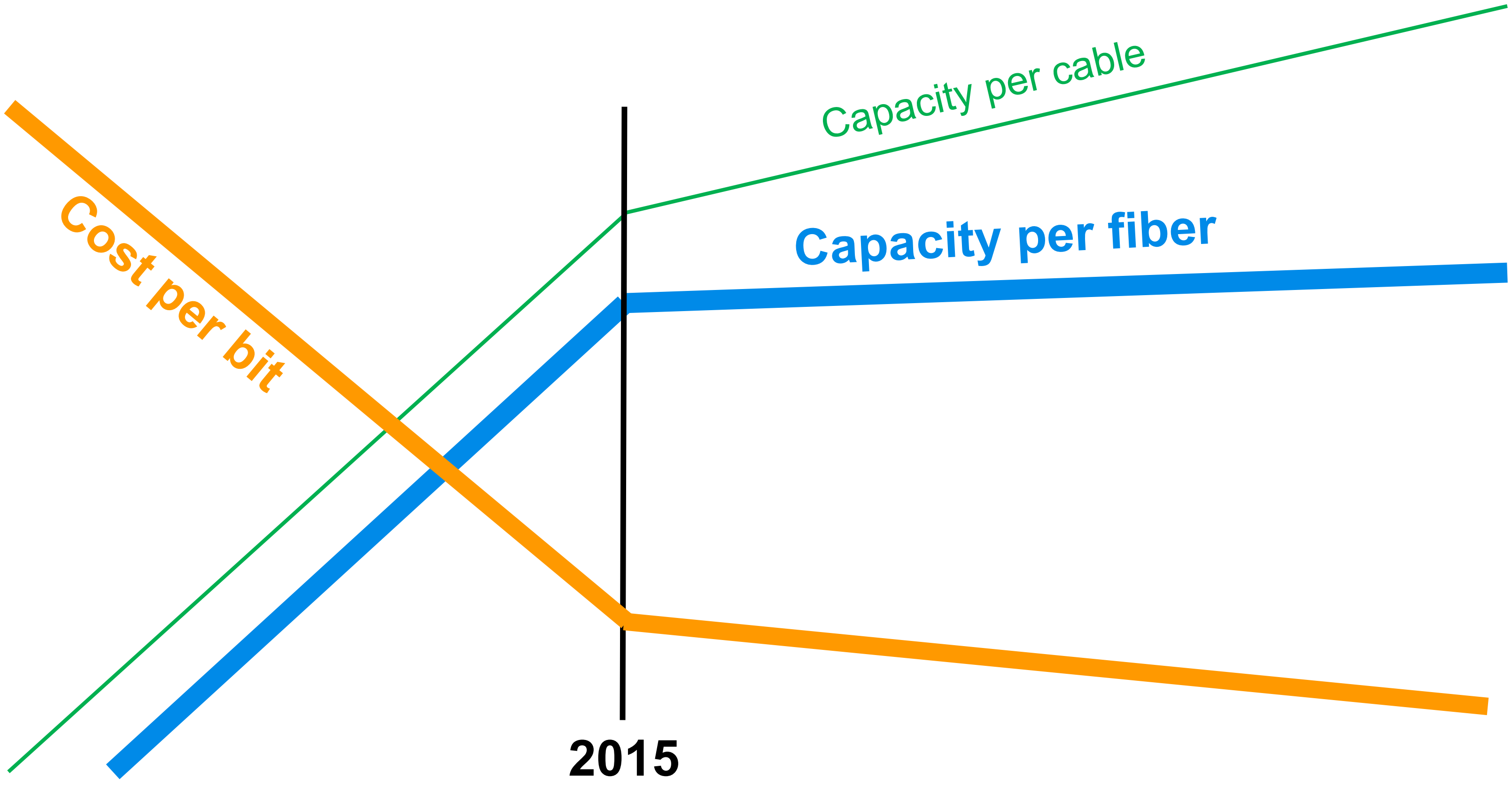
(Note: intermediate values between QPSK, 8QAM, 16QAM will be achievable)

Remarks about Shannon limit

- Shannon theory established since a century…
- Theoretical spectral density ~10 bit/s/Hz for transatlantic
- But practical penalties have to be considered
  - Ageing and repair operational margins today ~1 dB
  - Electrical analog ADC & DAC penalties today ~0,5dB
  - Non optimal FEC correction penalties today ~1 dB
  - Wavelength stability penalty today
  - Non-linear penalty coming with high OSNR (3 dB for 19dB OSNR)

Reaching the Shannon limit: cost impact

- 2015 (mature coherent technology) is a technology turning point



Outline

- What is a submarine Network
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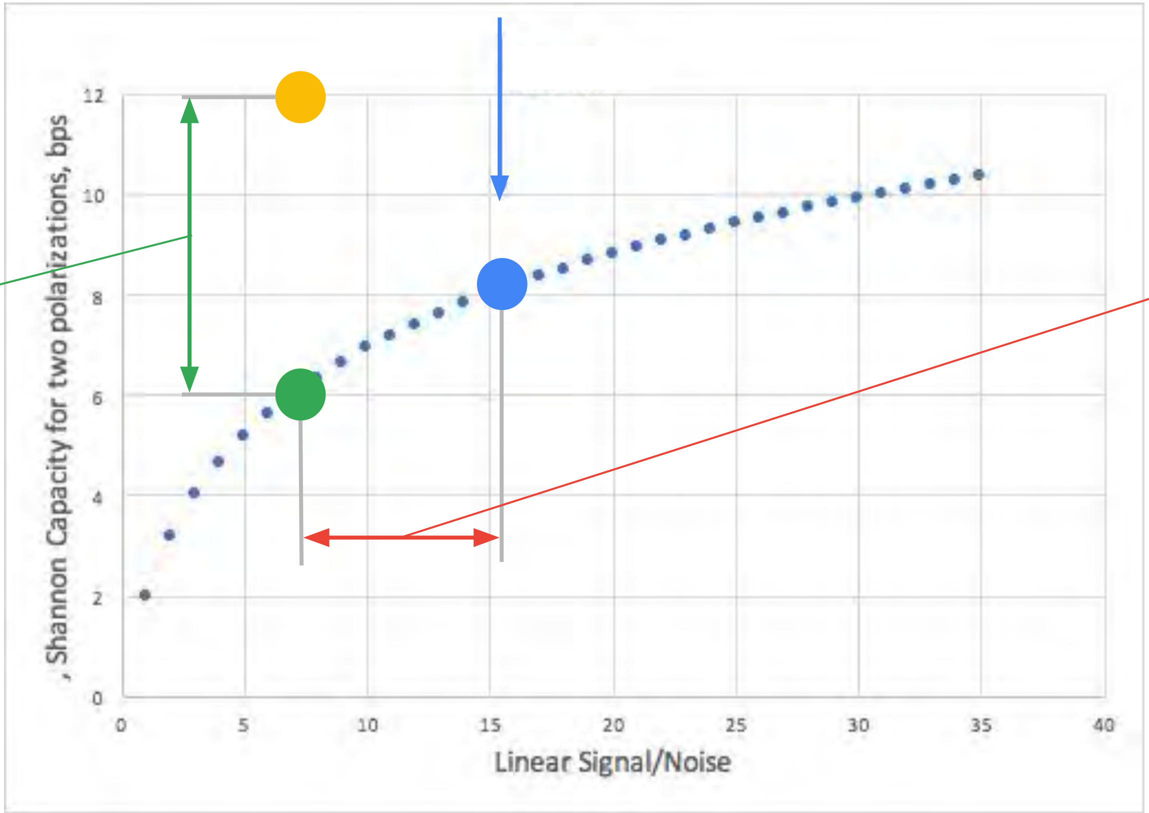
- Basics of optical communications
- Reaching the physical limit
- What’s next for technology

Further Capacity Scaling: Linear vs Log Term in Shannon

Baseline : SNR for Trans-Pacific cable FASTER designed in 2014



Linear term :
2x capacity increase by increasing #FP

Log term :
2x SNR change results in only 33% capacity increase

$$C = B \log_2(1 + \mathrm{SNR})$$

Channel capacity

Bandwidth

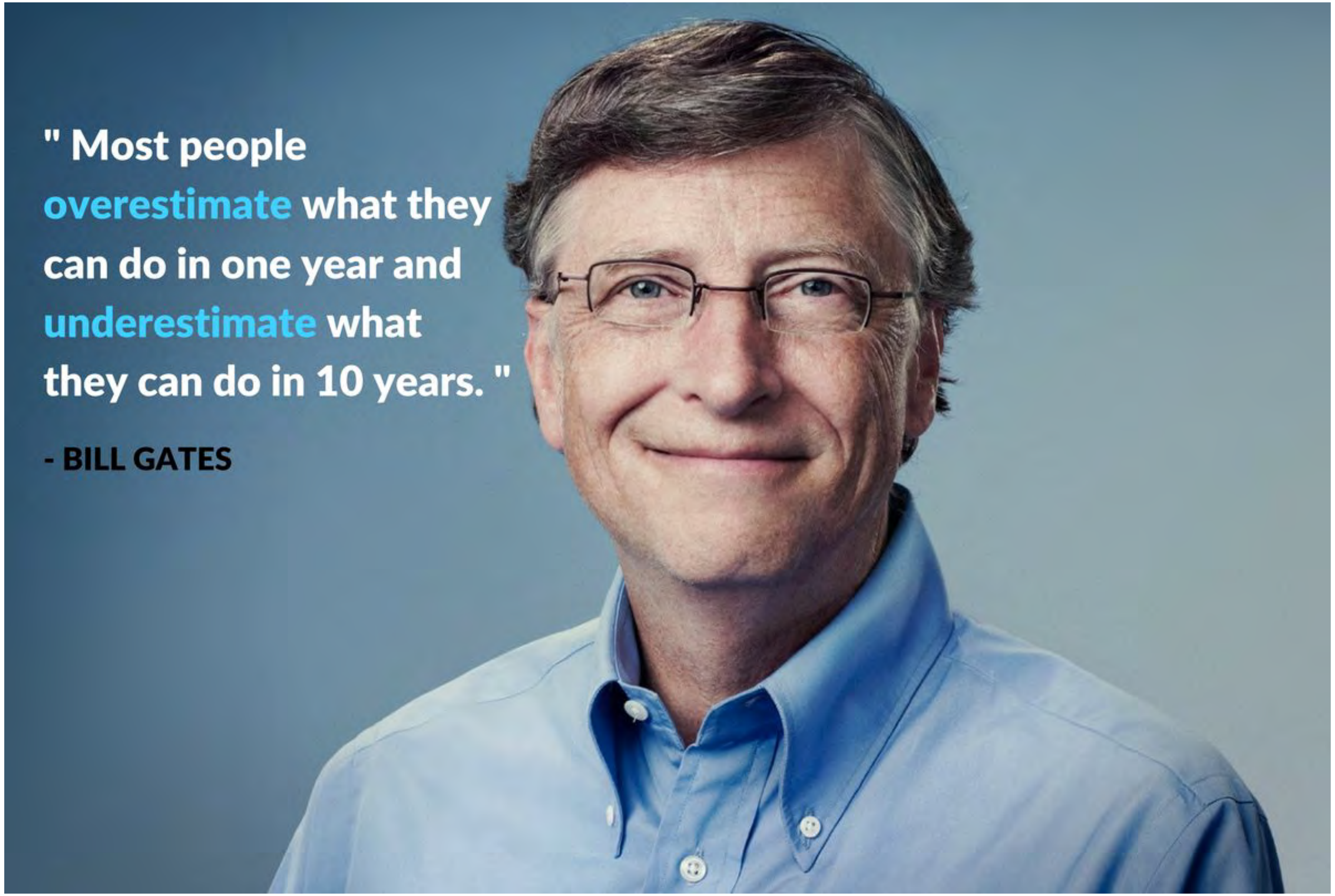
Signal to noise ratio

Evolution of telecom applications

- Develop low cost solutions
  - To feed internet everywhere to connect isolated populations (islands..)

- Optimising cost of terminals
  - Use of higher baud rates for cost efficiency
    - Limited by the analog chain: 60Gbaud today -> 100 +Gbaud **
- Wet plant cost
  - Reducing material cost *
  - Targeting reduction of marine cost ***
  - Reducing design life ?

Short-term and Long-term Objectives



> " Most people **overestimate** what they can do in one year and **underestimate** what they can do in 10 years. "
>
> - BILL GATES

Long Term Challenges in Subsea Systems

Challenges are beyond optronics

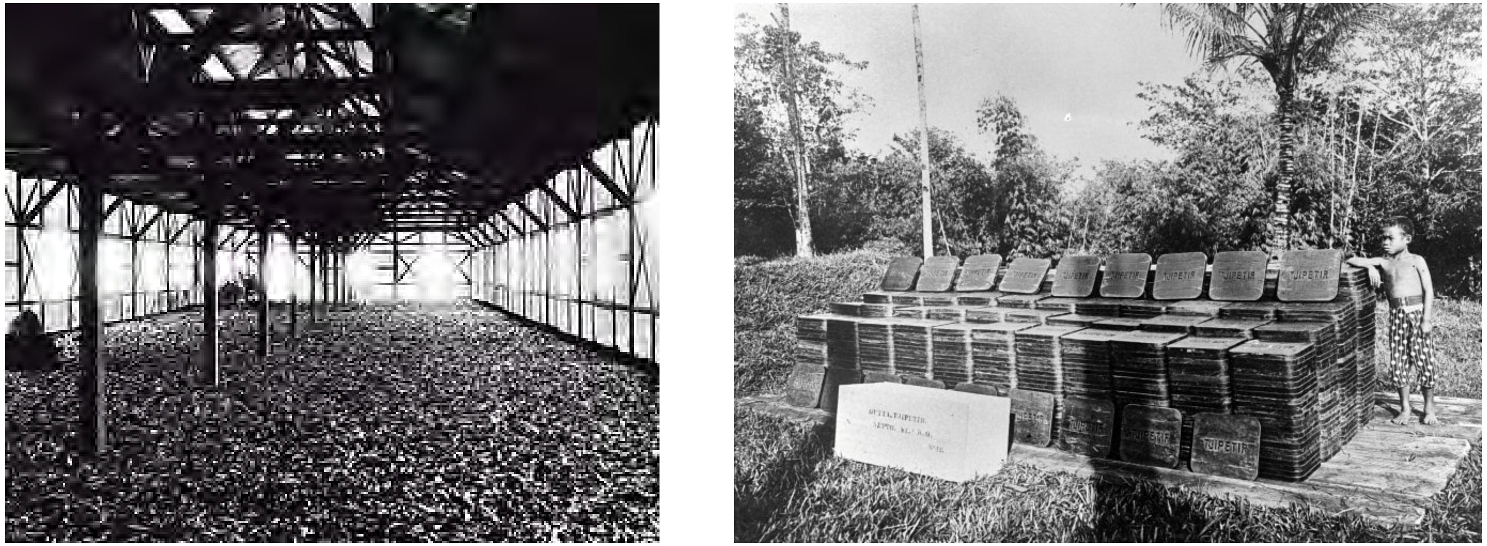
- High cost of cables and long project durations limits ubiquitous connectivity
- Capacity growth is higher than unit cost reduction
- Need for cable and landing physical diversity for high-availability services

- Marine operations largely unchanged for decades
- Slow cable laying and repair times
- Cable breaks and damages

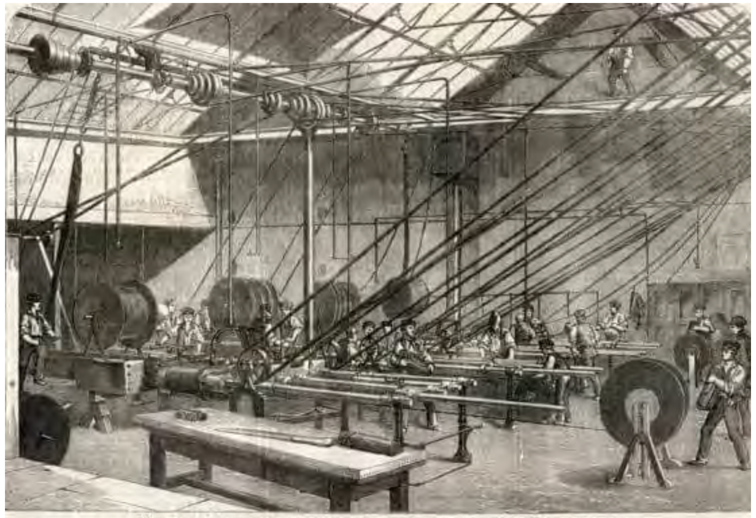
Cable ships overview

The Gutta-Percha

Pallaquium Gutta



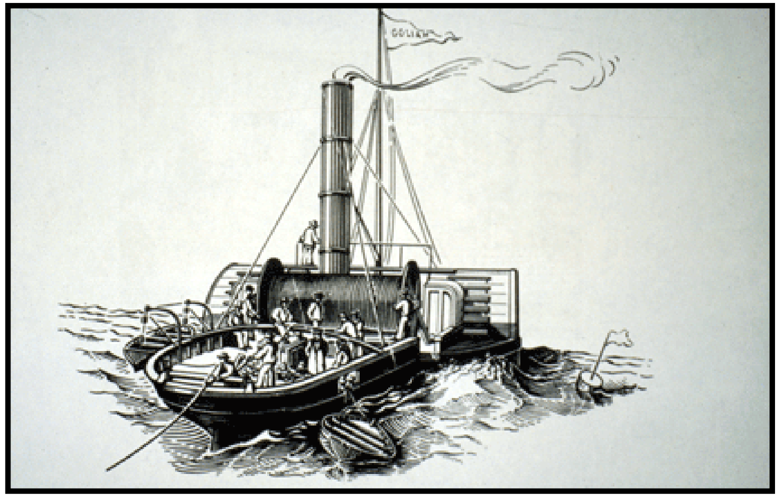
Tjipertir Plantation in Java



MACHINES COVERING WITH GUTTA PERCHA THE ATLANTIC CABLE WIRE, AT THE GUTTA PERCHA COMPANY'S WORKS, WHARF-ROAD.

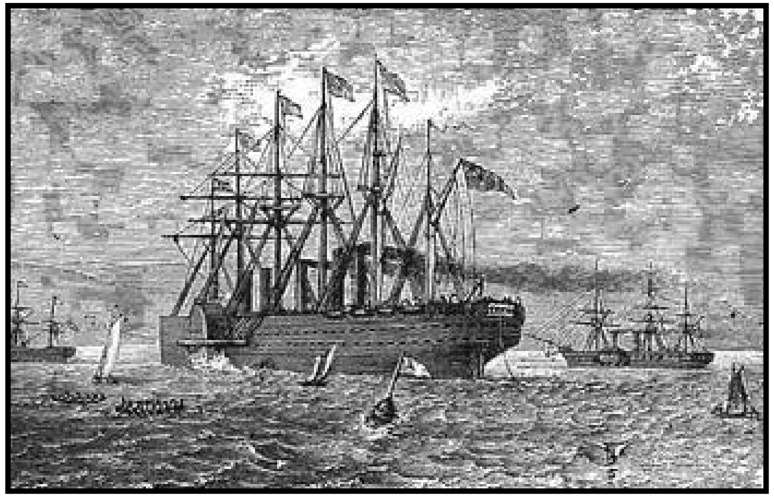
Compagnie du Gutta-Percha

Cable ships
a long history



Goliath: lays 1st international cable, UK-France, 1850-1

Source: Illustrated London News



Great Eastern: laying cable off Newfoundland, 1866

Source: Canadian Government

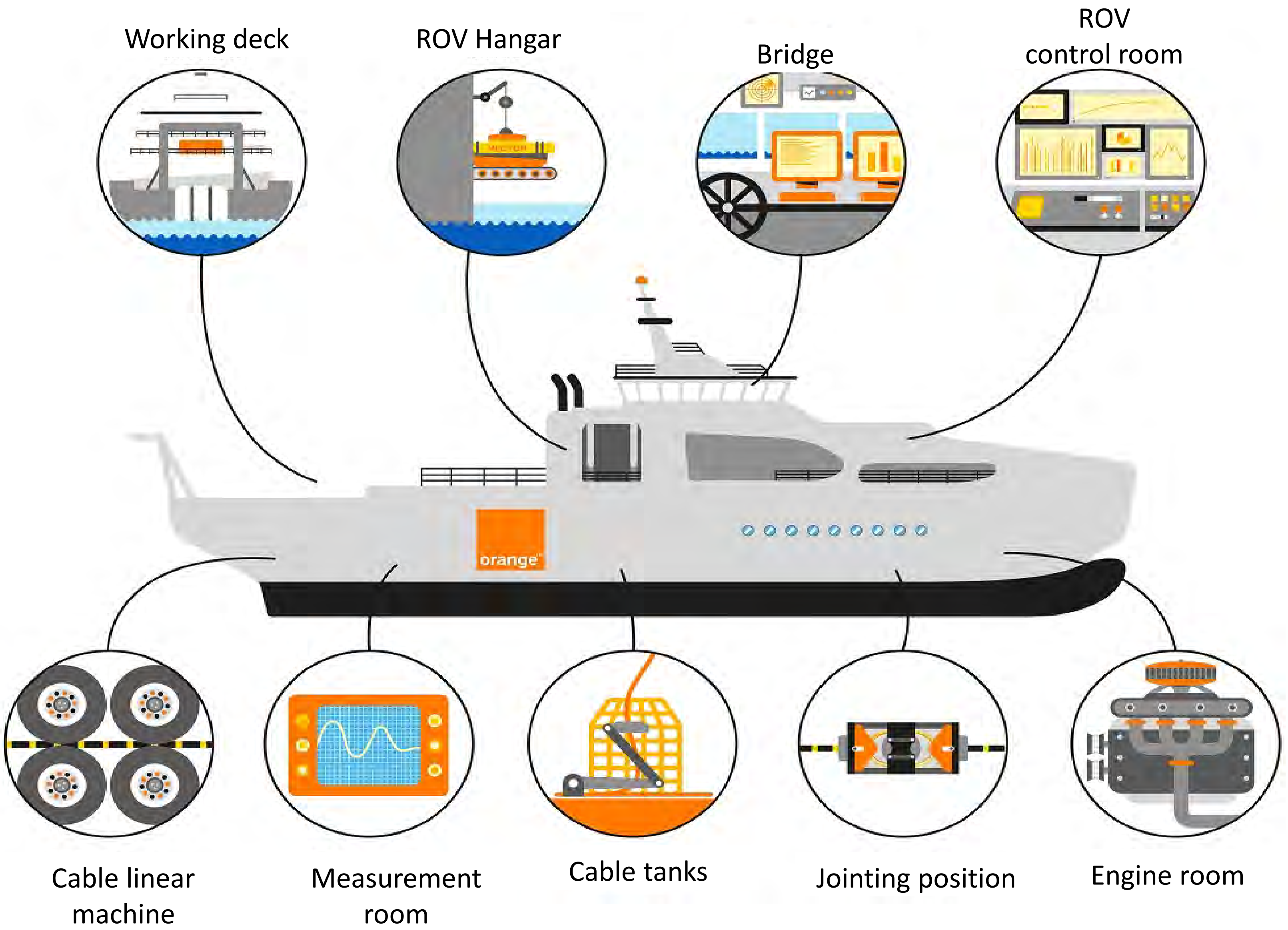
John Pender, named after pioneer cable maker, 1900

Source: Cable & Wireless

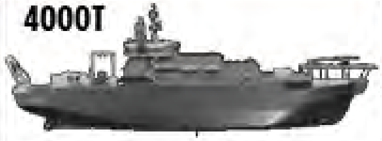
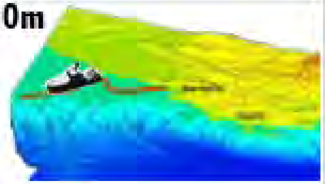
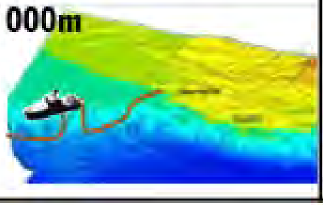
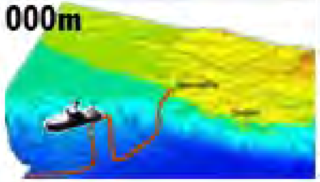
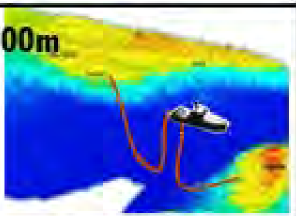
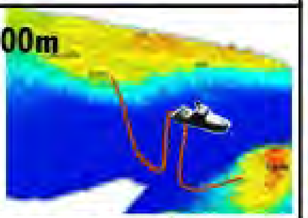
Monarch: laid 1st transatlantic telephone cable, 1955/6

Source: www.atlantic-cable.com

Cable ships : key elements



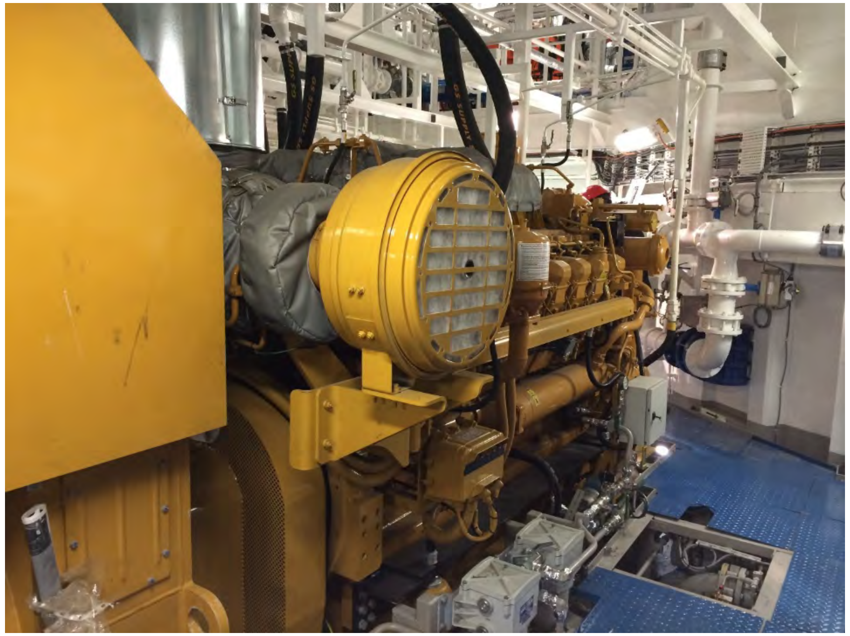
Cable ships : size and performances

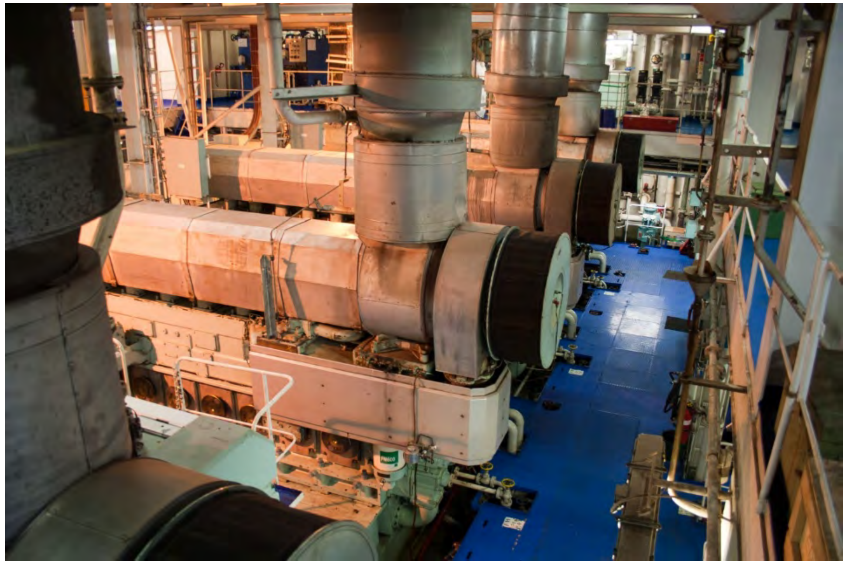
Volume	25x15m	50x10m	75x12,5m	100x20m	125x22,5m
Cable load	80T 	400T 	600T 	2500T 	4000T 
Autonomy at sea	15j 	20j 	25j 	35j-45j 	45j-60j 
Transit Speed (Sea State 4)	08nds 	09nds 	10nds 	12nds 	12,5nds 
Wave heigh at working area	0,8m 	1,0m 	1,25m 	2,0m 	3,0m 
Working depth	50m 	1 000m 	2 000m 	5 500m 	10 000m 

Cable ships : engines

- Performances : engines should be able
  - ✓ To sustain a transit speed of 12 knots
  - ✓ To keep the working position with a sea state
  - ✓ To pull a plough (bollard pull)

- Number of engines :
  - ✓ Usually 4 engines
  - ✓ The optimum of fuel consumption could be to use only 3 or even 2 engines in parallel. The 4 engines are used for transit





Cable ships : engines room

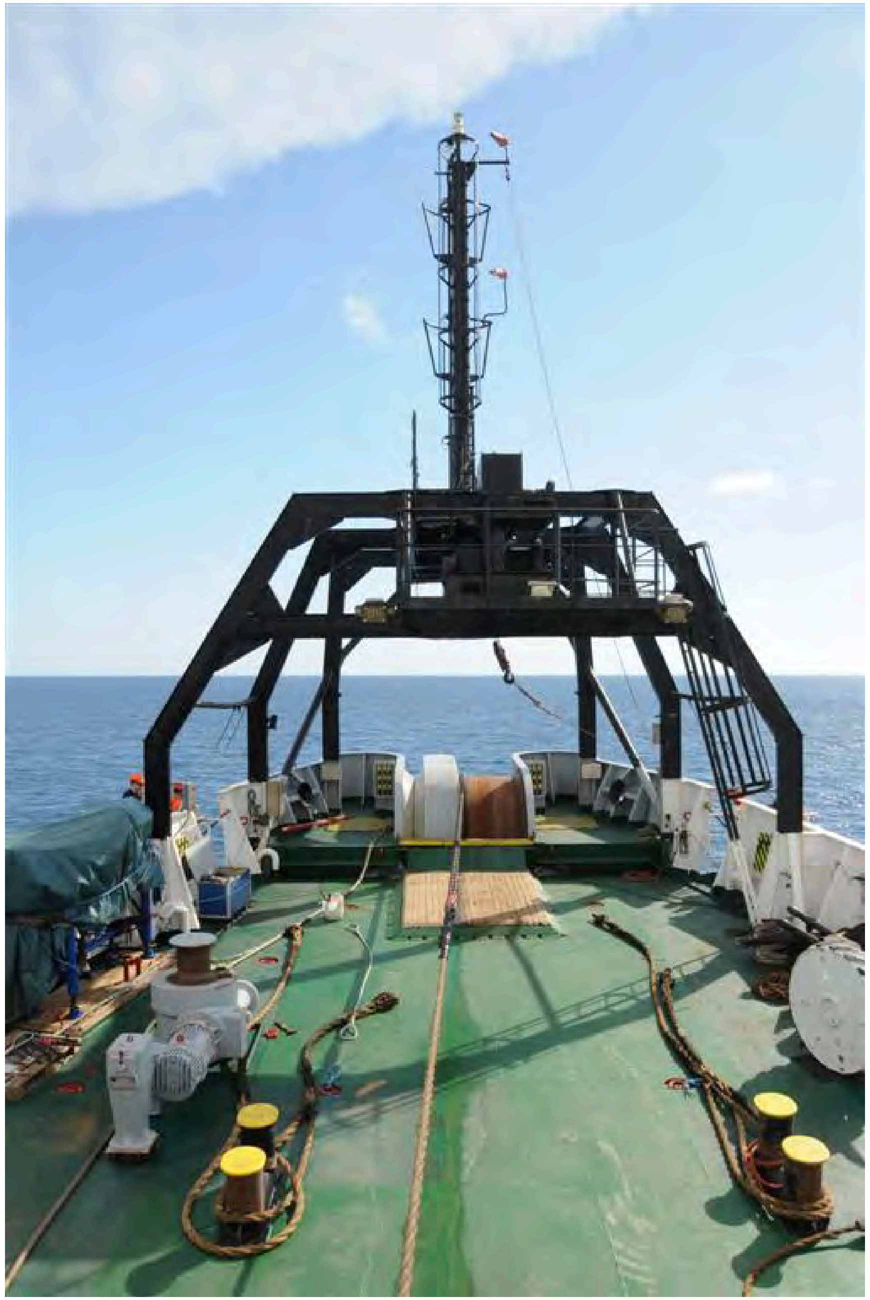
Cable ships : Stability

- Different devices for the propulsion:
  - Azimuthal propellers with 360° movement
  - Transverse tunnel propellers
  - The optimum of fuel consumption could be to use only 3 or even 2 engines in parallel. The 4 engines are used for transit
- The design of the bow is now optimizing the behaviour in the waves
- Dynamic Positioning : to keep an accurate position a cable ship use satellite information acquisition to command the different propellers
  - DP 2 : There is a double, independent system from data acquisition to propellers command

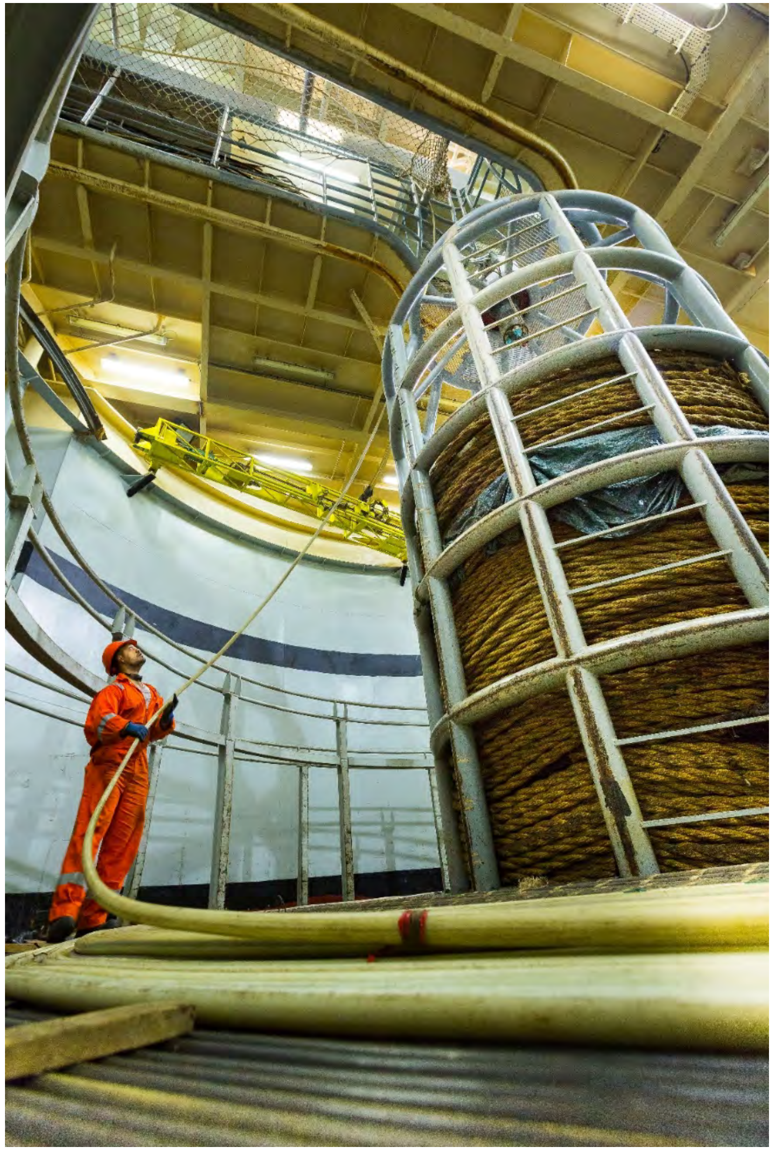
Reduced by 5/15% consumption in transit

Stabilize the ship by reducing the pitch

Sheaves and working D Deck

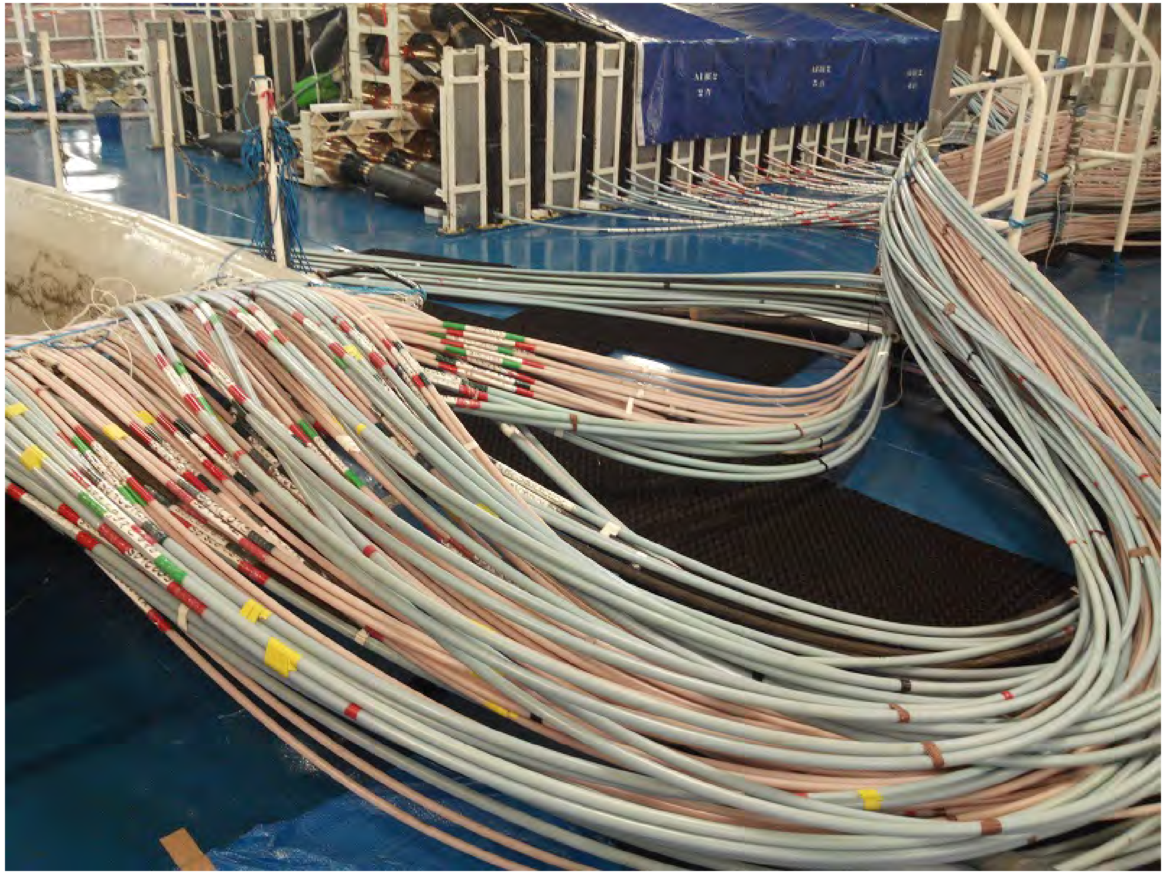


Cable tanks

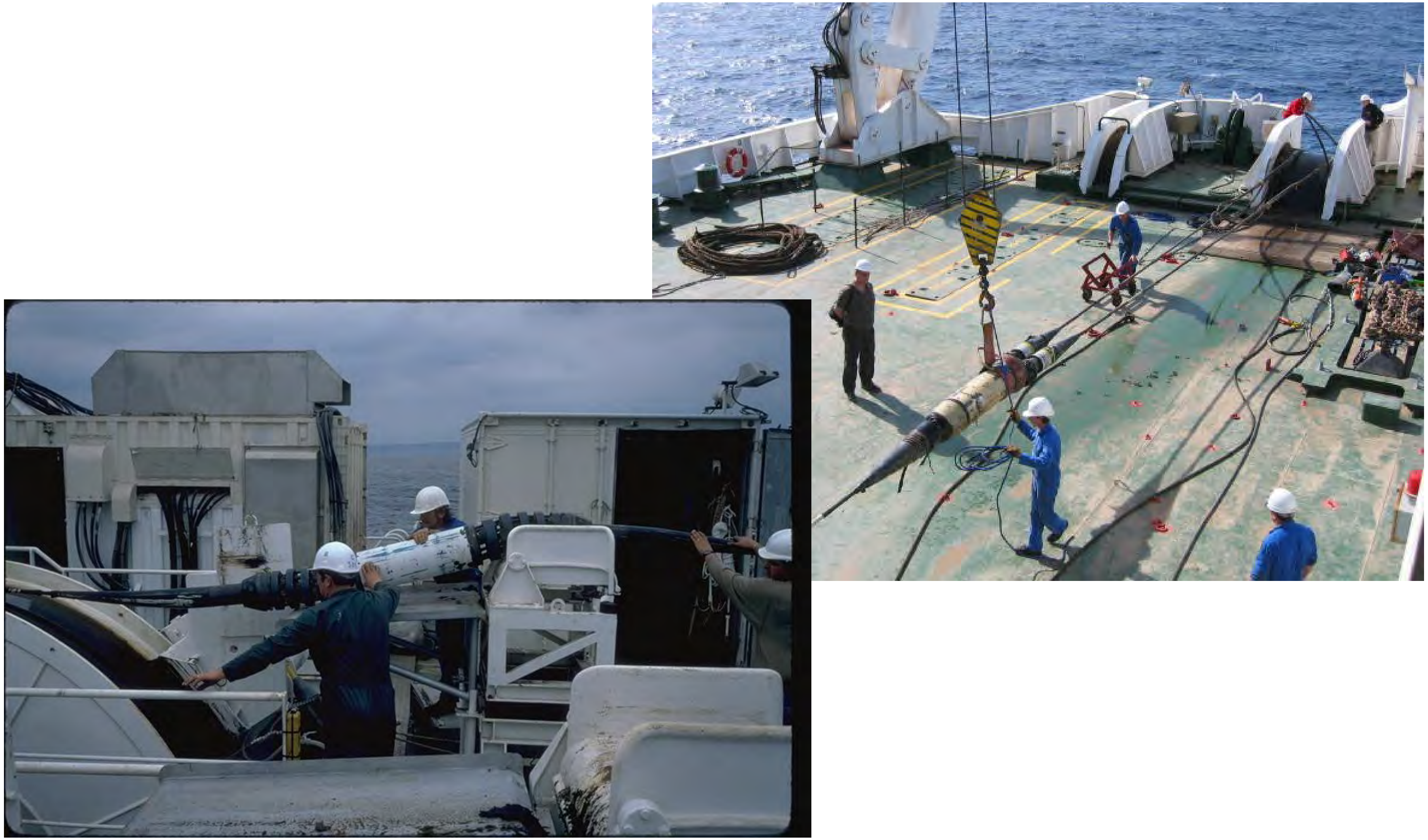


Buoys

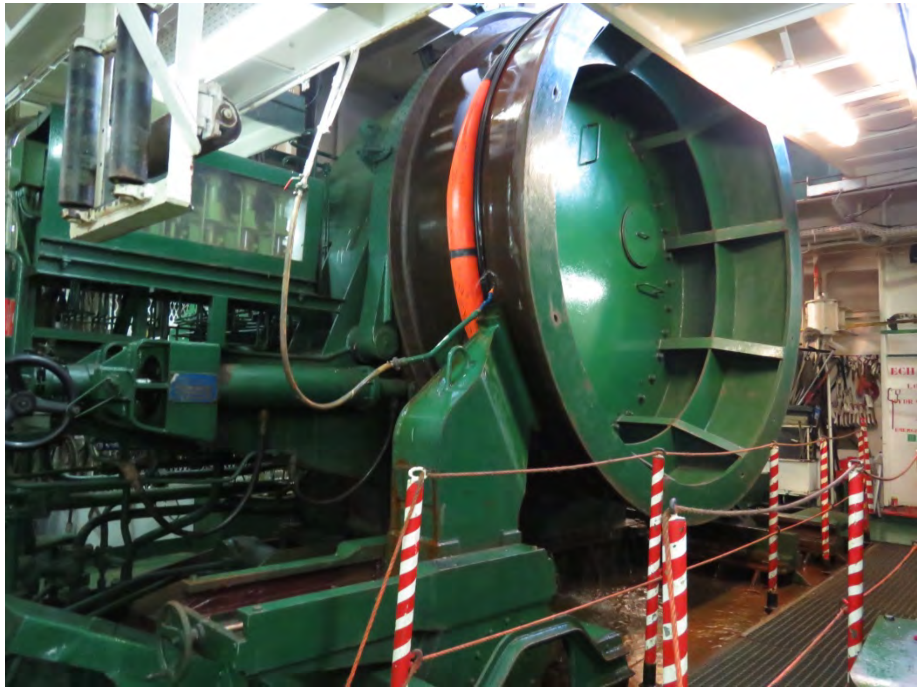
Repeater and Branching Unit handling



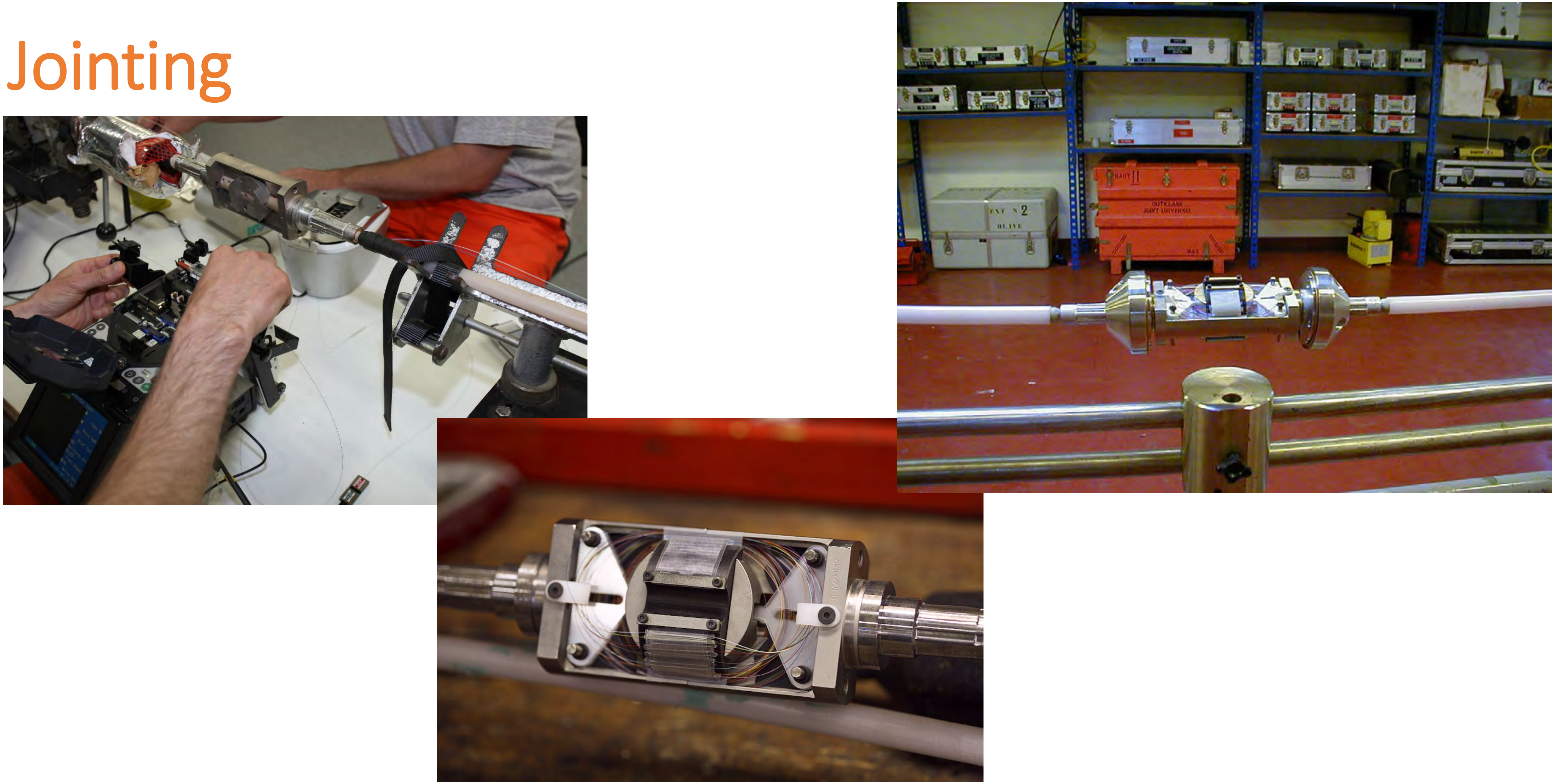
Repeater and Branching Unit handling



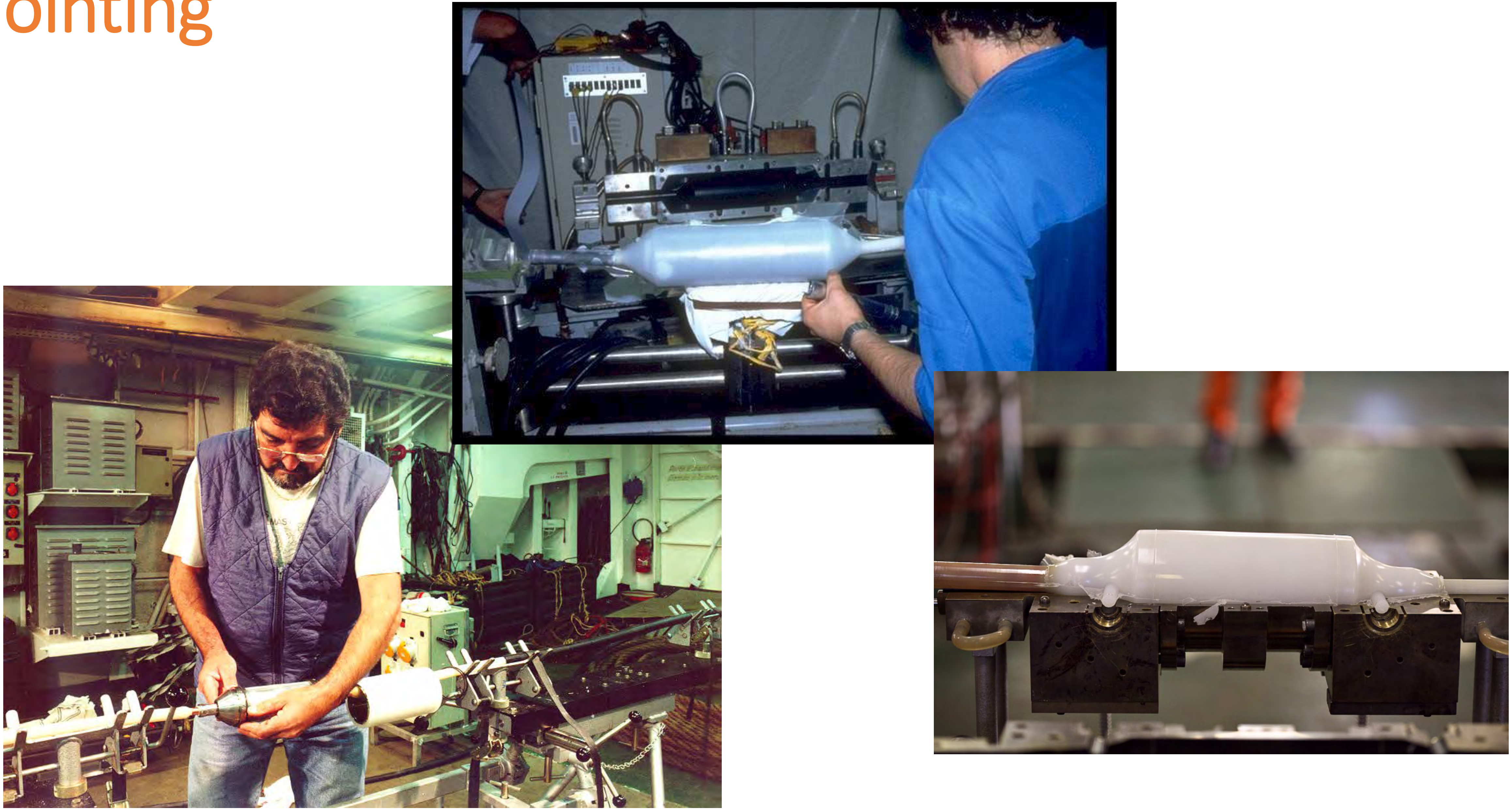
Cable machines & cable drums



Jointing



Jointing

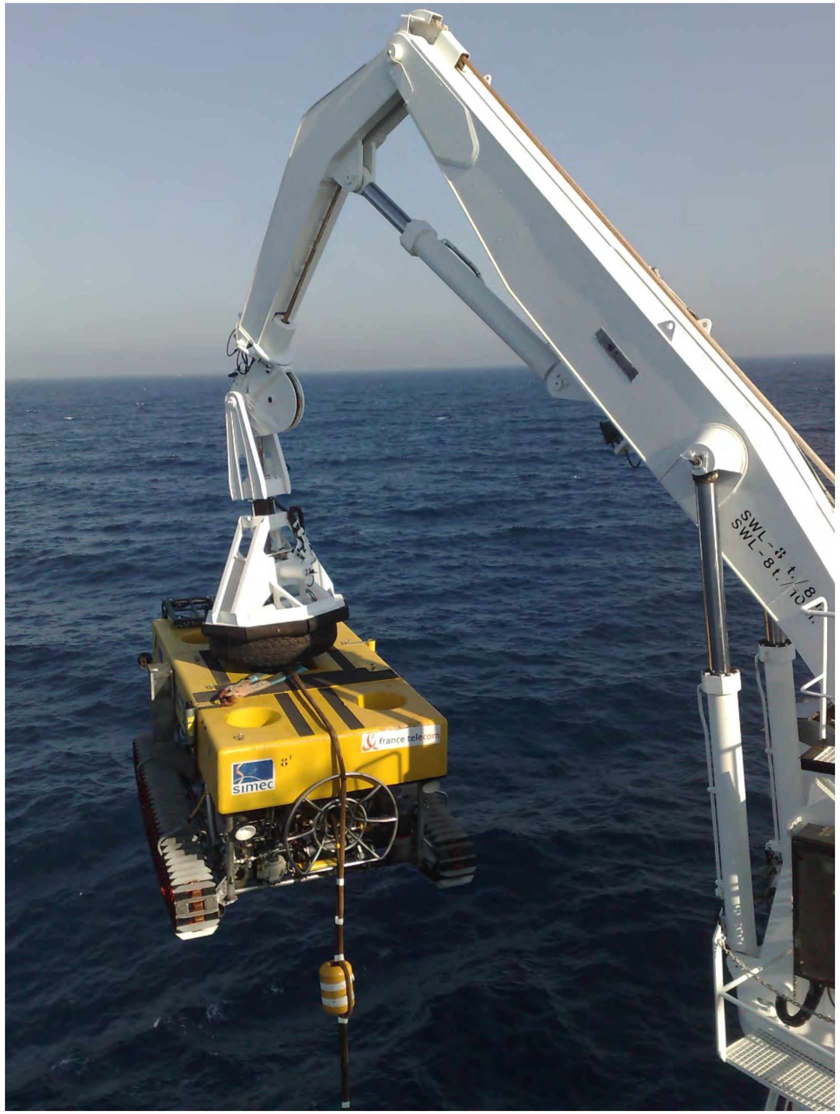


Jointing room

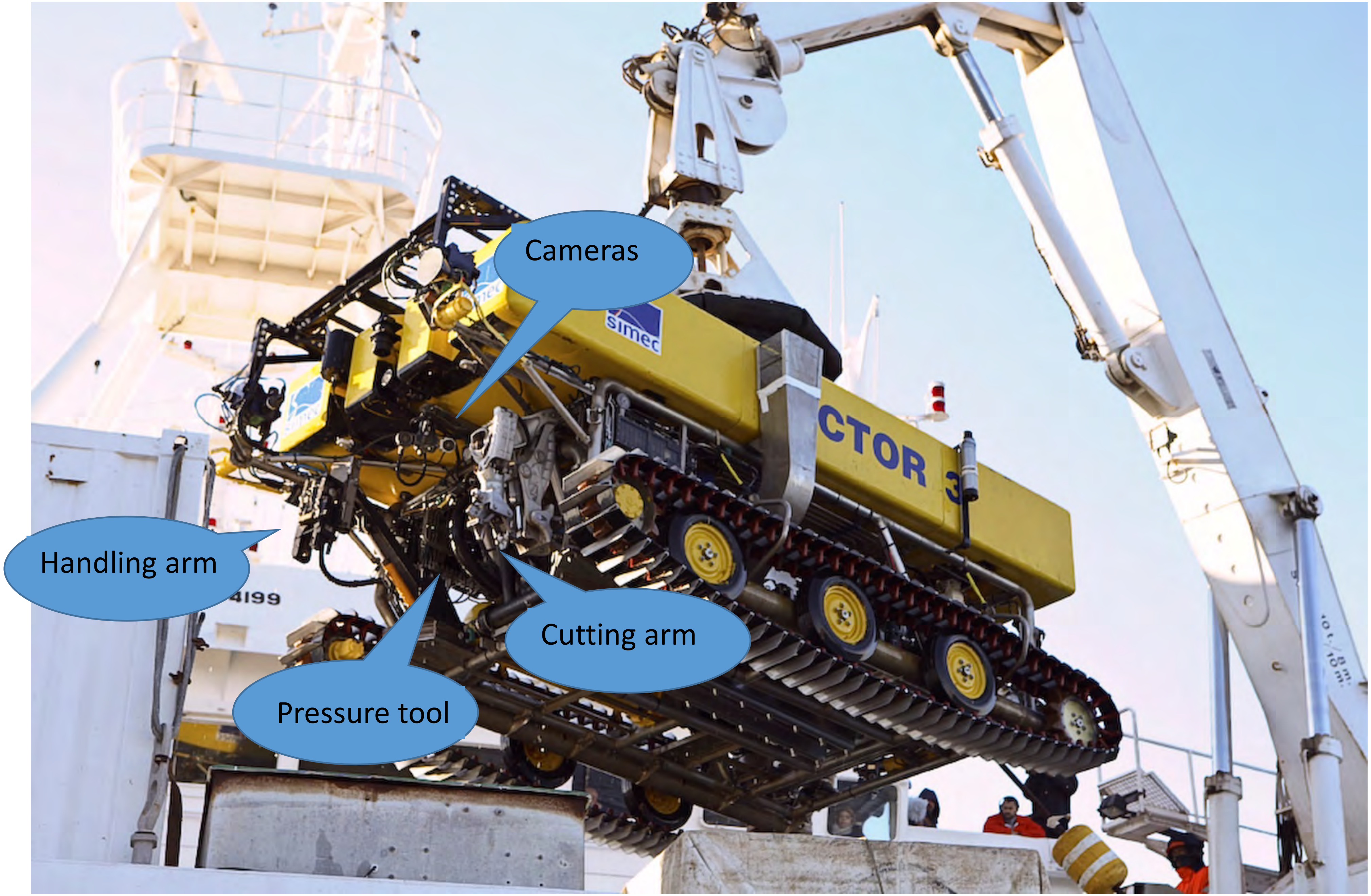
ROV

- The ROV has four functions
  - ✓ Finding the cable
  - ✓ Cutting the cable if necessary
  - ✓ Gripping the cable with a rope
  - ✓ Once the repair done, burial of the cable using high pressure tools

ROV :immersion

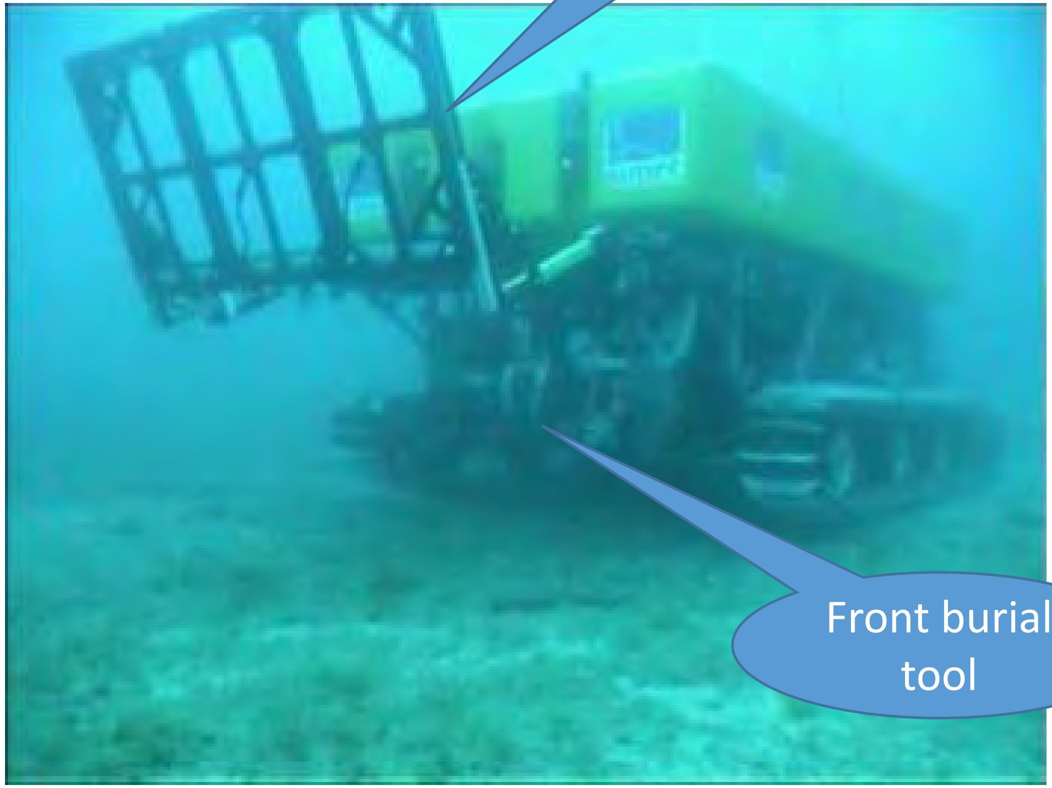


ROV



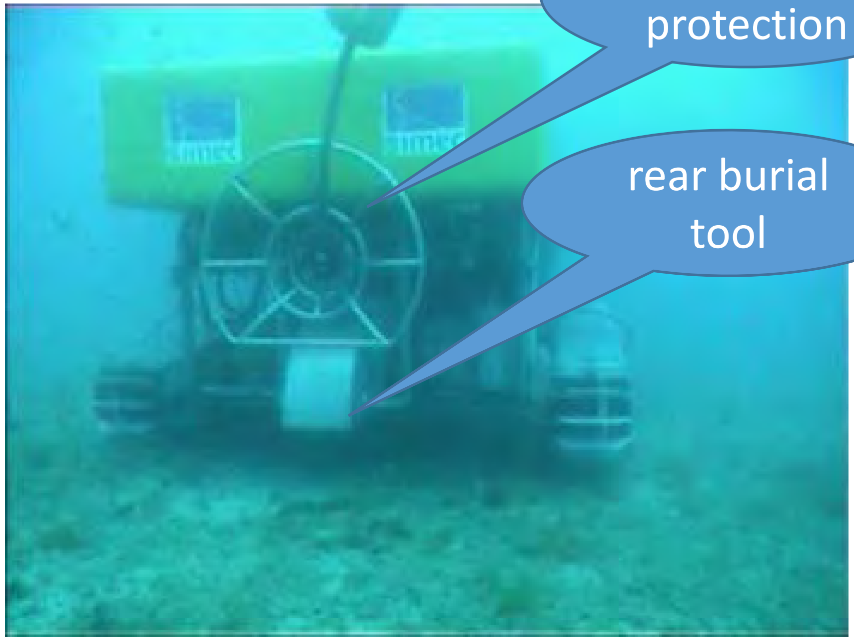
Cameras
Handling arm
Cutting arm
Pressure tool
simec
CTOR 3

ROV



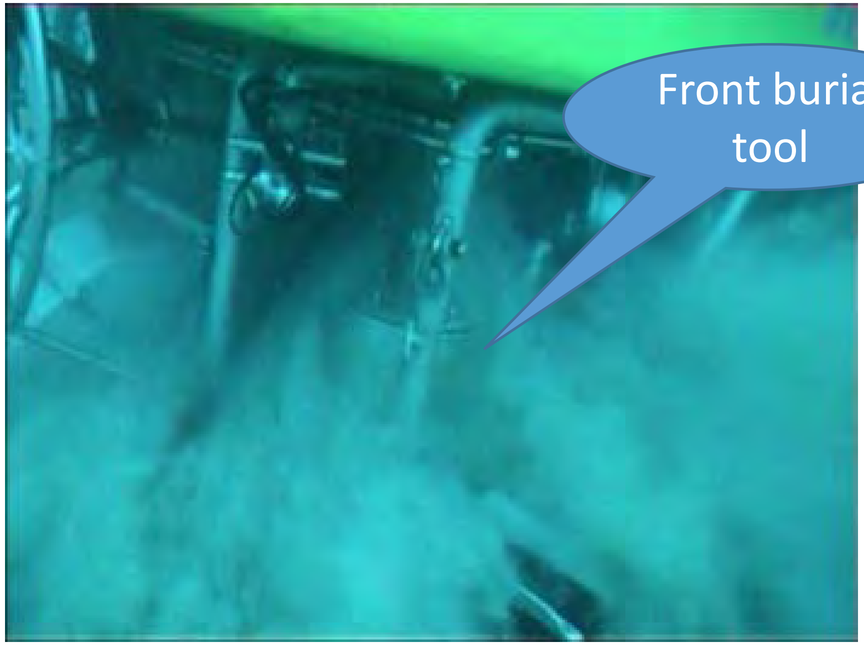
Detection tool

Front burial tool



Umbilical protection

rear burial tool



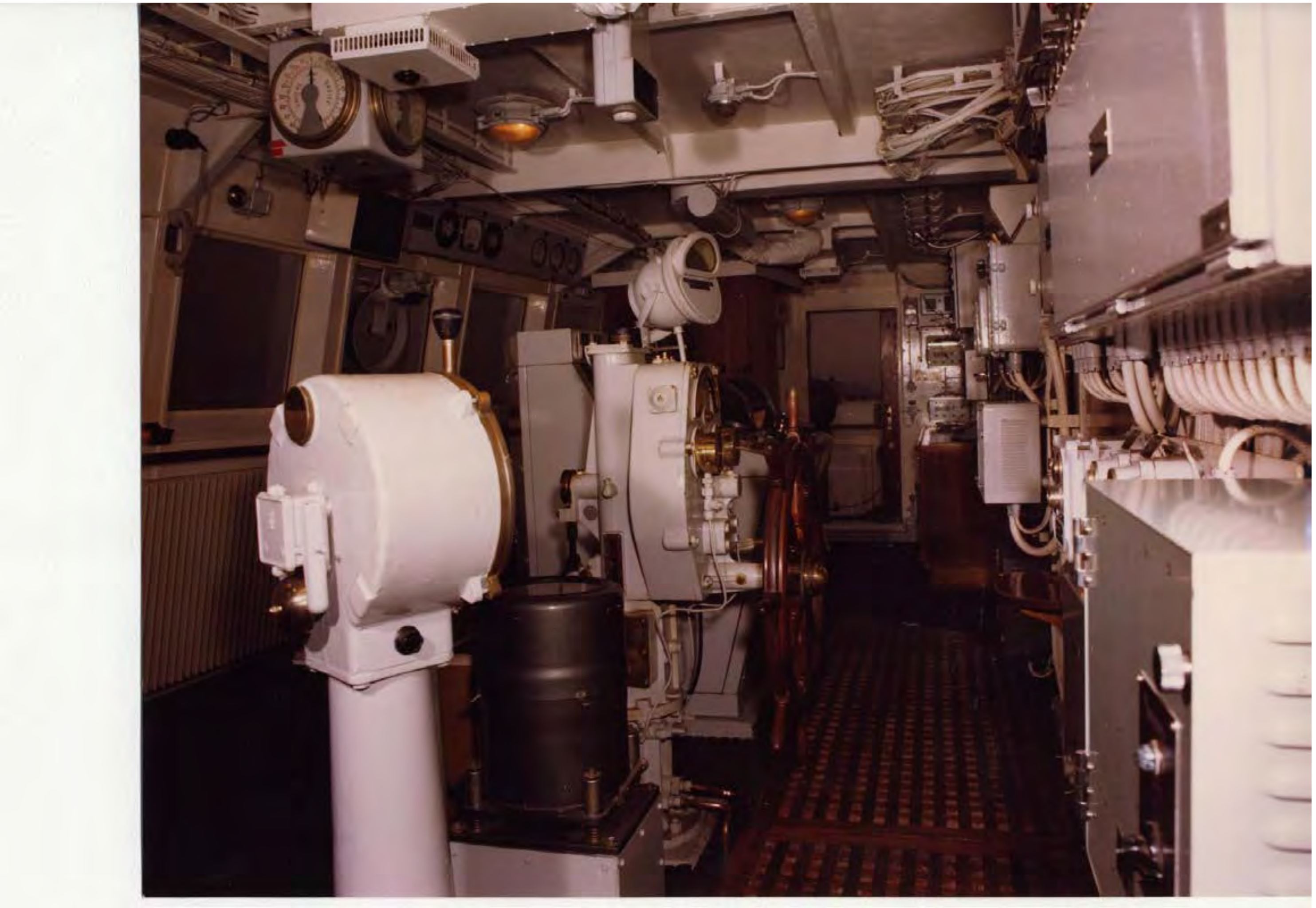
Front burial tool

ROV : control room

- Importance of coordinating the ROV progression with the ship navigation
- The ROV can be floating or progressing on the sea bottom using its tracks

Bridge

Bridge



Grapnels : cutting

Grapnels : retrieving

Food and beverage

Déjeuner

Cassolette d'escargots
Mousse de poisson
Filet de bœuf en croûte de poivre
Et sa garniture
Salade
Fromages
Gâteau automnal

Dîner

Salade de choux rouges
Lotte aux petits oignons
Flan de légumes
Salade
Fromages
Fruits

On board :

- The Captain also called Master is in charge of the vessel and of the people on board, including customer representatives
- The vessel is organized in 3 services:
  - ✓ Bridge, navigation, and deck operations
  - ✓ Engines and all electrical devices on board
  - ✓ General services :administrative, accommodation and food
- The crew organization is different in each company, but there are 50 persons per ship : officers, petty officers and seamen (AB for the deck Able Seamen, with a unique experience)
- There is also a dedicated team for the cable operation :
  - ✓ Telecom technician for measurement and relation with on shore stations
  - ✓ Jointers
  - ✓ ROV pilots and maintenance
  - ✓ Reporting
- This team is about 10 to 12 people, it exists synergies between this team and the crew

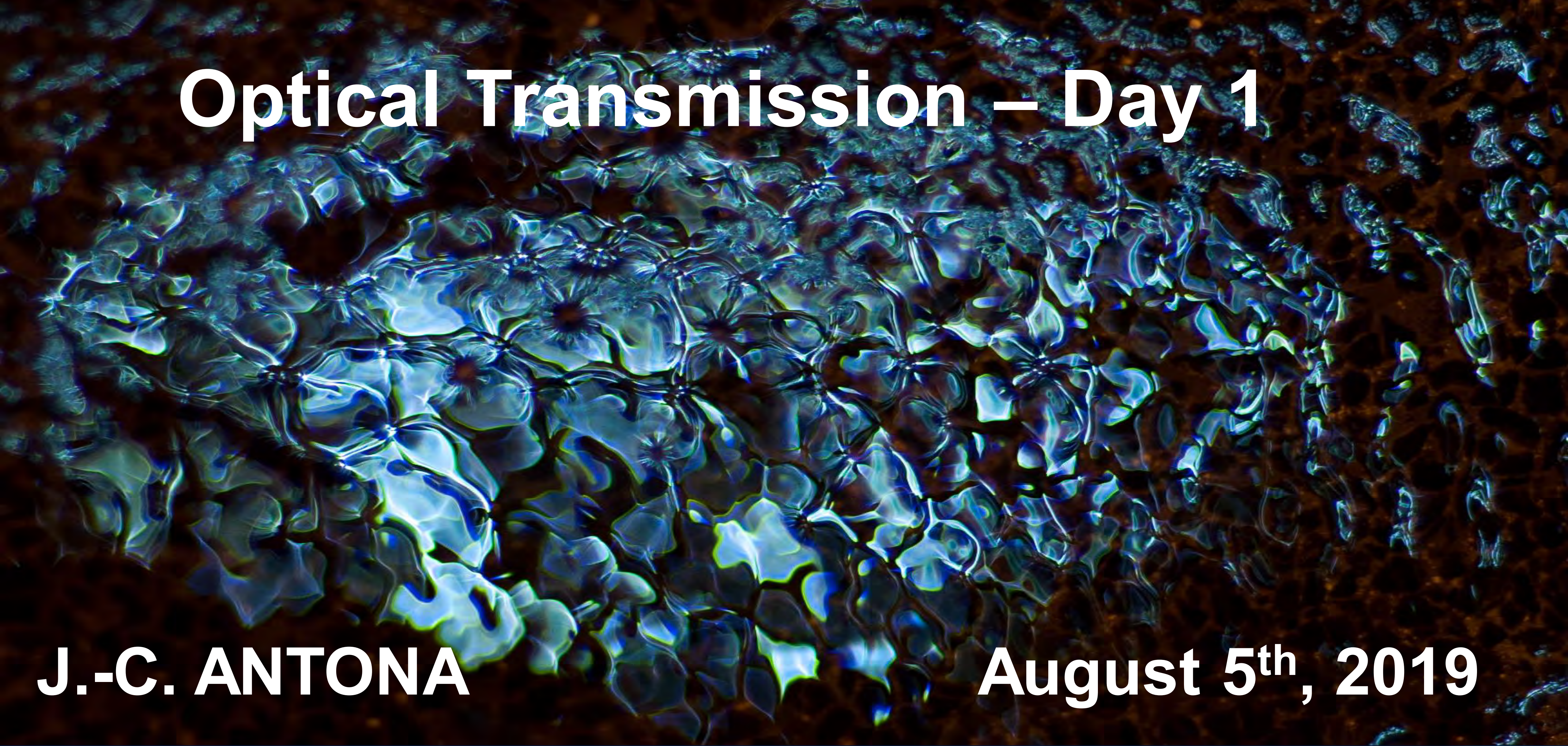
Route and Slack control

- The key point of a good lay (installation or repair) is a good slack management tool and an accurate navigation on the planned route
- Prior to an installation, a survey has provided among others a Route Position List (RPL) that has to be final position of the cable on the seabed
- In order to lay, or relay in case of maintenance operation, the points to be controlled are
  - ✓ The route followed by the vessel, according to the route that has been decided in the survey prior to installation
  - ✓ The speed of the vessel
  - ✓ The speed of the cable engine and the cable drums
- These points are referred to as Slack control. This allows the cable to be laid as flat as possible on the seabed and to avoid any kink due to wrong slack management
- There are several software that are dedicated to the slack management

Slack management : spaghetti and Chopsticks

The most important : the mascotte

- The troll of the Pierre de Fermat
- Forever the Pierre de Fermat will remember being born in Norway

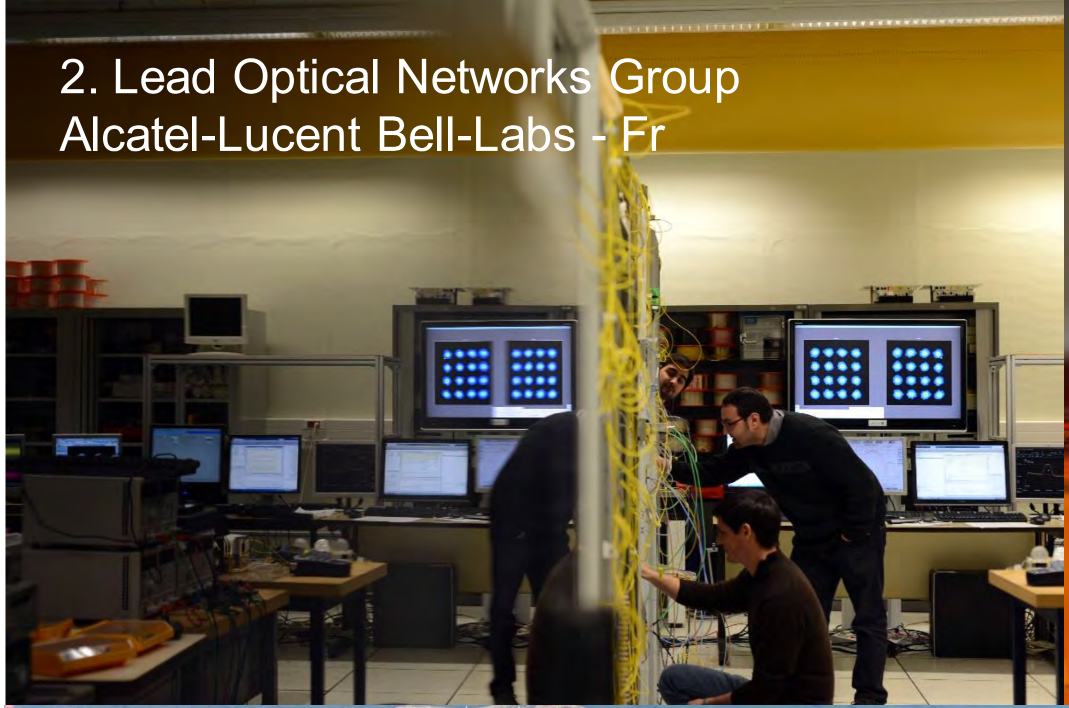


Optical Transmission – Day 1

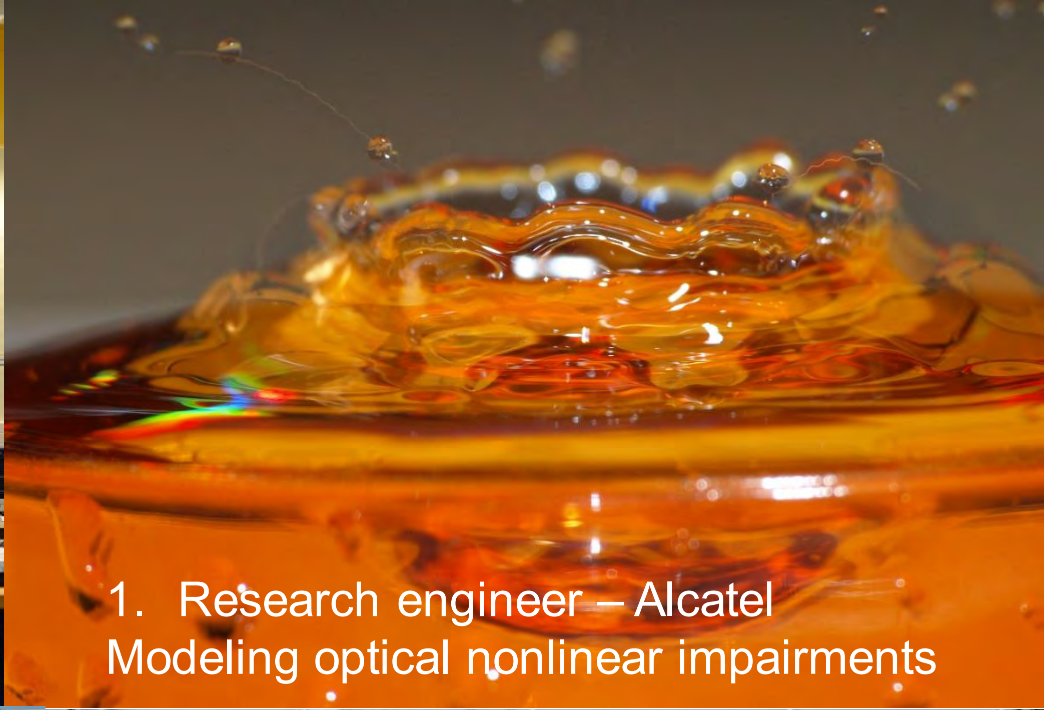
J.-C. ANTONA August 5th, 2019

ALCATEL
SUBMARINE
NETWORKS

J.-C. ANTONA in brief



2. Lead Optical Networks Group
Alcatel-Lucent Bell-Labs - Fr



1. Research engineer – Alcatel
Modeling optical nonlinear impairments

3. Alcatel Submarine Networks
System Design – Research & Techno.

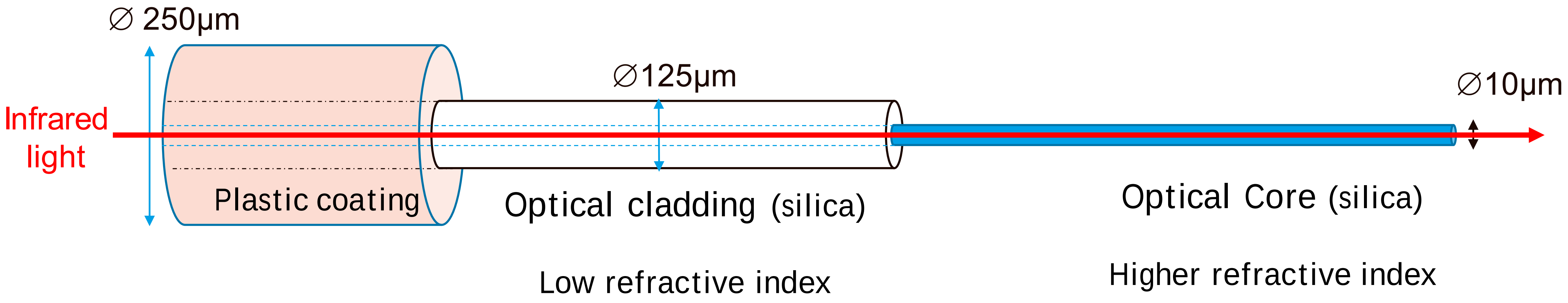
Objectives

- Lecture 1: Basics of digital optical communications
  - Optical Fiber characteristics
  - Principles of digital optical communications
  - Directions towards high capacities
  - Transmitters and (coherent) receivers

  Optional / Advanced: Introduction to Shannon theory

- Lecture 2: signal distortions in a submarine cable
- Lecture 3: system design

Optical fibre = ultra-thin glass waveguide

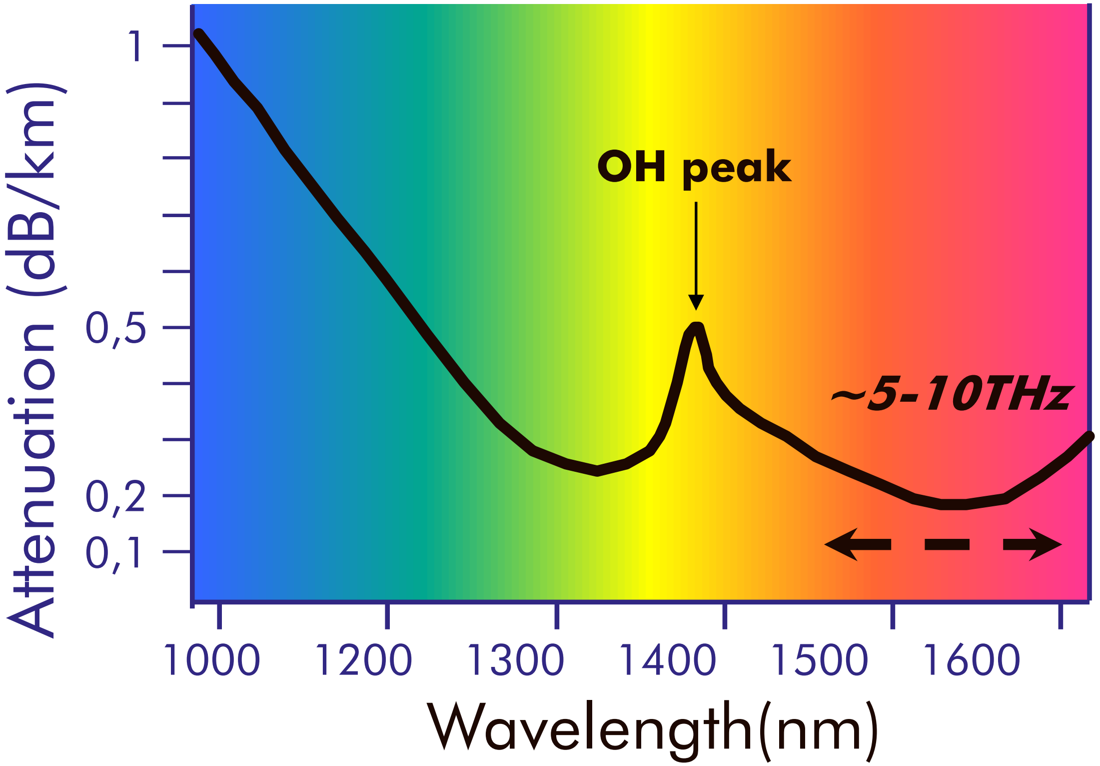


- If core section is small,

➔ single-mode propagation of light starting from a given wavelength

Optical fibre = ultra-transparent glass waveguide

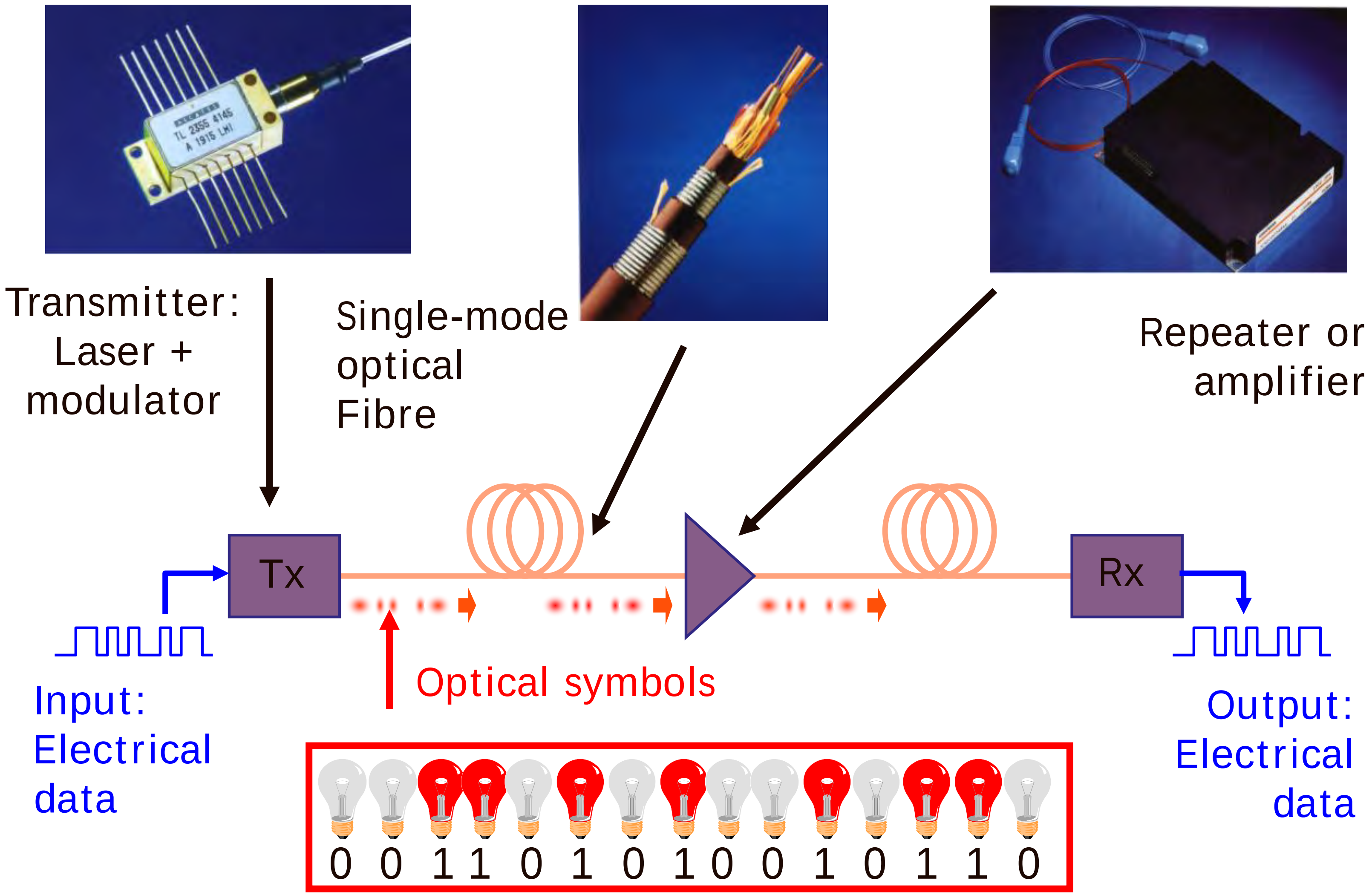
- Silica-based, ultra-transparent waveguide



Minimum attenuation around 1550nm

Terrestrial	0.2dB/km	-50% every 15km
Subsea	0.15dB/km	**-50% every 20km**

Digital Optical Communications: principle



Transmitter:
Laser +
modulator

Single-mode
optical
Fibre

Repeater or
amplifier

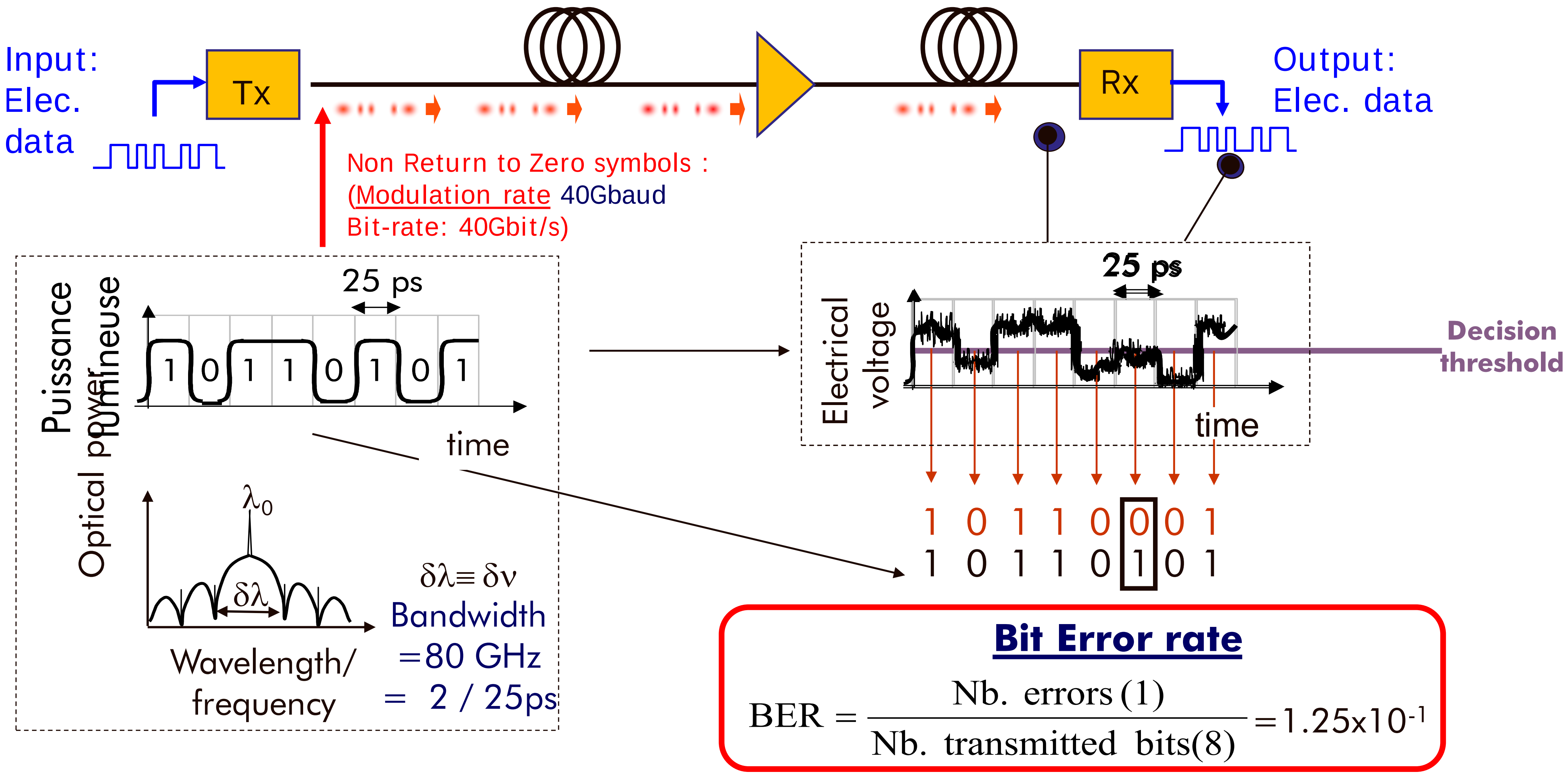
Input:
Electrical
data

Optical symbols

Output:
Electrical
data

0 0 1 1 0 1 0 1 0 0 1 0 1 1 0

Digital Optical Communications: usual criterion of quality



Non Return to Zero symbols :
(Modulation rate 40Gbaud
Bit-rate: 40Gbit/s)

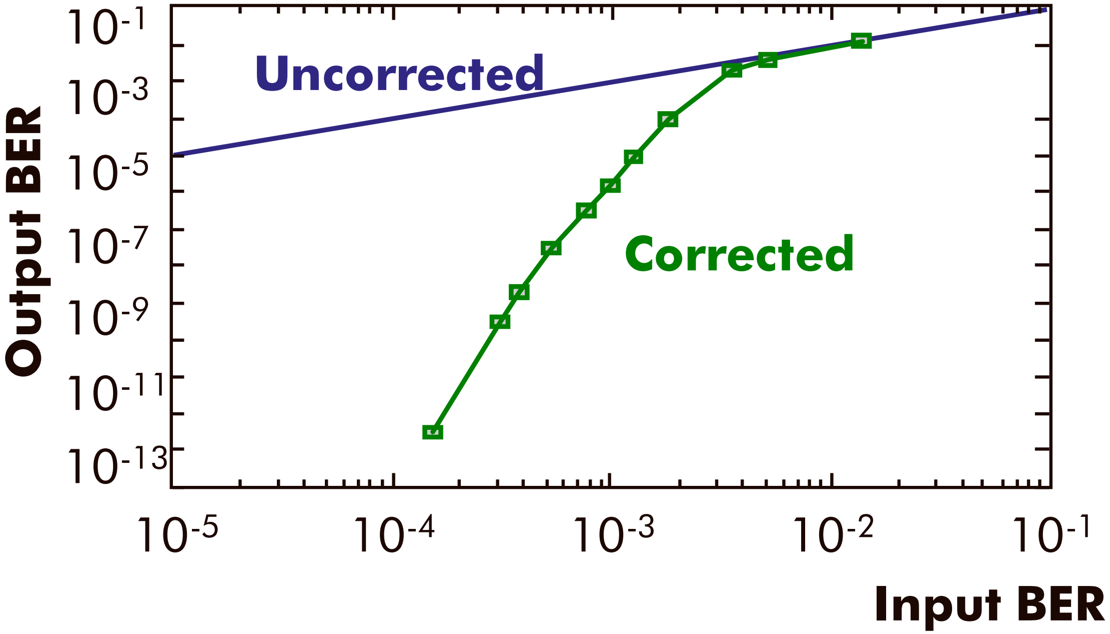
$\delta\lambda \equiv \delta\nu$
Bandwidth
$= 80$ GHz
$= 2 / 25$ps

Bit Error rate

$$\mathrm{BER} = \frac{\text{Nb. errors (1)}}{\text{Nb. transmitted bits(8)}} = 1.25\mathrm{x}10^{-1}$$

Forward Error Correction (FEC)
➔ Transport data free of errors

- Encoding at Transmitter with redundancy bits
- Decoding and error correction at Receiver

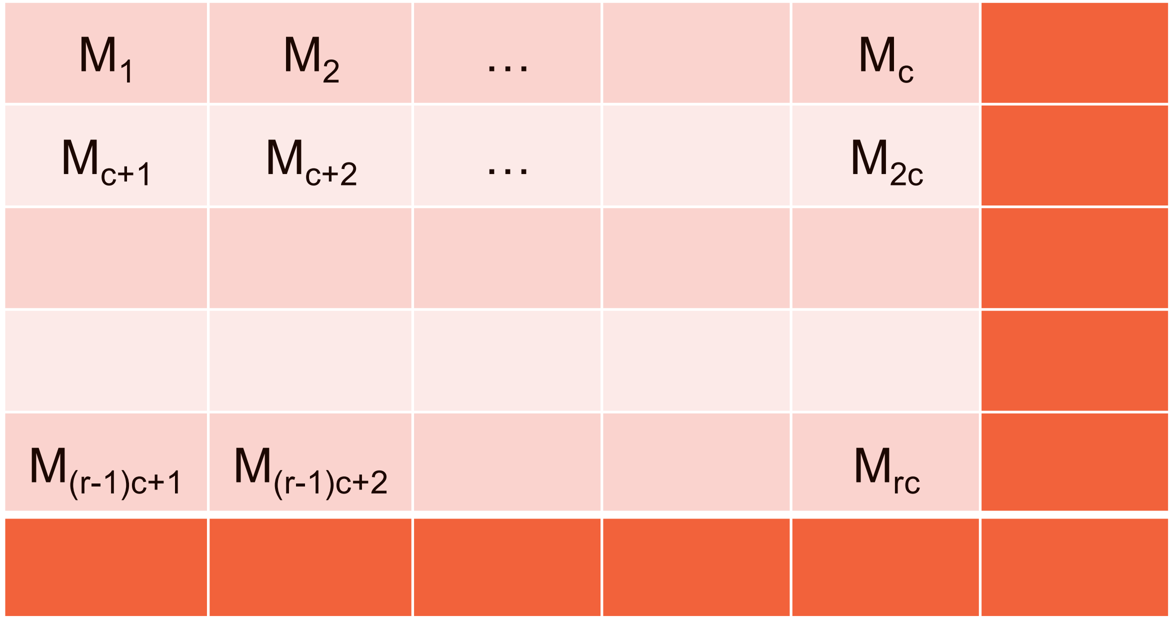


Example of error correction scheme: block code

- Message to transmit: information symbols M_1, M_2, ….M_N…

Example of error correction scheme: block code

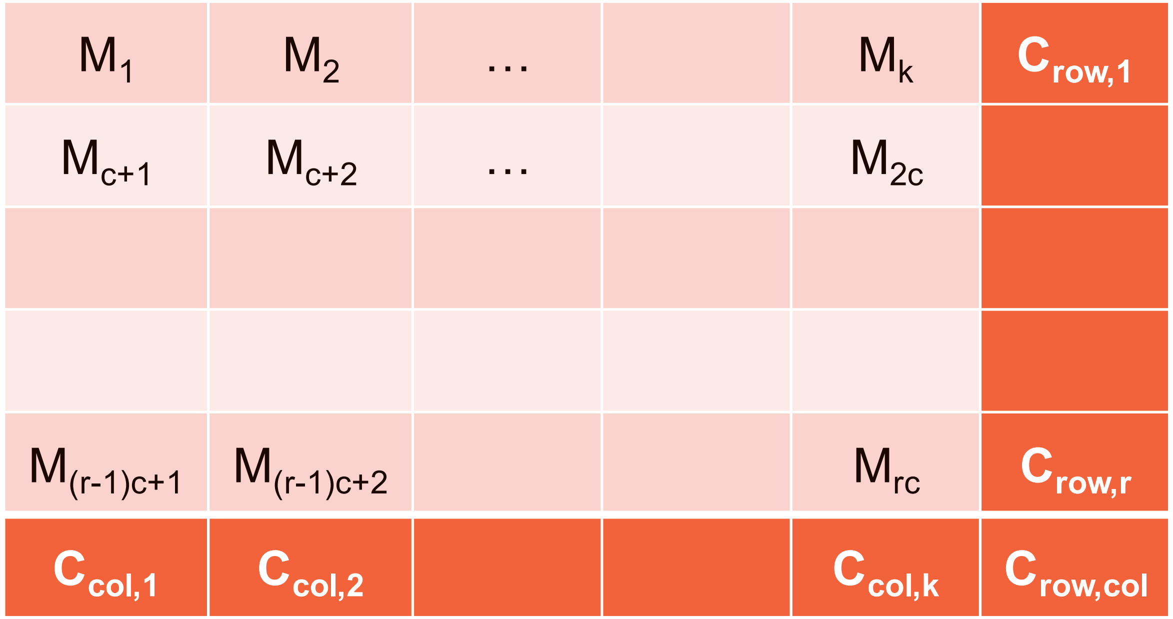
- Organization per block of k symbols: k = r rows * c columns



M_1	M_2	…		M_c	🟧
M_{c+1}	M_{c+2}	…		M_{2c}	🟧
					🟧
					🟧
$M_{(r-1)c+1}$	$M_{(r-1)c+2}$			M_{rc}	🟧
🟧	🟧	🟧	🟧	🟧	🟧

Example of error correction scheme: block code

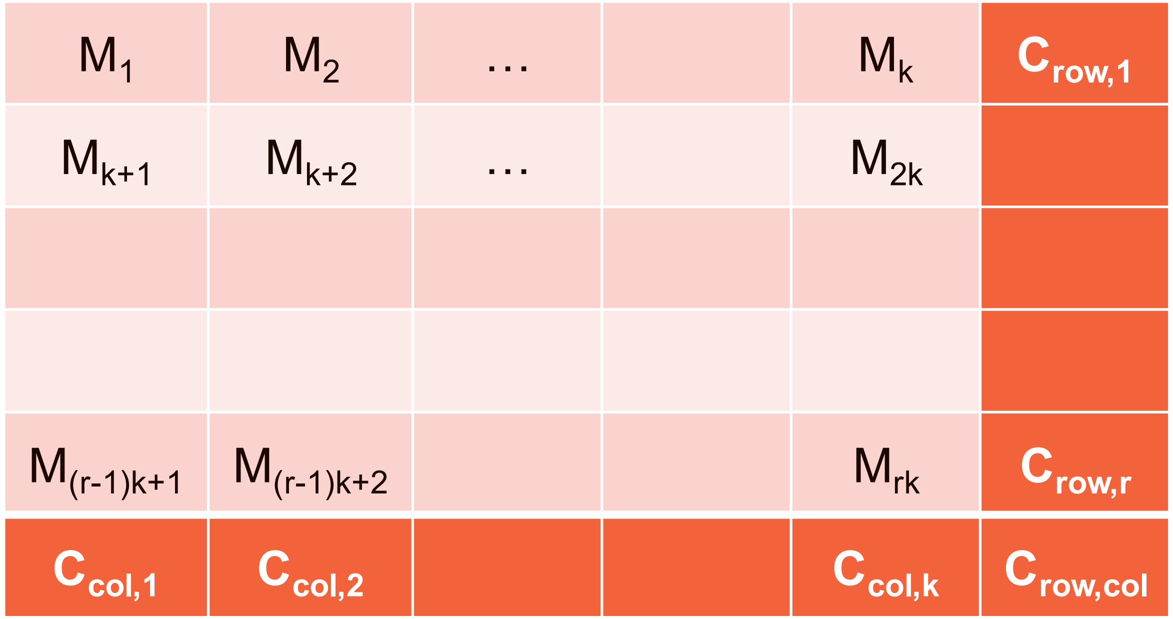
- Parity check for each row, and column



M_1	M_2	…		M_k	$C_{row,1}$
M_{c+1}	M_{c+2}	…		M_{2c}	
$M_{(r-1)c+1}$	$M_{(r-1)c+2}$			M_{rc}	$C_{row,r}$
$C_{col,1}$	$C_{col,2}$			$C_{col,k}$	$C_{row,col}$

Example of error correction scheme: block code

- Transmitted message: block of k+1 columns and r+1 rows
  - Code length: n = (c+1) (r+1), instead of k = c r



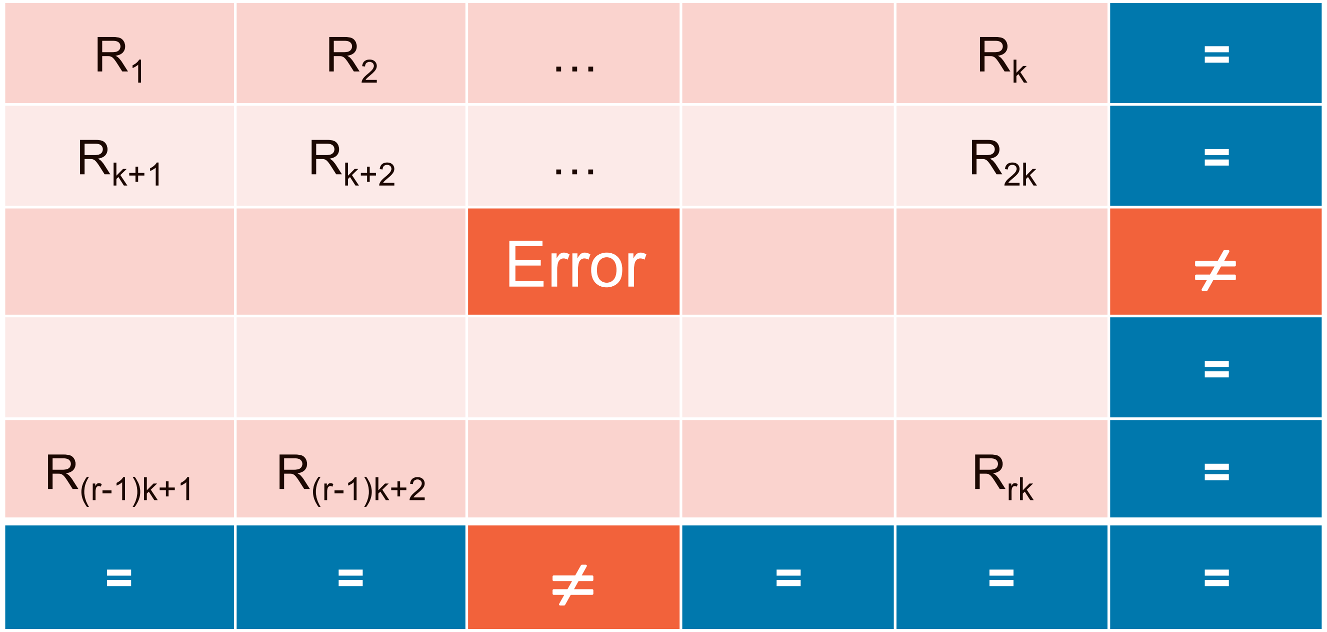
M_1	M_2	…		M_k	$C_{row,1}$
M_{k+1}	M_{k+2}	…		M_{2k}	
$M_{(r-1)k+1}$	$M_{(r-1)k+2}$			M_{rk}	$C_{row,r}$
$C_{col,1}$	$C_{col,2}$			$C_{col,k}$	$C_{row,col}$

Code rate : k/n

Overhead: n/k -1

Example of error correction scheme: block code

- Received block of k+1 columns and r+1 rows
  - Recalculation of check sums and comparison with received checks

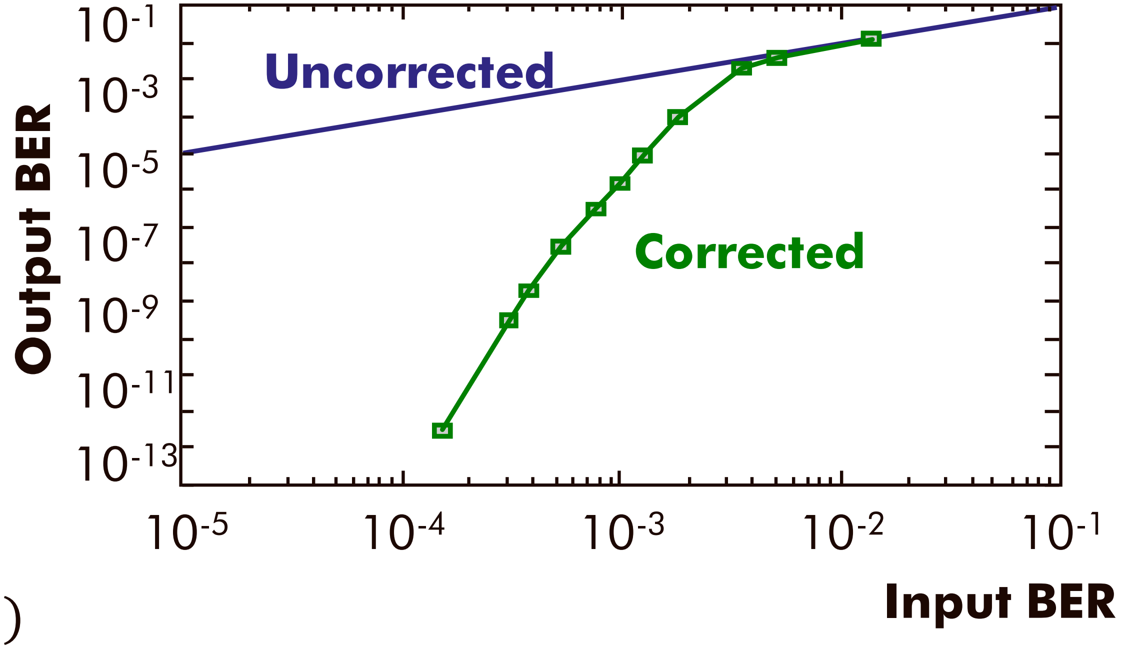


R_1	R_2	…		R_k	=
R_{k+1}	R_{k+2}	…		R_{2k}	=
		Error			≠
					=
$R_{(r-1)k+1}$	$R_{(r-1)k+2}$			R_{rk}	=
=	=	≠	=	=	=

Identification
of 1 error per block,

Forward Error Correction (FEC)
➔ Transport data free of errors

- Encoding at Transmitter with redundancy bits
- Decoding and error correction at Receiver



- Metric: Net Coding Gain
  - Extra-noise tolerated to reach a given BER (dB)
  - $NCG_{dB} = 10 * \log_{10}\left(\frac{Q^2_{correct}}{Q^2_{uncorr}}\right) + 10 * \log_{10}(code\ rate)$
- Typical

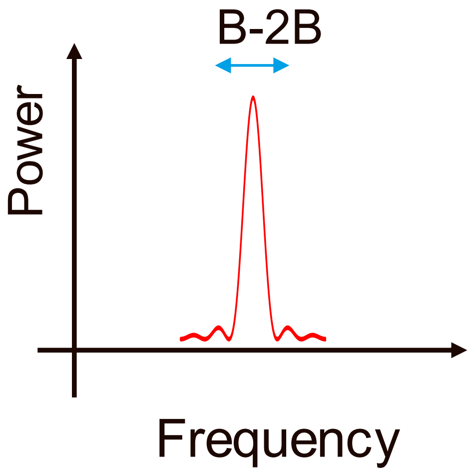
Type	Overhead	Net Coding Gain	Application
Reed Solomon 239-255	7%	5.8dB	Early 10G systems
Product codes	7%	8.3dB	10-40G
Soft Decision FECs	Ex: 25%	11-12dB	100G+ coherent

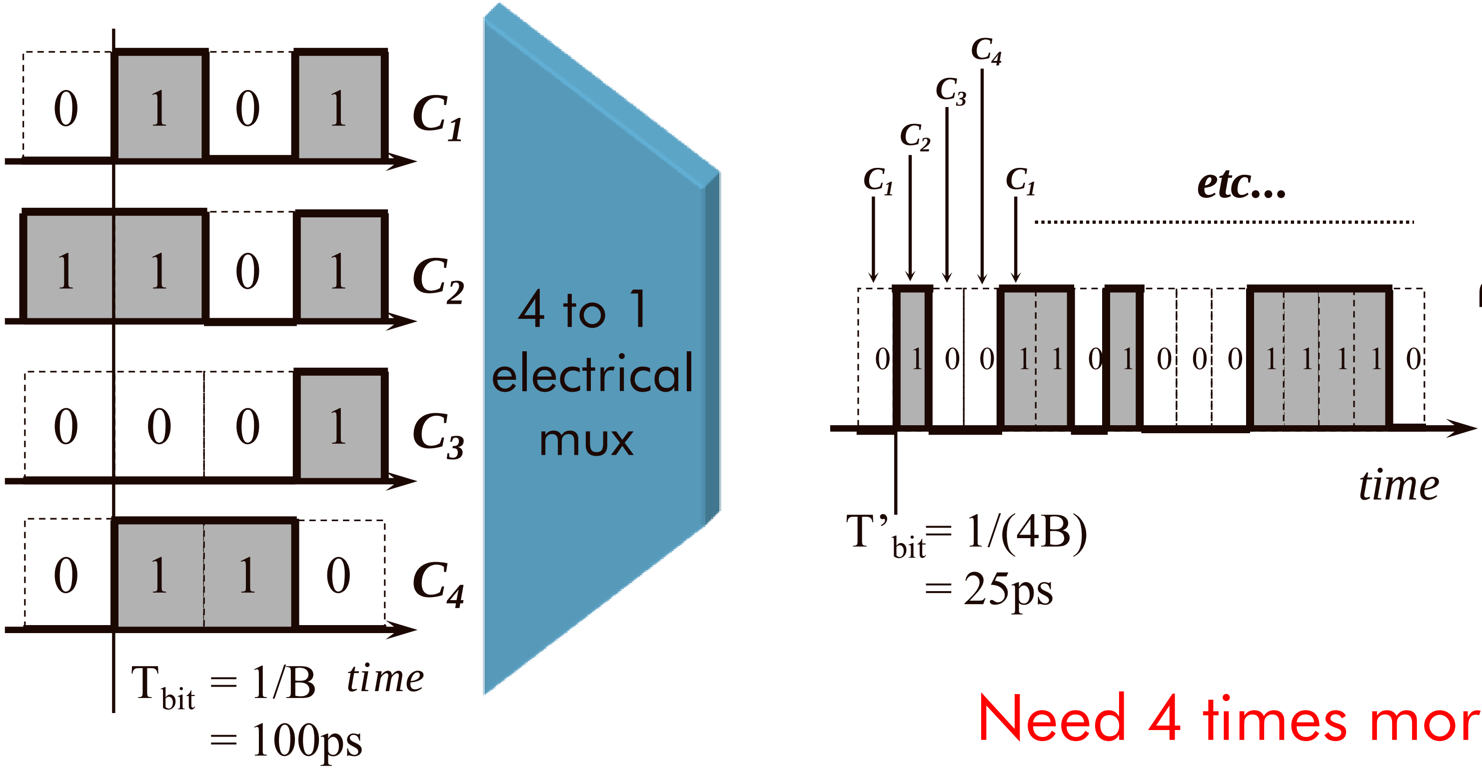
Paths to high data rates

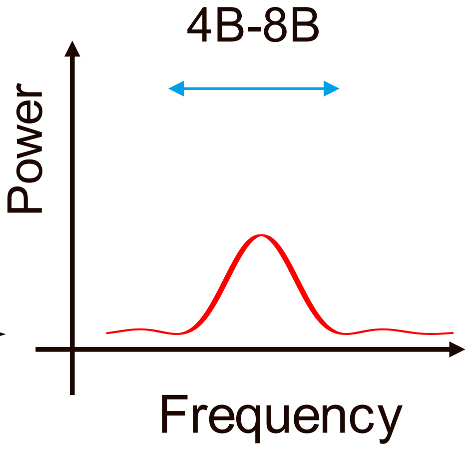
Increasing capacity
1. Higher modulation rates: Time-Division Multiplexing (TDM)

B=10Gbit/s electrical data streams

40Gbit/s electrical data streams



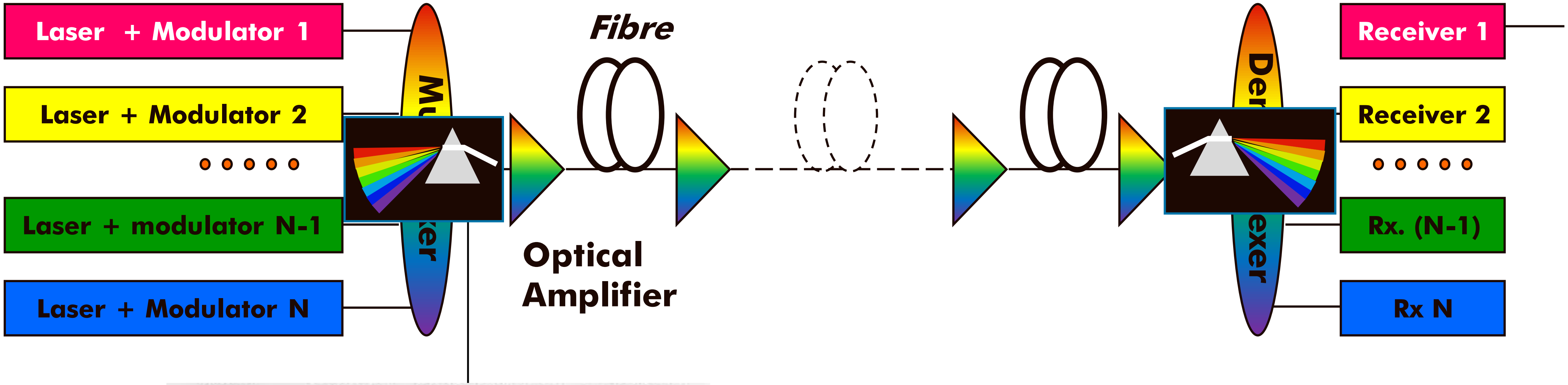


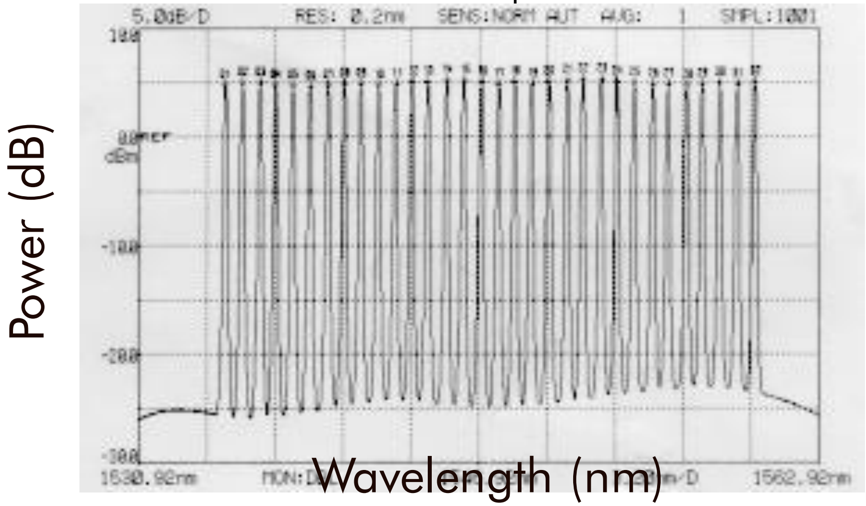


Need 4 times more power

Commercially available transceivers are modulated at up to 70Gbaud (Gsymbols/s)

Increasing capacity :
2. Wavelength-Division Multiplexing (WDM)



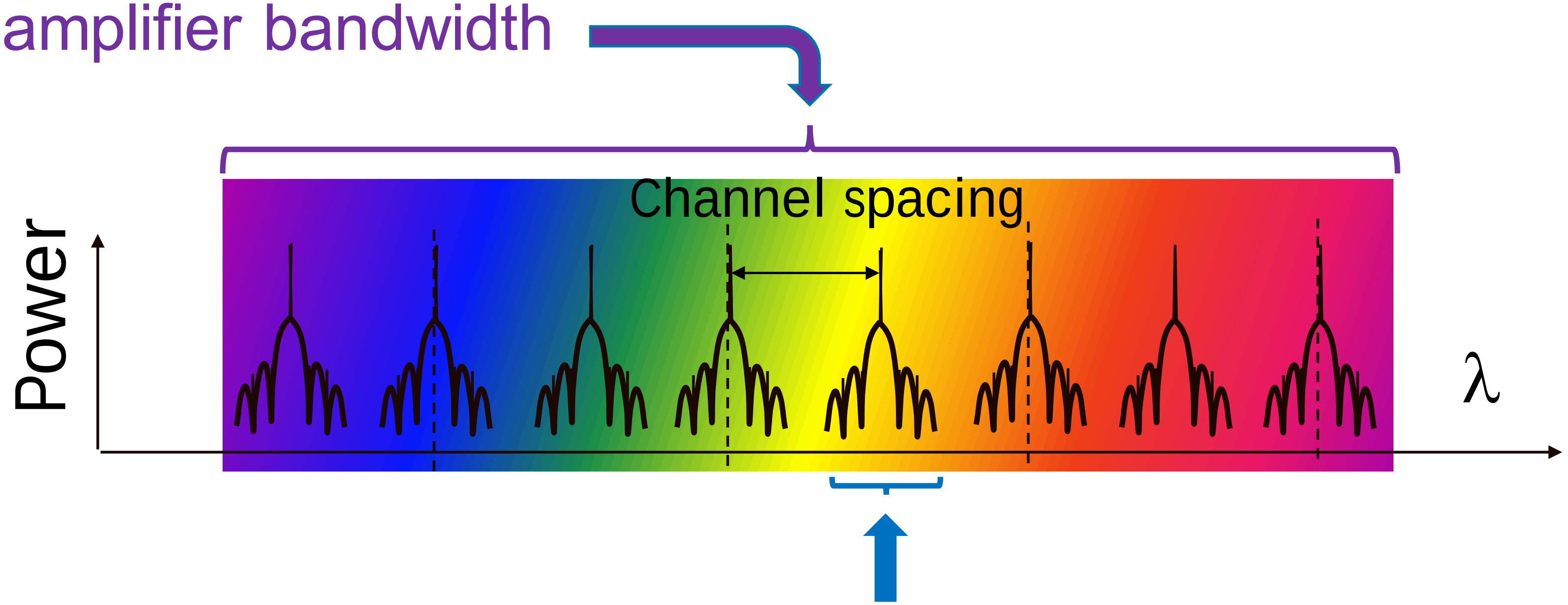


- Wavelength Division Multiplexing
  - Simultaneous transmission of several optical carriers (channels) at different wavelengths

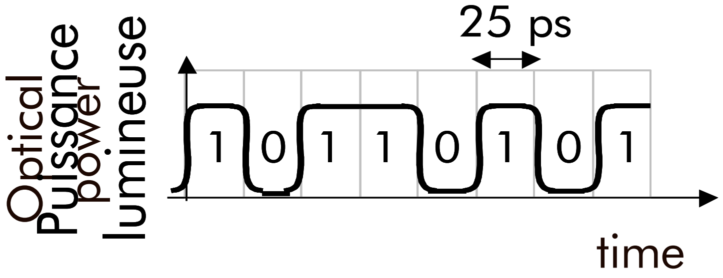
- Capacity : sum of channel bit-rates
  - Ex: 120x25Gbit/s = 3Tbit/s

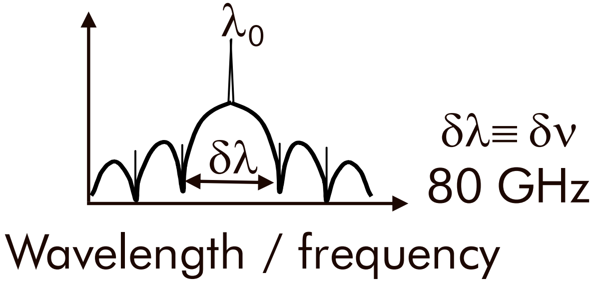
Limitations of WDM

- 1. Optical amplifier bandwidth



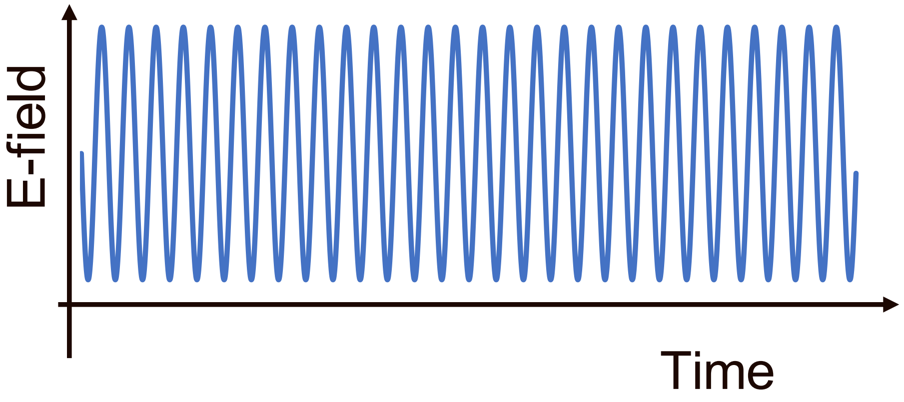
- 2. Channel spacing is limited by channel bandwidth
  - Typ: 1-2 x Modulation rate

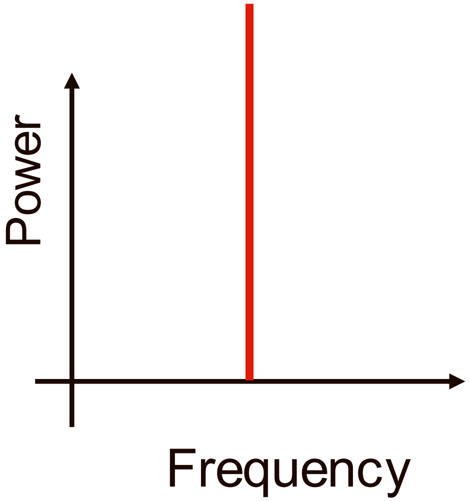




Increasing capacity:
3. Optical modulations

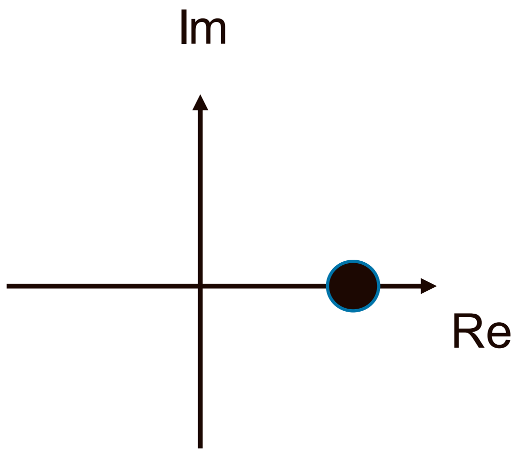
- Unmodulated light





0

Phase

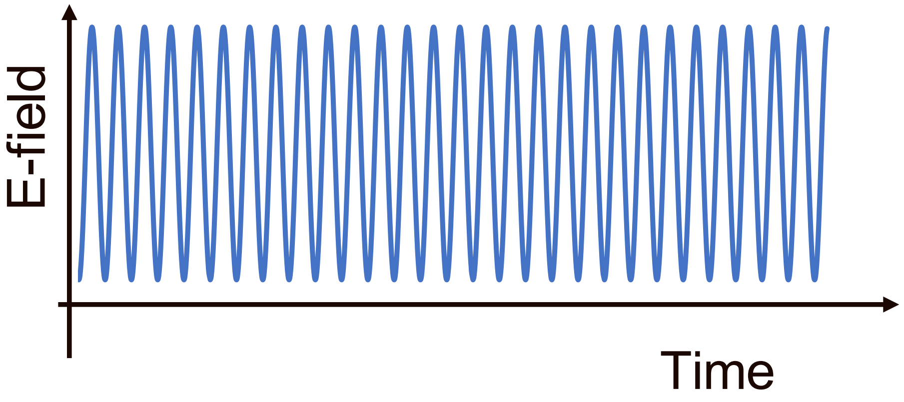


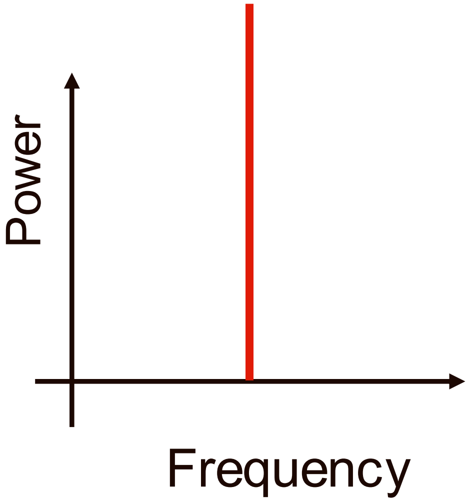
Complex amplitude
of the envelop

$$Wavelength = \frac{Light\ speed}{Frequency}$$

Increasing capacity:
3. Optical modulations

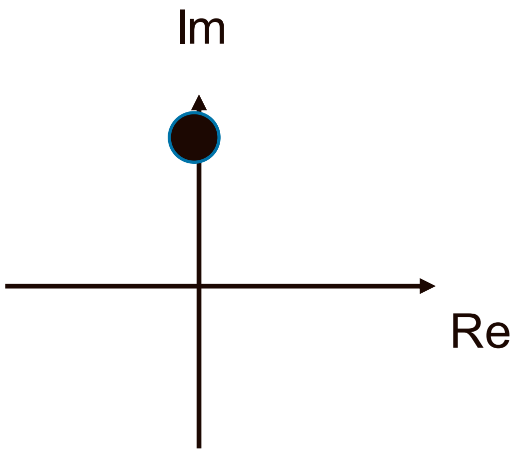
- Unmodulated light





$\pi/2$

Phase

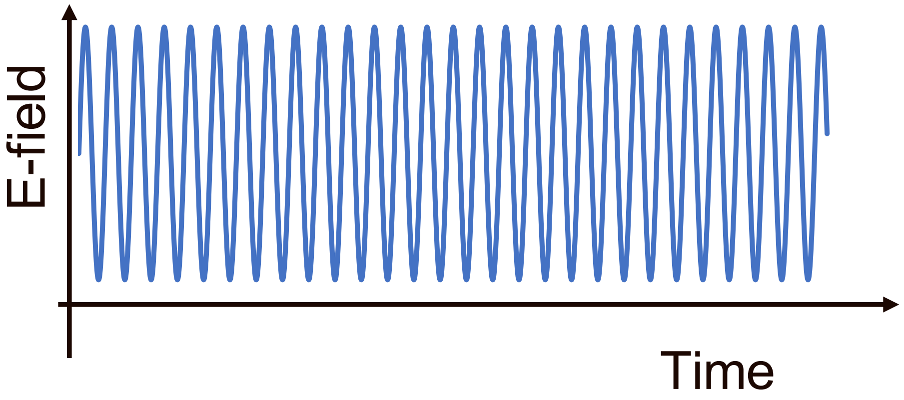


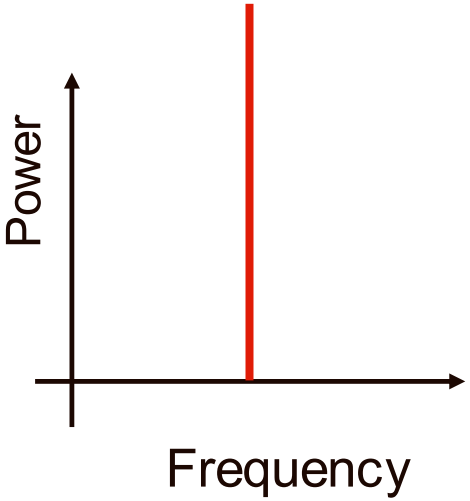
Complex amplitude
of the envelop

$$Wavelength = \frac{Light\ speed}{Frequency}$$

Increasing capacity:
3. Optical modulations

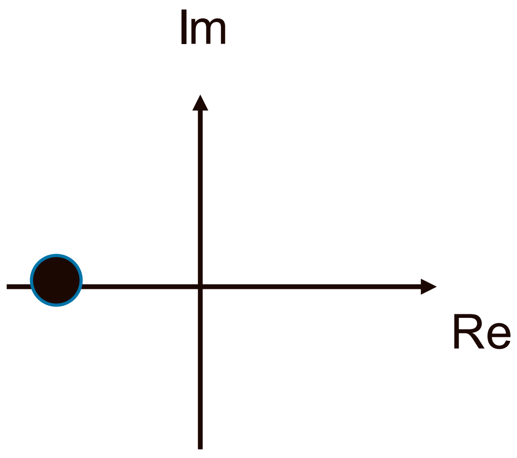
- Unmodulated light





π

Phase

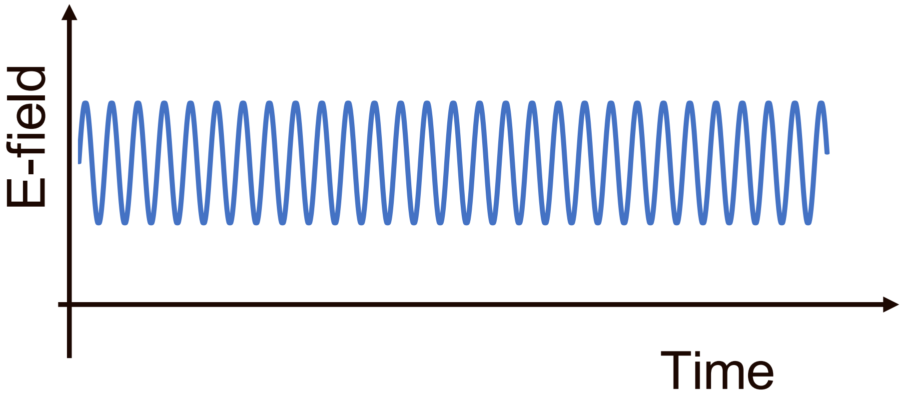


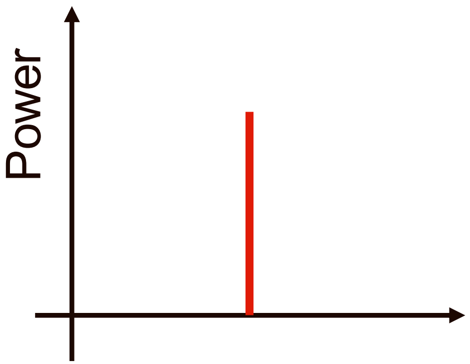
Complex amplitude
of the envelop

$$Wavelength = \frac{Light\ speed}{Frequency}$$

Increasing capacity:
3. Optical modulations

- Unmodulated light

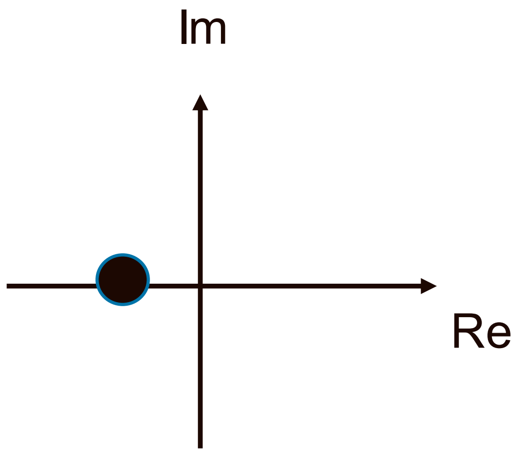




Frequency

π

Phase

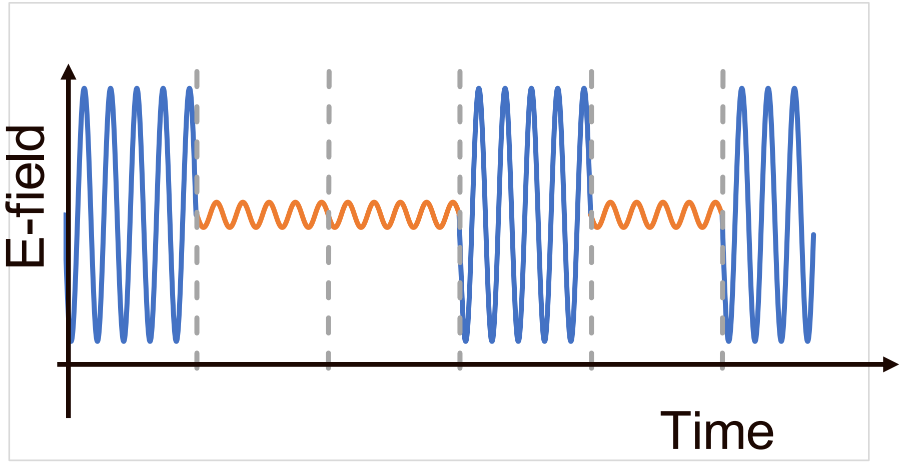


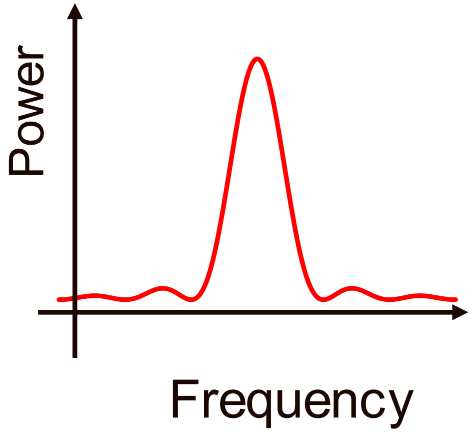
Complex amplitude
of the envelop

$$Wavelength = \frac{Light\ speed}{Frequency}$$

Increasing capacity:
3. Optical modulations

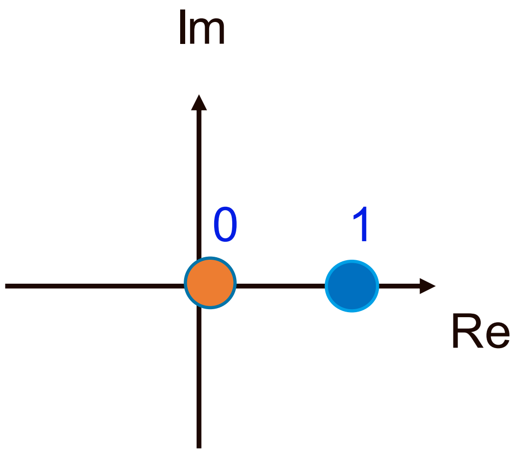
- Amplitude modulation : on-off keying (OOK)





0

Phase



Complex amplitude
of the envelop

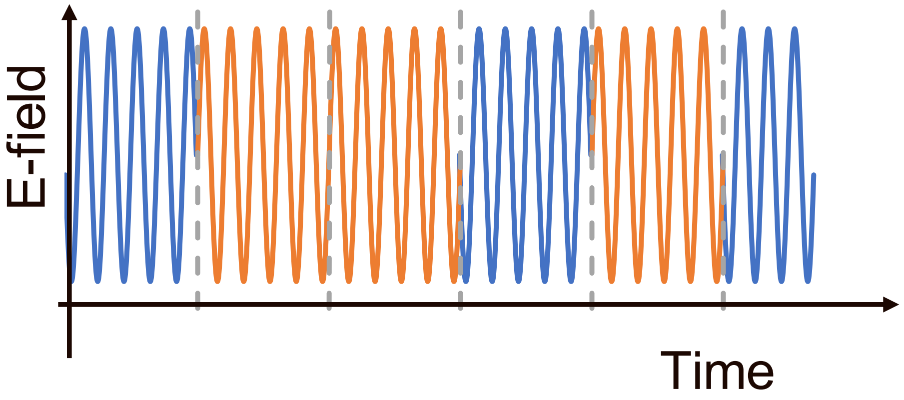
$$Wavelength = \frac{Light\ speed}{Frequency}$$

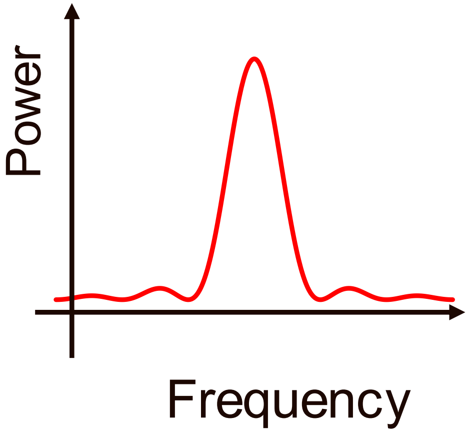
1 bit / symbol

Increasing capacity:
3. Optical modulations

Binary PSK
(BPSK)

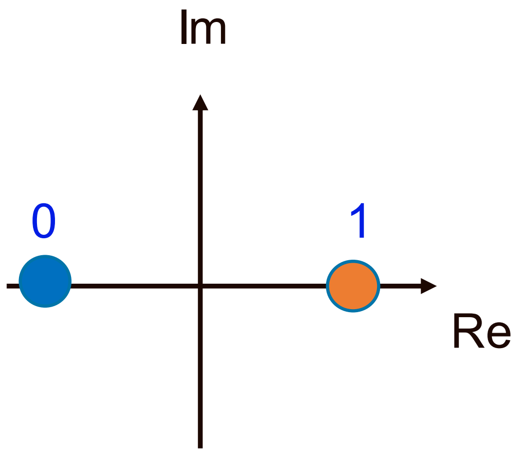
- Phase modulation: Phase Shift Keying (PSK)





$0, \pi$

Phase



Complex amplitude
of the envelop

$$Wavelength = \frac{Light\ speed}{Frequency}$$

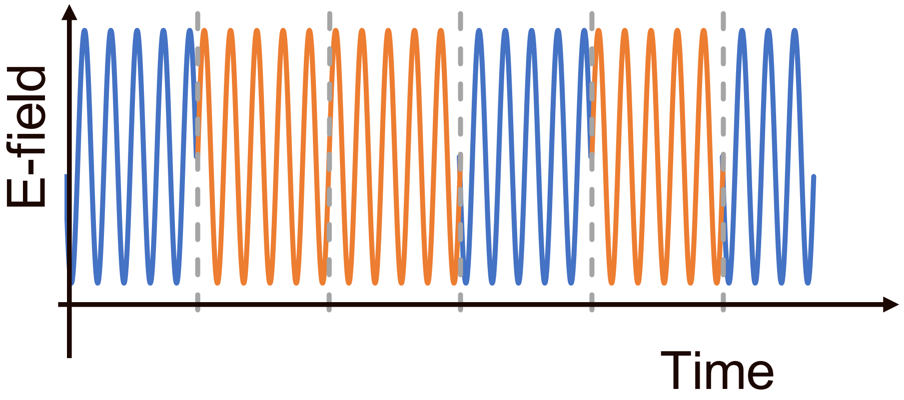
1 bit / symbol

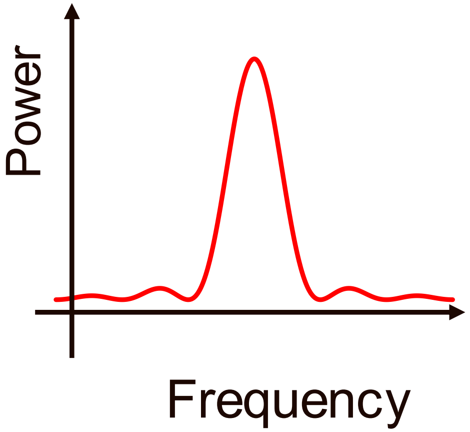
Increasing capacity:
3. Optical modulations

QPSK

(Quaternary PSK)

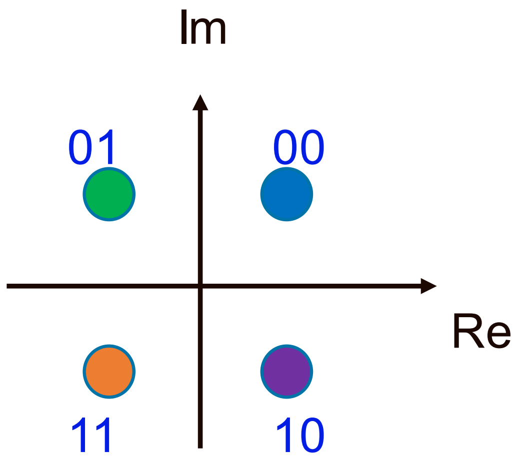
- Phase modulation: Phase Shift Keying (PSK)





0, π/2,
π,- π/2

Phase



Complex amplitude of the envelop

$$Wavelength = \frac{Light\ speed}{Frequency}$$

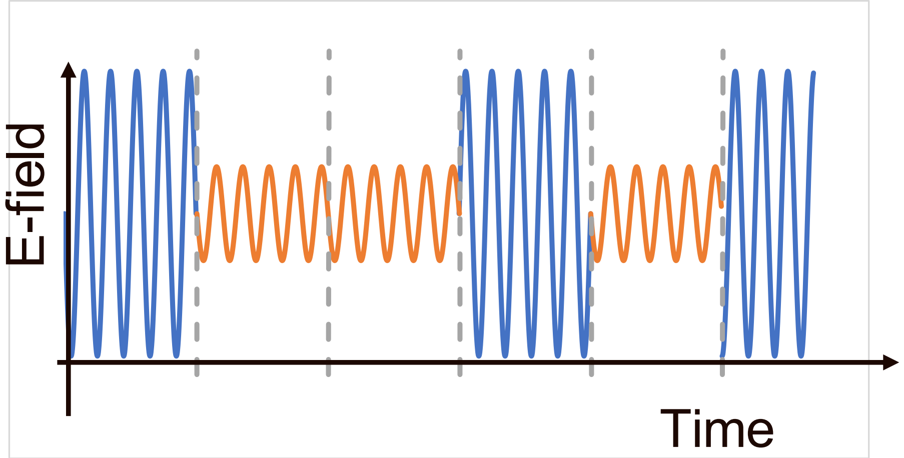
2 bits / symbol

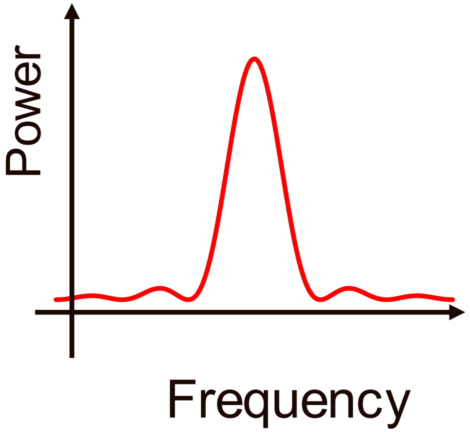
Increasing capacity:
3. Optical modulations

- Phase and amplitude modulation

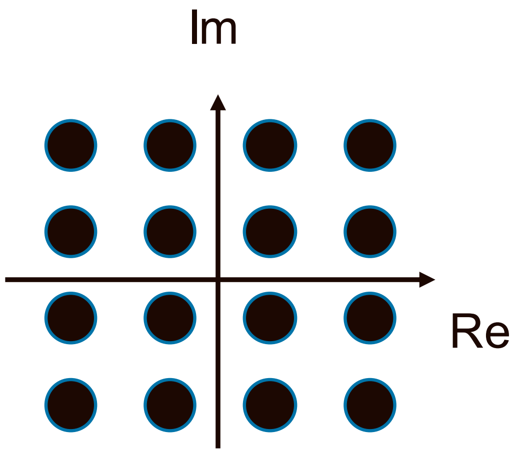
16 QAM

(Quadrature Amplitude Modulation)





$$Wavelength = \frac{Light\ speed}{Frequency}$$



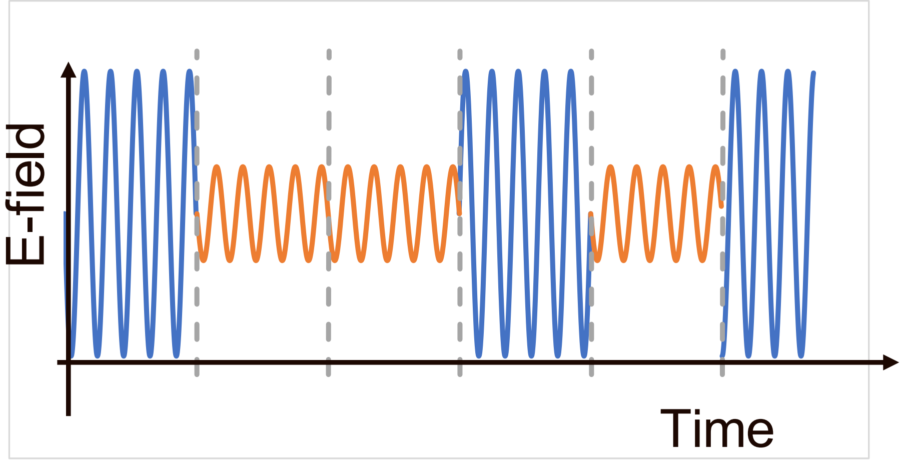
Complex amplitude of the envelop

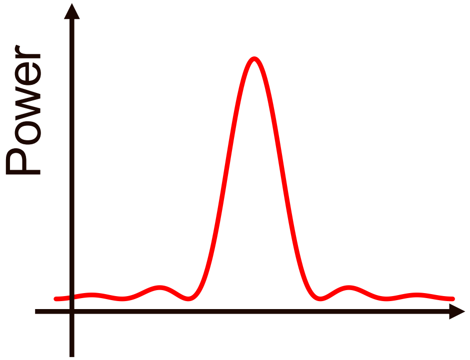
2^4 symbols

➔ 4 bits / symbol

Increasing capacity:
3. Optical modulations

- Phase and amplitude modulation



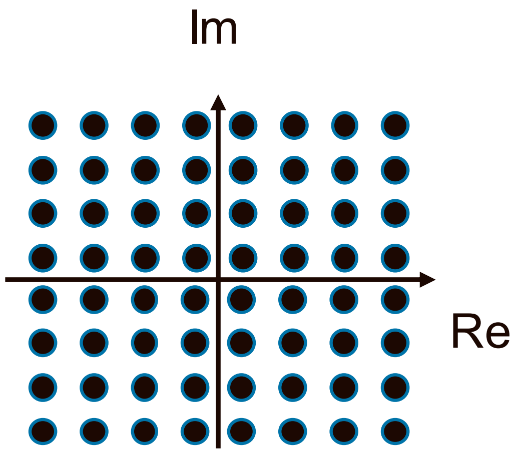


Frequency

$$Wavelength = \frac{Light\ speed}{Frequency}$$

64 QAM

(Quadrature Amplitude Modulation)

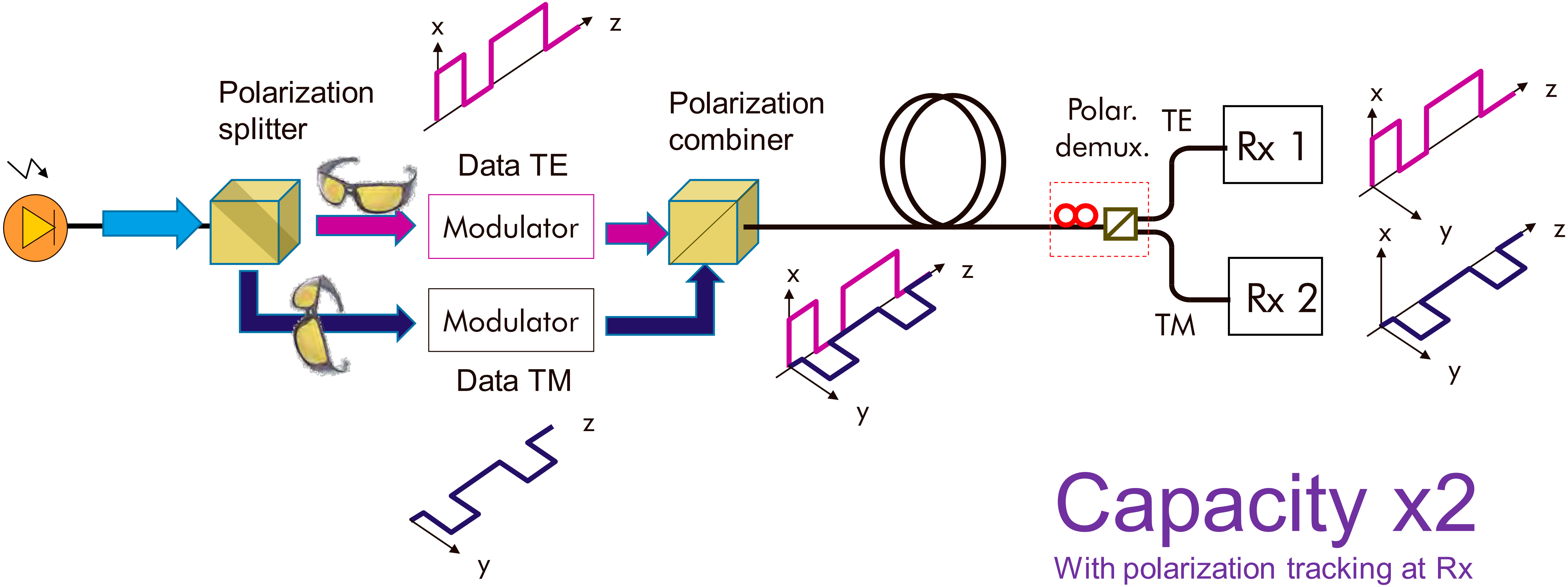


Complex amplitude of the envelop

➔ **6 bits / symbol**

The more the symbols, the less the system is resilient to noise

4/ Polarization Division Multiplexing (PDM)

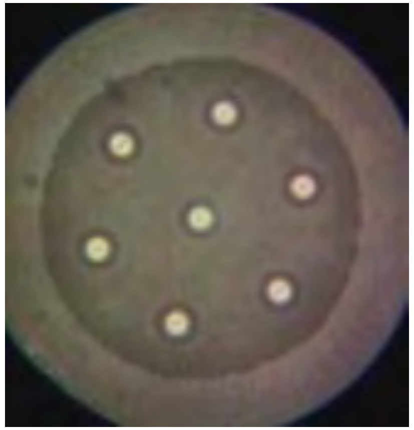


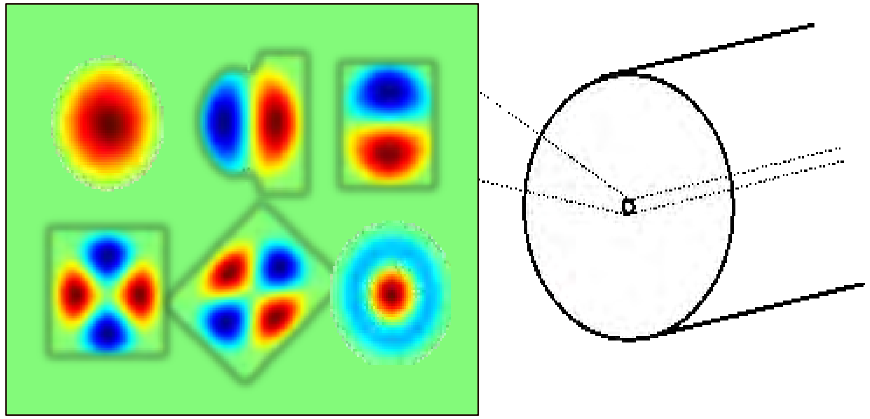
Capacity x2

With polarization tracking at Rx

5/ Spatial division multiplexing (SDM)

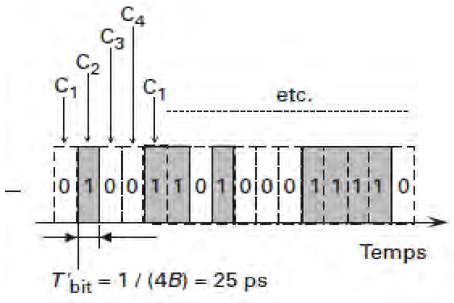
- Spatial parallelism to increase transported capacities
- Options: Multi-fiber, multi-core, multi-mode



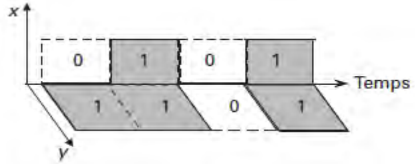


Directions to increase transported capacity

Increase of symbol rate (and spectrum width)

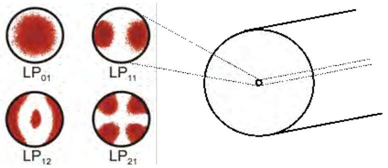


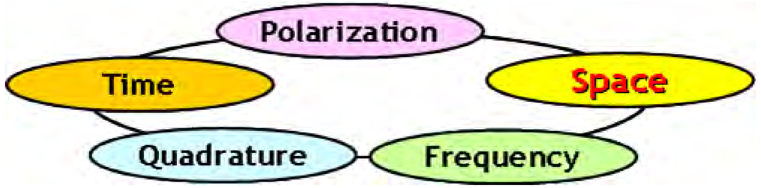
Bit rate x2 at fixed symbol rate



Multiplication of bit-rate by number of « modes »

Multi-core, mode, fiber





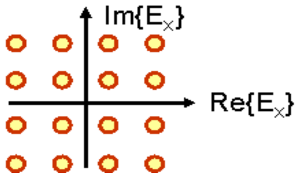
Polarization

Time

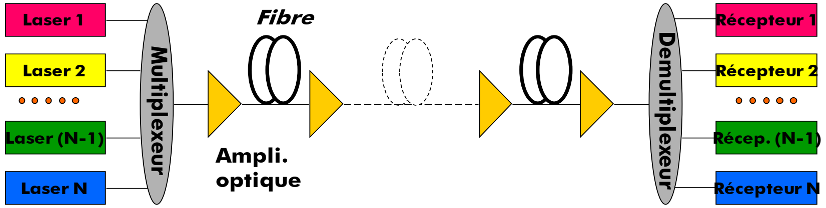
Space

Quadrature

Frequency



Increase number of bits per symbol

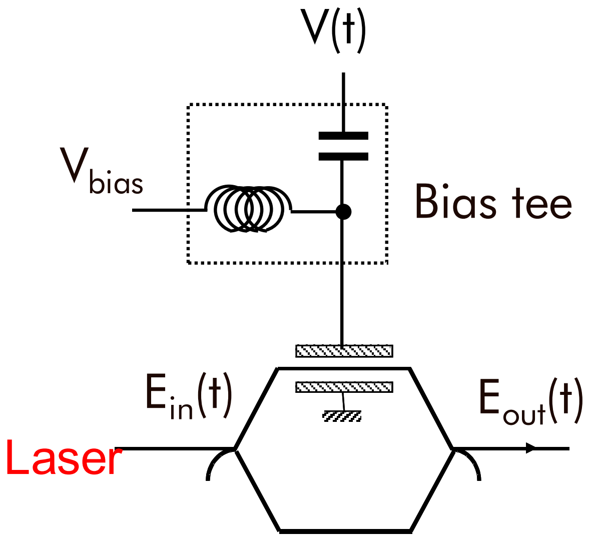


Multiplication of bit-rate by number of wavelengths

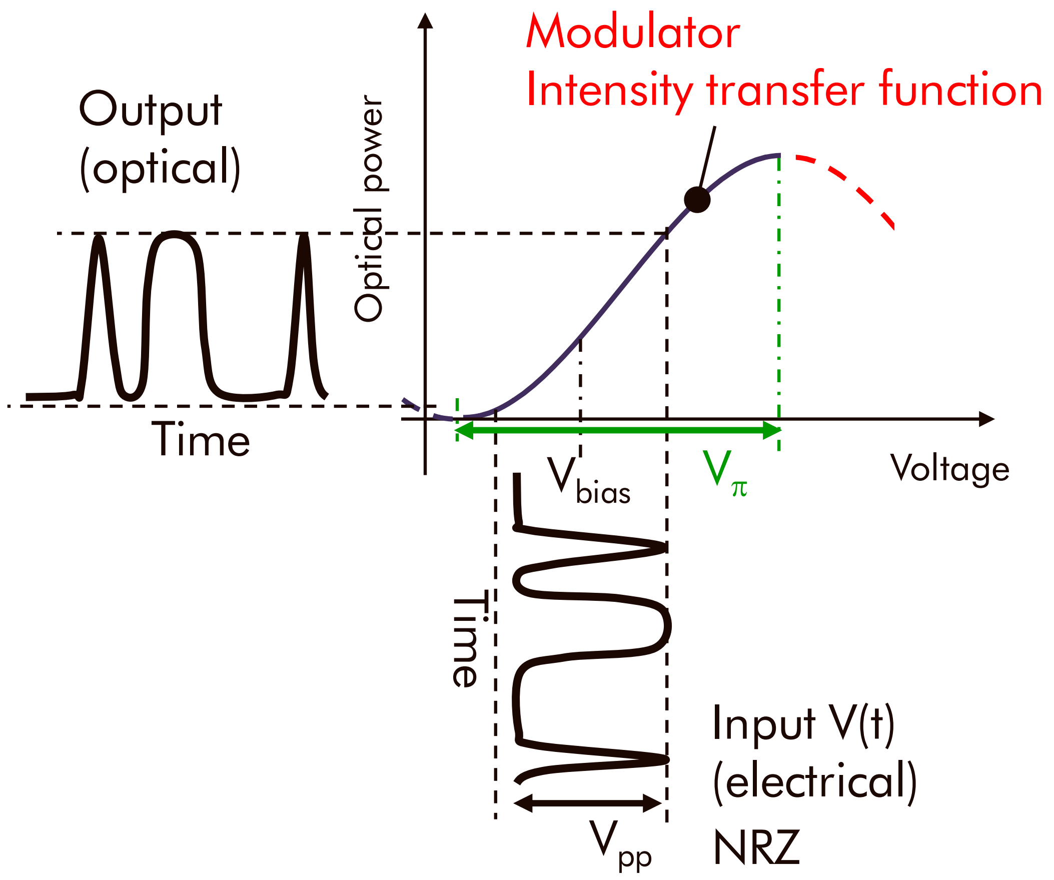
- Capacity (b/s) = $Nb_{\text{spatial modes}} * Nb_{\text{polars}} * Nb_{\text{wavelengths}} * Nb_{\text{bits/symbol}} *$ SymbolRate (baud) / Overhead
- $Nb_{\text{bits/symbol}} = \log_2 (Nb_{\text{symbols}})$

Ex: 120 channels, PDM-16QAM, 25 G information symbol / s = 24Tb/s * Nb Fibers

Modulation of light: principle



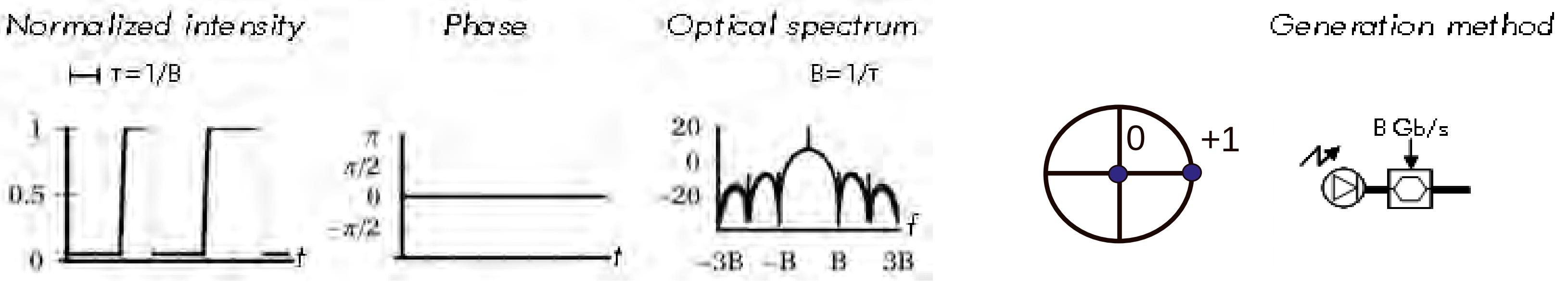
Electro-optic modulator



Independant control of swing voltage V_{pp} and bias.

Generation of main modulation formats (pre-coherent era)

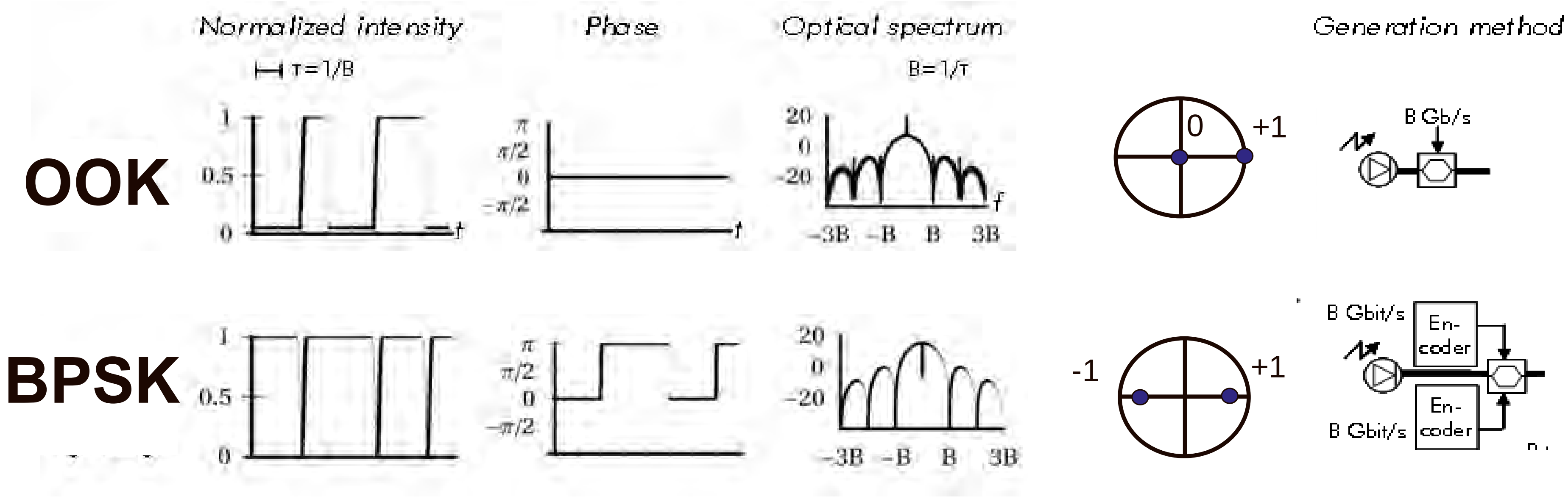
OOK



B=bit rate

From E. Desurvire et al., «EDFA, Device and System developments», Chapter 7, Wiley, 2002.

Generation of main modulation formats (pre-coherent era)



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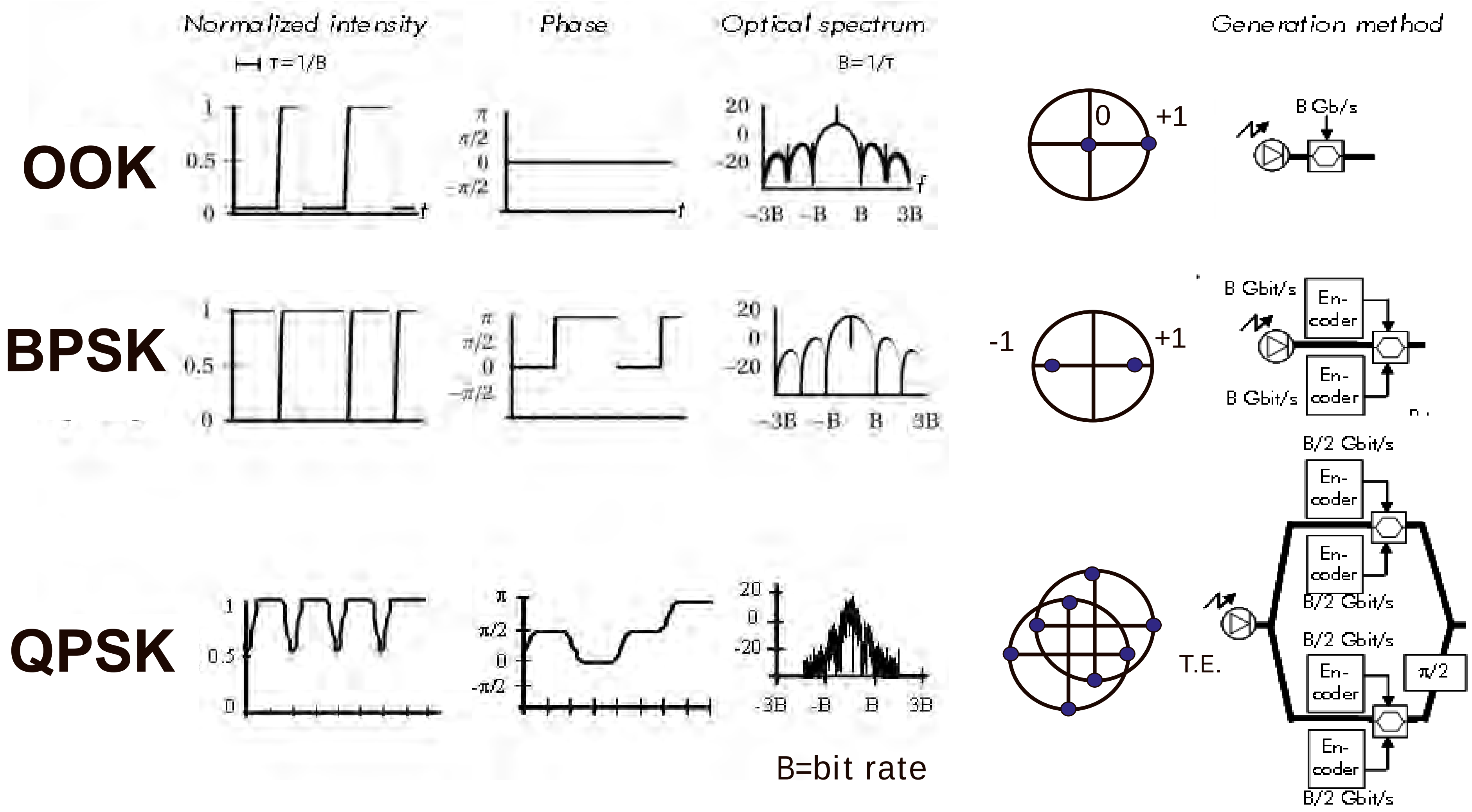
From E. Desurvire et al., «EDFA, Device and System developments», Chapter 7, Wiley, 2002.

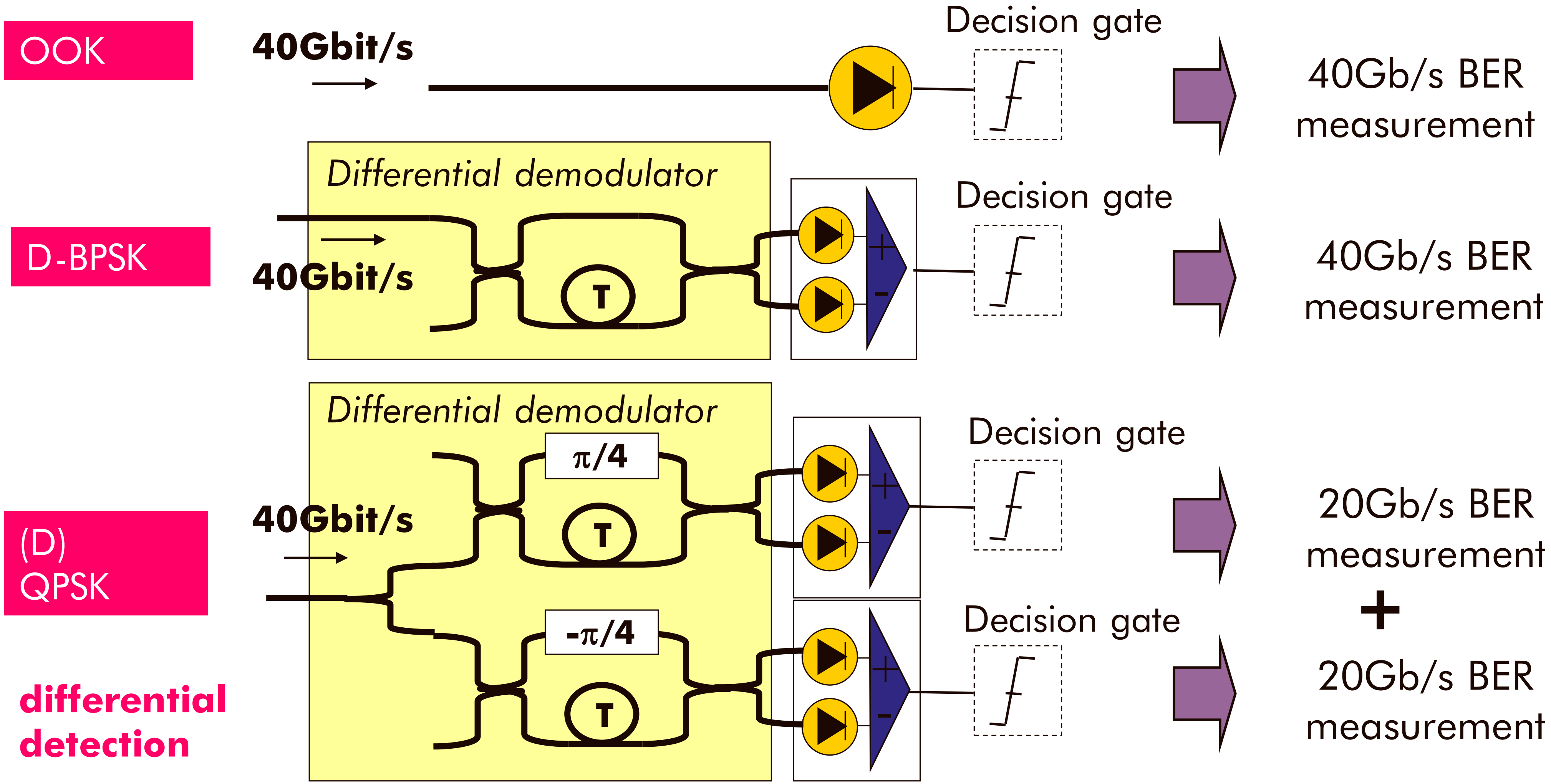
Generation of main modulation formats (pre-coherent era)



B=bit rate

From E. Desurvire et al., «EDFA, Device and System developments», Chapter 7, Wiley, 2002.

Direct (single-ended or differential) detection schemes



OOK

40Gbit/s

Decision gate

40Gb/s BER measurement

D-BPSK

Differential demodulator

40Gbit/s

Decision gate

40Gb/s BER measurement

(D)
QPSK

Differential demodulator

40Gbit/s

Decision gate

Decision gate

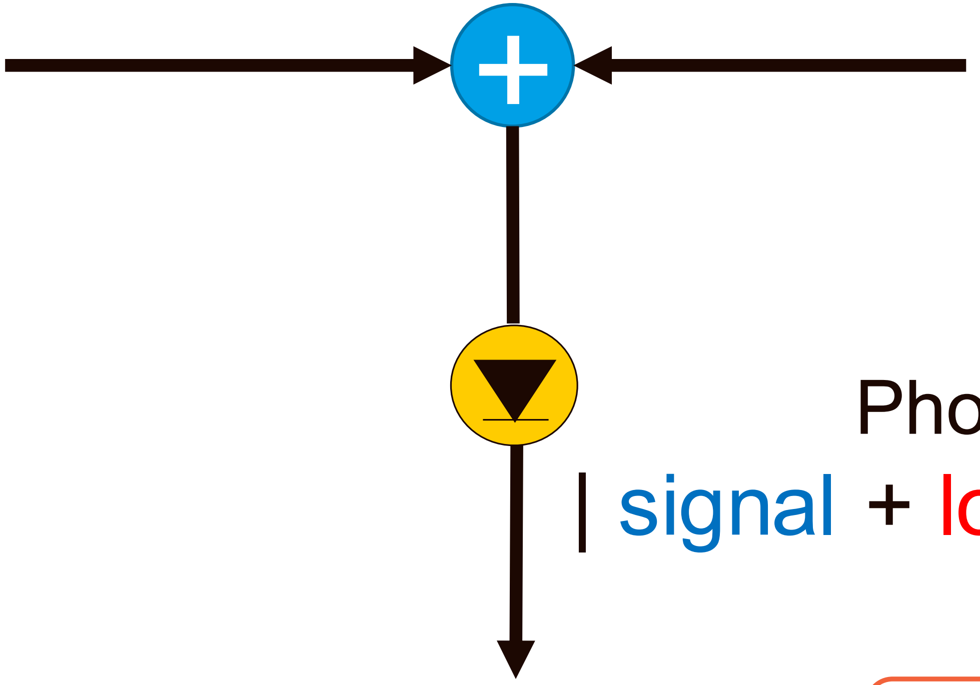
20Gb/s BER measurement

+

20Gb/s BER measurement

differential detection

Coherent detection: principle



Signal

$$s(t) = E_s(t) * e^{j\omega_s t}$$

Local oscillator

$$\mathrm{lo(t)} = E_{LO} * e^{j\omega_{LO} t}$$

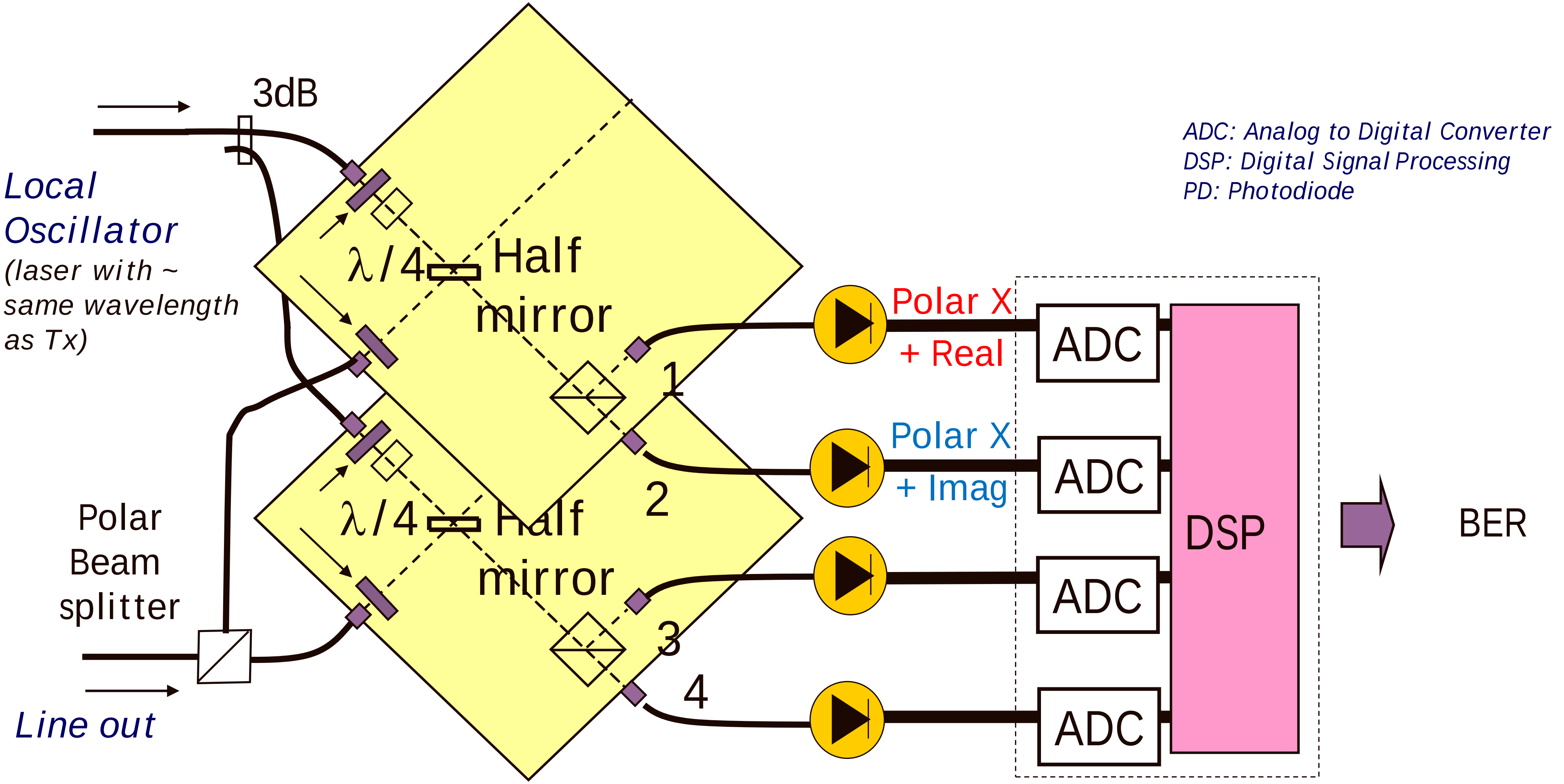
Photodiode

| signal + local oscillator|²

$$|s(t) + lo(t)|^2 = |E_s(t)|^2 + |E_{LO}(t)|^2 + 2 * Re\left(\boxed{E_s(t)} * E_{LO}^* * e^{j(\omega_s - \omega_{lo})t}\right)$$

What we seek

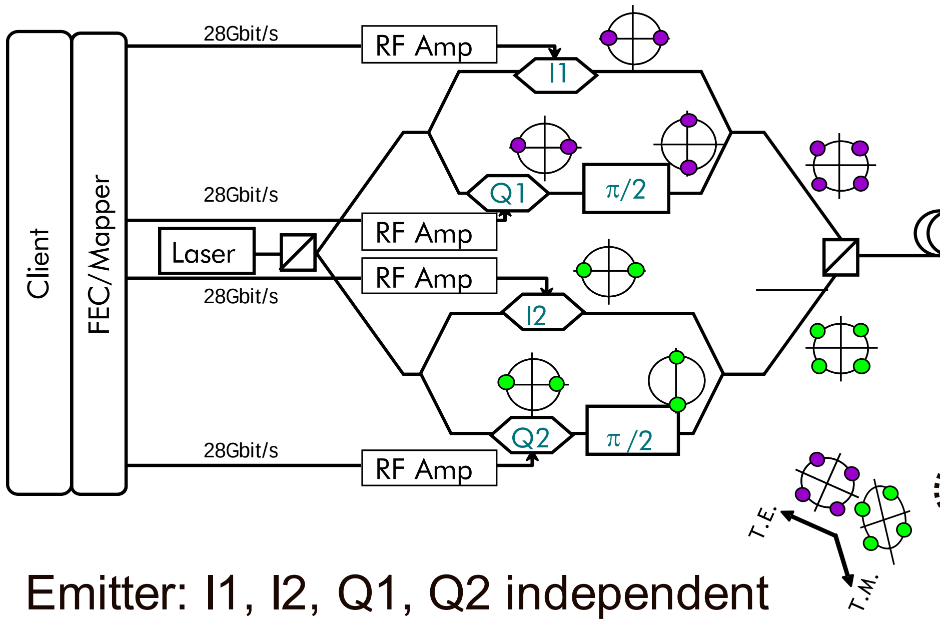
Coherent receiver (polarization independent)

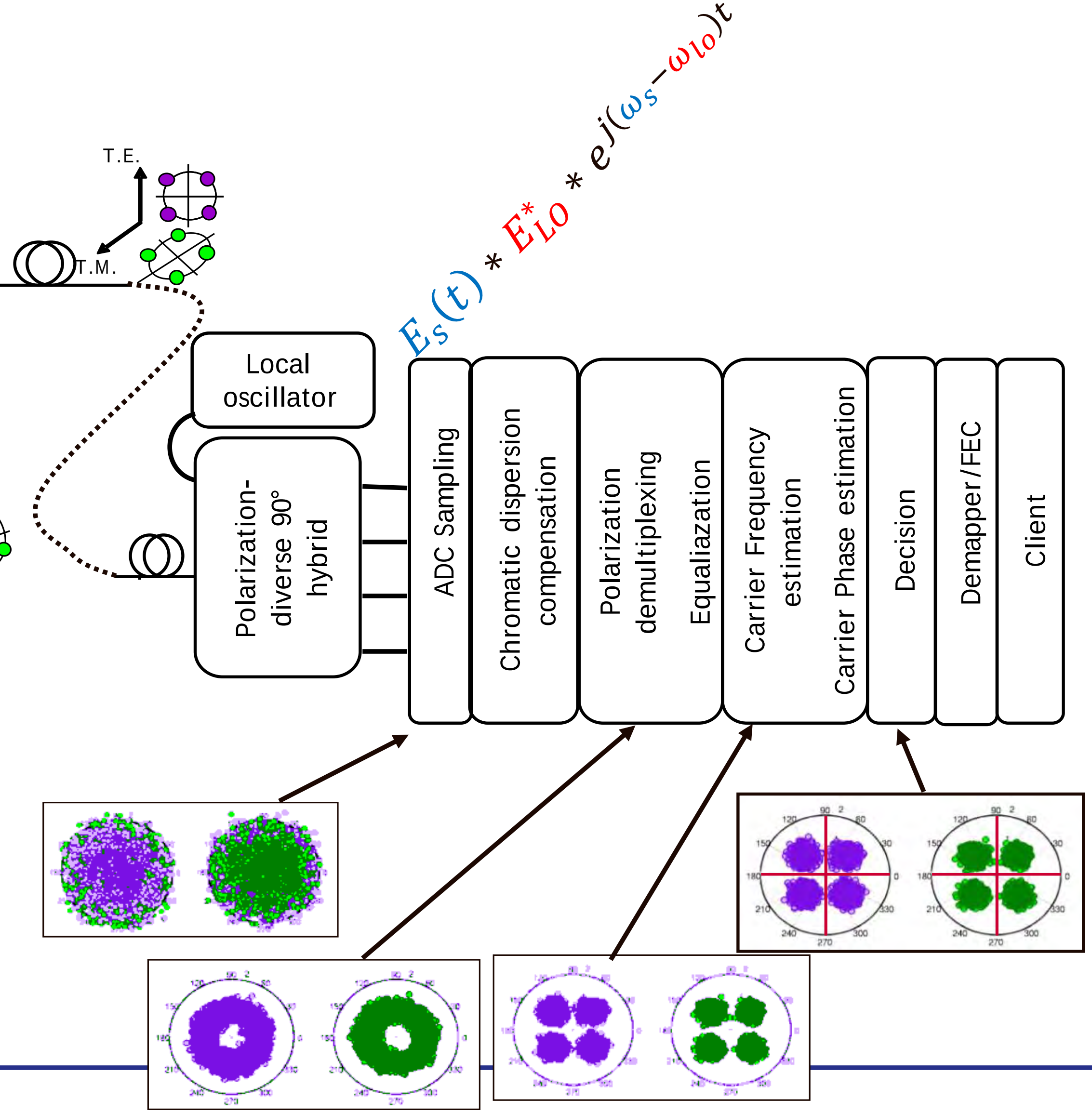


ADC: Analog to Digital Converter
DSP: Digital Signal Processing
PD: Photodiode

The photocurrents PD1, PD2, PD3 and PD4 provide full information on real and imaginary parts of signal along TE and TM polarization axes

100G Coherent systems architecture



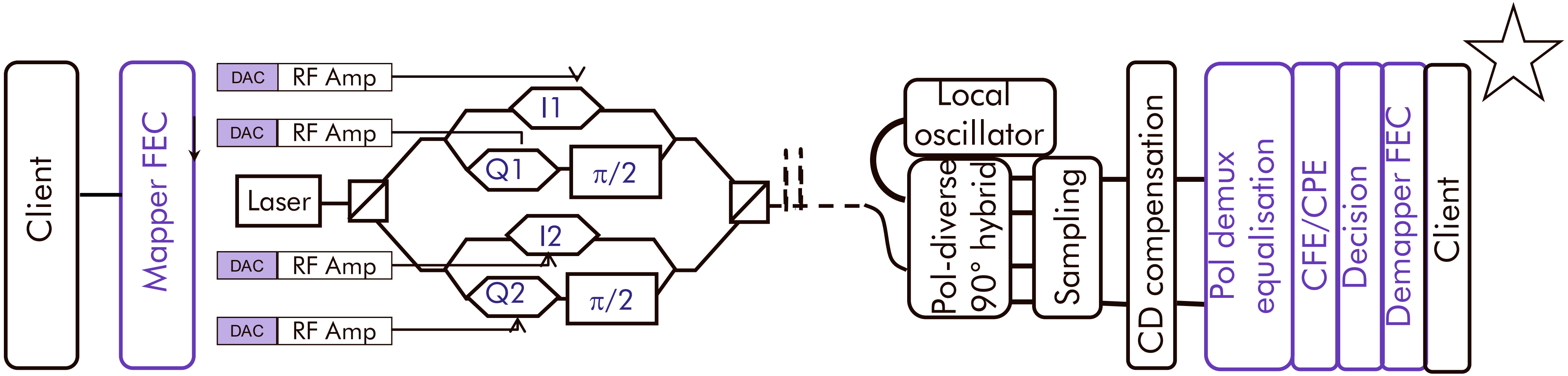


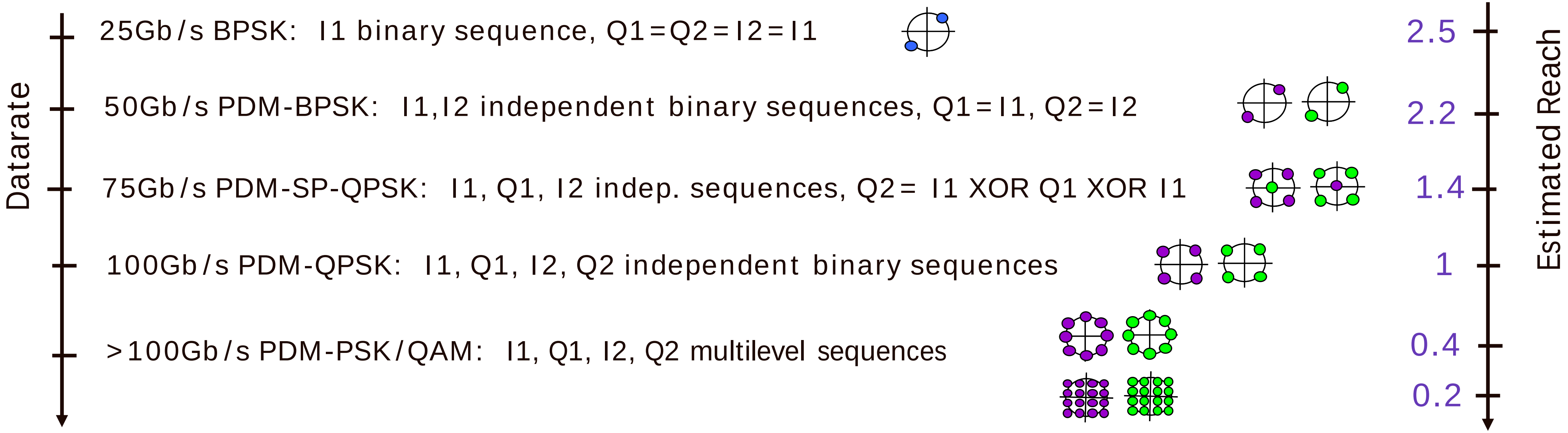
- Emitter: I1, I2, Q1, Q2 independent binary 28Gbaud binary sequences
- Modulation of in-phase and in-quadrature along two orthogonal polarizations

Coherent detection enables advanced modulation formats and efficient signal processing

ALCATEL SUBMARINE NETWORKS

Next step: Multi-format transceiver





25Gb/s BPSK: I1 binary sequence, Q1=Q2=I2=I1

50Gb/s PDM-BPSK: I1,I2 independent binary sequences, Q1=I1, Q2=I2

75Gb/s PDM-SP-QPSK: I1, Q1, I2 indep. sequences, Q2= I1 XOR Q1 XOR I1

100Gb/s PDM-QPSK: I1, Q1, I2, Q2 independent binary sequences

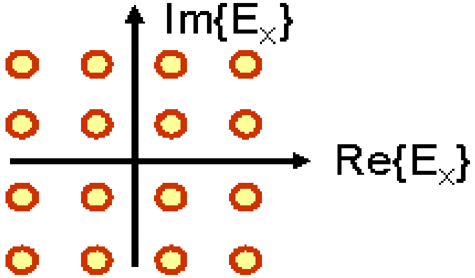
>100Gb/s PDM-PSK/QAM: I1, Q1, I2, Q2 multilevel sequences

➔Once committed to polarization-diverse I/Q modulation, coherent detection and electronic DSP for 100G technology, rate-adaptation come at a minimal cost

Take-Away

$$Capacity = Nb_{spatial\ modes} * Nb_{wavelengths} * Nb_{polars} * \frac{Nb_{bit/symbol}}{FEC\ Overhead} * \frac{Symbol\ Rate}{Signaling\ OH}$$

- Common modulations: Quadrature Amplitude Modulation
  - Uniform distribution of symbols, $Nb_{bit/symbol} = \log_2(\mathrm{Nb_{symbols}})$
  - High symbol count ➔ high rate, low resilience to noise



- Forward Error correction: encoding / decoding with extra bits
  - Error free after decoding provided BER lower than threshold

- Software-defined “Coherent” transceivers
  - High rate **Digital Signal Processing** enables mitigation of line impairements…
  - and **adaptation of bit-rate** (modulation) to **Quality of Transmission** (distance, signal to noise ratio)

At the heart of digital communications

2nd principle of thermodynamics

Statistical mechanics
$S = k_B \ln \Omega$

Shannon's theory of entropy
… in few words

Episode I: Entropy, but non troppo

- Entropy is a simple metric for information (or disorder)

- Properties
  - Rare event = more information

The New York Times

MEN WALK ON MOON

ASTRONAUTS LAND ON A PLAIN AFTER STEERING PAST CRATER

Voice From Moon: 'Eagle Has Landed'

A Powdery Surface Found by Armstrong

<u>Entropy:</u> $H(X) = f\,(p_X)$

$$\underset{\text{Event } X}{\uparrow} \qquad \underset{\text{probability } p_X}{\uparrow}$$

Event X — probability p_X

  - Independent events = Sum of information

$p_{X,Y} = p_X{}^*p_Y$ ⬎ ⬐ $H(X,Y) = H(X) + H(Y)$

$$f(p_X{}^*p_y) = f(p_X) + f(p_y)$$

➔ f is a logarithm: $\underline{H(X) \;=\; -\log_k\,(p_X)}$

Hull Daily MAIL

Hull-Live.co.uk

JANUARY SALES

MUM ON UNIVERSAL CREDIT WHO CAN'T AFFORD TO BUY HER TWO CHILDREN PRESENTS SAID...

'I HAD TO TELL MY KIDS SANTA IS NOT REAL'

PAGE 5

Santa

Episode I: Entropy, but non troppo

- Entropy of an event X: $H(X) = -\log_k(p_X)$

- Entropy of a random process X of probablity law $p_X(x)$
- = Average amount of information

$$H(X) = -\sum\!\!\!\!\!\int_{x} \log_K\big(p(x)\big) * p(x)$$

- Events (states) of equal probability ➔ $H = \log_K(\#\ \text{events})$

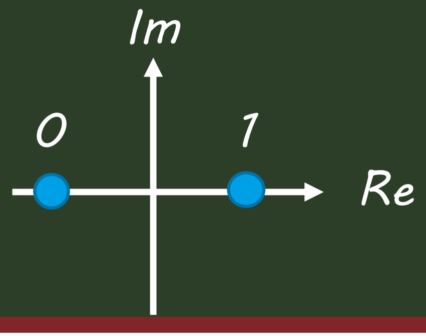
Episode I: Entropy, but non troppo

- Entropy of a random process X of probablity law $p_X(x)$

$$H(X) = -\sum_i log_k \left(p(x_i)\right) * p(x_i)$$

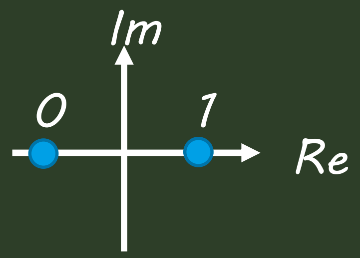
- Binary information: K=2 ➔ bit/symbol

- Example:
  - BPSK
    - 2 symbols, of probability ½
    - $H = -\log_2(\frac{1}{2})$ ➔ 1 bit/symbol

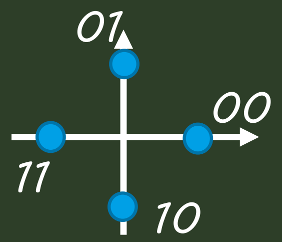


Episode I: Entropy, but non troppo

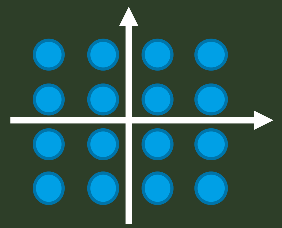
- BPSK
  - 2 symbols, of equal probability ½
  - $H = -\log_2 (½)$ ➔ 1 bit/symbol



- QPSK
  - 4 symbols, of equal probability ¼
  - $H = -\log_2 (¼)$ ➔ 2 bits/symbol



- 16QAM
  - 16 symbols, of equal probability 1/16
  - $H = -\log_2 (1/16)$ ➔ 4 bits/symbol

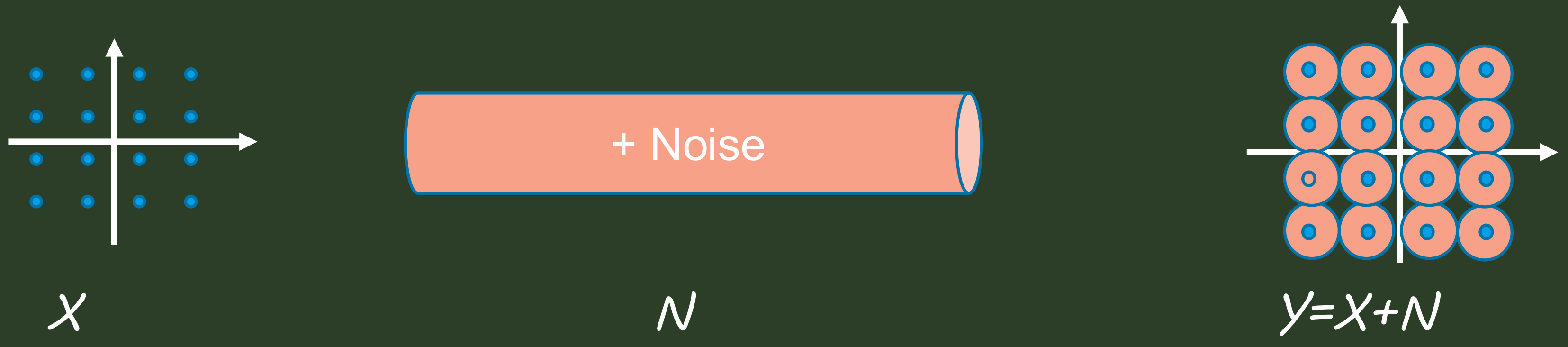


1001	1011	0011	0001
1000	1010	0010	0000
1100	1110	1010	1000
1101	1111	1011	1001

- Symbols with equal probality: $H = \log_2$ (# symbols)

Episode II: Mutual information, Capacity

- Propagation medium: Additive White Gaussian Noise



- How many useful bits could emerge from the noise ? $H(Y)-H(N)$

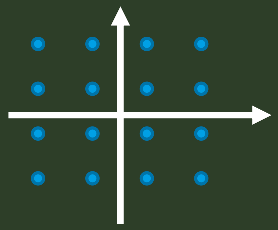
- <u>Mutual information:</u> $I(X;Y) = H(X) - H(X|Y) = H(Y) - H(Y|X)$

  $\leq H(X)$ → redundancy

- <u>Medium capacity</u> ←→ best modulation

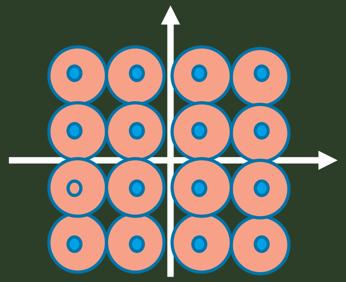
Episode II: Mutual information, Capacity

- *Propagation medium: Additive White Gaussian Noise*



X

N



Y=X+N

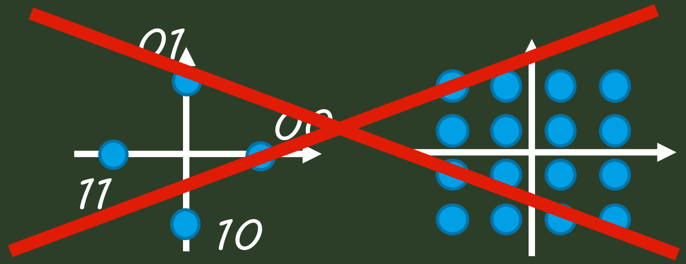
- *Medium capacity* = $\text{Max}_X \, (\, H(X+N) \,) - H(N)$

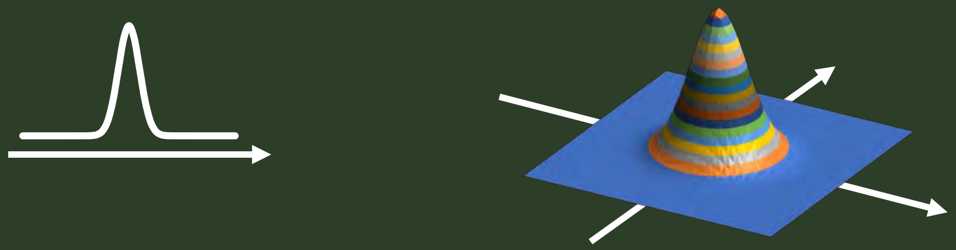
- *What can maximize the disorder in addition to a Gaussian noise ?*
- *Another Gaussian process …*

under constraint of fixed variance

Episode III: Shannon Capacity

- *Capacity achieving modulations*
  - ~~*Equally distributed symbols*~~ *Gaussian distribution of symbols*



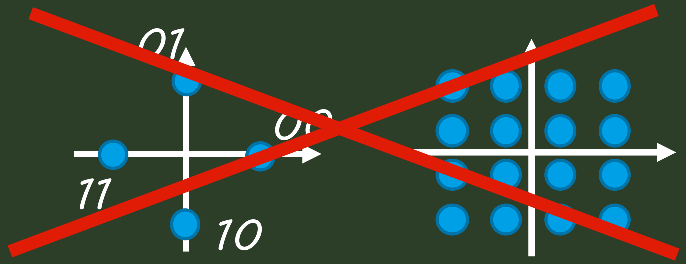


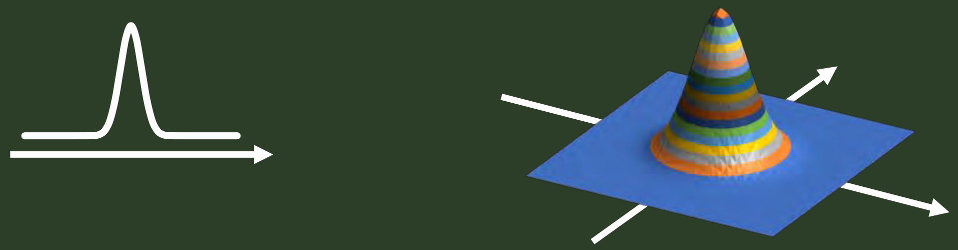
- *Shannon theorem : in theory (ideal modulation / demodulation)*

$$Capacity = \log_2 \left(1 + \frac{Signal\ power}{Noise\ power} \right) \quad bit/symbol$$

Episode III: Shannon Capacity

- Capacity achieving modulations
  - ~~Equally distributed symbols~~ Gaussian distribution of symbols



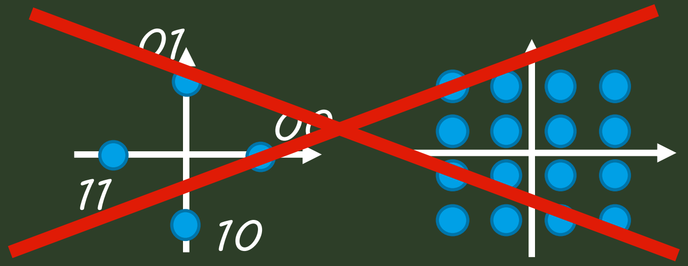


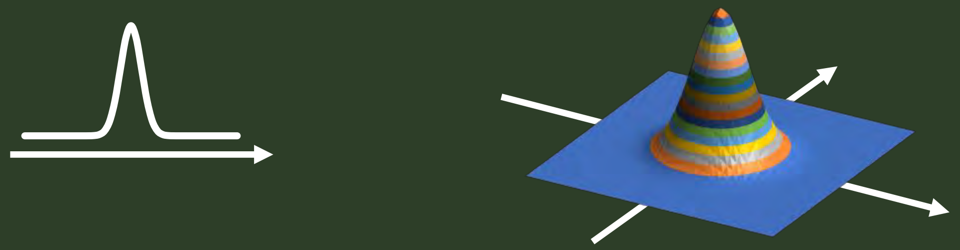
- Shannon theorem : in theory (ideal modulation / demodulation)

$$\text{Capacity} = \log_2 (1 + \text{SNR}) \quad \text{bit/symbol}$$

Episode III: Shannon Capacity

- Capacity achieving modulations
  - ~~Equally distributed symbols~~ Gaussian distribution of symbols





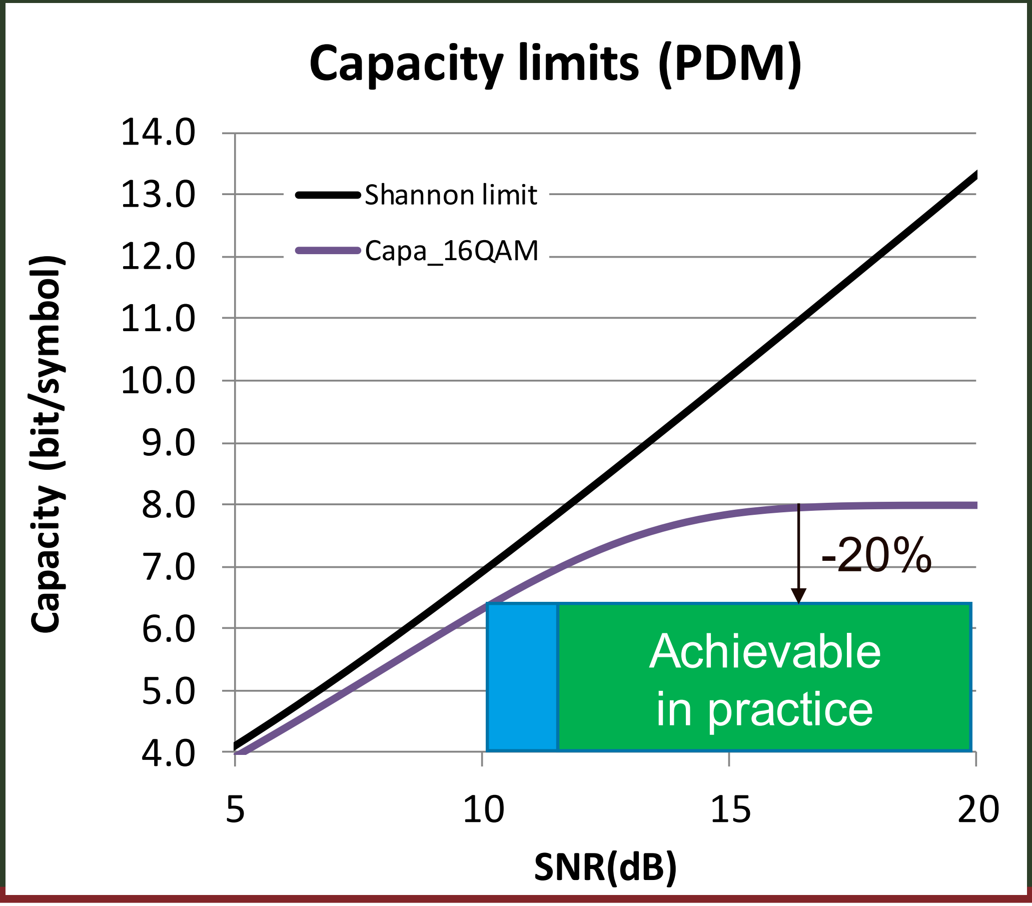
- Shannon theorem : in theory (ideal modulation / demodulation)

$$\text{Capacity} = 2_{\text{polars}} * \text{Bandwidth} * \log_2 (1+ \text{SNR}) \quad \text{bit/s}$$

Assuming channel modulation rate = channel spacing

Episode IV: Shannon capacity and modulation

- *X-QAM modulations and Shannon limit (Gaussian modulation)*

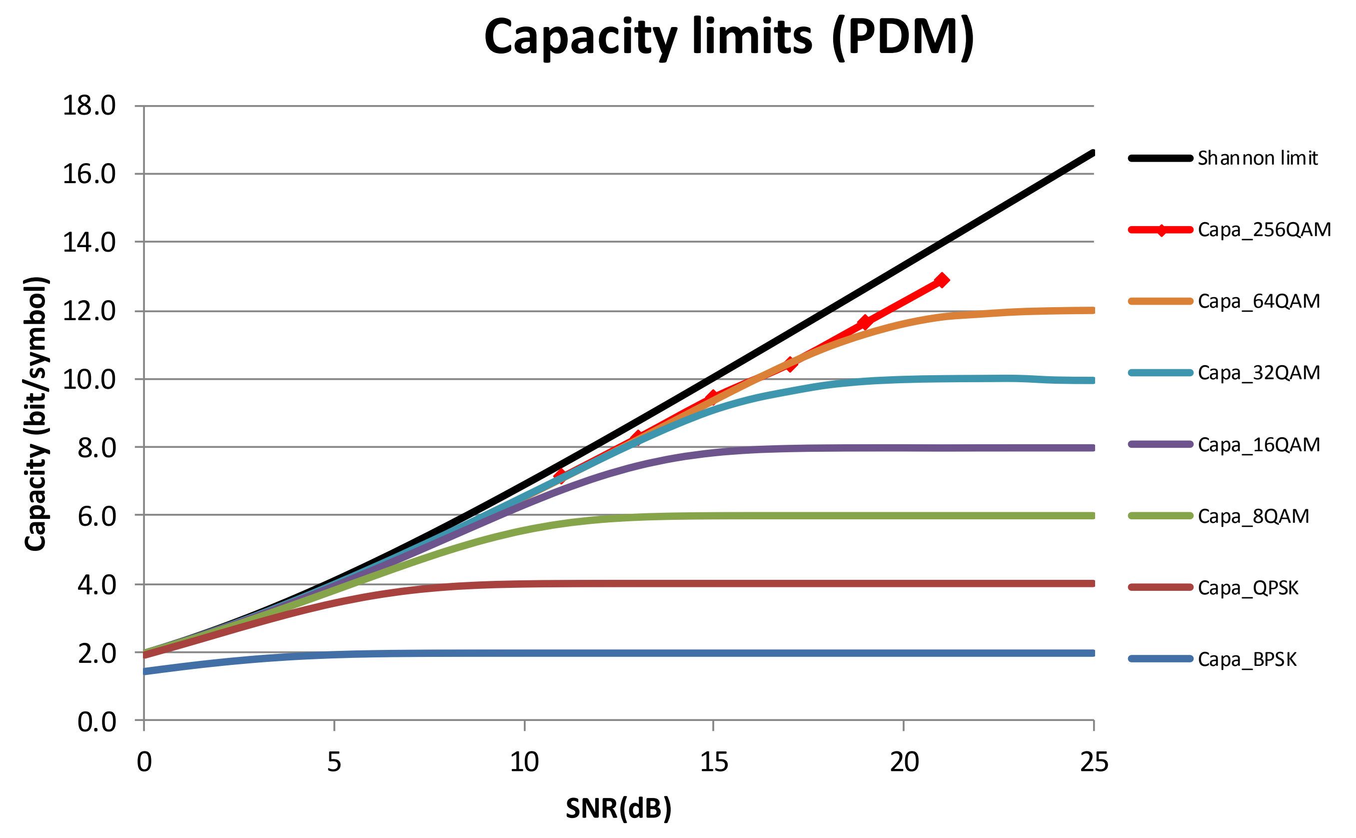


*PDM-16QAM: 2*4 = 8 bit/symbol*

With perfect 25% overhead
Forward Error Correction

Episode IV: Shannon capacity and modulation

- *X-QAM modulations and Shannon limit (Gaussian modulation)*



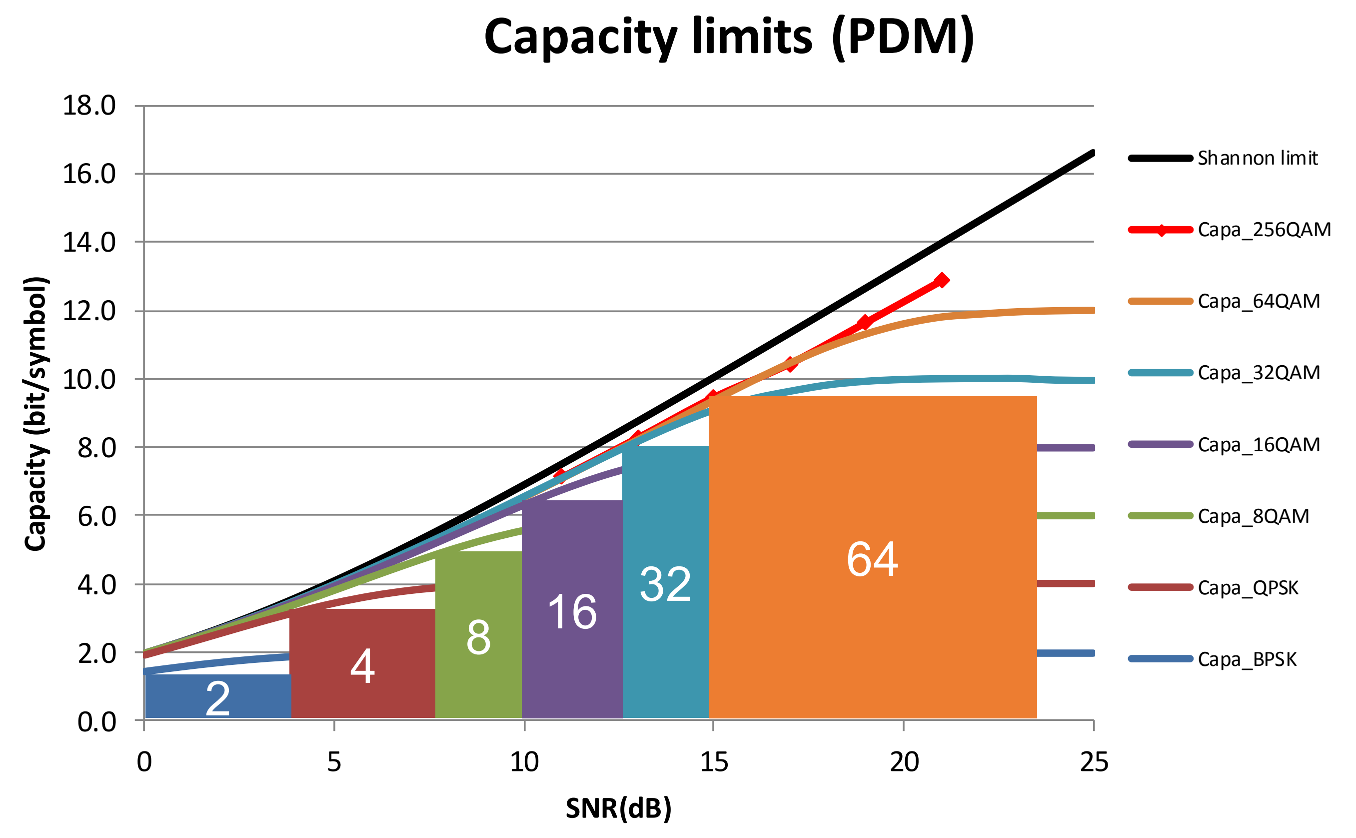
At high SNR,
whatever the size
of the QAM modulation,
there is a gap to Shannon limit.

Why ?
X-QAM assumption =
symbols on a grid,
with same probability

Towards
Geometric / Probabilistic
Constellation Shaping

Episode IV: Shannon capacity and modulation

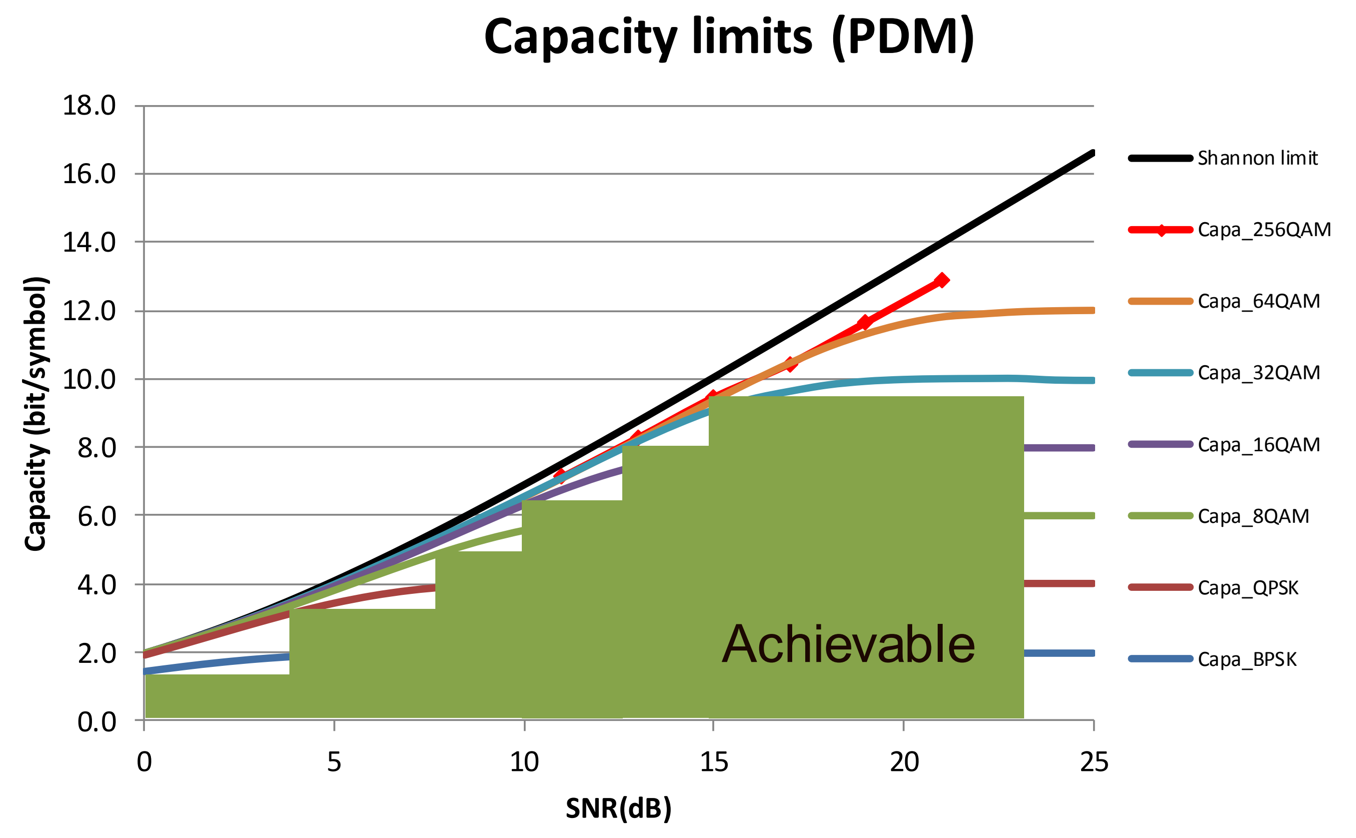
- *X-QAM modulations and Shannon limit (Gaussian modulation)*



With 25% overhead ideal FEC,
Achievable capacity becomes

Episode IV: Shannon capacity and modulation

- *X-QAM modulations and Shannon limit (Gaussian modulation)*



With 25% overhead ideal FEC,
Achievable capacity becomes

Constant FEC, multi-format
enables to stay
more or less
close to Shannon limit

Take-Away

$$Capacity = Nb_{spatial\ modes} * Nb_{wavelengths} * Nb_{polars} * \frac{Nb_{bit/symbol}}{FEC\ Overhead} * \frac{Symbol\ Rate}{Signaling\ OH}$$

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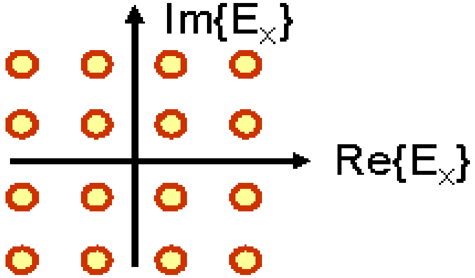
  - Uniform distribution of symbols, $Nb_{bit/symbol} = \log_2(\mathrm{Nb_{symbols}})$
  - High symbol count ➔ high rate, low resilience to noise



- Forward Error correction: encoding / decoding with extra bits
  - Error free after decoding provided BER lower than threshold

- Generalization:
  - Entropy (Av. nb bits/ symbol), mutual information (max spectral efficiency $\frac{Nb_{bit/symbol}}{FEC\ Overhead}$ after propagation)
  - Shannon capacity limit: $\mathrm{Max}\left(\frac{Nb_{bit/symbol}}{FEC\ Overhead}\right) = \log_2(1 + SNR)$, with Gaussian distribution of symbols

Life Cycle Of A Subsea Cable Project

Lecture 10-1 - System Planning
Subsea Optical Fiber Communication
Finland, 2019

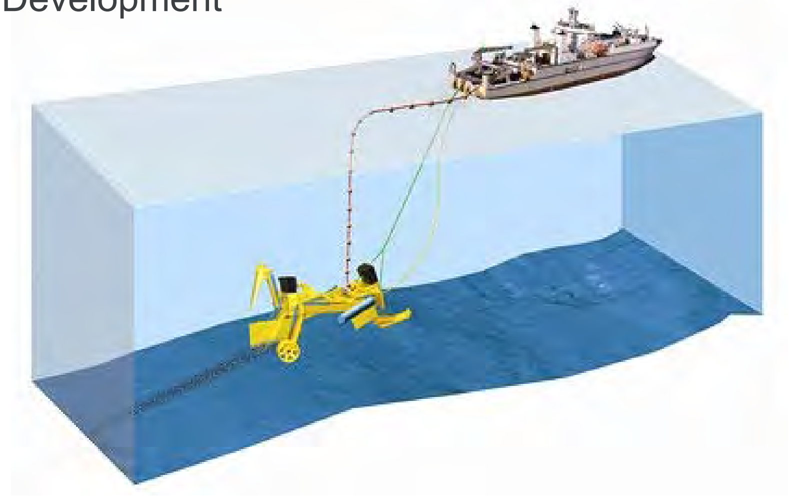
Google Cloud

Life Cycle of a Subsea Cable Project

Lecture 10.1

Michael D Francois - Google Network Infrastructure Development

1. Background
2. Initial Concept
3. From Concept to Project
4. System Financing
5. Supplier Negotiations
6. Guarantees



Google Cloud

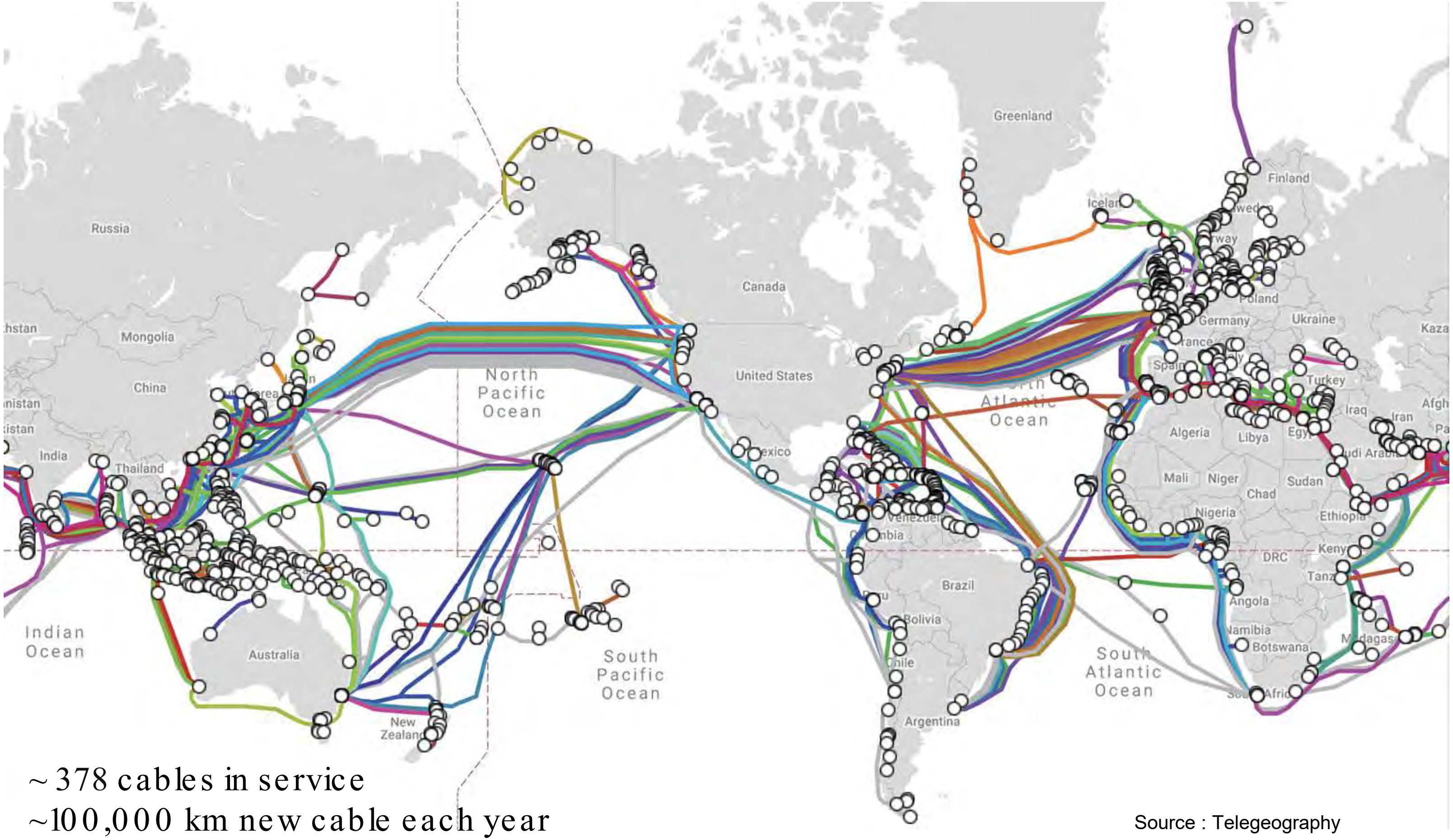
Background

A Brief History

- 1837 - Telegraph invented
- 1849 - England to France subsea cable
    - Fails after 8 days
- 1851 - England to France commercial success
    - Gutta-percha insulation
- 1858 - First transatlantic cable
    - Fails after 3 weeks as it is operated at voltages too high for the insulation
- 1861 - First US transcontinental telegraph cable completed
- 1868 - First commercially successful transatlantic cable
- 1876 - Bell patents telephone
- 1877 - Transatlantic phone call on Telegraph cable fails
- 1883 - Calls placed over 5 miles of underwater cable
- 1884 - San Francisco-Oakland phone service on Gutta-perche insulated cable
- 1920 - Chesapeake Bay cable uses loading cools underwater
- 1915 - Transcontinental US phone service begin
- 1950 - Repeated cable using polyethylene from FLorida to Havana
- 1956 - TAT-1 goes into service
- 1967 - HAW-1 goes into service
- 1980s - WDM systems begin to appear
- 1986 - First international submarine cable, UK-Belgium
- 1988 - First fiber optic submarine cable, TAT-8

Source : ICPC, Wikipedia

Global Subsea Network



~378 cables in service

~100,000 km new cable each year

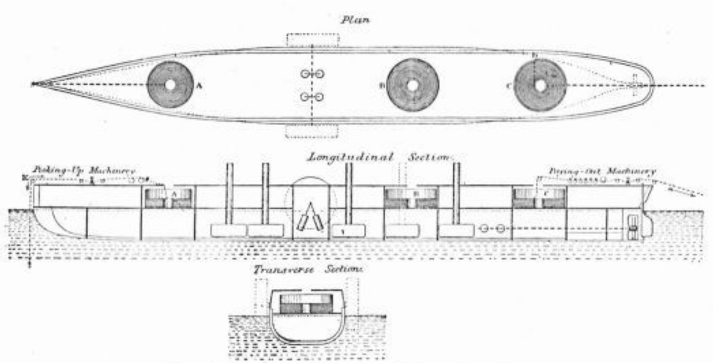
Source : Telegeography

Google

Transatlantic Telegraph Cable

153 years ago - the *SS Great Eastern*

THE "GREAT EASTERN" COMPLETING THE LAYING OF THE SECOND ATLANTIC CABLE IN TRINITY BAY, NEWFOUNDLAND, JULY 1866.
(By permission of Sir Charles Bright, F.R.S.E.)

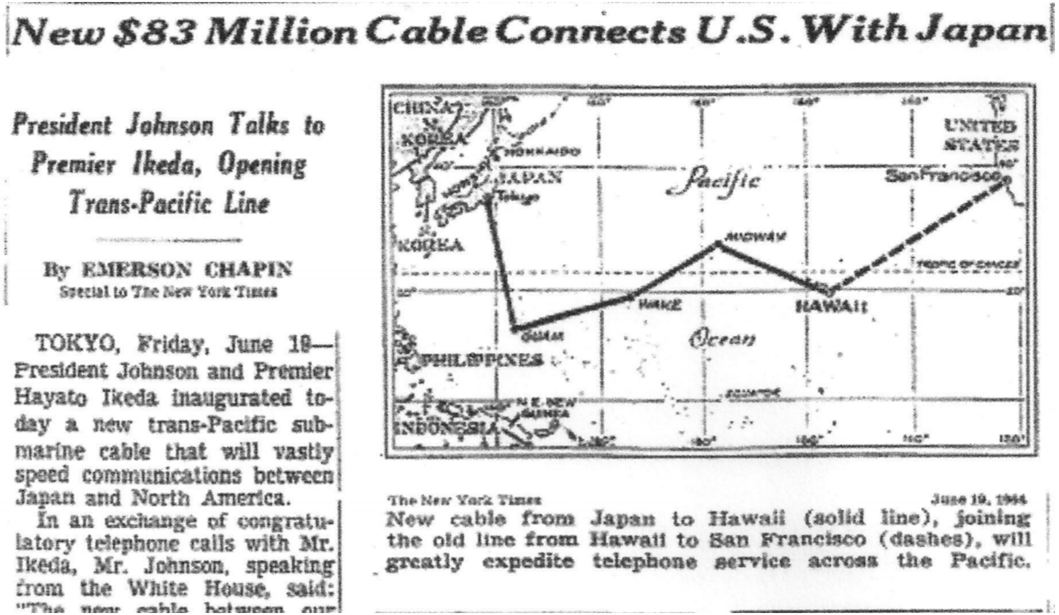


Plan of cable and machinery aboard the s.s. *Great Eastern.*
(By permission of Sir Charles Bright, F.R.S.E.)

The SS *Great Eastern* took 14 days to sail from Ireland to Newfoundland and lay the 2nd transatlantic cable; the first transatlantic cable was in service for 3 weeks.

Transpacific Telephone Cable

55 years ago - TPC-1



New $83 Million Cable Connects U.S. With Japan

President Johnson Talks to Premier Ikeda, Opening Trans-Pacific Line

By EMERSON CHAPIN
Special to The New York Times

TOKYO, Friday, June 19—President Johnson and Premier Hayato Ikeda inaugurated today a new trans-Pacific submarine cable that will vastly speed communications between Japan and North America.

In an exchange of congratulatory telephone calls with Mr. Ikeda, Mr. Johnson, speaking from the White House, said: "The new cable between our

The New York Times — June 19, 1964

New cable from Japan to Hawaii (solid line), joining the old line from Hawaii to San Francisco (dashes), will greatly expedite telephone service across the Pacific.

The first transatlantic Telephone cable was TAT-1, and was laid in 1956.

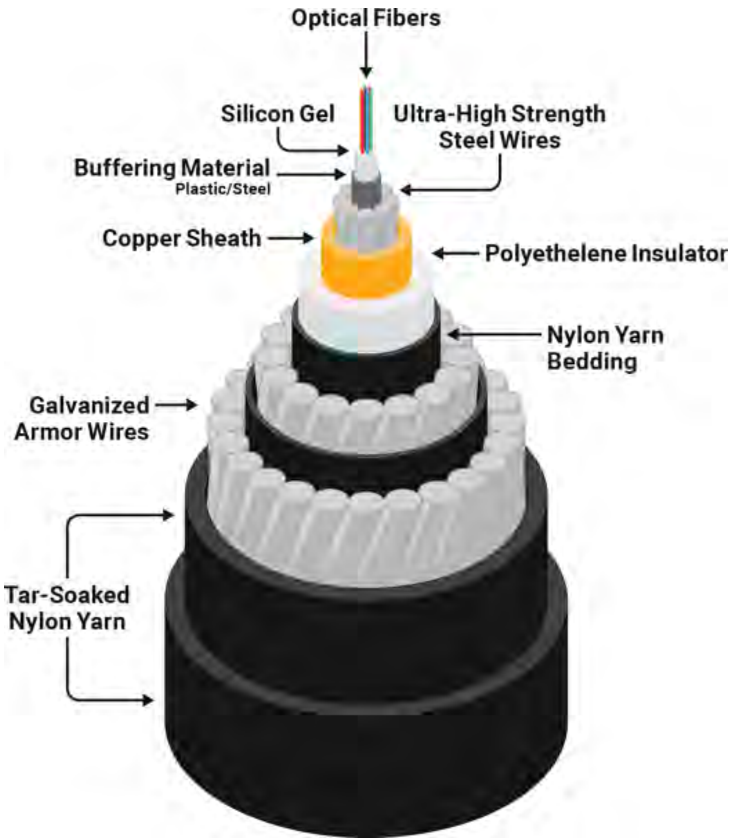
The first Transpacific submarine telephone cable was the aptly named Trans Pacific Cable (TPC-1),which went into service on June 19, 1964. It was a coaxial cable linking Hawaii, Midway Atoll, Wake Island, Guam, and Japan.

In Hawaii it connected to Hawaii No. 1 (HAW-1), to complete a path to the US mainland in Point Arena, CA. HAW-1 was built in 1957, and was the first telephone cable to connect Hawaii to the continental 48 states.

Submarine Cable Ships

Today

Submarine Cable

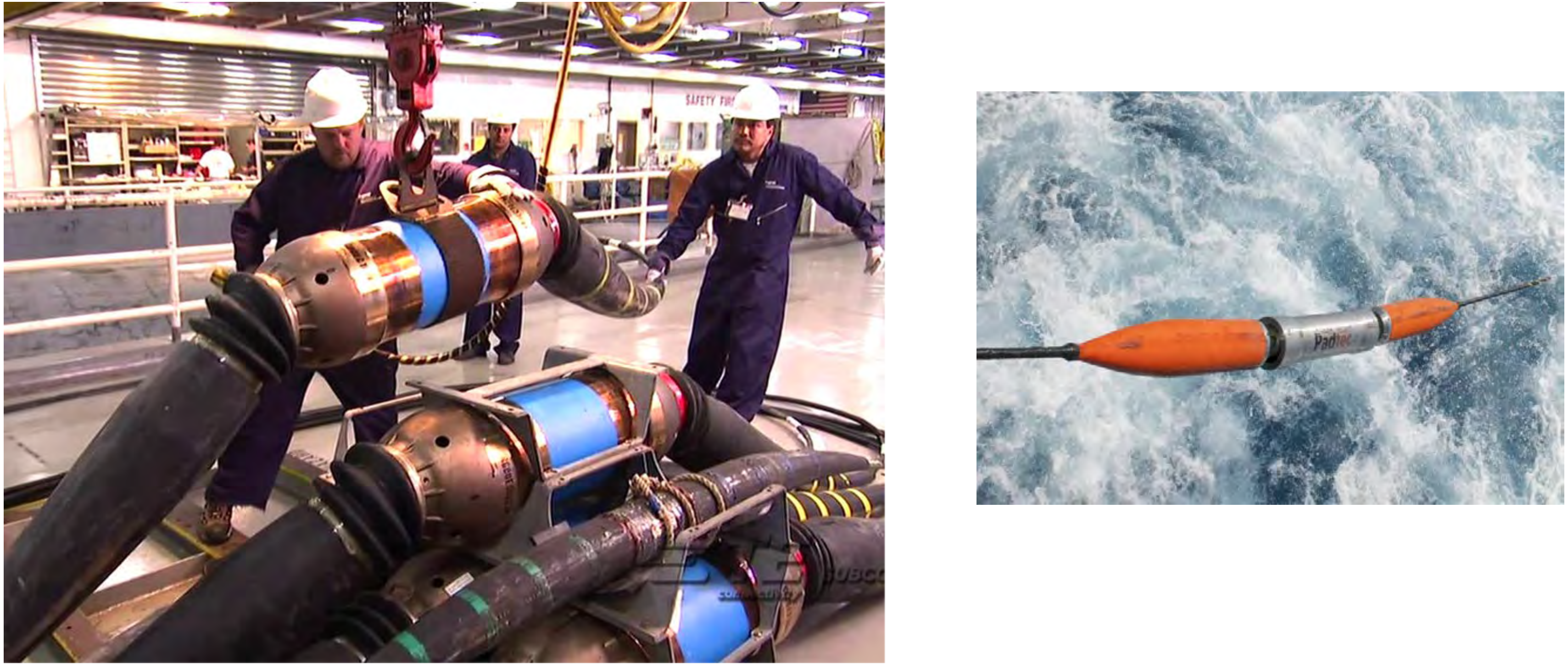


2019

1858

Google

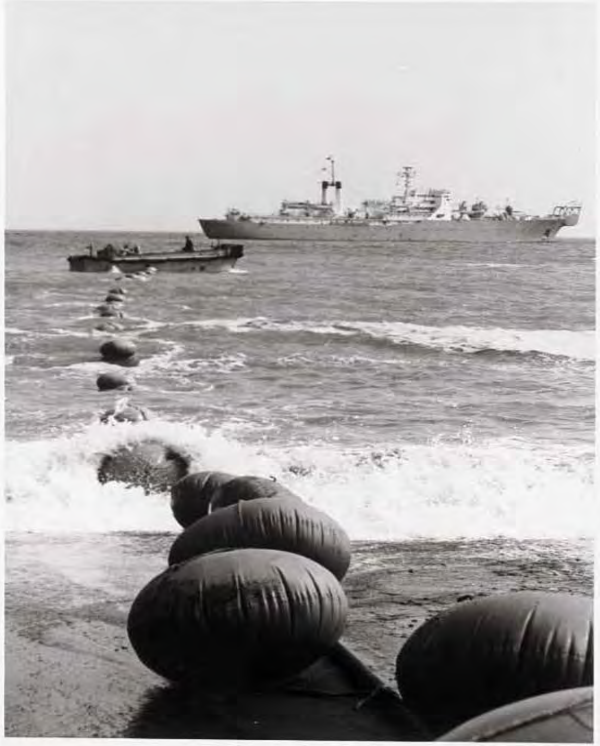
Building And Deploying Wet Plant



Landing A Submarine Cable

Landing A Submarine Cable

A direct beach landing is the easiest way to land, but it is not always possible



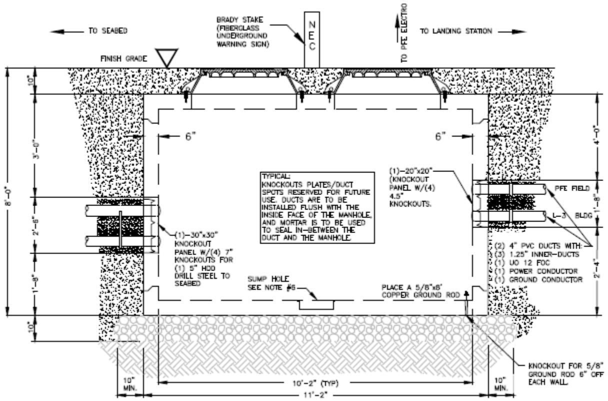
TPC-1（1964年開通）

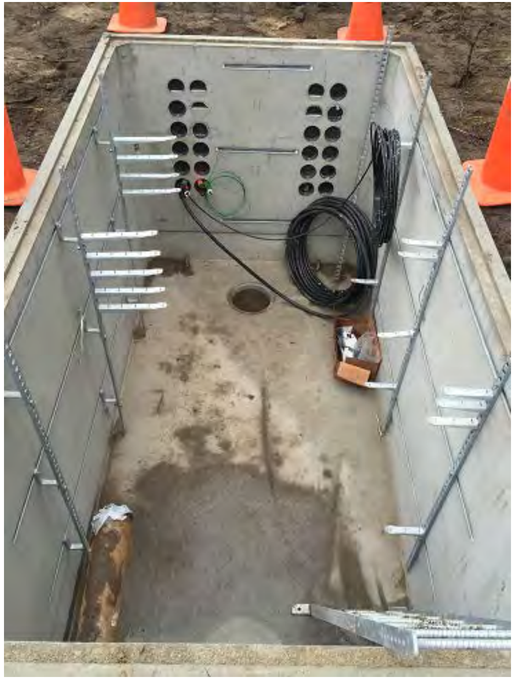
SJC（2013年開通）

Japanese Film on TPC-1:http://www.kagakueizo.org/movie/industrial/78/

Transition from Sea to Land & Shore Plant

Beach Manhole (BMH) Construction





Background

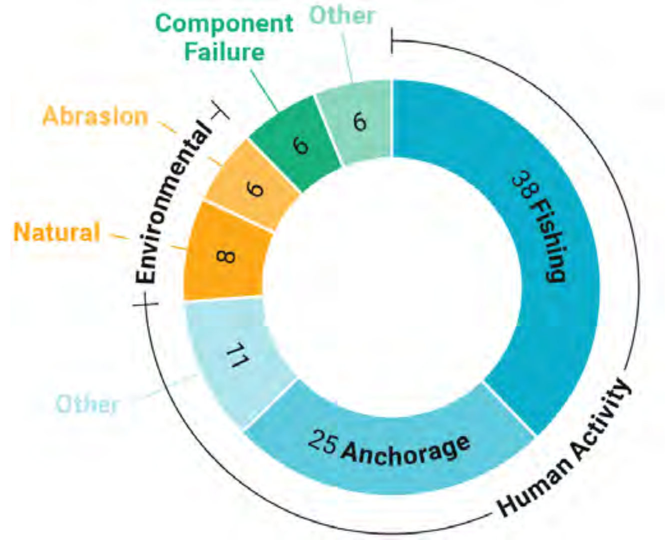
- Submarine Cables have a *Technical Complexity*
  - They are composed of various high tech components which require engineering knowledge to design, evaluate, operate and maintain
- There is also an *Administrative Complexity*
  - Multi-national constraints
  - Long term supplier relationships
  - Geopolitical considerations
- *Specific Skills* are required for various aspects of a successful project
  - Marine Operations, Legal, Optical Engineering, Finance, Permitting, Planning. Negotiating, etc
- And the *Timescale* is significant
  - From Concept to Contract-In-Force : 6 – 24 months
  - Construction : 12 – 24+ months
  - Operation : 25 years (technical), ~15 years (commercial)

Background

- Price range of a subsea cable
    - From $10m
        - Point-to-point repeaterless system short distance, though can still be international
    - To $1b
        - Intercontinental transoceanic multipoint system

- System Quality Has To Meet Requirements
    - Outages
    - Planned System Life
    - High reliability
    - Technical Must Haves (Latency, Redundancy, Reliability, Capacity, etc)

Causes of Cable Faults



Source: Telegeography

Initial Concept

How Do We Plan Cables?

Business Case

- Traffic Forecast & Capacity Planning
- Strategic considerations
- Regional Considerations
- Decision Analysis
- Budget Approvals

Design+Pre-Build

- Design Engineering
- Supplier Selection
- Construction Build Agreement
- Permitting and Compliance
- Contract-in-Force

Cable Deployment

- Marine Survey
- Cable Lay
    - Trunk
    - Branches
- Cable Landings
- Ready for Service

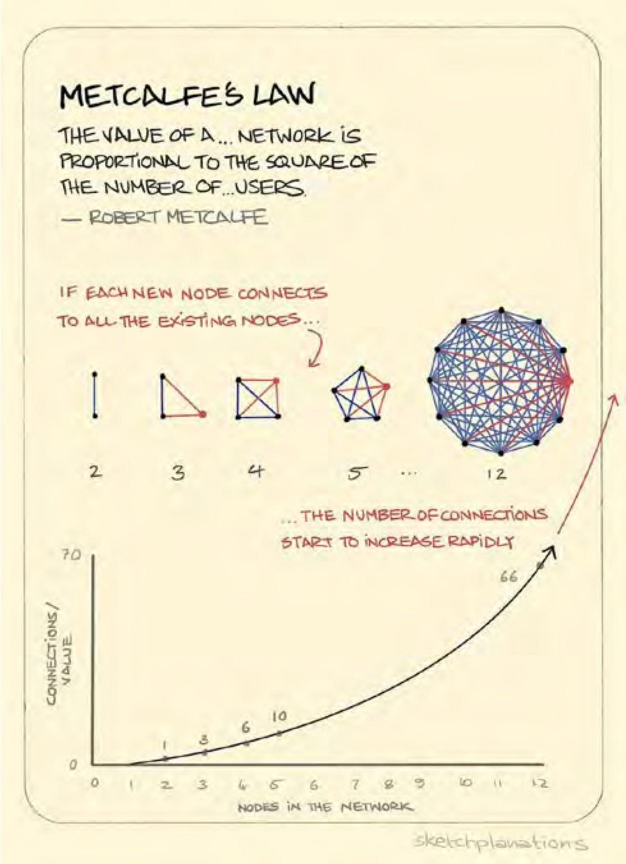
Cable Maintenance

- Ongoing Marine Maintenance
- Terrestrial Network Integration
- Upgrades

Business Case

- What are the drivers for a new submarine cable?
- Connectivity analysis
  - Connecting countries across oceans
    - Population
    - Internet penetration
    - Existing connectivity - Does it scale?
    - Interconnection within global network - Does it fit?
  - Financial Analysis
    - Is there a return on the investment?
    - In what timeframe?

- Metcalfe's Law
  - The value of a telecommunications network is proportional to the square of the number of users of the system.



Source: Sketchplanations

Markets & Traffic

Market Types for Subsea Cable Systems

- Transoceanic:
  - Higher demand, potentially many capacity sellers
  - Capacity tends to become a commodity

- Regional:
  - Less demand, potentially fewer sellers
  - Less price pressure, long term purchase
  - Capacity remains a strategic resource

Market Analysis

- Existing and planned resources with common connectivity and capacity analysis
  - Source and Destination
- SWOT Analysis
  - Strengths, Weaknesses, Opportunities, and Threats
  - Local partnerships, average capacity cost, marginal capacity cost analysis, market size

Technical Design Decisions

Technology analysis

- Impact on capacity availability & costs
- Pace of technology evolution
  - Advantages & availability of next generation
  - Is a major breakthrough expected?
- Which technology is best adapted to market ?
  - Do you need a plane or a car to travel 60 km?
  - Tailored to needs
- What is the best value for the money?
  - Return on Investment
  - Upgrades

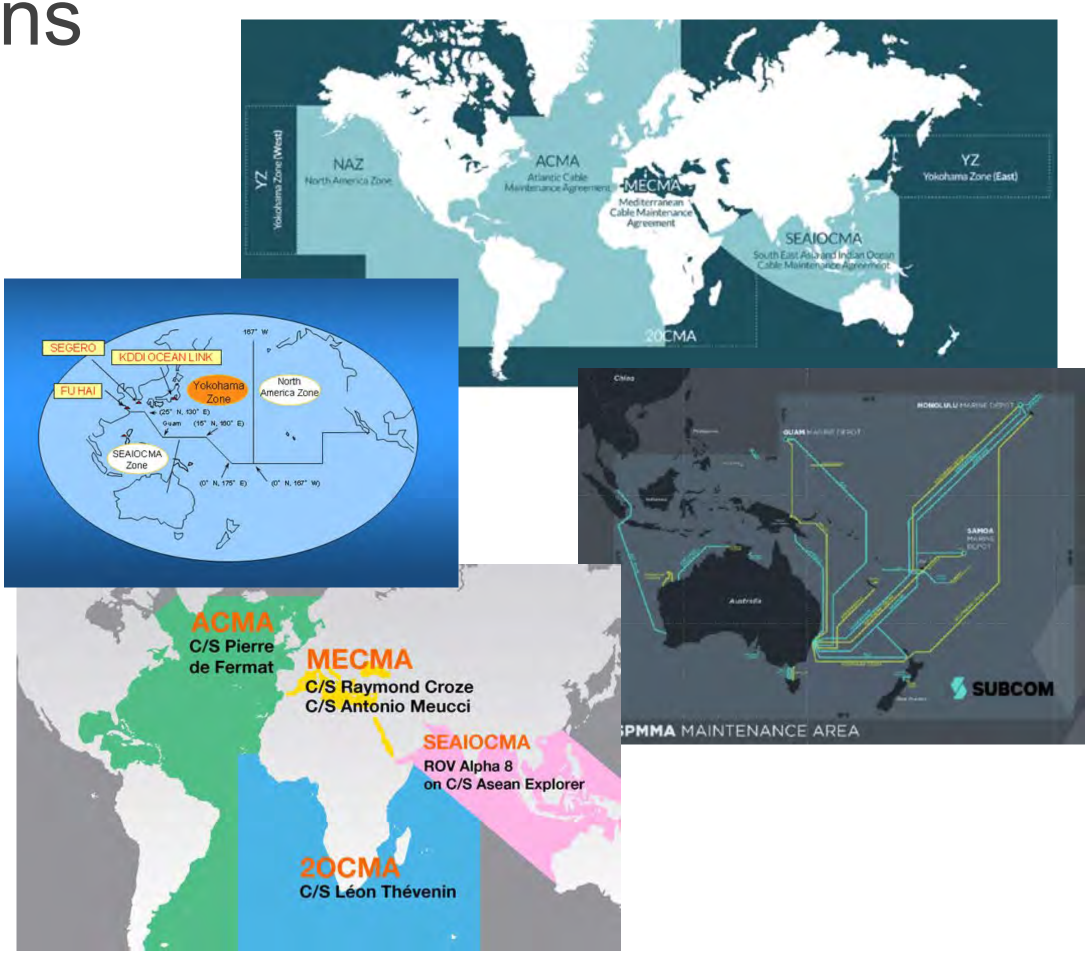
Maintenance Decisions

Maintenance Clubs

- SEAIOCMA - South East Asia and Indian Ocean Cable Maintenance Agreement
- ACMA - Atlantic Cable Maintenance Agreement
- PIOCMA - Pacific and Indian Ocean Cable Mutual Agreement
- NAZ - North American Zone
- MECMA - Mediterranean Cable Maintenance Agreement
- Yokohama Zone Agreement
- SPMMA - South Pacific Marine Maintenance Agreement
- 20CMA - Two Oceans Cable Maintenance Agreement

Private Maintenance

- Arrangements between individual cable owners and ship owners



From Concept
To Project

Business Case

Why You Need One

Preparing the business case involves an assessment of:

- The opportunity
- potential benefits/revenues
- risks and mitigations
- technical solutions available
- costs (WACC/NPV)
- timeline
- impact on current operations, and
- capability to deliver the project

Is The Project Worth Doing?

- Executive Summary
- Deal Summary
  - Financial Appraisal
  - Sensitivity Analysis
  - Revenue Opportunity
- Project Definition
  - Background Information
  - Business Objective
  - Benefits and Limitations
  - Legal/Policy Risks and Mitigation Plan
  - Market Assessment
  - Technical/Network Risk and Mitigation Plan
  - Capacity Planning/Marketing Plan
  - Project/Purchasing Strategy
- Project Organization
  - Project Governance
  - Progress Reporting

Consortium Cables

Legal Structure

- No or lightweight legal entity
- Relationship based on a Construction and Maintenance Agreement (C&MA) or a Joint Build Agreement (JBA)
- Negotiated capacity allocation and usage rules
- Landing Rights

Relationship Management

- Various committees are formed to reach consensus on issues
- Can be UN-like

Come In Many Flavors

- Large Consortiums of International Carriers
    - SMW-3, AAE-1
- Mid-sized Consortius of Various Partners
    - Indigo, Havfrue
- Small Consortiums of Specialty Partners
    - JGA
- Partnership Cables
    - Havfrue
- Shared Interests are Key to Success
- Decisions by consensus
- Voting right based on various factors
    - Mostly investment level

Private Cables

- Built by Telecom Operators to address specific requirements and/or seize opportunities
  - Telstra's Endeavour
- Built by Non-Carriers to address specific traffic flows, scalability and resiliency requirements
  - Google's Curie
- Business case needs to be strong to cover the level of investment
  - Risk and revenues are weighted differently by debt and equity providers

Legal Structure

- Entity structure based on tax/legal/regulatory policies
- Often involves partners for permits and landing rights
- Owned capacity allocation and negotiated usage rules
- Landing Rights/Permits

Relationship Management

- Bilateral relationships with Customer and Supplier

Maintenance

- Several options available to cover marine maintenance

Forming A Consortium

If Your Analysis Leads You To A Consortium

- Each partner will have to build their own business case
- The economics and costs of capital may be different for each party
- The upside and risks will be different for each party
- Hopefully everyone's plan is NOT built on the same customer base
- Forming the consortium itself, and getting other parties interested, takes negotiations and an outcome that allows each party to pass their own hurdles

Market Assessment

- What is the addressable market for the cable?
- Why is the cable needed?
- Where does this cable go?
- Who will make use of this cable?
- When will this cable be Ready for Service?
- How will this cable meet requirements now, and in the future?

  - Capacity need projections (3–10 years)
    - Most sales occur early in system life
  - Competition (existing, planned and future)
    - Who else is serving or looking ar serving this route?
  - Capacity pricing (now & after)
    - How much capacity exists now, and how much later?
    - What is the effect of bringing the new capacity to market?

Market Data Points

Data Points

- GDP/Distribution of Wealth
- Population
- Internet Penetration Rate
- IP Usage
- Age of Population
- Education/Literacy
- New Applications
- Mobile vs Broadband vs Leased Line
- Number of Businesses

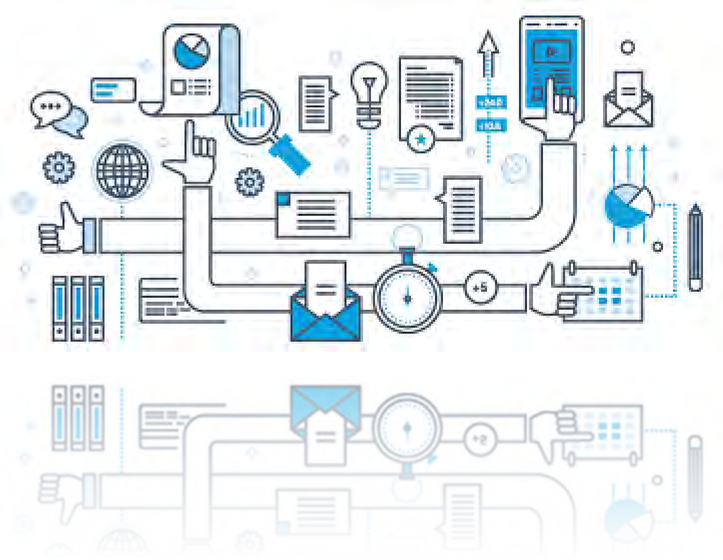
Example Sources

- UN-ITU
- Telegeography
- Market Analytic Firms
- Consultants

System Features

Design Considerations

- Ultimate Capacity
- Topology of System
- Fiber Count
- Traditional or SDM systems
- Wavelengths per Fiber Pair
- Type of Fiber
- Type of Armoring
- Repeated or Unrepeated
- Branches and Type
- Number, type and spacing of repeaters
- Power Budget & Design
- Environmental Considerations
- Types of Landings
- SLTE
- Open Systems



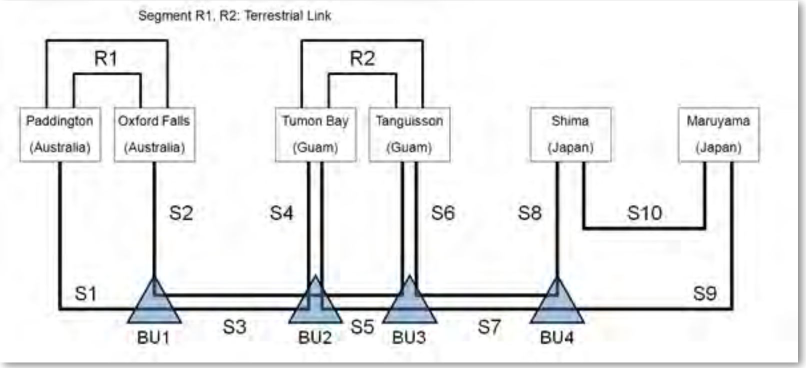
Topologies

Ring - *Southern Cross Cable System*

- Provides high reliability ar a higher cost

Semi Collapsed Ring - *Australia Japan Cable*

- Protects close to shore, where most damage occurs



Point to Point - CeltixConnect-1

- Least Expensive, No Protection

System Features

Cable configuration :

Fault history should be taken into account

- Channel system type
    - ≥ fault per winter (6 months) per 400 km
    - Ring and double landing (2 x 200 km in shallow water)
    - **Unavailability:** 0.3 day/year (single landing ~ 7.5 d/y)

- Mediterranean system type
    - 1 fault every two years 1000 km (shallow water)
    - Single landing (200 km but < 50 km in shallow)
    - **Unavailability** : 0.4 day/year (double landing ~ 0.01 d/y)

Initial Cable Route

It's a question of today's money vs future hedwins

Marine & Landing risk assessment: it's a business of experience

- In 150 years, you'll probably not be the first to go there
- Don't hesitate to call on the people who know
- Learn from past catastrophes (and success)

Beware: Regulatory Authorities, Ecologists and Fishermen love subsea systems (time & money consuming)

Some routes are better than others

System Features

Initial Cable Route

Landing selection
- Marine suitability (onshore, offshore activities)
- Backhaul connection (Is there someone out there?)
- Station size (DWDM upgrade !!!)

Route selection : Don't be pound wise and penny foolish: it is often better to protect once now, than repair ten times later
- Cable type and armor
- Burial (plough preferred)
- Shore ends
- Cable and Pipe crossings

Price estimates

- In-house
    - Determine equipment BoQ
    - Use previous unit prices
    - Estimate other costs
    - Always prepare data before engaging supplier
    - Try to understand their current position

- Rough Orders of Magnitude (ROM)
    - Most suppliers are happy to provide it
    - Not always very accurate
    - Should be a not to exceed cost

- First firm offers

Commercial Aspects To Consider

Product Design

- 10g/100g, Spectrum, Fiber Pairs, Protected, Unprotected, Upgrade rights,
- Upgrade rights
- Ownership or IRU
- Use Restrictions, Rights Transfer, Portability

Review of Market Prices

- vs existing: pricing higher would require no supply, is very hard to do
- vs planned: keep same level or lower if supply exists

Special offers

- Pre-sales
- Bulk purchase
- Can be driven by system configuration

Consortia - Carrier Perspective

- Notional capacity = capacity required to be sold to finance the initial system investment
- During the pre-sales process, pricing can be often be negotiated to cost place basis
- Upgrade capacity
    - There are variety of solutions
    - Forward pricing on wavelengths
    - Spectral pricing on fractional IRUs
        - Alien SLTE
    - Access to uplifts to system capacity can be negotiated for at a cost+ basis
    - Be aware that consortium sometimes need to work together to complete upgrades and establish timelines

Consortia - Non-Carrier Perspective

- Want to ensure swap/resale rights
- Want to control upgrade timing

Commercial Aspects To Consider

Private cables

- Pre-sales (before CIF)
  - Demonstrate there is a market &reduces financial risk
  - Generally only covers part of the investment in the system cost
- Post-CIF capacity pricing
  - The Market Is Alway Right
  - Also, Sometimes The Market Is Wrong
    - Be prepared to adapt your pricing
    - Someone buys, someone sells, each wants to feel they got a good deal
  - Price Elasticity of Demand (E_d)
    - How much demand is there if nothing changes but the price?

Permitting

Landing & Operating

- Working permits: usually supplier's responsibility
- Authorizations in principle: right to land/own a system on national territory, RoW, etc. Usually cable owner's responsibility
- Telecom licenses : Cable owner/operator's responsibility (possibly through local partnership)

Exclusive Economic Zone / International Waters

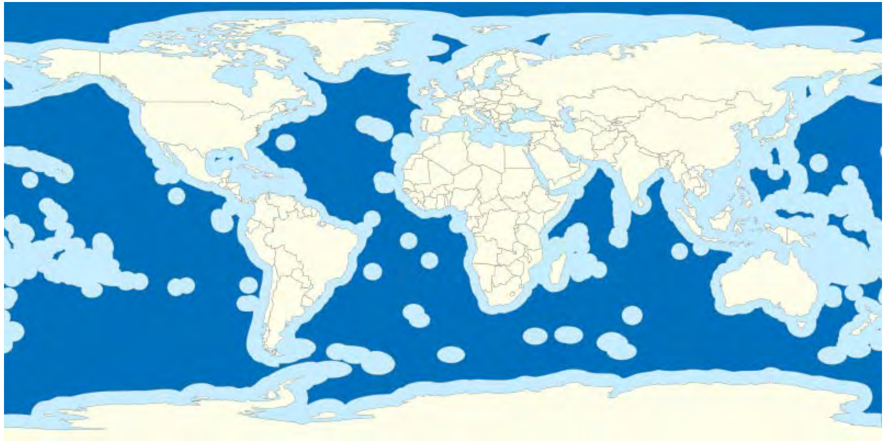
- The United Nations Convention on the Law of the Sea (UNCLOS)
    - Also Called Montego Bay Convention
- 167 nations have ratified as of 2016
    - The US Situation: Part XI: Minerals
- Waters are still disputed
    - South China Sea

Agreements with other seabed users

- Cable & pipe owners
- Oil exploration & platforms
- Sand dredgers
- Fishermen

EEZs Around The World

International Waters (Dark Blue) beyond EEZ (Light Blue)



System Financing

Financial Structures

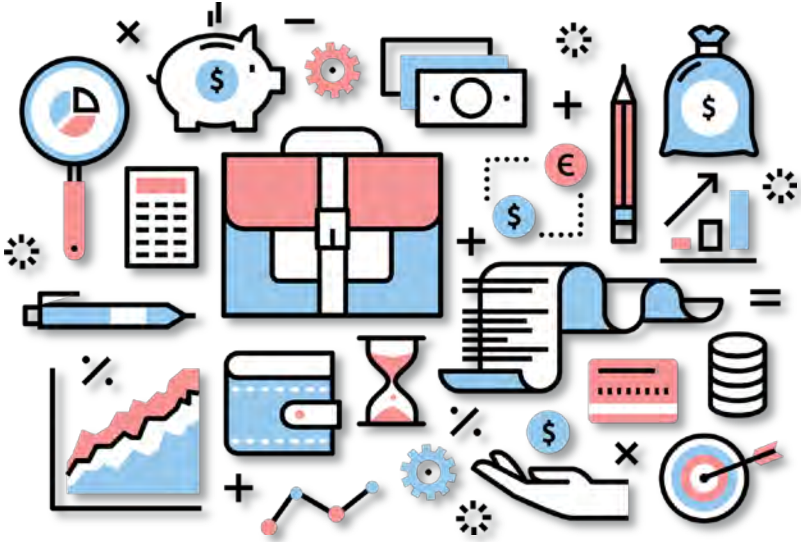
Consortia are “full-equity/no-debt” schemes

- There is no debt to be repaid
- Cash flow must be budgeted
- The restrictions that can come with debt are avoided
- Step in rights may be part of the agreement

Private Cable can can have different types of fund sources

- Some companies an self fund
- Some may involve a mix of debt and equity
- This mix of funding can carry risk, that needs to have a mitigation plan

Different tranches may be needed over time, based on project success and market conditions



Financing

- Consortiums
  - Government Financing
  - Supplier Financing
  - Banks/Private Equity/Debt
  - Carrier Financing
  - Non-Carrier Financing
- Private Cables
  - Government Financing
  - Supplier Financing
  - Banks/Private Equity/Debt
  - Carrier Financing
  - Non-Carrier Financing

Expectations of Financing Entities

- Government Financing
  - Sometimes a grant to open access to an underserved market
  - Sometimes research driven
- Supplier Financing
  - Sometimes to cover a gap
- Banks/Private Equity/Debt
  - Looking for a return on investment
- Carrier Financing
  - Looking for a return on investment
- Non-Carrier Financing
  - Looking for ROI, but not necessarily on telecom products

WACC

- The weighted average cost of capital(WACC) is the rate that an entity (Consortium or Company) is expected to pay on average to all its security holders to finance the asset of the submarine cable.

- The WACC is the minimum return that a Company or Consortium must earn on the submarine cable to satisfy its creditors, owners, and other providers of capital.

- WACC helps in understanding the overall return of the investment. It is commonly used by Finance teams to evaluate the best opportunities for future endeavors.

WACC = Cost of Equity + Cost of Debt (After Tax)

The Formula for WACC

$$\text{WACC} = \left(\frac{E}{V} \times Re\right) + \left(\frac{D}{V} \times Rd \times (1 - Tc)\right)$$

where:

E = Market value of the firm's equity

D = Market value of the firm's debt

$V = E + D$

Re = Cost of equity

Rd = Cost of debt

Tc = Corporate tax rate

Source : Investopedia

Generally used as the discount rate in an NPV calculation, and shown as percentage. Based on public filings, Walmart had a WACC of ~ 6.1% in 2016, was paying that amount for capital raised via debt and equity

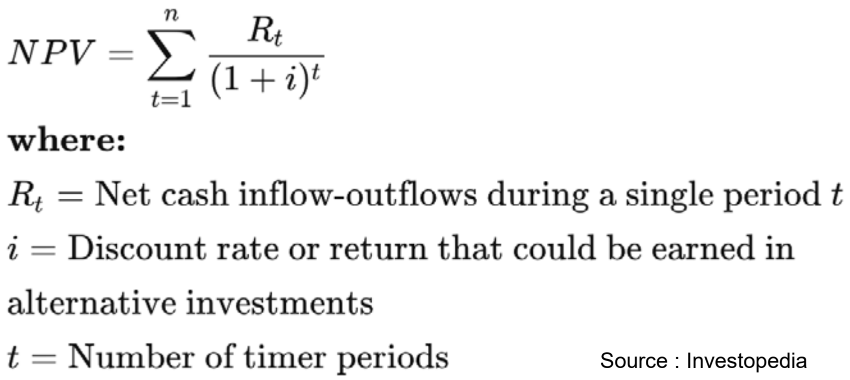
NPV

- Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting and investment planning to analyze the profitability of a projected investment or project.

- The NPV rule says that only investments with a positive NPV should be invested in.

- A NPV that is positive indicates the projected earning/return exceed the costs that are anticipated to be incurred.

NPV = Today's Value of Expected Cash Flow - Today's Value of Invested Cash



$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t}$$

where:

R_t = Net cash inflow-outflows during a single period t

i = Discount rate or return that could be earned in alternative investments

t = Number of timer periods

Source : Investopedia

Supplier Negotiations

Negotiations

- Be dispassionate: Emotions tend to blow up negotiations
- Prepare, and do you research, and prepare some more
- Make sure you are negotiating with the person able to actually make the decision
- Focus on your goal, and not on who is right
- Make human contact
- Acknowledge the suppliers position and the ability
- Embrace difference; different can be good, can be profitable, and leaves room for creativity
- When people become irrational (it happens), use empathy to reduce the emotion. Otherwise no one will hear anything
- Try to understand the supplier's position; you need to know their motivation and goal if you are to persuade them
- Incremental steps are best; trying to solve everything at once usually leads to failure
- Know the standards! A powerful tool, and you can hold all sides to them
- Be transparent, and not manipulative. This will be a long term relationship.

Supply Contract

- The end result of the business plan, engineering, project plan, financing and vendor negotiations is the Supply Contract
- The Supply Contract represents the common understanding between the cable owner(s) and builder
- When signed, this is generally when you are Contract-in-Force, and pre-sales end
- The contract's outcome is the submarine cable system
- The supply contract specifies the CAPEX that will be spent on the system

- A good Supply Contract is they key to a smooth implementation &a system that performs as designed
- Gives parameters so that the project has a timeline and budget
- It is key to maintain a good relationship with the supplier during implementation and beyond
- A fine contract should make lawyers unnecessary down the road

Suppliers

- Suppliers love Contract Variances
- Suppliers don't love commitments as much as CVs
- Make sure to speak to all suppliers, because more data points and knowledge helps when developing your business plan
- In the end, you will be in partnership with your supplier for decades, most likely
- Different suppliers are, of course, good at different things
- You can have multiple suppliers, but this can create complexities, and all relationships and responsibilities, handoffs and acceptance criteria need to be well document and understood

Steps to the Supply Contract

- Rough order of Magnitude (ROM)
- RFQ/ITT (Request for Quote/Invitation To Tender)
  - Needs to be prepared to allow a good comparison of offers
- Clarification and Follow Up
  - Have them sharpen pencils, be more specific
- Trim number of bidders
- Request Best and Final Offer (BAFO)
- Select your supplier based on best fit to all requirements

Supply Contract Contents

- General Terms & Conditions
- Supplier responsibilities : Scope of Work, permits, custom clearance
- Purchaser protection: warranties & guarantee, liquidated damages
- Payment procedures
- Contract variations process
- Termination clause
- Force Majeure
- Transfer of Title upon meeting Acceptance Criteria

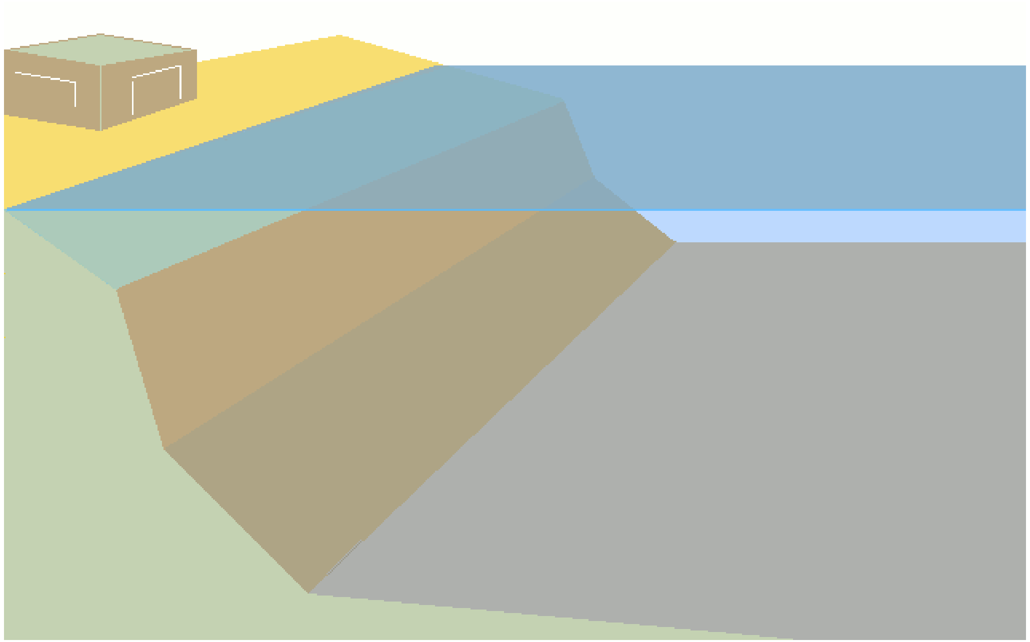
- Technical Specifications
  - Detailed technical description
  - Functionalities of equipment/system
  - Availability & reliability requirements
  - Safety/environmental requirements
  - Quality Assurance
  - Commissioning (tests & procedures)
    - Provisional Acceptance
  - Long-term assistance over system life
    - Including software

Guarantees

Guarantees & Warranties

- Parental Guarantee
  - Protects against insolvency of contractor
- Performance Guarantee
  - Protects buyer if system doesn't perform as promised
- Advance Payment Guarantee
  - Protect buyer who make payments at milestones of project doesn't complete

- Warranty
  - A financial guarantee to ensure satisfactory quality during a specific period
- Expressed Warranties
  - Written in the contract
- Implied Warranties
  - Nor written, but still binding



For more info on submarine cables

- Watch on YouTube: A Journey To The Bottom Of The Internet

Google Cloud

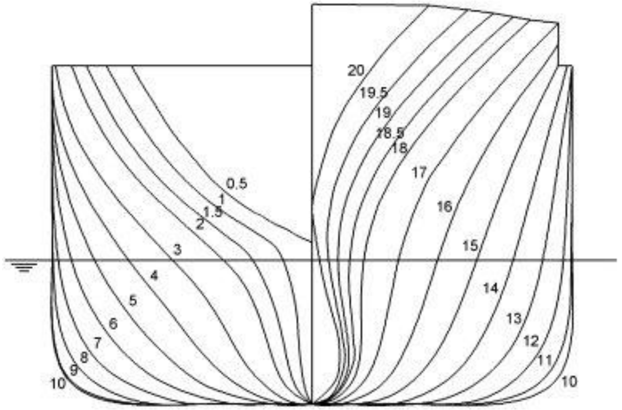
SUBCOM

Marine Construction Overview

Chris Carobene

Vice President
Marine & Network Construction

Chris Carobene – 26 years at SubCom….!



Agenda

Process Overview

Construction Activities

Vessels and Tools

CURIE Examples

Process Overview

Marine Construction - Objective

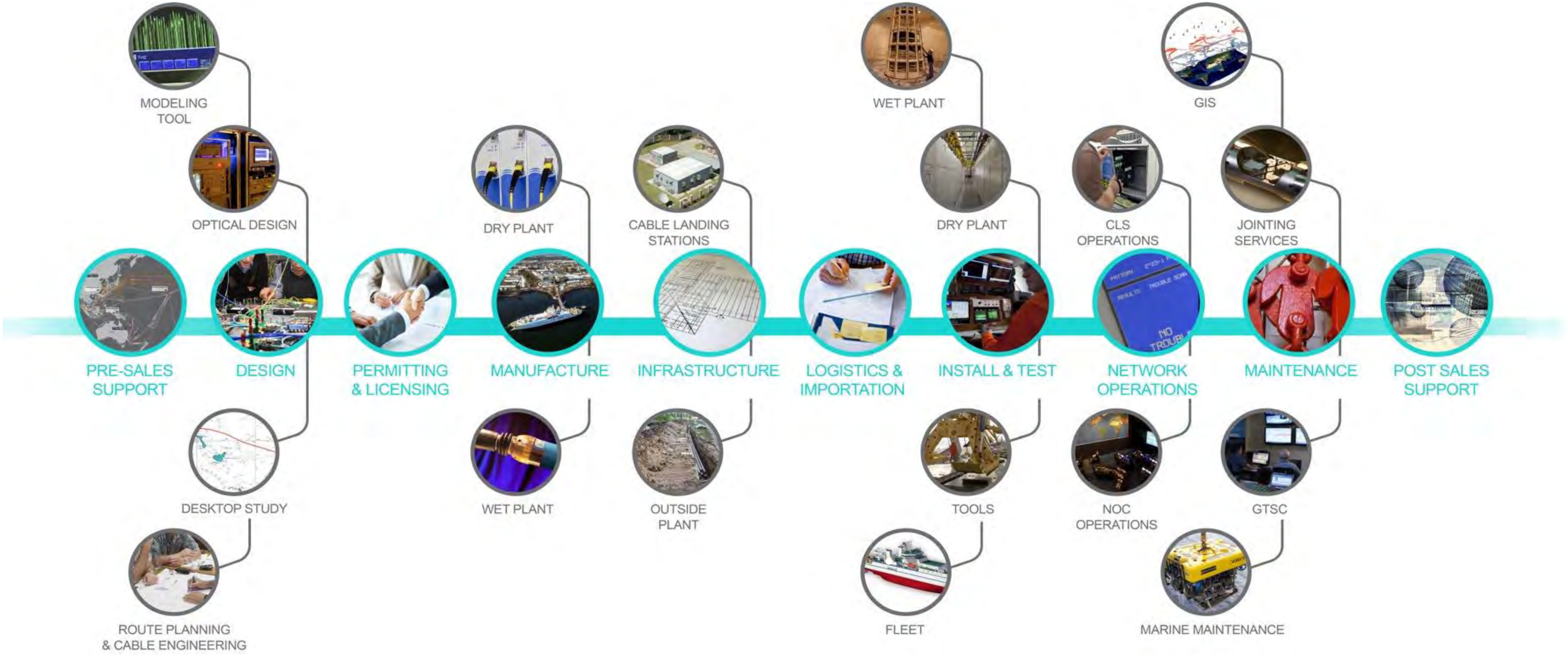
Building the Network

Install the equipment and infrastructure necessary for the undersea network

Maximize network performance by protecting submarine cables using a robust construction process

Managing and mitigating risk throughout the construction process

Project Process & Key Components



MODELING TOOL

WET PLANT

GIS

OPTICAL DESIGN

DRY PLANT

CABLE LANDING STATIONS

DRY PLANT

CLS OPERATIONS

JOINTING SERVICES

PRE-SALES SUPPORT

DESIGN

PERMITTING & LICENSING

MANUFACTURE

INFRASTRUCTURE

LOGISTICS & IMPORTATION

INSTALL & TEST

NETWORK OPERATIONS

MAINTENANCE

POST SALES SUPPORT

DESKTOP STUDY

WET PLANT

OUTSIDE PLANT

TOOLS

NOC OPERATIONS

GTSC

ROUTE PLANNING & CABLE ENGINEERING

FLEET

MARINE MAINTENANCE

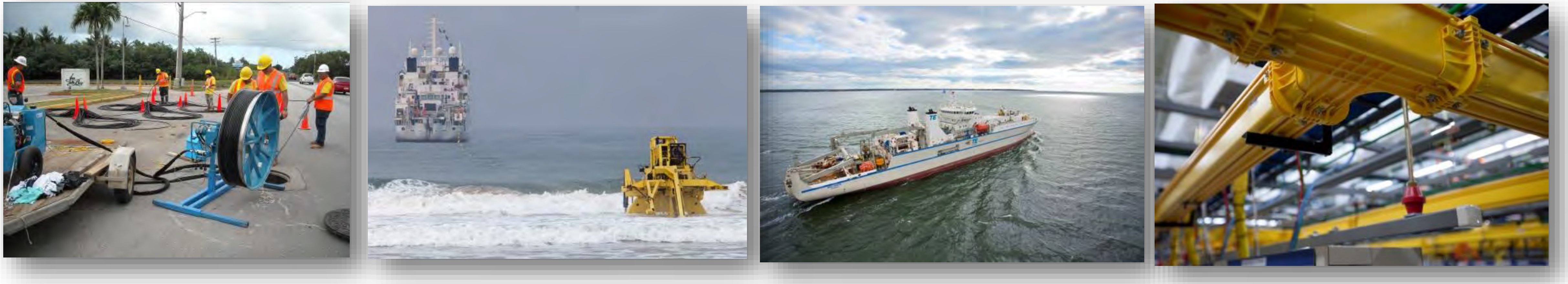
Ethics

Safety

Quality

Construction Activities

Scope of Marine Construction



Terrestrial
- ✓ land cable
- ✓ ocean ground
- ✓ station splice
- ✓ OSP construction

Pre-Laid Shore End
- ✓ shallow water vessel
- ✓ route clearance
- ✓ cable lay
- ✓ cable burial
- ✓ split pipe

Main Lay
- ✓ cable loading
- ✓ route clearance
- ✓ cable burial
- ✓ surface lay
- ✓ ROV inspection / burial

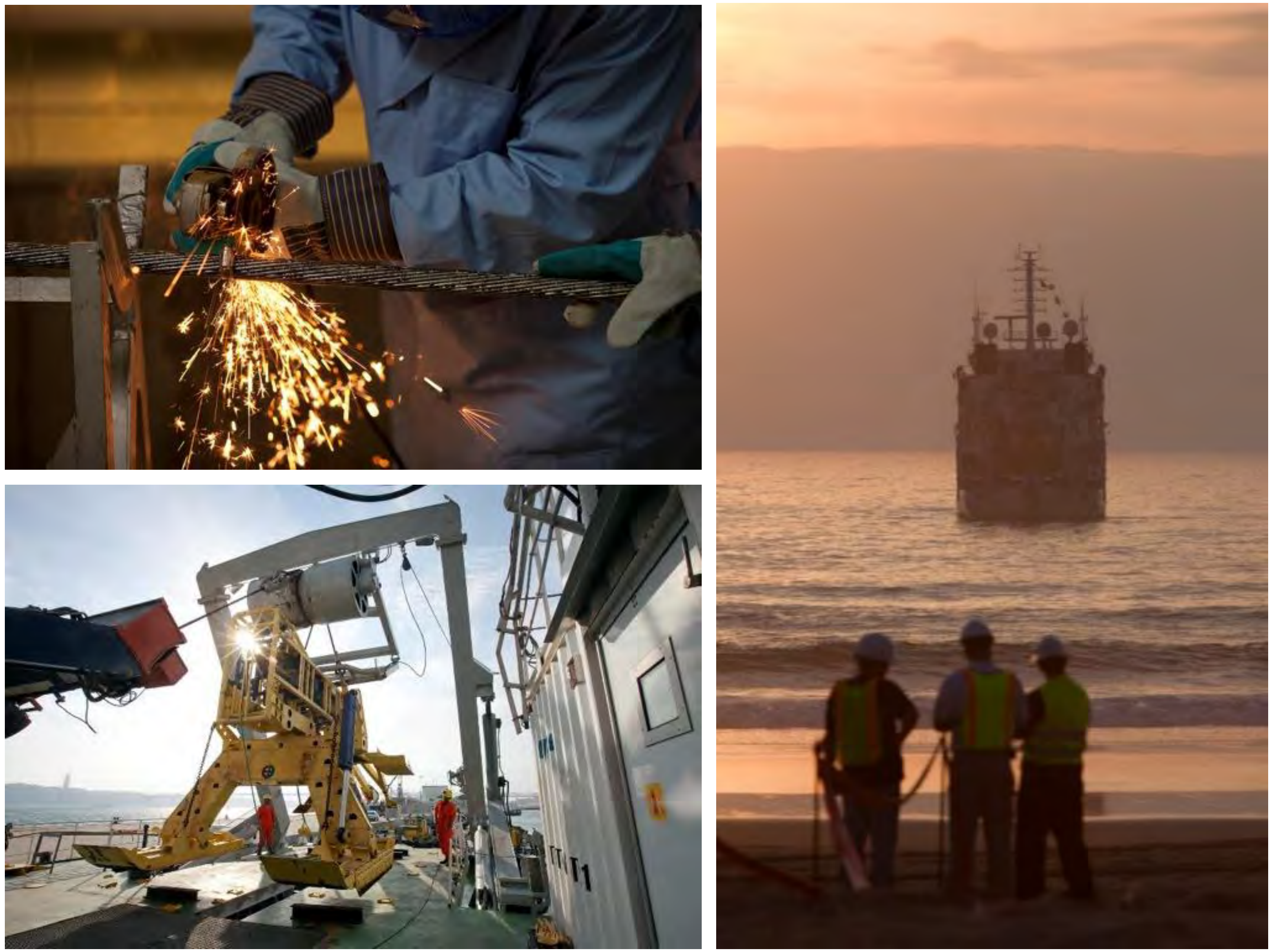
Direct Landing
- ✓ cable landing
- ✓ beach splice
- ✓ cable positioning
- ✓ diver burial
- ✓ Uraduct

Terminal
- ✓ Equipment installation

Construction Process

Four main phases of construction process:

- Planning
- Data Collection & Validation
- Execution
- Support & Maintenance



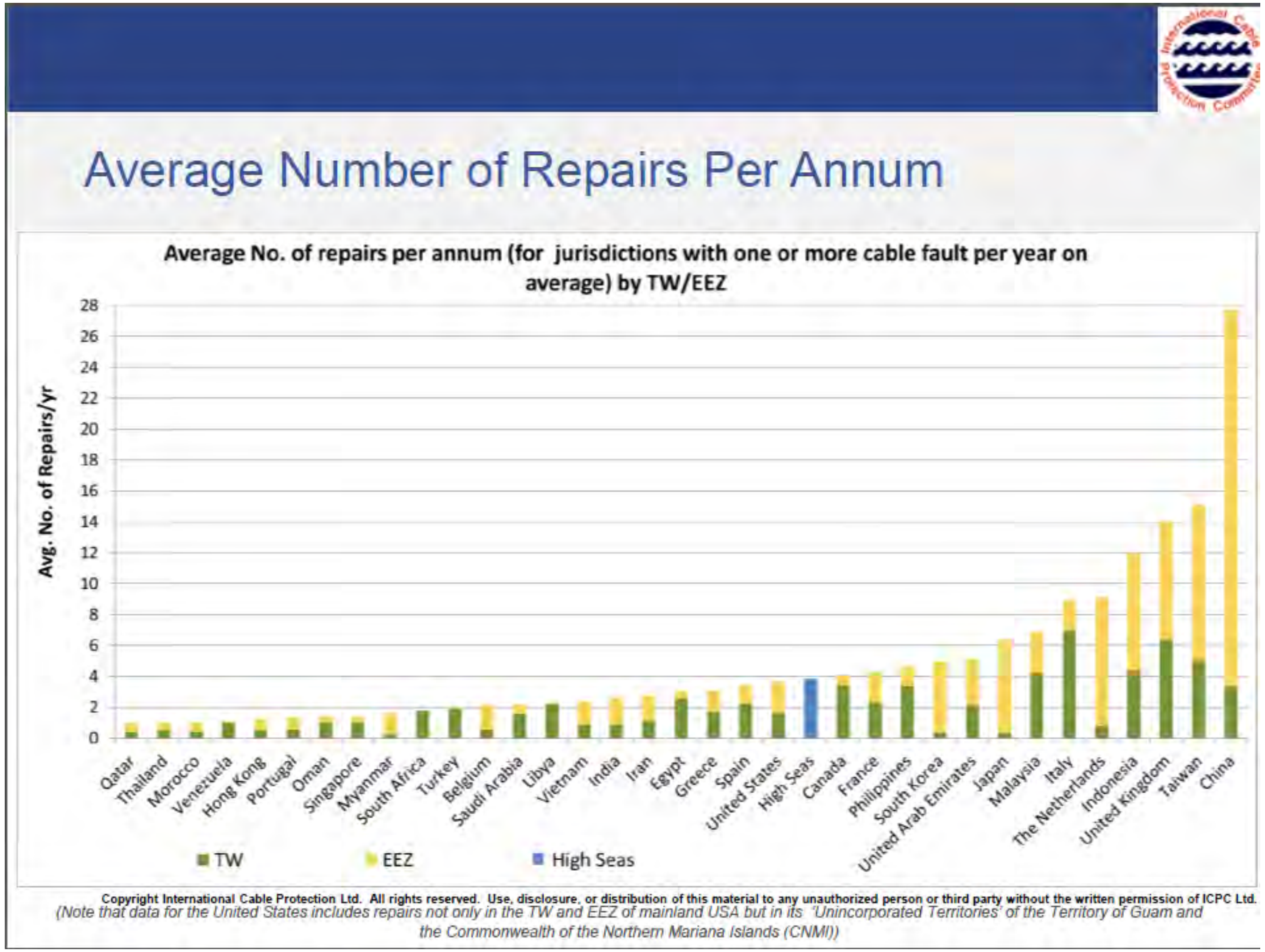
Planning - Risk Identification

Key Risk Areas:

- **Personnel** – Dangerous environment with high tensions and heavy machinery
- **Vessel, Tools & Equipment** – Break-down causes delay and budget overrun
- **Cable System** – Systems need to survive in a harsh environment for 25yrs

The majority of cable failures are the result of interaction with other human activity.

Historical Cable Fault Causes Guide Risk Assessment and Mitigation

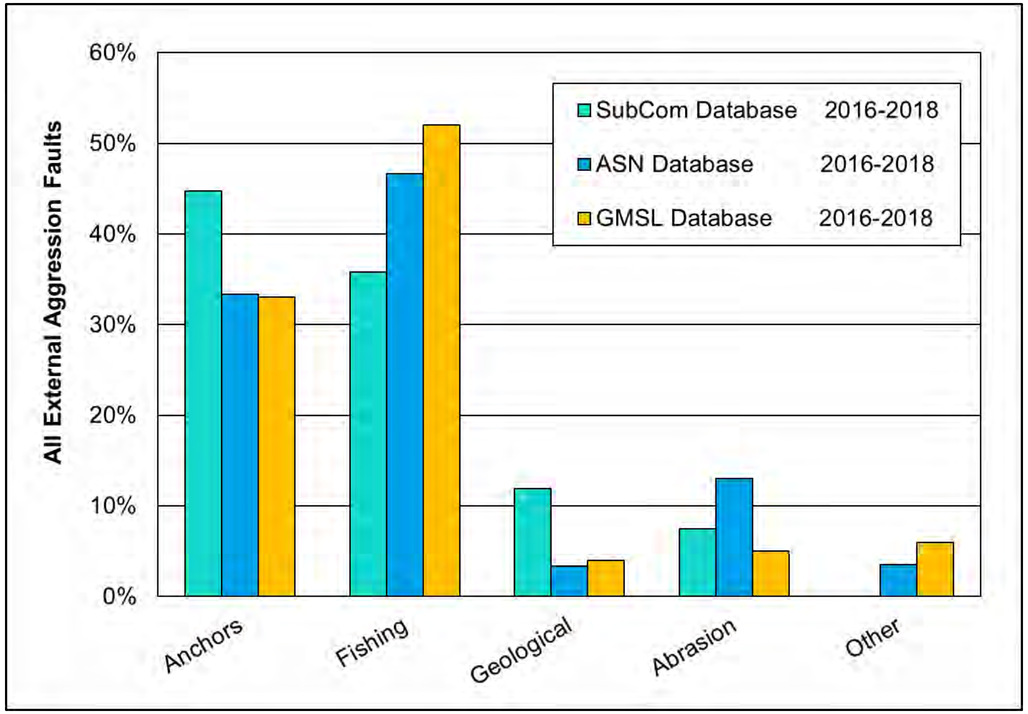


Average Number of Repairs Per Annum

Average No. of repairs per annum (for jurisdictions with one or more cable fault per year on average) by TW/EEZ

(Note that data for the United States includes repairs not only in the TW and EEZ of mainland USA but in its 'Unincorporated Territories' of the Territory of Guam and the Commonwealth of the Northern Mariana Islands (CNMI))

80% of all cable faults are the result of external aggression (e.g. fishing & anchoring).



Suboptic 2019. M. Kordahi et al. New Orleans, LA, April 2019

ICPC Plenary 2019, A. Palmer-Felgate el al, Cape Town, April 2018. Averages over between 5 to 10 years of data depending on maintenance zone.

Submarine Cable Protection

Given the economic and national-security importance of submarine cables, it's critical to protect them from physical damage.

Ship anchors and commercial fishing gear pose—by far—the most significant risks of damage to undersea cables.

- An undersea cable repair can cost in excess of US **$1 million** and typically takes 2+ weeks to return the cable to service—or more, depending on permitting requirements, weather, and other factors.

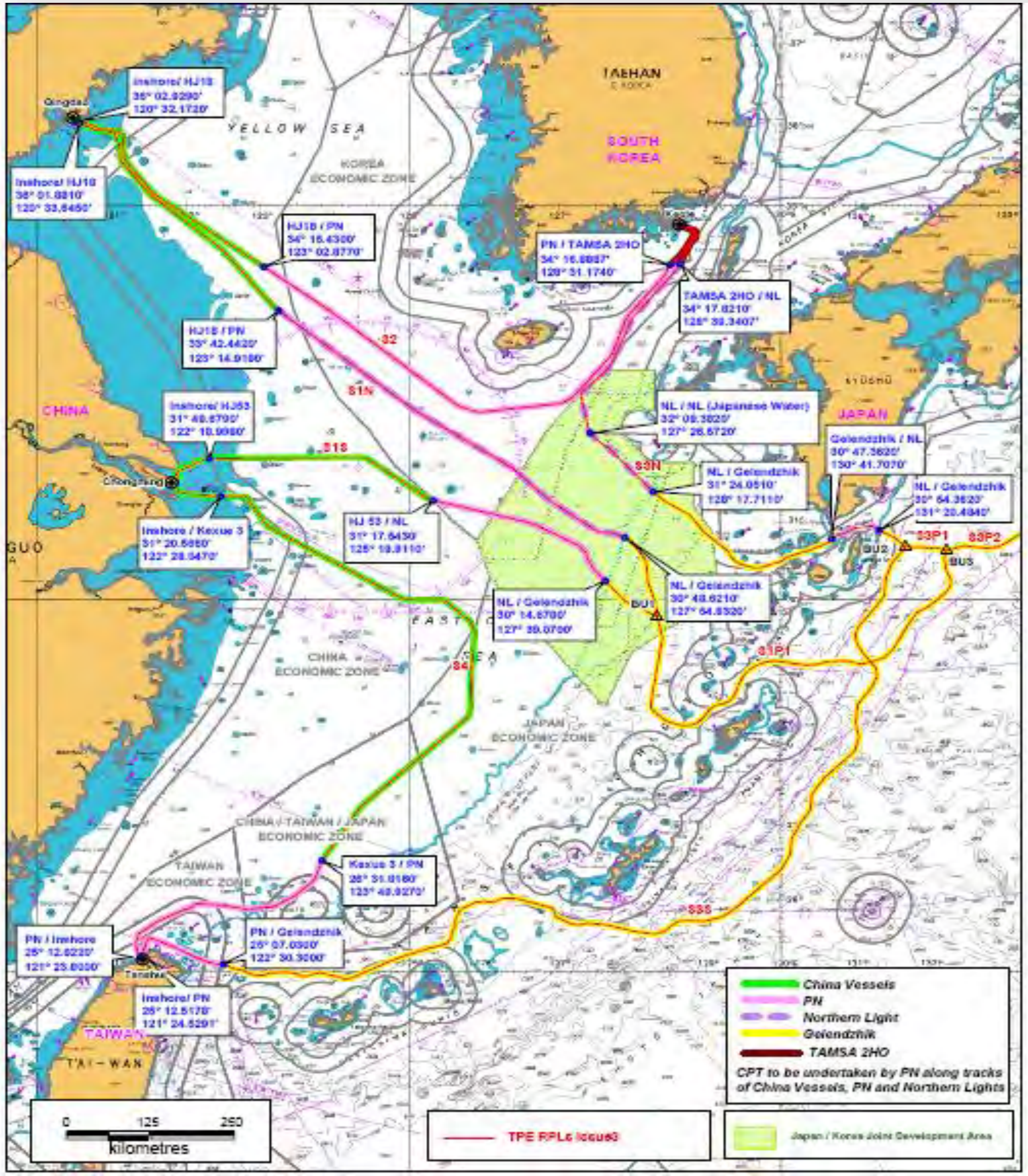
- Fishing practices and patterns continue to be a **primary consideration** in undersea cable projects.
- **>90% of cable faults** (2010-2015) **are caused by external aggression**; of this percentage, ~75% are attributed to fishing or anchoring.
- **Regional variation in fishing risks are analyzed to tailor marine liaison analyses and outreach strategies.**

Initial Design - Desktop Study

Identify a safe and economical cable route

Design Considerations:

- Landing Points
- Maritime Boundaries
- Geopolitics - Contested Areas
- Cable Fault Data Base
- Deep Burial
- Pre-Laid Shore Ends & Direct Landings
- Horizontal Directional Drilling
- Permitting & Fisherman Negotiations
- Natural and manmade obstacles
- Mineral/Oil & Gas exploration
- Cable selection
- Branching Unit deployments
- Other submarine cables
- Pipelines
- Unexploded Ordnance
- Cable / Pipeline Database



Agreement with other seabed users is critical to the survivability of the system

Risk Management

Risk Identification & Assessment

- Identify each risk
- Determine the threat level

Avoidance – Primary mitigation is to simply avoid

- Routing directly to deep water
- Avoiding areas of intense fishing and anchorages

Mitigation – When the risk can't be avoided

- Burial
- Cable Armoring

Risk Management balances cost of mitigation against the risk of future system downtime.

Planning Activities - Permitting

- **Landing Permits License – Permission to operate a telecom network**

- **Proprietary Permits**
  - Rights of way, easements, wayleaves and seabed lease agreements
  - Cable Crossing Agreements
  - Pipeline Crossing Agreements
  - Hydrocarbon and Mineral Lease Blocks/Concession agreements
  - Environmental Impact Assessments
  - EEZ notifications
- **Operational Permits**
  - Notices to mariners
  - Navy/coastguard permits/notifications
  - Local authorities and municipalities
  - Work Visas
- **Other Permissions may be Prerequisites**
  - Fisheries
  - Native communities


Its about time!!

Early due diligence with all stakeholders is critical to minimizing the permitting interval.

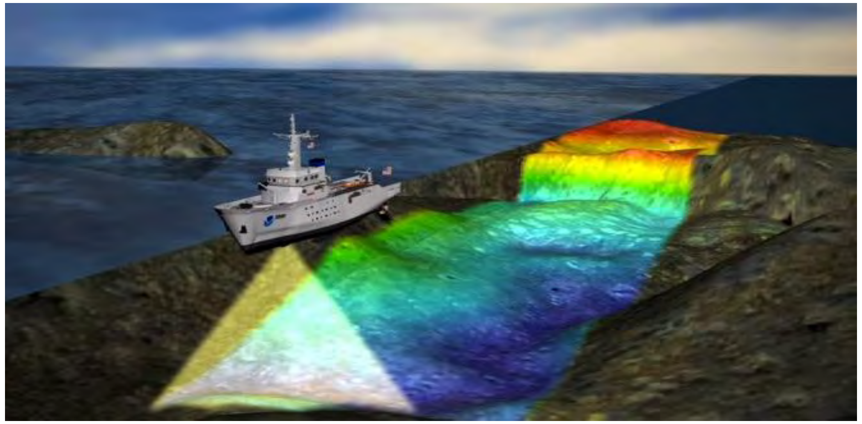
Data Collection - Cable Route Survey

Data Collection – Survey & Inspections

- ✓ Bathymetry, geotechnical, sub-bottom, and side scan data to support route engineering, cable selection, installation and burial

Analysis of Results – Results

- ✓ Revised RPL & SLD
- ✓ Cable Armoring & Protection
- ✓ Burial Conditions
- ✓ Recommendations for Installation Procedures



Landing Site Survey | Diver Swim | Small Boat | Shallow Water | Deep Sea

Design Validation - Cable Route Engineering

Installation Planning – Methods of Procedure

Modelling

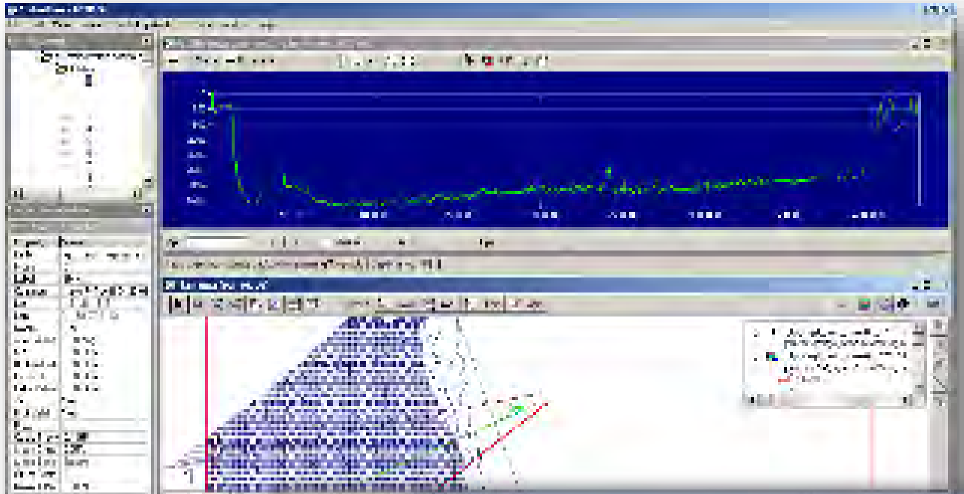
GIS environment to display bathymetry, geophysical information, nautical charts, global maritime boundaries, oil and gas lease blocks.

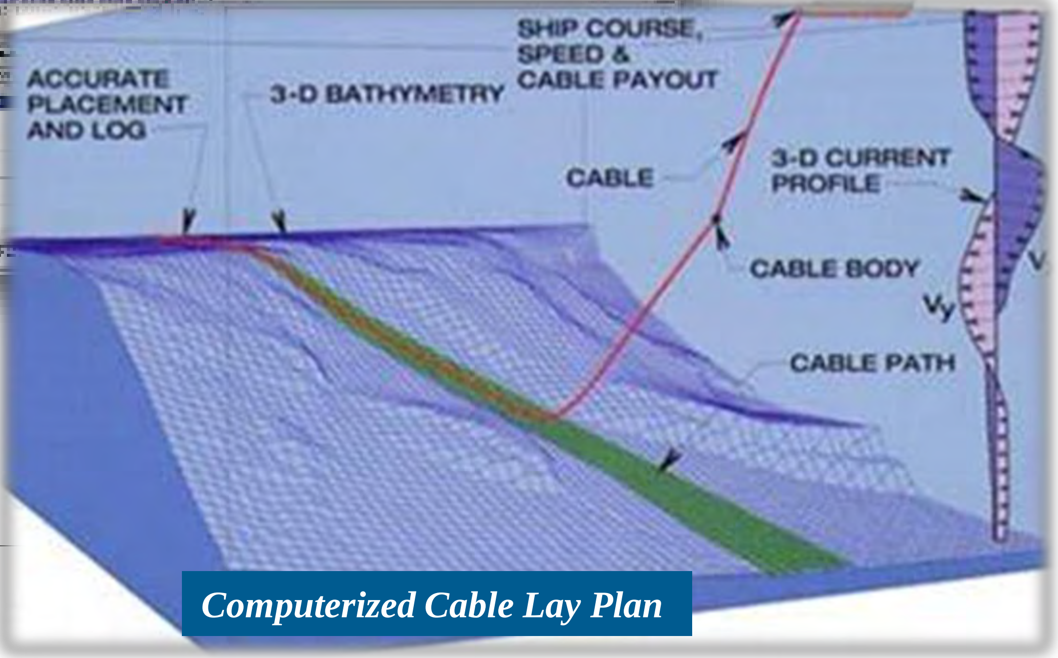
Cable Route Engineering

Slack, cable type transition, repeater and joint body locations. Any changes to the route are calculated automatically and results are updated

Software modeling of the cable as it is deployed allows validation of the plan before heading to sea.

Electronic - Bottom Profile, Bathy and RPL





Computerized Cable Lay Plan

Installation Activities - Terrestrial

Shore End & Terrestrial

– Shallow water installation
– Cable landing operations
– Land cable installation
– Ocean ground bed installation
– Station cable terminations

Terminal Installation

– Station layout
– PFE installation
– SLTE installation
– ODF installation
– Fiber Guide installation
– Power and data cabling

Installation Activities – Marine

Route Clearance

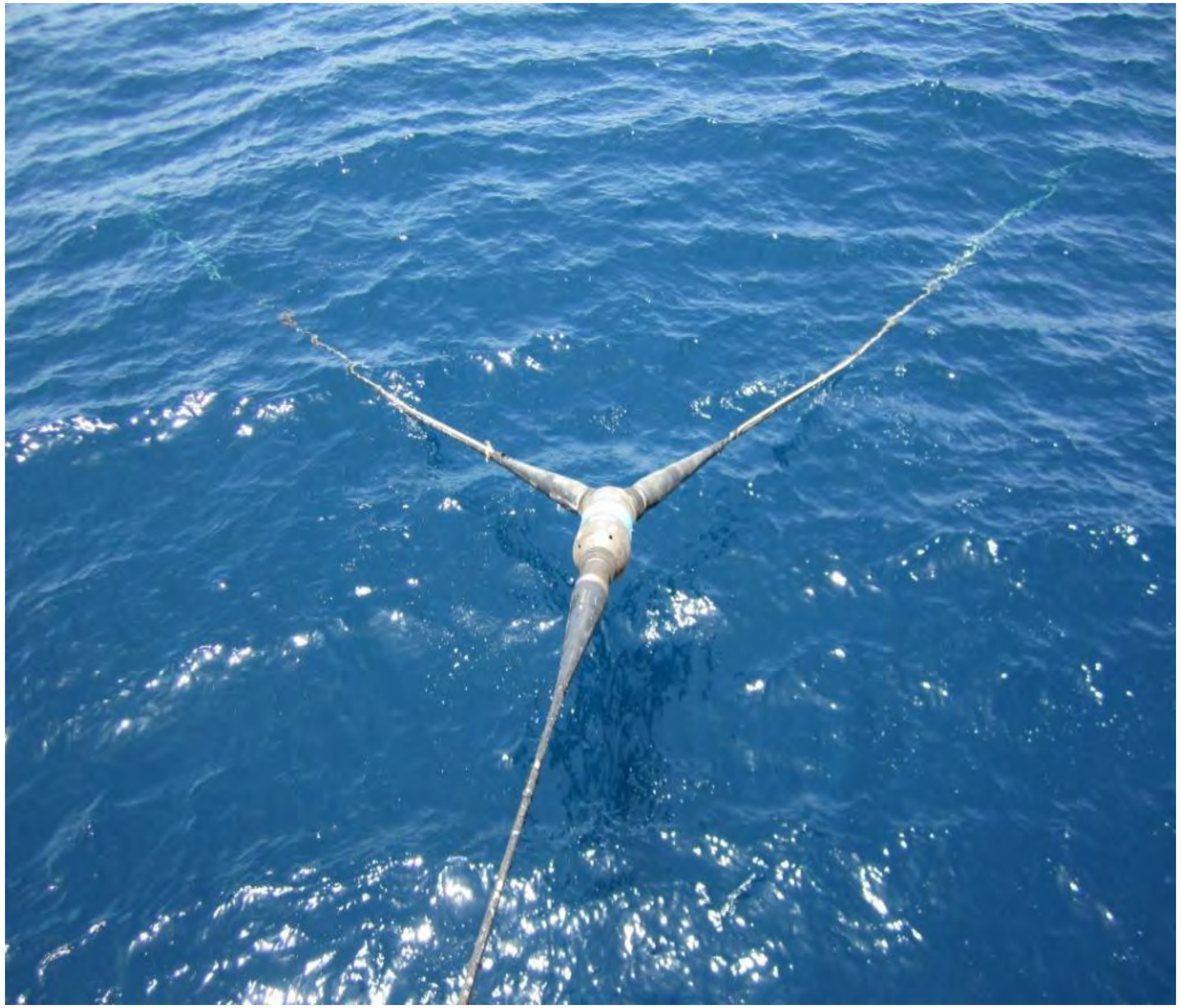
- Clears out-of-service cables / discarded fishing nets
- Reduces risk to burial equipment
- Accommodates future maintenance

Main Lay & Burial

- Cable loading
- Cable installation
- Slack to cover seabed contours
- Burial to mitigate fishing & anchors
- Splicing and Testing

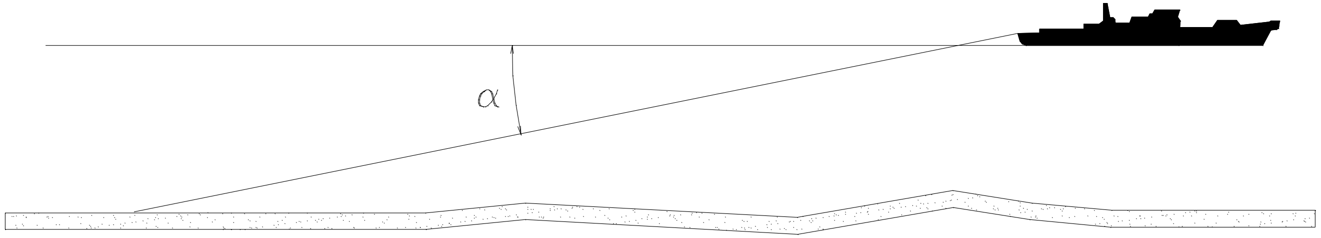
Post Lay Inspection & Burial

- Supplements the sea plow burial
- Verifies the installation



Surface Laying – Critical Angle

Critical Angle "alpha" is the entry angle that the cable makes with the surface of the water.

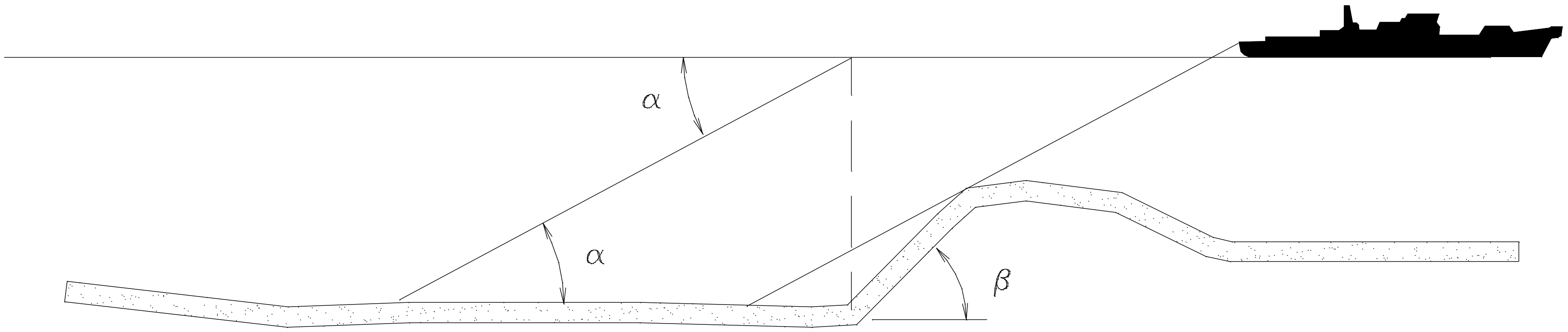


Alpha is a function of the cable's hydrodynamic constant and the vessel's speed:

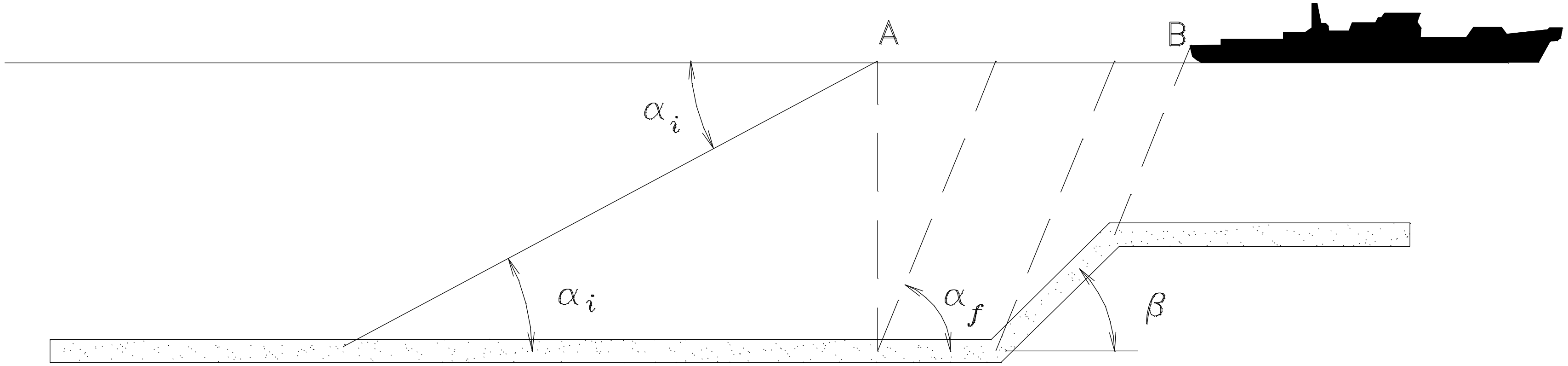
$$\alpha = \arccos\left(\sqrt{1 + \frac{1}{4}\left(\frac{H\pi}{V_s 180}\right)^4} - \frac{1}{2}\left(\frac{H\pi}{V_s 180}\right)^2 \right)$$

For critical angles less than 30°, alpha can be closely approximated: $\alpha = \frac{H}{V_s}$

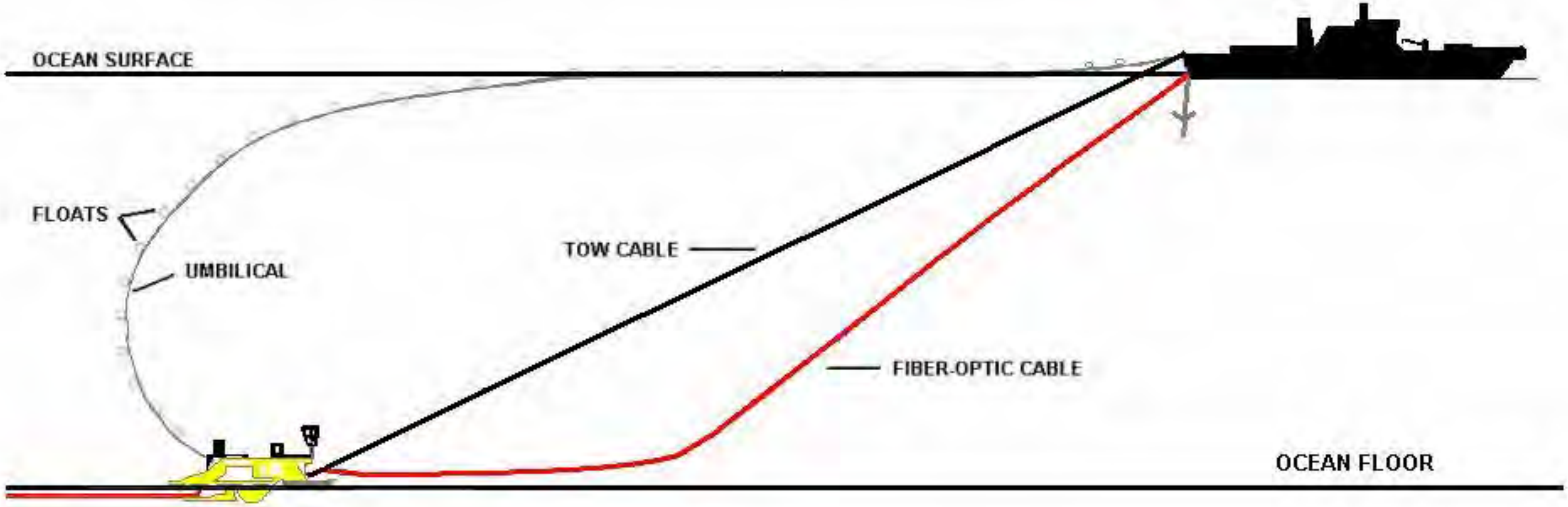
Surface Laying – Slack Management



Matching Alfa to the angle of the seabed ensures that the cable properly follows the seabed contours.



Cable Burial - Plows



Sea plow used to bury cable

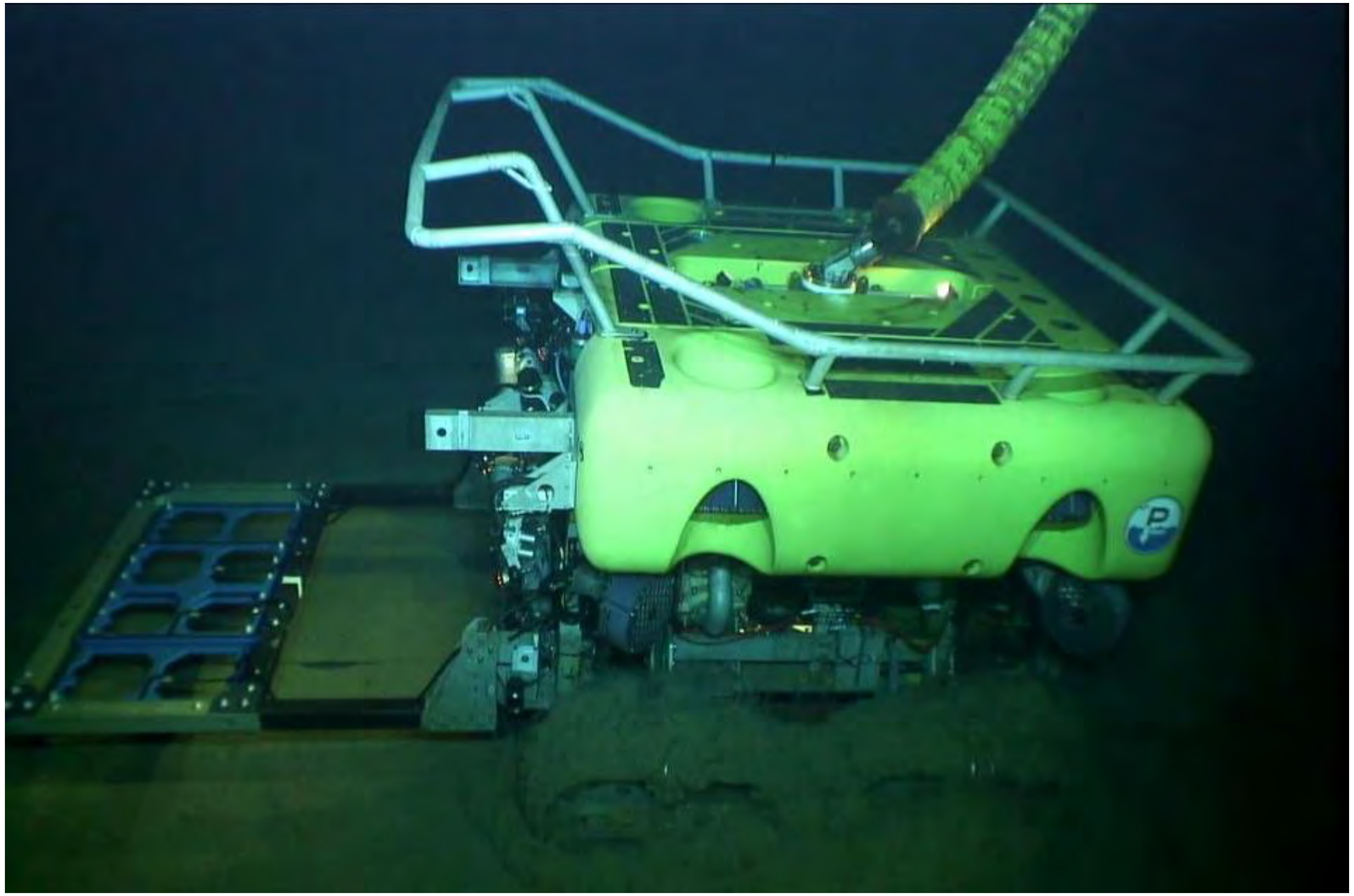
Note: distance of the plow from the ship, and lengths of the fiber-optic cable and tow cable, vary depending principally on sea-floor depth.

Burial Tools - Plows

- Modern **Subsea Telecom Cable Plow** - simultaneous cable lay & burial
- **3m burial** capability
- Tow force of **80 tons** or greater

ROV Survey & Burial

- The ROV can be operated on tracks or in free-fly mode.
- Post main-lay the ROV deploys to the seabed.
- The cable is located using cameras, sonar or specialized cable detection equipment.
- The cable is inspected and/ or buried using water jets on deployable jetting swords.
- Burial takes place to target depth or a maximum of 3 jetting passes.
- When jetting is complete, a final inspection pass is conducted to record burial results.
- The ROV can also be used to cut, recover and bury cables during cable repair operations.

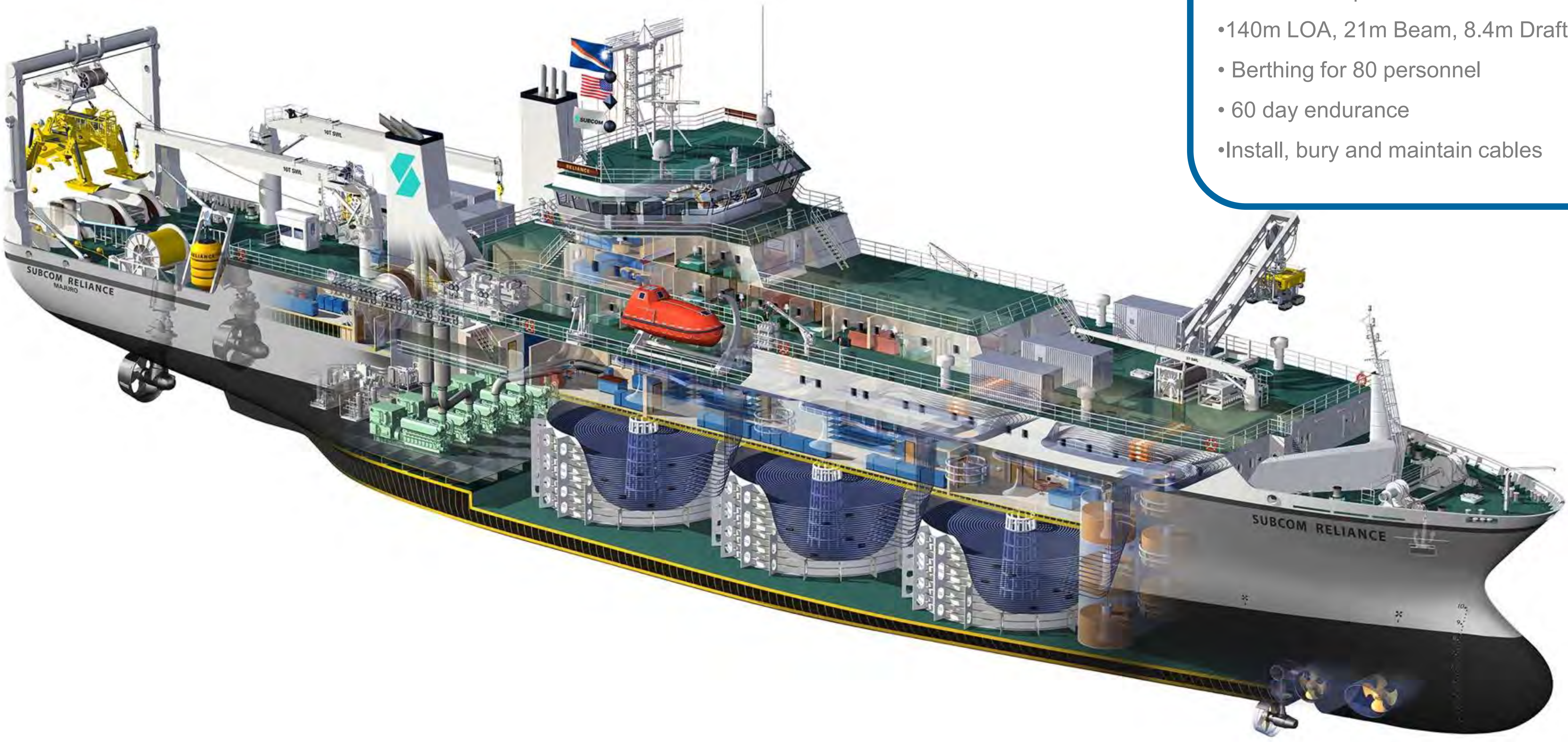


ROV Submarines

- Cable Burial **ROV** (Remotely Operated Vehicle)
- **2 or 3 meter** burial capability
- **Water jets** bury cable

Cable Ship Features

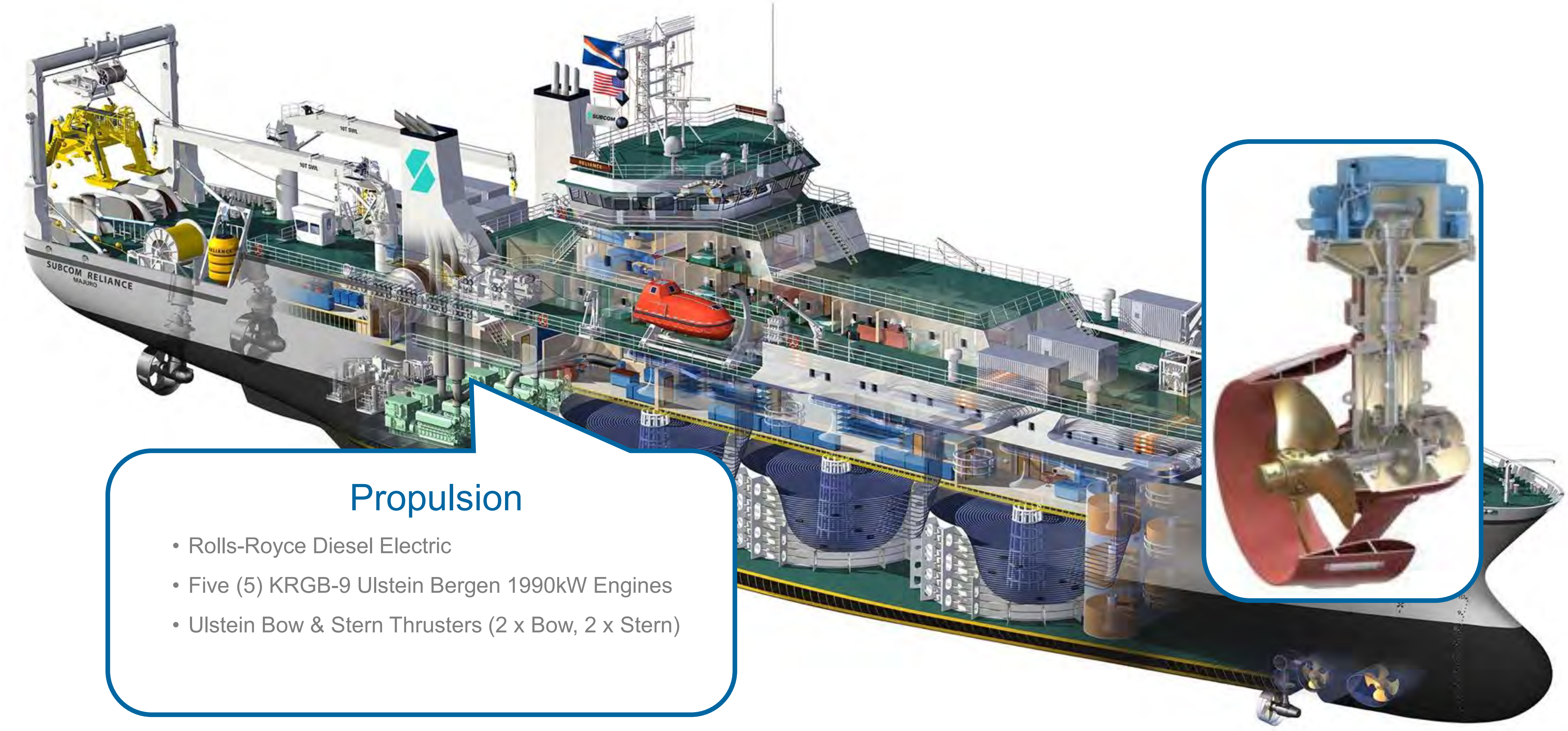
Installation – Cable Ships



Modern Cable Ship

- Multi-function cable lay vessel
- World wide operations
- 140m LOA, 21m Beam, 8.4m Draft
- Berthing for 80 personnel
- 60 day endurance
- Install, bury and maintain cables

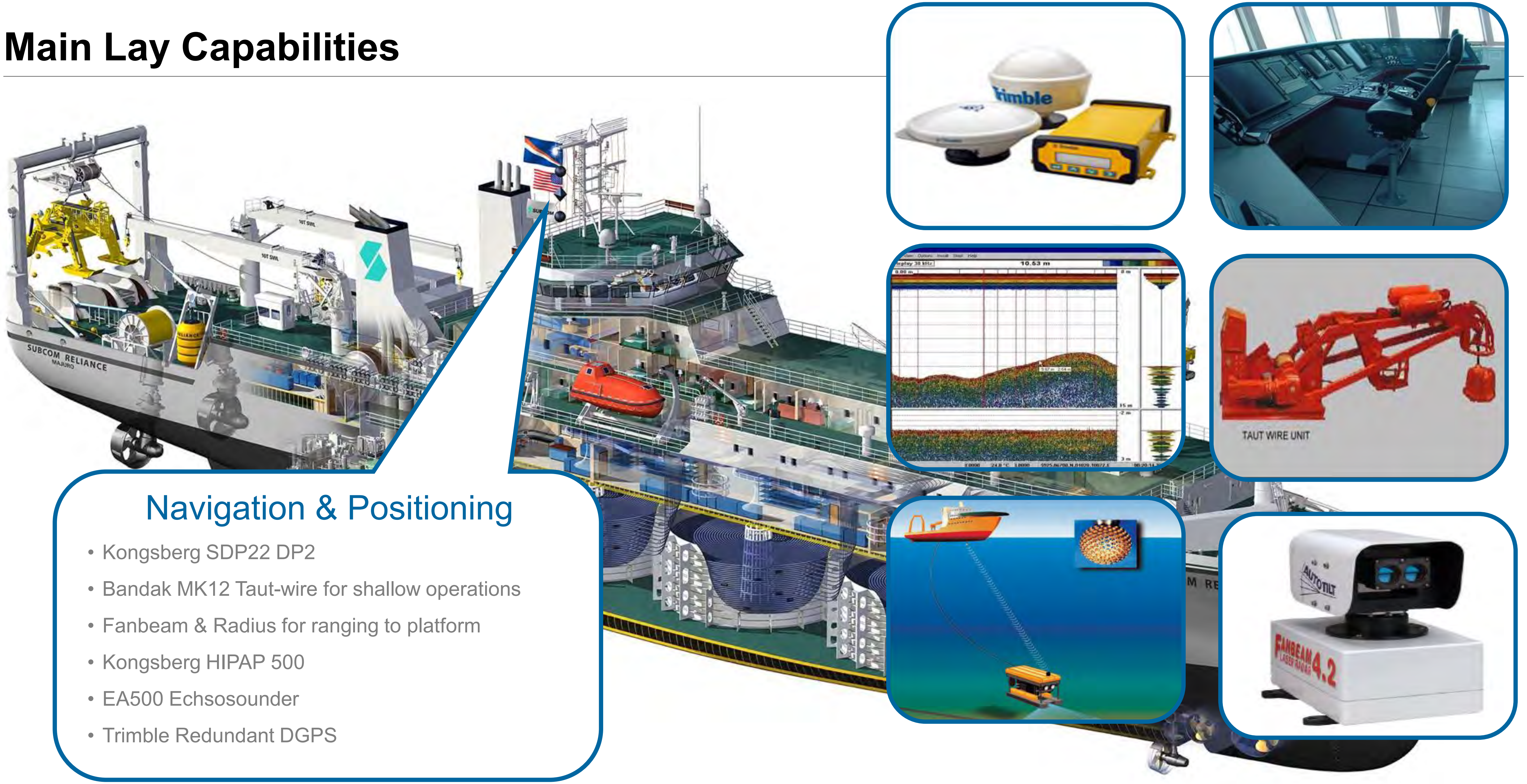
Main Lay Capabilities



Propulsion

- Rolls-Royce Diesel Electric
- Five (5) KRGB-9 Ulstein Bergen 1990kW Engines
- Ulstein Bow & Stern Thrusters (2 x Bow, 2 x Stern)

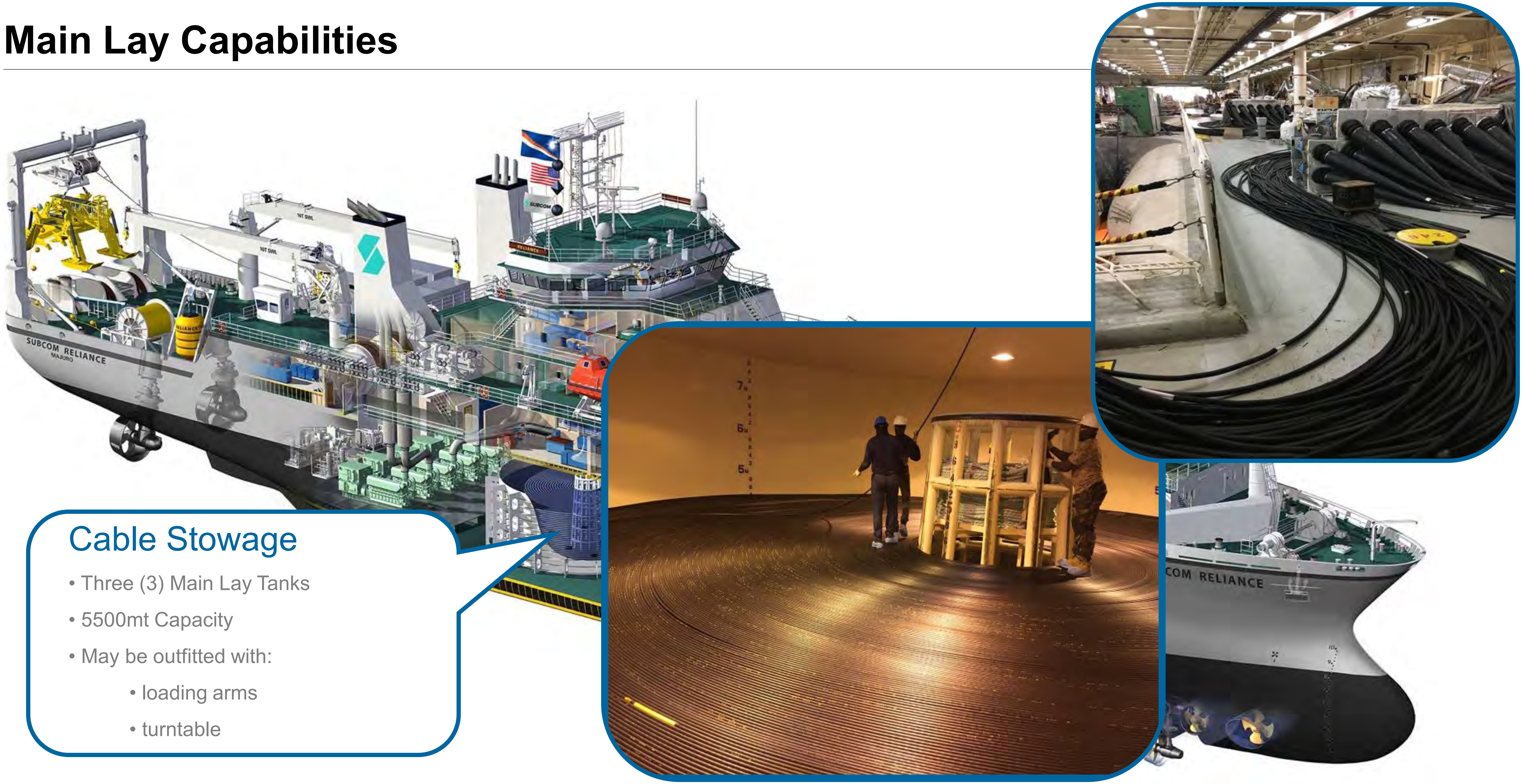
Main Lay Capabilities



Navigation & Positioning

- Kongsberg SDP22 DP2
- Bandak MK12 Taut-wire for shallow operations
- Fanbeam & Radius for ranging to platform
- Kongsberg HIPAP 500
- EA500 Echsosounder
- Trimble Redundant DGPS

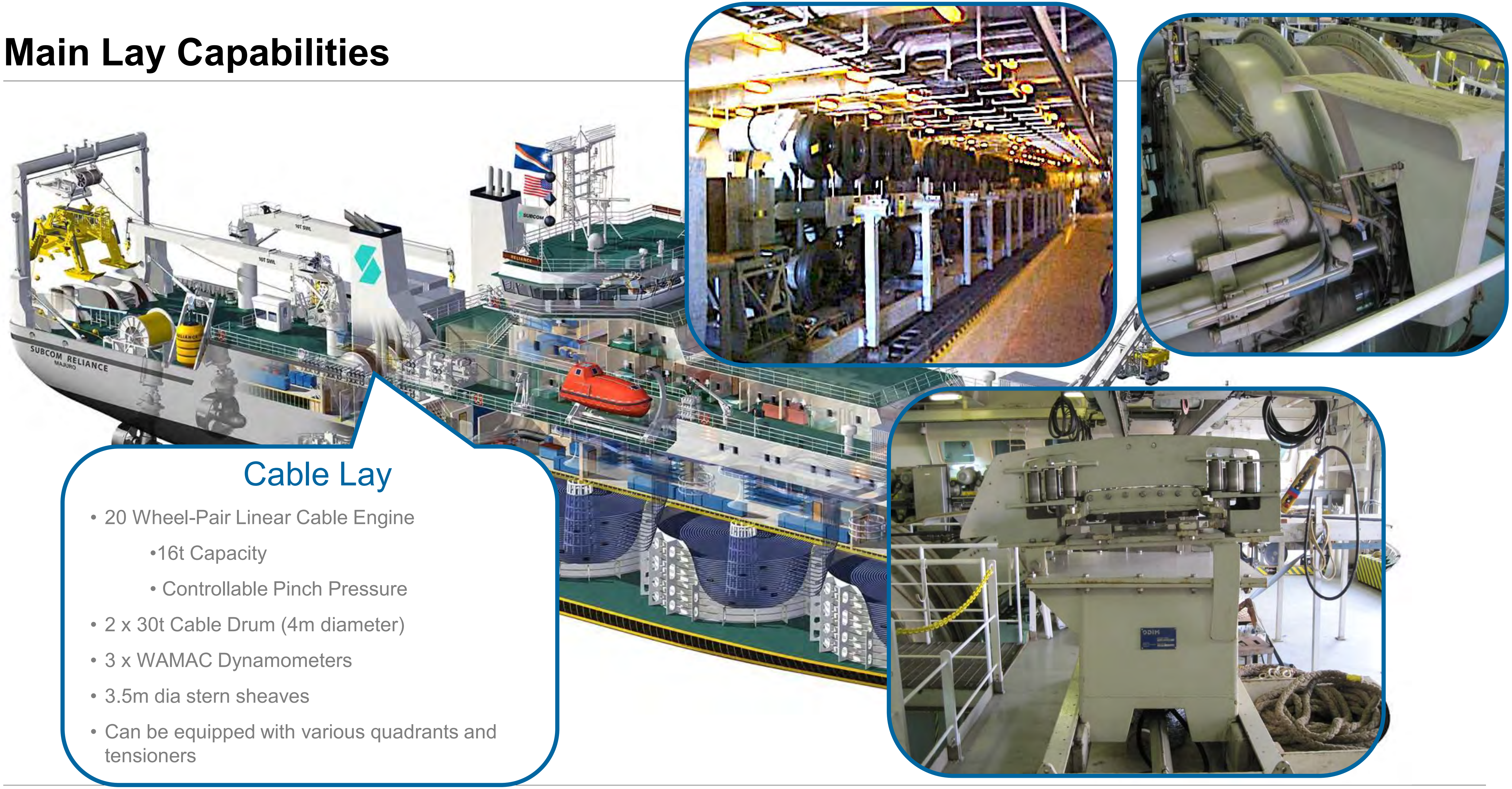
Main Lay Capabilities



Cable Stowage

- Three (3) Main Lay Tanks
- 5500mt Capacity
- May be outfitted with:
    - loading arms
    - turntable

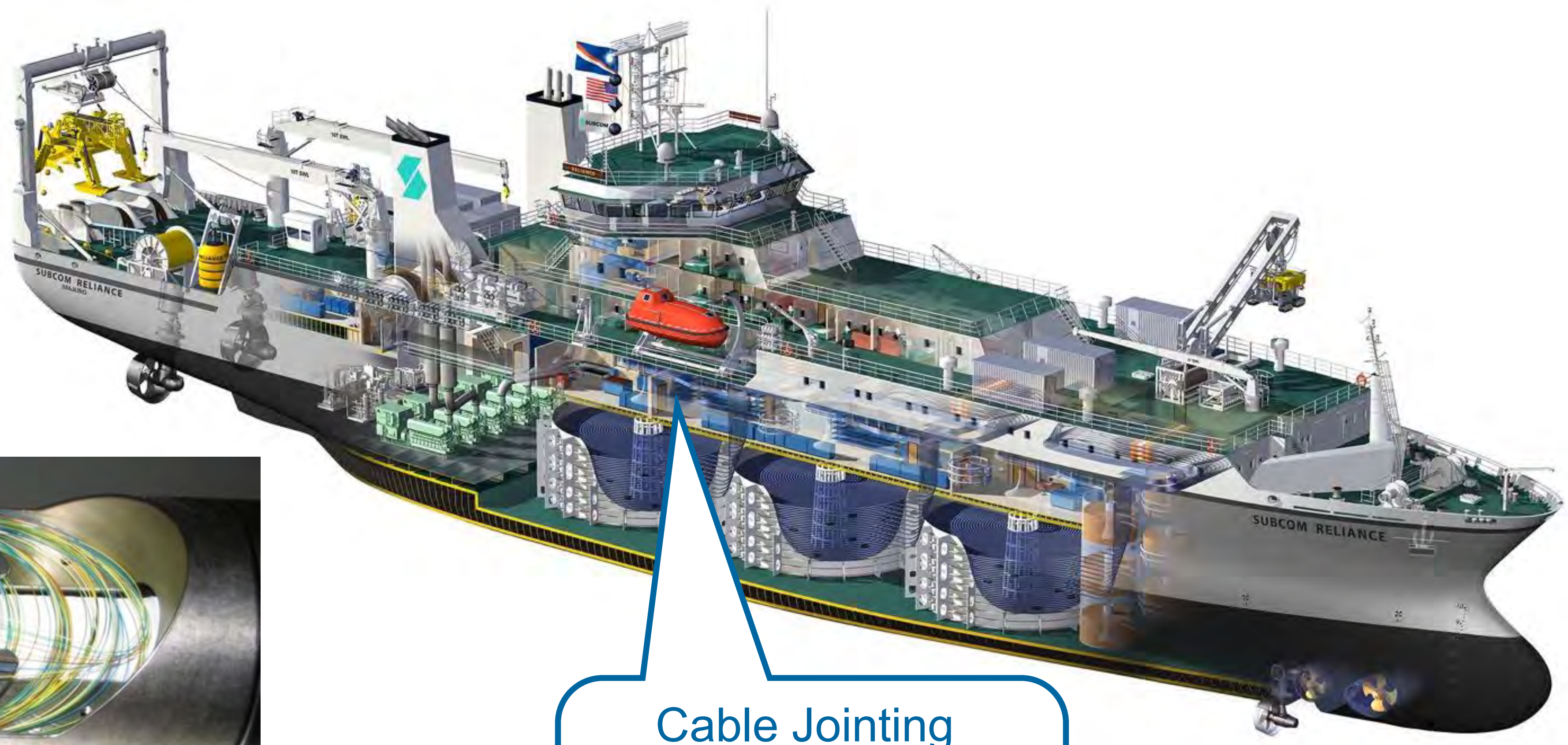
Main Lay Capabilities

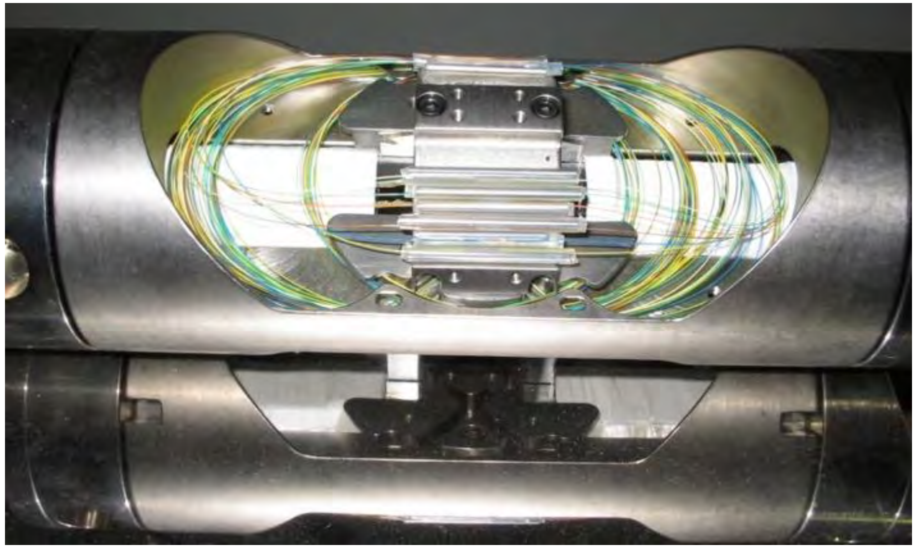


Cable Lay

- 20 Wheel-Pair Linear Cable Engine
  - 16t Capacity
  - Controllable Pinch Pressure
- 2 x 30t Cable Drum (4m diameter)
- 3 x WAMAC Dynamometers
- 3.5m dia stern sheaves
- Can be equipped with various quadrants and tensioners

Main Lay Capabilities

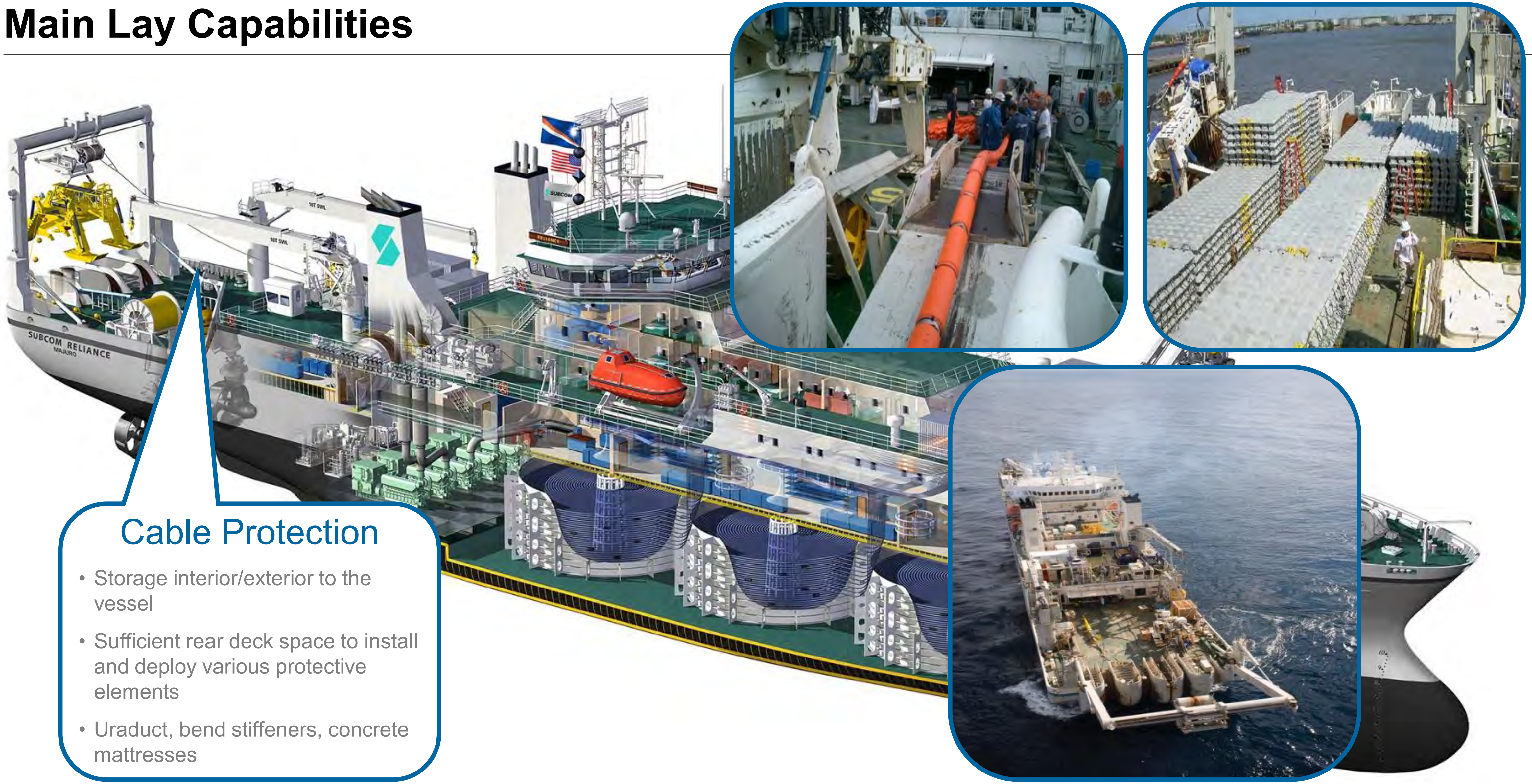




Cable Jointing

- Interior jointing and testing area
- Specialized jointing equipment can be mobilized on cable highway or on stern

Main Lay Capabilities

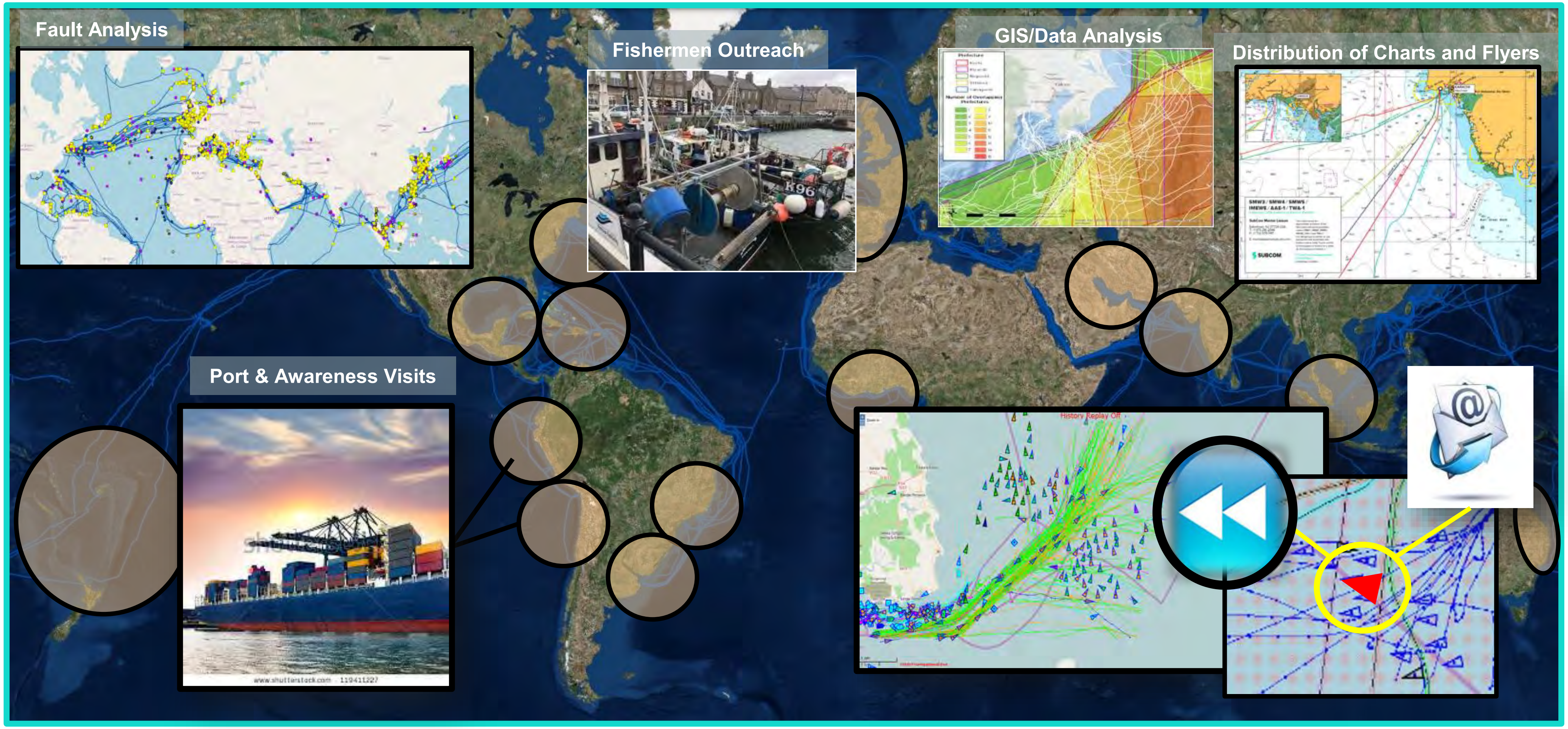


Cable Protection

- Storage interior/exterior to the vessel
- Sufficient rear deck space to install and deploy various protective elements
- Uraduct, bend stiffeners, concrete mattresses

Post Installation - Cable Awareness & Support

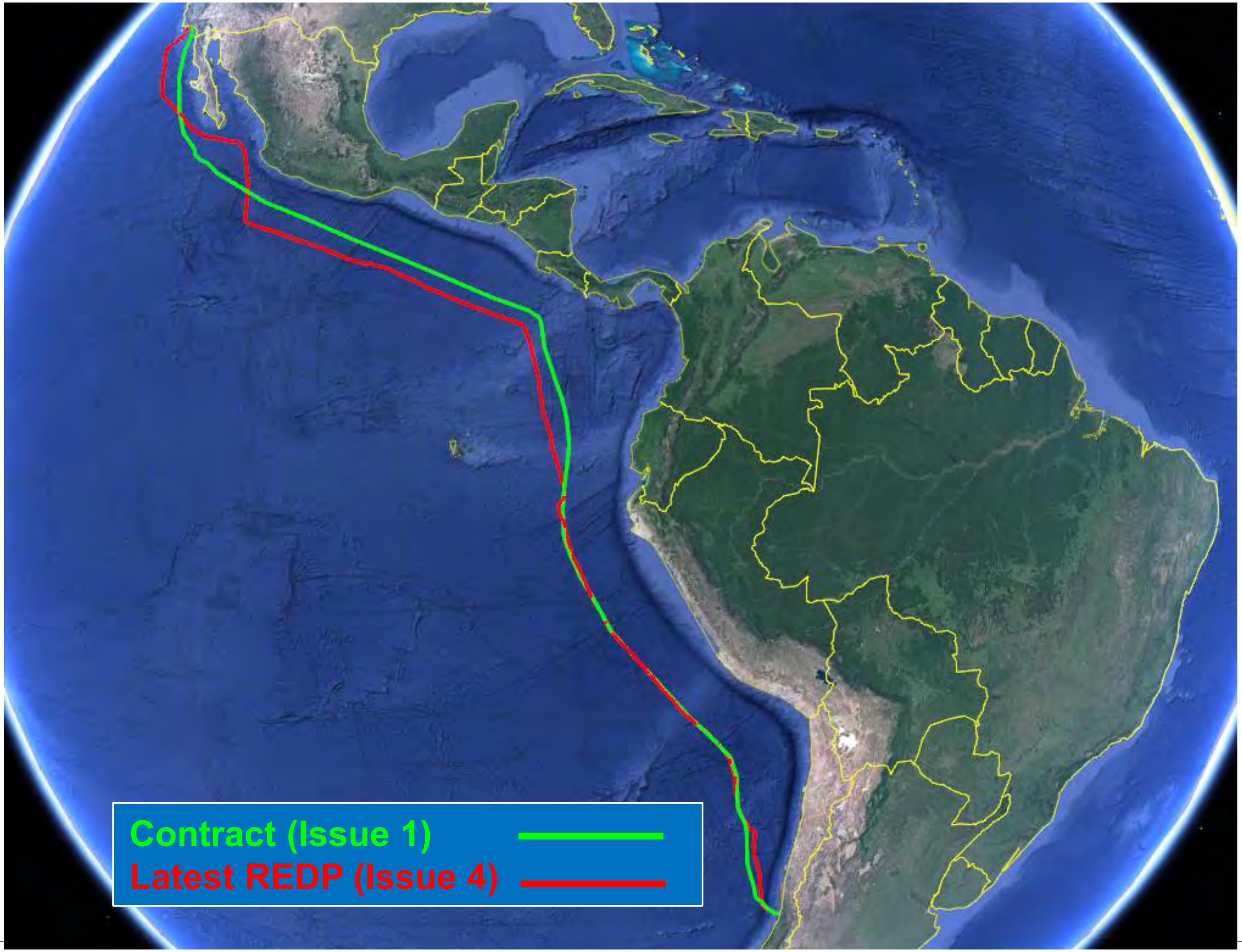
To capture fishing risks, different tools are utilized to spatially and temporally identify fishing profiles to inform system design and ensure maximized cable awareness outreach strategies



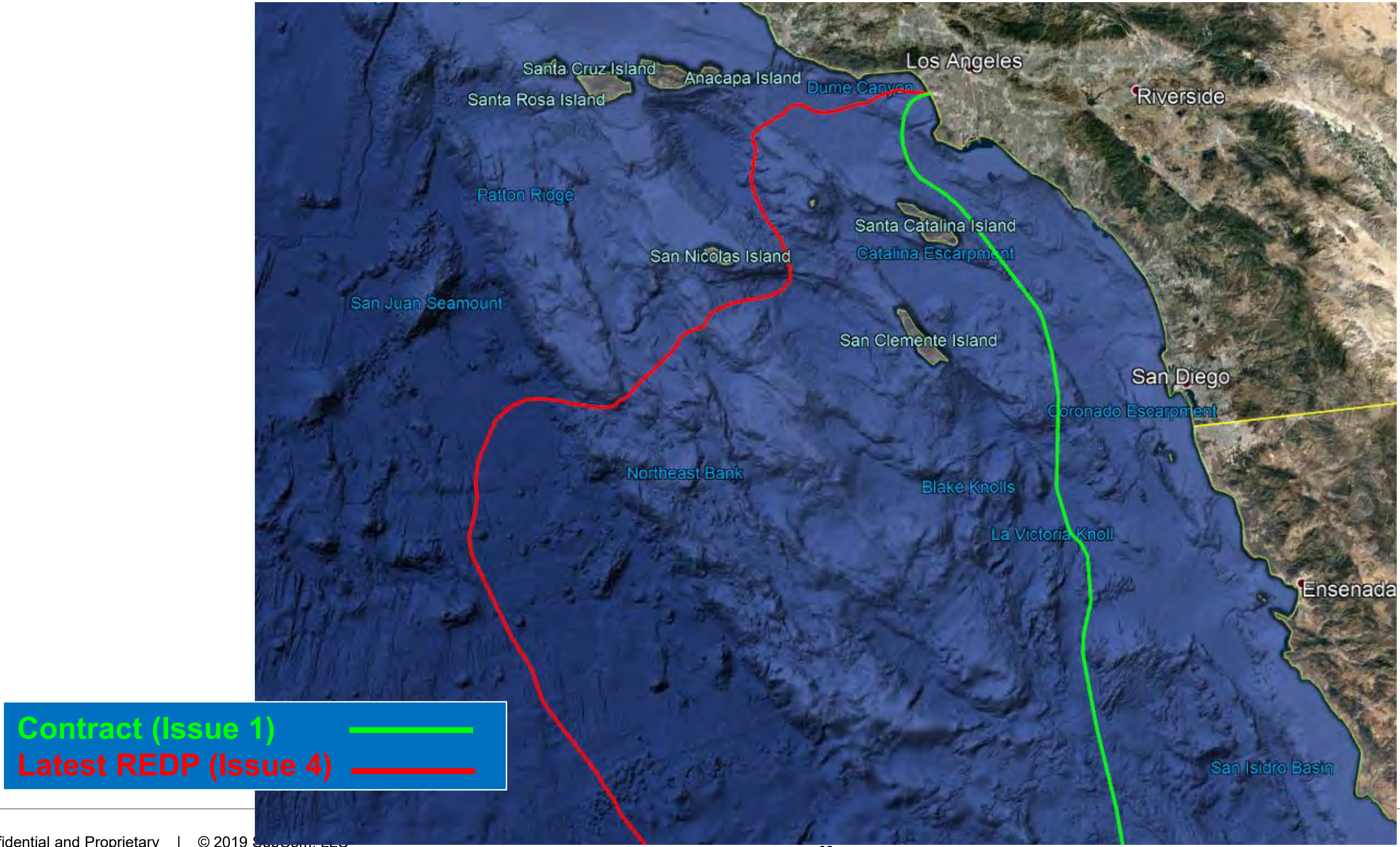
Curie Project Highlights

Curie Cable System – Concept

Curie Cable System – Initial vs Final Routing



Curie Cable System: Segment 1 DTS Changes

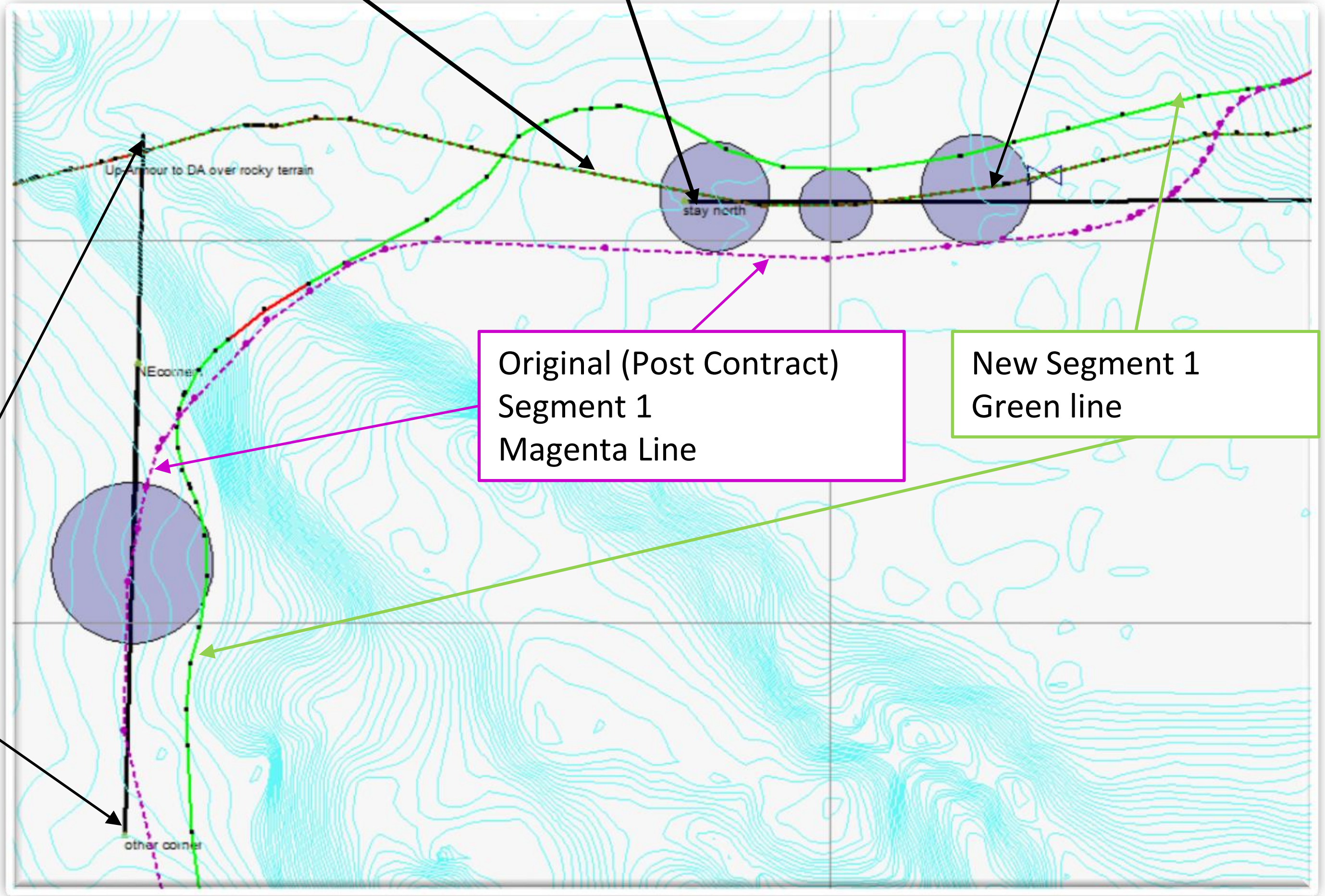


Contract (Issue 1) 🟩

Latest REDP (Issue 4) 🟥

Curie Cable System: Segment 1 DTS Changes

Based on advice from the Navy to avoid an underwater range



Other Cable

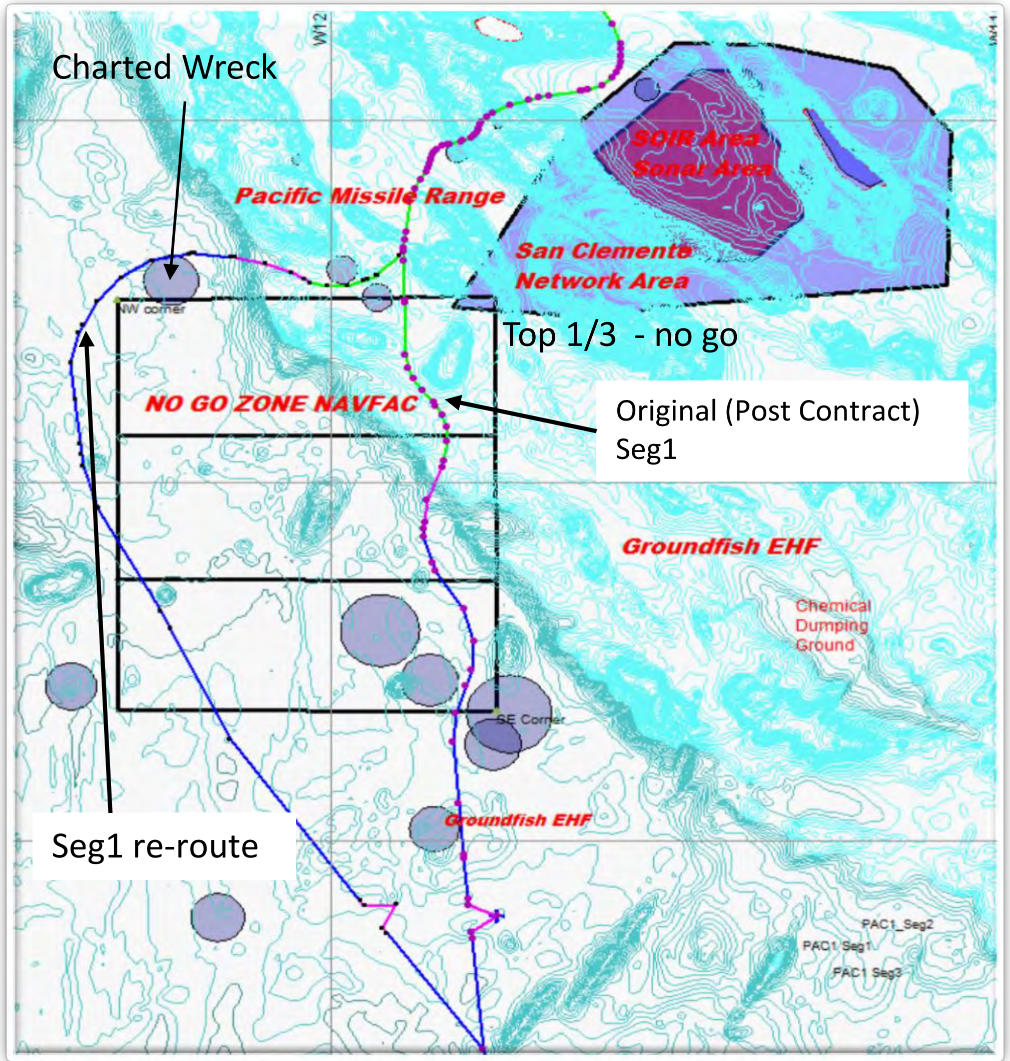
Areas to avoid

Original (Post Contract) Segment 1 Magenta Line

New Segment 1 Green line

Route East of this Line

Curie Cable System: Segment 1 DTS Changes

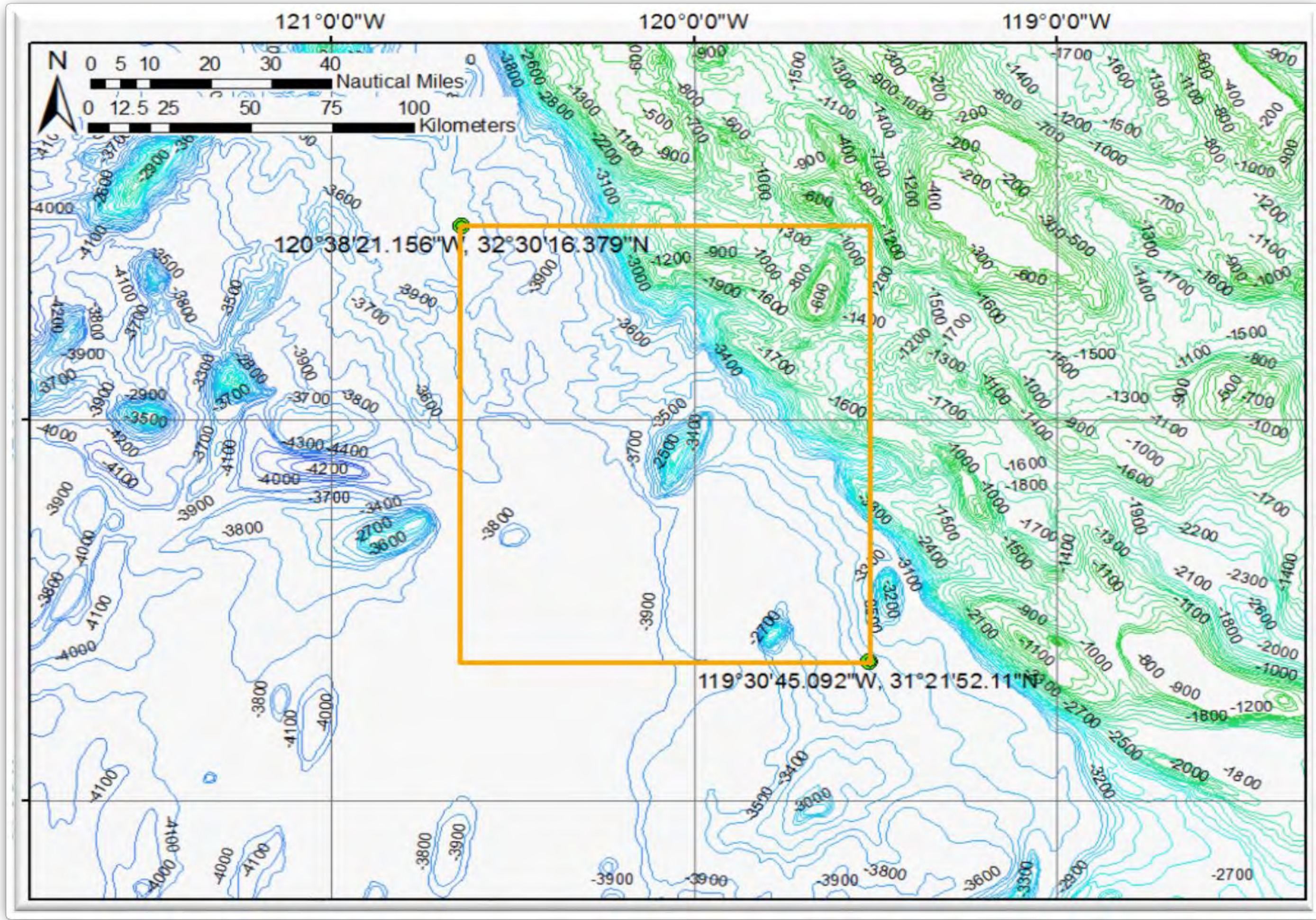


Charted Wreck

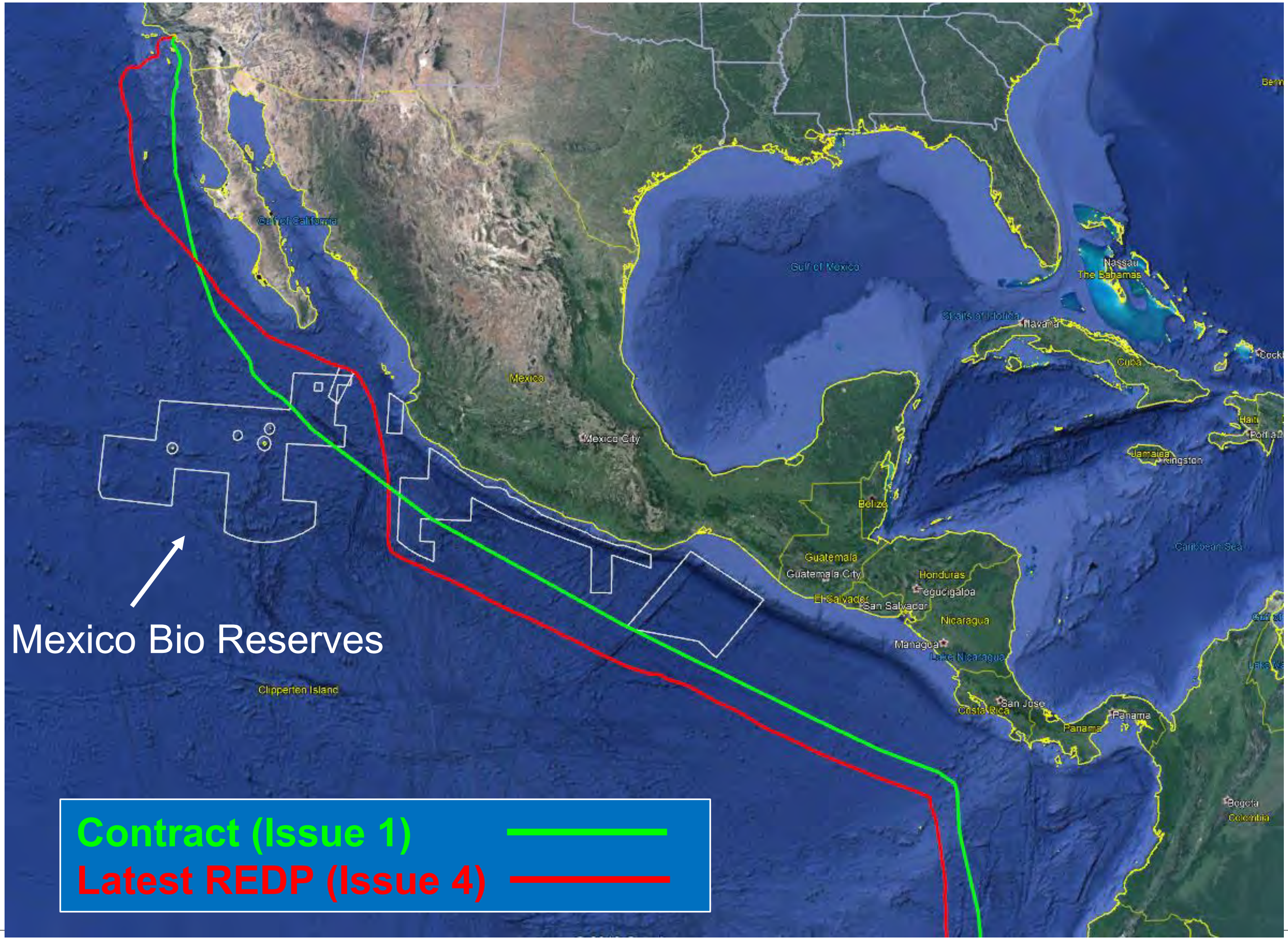
Top 1/3 - no go

Original (Post Contract) Seg1

Seg1 re-route

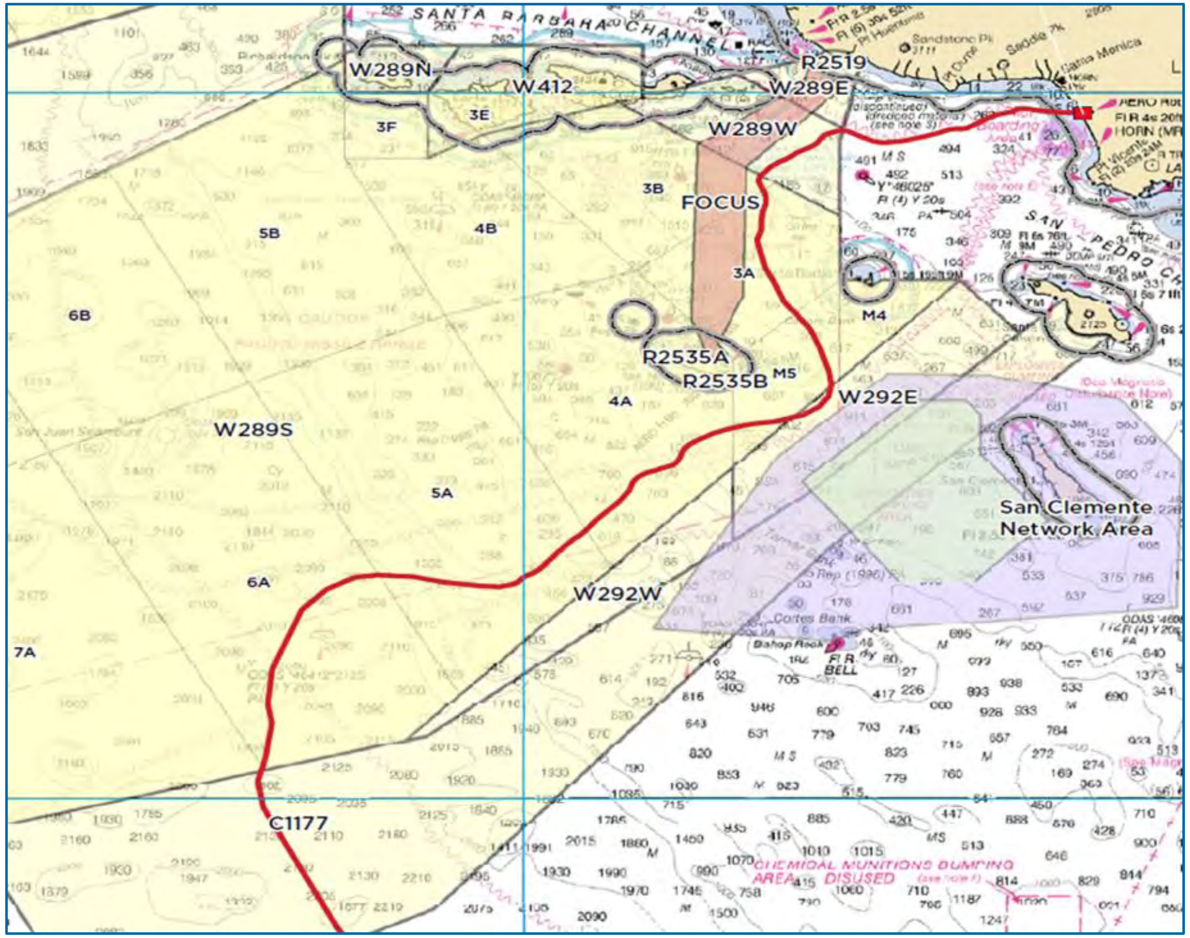


Curie Cable System: Segment 1 Mexico Bio Reserve Changes



Mexico Bio Reserves

CURIE – ROV Survey (Touch Down Monitoring)



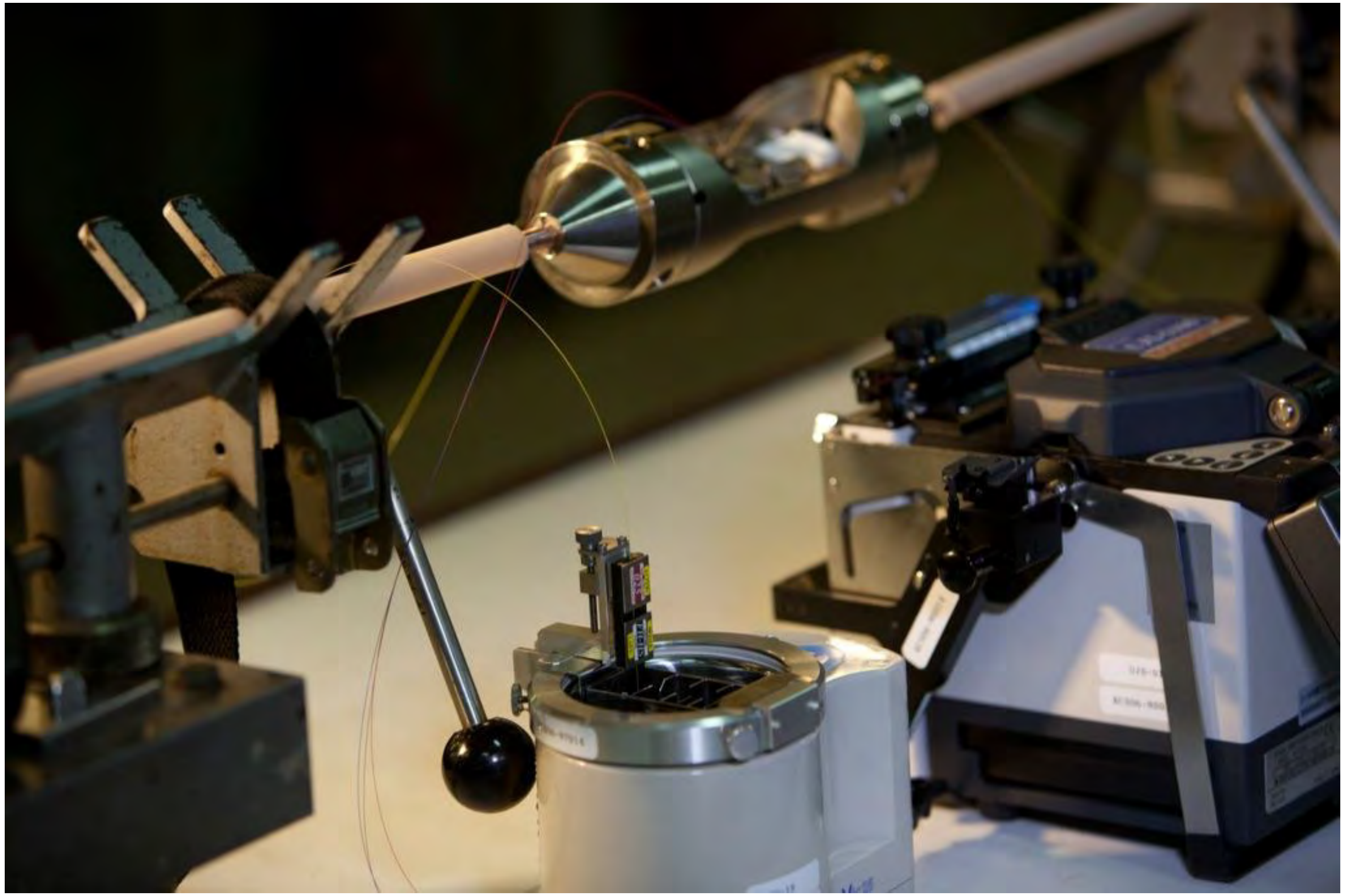
Dummy Ordinance & Gear on route

Cable was recovered and re-laid away from obstructions.

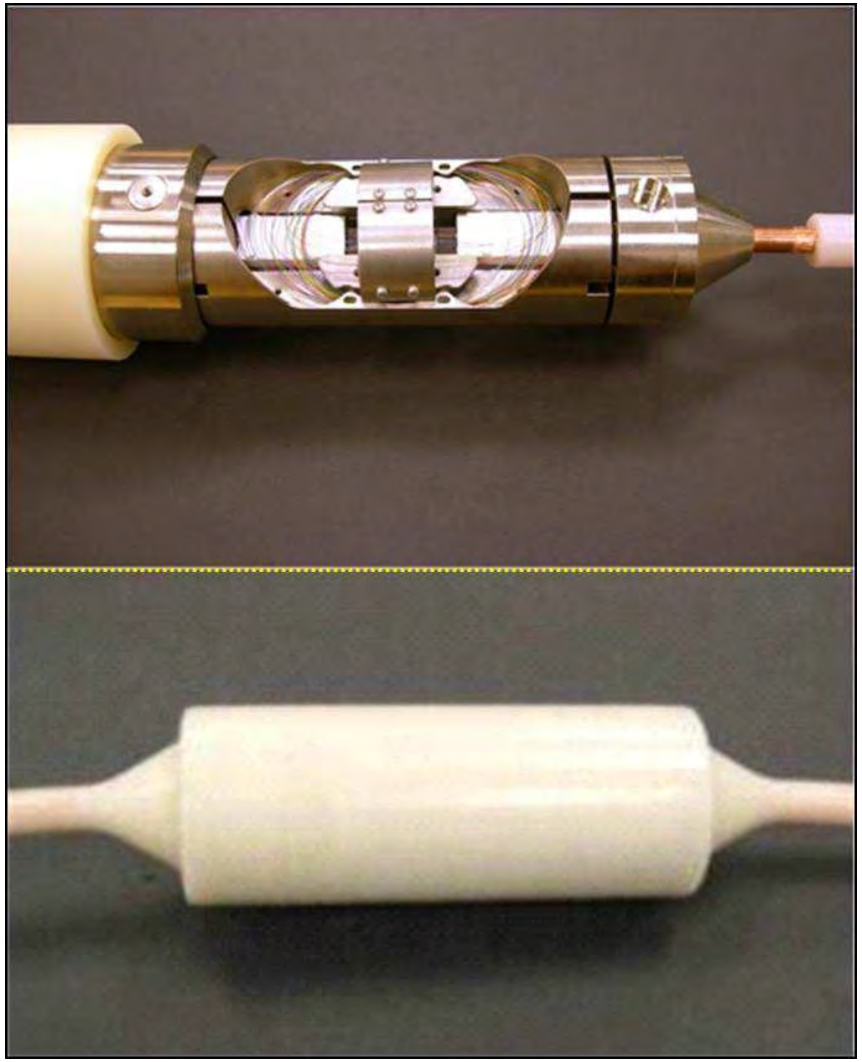
CURIE – Jointing & Testing

20 at sea joints performed including:

- 1 final splice
- 1 Ship to Ship splice
- 3 branching unit installation
- 5 Tank to Tank
- 7 cuts / joints for Gain Tilt measurement testing
- 3 for weather and other operational events



CURIE – Jointing & Testing



CURIE – Landing in Chile

Direct Landing - 350m to shore

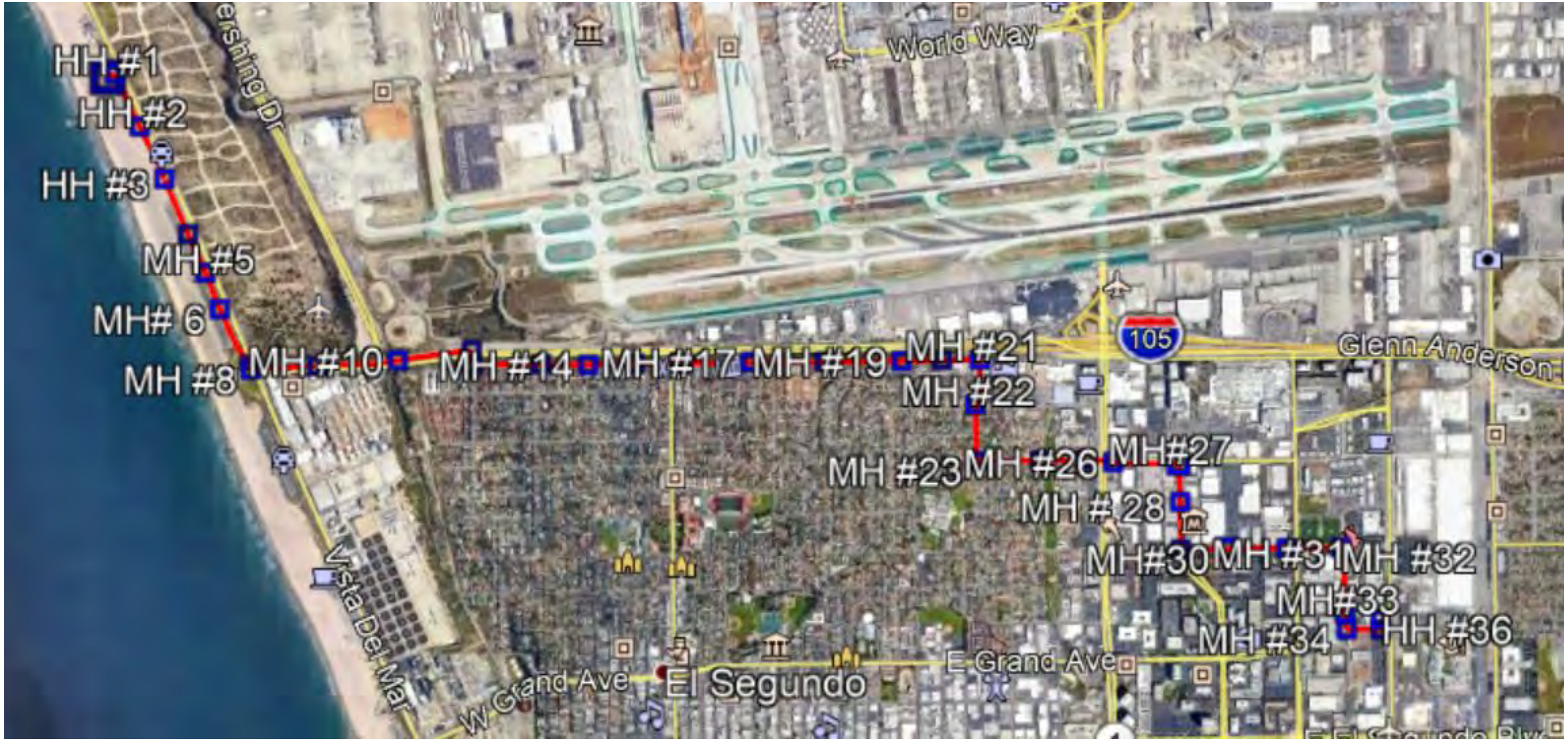
CURIE – Horizontal Directional Drill (California)

Dockweiler Park, Los Angeles, California

- 1,300m bored conduit
- County Harbor and Parks Scheduled events required all work to stop
- Hard and rocky conditions
- Weather delays
- High surf conditions
- Reduced work site

CURIE – Conduit Construction in Los Angeles

- Approx. 25,000ft of conduit installation with Manholes and Handholes



CURIE – Outside Plant (OSP)

City of Los Angeles Conduit Construction

Open Trench Construction

Directional Drilling

Terrestrial Cable Installation

Questions?

Thank You!

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Networks Topologies and Supervisory

Yoshihisa INADA

NEC Corporation

Biography

Mr. Yoshihisa Inada is Senior Manager at Submarine Network Division, NEC Corporation. He is currently the head of SLTE development group. Working in the submarine industry for the past 18 years, he has made significant contributions to the development of submarine cable transmission systems and relevant advanced products, from 10Gb/s to 100Gb/s and beyond.

He received his B.E. and M.E. degrees in Communication engineering from Osaka University in 1996 and 1998, respectively.

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Contents

Contents

Network topology of sub-sea cable

Sub-sea cables play important roles as global infrastructure nowadays.

- 1995 => Sub-sea cable : Satellite = 50:50
- 2014 => Sub-sea cable : Satellite = 99:1

The network topology is to be optimized in following points.

- To maximize the system availability
  - Against the equipment failures (transponder failure, repeater failure..)
  - Against the cable failures (cable cut/damage..)
  - Against the optical path failure (fiber cut/damage..)
  - Against the powering path failure (powering line shunt..)

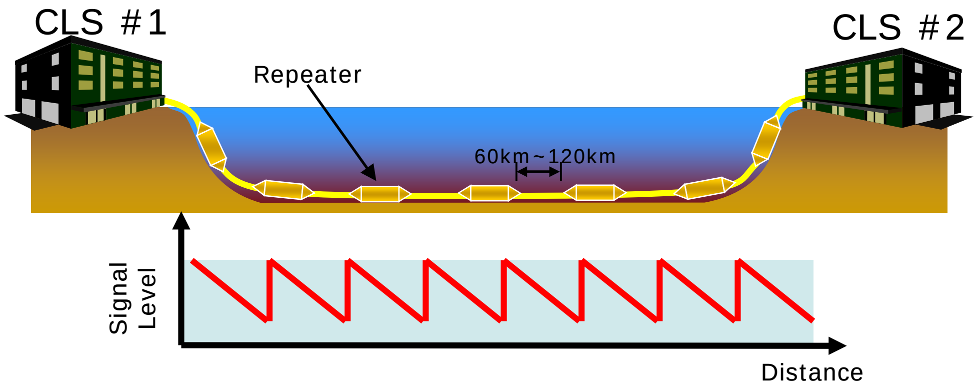
- To maximize the system flexibility
  - For the capacity (capacity expansion as demand)
  - For the connectivity (capacity connection change as demand)

- To justify the cost
  - Equipment cost (repeater, cable, transponder..)
  - Installation cost (vessel, landing..)
  - PJ management cost (Permission, Insurance..)

System Classify

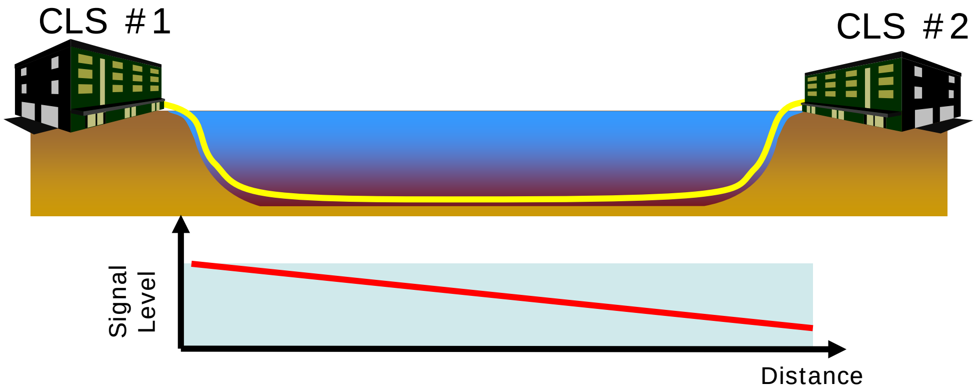
Repeated

- Amplified by chained repeaters
- ~ 15,000km
- Trans oceanic application



Un-Repeated

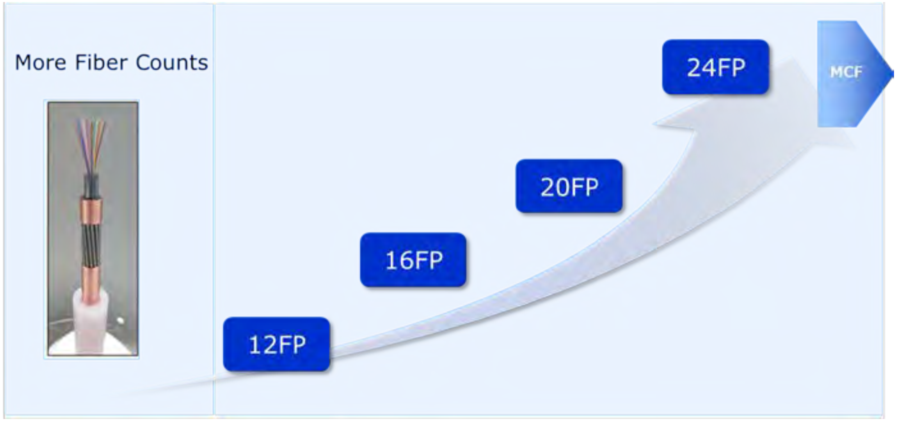
- Non amplified
- < 400km
- Regional application



CLS : Cable Landing Station

Overview of Current Submarine Technologies

Cable



More Fiber Counts

12FP

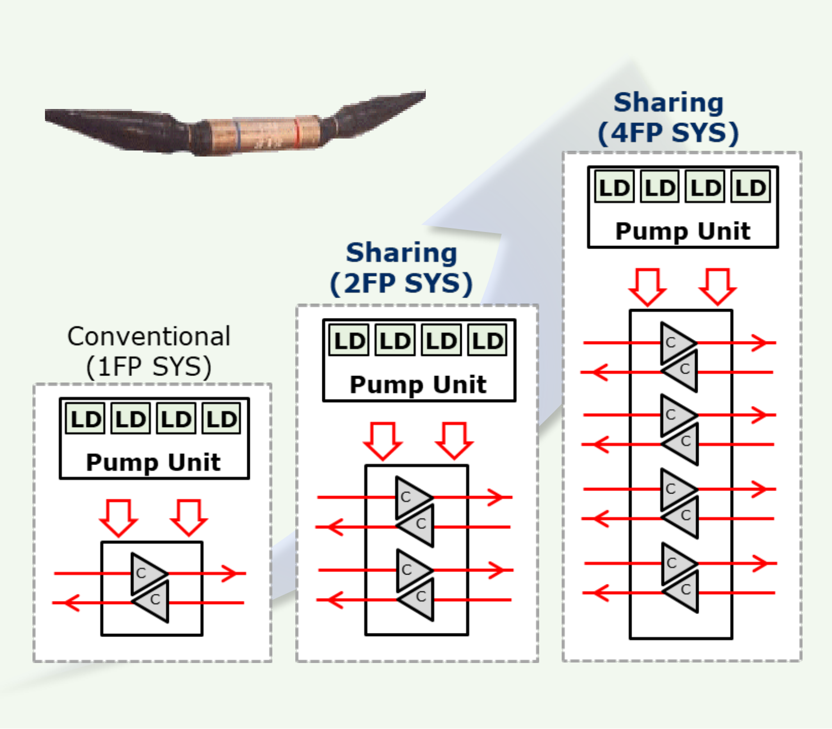
16FP

20FP

24FP

MCF

Repeater



Conventional (1FP SYS)

LD LD LD LD

Pump Unit

Sharing (2FP SYS)

LD LD LD LD

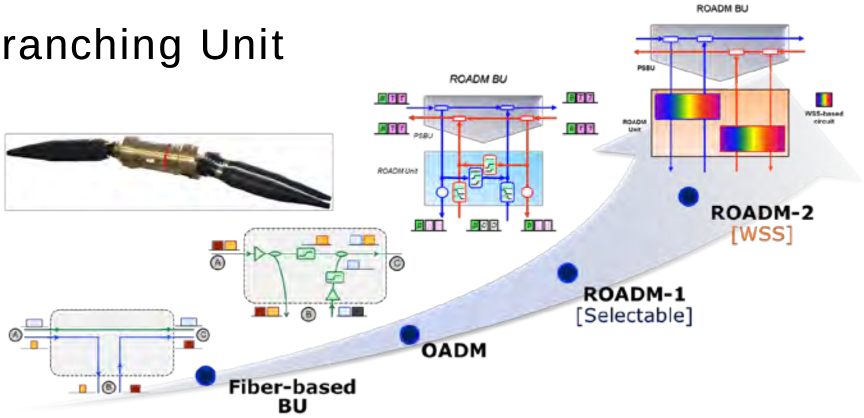
Pump Unit

Sharing (4FP SYS)

LD LD LD LD

Pump Unit

Branching Unit



Fiber-based BU

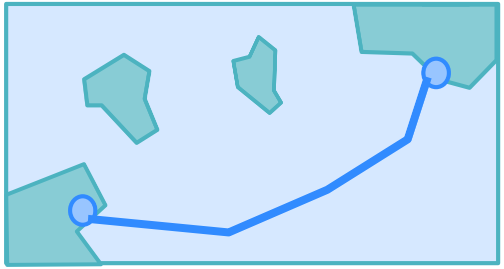
OADM

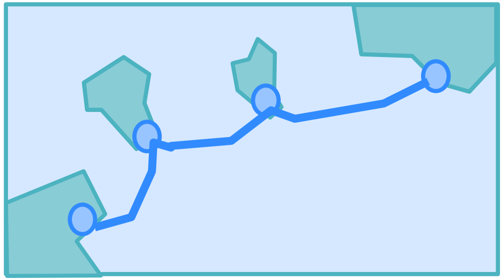
ROADM-1 [Selectable]

ROADM-2 [WSS]

Regional system (Repeatered vs Un-Repeatered)

- In regional systems, both repeatered and un-repeatered are candidates.



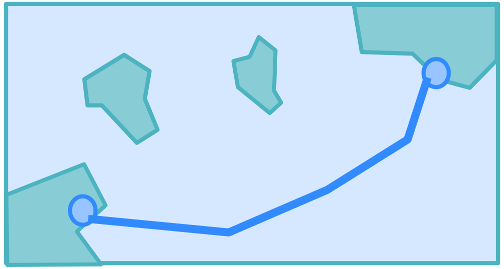


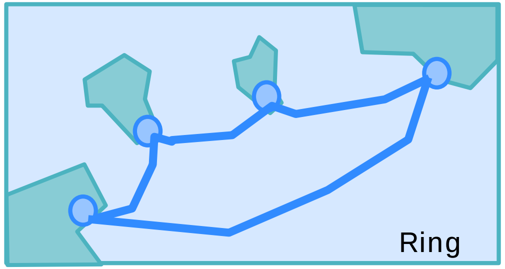
	Repeatered	Un-repeaterd (Festoon)
Connectivity	Point-to-point	Festoon
Capacity (FPs)	8～20 FP	～50 FP
System Cost	Equipment: Repeater, Cable, PFE Installation: Vessel + Landing	Equipment: Cable w/o copper Installation: Vessel + Multiple Landing

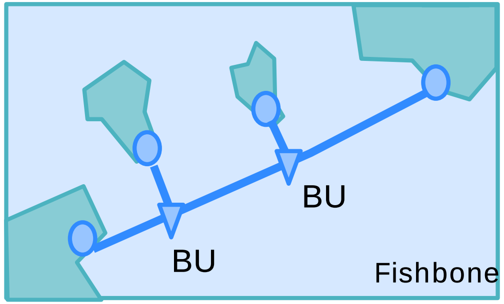
Transoceanic repeatered system

In transoceanic systems, there are several options for the network topology.

- Point-to-point
- Ring
  - Cable redundancy as route diversity
- Fishbone
  - Fiber redundancy as collapsed ring
  - Various optical path (Fixed OADM, Selectable OADM, Reconfigurable OADM)
  - Various powering path (Non-switching, Power switching)



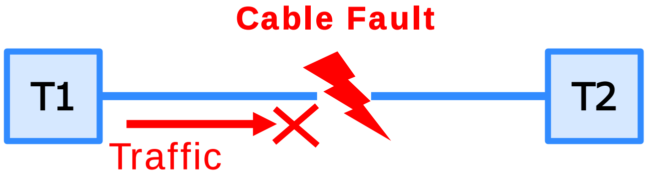




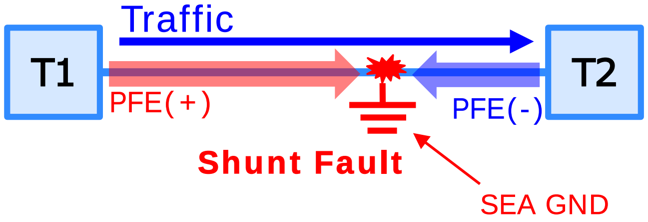
Point-to-point

Point-to-point Configuration

Cable complete fault



Cable shunt fault



System availability

- Cable complete fault impacts on all the traffics
- Cable shunt fault does not impact thanks to double end feeding.

Flexibility

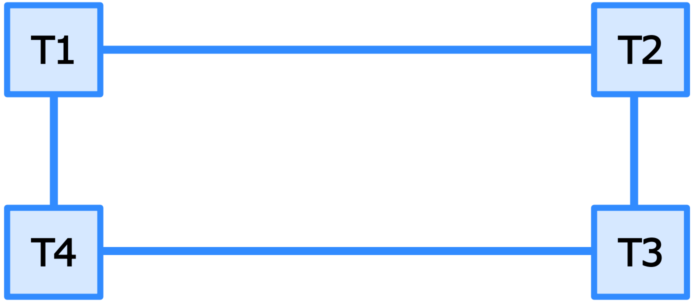
- Capacity is fixed at planning stage
- Connectivity is fixed at planning stage

System cost

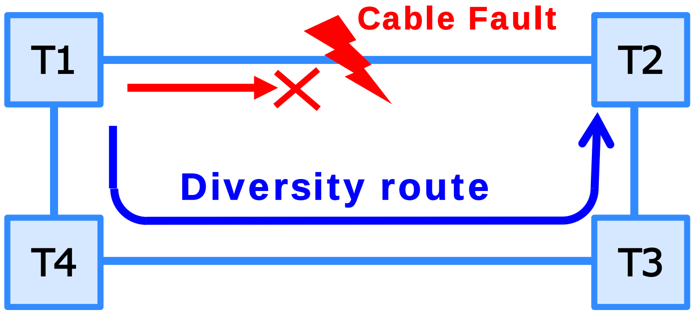
- Baseline of submarine cable

Ring

Ring Configuration



Robustness to Cable Fault



System Availability

- Cable complete fault dose not impact thanks to route diversity

Flexibility

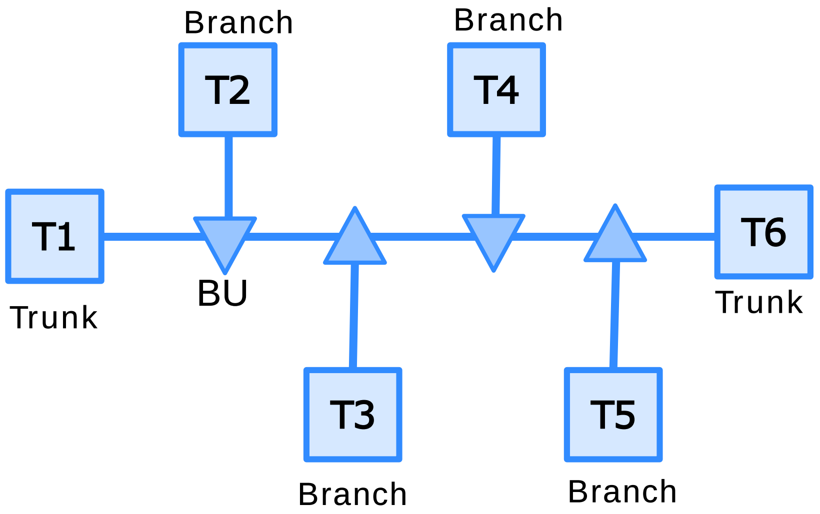
- Capacity is fixed at planning stage
- Connectivity is fixed at planning stage
- Both flexibilities can be improved by dry ROADM in station.

System cost

- In general, double of point-to-point

Fishbone

Fishbone Configuration



BU: Branching Unit

System Availability

- Cable complete fault dose not impact on the traffics in other segment cables
- Cable shunt fault dose not impact thanks to double end feeding and power switching BU.

Flexibility

- Capacity can be changed as demand in case of ROADM BU
- Connectivity can be changed as demand in case of ROADM BU

System cost

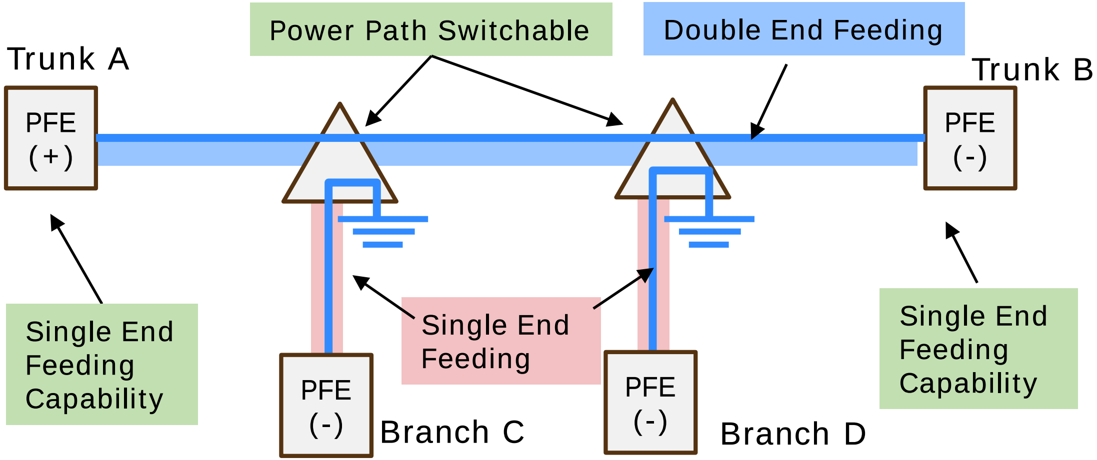
- In general, lower than ring configuration

Widely introduced in the latest submarine network

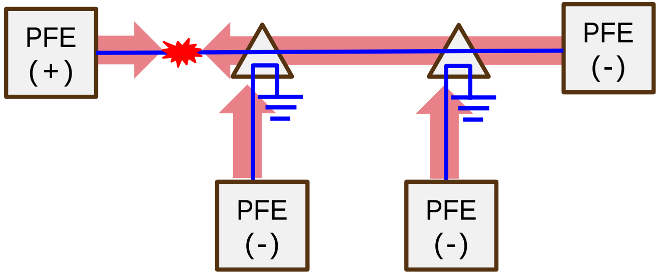
Powering Topology (Availability)

Features:

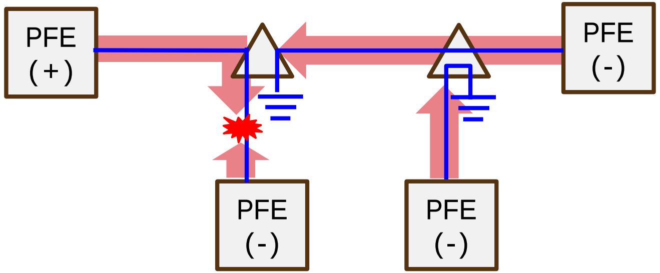
- Trunk Double End Feeding with Single End Feeding capability
- Branch : Full Equipment Redundancy
- BU : Power Path Re-configurable



Shunt fault in Trunk → Powering can be kept



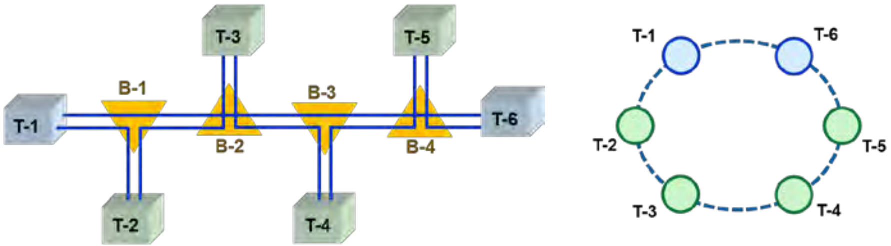
Shunt fault in Branch → Powering pass is reconfigured Powering can be kept



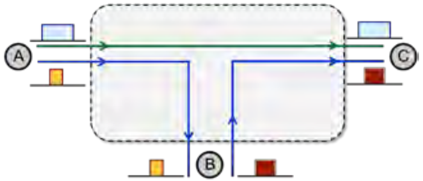
Traffic Topology

Fiber-based Traffic Topology

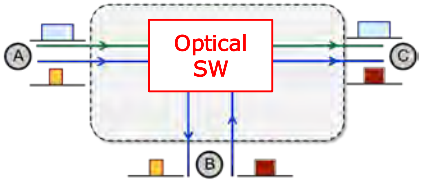
Architecture



Fixed BU

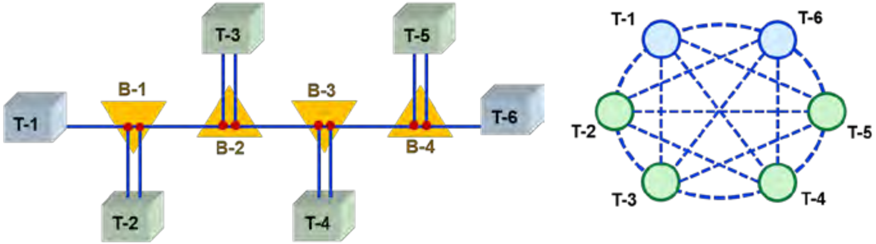


OPSW BU

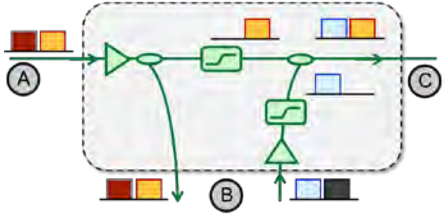


Wavelength-based Traffic Topology

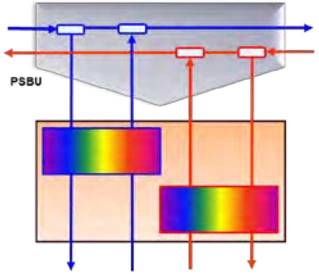
Architecture



Fixed OADM BU



ROADM BU



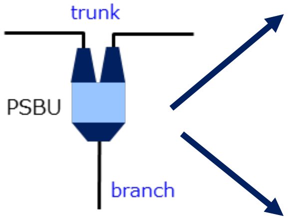
Technology - Fiber-based Traffic Topology

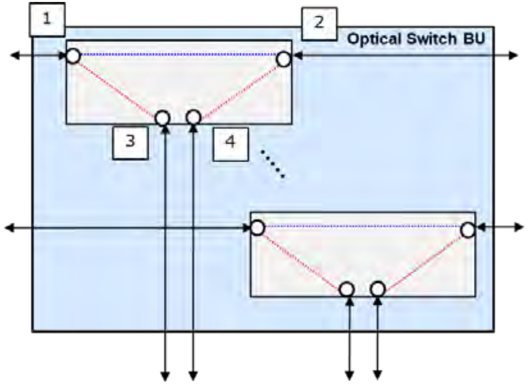
1 x 2 Fiber Pair Switch

- One (1) trunk fiber pair switched to two (2) branch FPs
- Switching State
  - State 1: 1-2
  - State 2: 1-3 & 2-4

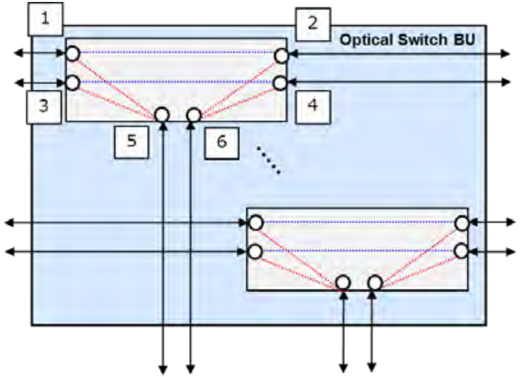
2 x 2 Fiber Pair Switch

- Two (2) trunk fiber pair switched to two (2) branch FPs
- Switching State
  - State1: 1-2, 3-4
  - State2: 1-2, 3-5 & 4-6
  - State3: 3-4, 1-5 & 2-6



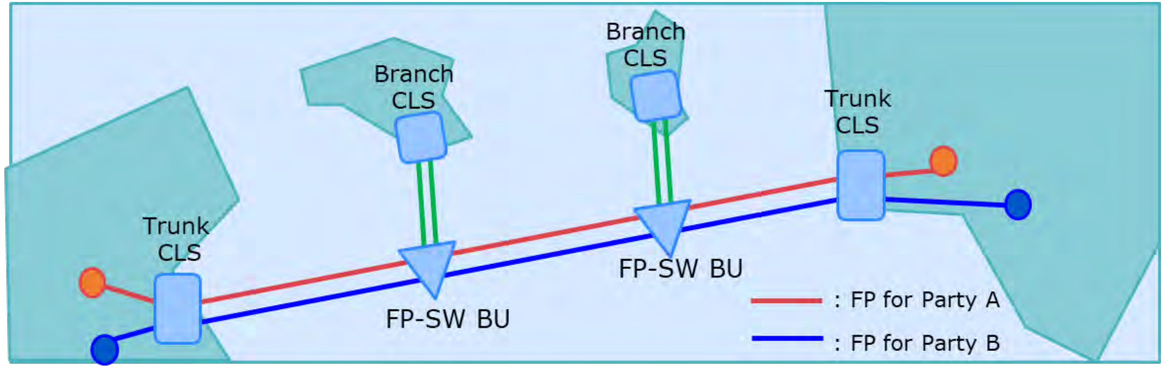


1 x 2 switch



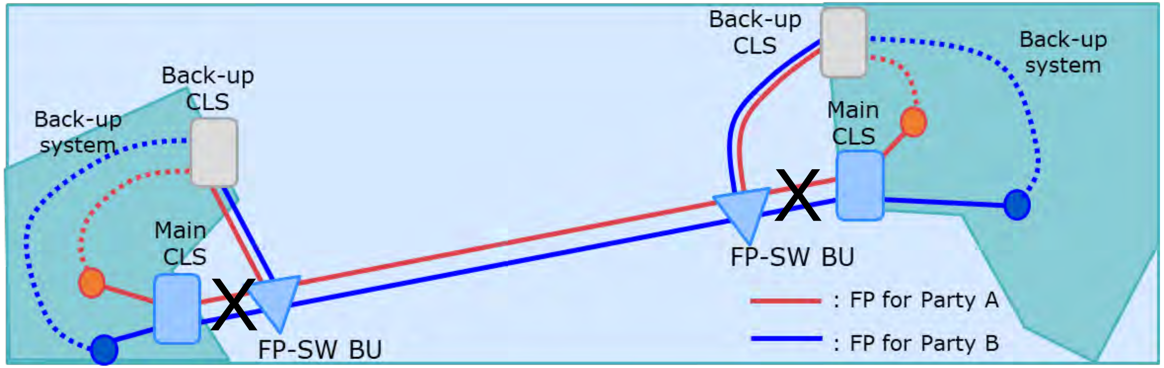
2 x 2 switch

FP Switching Network in SDM -Examples



Trunk-Branch FP Sharing

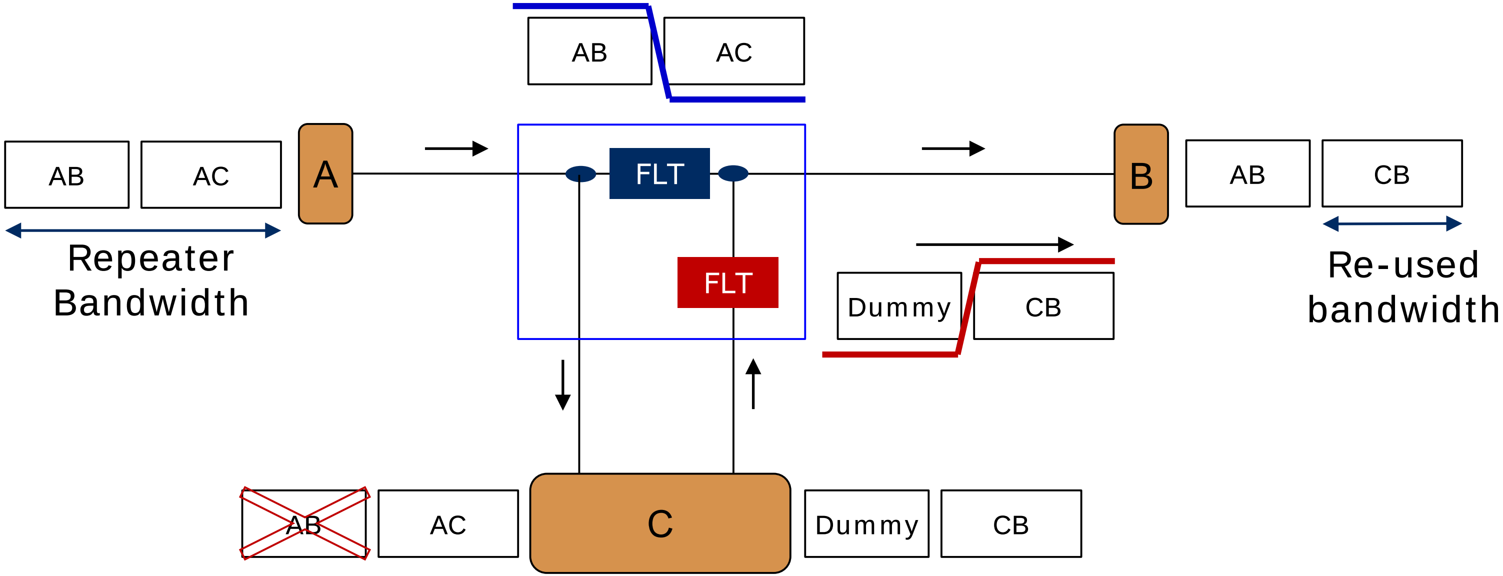
- ✓ Party A / B share branch FP
- ✓ Trunk - Branch FP Routing as needed



Shore-end Protection Network

- ✓ Cable fault at shore end to be restored by FP Switching

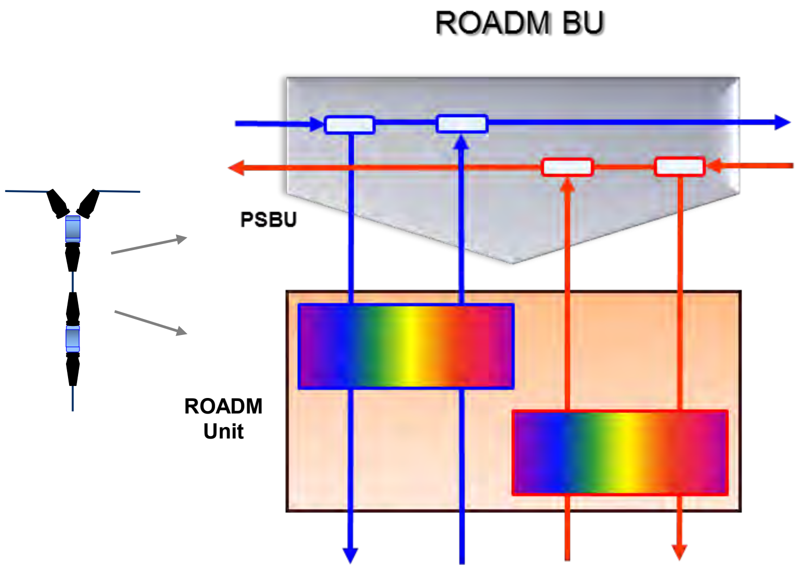
Principle of OADM networks: Wavelength reuse



Equivalent circuits for opposite direction

Technology - Re-configurable OADM (RODAM)

Apply WSS for spectrum re-configuration



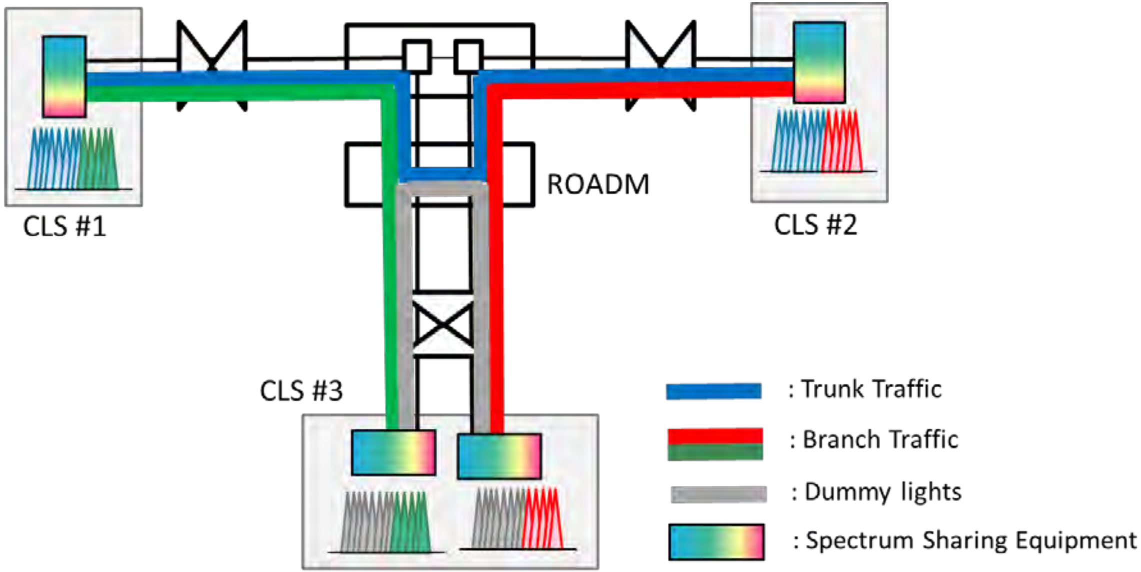
- Unlimited add/drop ratio re-configurability
- Tunable attenuation adjustment
- Reconfiguration and adjustment control by remote command from terminal station

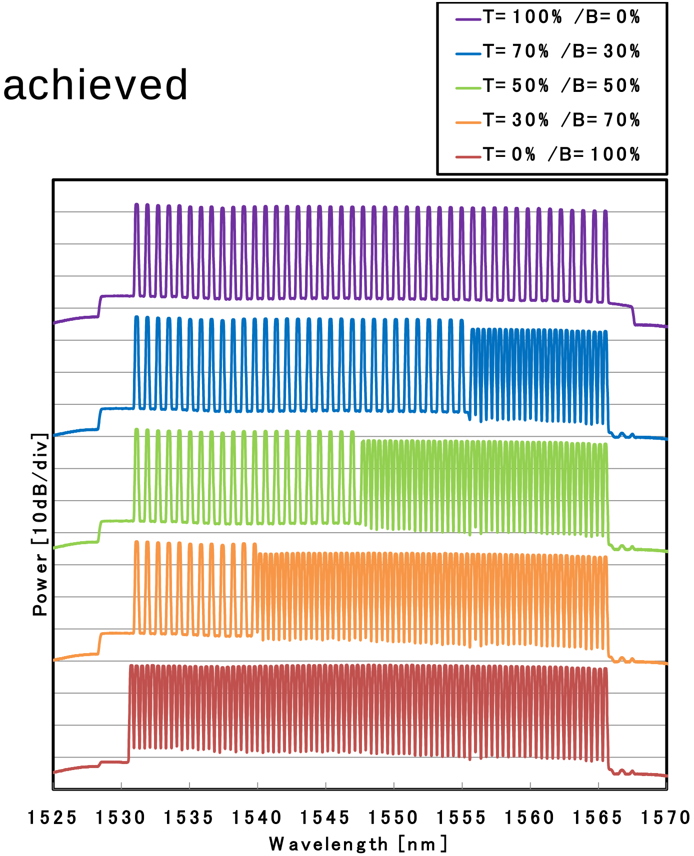
WSS : Wavelength Selective Switching

Technology - Re-configurable OADM (RODAM)

Switching flexibility of add/drop ratio

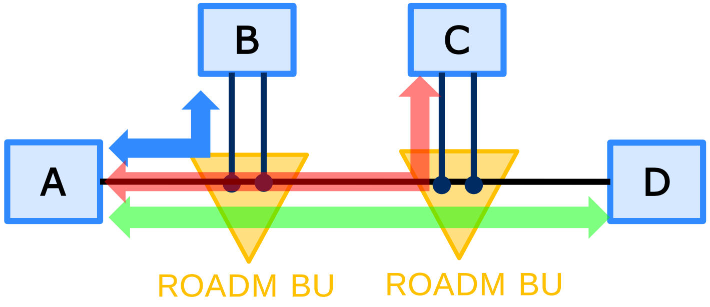
- Flexible switching with any add/drop ratio can be achieved

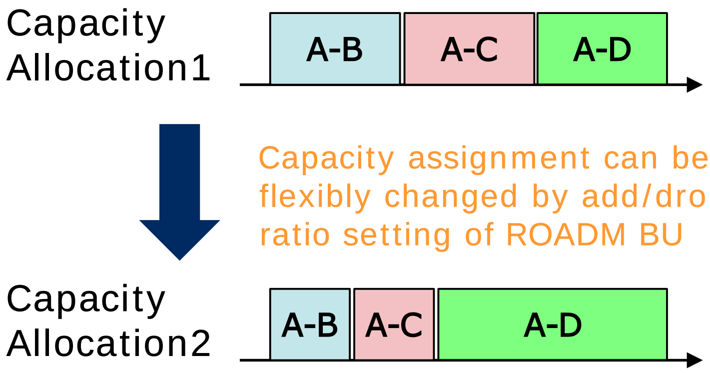




Optical Path(Flexibility)

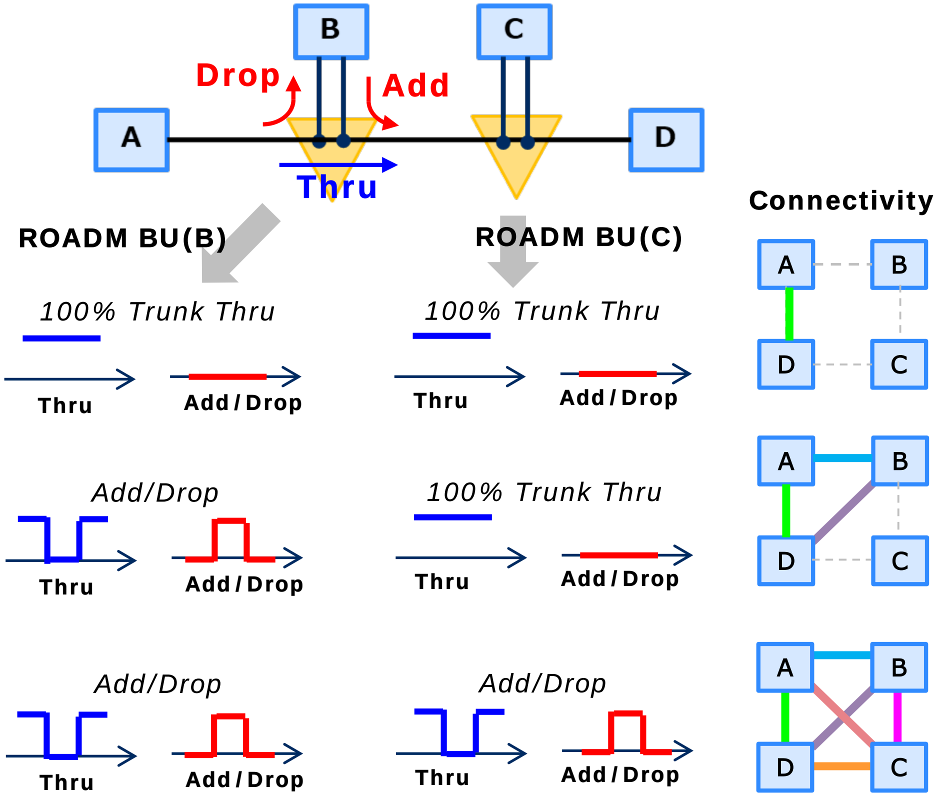
Capacity Allocation





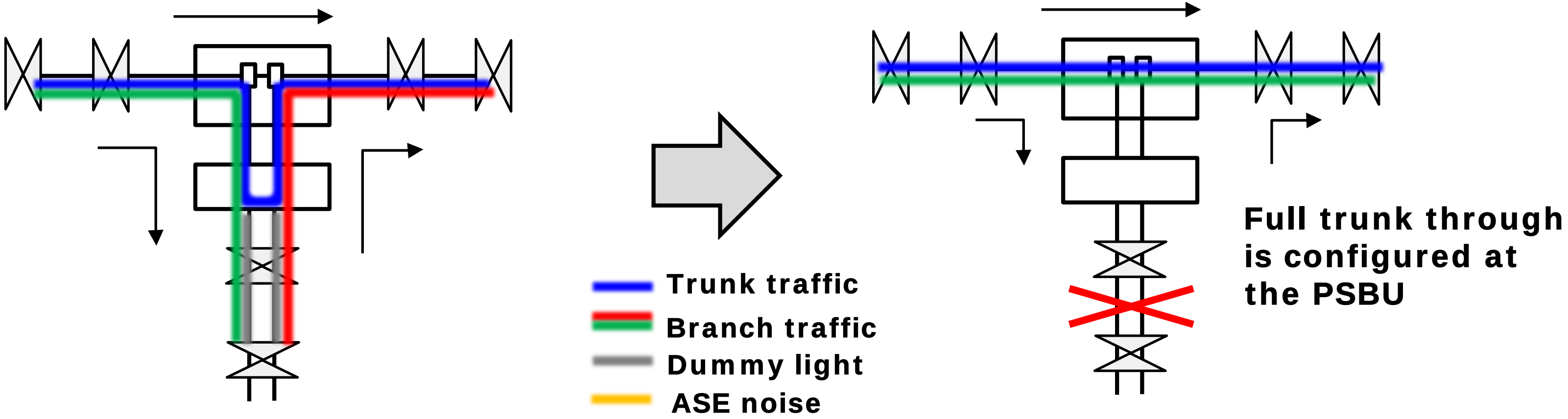
Capacity assignment can be flexibly changed by add/drop ratio setting of ROADM BU

Connectivity



Optical path reconfigurations under Cable Faults

Branch fault



Trunk traffic

Branch traffic

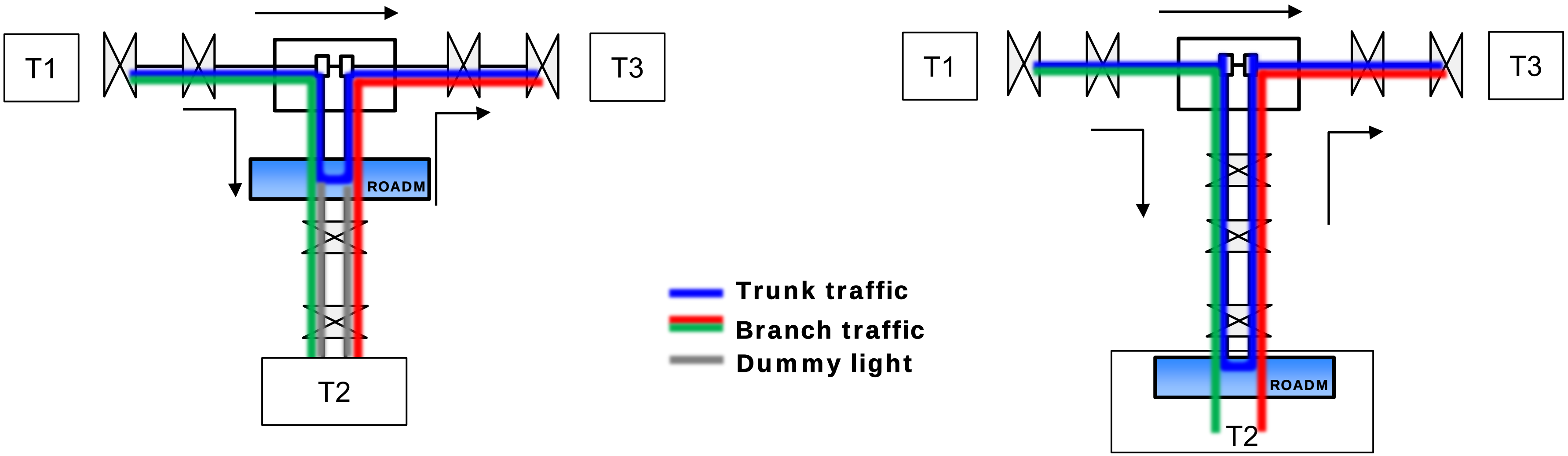
Dummy light

ASE noise

Full trunk through is configured at the PSBU

- Optical switches in the BU react automatically against branch faults
- General criteria is to maximize trunk traffic availability

Connectivity options: Wet ROADM vs Dry ROADM



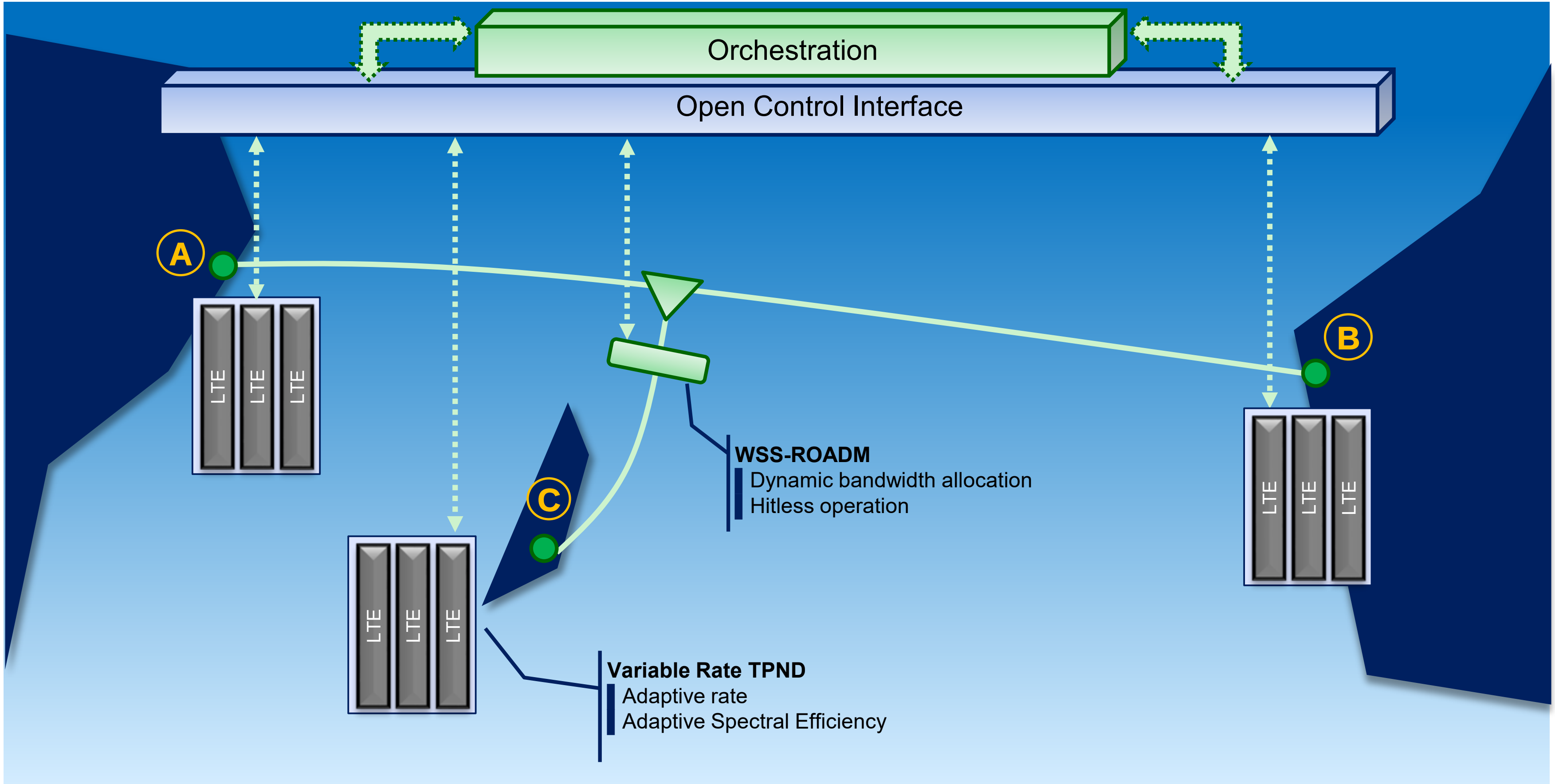
Wet ROADM

- Lowest Latency T1-T3
- Large OSNR T1-T3
- Trunk traffic privacy

Dry ROADM

- Lower equipment, installation and maintenance cost
- Latency and OSNR penalty T1-T3

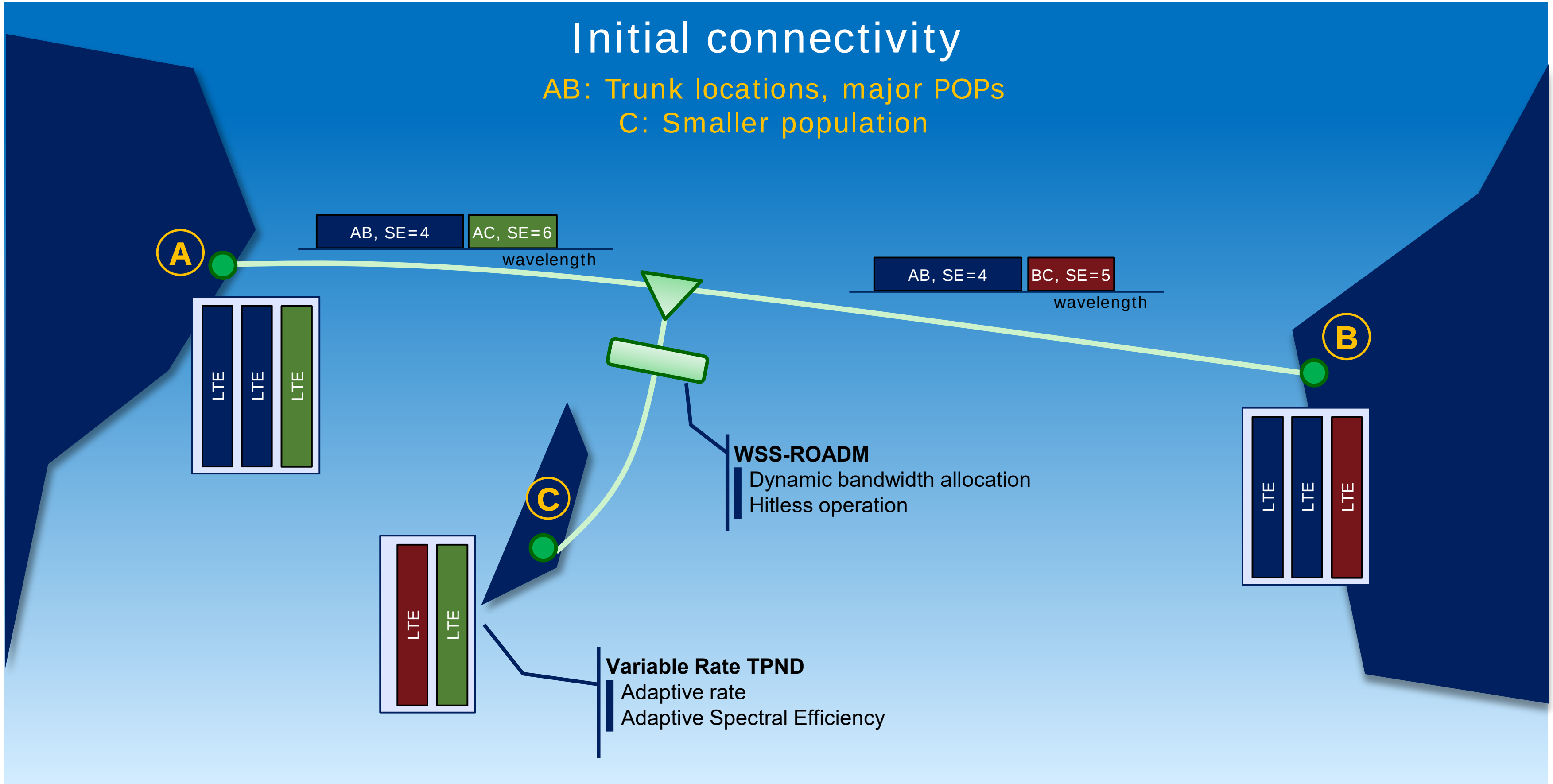
Dynamic submarine networks



WSS-ROADM
- Dynamic bandwidth allocation
- Hitless operation

Variable Rate TPND
- Adaptive rate
- Adaptive Spectral Efficiency

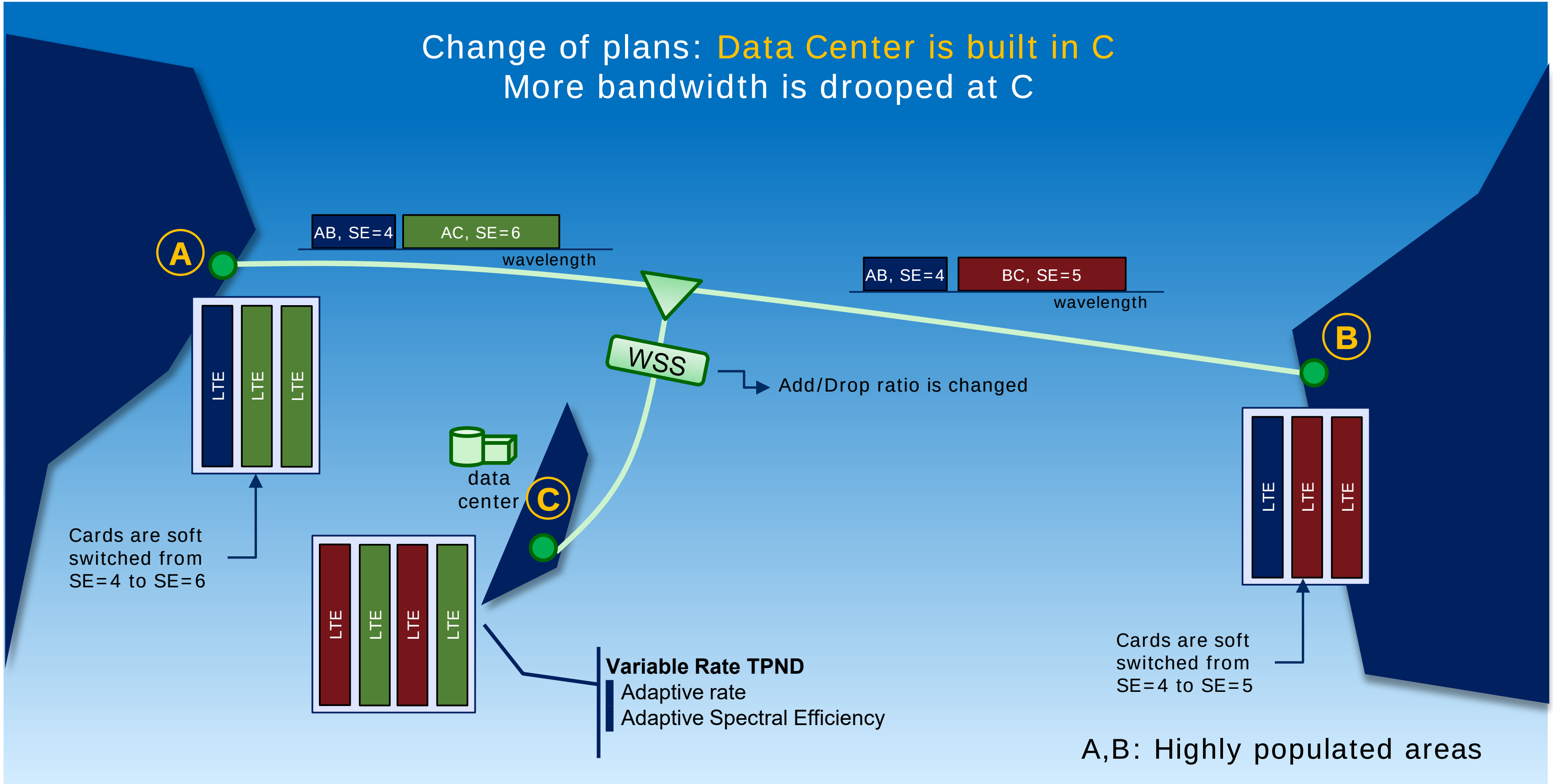
Dynamic/Adaptive submarine networks



WSS-ROADM
- Dynamic bandwidth allocation
- Hitless operation

Variable Rate TPND
- Adaptive rate
- Adaptive Spectral Efficiency

Dynamic/Adaptive submarine networks



Change of plans: Data Center is built in C
More bandwidth is drooped at C

Add/Drop ratio is changed

Cards are soft switched from SE=4 to SE=6

Cards are soft switched from SE=4 to SE=5

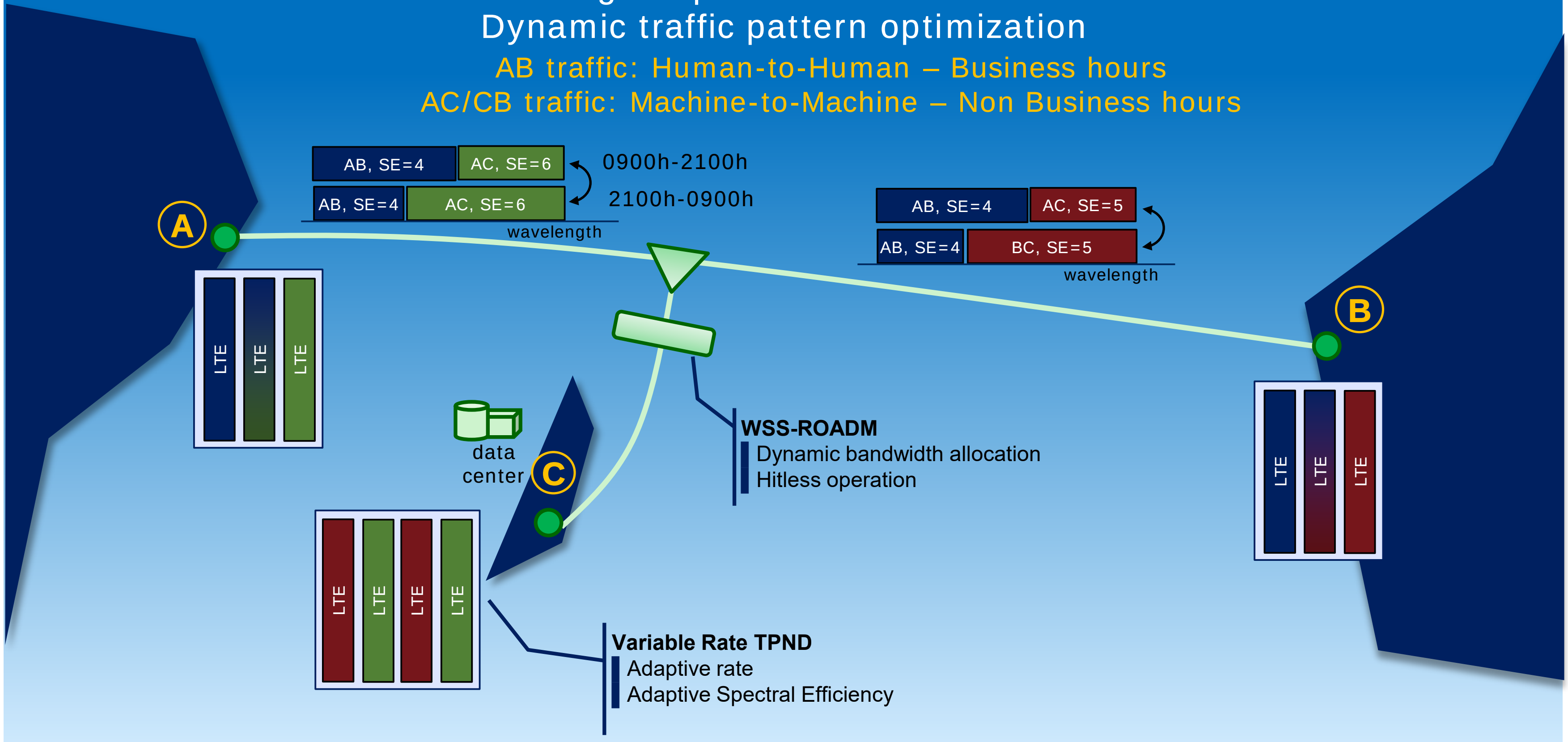
Variable Rate TPND
- Adaptive rate
- Adaptive Spectral Efficiency

A,B: Highly populated areas

Dynamic/Adaptive submarine networks

Change of plans: DC is built in C
Dynamic traffic pattern optimization

AB traffic: Human-to-Human – Business hours
AC/CB traffic: Machine-to-Machine – Non Business hours

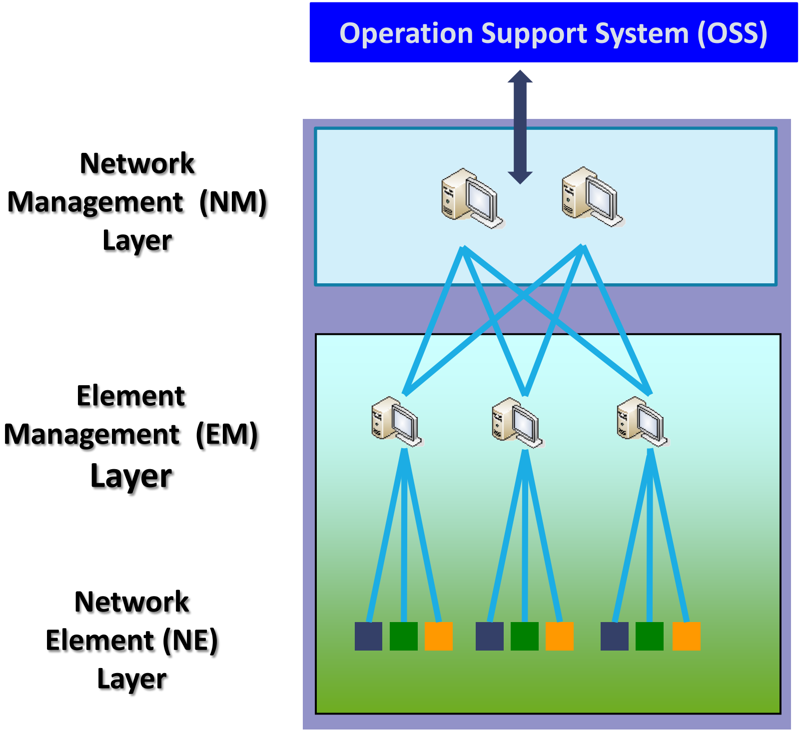


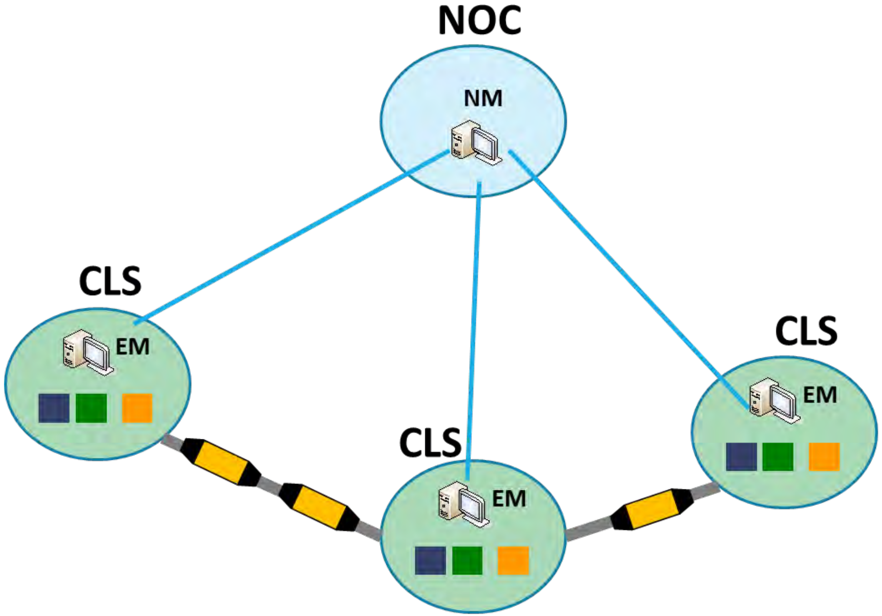
WSS-ROADM
- Dynamic bandwidth allocation
- Hitless operation

Variable Rate TPND
- Adaptive rate
- Adaptive Spectral Efficiency

Contents

Management Overview





NOC : Network Operation Center
CLS : Cable Landing Station

Network Element Layer

Equipment composed in submarine network

- Submarine Line Terminal Equipment (SLTE)
- Power Feeding Equipment (PFE)
- **Wet Plant (Repeaters, Cable, BU)**
- Other transmission equipment…

SLTE

PFE

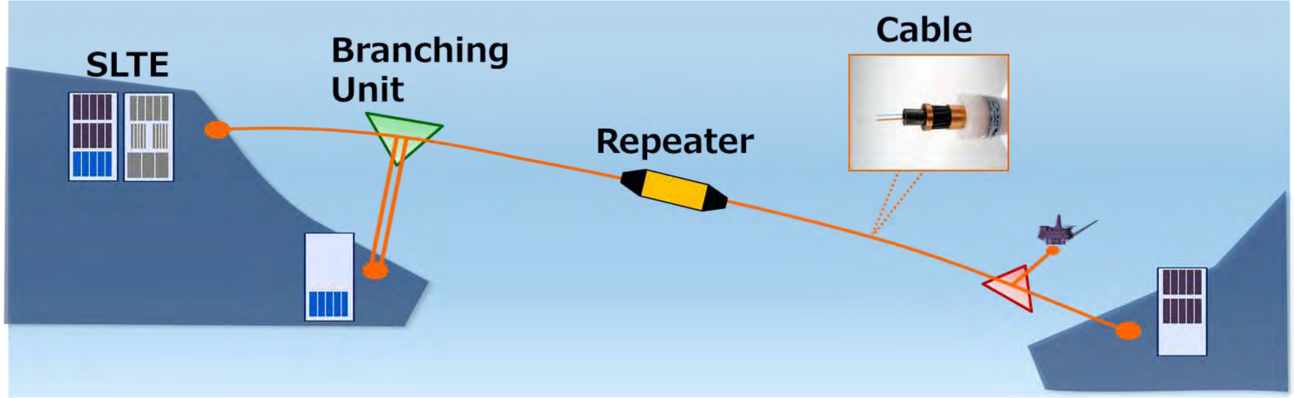
Submarine Repeater

Wet-plant Supervisory is unique function compared to terrestrial network

Wet-plant Supervisory and Control

Wet-plant equipment is supervised and controlled remotely from SLTE

- Submarine Repeater
- Cable, Fiber
- Branching Unit (Power Switching, Optical Switching, ROADM)



Repeater

- Pin, Pout, Gain,
- Pump LD Fail
- Gain Tilt

Cable/Fiber

- Fiber Loss Increase
- Fiber Cut
- Open/Shunt Fault

Branching Unit

- Health of active components (AMP, WSS)
- WSS setting of ROADM
- Power switching setting

Supervisory method

Command / Response method

- SV LSI in submarine repeater
- Direct measurement for each component operating condition
- Two transmission method
  - Dedicated WL
  - Superimpose to WDM traffic signal

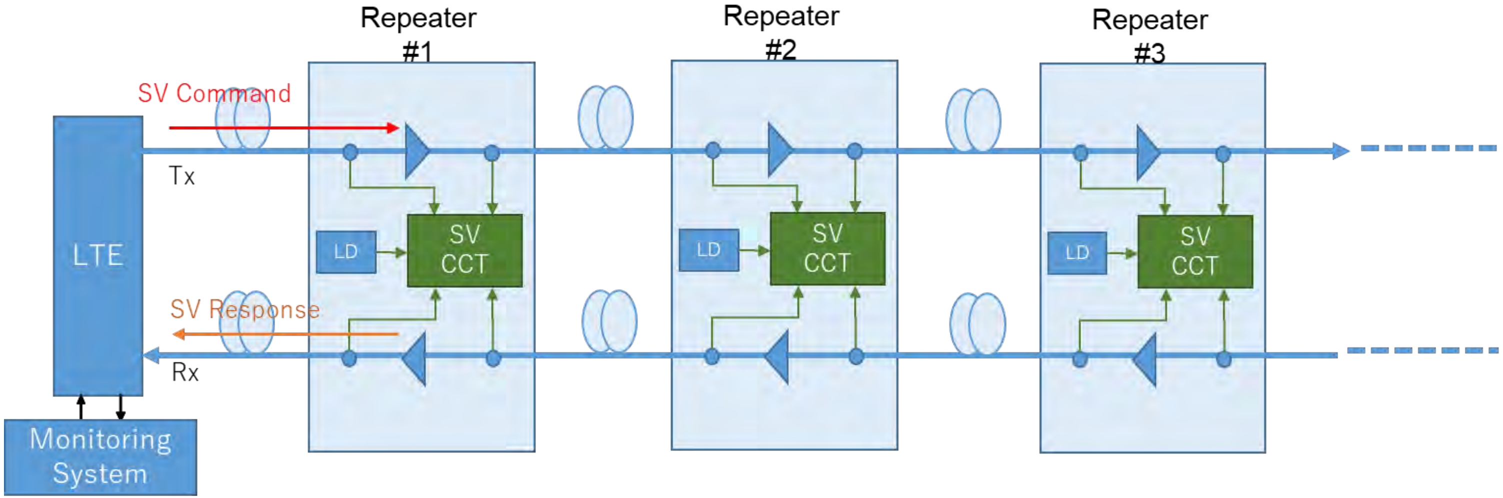
Optical loop-back method

- Passive optical circuit in repeater
- Dedicated wavelength assignment
- Advanced signature analysis provides automatic fault localization and fault mode analysis function

Supervisory method (1): Command & Response

Active Method (Command & Response)

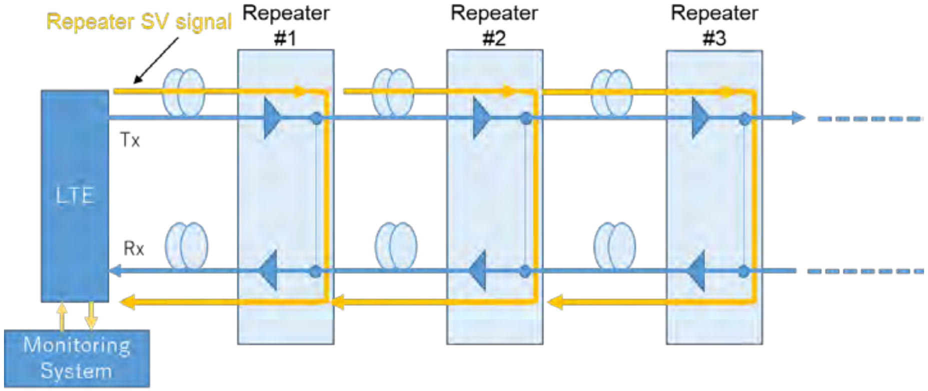
- A command from LTE invoke a response or reply from repeater.
  - Each repeater has Electric SV circuit and unique address.
- Output power, Input Power and LD current are read by SV circuit
- The communication method used is typically Amplitude Shift Keying (“ASK”), which modulation is applied to the overall optical output of SLTE or repeater



Supervisory method (2): Optical loop-back

Passive Method (All optical)

- SV signal (allocated in out band of traffic signal wavelengths) is launched from LTE (Tx).
- Dedicated SV signal is returned through loop-back circuit in each repeater
- Returned SV signal is measured at LTE (Rx)
  - Roundtrip time : identify repeater location
  - Roundtrip optical level : measure Round trip gain
- Measured round trip gain is analyzed
  - Repeater power reduction
  - Span cable loss increase
  - Fiber cut

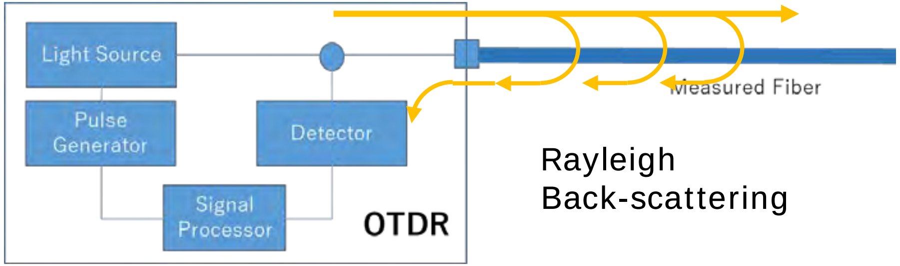


OTDR (Optical Time Domain Reflection)

Method

- Measure loopback signal or back-scattered light on time domain
  - ✓Rayleigh back-scattered light
  - ✓Fresnel reflection
  - ✓Loopback signal through submarine repeater loopback circuit

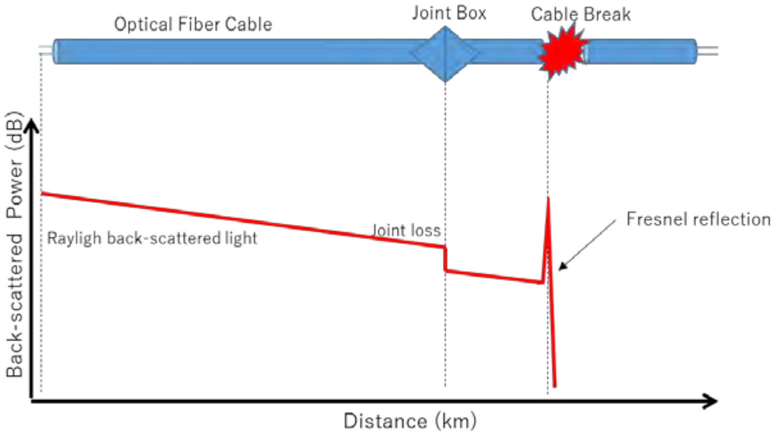
Typical OTDR Configuration



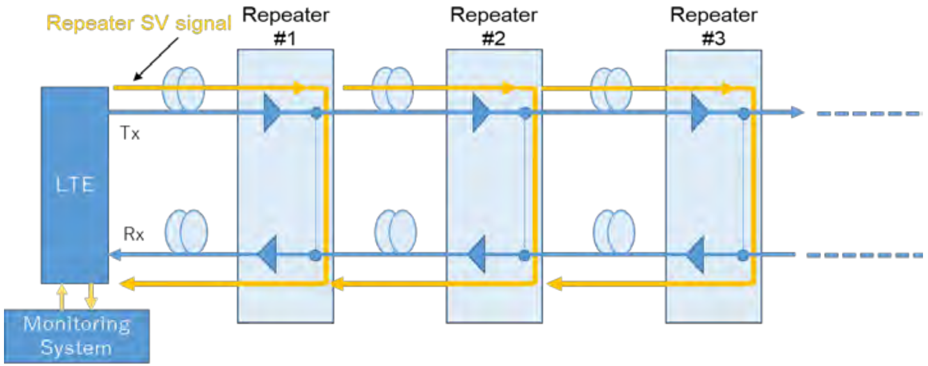
OTDR Configuration

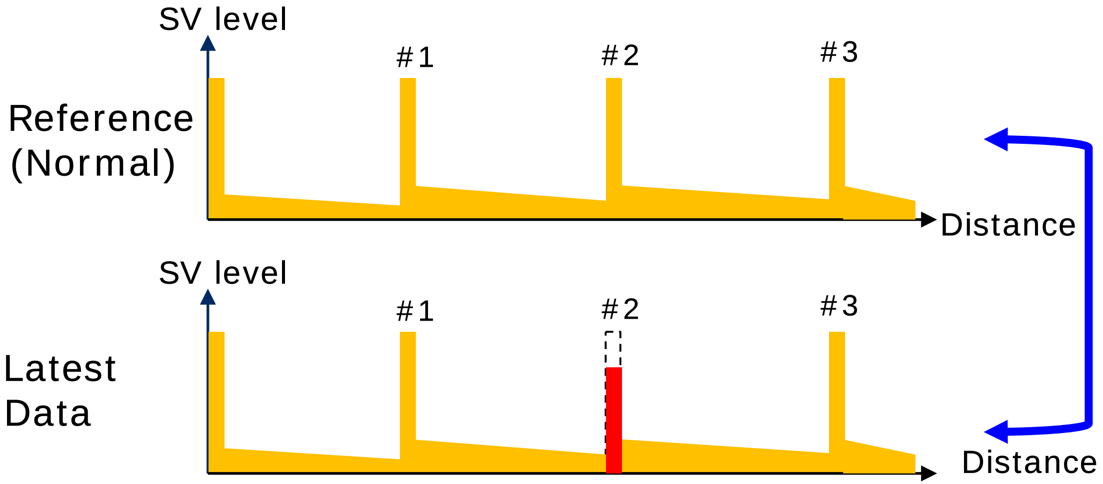
- Transmitter sends a optical pulse signal to the fiber
- Back-scattered light or loopback signal returns to the OTDR through the fiber
- OTDR receiver directs to a Back-scattered light over time and analysis on time domain

OTDR Trace Example



Fault Mode Analysis





Latest data is compared to the base line data and analyzed

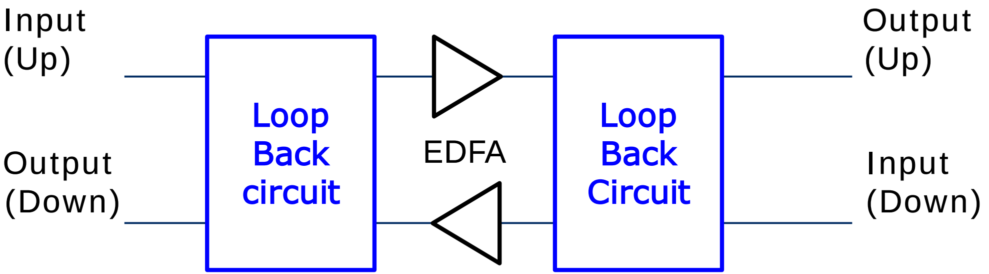
- Repeater power reduction
- Span cable loss increase
- Fiber cut

Automatic fault localization and fault mode analysis function are available

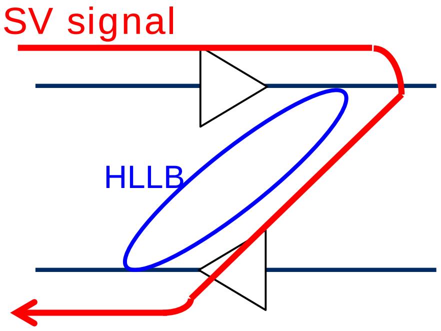
- No signature analysis is required by the station staffs.

Repeater Loop-back Circuit

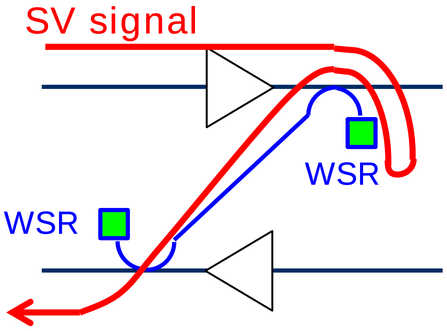
Submarine Repeater



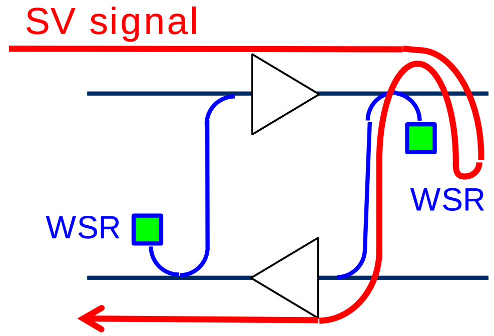
High loss loopback



Loopback Circuit with Reflector(1)



Loopback Circuit With Reflector(2)



WSR: Wavelength Selective Reflector

Cable Faulty Point Localization (C-OTDR)

Standard OTDR equipment is not used for Repeatered submarine cable system, by the following reasons

- Isolator installed in Repeater; Isolator cut-off back scatted light
- Deterioration of receiver sensitivity by ASE noise of submarine repeater

C-OTDR (Coherent-Optical Time Domain Reflectometer) is widely used for faulty point localization of submarine cable system

- High receiver sensitivity by coherent detection
- Effective ASE noise reduction generated in submarine repeaters

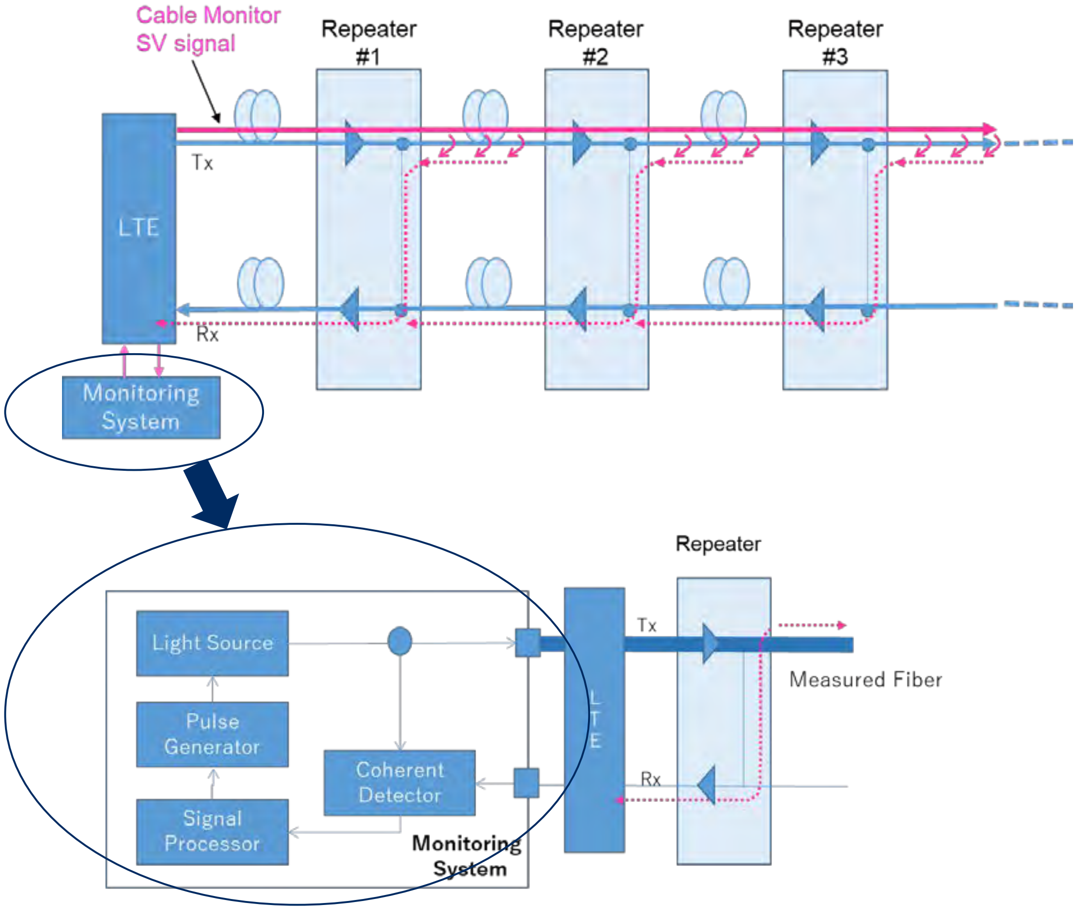
Method

- Measure back-scattered light on time domain using **by coherent detector**
  - ✓Rayligh back-scattered light
  - ✓Fresnel reflection

C-OTDR

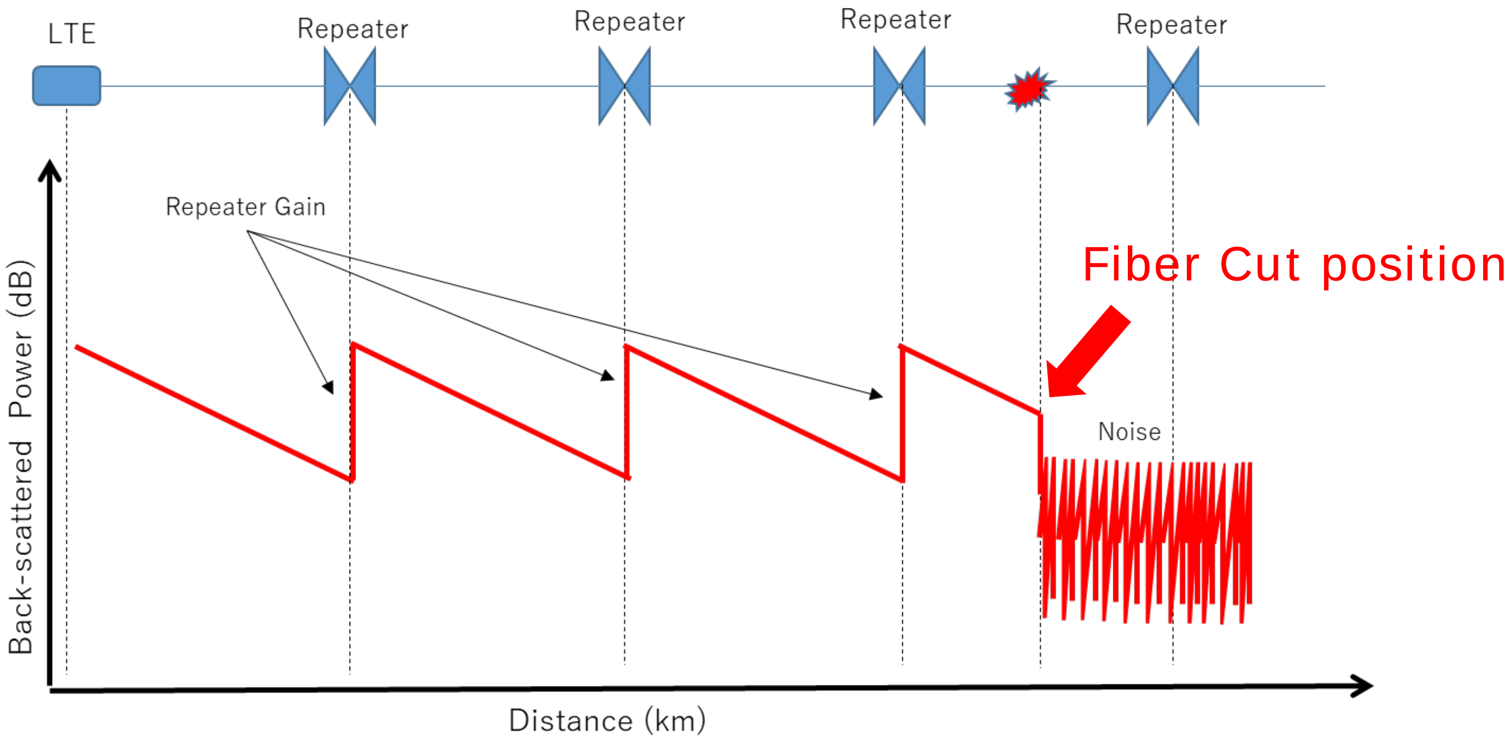
C-OTDR Configuration

- Dedicated SV signal transmitter sends a probe light to the fiber.
- The Rayleigh backscattered light returns through the loop back circuit of submarine repeater.
- Monitoring system with C-OTDR receiver directs to a returned back-scattered light over time and analysis on time domain.(OTDR method)
- Only C-OTDR trace for up-stream direction fiber is measurable.



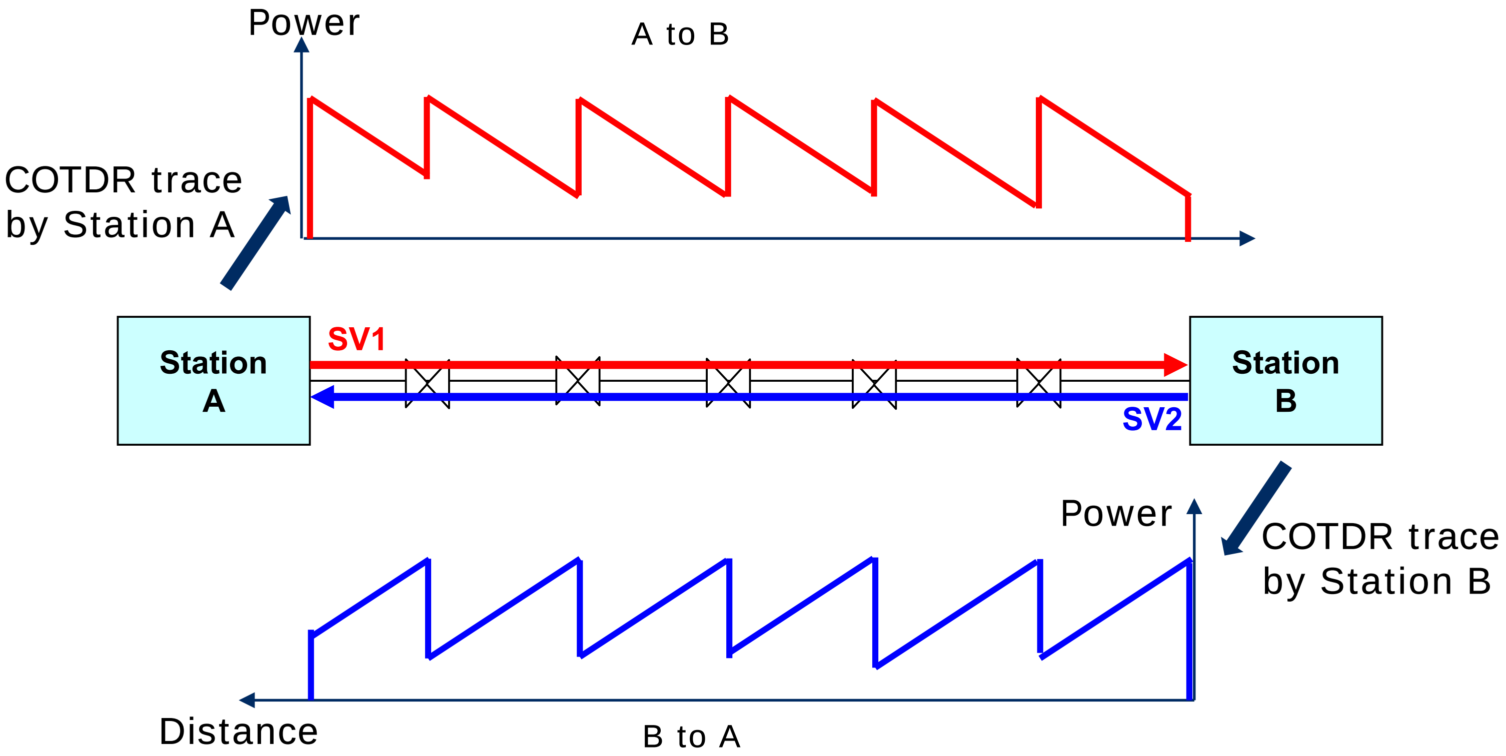
C-OTDR (Coherent-Optical Time Domain Reflection) (3/3)

Fiber Trace Example

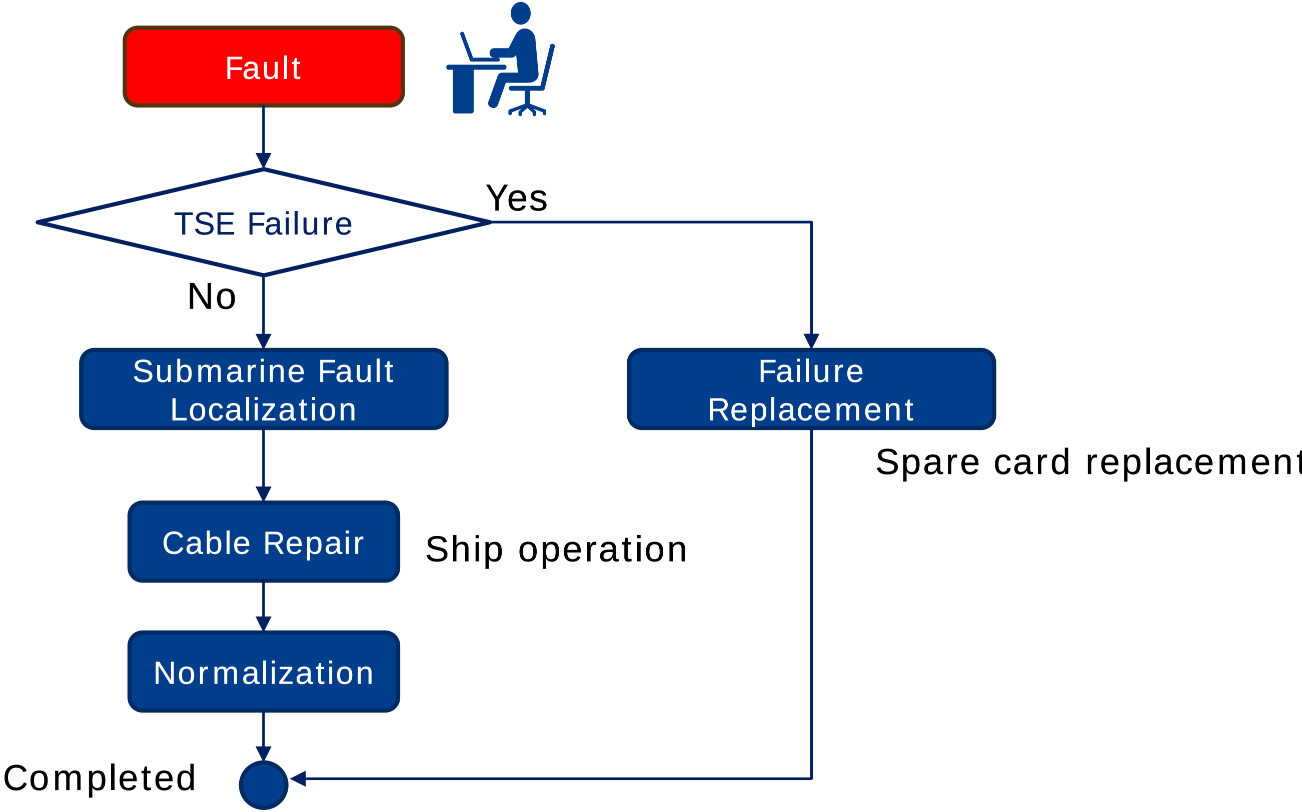


COTDR monitoring for submarine cable system

Point-to-point



System Monitoring Steps



Fault

TSE Failure

Yes

No

Submarine Fault Localization

Failure Replacement

Spare card replacement

Cable Repair

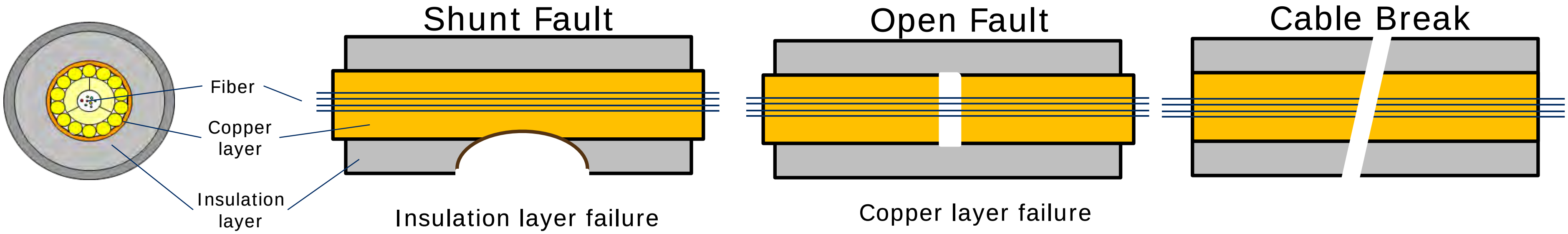
Ship operation

Normalization

Completed

System monitoring for Submarine Fault

Fault Type		Fault Localization Method
Cable Fault	Shunt Fault	• Repeater Monitoring • DCR Measurement
	Open Fault	• Capacitance Measurement (very rare in submarine portion)
	Cable Break	• Repeater Monitoring • DCR Measurement • Back-scatter Test (OTDR Measurement • C-OTDR Measurement
Repeater Fault		• Repeater Monitoring



Submarine Fault Localization Technique

OTDR Test / C-OTDR Test

- Measure fiber break point along fiber

Direct Current Resistance (DCR) Test

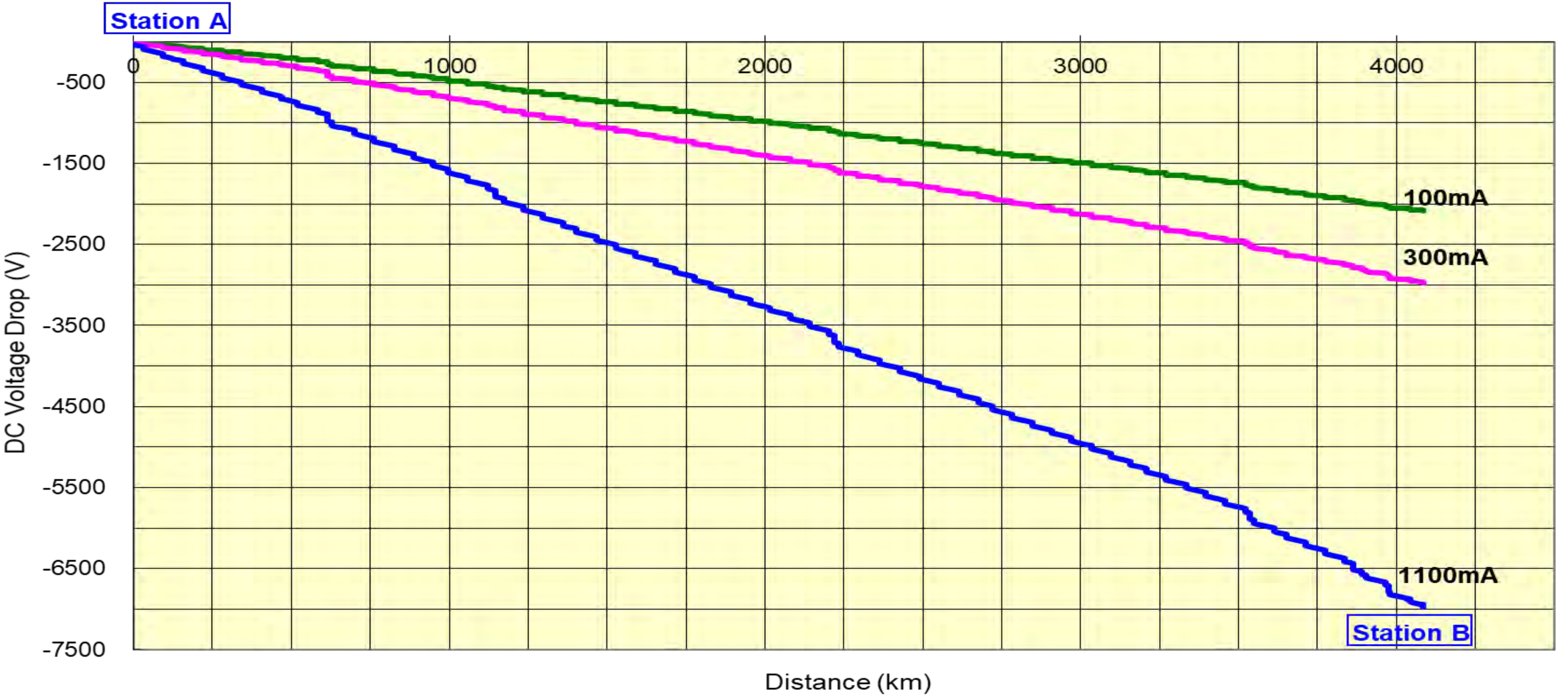
- Apply direct current and read voltage
- The faulty point is estimated from the calculation from cable resistance and/or repeaters drop voltage, which were pre-measured before system installation at factory

Capacitance Test

- Measure capacitance of system
- The faulty point is estimated from the calculation from cable capacitance

DCR Measurement

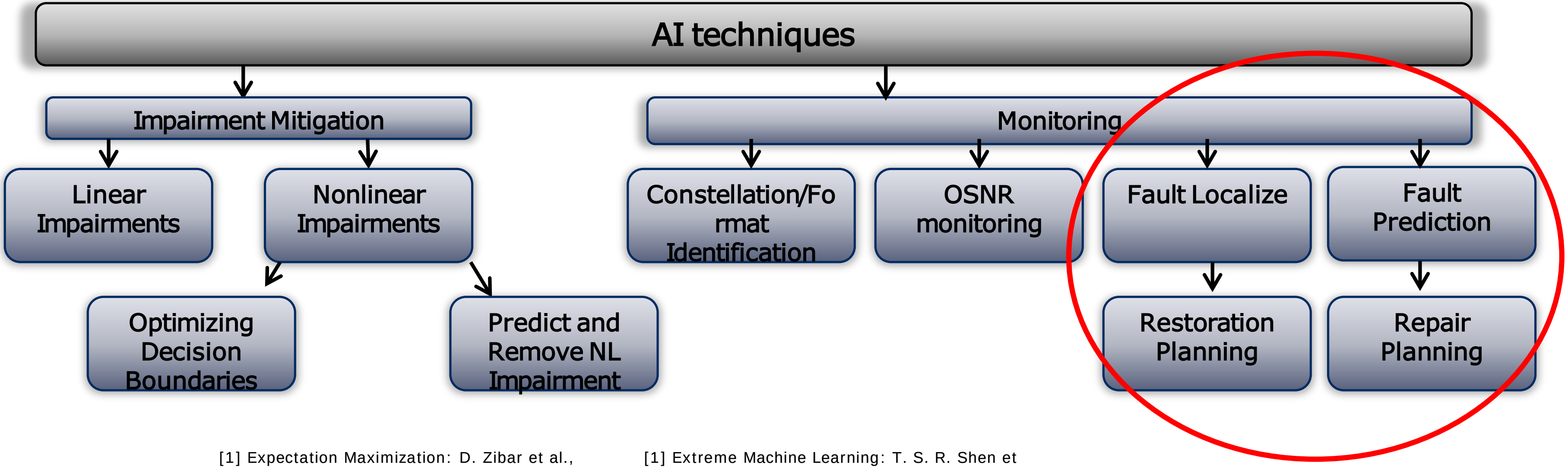
DCR Calculation : $V_{CABLE} + V_{REP} + V_{BU} + V_{PFE} + V_{EARTH}$



Contents

Network Supervisory by Artificial Intelligence

- Artificial intelligence techniques has been discussed in many areas of optical communication system
- AI techniques excel with abundance of data. Optical transmission has plenty of data.



[1] Expectation Maximization: D. Zibar et al., Opt. Express 20, B181-B196 (2012)
[2] K-means clustering: L. Pakala et al., Photon. Network., ITG Symposium, (2015)
[3]K-nearest neighbors: D. Wang et al., IEEE Photon. Technol. Lett. p.2102, (2016)

[1] Extreme Machine Learning: T. S. R. Shen et al., in Proc. OECC, 2011, pp. 816–817.
[2] Artificial Neural Network: M. A. Jarajreh et al., IEEE Photon.Technol. Lett., 27(4), 2015
[3] SVM: E. Giacoumidis et al., OFC2016 , Th2A.49 (2016)

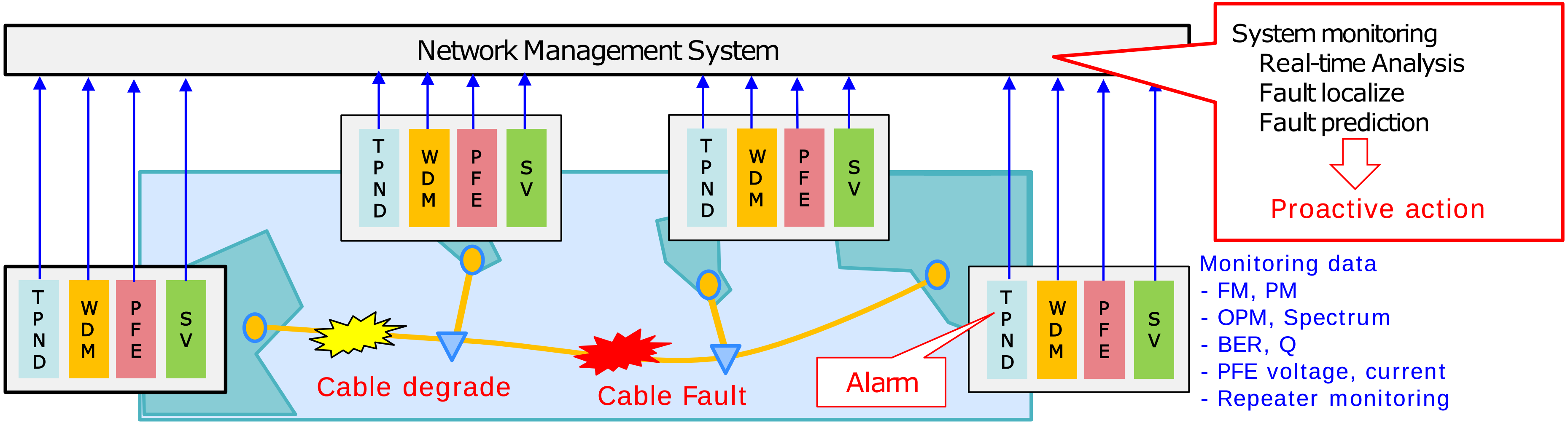
Network Management by Artificial Intelligence

- Wet-plant supervisory becomes more important for recent submarine cable system
  - Increased connectivity
  - Increased flexibility

➡ Fault localization becomes complicated

- Wet-plant fault localization and fault prediction is promising candidate of AI
  - Analysis of plenty monitoring data from NEs from all the stations (Big data)
  - Fault localization and root cause analysis without time consuming human investigation
  - Fault prediction

➡ Maintenance efficiency Improvement (cost reduction)



System monitoring
Real-time Analysis
Fault localize
Fault prediction

Proactive action

Monitoring data
- FM, PM
- OPM, Spectrum
- BER, Q
- PFE voltage, current
- Repeater monitoring

SDM Technology for Submarine Systems

Submarine systems have specific limitations

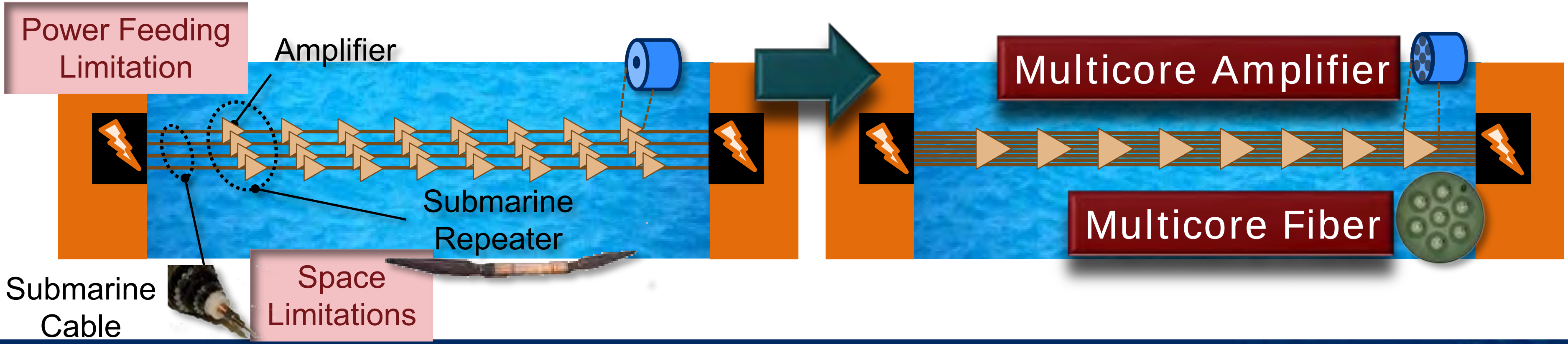
- Space limitations due to cable structure, manufacturing, handling and deployment
- Power limitations due to feeding of the optical amplifiers from the land

SDM can help increase capacity despite these limitations

- Higher signal density per cable area unit
- Higher power efficiency through sharing and pumping techniques

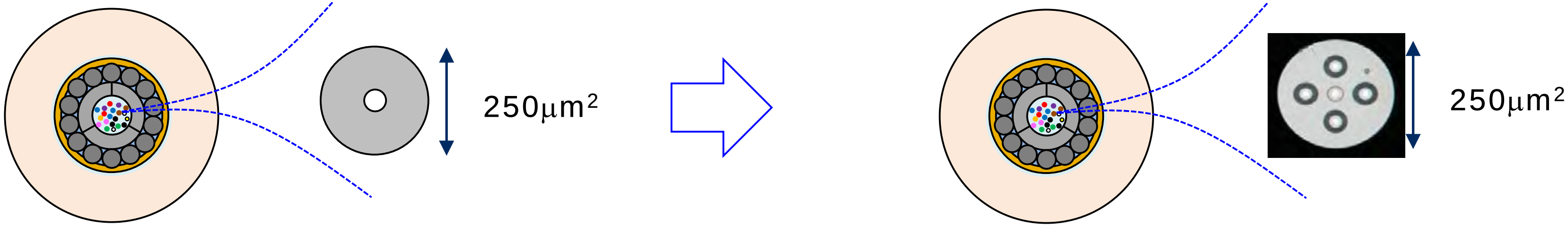
Different flavors of SDM

- Single core fiber SDM (SDM 1.0 or SDM 0.0): increasing number of fiber pairs (>8fp)
- **Multicore SDM: High density and good uniformity among cores**



Different flavors of SDM: Multicore fiber transmission

- Multicore fibers have the potential to increase the core density in submarine cables



$250\mu m^2$

$250\mu m^2$

- NEC/KDDI confirmed for first time 6000km+ multicore transmission in 2012

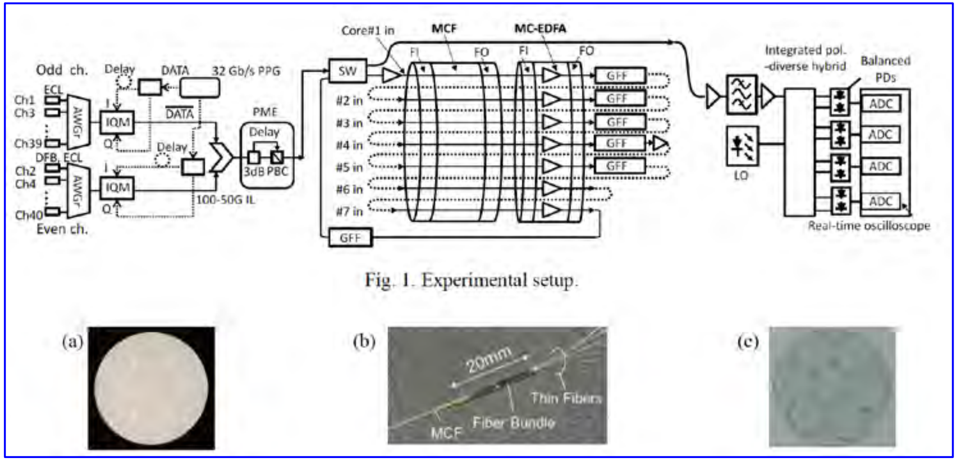


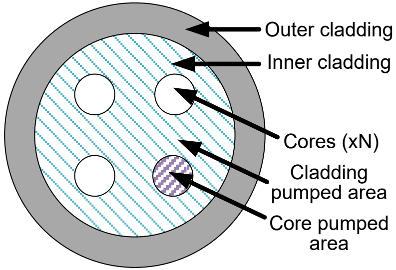
Fig. 1. Experimental setup.

- ◎ Submarine Transmission with multicore fiber is confirmed long ago
- ◎ There is catch…special SLTE is required to eliminate inter-core cross-talk

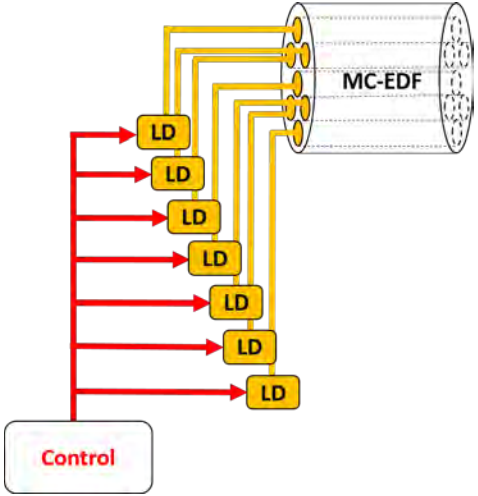
Different flavors of SDM: Multicore fiber amplifiers

Pumping Scheme

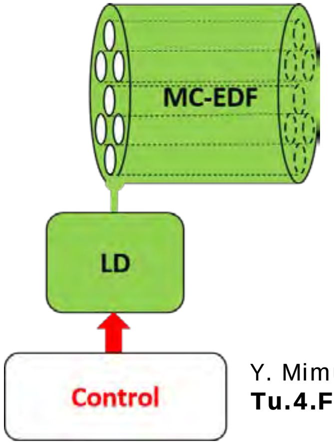
- Core pumping
- Cladding pumping
- Hybrid pumping(Core/Clad)



Individually Core Pumped

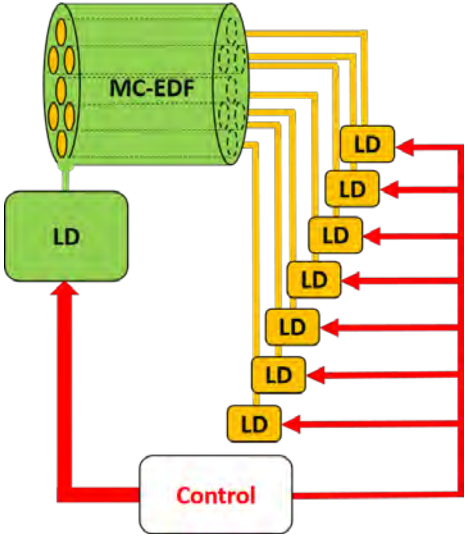


Clad pumping



Y. Mimura *et al.*, ECOC 2012, **Tu.4.F.1** (2012)

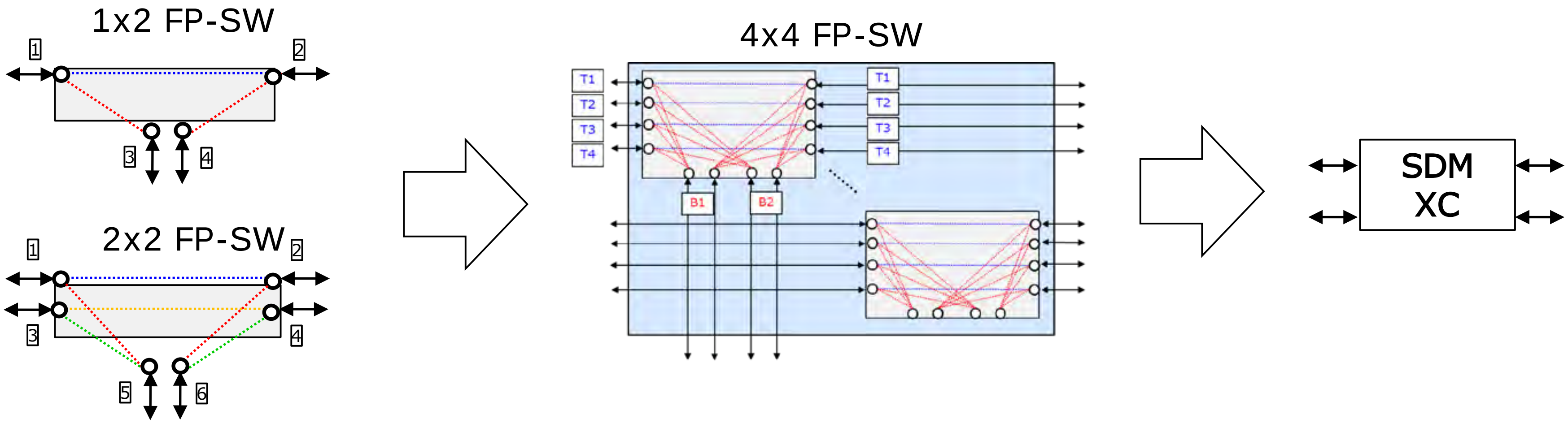
Hybrid pumping Scheme



E. Le Taillandier de Gabory *et al.*, OFC 2017 **Th.1.C.1** (2017)

Connectivity in next gen SDM networks

- Multicore technologies will enable many space channels with better power efficiency and space usage.
- Then, network topology and traffic routing will gradually shift from wavelength switching to space-channel switching (FP first, FC later..)



Orchestrating a brighter world

NEC brings together and integrates technology and expertise to create
the ICT-enabled society of tomorrow.
We collaborate closely with partners and customers around the world,
orchestrating each project to ensure all its parts are fine-tuned to local needs.

Every day, our innovative solutions for society contribute to
greater safety, security, efficiency and equality,
and enable people to live brighter lives.

SUBCOM

Submerged Plant Equipment

Lecture I

Georg Mohs

August 6, 2019

Submerged Plant Equipment Characteristics

High performance:

- Ultra-long transmission distance up to 14,000 km!!
- High data capacity: 250 Tb/s across the Atlantic!

Space & Power Limitations:

- All functionality must fit inside an undersea body.
- Equipment must be powered from shore through the cable conductor.

Reliability for a 25 year lifetime in the undersea environment:

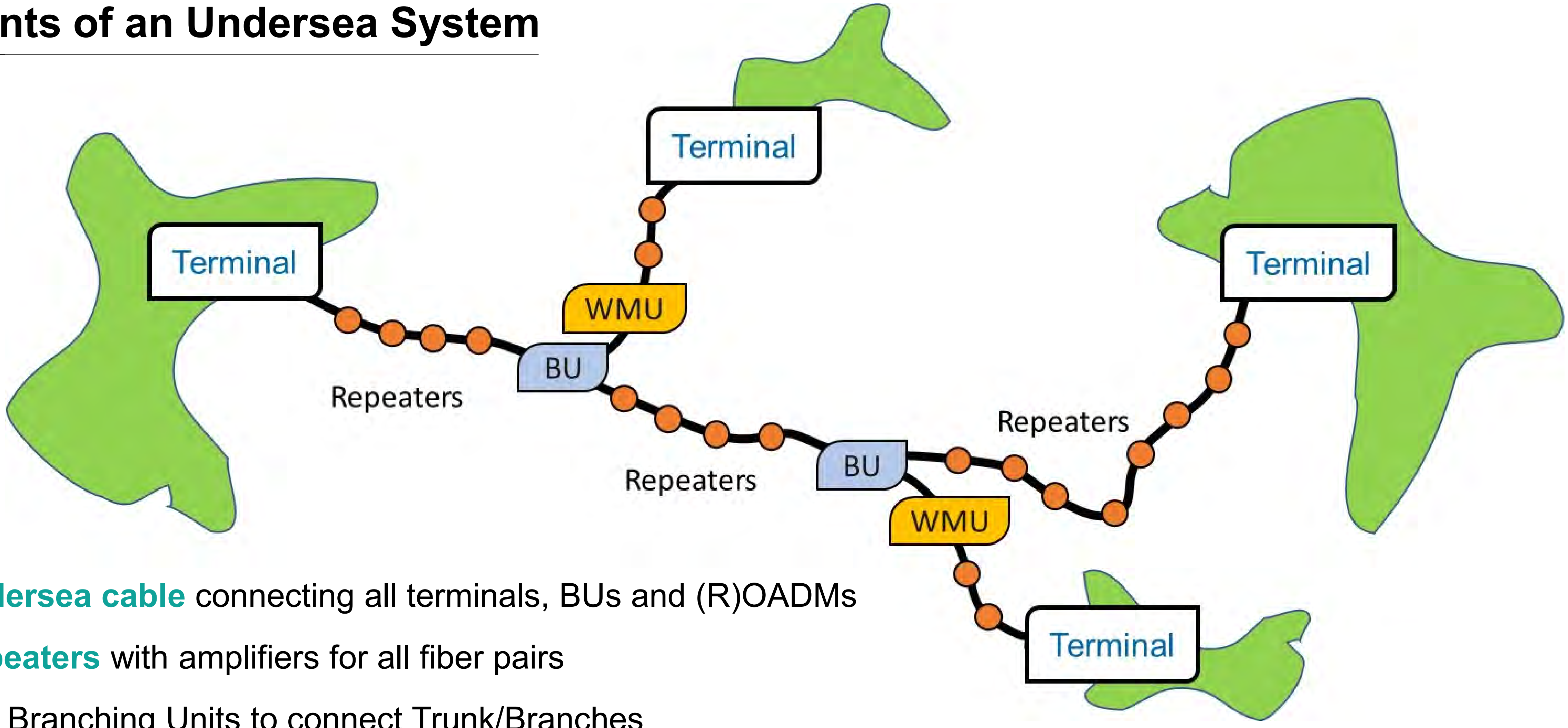
- Water-proof and pressure-stabilized body
- High reliability optics/electronics.

Deployment:

- Equipment must support shipboard storage, deployment, and retrieval for repairs.

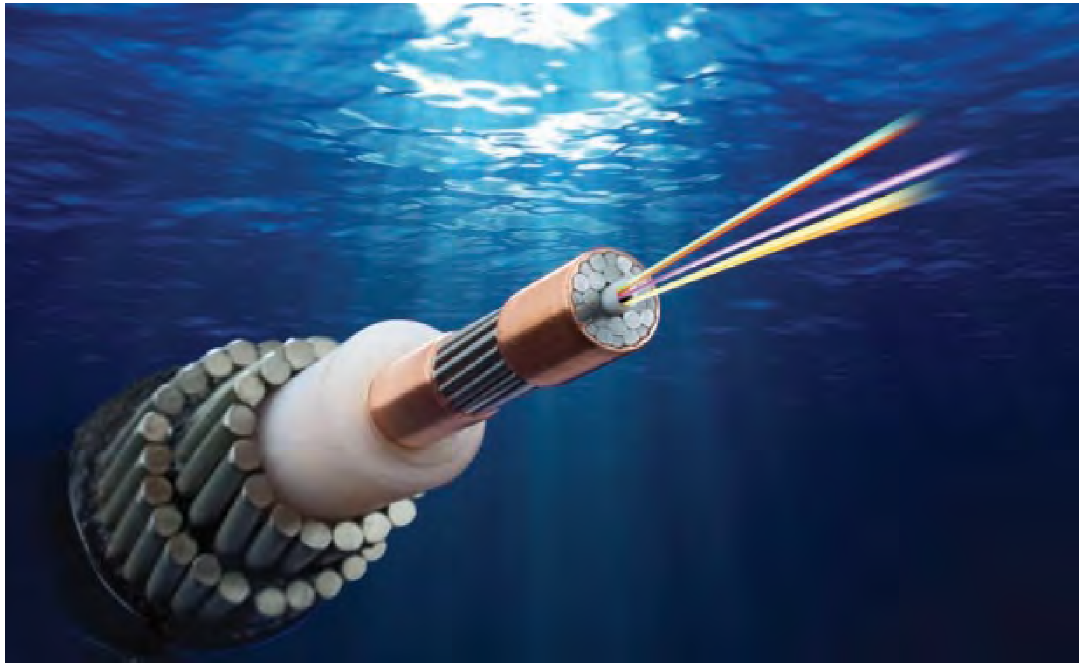
Unique technology for a unique environment

Elements of an Undersea System



- **Undersea cable** connecting all terminals, BUs and (R)OADMs
- **Repeaters** with amplifiers for all fiber pairs
- **BU**: Branching Units to connect Trunk/Branches
- **WMU: **Wavelength Management Units – (R)OADM

Outline



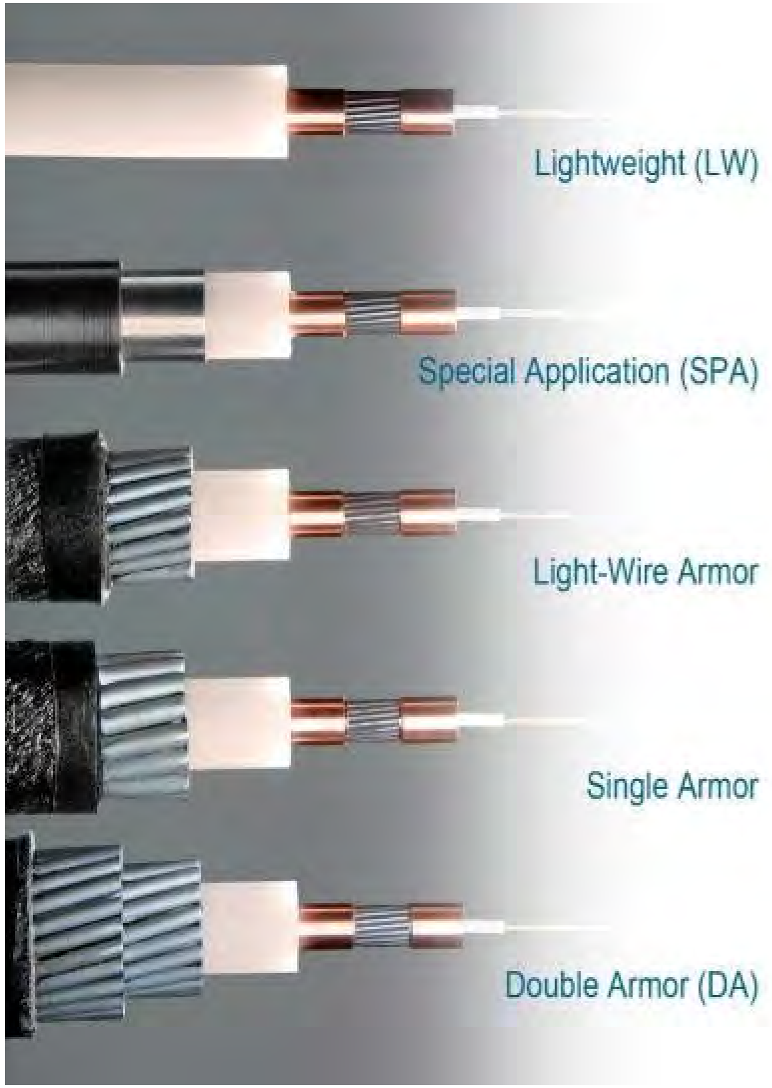
- Cable
- Repeaters
  - Amplification and gain equalization
  - Self-healing of a chain of amplifiers; gain tilt
  - Pump manifold and reliability
  - Line Monitoring and High Loss Loopbacks (HLLBs)
  - L-band amplification
  - The pressure vessel
- Branching Units
  - Fiber routing and optical switches - Why only one branch leg (3 port BUs)?
  - Electrical reconfiguration – Recovering from shunt faults
- Wavelength Management Units: (Reconfigurable) Optical Add Drop Multiplexing
- System Reliability

Undersea Fiber-Optic Cable

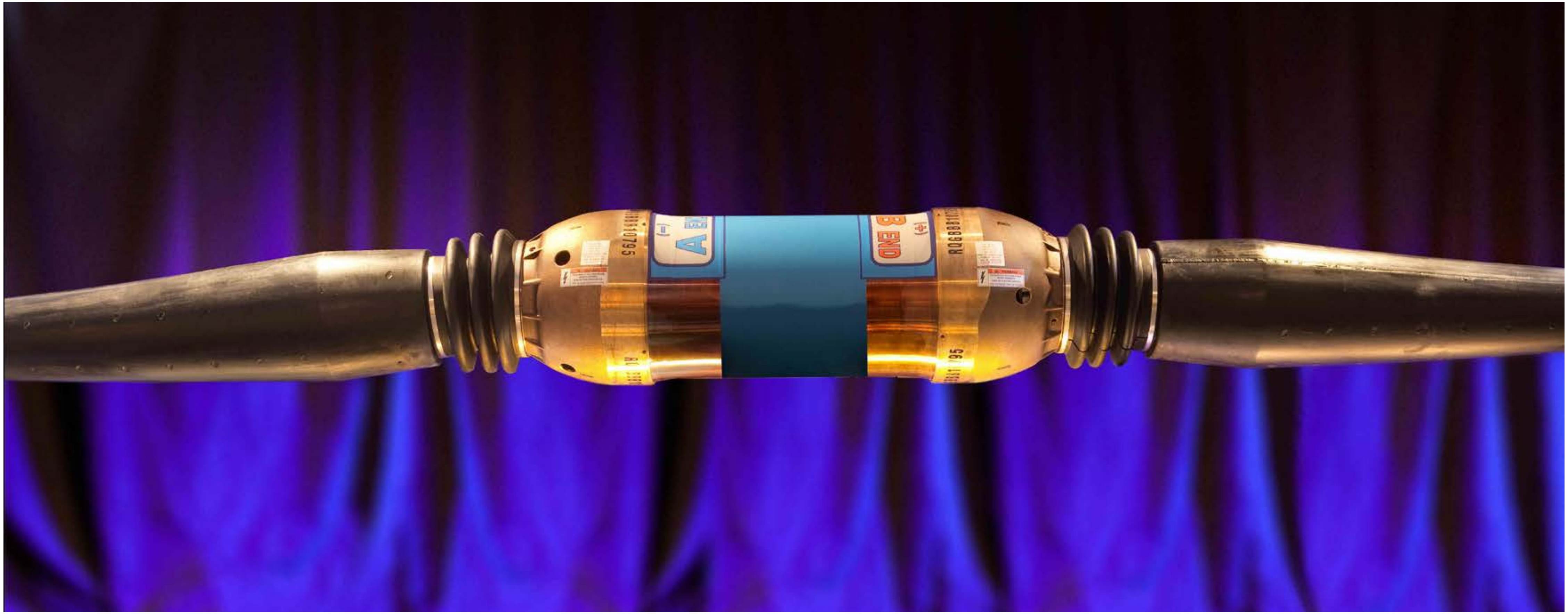
Cable Characteristics:

- **Fibers:** Benign environment for optical fibers
- **Strength:** For deployment and retrieval
- **Electrical:** Power for repeaters and network elements
- **Armoring:** Protection against external aggression

More on cable next by Marsha!

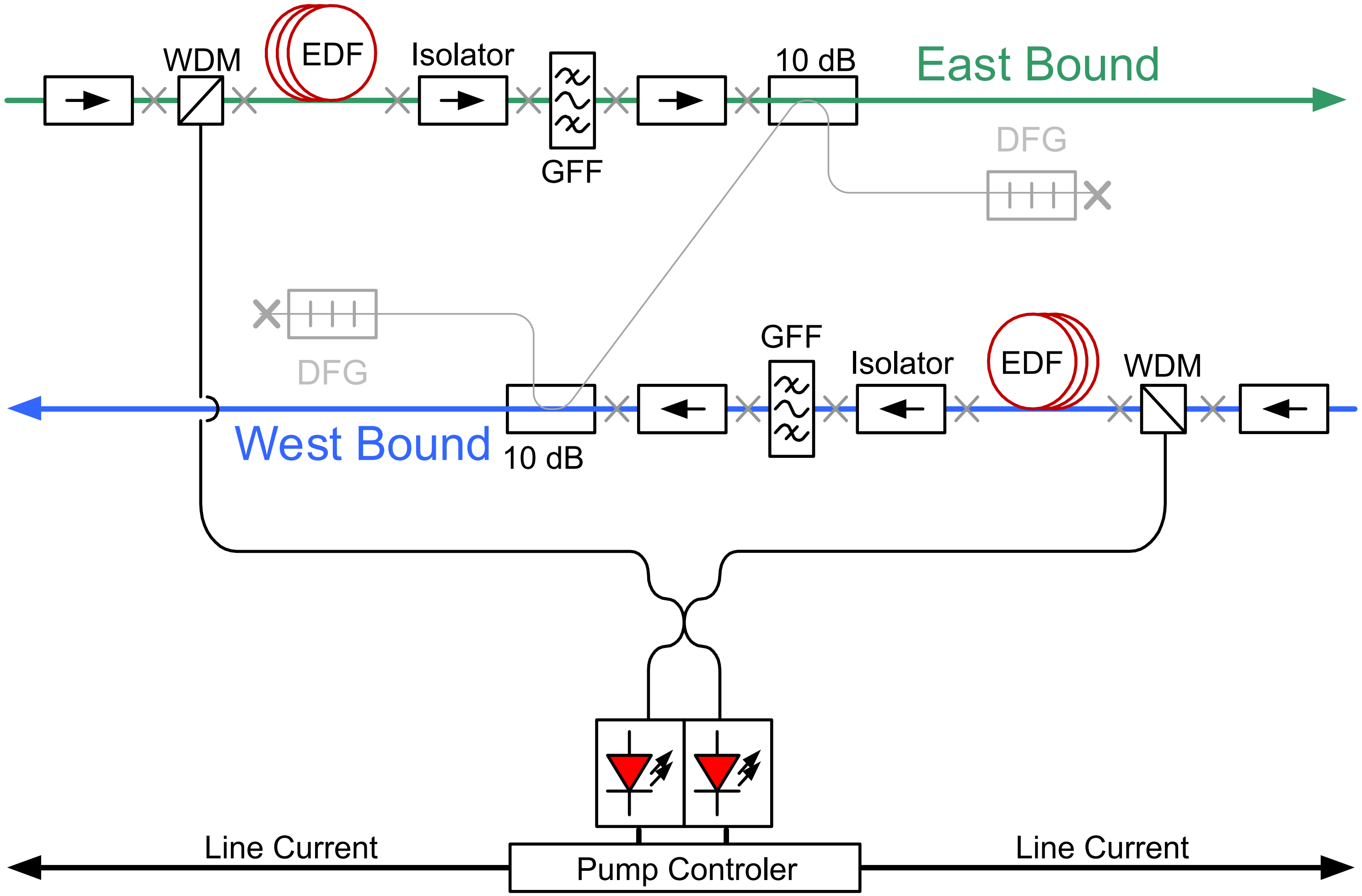


Repeater



The Repeater

- The modern repeater is an amplifier for the optical data signals on the fiber
- Amplification for fiber pairs
    - both directions of traffic: east and west bound
- High performance design for ultra-long distance transmission
    - Forward pumping for low noise figure
    - Single stage design
- 25 year design life
    - High reliability components
    - Higher order pump manifold
- COTDR path for fault localization



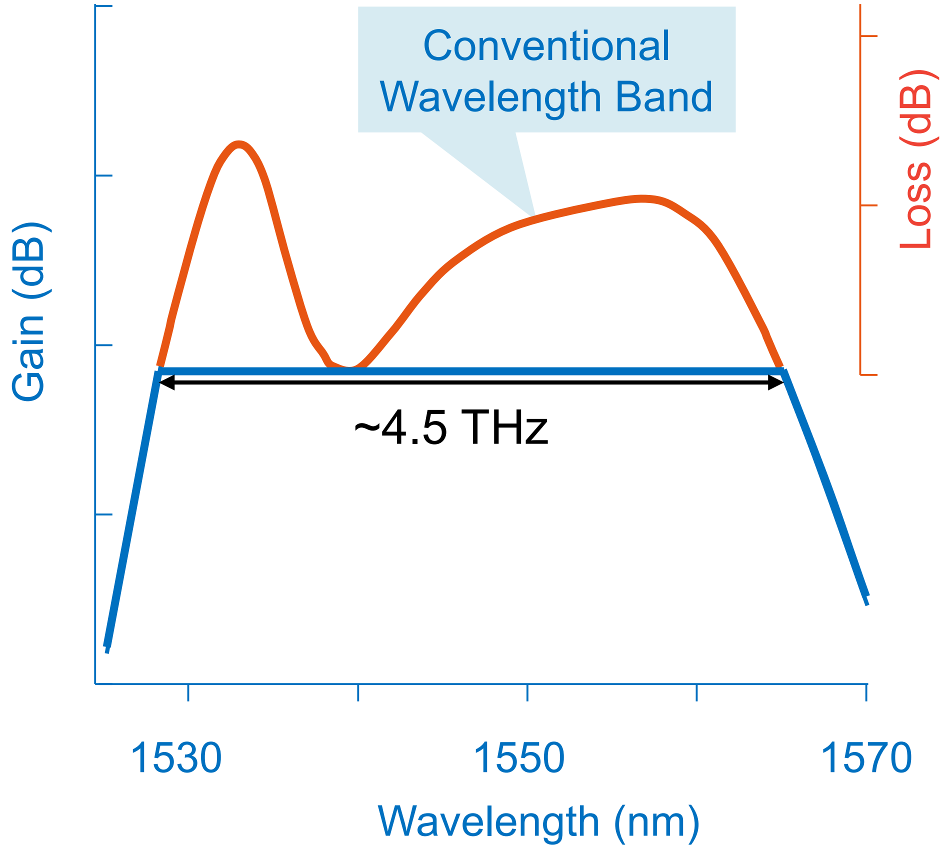
Amplification

Erbium Doped Fiber (EDF):

- Amplification around 1550 nm
- Bandwidth around 4.5 THz (1529 – 1565 nm)
- Optical pumping near 980 nm
- Significant gain variation across the amplification bandwidth (gain shape)

Gain Flattening:

- Gain flattening filter (GFF) to minimize gain variation across the amplification band
  - GFF is typically a Fiber Bragg Grating (FBG)
  - FBG reflection tuned to follow the EDF shape
  - Optical isolators suppress reflections and avoid lasing of the amplifier
- 0.1 dB gain variation leads to 10 dB across 100 repeaters (ignoring spectral-hole burning – more later)

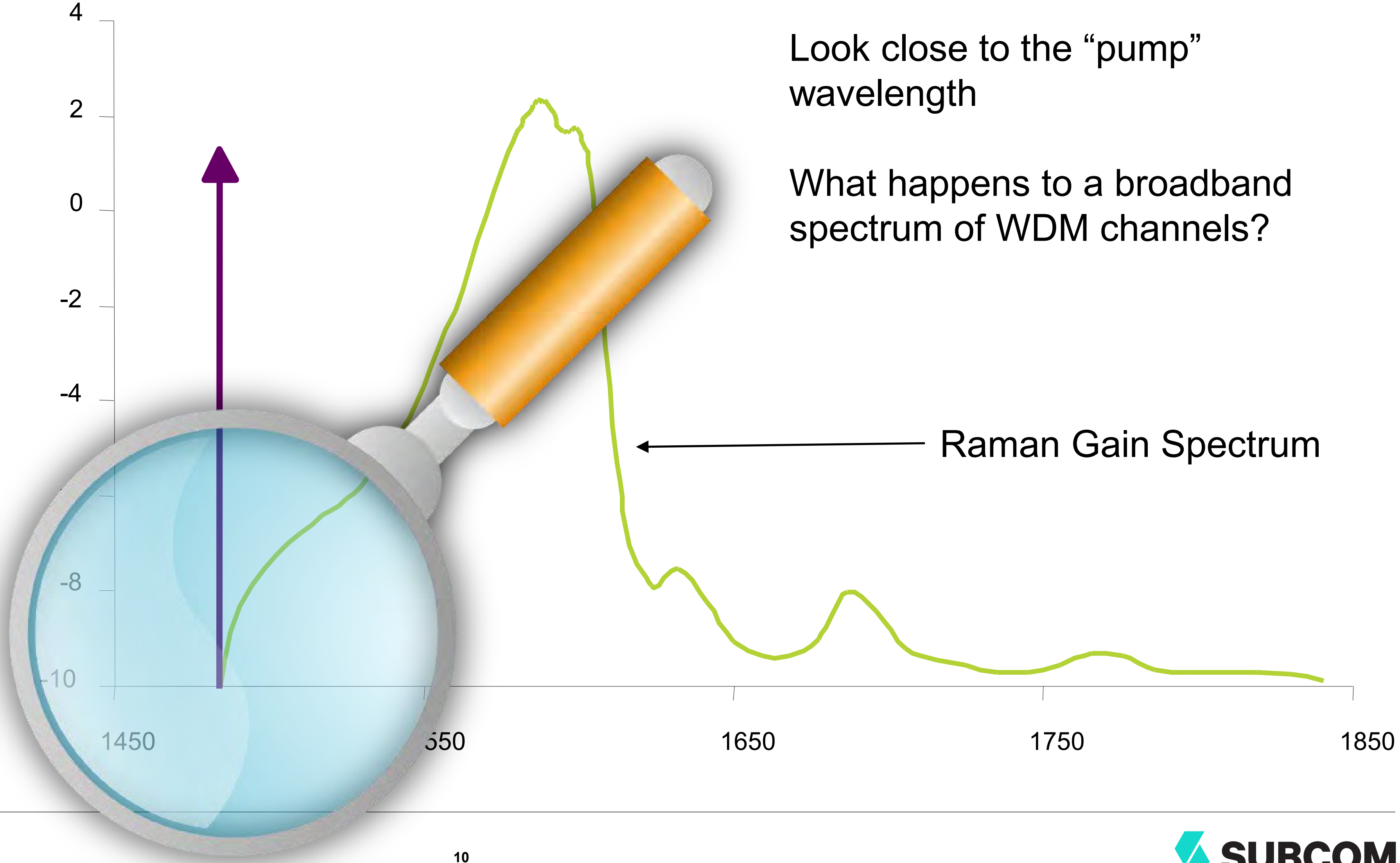


Gain Equalization

- EDF Shape
- Fiber Loss Shape
- Raman Gain
- Spectral-Hole Burning

Stimulated Raman Scattering

- Nonlinear scattering of light with optical phonons (lattice vibrations)
- A higher energy photon is scattered creating a phonon and lower energy photon

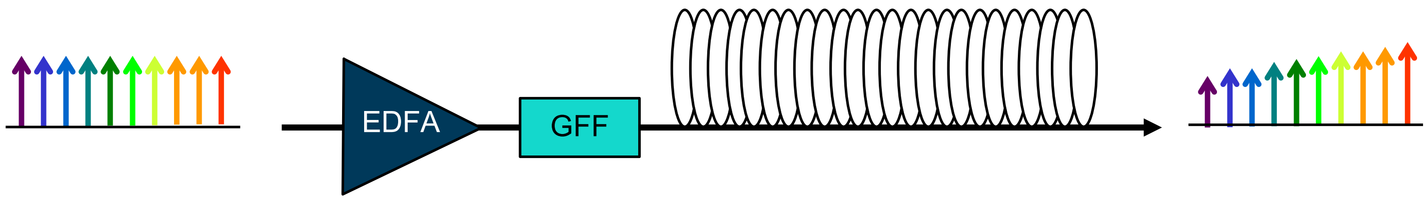


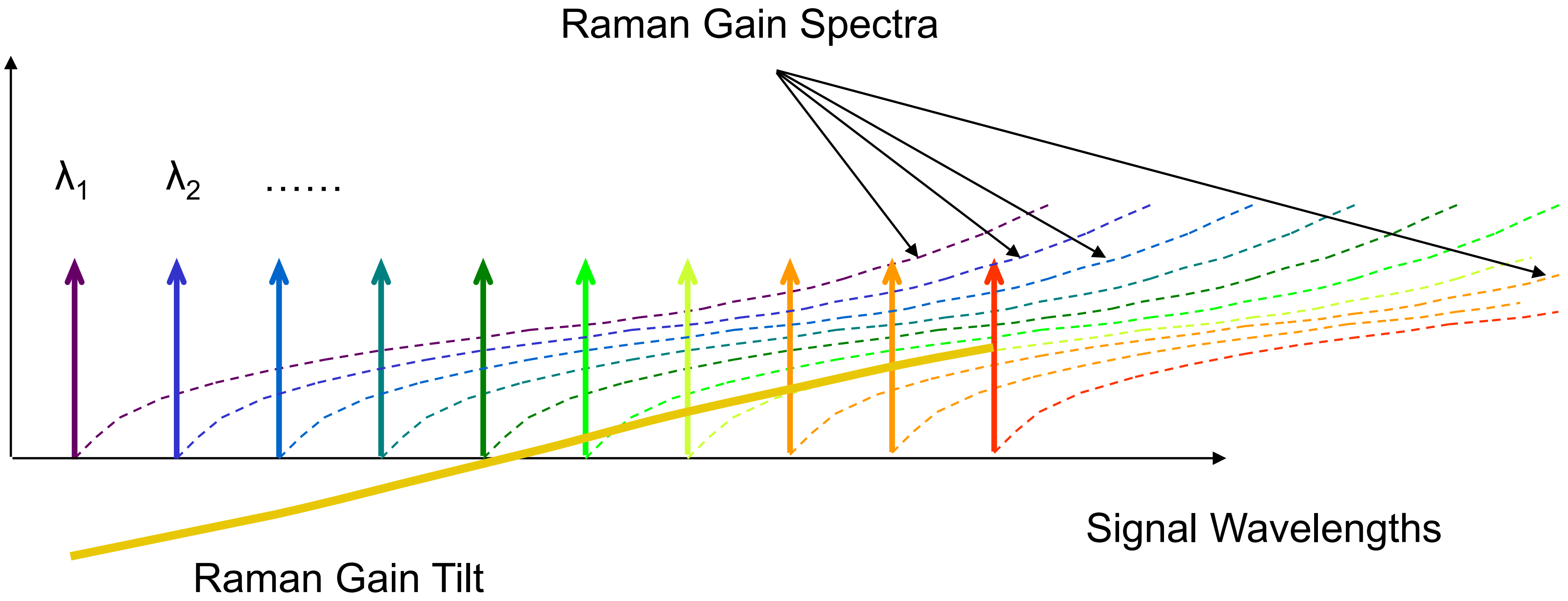
Look close to the “pump” wavelength

What happens to a broadband spectrum of WDM channels?

Raman Gain Spectrum

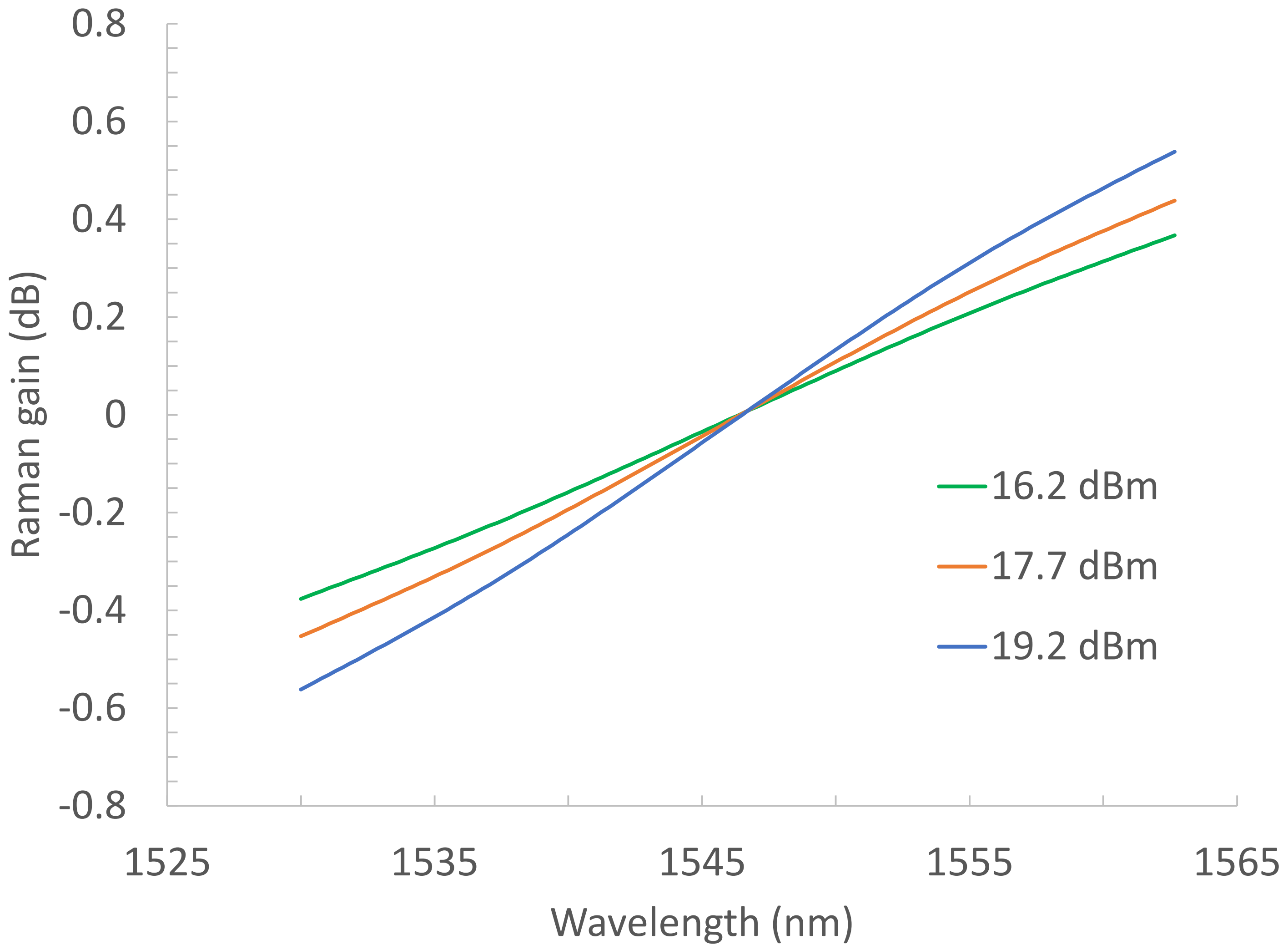
Intra-Band Raman Effect





Raman Gain Tilt

- Power transfer from short to long wavelengths
- Amount of power transfer depends on
  - Repeater power level (nonlinear)
  - Fiber (effective area)
  - Span length



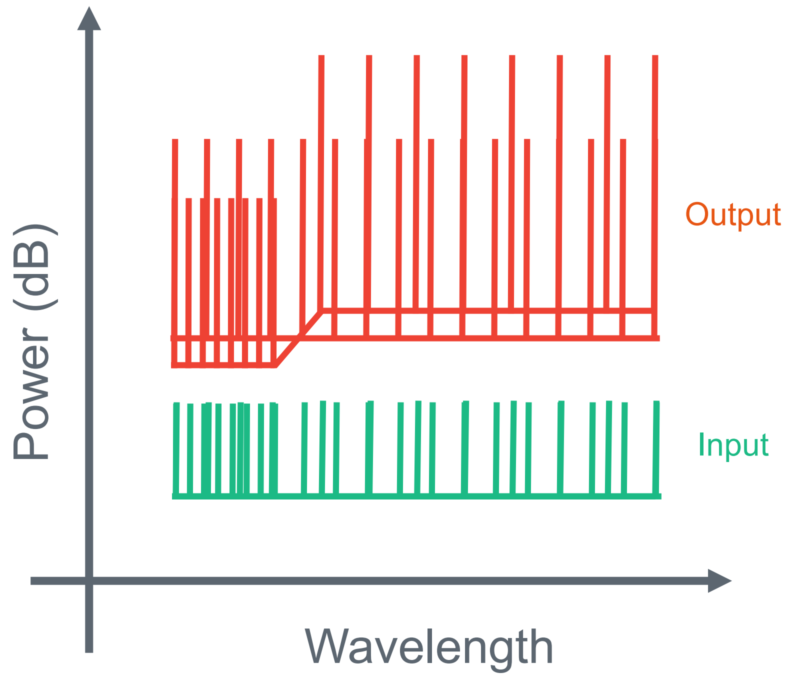
Gain Equalization

- EDF Shape
- Fiber Loss Shape
- Raman Gain
- Spectral-Hole Burning

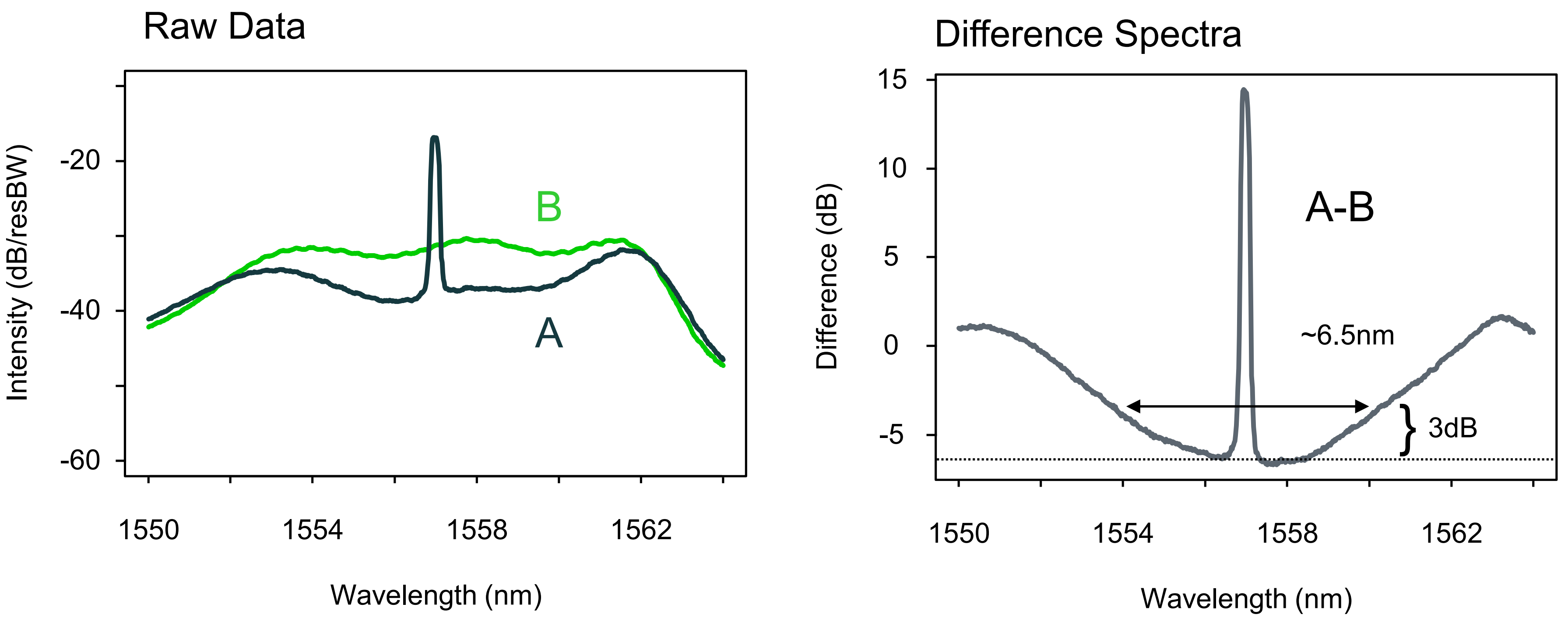
Spectral-Hole Burning

EDFAs tend to equalize power spectral density across the band

- Amplification depends on spectral loading of the EDFA
- Lower amplification where the power is high and higher amplification where the power is low
- Nonlinear effect
- Must be included when designing the gain management
- Tends to mitigate any residual gain error
- Tends limit effectiveness of pre-emphasis

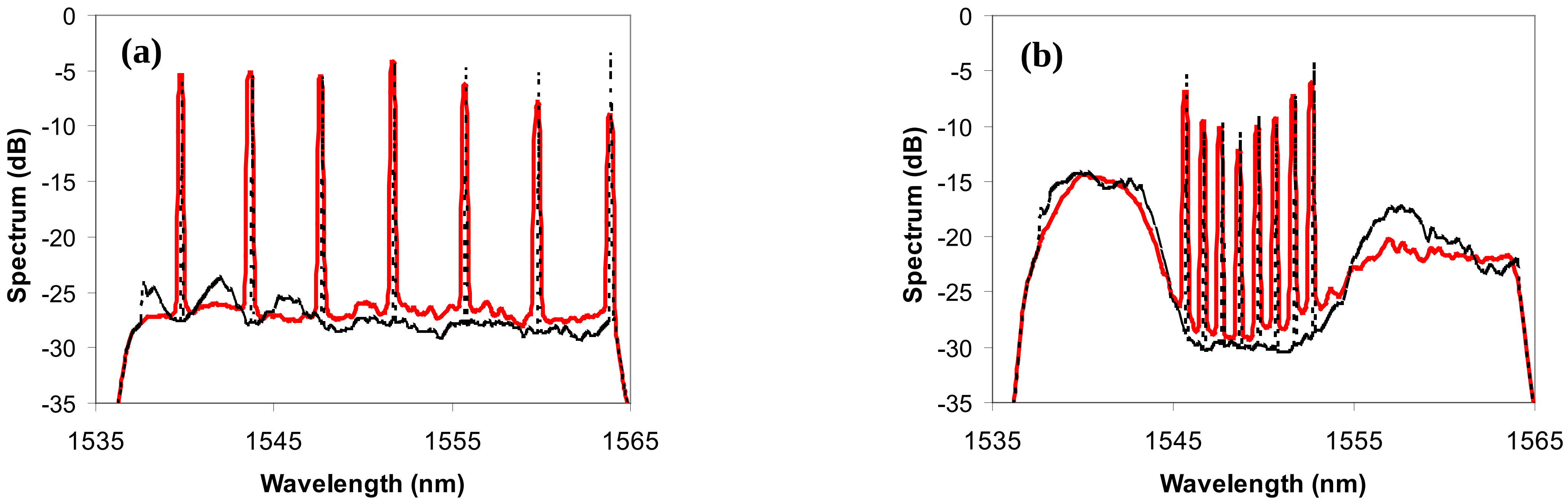


Spectral Hole-Burning in a 5,000km Amplifier Chain



Spectral Hole-Burning in WDM Systems*

Measured and simulated gain vs. wavelength using an installed 6,650km undersea cable system



* A. N. Pilipetskii et al., OFC’03

Gain Management in System Assembly

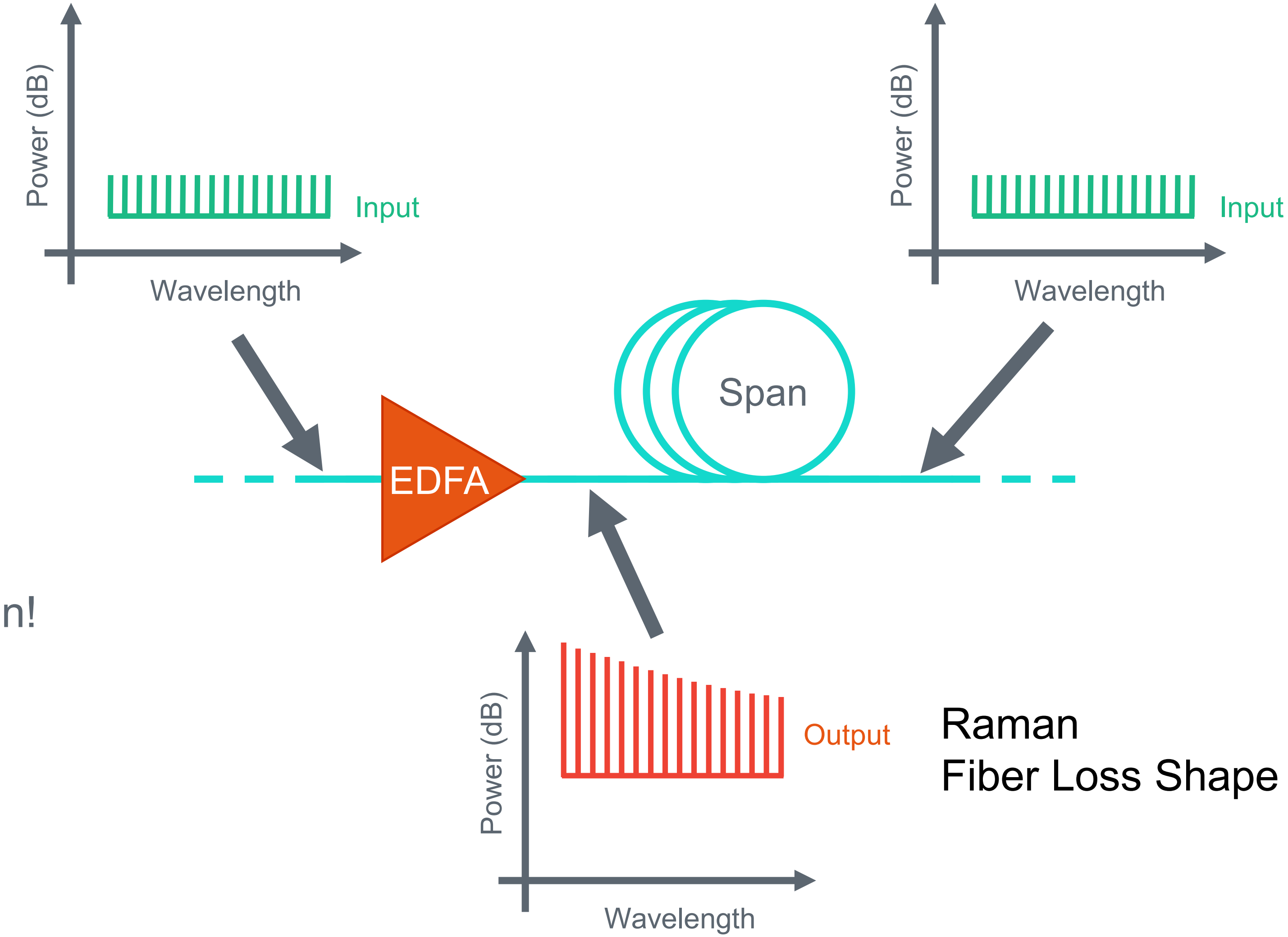
Repeater Design

Main Contributors to Gain Variation

- EDF shape
- Fiber loss shape (see Marsha)
    - Fiber loss minimum near 1565 nm
- Intra-band Raman effect
- Spectral-hole burning

Gain Equalization for amplifier/span combination!

- Precise characterization and custom gain flattening filter for each system design
- Results in nominal amplifier design

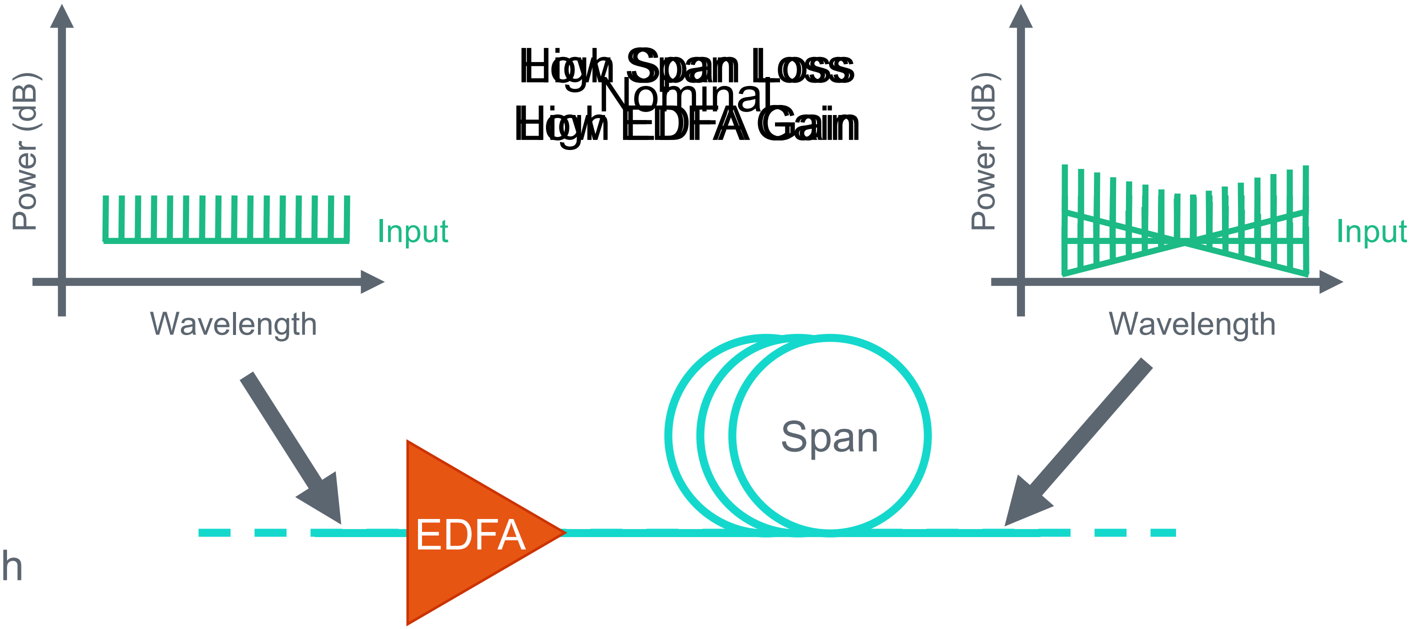


Raman
Fiber Loss Shape

Gain and Loss

What happens with manufacturing variations?

- Span loss is higher/lower than nominal
- EDFA gain is higher/lower than nominal



Repeaters run is constant pump power mode

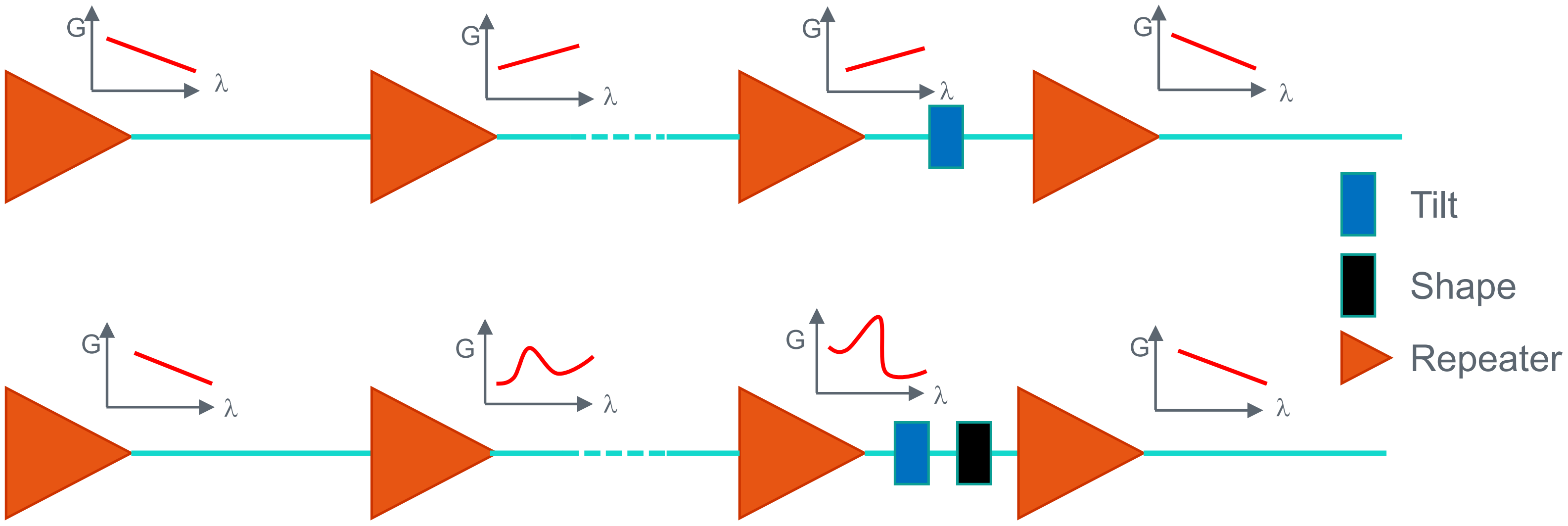
- Output power set by pump power
- Nominal gain set by EDF length
    - Average inversion determines optical bandwidth

Spectral Tilt

- Deviation from nominal gain and/or loss leads to a spectral tilt (first order, also some shape)

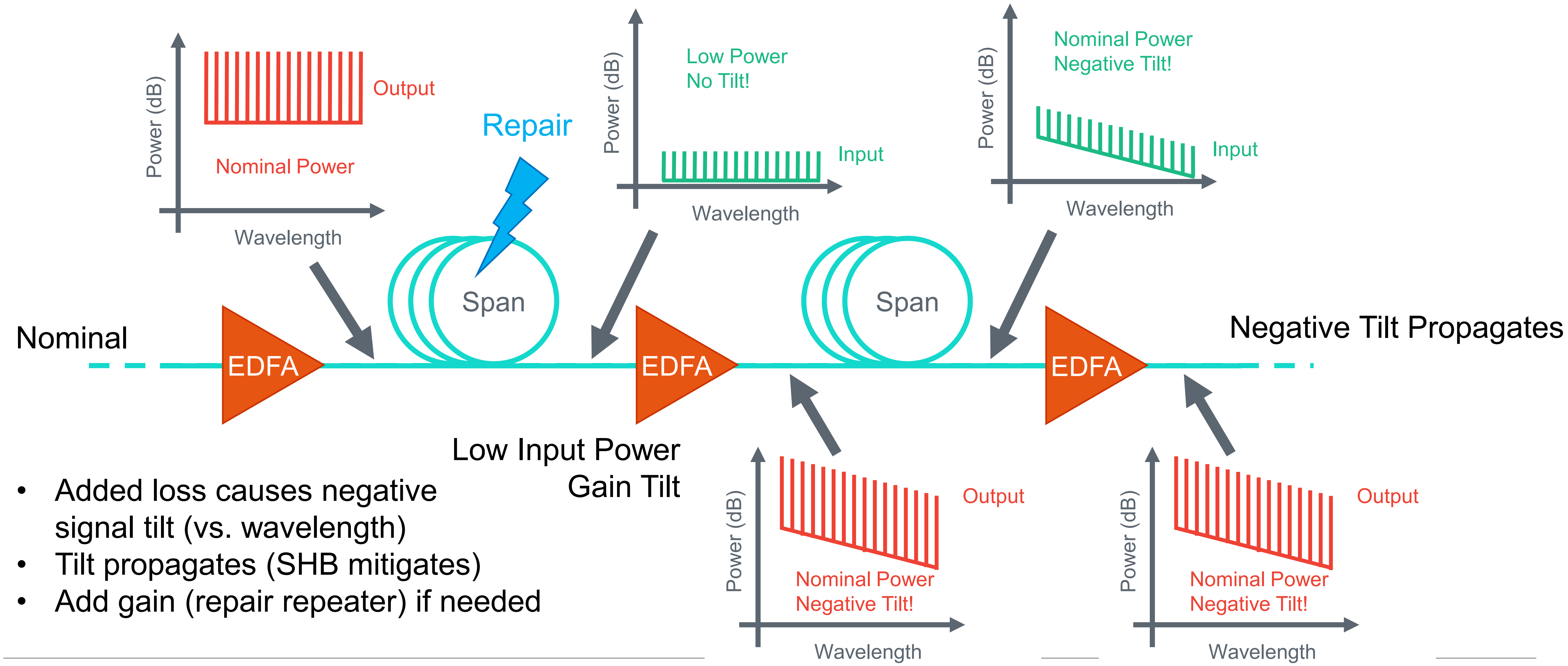
Gain Management

1. Gain equalization per amplifier/span combination
   - Gain flattening filter (GFF) – Typically a Fiber Bragg Grating
2. Gain tilt equalization
   - Adjustable (during system assembly) loss point (Loss Build Out – LBO) every several spans
3. Second order gain shape correction to address systematic GFF shape error
   - Shape Correction Unit (custom gain equalization filter)



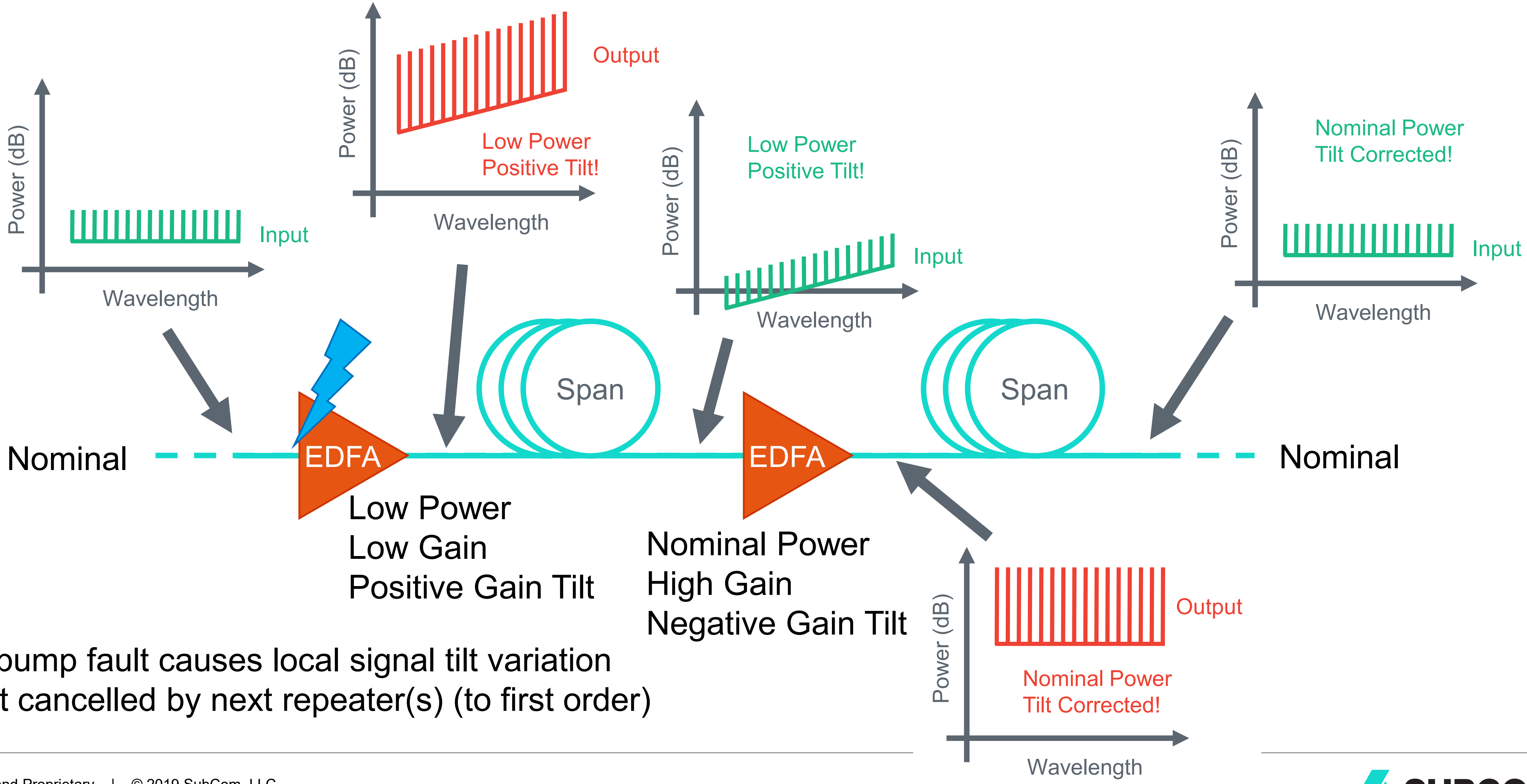
Gain Management During System Life

Loss Fault



- Added loss causes negative signal tilt (vs. wavelength)
- Tilt propagates (SHB mitigates)
- Add gain (repair repeater) if needed

Pump Fault in a Chain of Repeaters



Low Power
Low Gain
Positive Gain Tilt

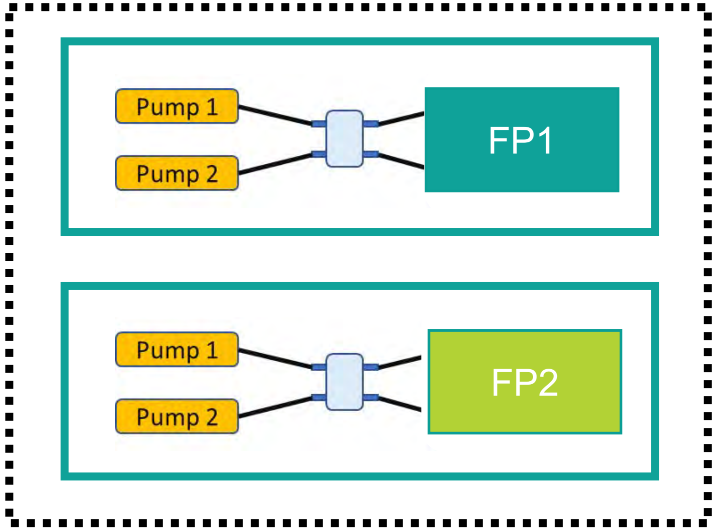
Nominal Power
High Gain
Negative Gain Tilt

- A pump fault causes local signal tilt variation
- Tilt cancelled by next repeater(s) (to first order)

Repeater Pump Manifold

Pump Sharing: Higher Reliability

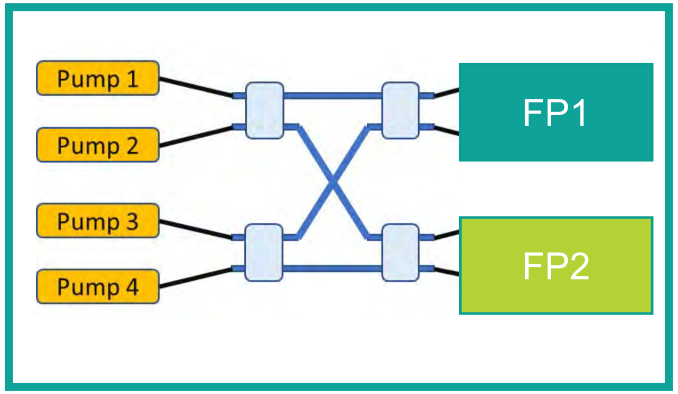
2 FPs = 2 Sets of “2 pumping 2 Fibers”:



Traditional:

“Fiber Pair Independence”
(One pump-pair per FP)
(2.6 FIT per FPs)

2FP = 1 set of “4 pumping 4 Fibers”:



New “Pump Sharing / Farming”

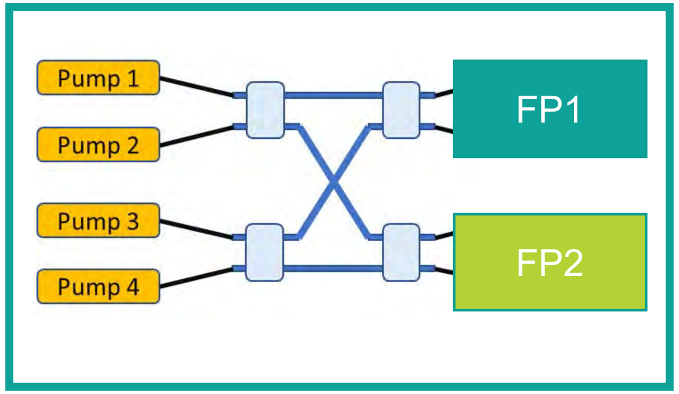
(Power shared over 2 FPs)
(0.001 FIT per FP)

Higher Reliability

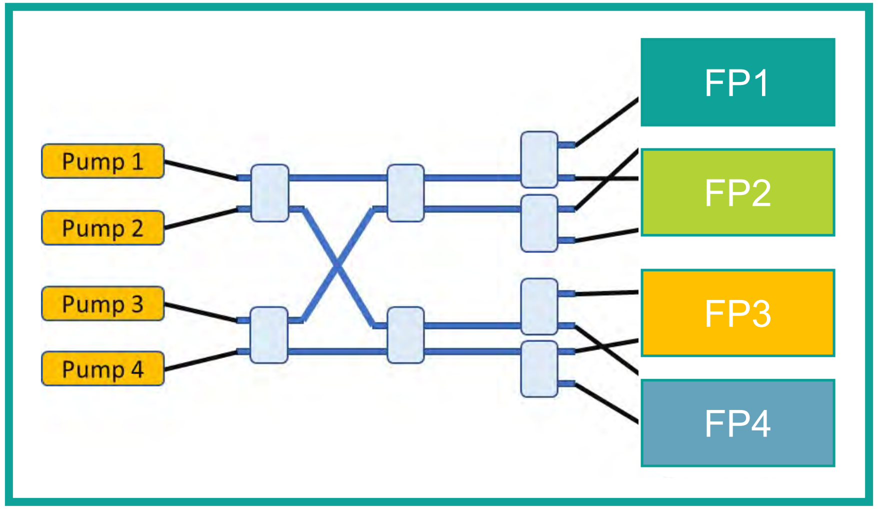
Pump Sharing: SDM / More Fiber Pairs

Pump Lasers are combined and shared in sets of four

“4 pumping 4 Fibers”



“4 pumping 8 Fibers”:



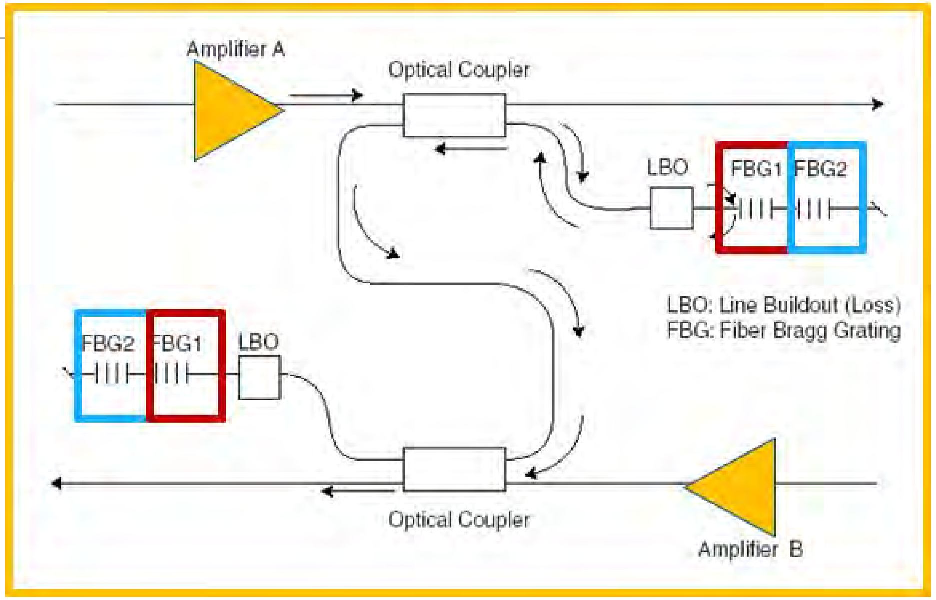
Support for twice as many FPs, with higher reliability

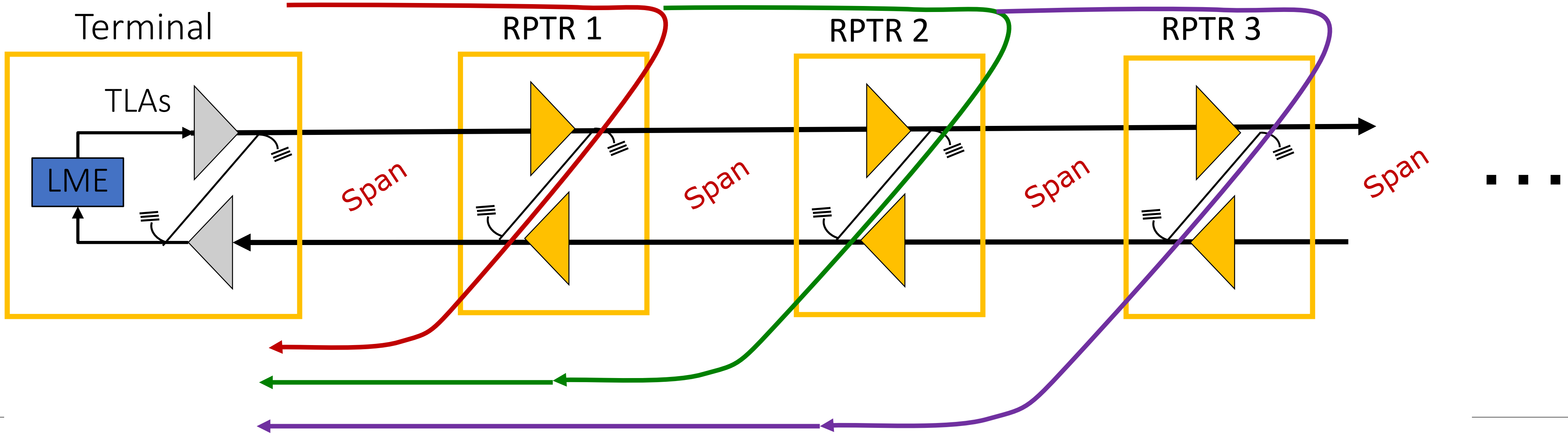
Line Monitoring System

Line Monitoring System

- Provides Undersea Monitoring and Fault Detection
- All optical principle, no active components in the repeaters
- Two operating modes: HLLB mode and COTDR mode

High-Loss Loopback Circuit
For one Amp-Pair





In-Service Line Monitoring

Line Monitoring System Signals

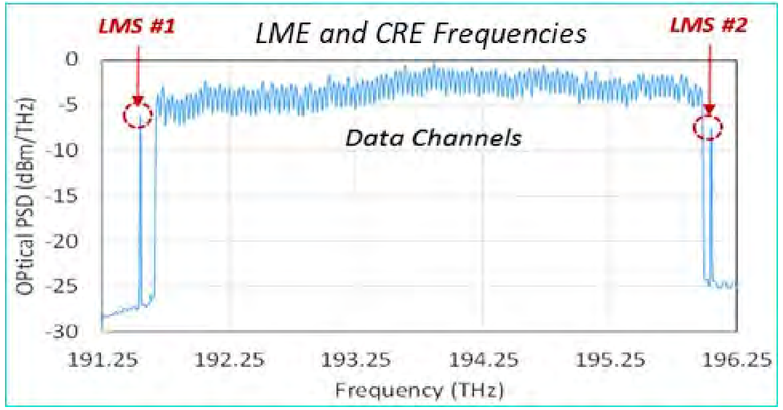
- LMS tones on the short and long wavelength side of the data transmission band

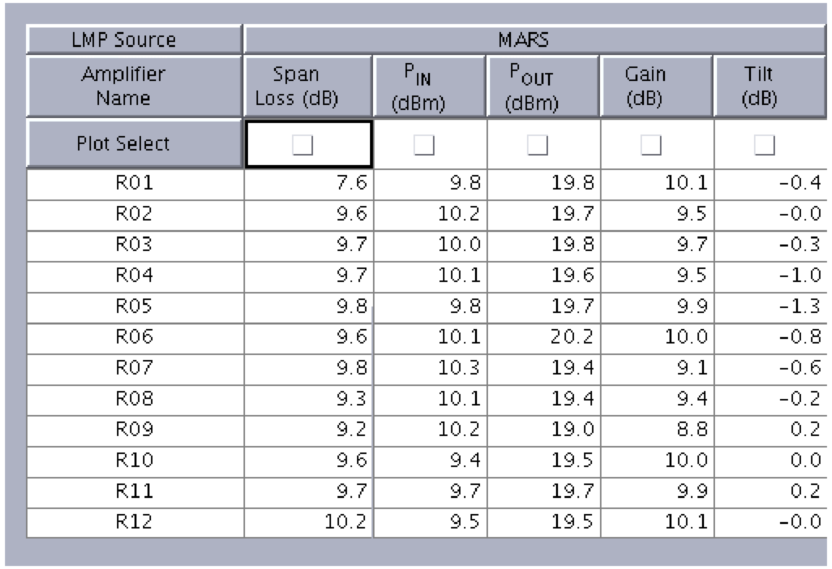
Automated Signal Interpretation

- Automatic Signature Analysis detects changes in loop gain and extracts span loss and repeater output powers.
- Reported parameters include span length, span loss, repeater input and output power levels, and tilt

Active Line Monitoring Systems are also in use

- Input and output power levels detected with photodiodes and reported to shore via command channel





LMP Source	MARS				
Amplifier Name	Span Loss (dB)	P_{IN} (dBm)	P_{OUT} (dBm)	Gain (dB)	Tilt (dB)
Plot Select	☐	☐	☐	☐	☐
R01	7.6	9.8	19.8	10.1	-0.4
R02	9.6	10.2	19.7	9.5	-0.0
R03	9.7	10.0	19.8	9.7	-0.3
R04	9.7	10.1	19.6	9.5	-1.0
R05	9.8	9.8	19.7	9.9	-1.3
R06	9.6	10.1	20.2	10.0	-0.8
R07	9.8	10.3	19.4	9.1	-0.6
R08	9.3	10.1	19.4	9.4	-0.2
R09	9.2	10.2	19.0	8.8	0.2
R10	9.6	9.4	19.5	10.0	0.0
R11	9.7	9.7	19.7	9.9	0.2
R12	10.2	9.5	19.5	10.1	-0.0

Example RPT for One Traffic Direction

Out-of-Service COTDR Measurements

Rayleigh Scattering

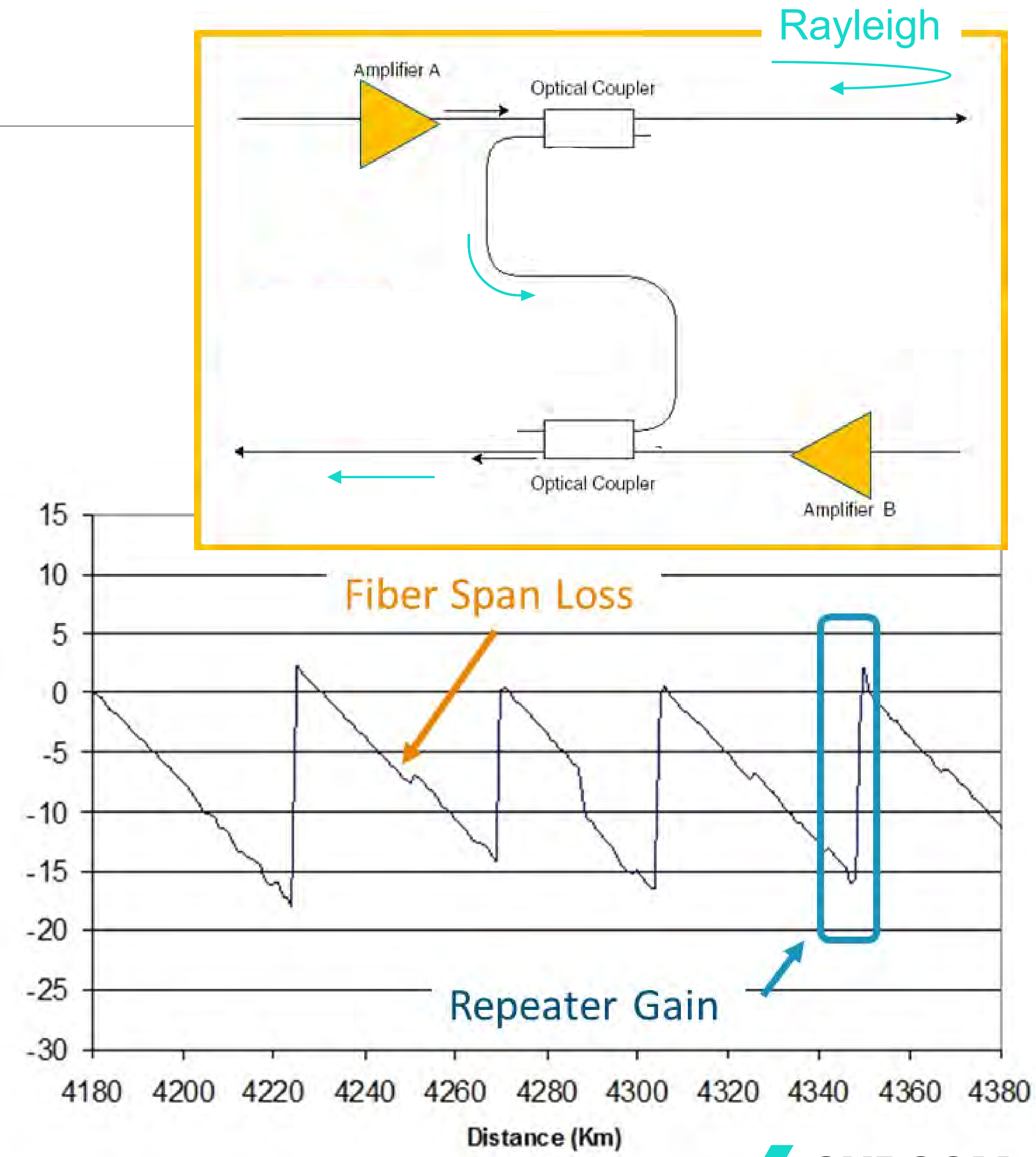
- Fiber reflects optical power back towards the transmitter (< -30 dB)

Optical Time Domain Reflectometry (OTDR)

- Send pulse, look for reflected signal

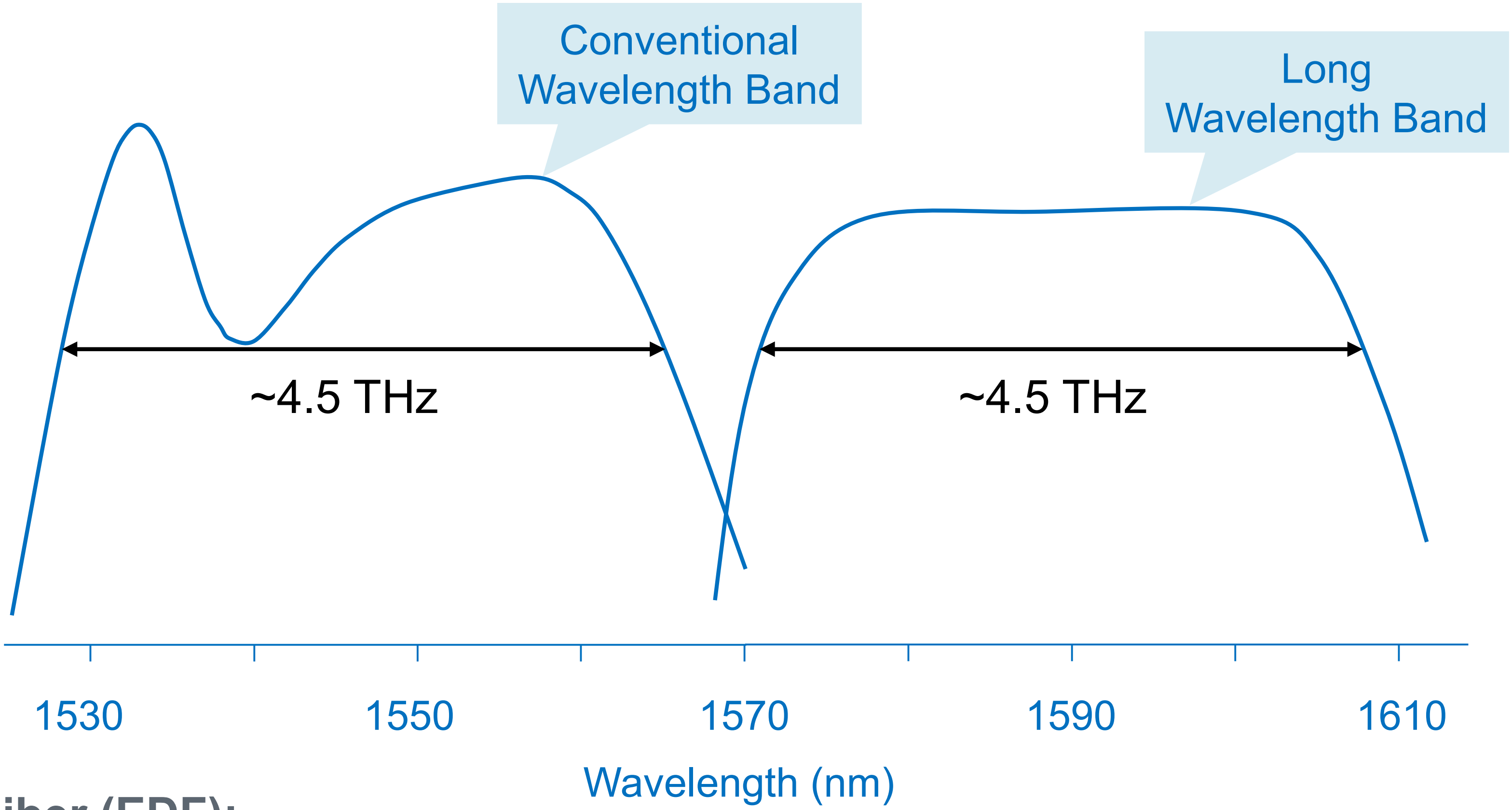
Coherent (Correlation) OTDR (COTDR)

- Send pulse (pattern) on outbound path, look for reflection on inbound path through High-Loss Loopback
- Works over multiple spans for >10,000 km
- **Locate faults with <1km accuracy**



C+L

C+L: Doubling Fiber Pair Bandwidth

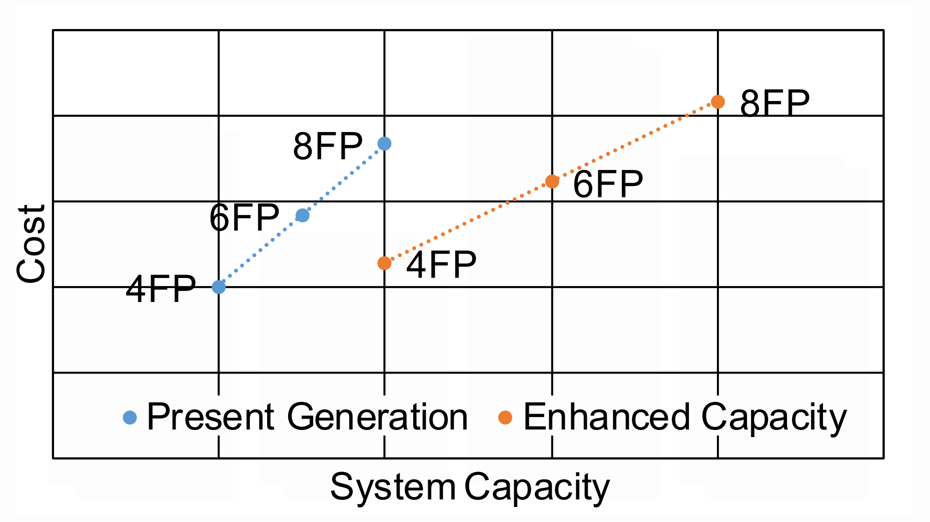


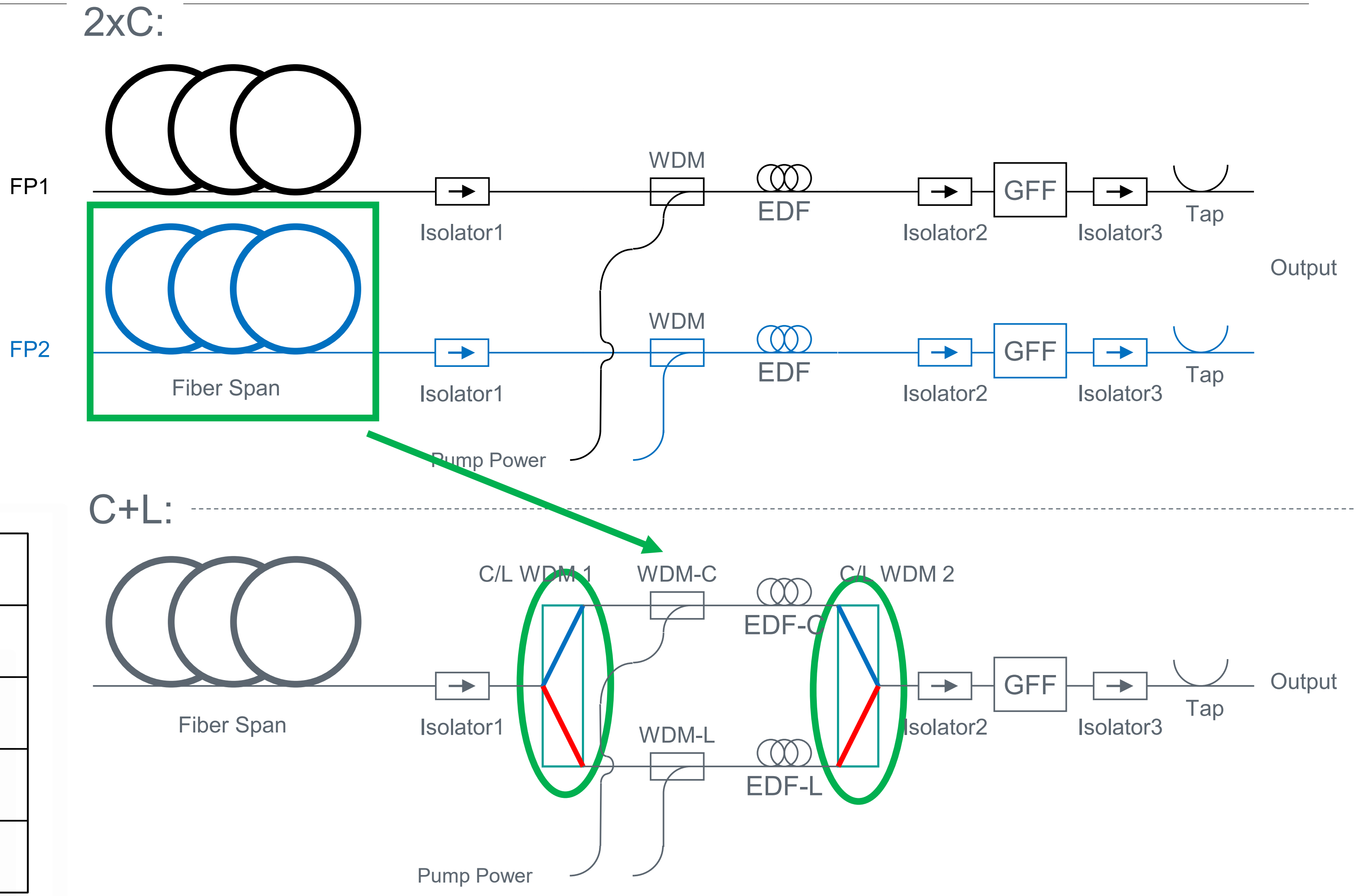
Erbium Doped Fiber (EDF):

- Amplification in the C-band (1529 – 1565 nm)
- Amplification in the L-band (1570 – 1608 nm) (if no light in C-band)

C+L Architecture

- Nearly double the capacity per fiber pair
- Enables compact cable designs with fewer fiber pairs for the same capacity





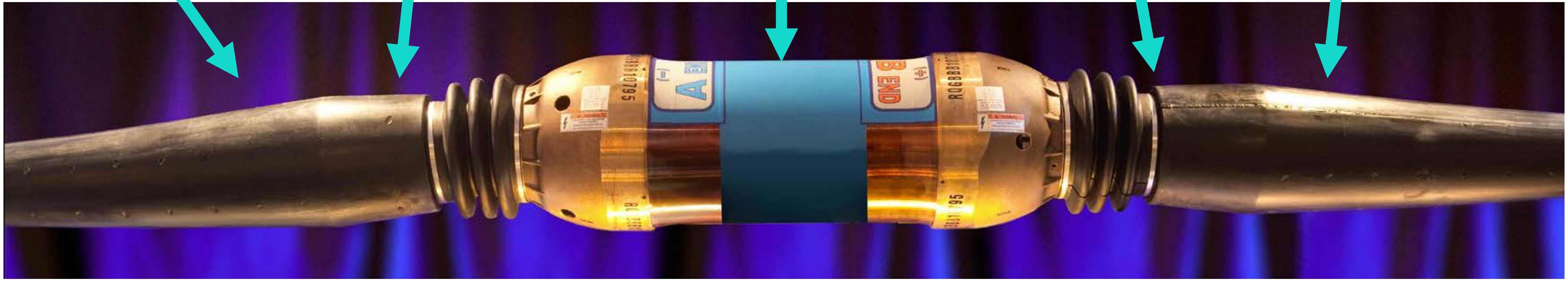
Repeater Mechanical

Pressure Vessel

- Cylindrical shape
- Material: BeCu
  (also Stainless Steel or Titanium)
- Good to 8000m

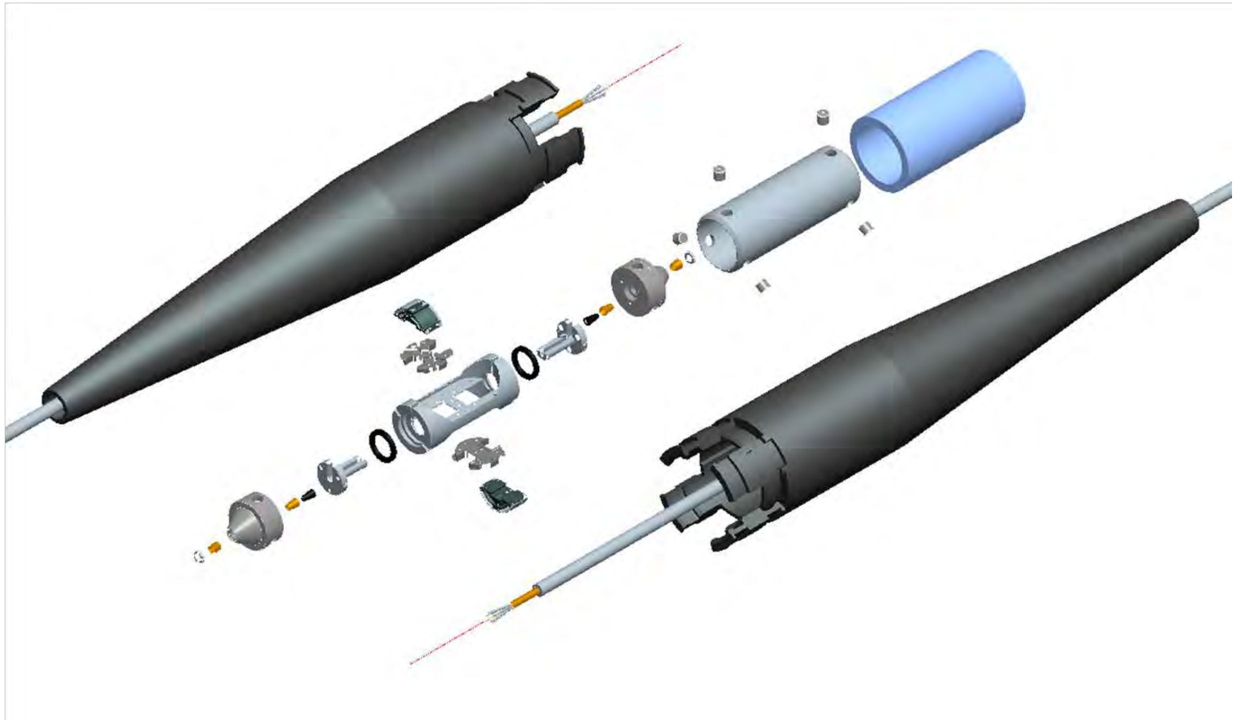
Feature	Nominal Value
Overall Length	498 cm (196 in.) w bend limiting boots
Diameter (largest)	33 cm (13 in)
Design Depth/Pressure	8000 m (~ 12000psi)
Approximate Weight Body with cones	225 kg (493 lb)

Cable Bend Limiter Coupling Pressure Vessel Coupling Cable Bend Limiter

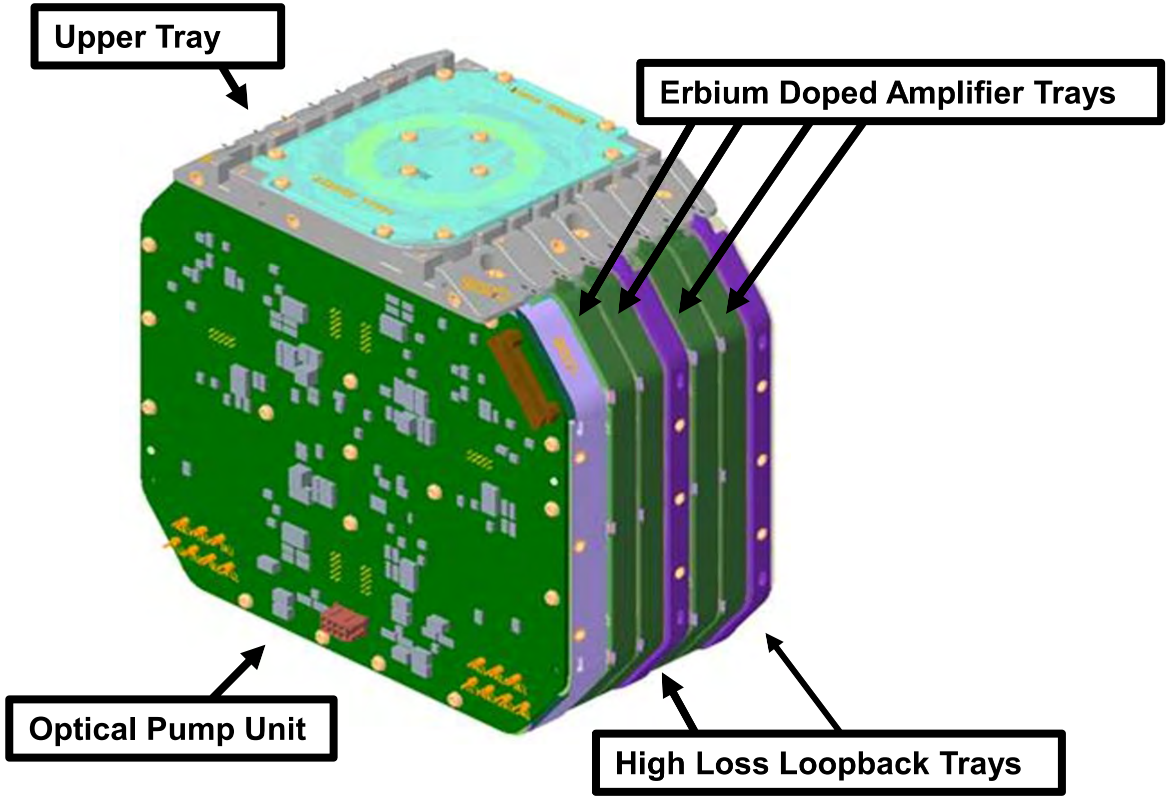


Cable to Repeater Coupling

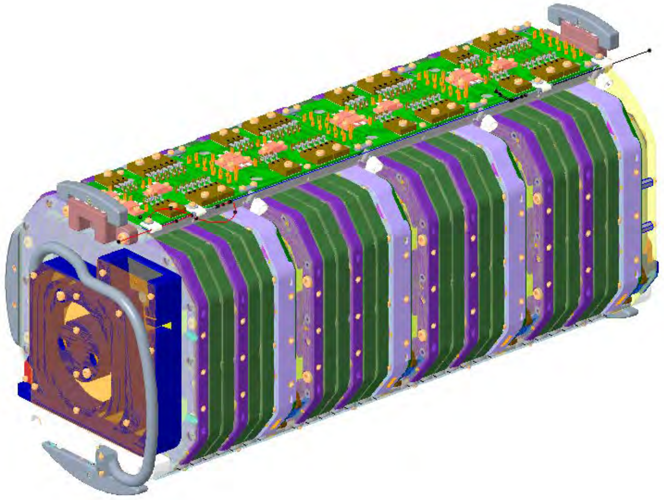
Millennia Joint



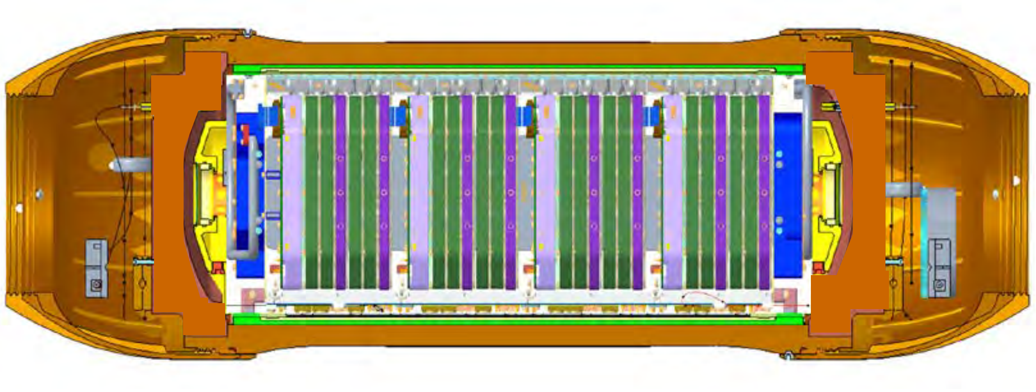
Repeater Mechanical Design – 16 FP Repeater



Dual Amplifier Quad Supports 4 Fiber Pairs

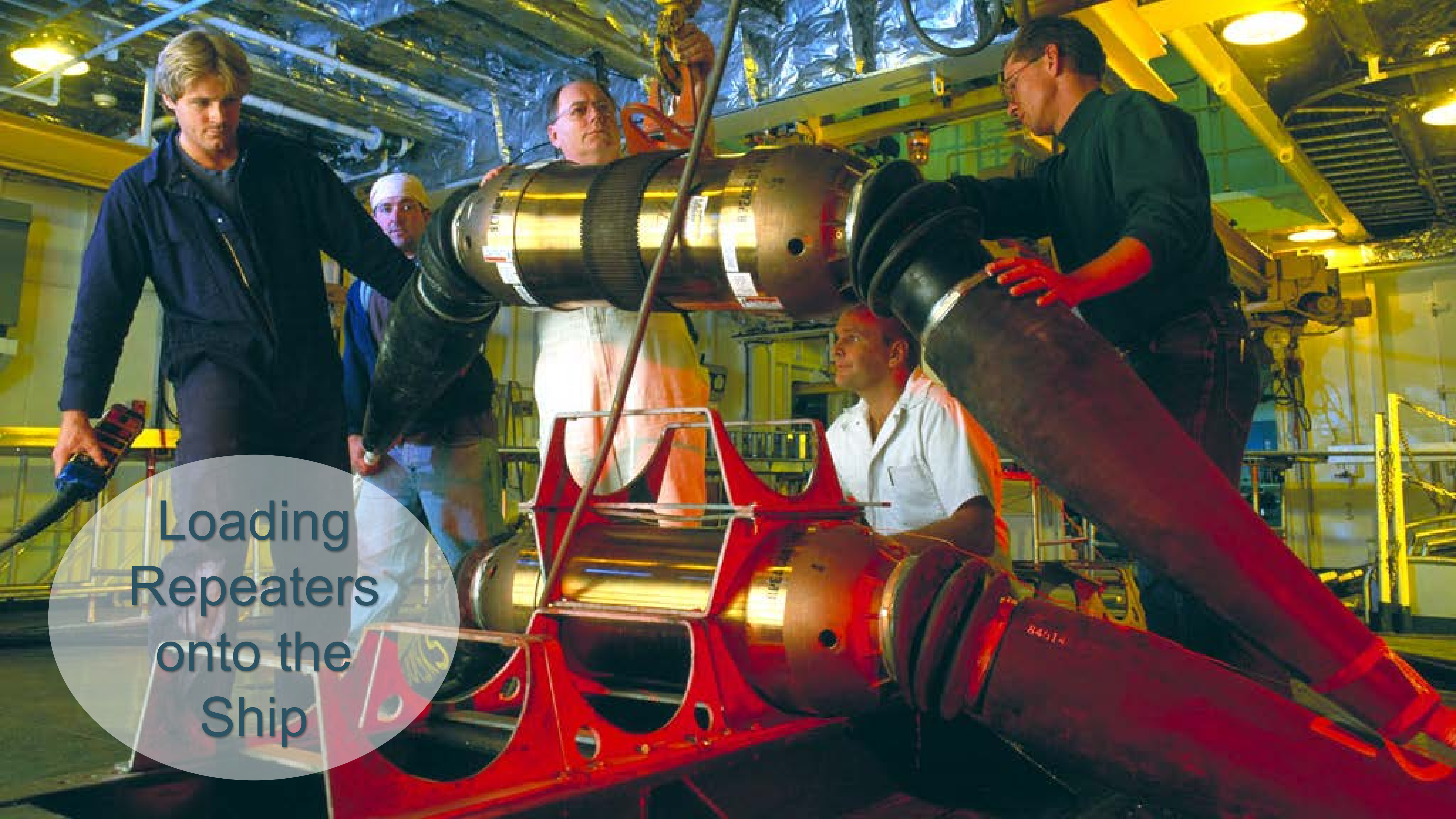


Up to Four Dual Amp Quads in a Network



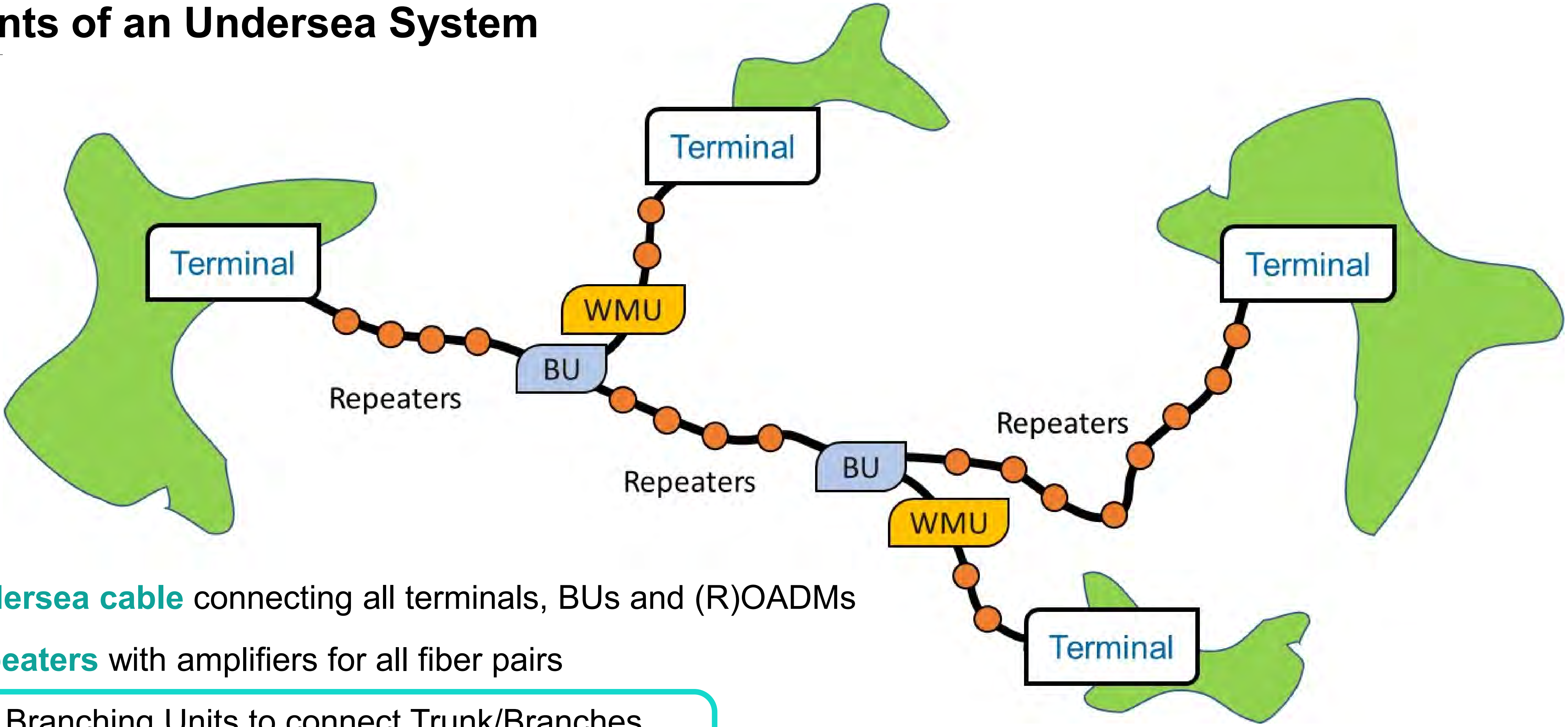
16 FP Repeater Network in Type 300 Repeater Housing

Loading Repeaters onto the Ship



Repeaters on Board Ship Ready for Deployment

Elements of an Undersea System



- **Undersea cable** connecting all terminals, BUs and (R)OADMs
- **Repeaters** with amplifiers for all fiber pairs
- **BU**: Branching Units to connect Trunk/Branches
- **WMU**: Wavelength Management Units – (R)OADM

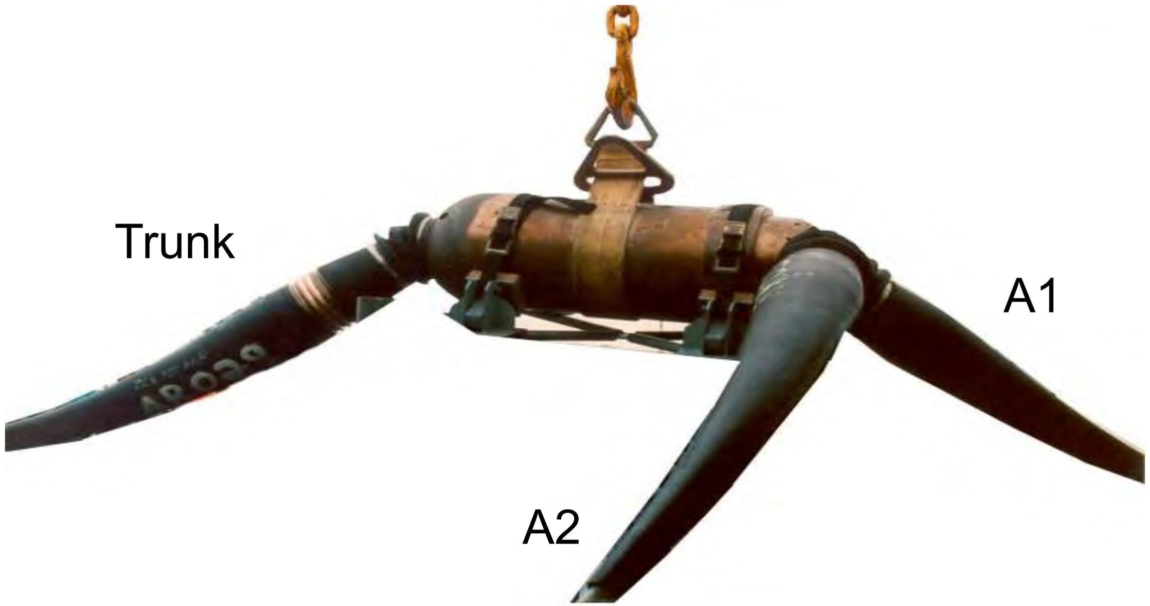
Branching Units

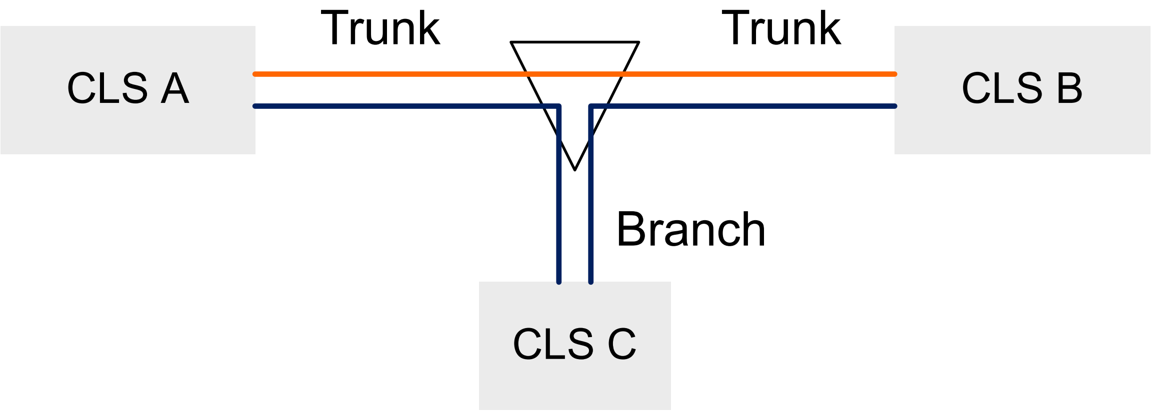
Branching Unit – Fiber Routing

The branching unit (BU) enables connections other than simple point to point

The Branching Unit

- A 3-port device: Trunk, A1 and A2
- Enables the creation of a branch of the main trunk
- Provides fiber routing and optical connectivity between 3 points
- Enables later network expansion





CLS A

Trunk

Trunk

CLS B

Branch

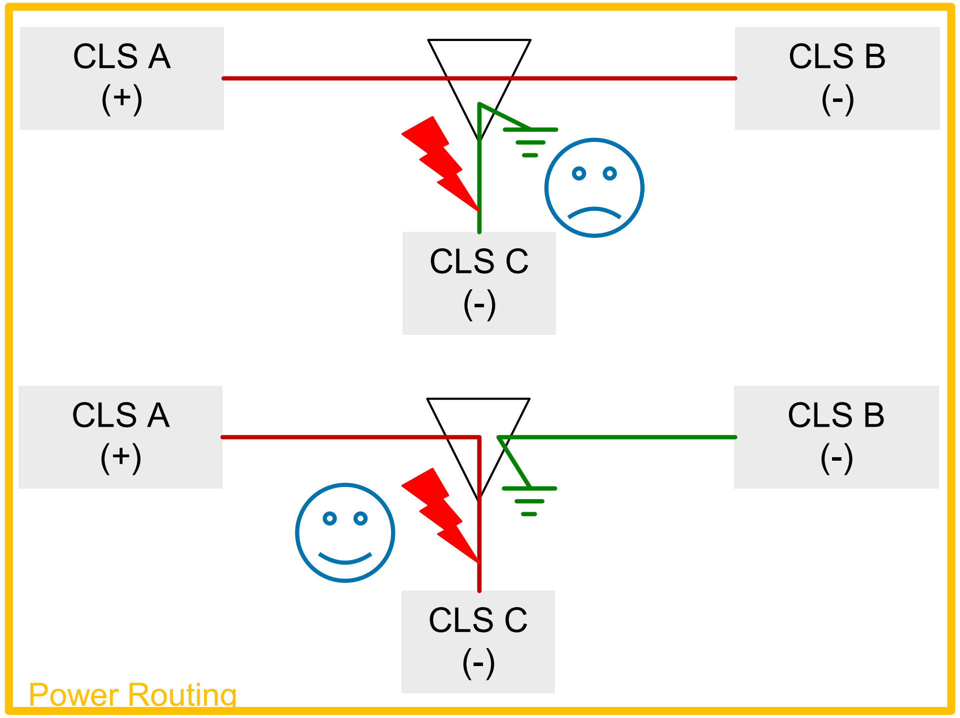
CLS C

Power Switched Branching Unit

The branching unit can also contain remote controlled high voltage relays to enable switching of the power path

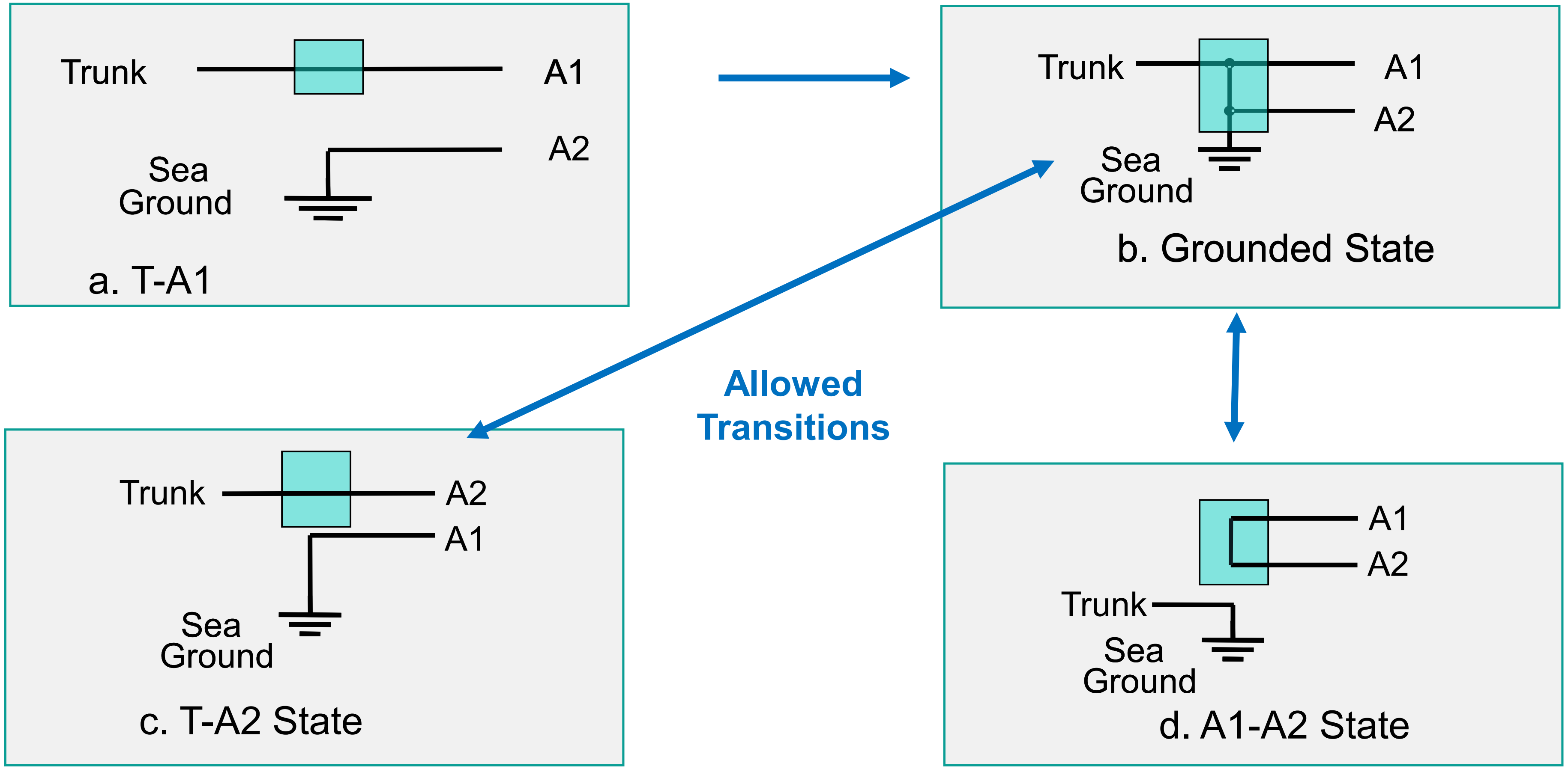
Cable Fault Recovery and Isolation:

- Recover from shunt faults (see also lectures by Katsuji Yamaguchi)
- Maintain traffic on unaffected segments during a ship repair
- Optical command control from shore



Power Switching States in the eBU

Power Switching States for Normal System Operation



a. T-A1

b. Grounded State

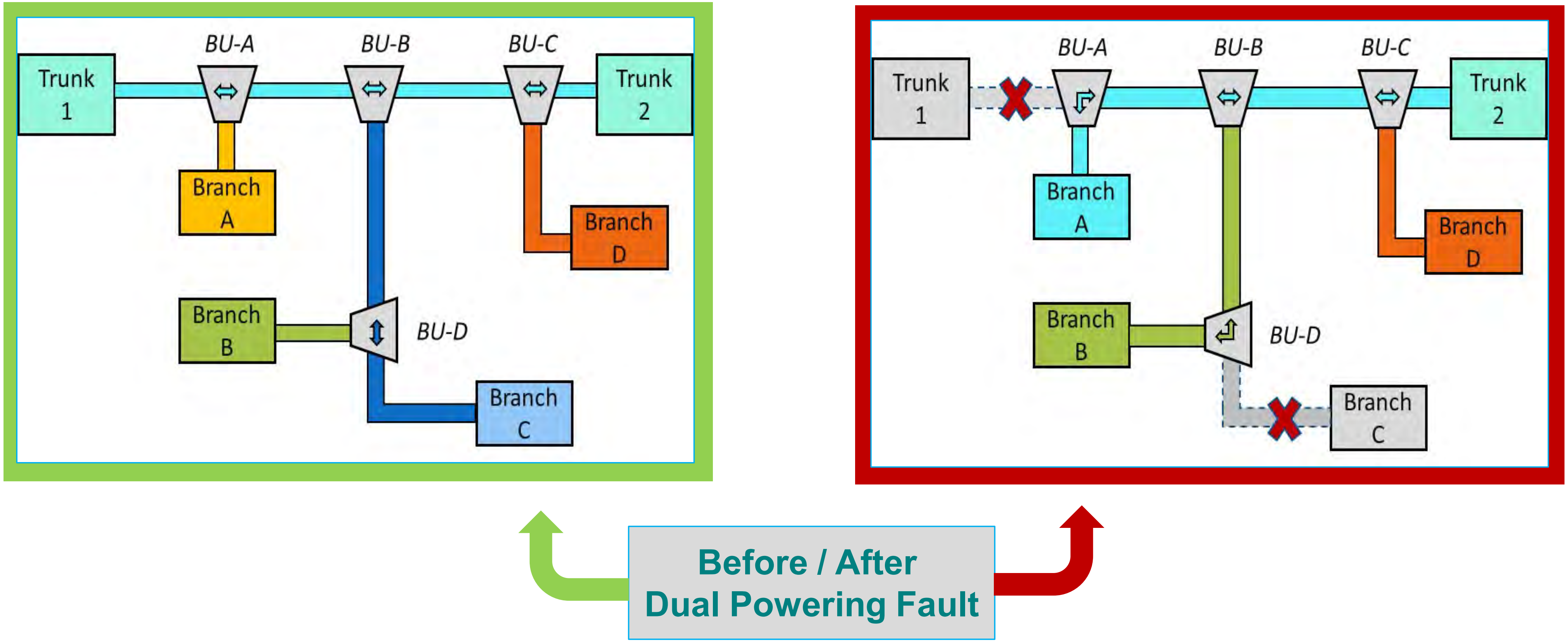
c. T-A2 State

d. A1-A2 State

🟩 - **Powering Electronics**

|

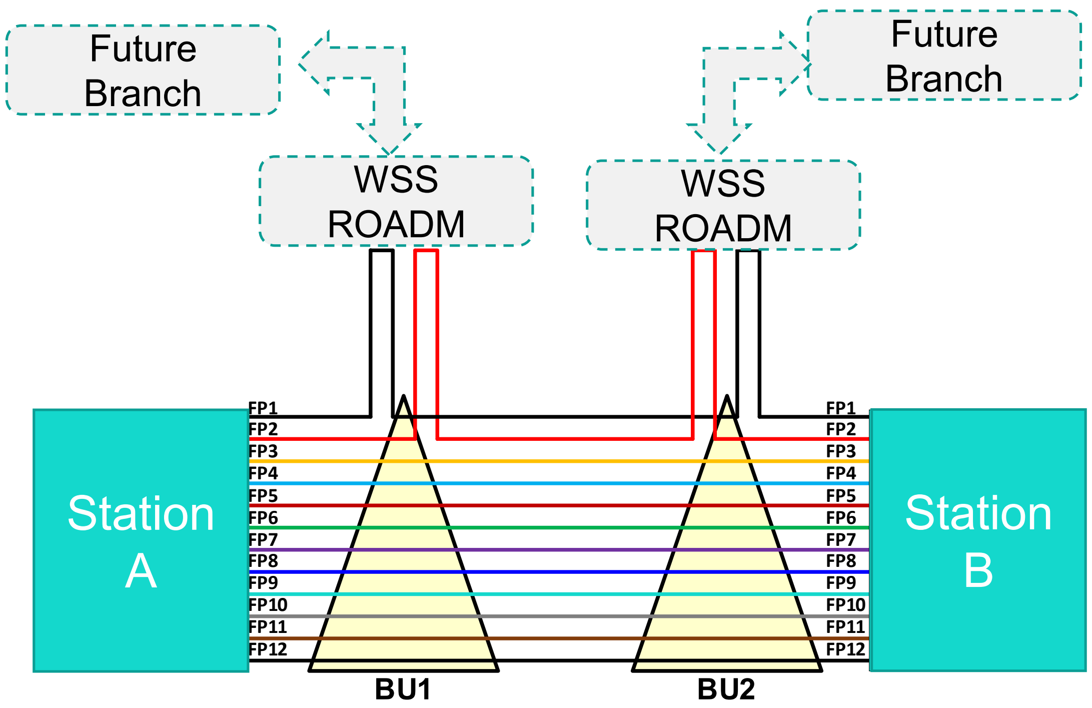
Submarine System Powering with Branches



Before / After
Dual Powering Fault

Powering submarine systems also requires creative architectures.

Future Network Expansion



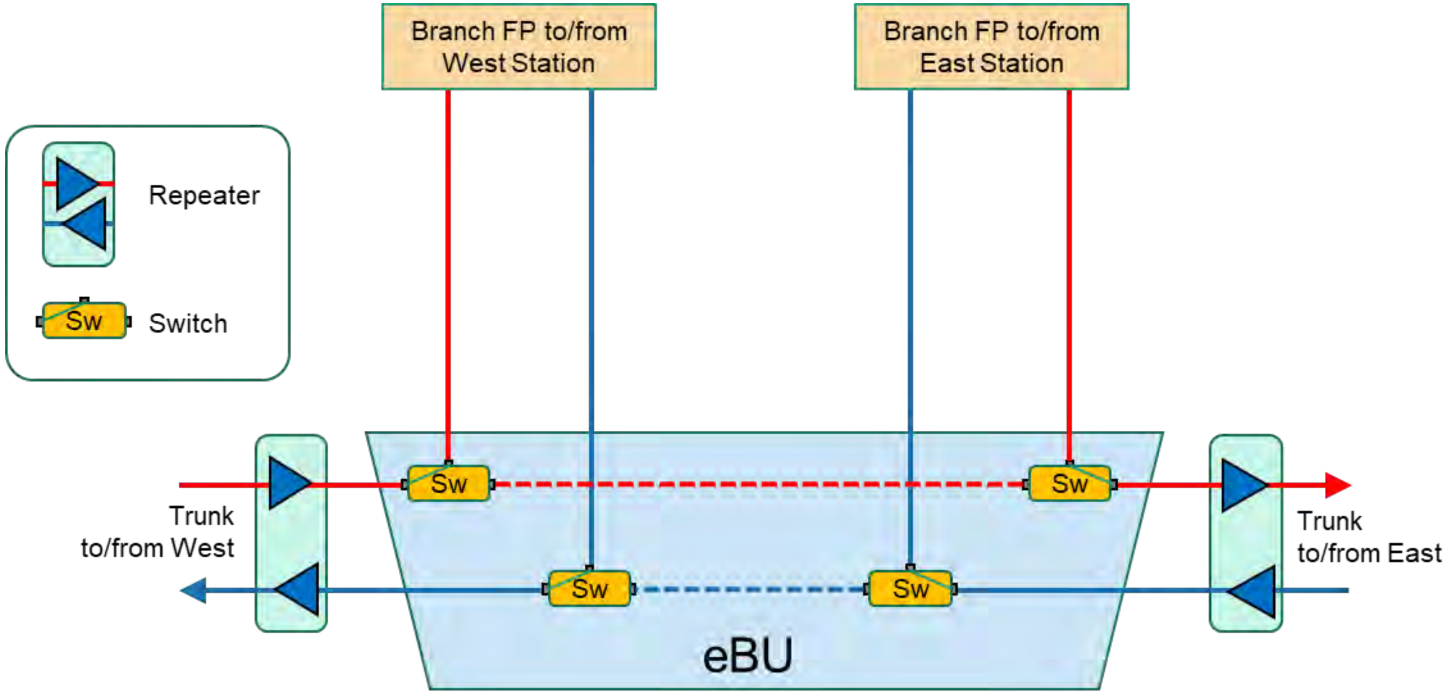
- BUs with stubs can be inserted into a cable to enable future connectivity without cutting into the trunk cable
- Any number of trunk FPs can be accessed for connection to a branch state
- Stubs can also support later addition of WSS ROADM or Dry ROADM.

Branching Unit – Fiber Switching

Today's branching units also contain remote controlled optical switches for even more functionality

User configurable remote fiber switching allows

- Autonomous or/and manual fault recovery
- Isolating the branch for a repair or later network expansion
- Adding and/or re-routing traffic in a branch



Cross-Cable Architectures

Fiber Switched BUs can provide intra-cable connectivity.

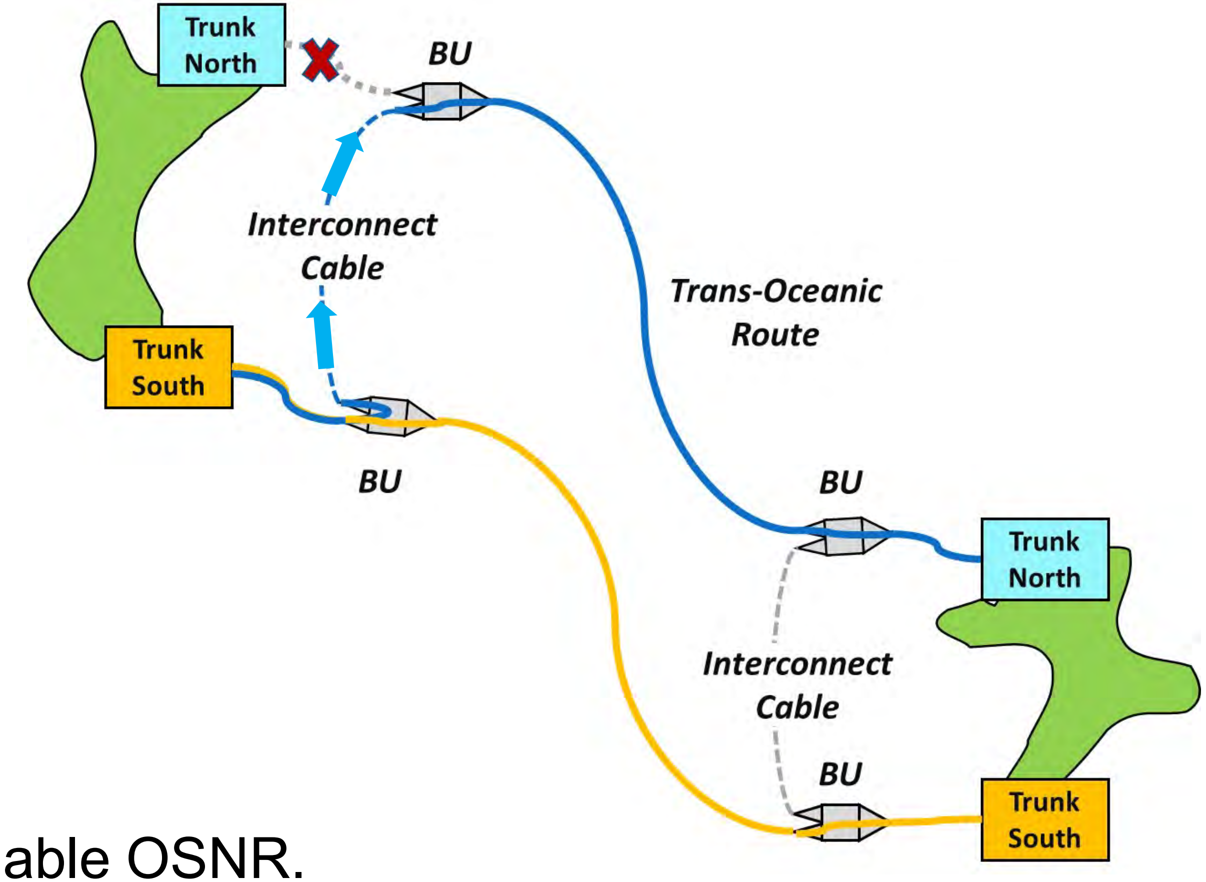
- Use for fault recovery, or for capacity routing flexibility.

Increases overall network availability.

- Protect on a FP basis, or use ROADMs to prioritize spectrum.

Increases path length:

- Could adjust channel data rates to match available OSNR.



Why Only 3-Port BUs?

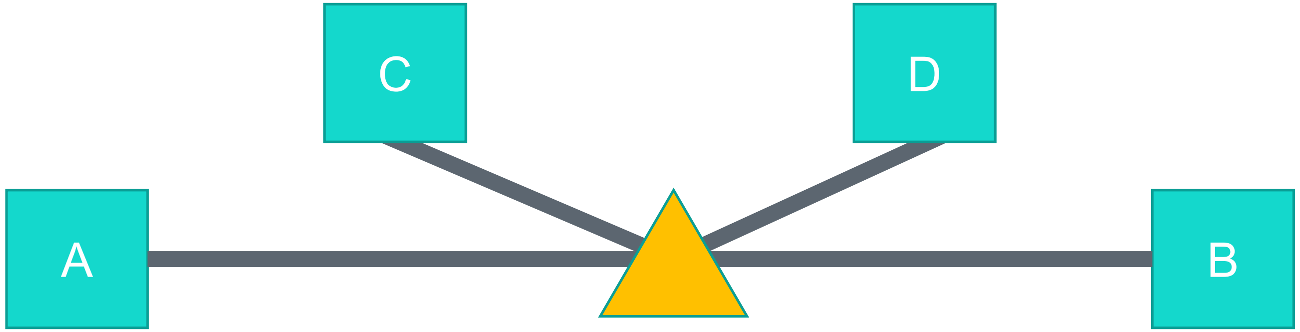
BU placement is typically optimized for overall cable length

- Lower cost
- Lower latency

There are additional marine considerations to best protect the BU

- Seafloor conditions

(4-Port BUs exist for special applications)



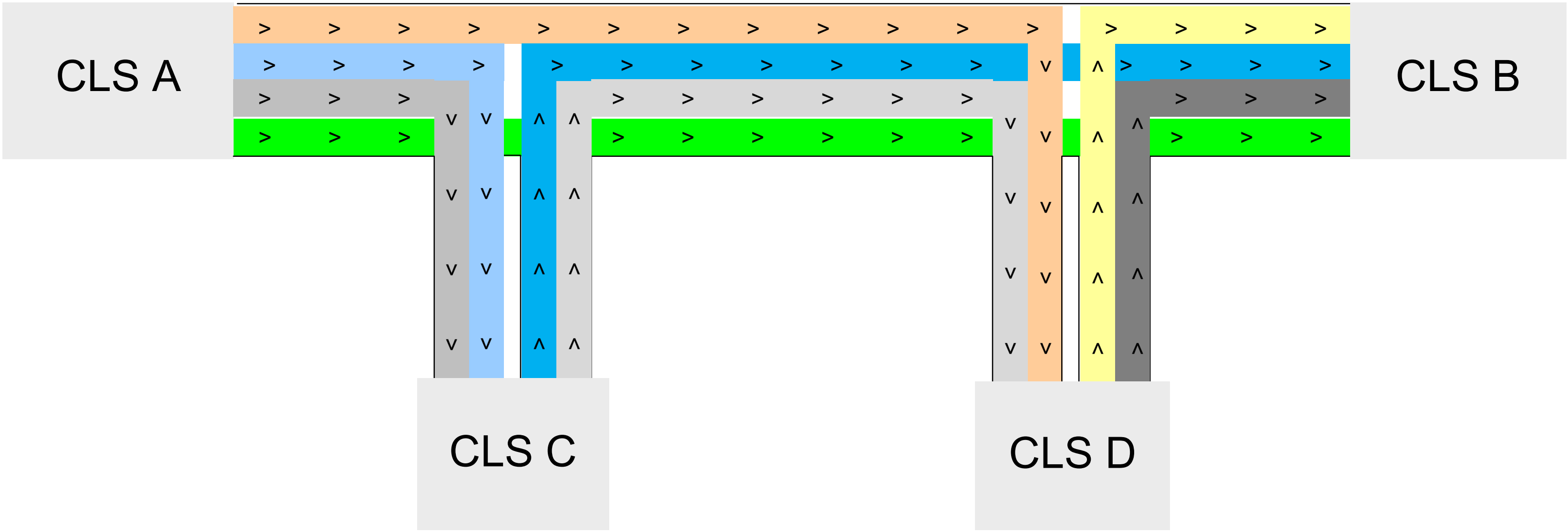
4-Port BU

Optical Add Drop Multiplexing

Undersea Optical Add Drop Multiplexing (OADM)

Enhanced Connectivity options

Multiple DLS on a single fiber pair



Wavelength Re-use

Bandwidth on a trunk fiber pair can be used for multiple DLS

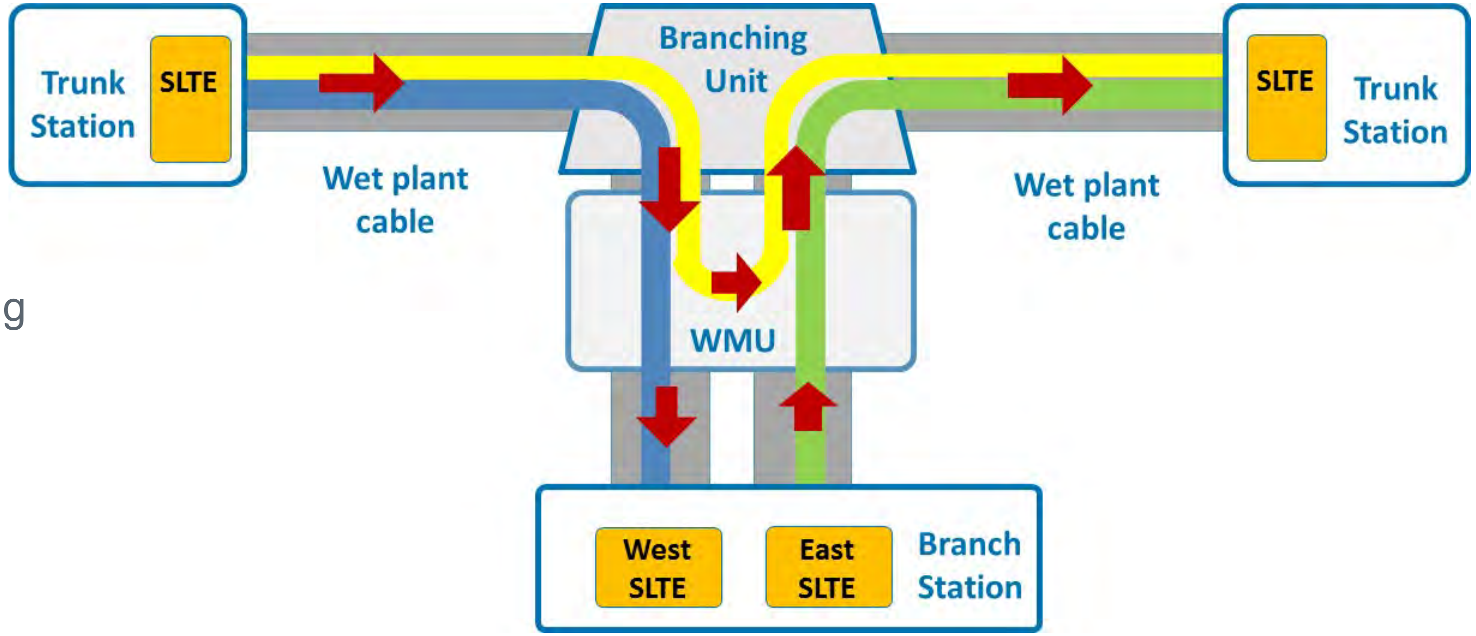
Optical Add/Drop Multiplexing (OADM) Node

Components in an OADM Node include:

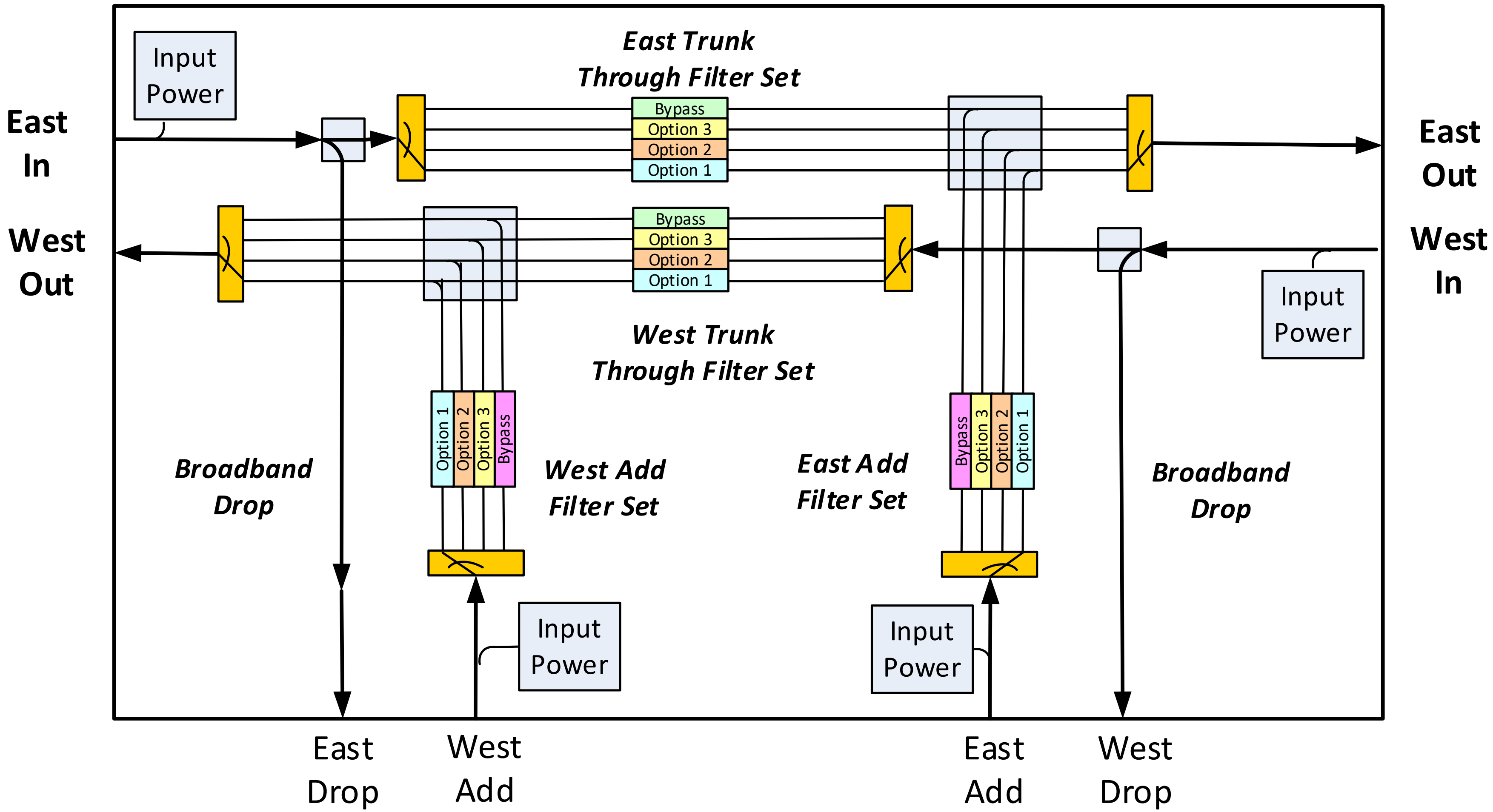
- Branching Unit
- OADM Unit:
    - Passive fixed filtering
    - Switchable filtering
    - Wavelength Selective Switch based filtering

Modular OADM options:

- OADM unit can be deployed when the branch is landed
- Simplified sparing (universal spare for BU)
- Repair operation does not affect express fiber pairs



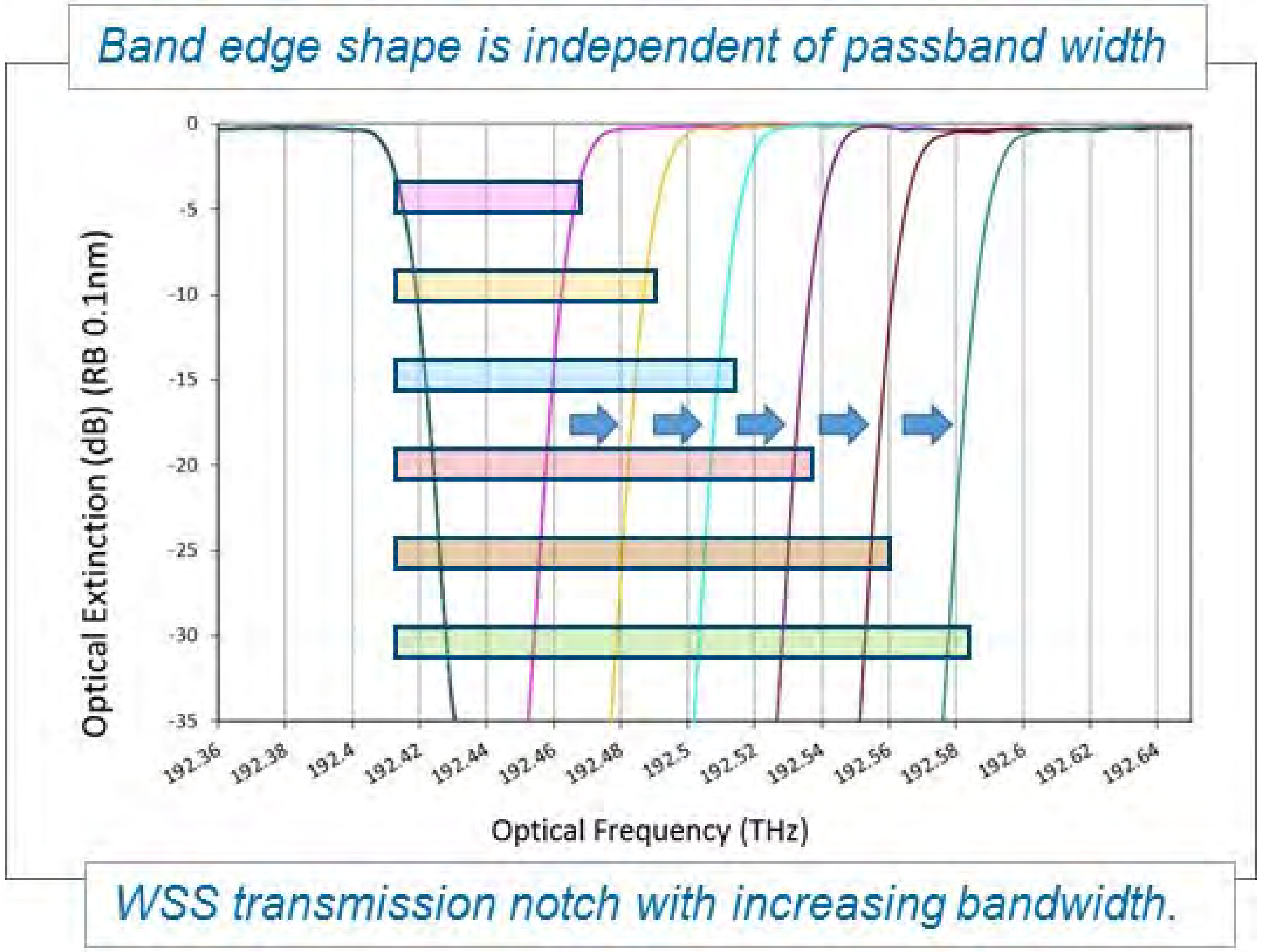
Switched Filtering



Wavelength Selective Switch

The Wavelength Selective Switch (WSS) is a pixelated device that supports reconfigurable filtering

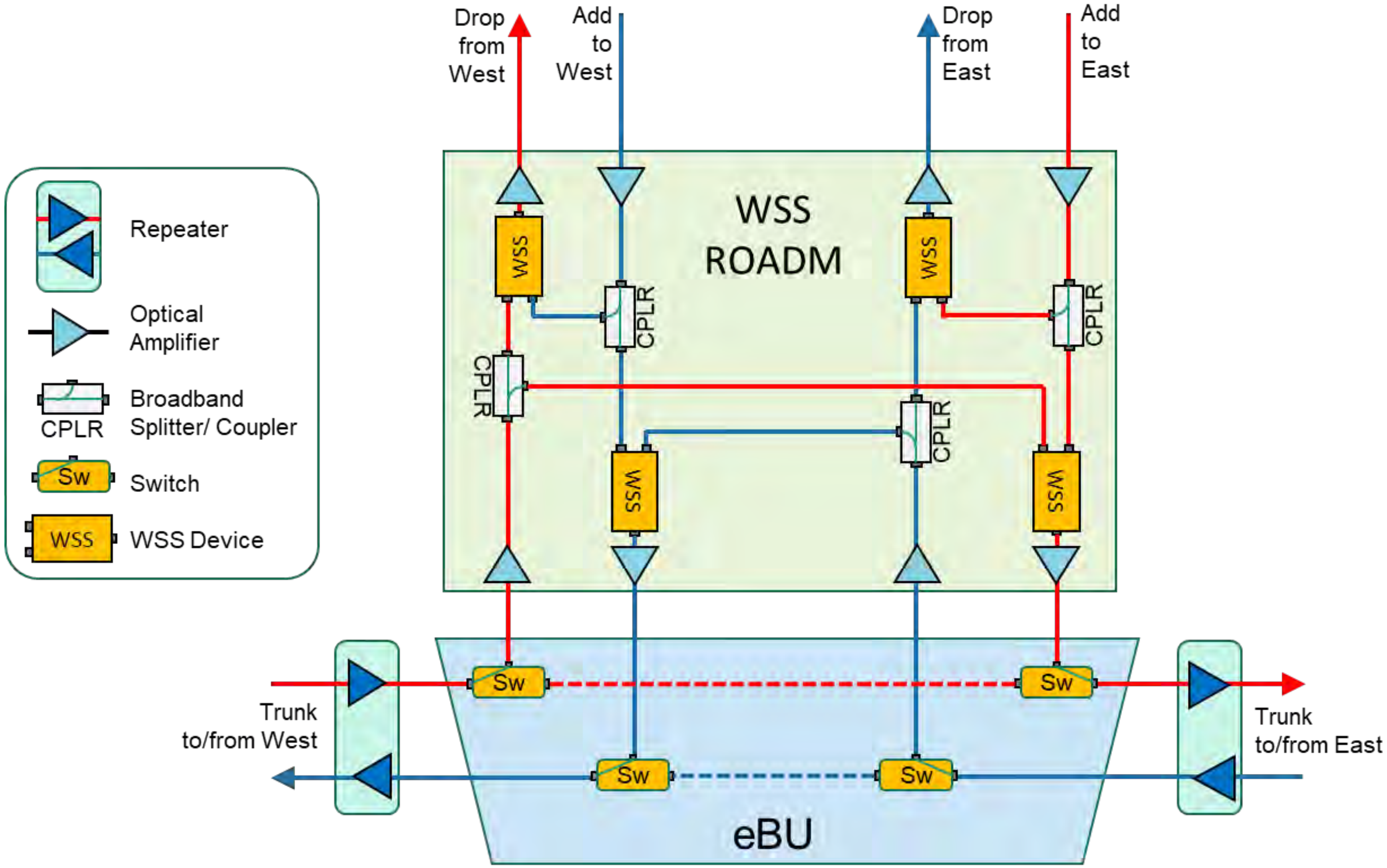
- Key specifications:
  - Grid-flexible channel plan with a fine granularity e.g. 6.25 GHz
  - Very steep filter edges
    30 dB transition in approximately 20 GHz



Band edge shape is independent of passband width

WSS transmission notch with increasing bandwidth.

Branching Node Example: PSBU + WSS ROADM

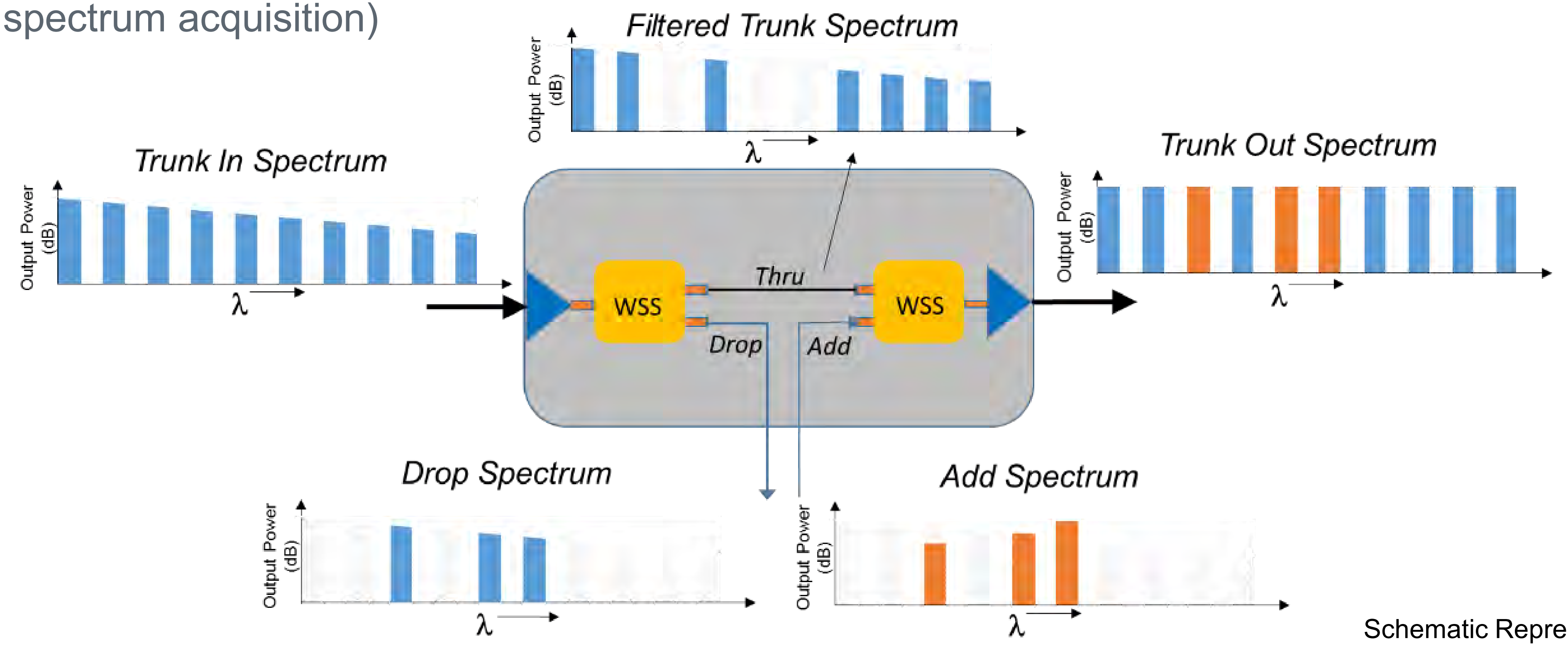


- Bi-directional Branch Access
- WSS Filtered Add/Drop
- Automatic bypass switching provided by eBU

Reconfigurable Optical Add Drop Multiplexing

Wavelength Selective Switch based OADM nodes support

- In service, gridless capacity reallocation
- Inline dynamic gain equalization
- (Optical spectrum acquisition)



Schematic Representation

* Schematic representation

System Reliability

System Reliability

System Design Life is typically 25 years

Transmission affecting failures require ship intervention

- Costly
- Takes time

Design for reliability

- High reliability components
- Redundancy

Expected number of ship repairs due to intrinsic failures is in the range of 0-3 depending on system size and complexity

Failures in Time

Failure Rate

- A common measure for failure rate is FIT, defined as the number of failures in 10^9 device hours (114,046 years).
- Use average failure rate λ
- Probability of failure is

$$\boxed{P_{fail} = 1 - e^{-\lambda t_{System}}} ,$$

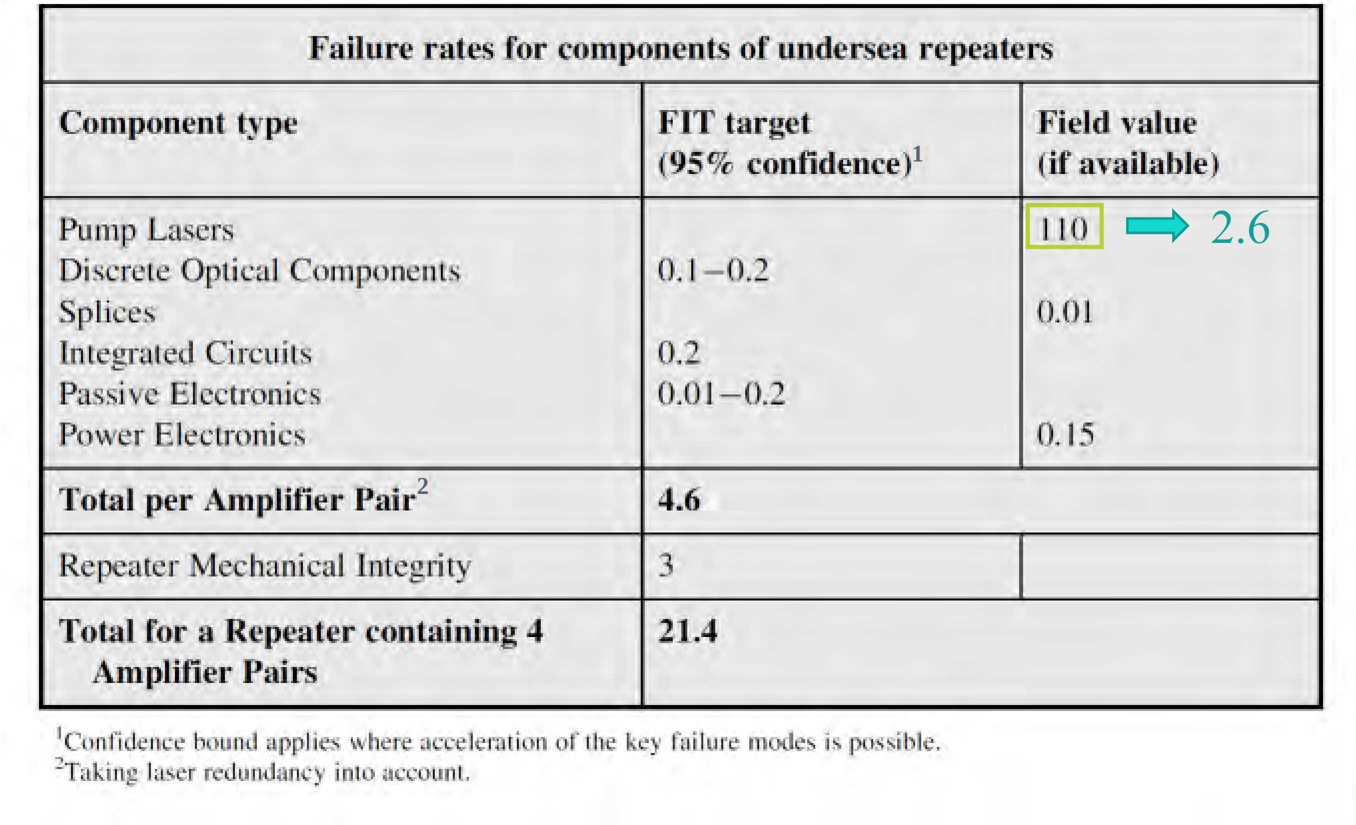
where t_{System} = 25 years

- Effective failure rate for redundant components (n=2 for 1x1)

$$\lambda_{effective} = \frac{-\ln(1 - P_{fail}^{n})}{t_{System}}$$

- Total FIT is the sum of all single points of failure (including effective FIT rate from redundancy)
  - Reliability: $R=1-P_{fail}$

110 FIT means 2.4% will fail in 25 years



Failure rates for components of undersea repeaters

Component type	**FIT target (95% confidence)**[1]	**Field value (if available)**
Pump Lasers		110 → 2.6
Discrete Optical Components	0.1–0.2	
Splices		0.01
Integrated Circuits	0.2	
Passive Electronics	0.01–0.2	
Power Electronics		0.15
Total per Amplifier Pair[2]	**4.6**	
Repeater Mechanical Integrity	3	
Total for a Repeater containing 4 Amplifier Pairs	**21.4**	

[1] Confidence bound applies where acceleration of the key failure modes is possible.

[2] Taking laser redundancy into account.

From *Undersea Fiber Communication Systems* 2nd Edition
by Jose Chesnoy (Editor), Academic Press ISBN: 978-0128042694

Ship Repairs

- Failures are Poisson distributed.
- The expectation value of the distribution is the number of ship repairs.
- For Poisson the expectation value corresponds to the failure rate

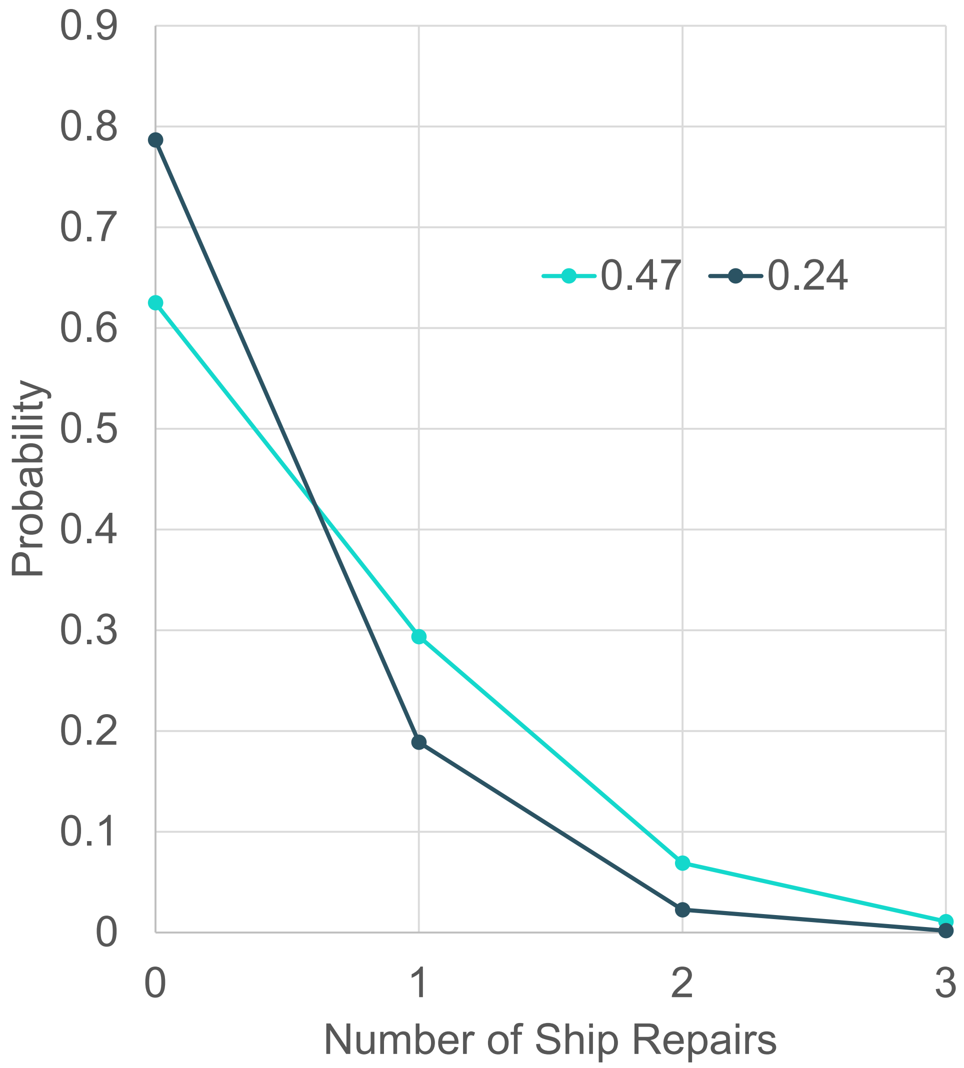
Example

- 100 Repeaters
- 4 Fiber Pairs

Example for Repeaters Only

- 800 Pumps (110 FIT)
- 19 Pump failures in 25 years
- 4x4 pump redundancy: no repeater failure due to pump failure

- Repeater: 11 FIT
- Expected number of ship repairs in 25 years: 0.24



External Aggression

Majority of cable failures are due to external events:

- Ship anchors
- Earthquakes and mud slides
- Abrasion

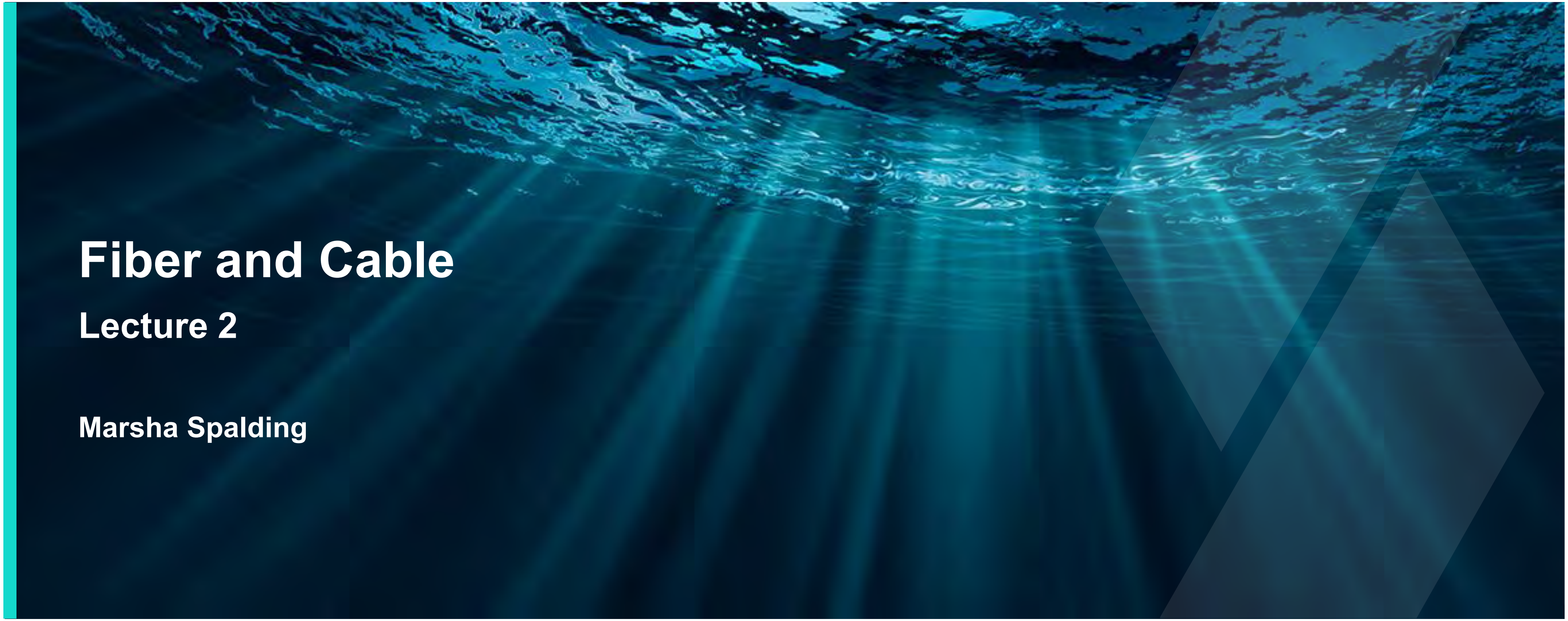
Good reasons to armor or bury cable near shore.

Summary

- Cable
- Repeaters
  - Amplification and gain equalization
  - Self-healing of a chain of amplifiers; gain tilt
  - Pump manifold and reliability
  - Line Monitoring and High Loss Loopbacks (HLLBs)
  - L-band amplification
  - The pressure vessel
- Branching Units
  - Fiber routing and optical switches
  - Electrical reconfiguration – Recovering from shunt faults
- Wavelength Management Units: (Reconfigurable) Optical Add Drop Multiplexing
- System Reliability

Thank You

SUBCOM



Fiber and Cable

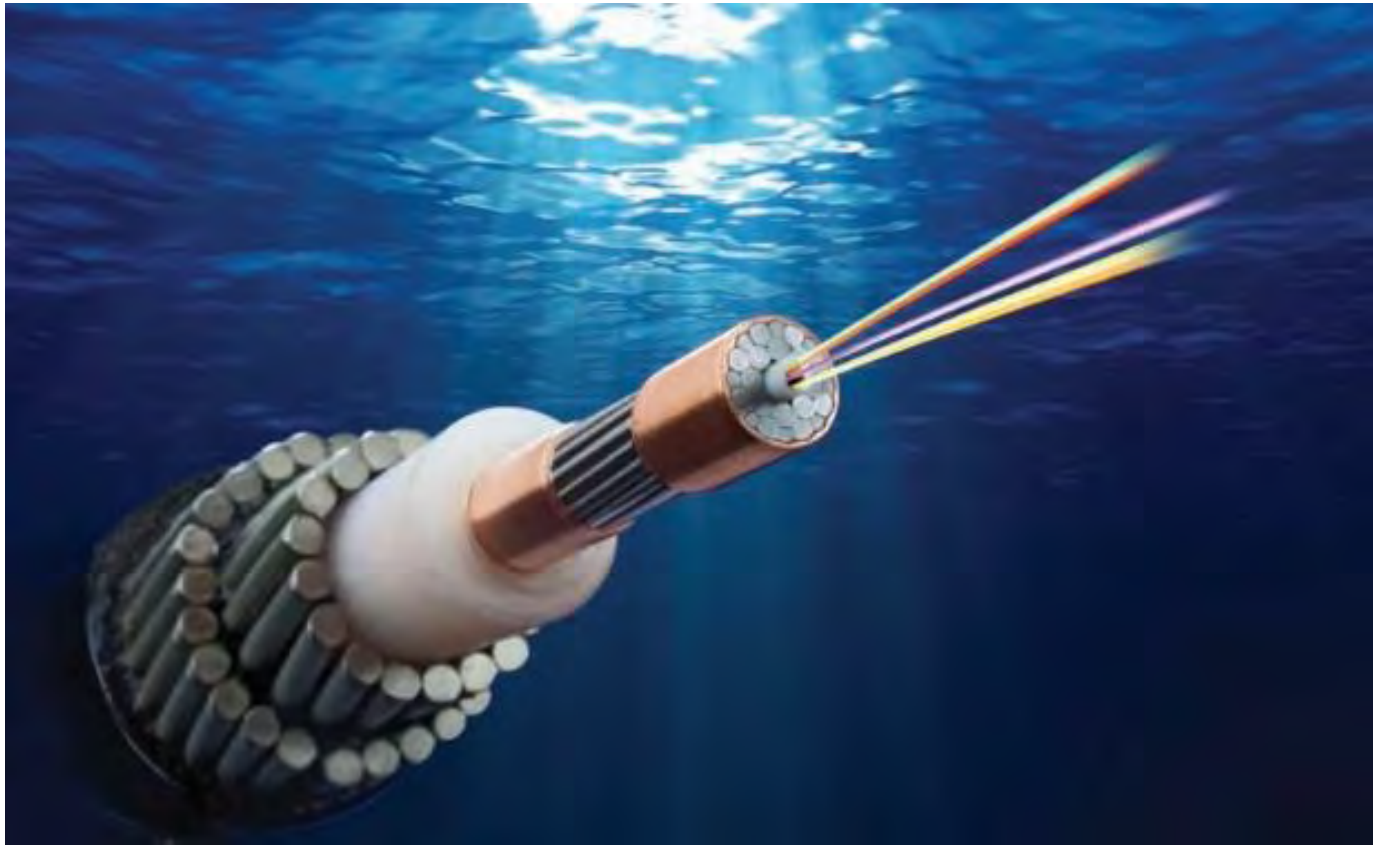
Lecture 2

Marsha Spalding

August 8, 2019

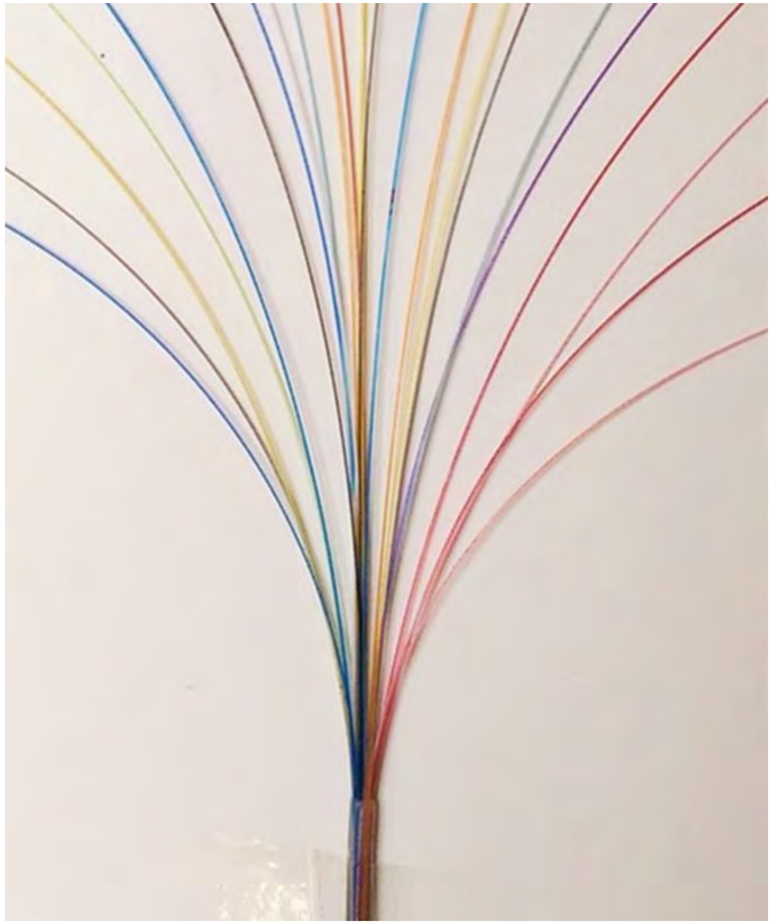
Outline -- Cable

- Primary Cable Functions
- Foundations of Design
- Cable Types and Families
- Cable Characteristics and Handling
- Cable Qualification
- Cable Manufacture
- New Challenges

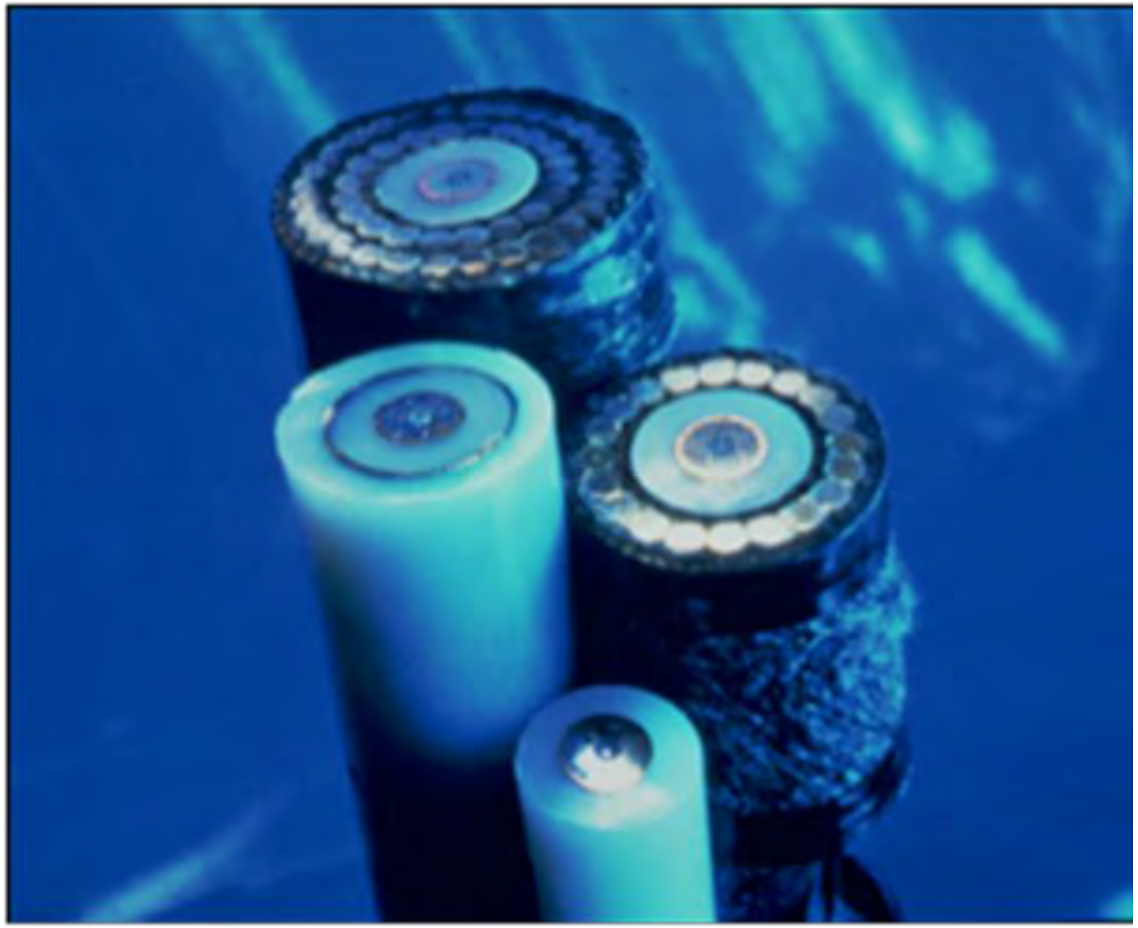


Fiber and Cable Go Hand in Hand

Optical Fiber is the **Heart** of the Cable System



Cable **Protects the Fiber** and **Carries Power**



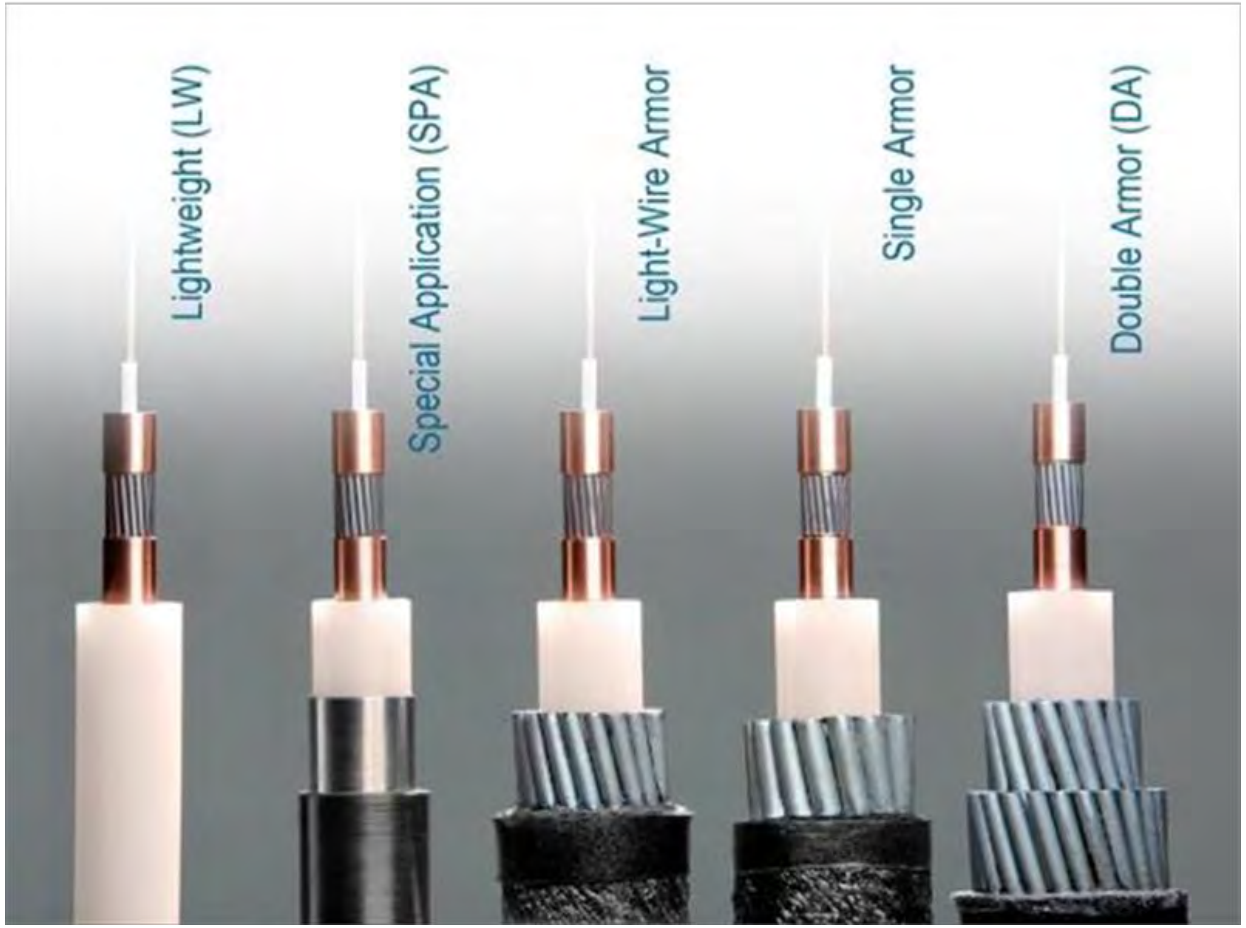
High Level Functionality

Fibers: Benign environment for optical fibers

Strength: For deployment and recovery

Electrical: Power for repeaters and network elements

Armoring: Protection against external aggression



Primary Cable Functions

Protect the Fiber

Benign Environment against:

- Tensile stress
- Bending (cushion)
- Pressure
- Water diffusion
- Hydrogen penetration

Longevity:

- Abrasion Resistance
- Water penetration resistance (cable cut)

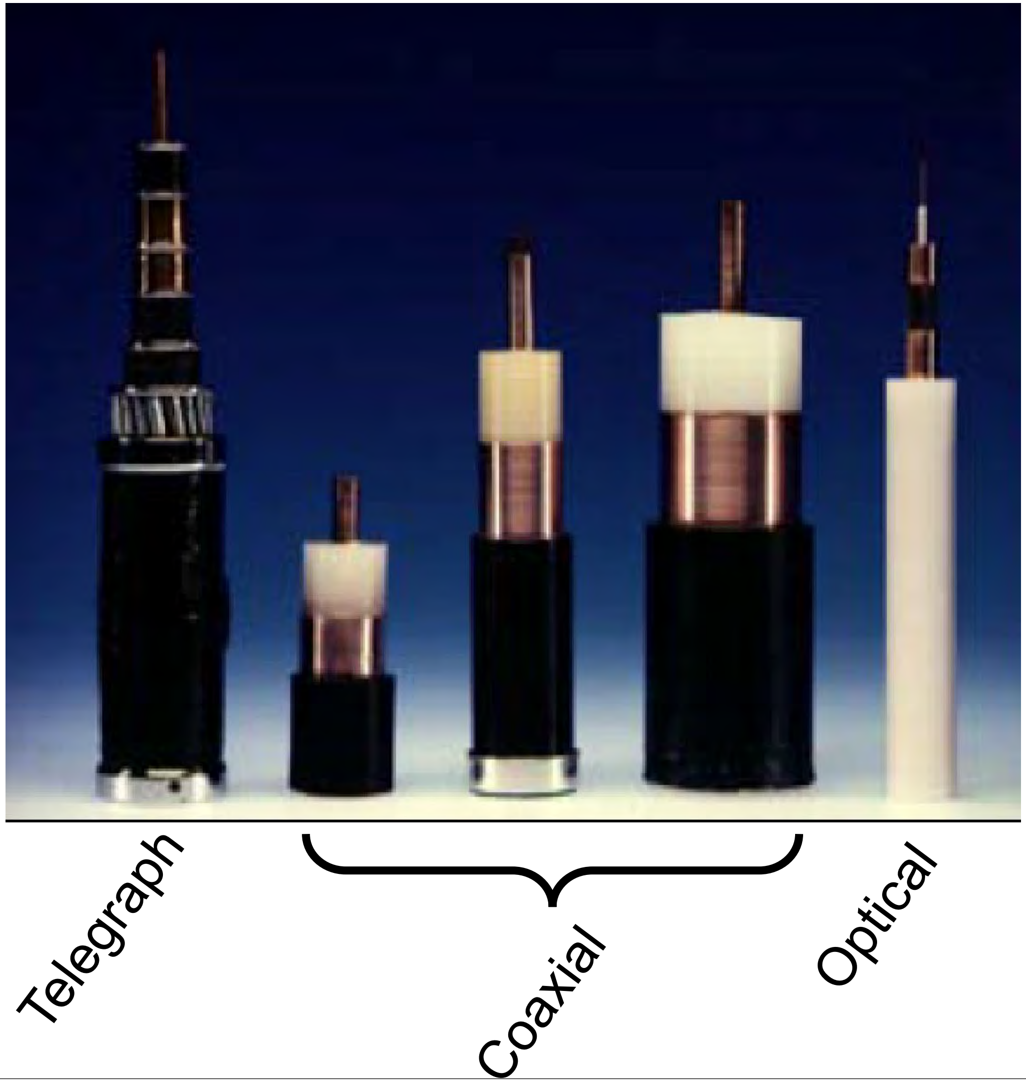
Carry the Power

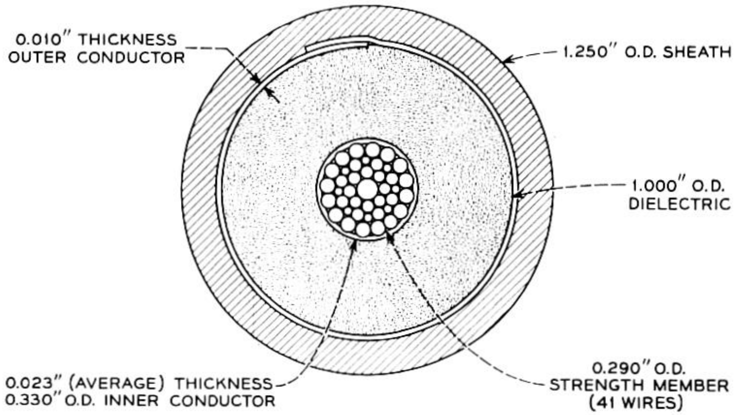
Powering:

- Low electrical resistance conductor
- Insulation from Sea Ground

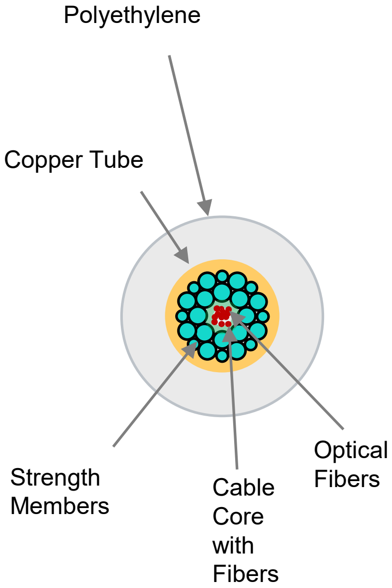
Foundations of Design

Learning from our Forefathers





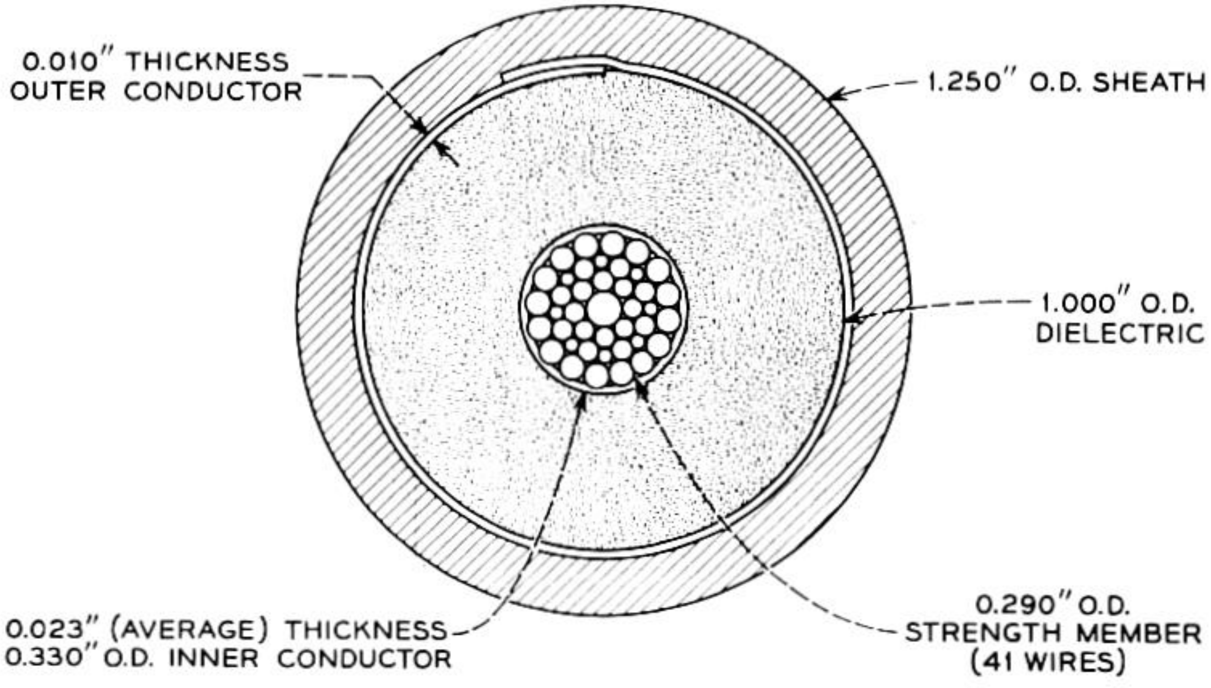
SD Coaxial Cable



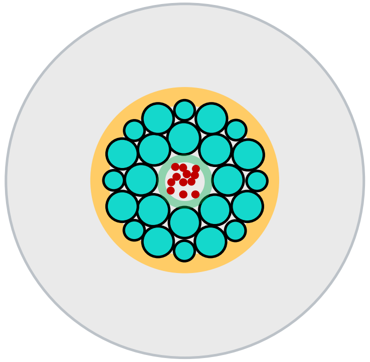
SL Optical Cable Concept

Foundation of Design -- Steel Strand Wire Configuration

Interlocking Strength Members Resist External Pressure – *Tried-and-True Cable Design*



SD Cable



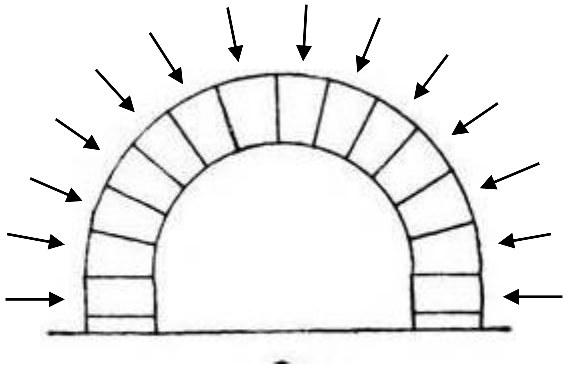
SL Cable

- Re-sized first two layers of SD interlocking steel wires

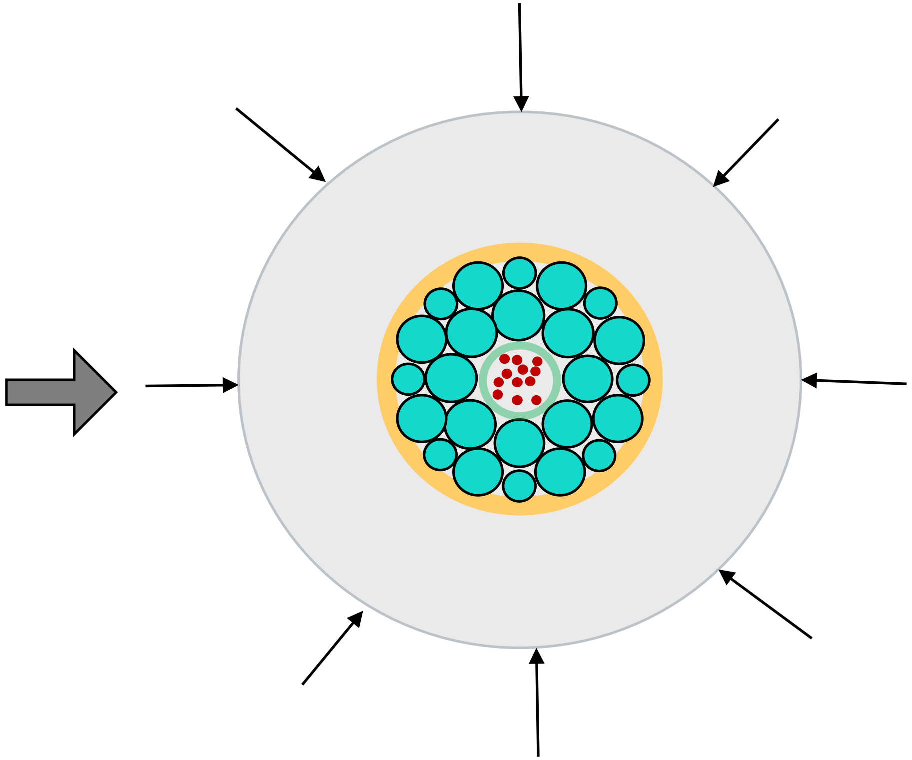
Steel Strand Wire Approach

Interlocking Strength Members Resist External Pressure

Pressure



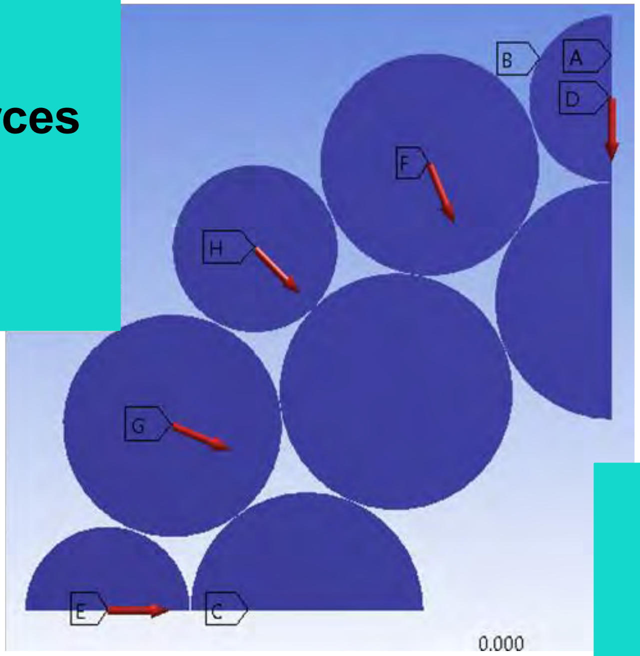
Hydrostatic Pressure



Steel Strand Wire Package Analysis

Finite Element Modeling - Compressive Load on Strand Wire Package

Compressive Radial Forces Studied



Strand Package Stability Confirmed

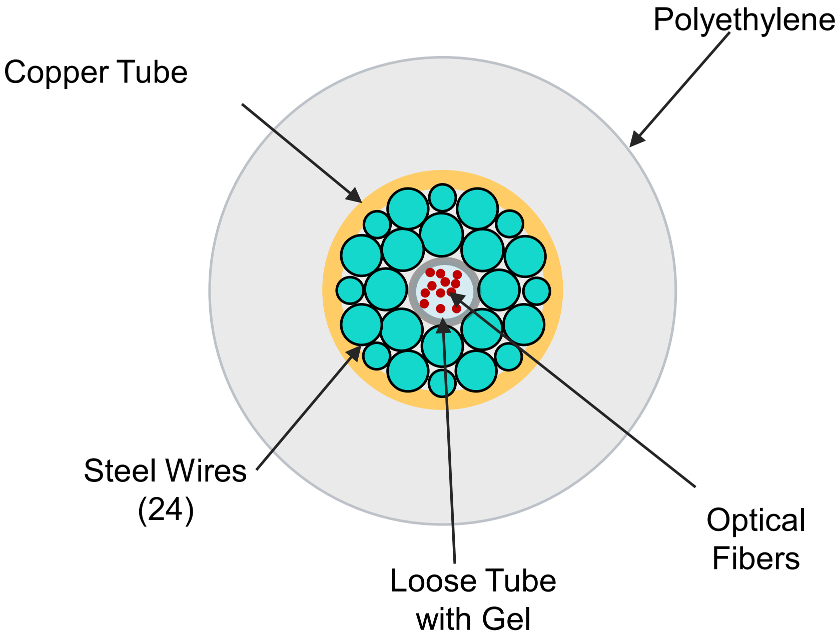
Functionality Satisfied -- Simply

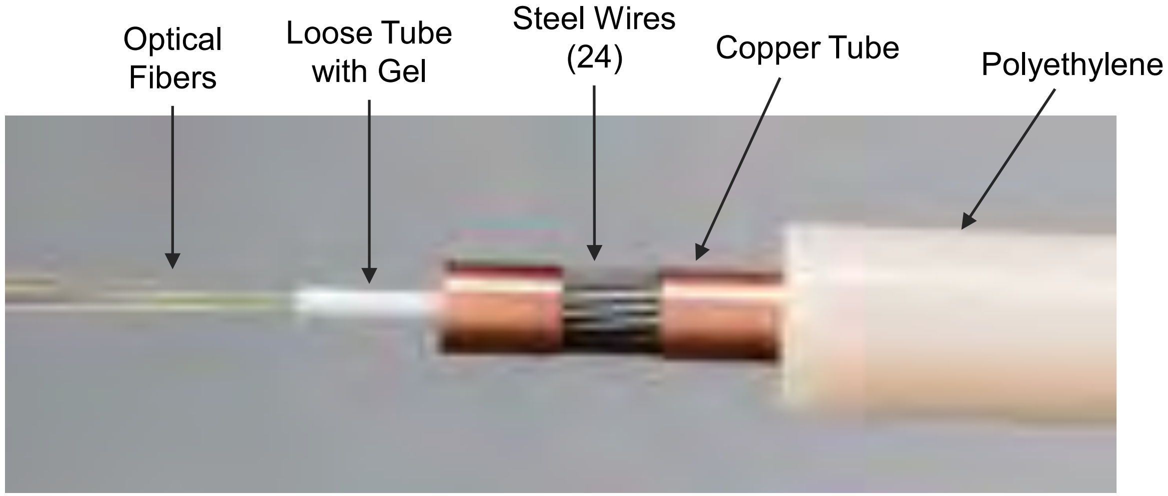
Loose Tube & Gel:*
- ✓ Fiber cushion
- ✓ Prevents axial water penetration (cable cut)

Steel Wires:
- ✓ Tensile strength
- ✓ Pressure resistance

Copper Sheath:
- ✓ Electrical conduction
- ✓ Hermetic & H_2 barrier

Polyethylene Jacket:
- ✓ Electrical insulation
- ✓ Abrasion protection

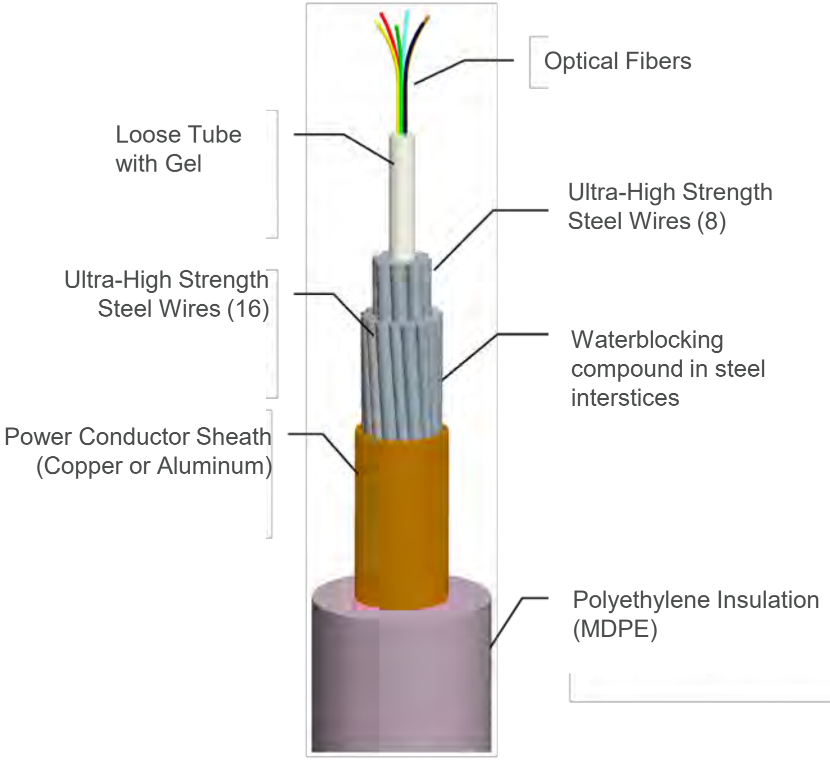




* Original SL Cable used extruded tight buffer core that was changed to Loose Tube with A_{eff} ~65μm^2 fibers

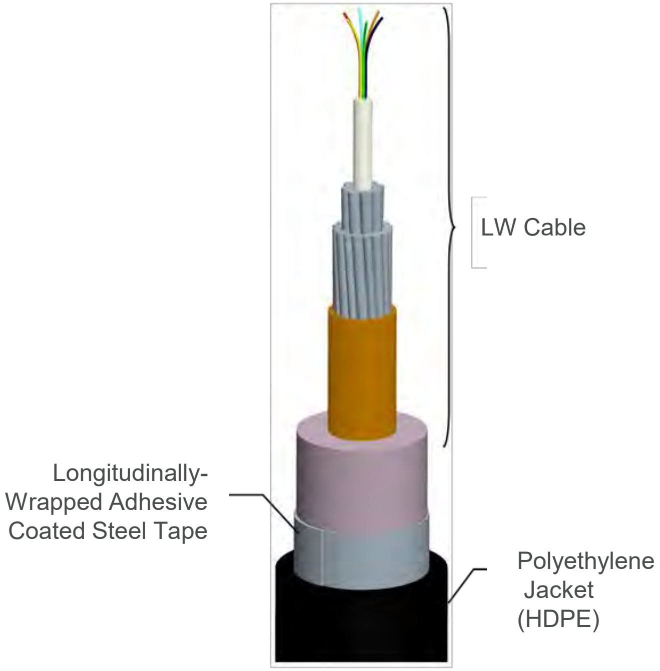
Cable Types and Families

LW Cable – Deep Water Use

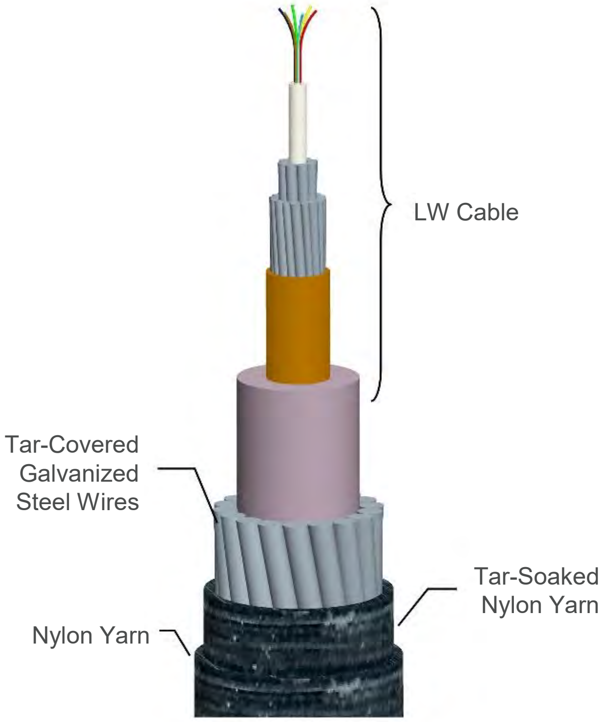


LW Cable

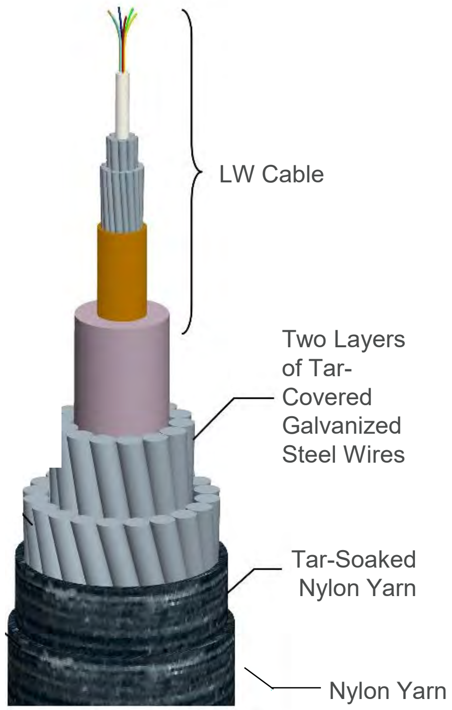
Protected Cables



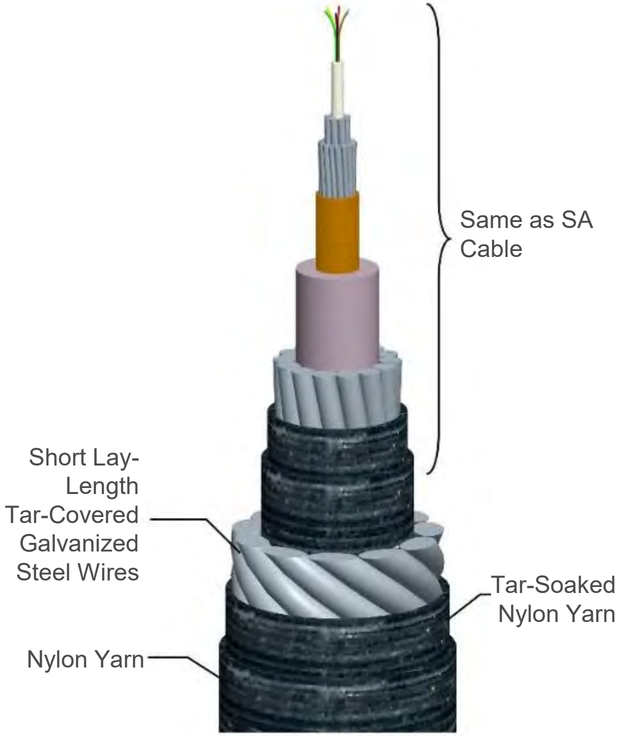
Special Applications Cable (SPA)



Light Wire Armor (LWA) and Single Armor (SA)



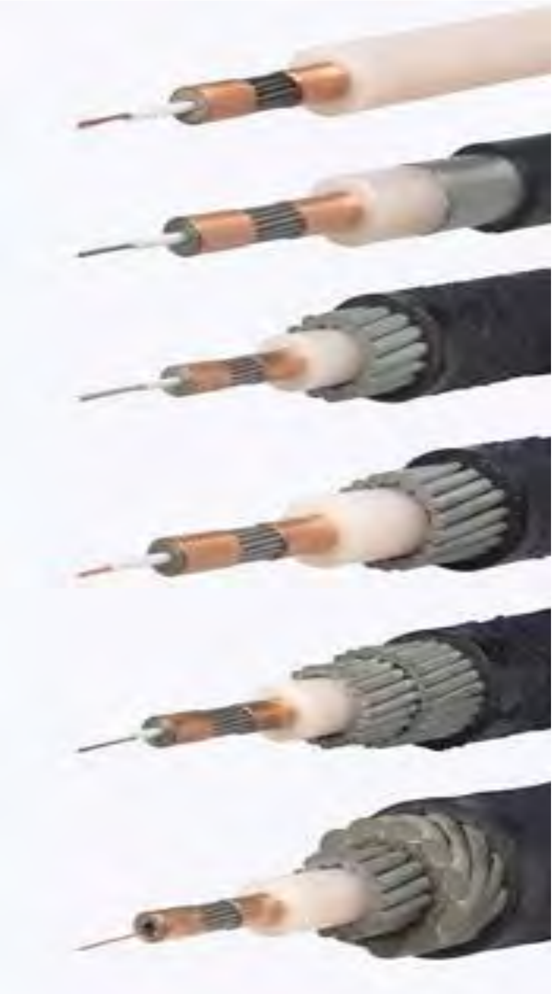
Double Armor – High Strength (DA) And Double Armor- High Abrasion (DA-HA)



Rock Armor (RA)

Increasing Level of Protection

Cable Type Applications



Lightweight (LW)

Special Application (SPA)

Light-Wire Armor (LWA)

Single Armor (SA)

Double Armor (DA)

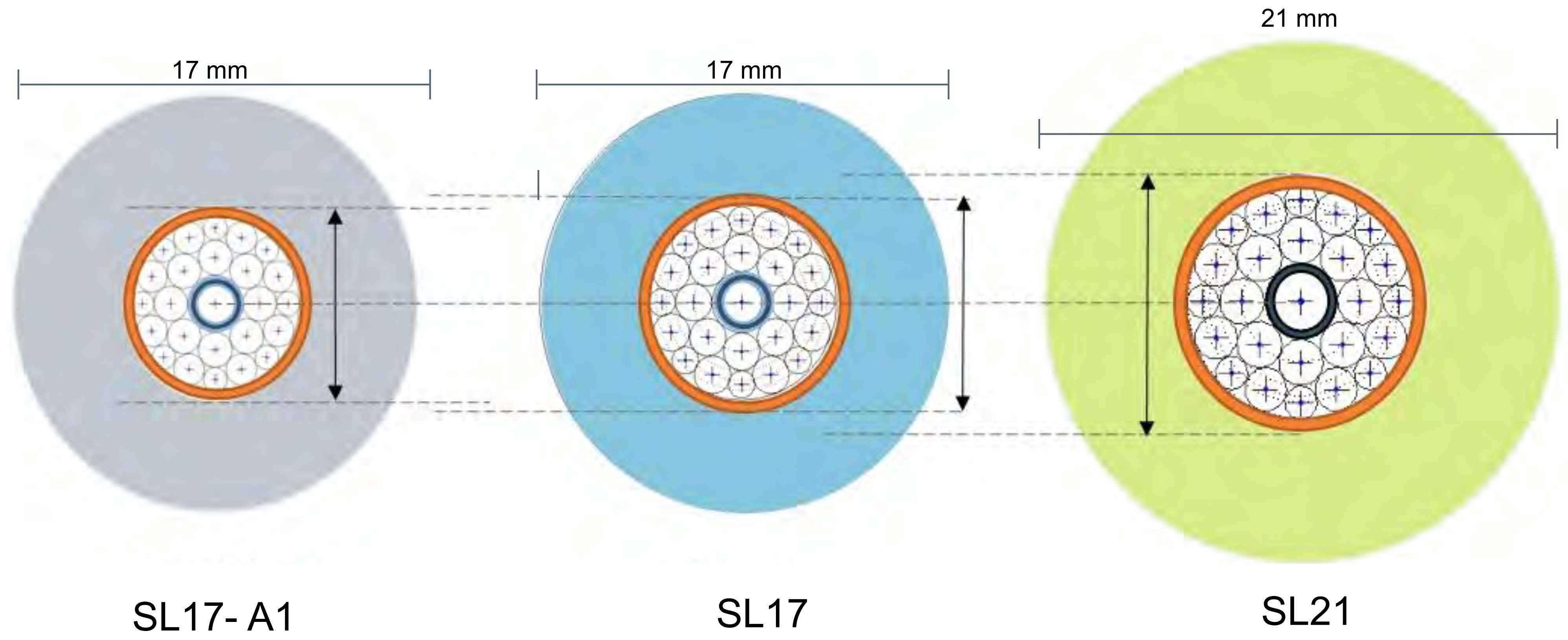
Rock Armor (RA)

Type	Max Depth	Applications
LW	10,000m	Benign, sandy bottom. Deepwater deployment.
SPA	6,500m	Rough seabed. Risk of moderate abrasion and/or attack by marine life.
LWA	2,000m	Rocky terrain. Some risk of fishing damage. Used for burial in areas of decreased risk of external aggression. Shallow water deployment.
SA	1,500m	Rocky terrain. Moderate risk of fishing damage. Shallow water deployment.
DA	800m	Very rocky terrain. High risk of fishing damage. Pipeline crossings. Near shore deployment.
RA	200m	Extremely rocky terrain. Very high risk of fishing damage. High risk of abrasion. Risk of crushing.

Additional cable types are qualified such as DA-HA (High Abrasion), Dynamic Riser Cable for platforms, etc.

Armored Cables for Harsh, Shallow Areas

Cable Families: SL17-A1, SL17 and SL21



14mm OD versions of SL17-A1 and SL17, named SL14-A1 and SL14, are qualified for lower voltage applications

Cable Characteristics and Handling

Cable Mechanical Properties: Tensile Strength Ratings

Industry Standard Cable Tensile Strength Ratings

- Breaking Strength (Ultimate Tensile Strength, **UTS**)
  - Sufficiently larger than NTTS
  - Initial Strength-to-Weight Parameter ➔ **Cable Modulus = UTS / Weight in Water**

- Nominal **<u>Transient</u>** Tensile Strength (**NTTS**)
  - Maximum allowable <u>short-term cable tension</u> (cumulative over ~ 1 hour)

- Nominal **<u>Operating</u>** Tensile Strength (**NOTS**)
  - Maximum allowable <u>average operational tension</u> for repair period (typically 48 hours)

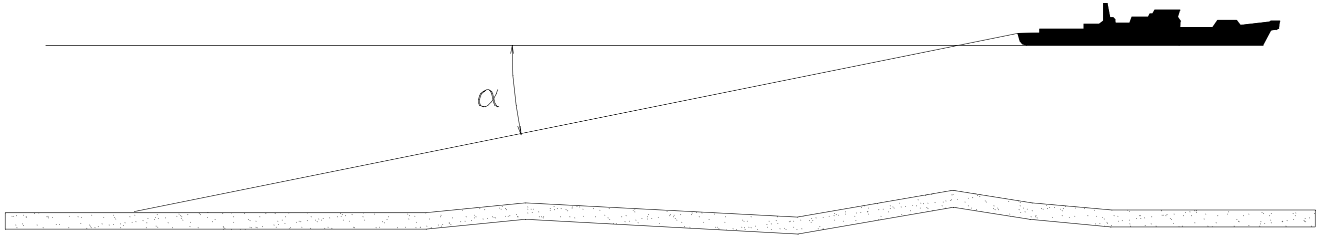
- Nominal **<u>Permanent</u>** Tensile Strength (**NPTS**)
  - Maximum allowable <u>permanent tension</u> applied to cable on the seabed after installation

Cable Mechanical Properties: Tensile Strength Ratings

Tensile Strength	LW		SPA		LWA		SA		DA		RA	
	SL17	SL21	SL17	SL21	SL17	SL21	SL17	SL21	SL17	SL21	SL17	SL21
NTTS (kN)	58	81	58	81	200	237	260	305	395	453	270	306
NOTS (kN)	41	57	41	57	140	168	185	216	280	324	190	217
NPTS (kN)	19	27	19	27	80	94	105	122	160	183	110	122

Surface Laying – Critical Angle

Critical Angle "alpha" is the entry angle that the cable makes with the surface of the water.



Alpha is a function of the cable's hydrodynamic constant and the vessel's speed:

$$\alpha = \arccos\left(\sqrt{1+\frac{1}{4}\left(\frac{H\pi}{V_s 180}\right)^4} - \frac{1}{2}\left(\frac{H\pi}{V_s 180}\right)^2\right)$$

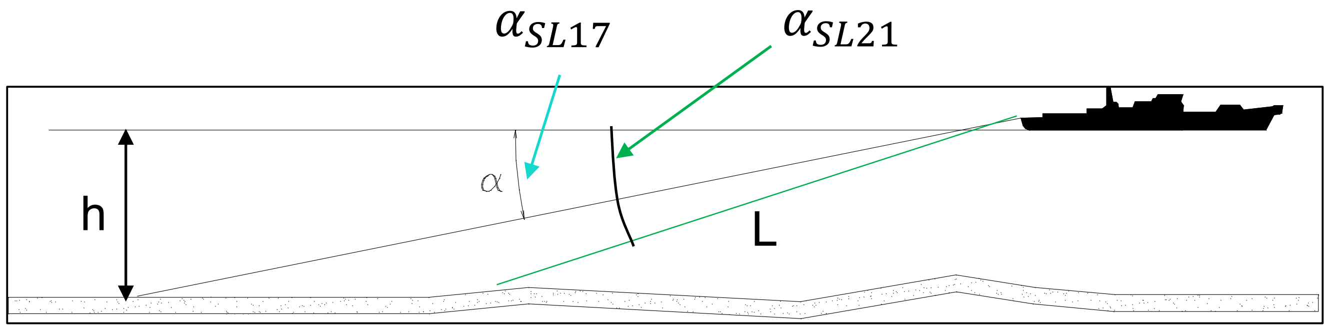
Hydrodynamic constant –

Related to Cable Weight in Water, Cable Diameter, and Drag Coefficient

For critical angles less than 30°, alpha can be closely approximated: $\alpha = \frac{H}{V_s}$

Critical Angle – Calculation of Catenary Length during Lay

For the same vessel speed…



$$H = \left(\frac{180}{\pi}\right)\sqrt{\frac{2w}{(C_d \rho d)}}$$

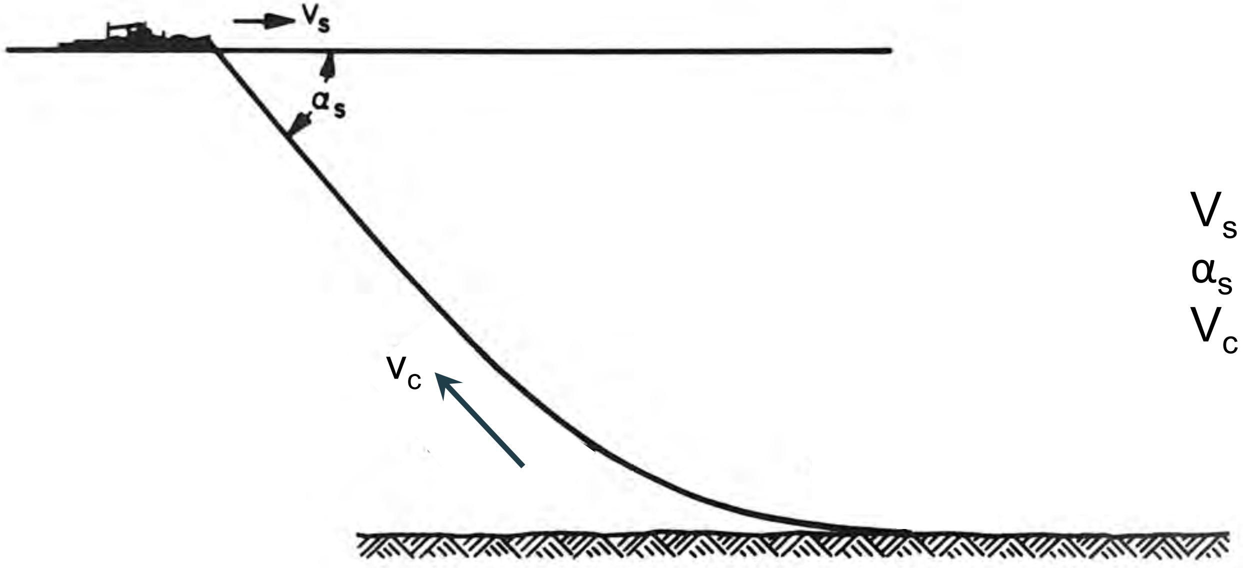
$$L = \frac{h}{\sin \alpha}$$

LW Cable	**H** (degree-knots)	**α** (for 2 knots vessel speed)	**L** (m) (for 5000m water depth)	**Lay Tension at ship** (kN) (5000m water depth)
SL17	46	23°	12.8	18 (NTTS=58)
SL21	48	24°	12.3	24 (NTTS=81)

SUBCOM

Cable Recovery

Highest cable tension is during recovery (not laying) due to the downward drag force as the cable moves through the water



V_s = ship speed
α_s = recovery angle
V_c = recovery speed

Recovery of an Undersea Cable

Cable Recovery

❑ Recovery Tension

- Proportional to **Water Depth** and **Cable Weight**
- Significantly affected by Recovery Conditions -
  Recovery Speed, Recovery Angle, Sea Conditions

Recovery Tension @ Ship, Ts = $wh + T_{bottom} + T_{wave\text{-}induced}$

(For a surface-laid cable, without a repeater)

From 5000m water depth:

SL17 LW Recovery Tension ~ 46 kN (SL17 LW NTTS = 58 kN)

SL21 LW Recovery Tension ~ 62 kN (SL21 LW NTTS = 81 kN)

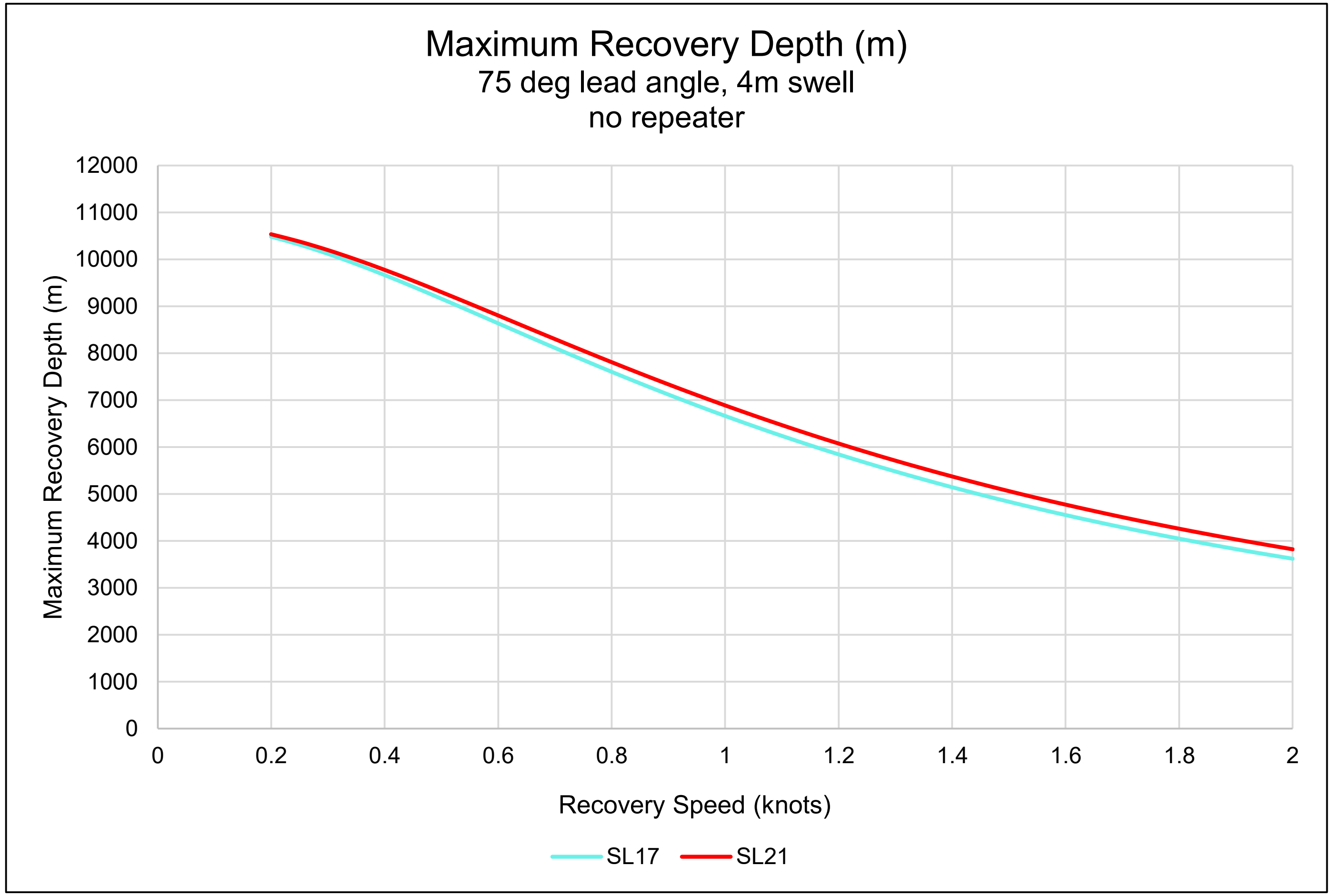
(For typical recovery conditions of 1 knot recovery speed, 75 degree lead angle, and 4m sea swell)

Cable Recovery

❑ Recovery Depth Curves

For Maximum Recovery Depth Calculation,

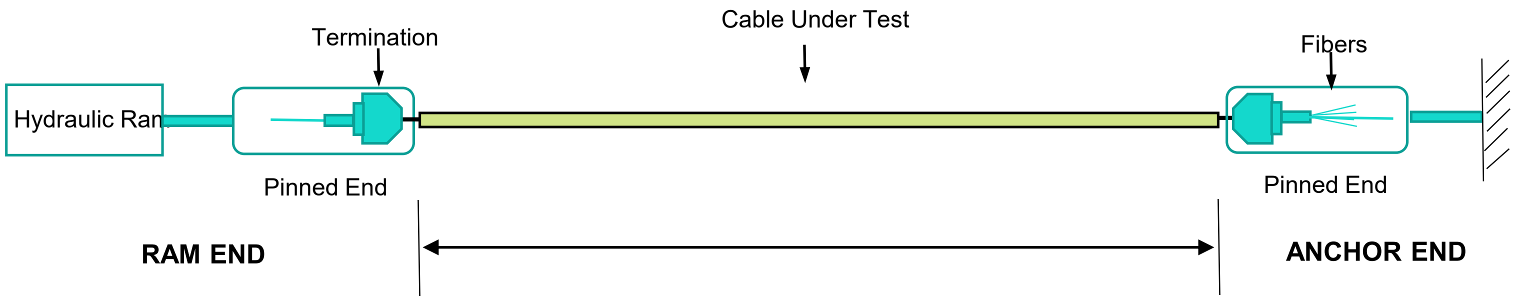
NTTS is set equal to **Ts**

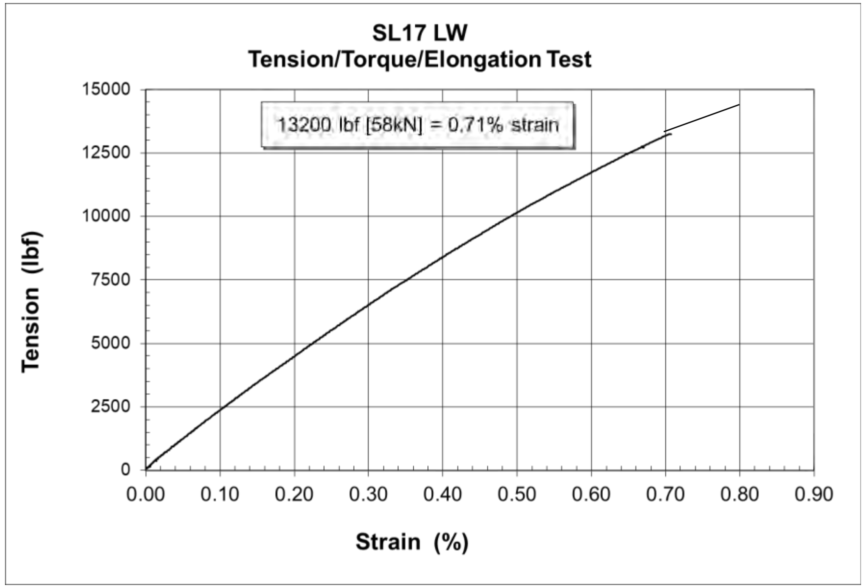


Cable Mechanical Properties: Tensile Strength Characterization

Tensile Strength:

- ☐ Experimentally verified through Tensile Testing
  - ➢ Cable Tension vs. Cable Elongation Curve





SL17 LW

- ☐ Highest Cable Tension levels are typically encountered during Recovery at Maximum Depth
  - ➢ Recovery operations aim not to exceed **Nominal Transient Tensile Strength** (**NTTS**)

Cable Qualification

Qualification Test Program

Cable qualification program in conformance with ITU-T Recommendation G.976

SubCom Qualification Test	ITU-T G.976 (05/2014)	
	Reference Paragraph	Test Item
Cabled Fiber Optical Performance	8.2.1.1; 8.2.1.2	Transmission: Manufactured loss
Extended Range Temperature	8.2.1.3	Transmission: Temperature
Reverse Flexure with Temperature	8.2.1.3; 8.2.2.5	Transmission:Temperature Mechanical: Sheave
Reverse Bend	8.2.2.5	Mechanical: Sheave
Tension/Torque/Elongation	8.2.1.2; 8.2.2.1; 8.2.2.2	Transmission: Cabled fiber strain Mechanical: Tensile (fixed)
Tension/Torque/Rotation	8.2.1.2; 8.2.2.1; 8.2.2.2	Mechanical: Tensile (free)
Stopper Test	8.2.5.2	Operational: Stopper
Adhesion	8.2.5.1	Operational: Adhesion
Crush & Impact Test	8.2.3.1, 8.2.3.2	Operation: Installation Equipment
Water Ingress	8.3.4.1	Reliability: Water Ingress
HV & Insulation Resistance	8.3.4.2, 8.2.4.4	Reliability: HV & Insulation Resistance
Sea Trial*	8.2.5.3	Operation: Installation Equipment

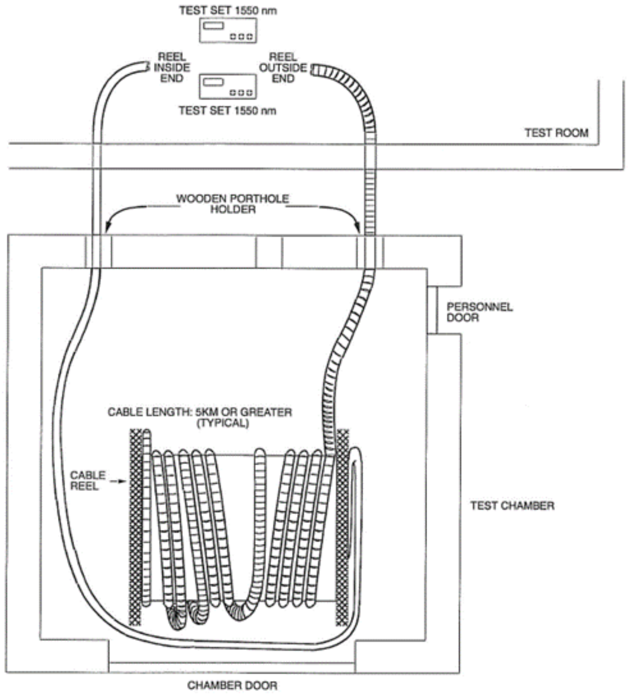
* Verification test

Qualification Test Program

- Extended Range Temperature

Sample: 10-15km long cable on a reel, placed in an environmental temperature chamber

Test Description: Sample is subjected to a temperature profile ranging from -20 °C to +60 °C



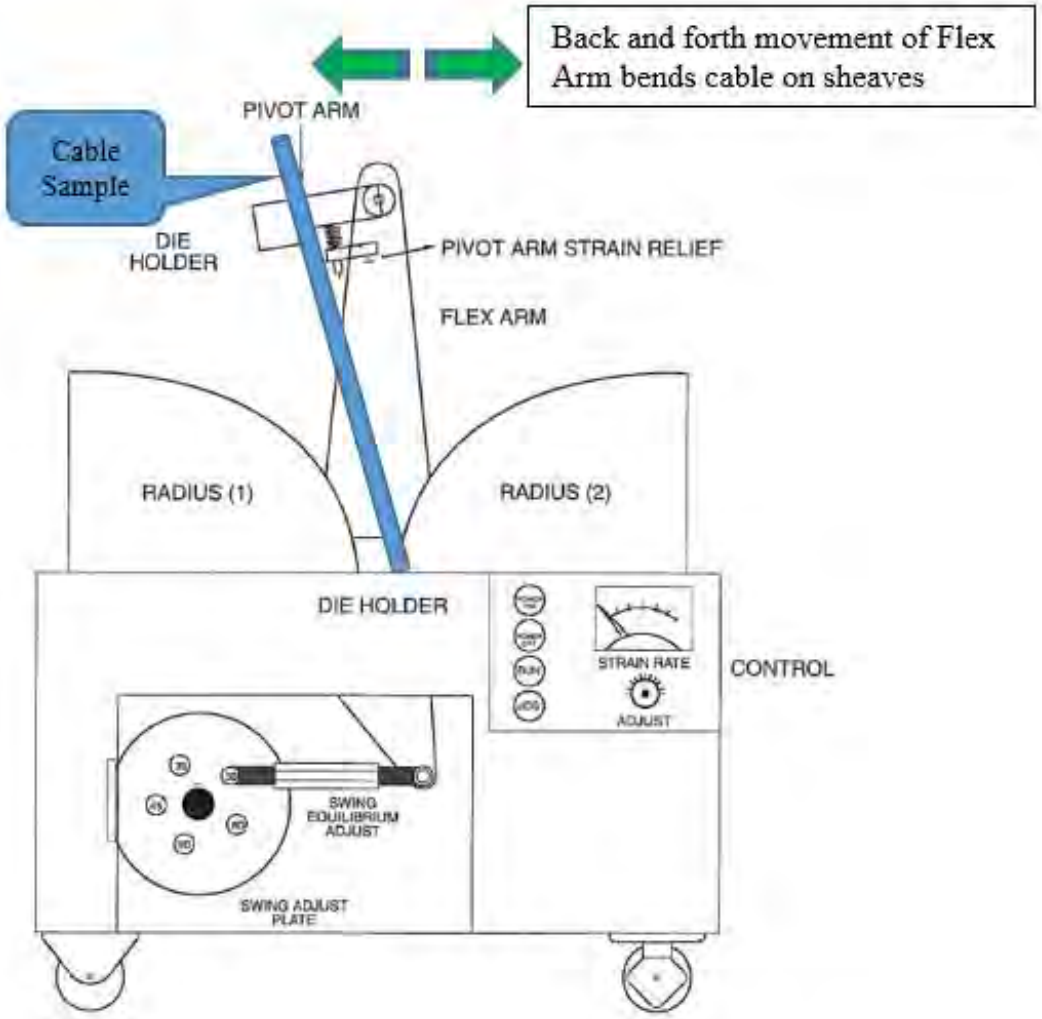
Qualification Test Program

☐ Reverse Flexure with Temperature

Sample:
A ≥100m-long cable sample, placed in an environmental temperature chamber and subjected to small radius bending

Test Description:
Sample is subjected to flexing while at temperatures ranging fı
–20°C to +60°C.

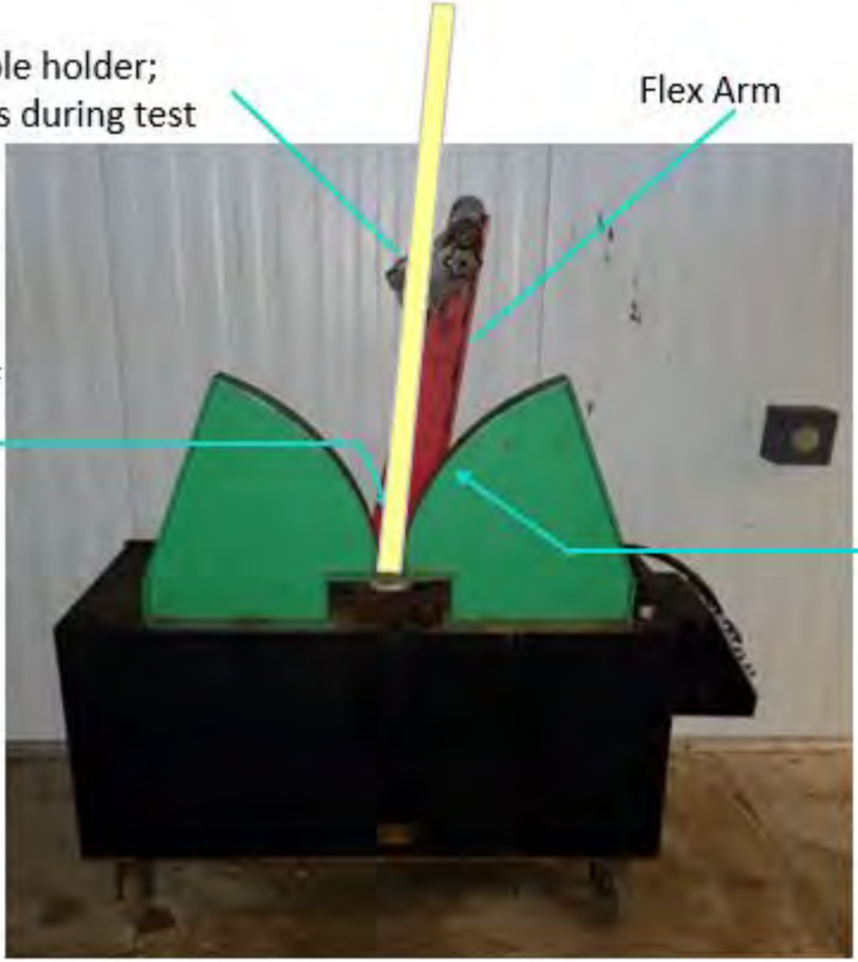
Simulates low-tension loading from the cable factory to the shi
during very hot or very cold weather conditions


Back and forth movement of Flex Arm bends cable on sheaves

Cable Sample

Cable Mechanical Properties

Reverse **Flexure** with Temperature

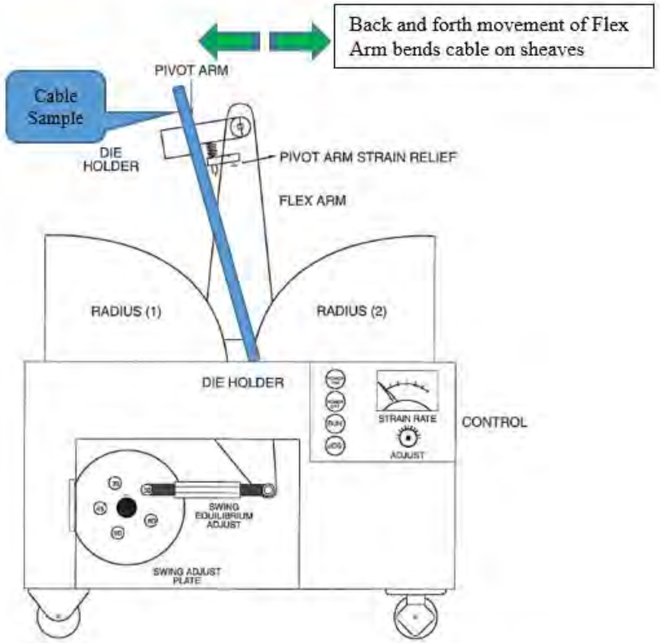


Sample holder; Pivots during test

Flex Arm

One end of sample captured between bend radii

0.5m Bend Radius



Back and forth movement of Flex Arm bends cable on sheaves

Cable Sample

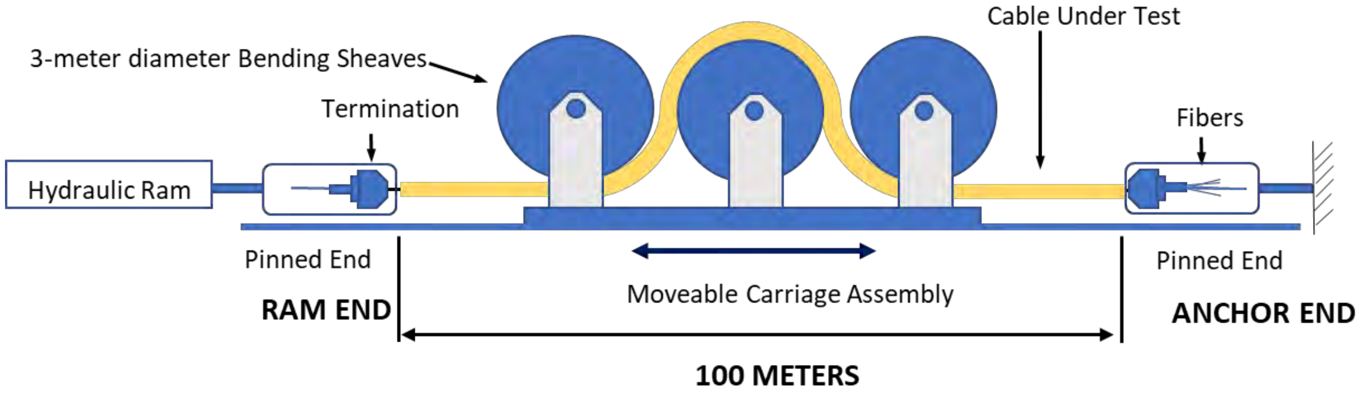
Qualification Test Program

☐ Reverse Bend

Sample: 100m-long cable sample in a tensile bed.

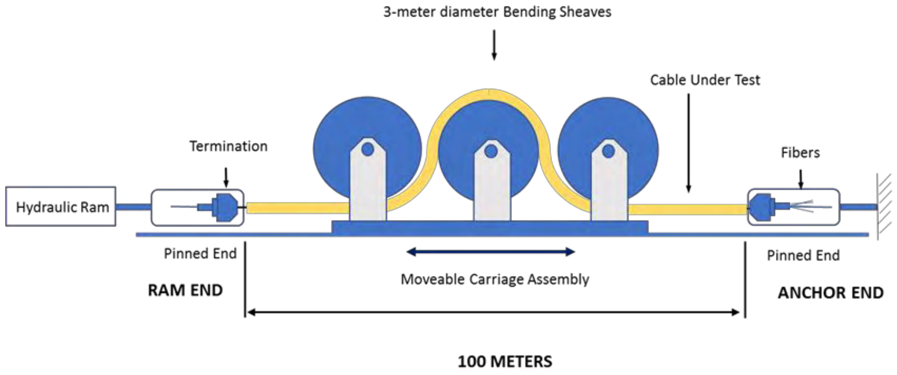
Test Description:

- The cable is routed through three 3m diameter sheaves attached to a moveable carriage.
- Tension applied up to NTTS.
- Carriage traverses over a portion of the sample and impart cycles of reverse bends at different tension levels.



Cable Mechanical Properties

REVERSE BEND TEST



3-meter diameter sheaves

Moveable carriage traverses over a 70m portion of 100m long test specimen

100m test specimen

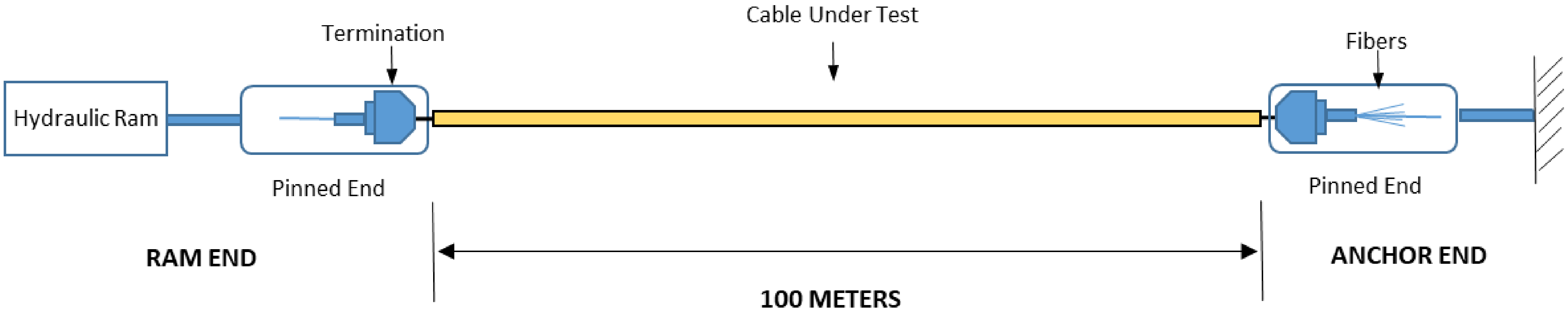
Qualification Test Program

☐ Tension/Torque/Elongation

Sample: 100m long cable sample in a tensile bed.

Test Description:

- Cable ends pinned against rotation.
- Tension applied incrementally to NTTS.
- Optical loss monitored, along with tension, torque and elongation.

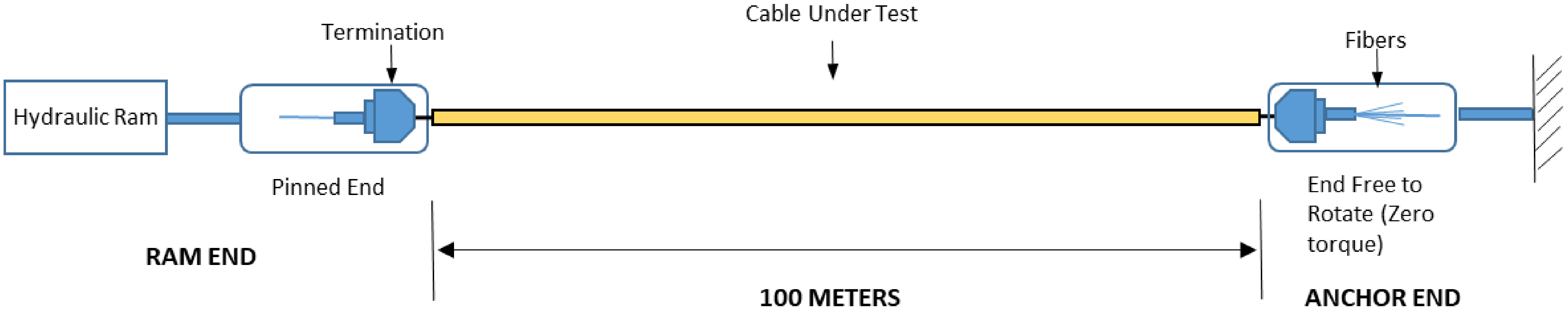


Qualification Test Program

- ☐ Tension/Rotation/Elongation

Sample: 100m long cable sample in a tensile bed.

Test Description:
- One cable end pinned against rotation, other end free to rotate.
- Tension applied incrementally to NTTS.
- Optical loss monitored, along with tension, rotation and elongation.

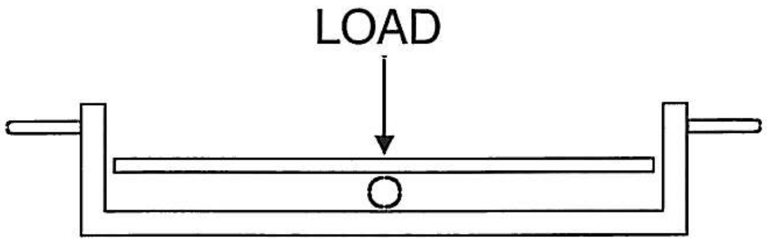


Qualification Test Program

- ☐ Crush

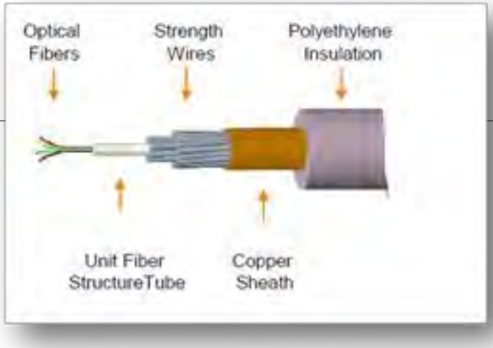
  Sample: ~5m long cable sample

  Test Description:
  The sample is placed between two flat plates over a 10cm long section of the cable, and then loaded.



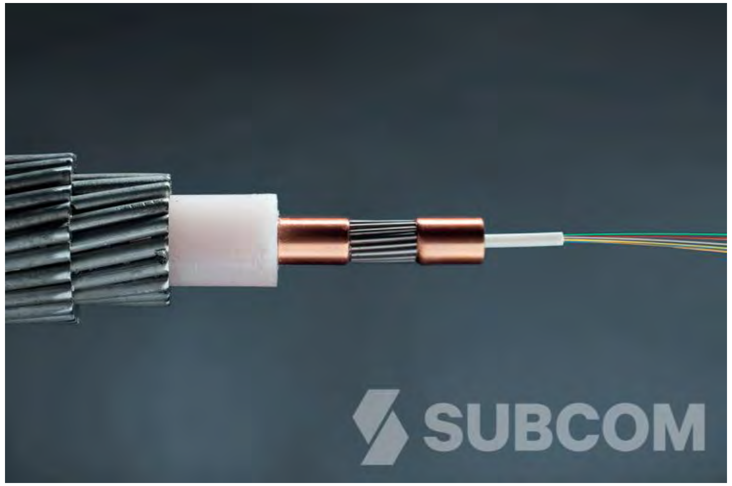
Cable Manufacture

Cable Manufacturing -- LW



Loose Tube → Power Conductor → Polyethylene Extrusion

Cable Manufacturing -- Armoring



New Challenges

Next Generation Cable:

- Improved Fiber Cushioning for New Fibers?
- Higher Voltage Capability?
- More Economical & Efficient Power Conduction?
- New Insulating Material?
- Quicker Jointing Process?
- ???

How will you progress Subsea Communications?

SUBCOM

Thank You

Optical Transmission – Lecture 2

Propagation impairments

ALCATEL
SUBMARINE
NETWORKS

Do you speak dB (deciBels) ?

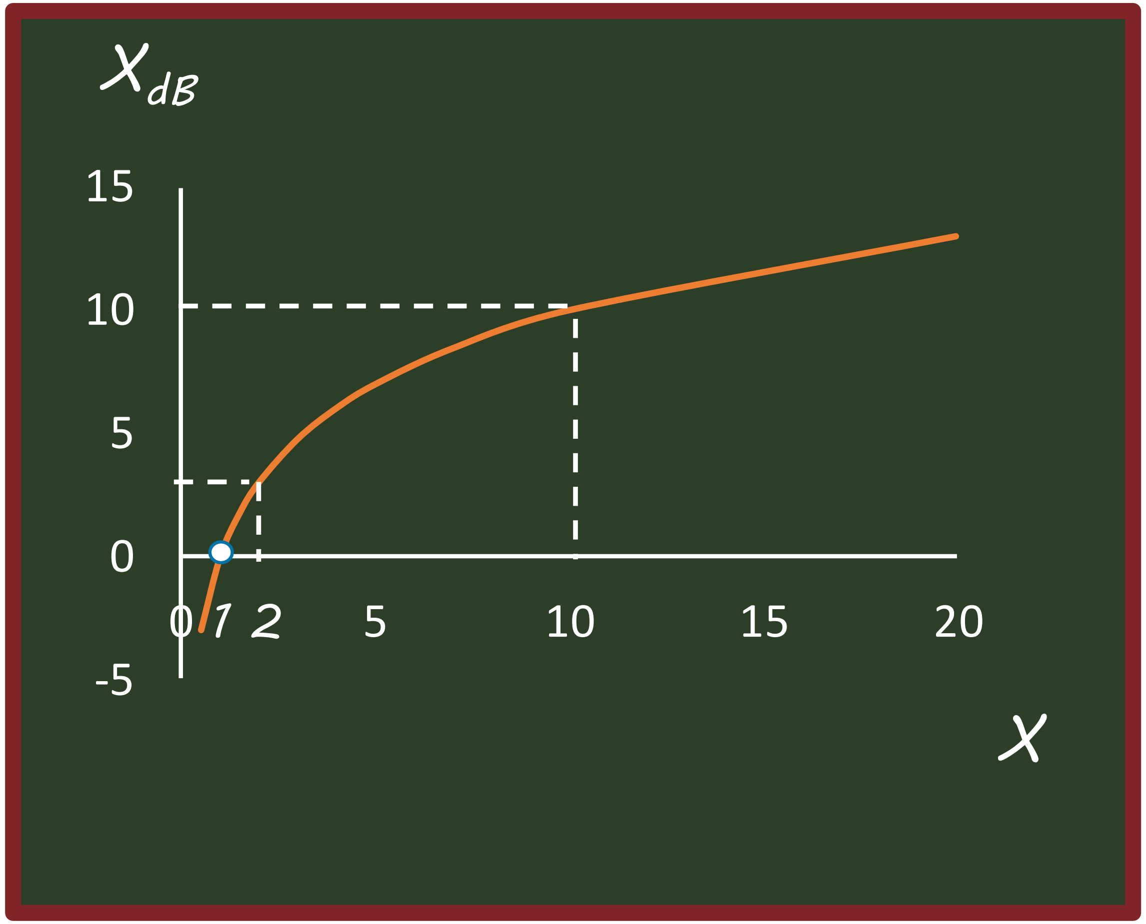
- We often express ratios in dB (logarithmic) scale

$$X = A/B \quad \rightarrow \quad \underline{X_{dB} = 10\log_{10}(X)}$$

- $1x \leftrightarrow 0dB,\ 2x \leftrightarrow 3dB,\ 10x \leftrightarrow 10dB$

- Product of ratios = sum in dB

$$10\ \log_{10}(X_1 * X_2) = X_{1,dB} + X_{2,dB}$$



Do you speak dB ?

- We often express ratios in dB (logarithmic) scale

$X = A/B$ ➔ $\underline{X_{dB} = 10\log_{10}(X)}$

- $1 \leftrightarrow 0dB$, $2 \leftrightarrow 3dB$, $10 \leftrightarrow 10dB$
- Product of ratios = sum in dB

$$10\ \log_{10}(X_1 * X_2) = X_{1,dB} + X_{2,dB}$$

$$10\ \log_{10}(X_1 / X_2) = X_{1,dB} - X_{2,dB}$$

- We also express powers in dBm = Ratio of the power « per mW »

$$\underline{P_{dBm} = 10 * \log_{10}\left(\frac{P_{Watt}}{10^{-3}Watt}\right)}$$

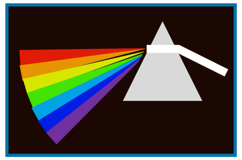
- Product of power P_1 by ratio X

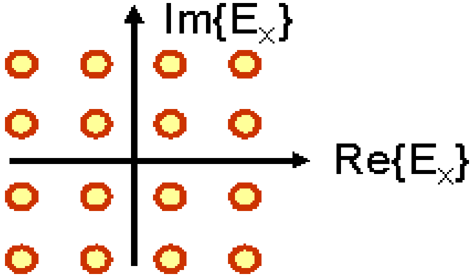
$$P_{2,dBm} = P_{1,dBm} + X_{dB}$$

- ! We can sum Watts, not dBm

Back to Lecture 1

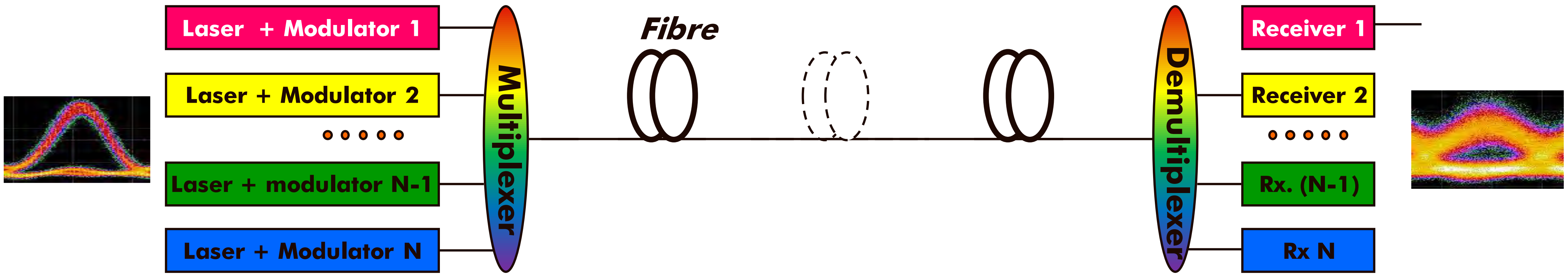
$$Capacity = Nb_{spatial\ modes} * Nb_{wavelengths} * \overbrace{Nb_{polars} * Nb_{bit/symbol}}^{\text{Spectral efficiency}} * \frac{Symbol\ Rate}{Overhead\,(FEC, signaling)}$$





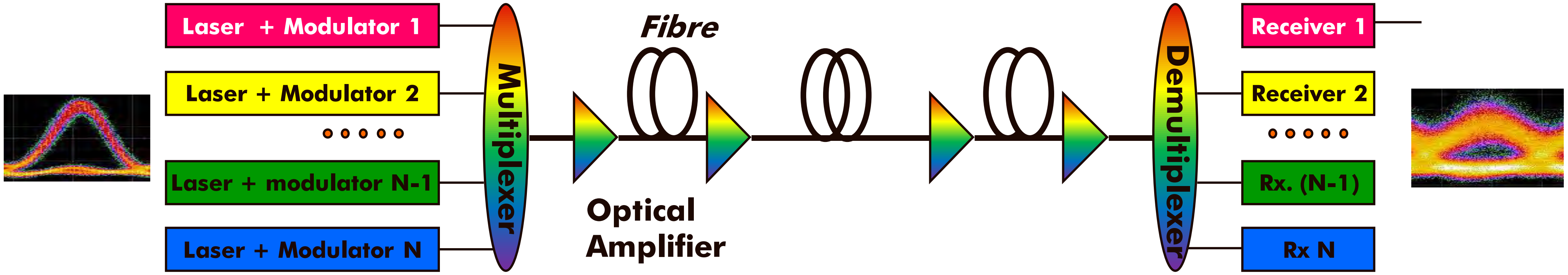
- Software-defined “Coherent” transceivers
  - Linear receiver assisted by high rate **Digital Signal Processing** enables mitigation of line impairements…
  - and **adaptation of bit-rate** (modulation) to **Quality of Transmission** (distance, signal to noise ratio)

One transmission line, multiple sources of signal impairments



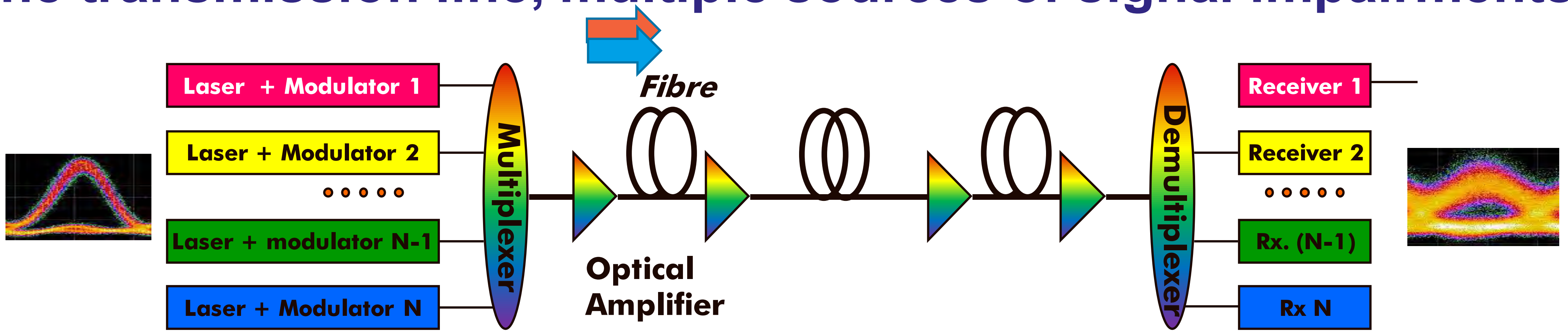
Physical effect	Impact	Mitigation	Limitations
Attenuation	Undetectable Signal		

One transmission line, multiple sources of signal impairments



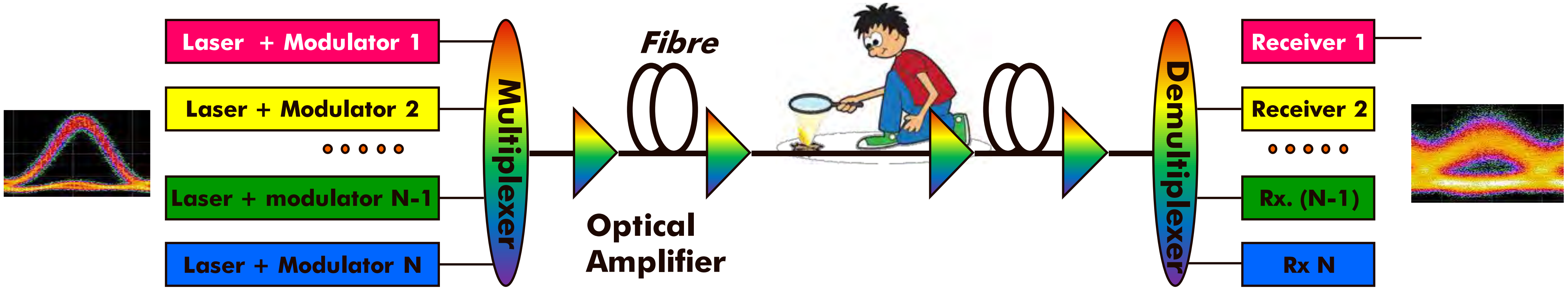
Physical effect	Impact	Mitigation	Limitations
Attenuation	Undetectable Signal	Optical amplification	Amplifier noise, SNR_{ASE}

One transmission line, multiple sources of signal impairments



Physical effect	Impact	Mitigation	Limitations
Attenuation	Undetectable Signal	Optical amplification	Amplifier noise, SNR_{ASE}
Chromatic Dispersion Frequency dep. Speed	Pulse broadening	~~Inline optical~~ Electronic Dispersion compensation	Imperfect compensation

One transmission line, multiple sources of signal impairments



Laser + Modulator 1

Laser + Modulator 2

Laser + modulator N-1

Laser + Modulator N

Multiplexer

Fibre

Optical Amplifier

Demultiplexer

Receiver 1

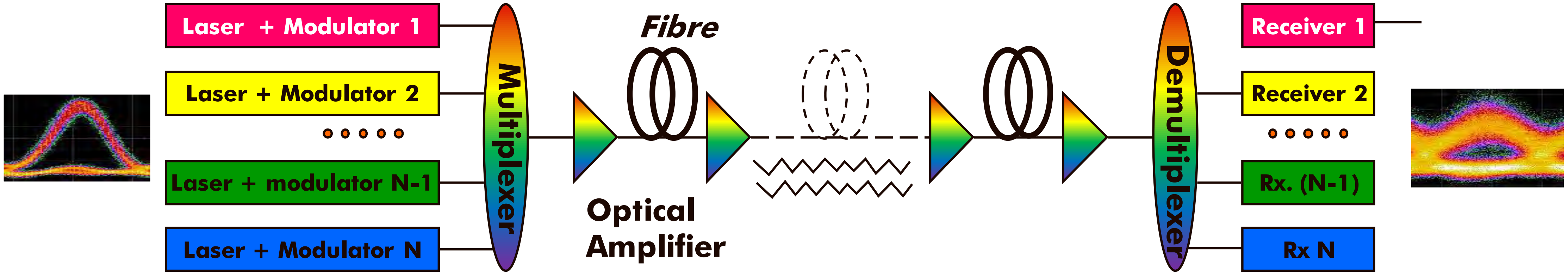
Receiver 2

Rx. (N-1)

Rx N

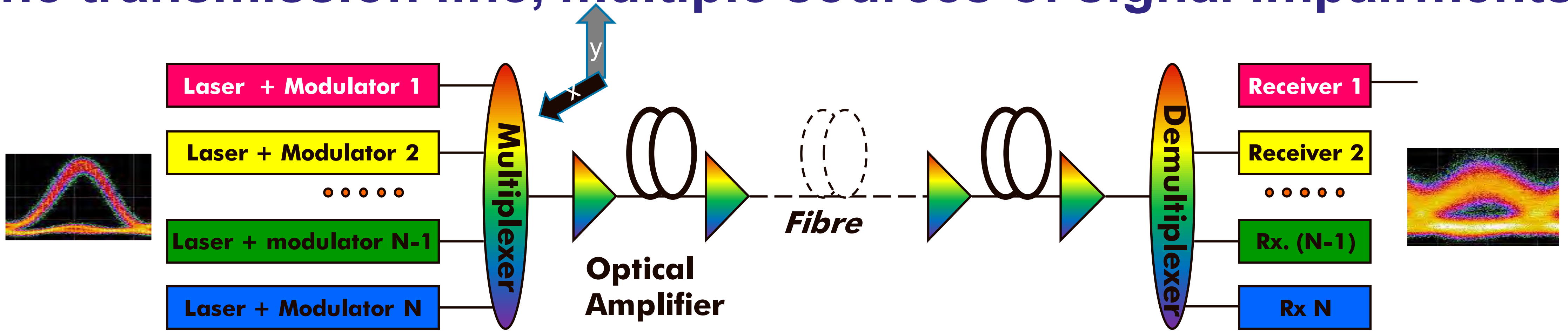
Physical effect	Impact	Mitigation	Limitations, metrics
Attenuation	Undetectable Signal	Optical amplification	Amplifier noise, SNR_{ASE}
Chromatic Dispersion Frequency dep. Speed	Pulse broadening	~~Inline optical~~ Electronic Dispersion compensation	Imperfect compensation
Kerr effect (power →phase)	Power-dep. Distortions	~~Dispersion management,~~ electronic mitigation	Repeater count & power

One transmission line, multiple sources of signal impairments



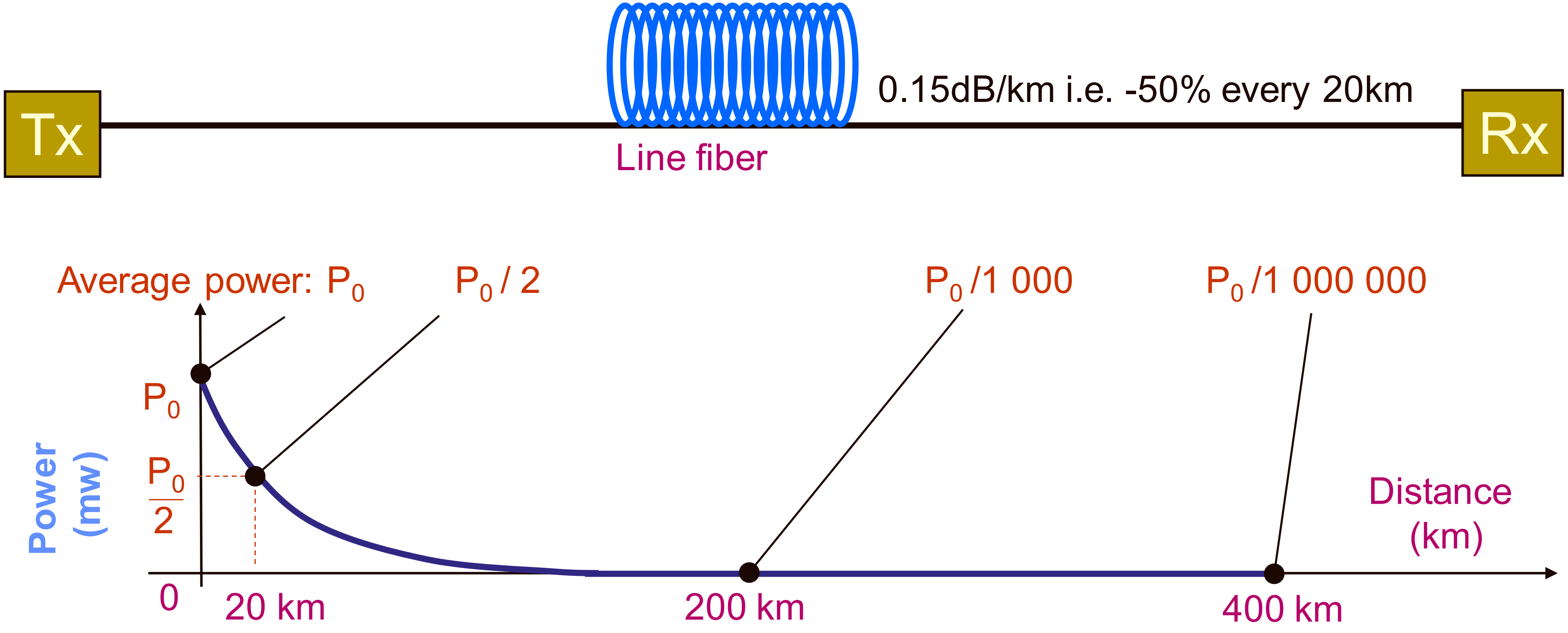
Physical effect	Impact	Mitigation	Limitations
Attenuation	Undetectable Signal	Optical amplification	Amplifier noise, SNR_{ASE}
Chromatic Dispersion Frequency dep. Speed	Pulse broadening	~~Inline optical~~ Electronic Dispersion compensation	Imperfect compensation
Kerr effect (power →phase)	Power-dep. distortions	~~Dispersion management,~~ electronic mitigation	Repeater count & power
GAWBS: acoustic waves	Phase & polar shifts	Temperature = 0 K …	Length, Effective area

One transmission line, multiple sources of signal impairments



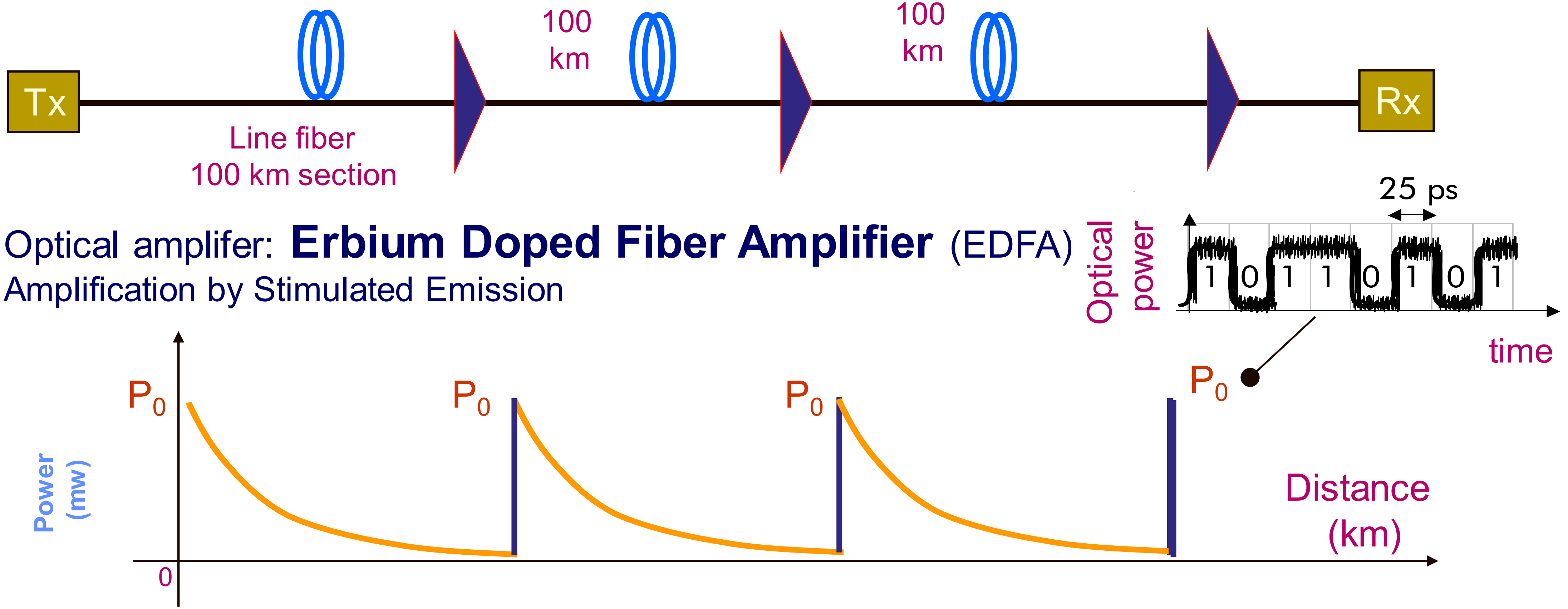
Physical effect	Impact	Mitigation	Limitations
Attenuation	Undetectable Signal	Optical amplification	Amplifier noise, SNR_{ASE}
Chromatic Dispersion Frequency dep. Speed	Pulse broadening	~~Inline optical~~ Electronic Dispersion compensation	Imperfect compensation (ASIC)
Kerr effect (power →phase)	Power-dep. distortions	~~Dispersion management,~~ electronic mitigation	Repeater count & power
GAWBS: acoustic waves	Phase & polar shifts		Length, Effective area
PMD (polar. dep. speed)	Time-varying distortions	Electronic mitigation	ASIC implementation

Impact of fiber attenuation



Fiber attenuation is low (0.15dB/km) but not enough to reach 1000 km

From optical amplification to amplifier noise

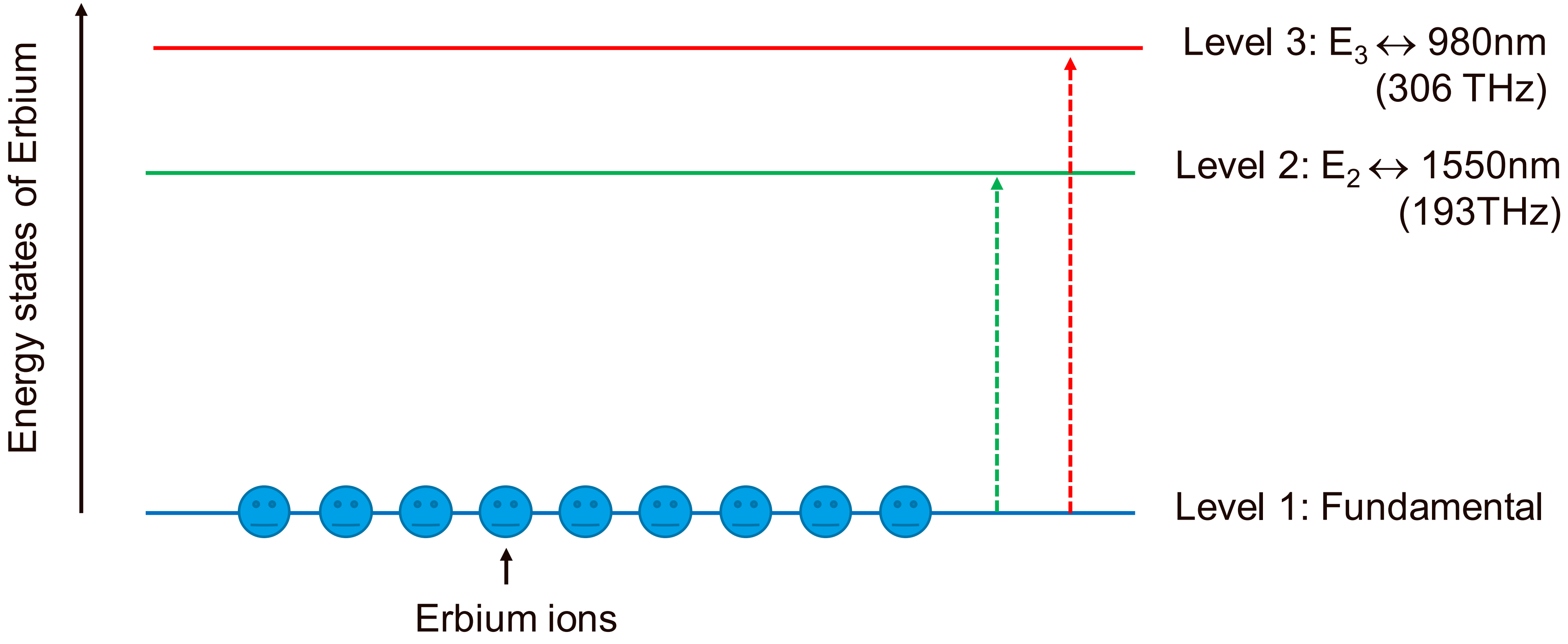


Optical amplifer: **Erbium Doped Fiber Amplifier** (EDFA)
Amplification by Stimulated Emission

Limitation: **A**mplified **S**pontaneous **E**mission (**ASE**)

Principles of optical amplification

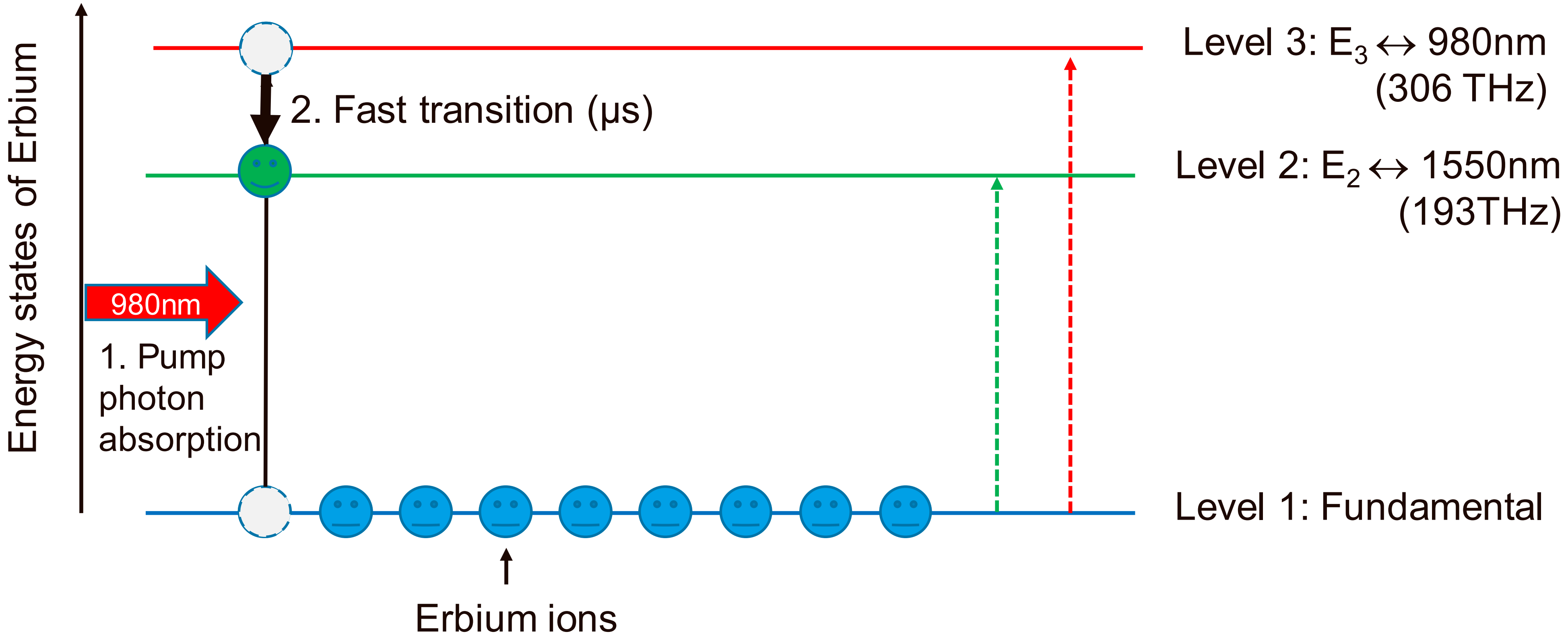
Energy of a photon: $\frac{h*c}{\lambda} = h\nu$



All Erbium ions in the fundamental state

Principles of optical amplification
Optical pumping

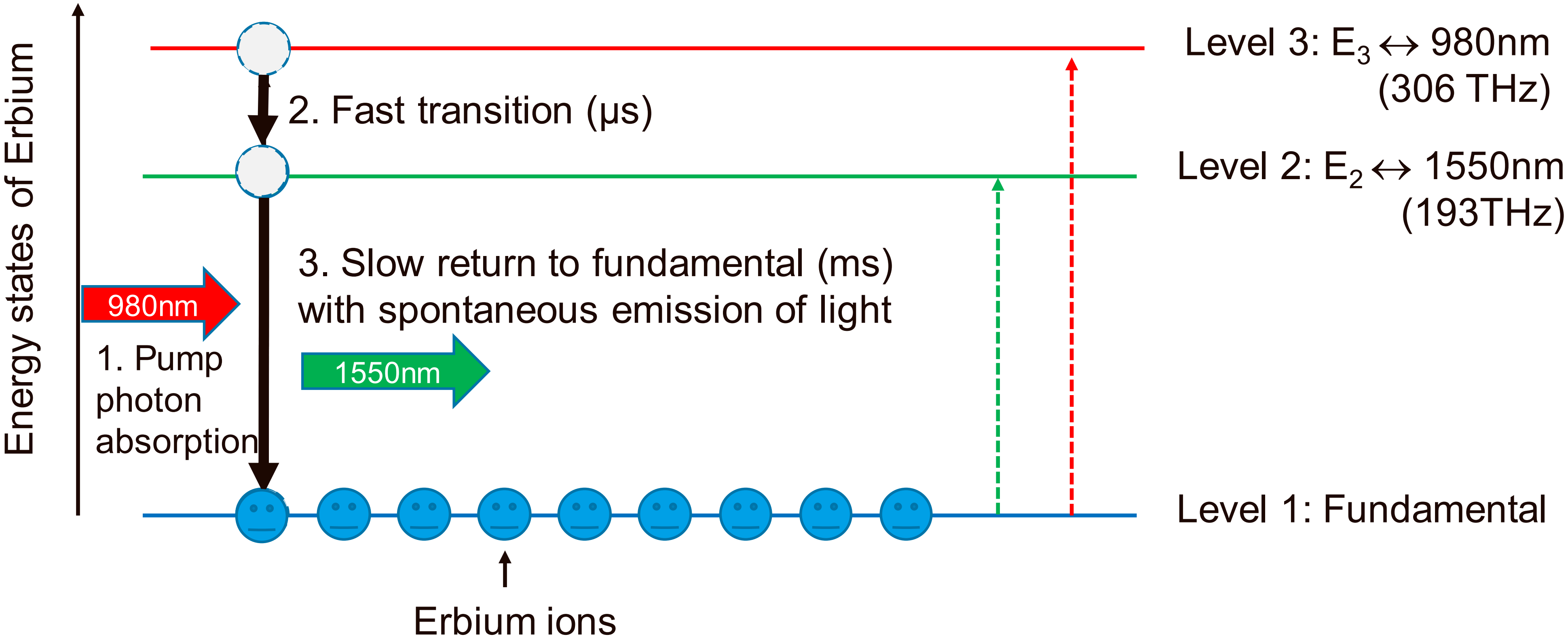
Energy of a photon: $\frac{h*c}{\lambda} = h\nu$



Pump photons transfer Erbium ions into an excited state

Principles of optical amplification
Optical pumping

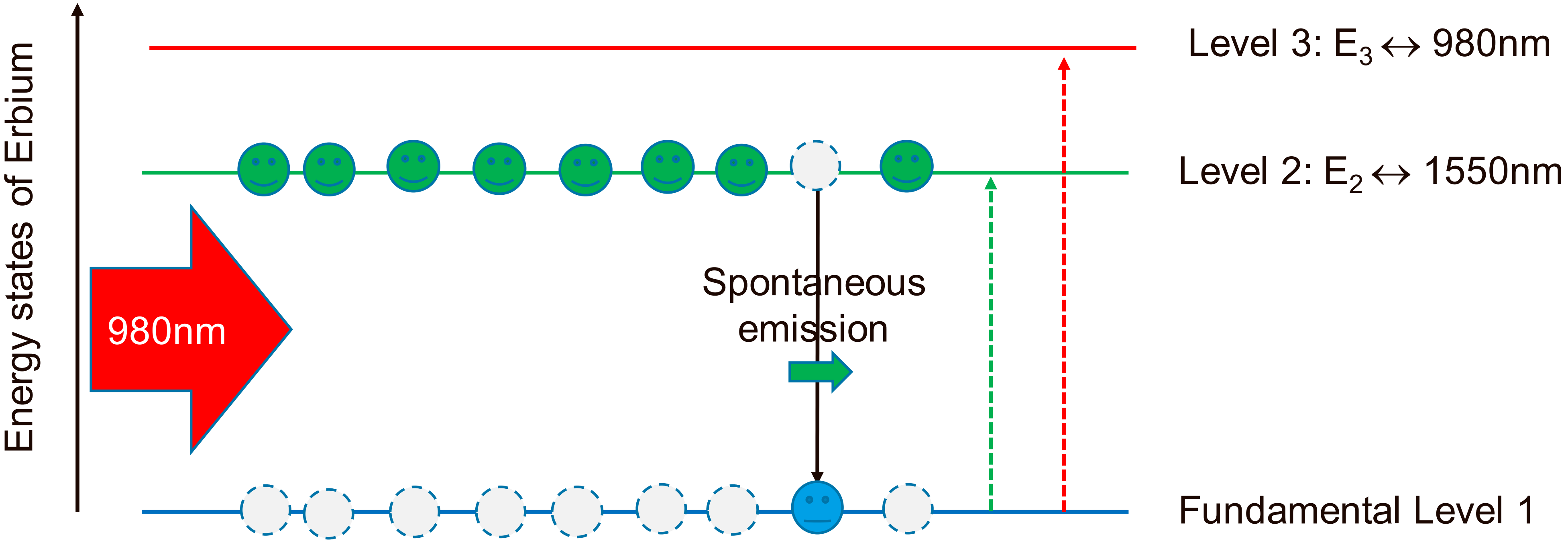
Energy of a photon: $\frac{h*c}{\lambda} = h\nu$



Pump photons transfer Erbium ions into an excited state

Principles of optical amplification
Population inversion

Energy of a photon: $\frac{h*c}{\lambda}$

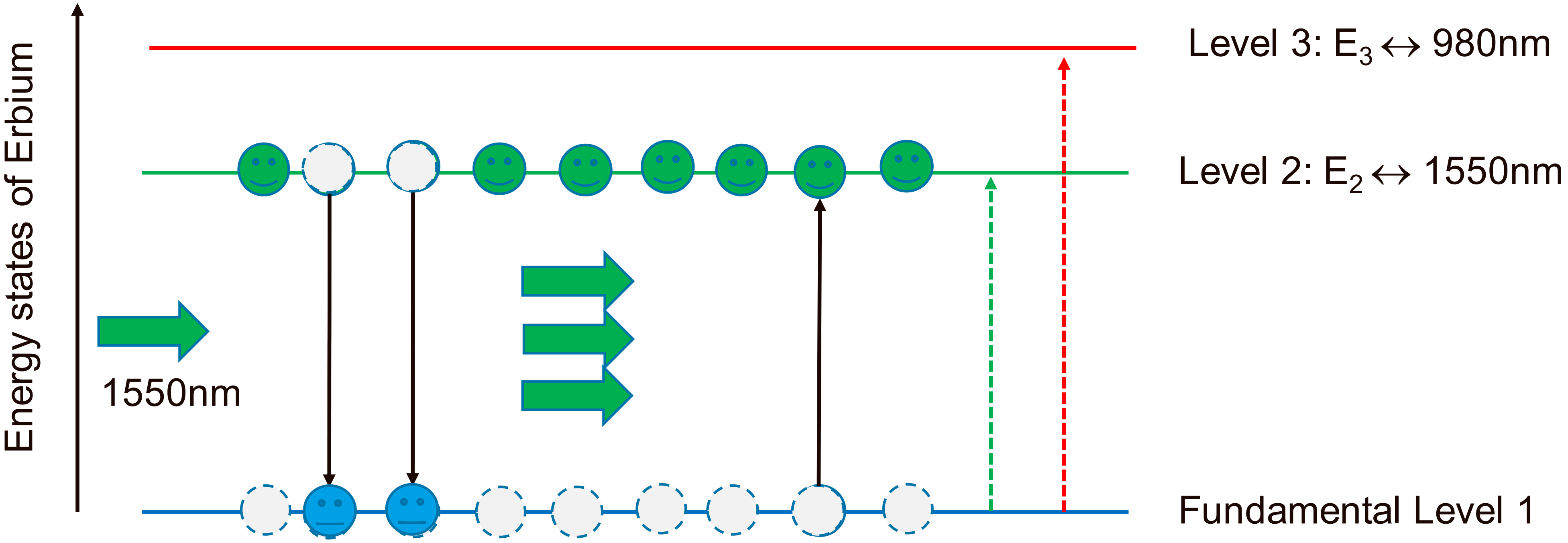


Strong pump power : almost all ions in level 2
Ready for signal amplification !

Principles of optical amplification

Incoming signal photons in presence of population inversion

Energy of a photon: $\frac{h*c}{\lambda}$



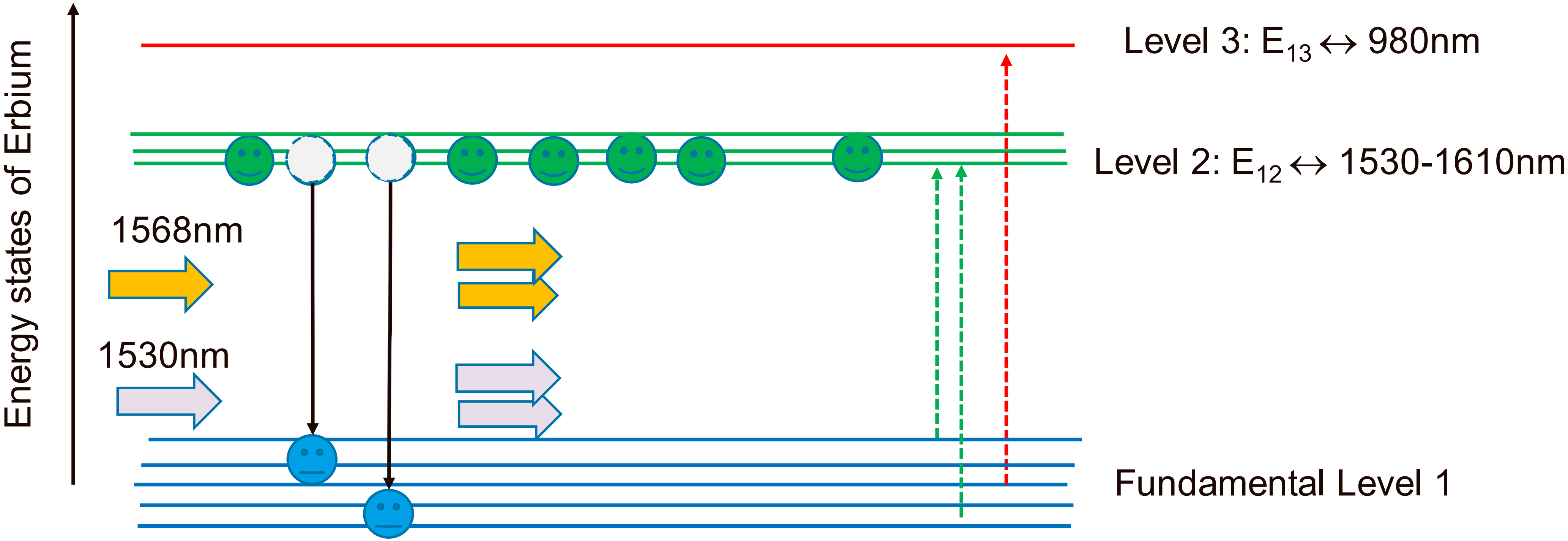
Competition between stimulated (+spontaneous) emission and absorption

Population inversion ➔ Amplification (+ spontaneous emission noise)

Principles of optical amplification with EDFA

Wideband amplification

Energy of a photon: $\frac{h*c}{\lambda}$

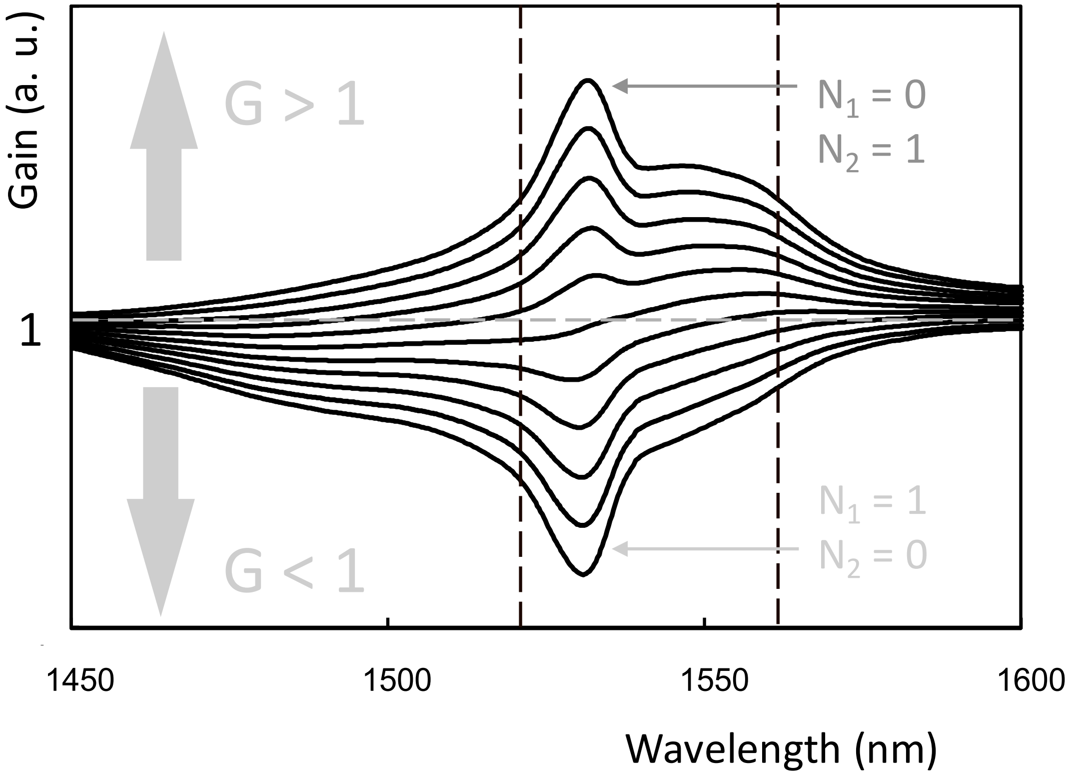


Stark effect: myriad of sublevels ➔ amplification over wide range of wavelengths

Gain and population inversion

$$G\ (\lambda_s) = \sigma_e(\lambda_s)\overline{N_2} - \sigma_a(\lambda_s)\overline{N_1}$$

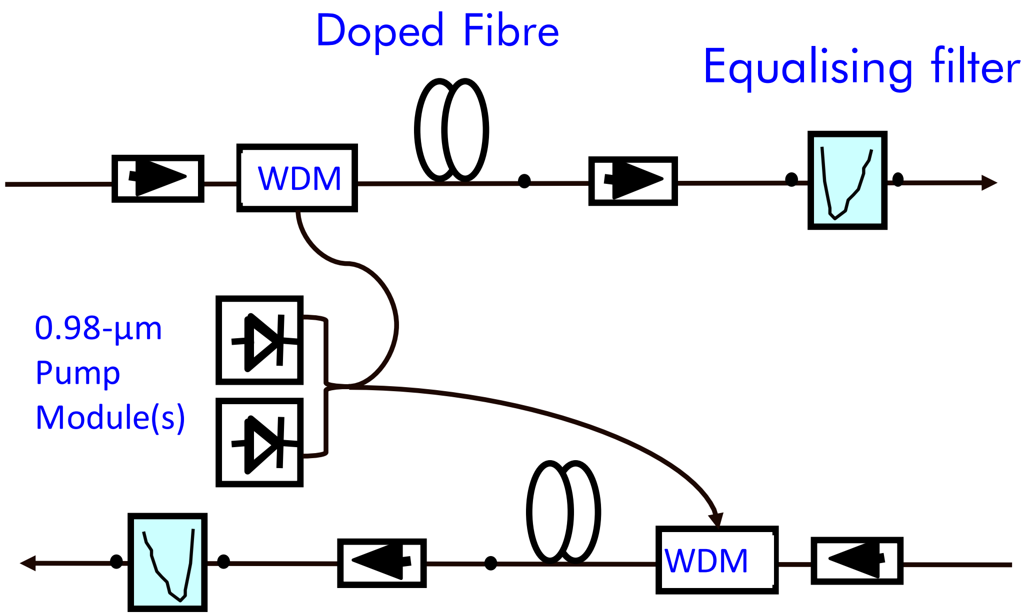
$N_1 + N_2 = N_t$

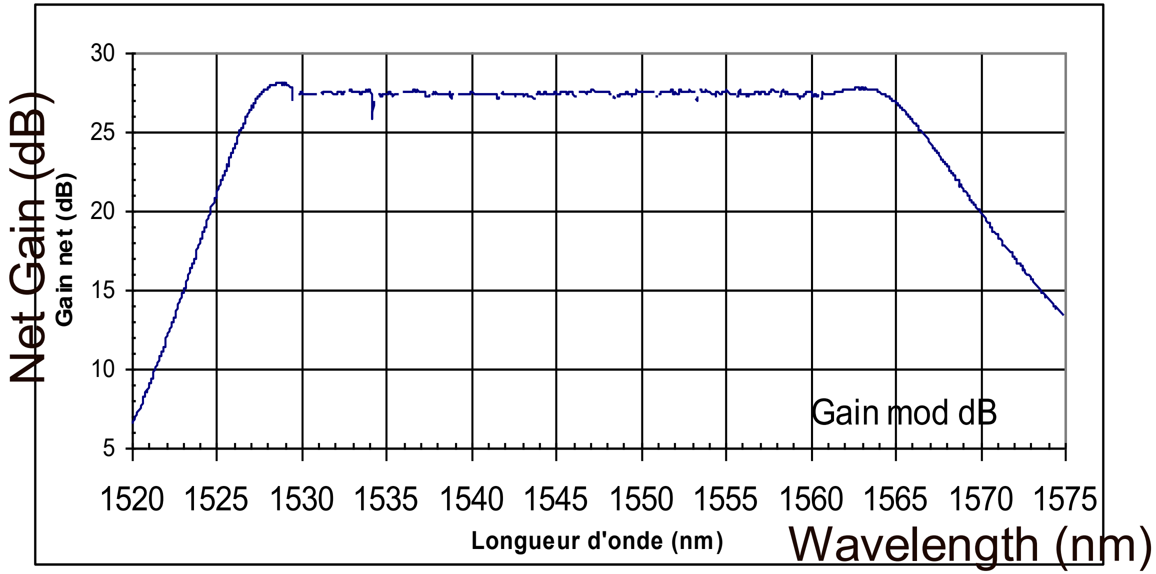


Whatever the inversion, the gain is not flat!

With a constant gain (population inversion) one can control the spectral profile using a fixed equalization optical filter

Typical optical amplifier with optical equalization





Typical features of subsea repeaters

- Total output power : up to 21dBm
- Equalizing filter adapted to fixed inter-amplifier section (span)
- Flatness within ± 0.1dB over up to 5THz (40nm)
- Noise figure ~ 4-5 dB

Quality of transmission parameter: OSNR

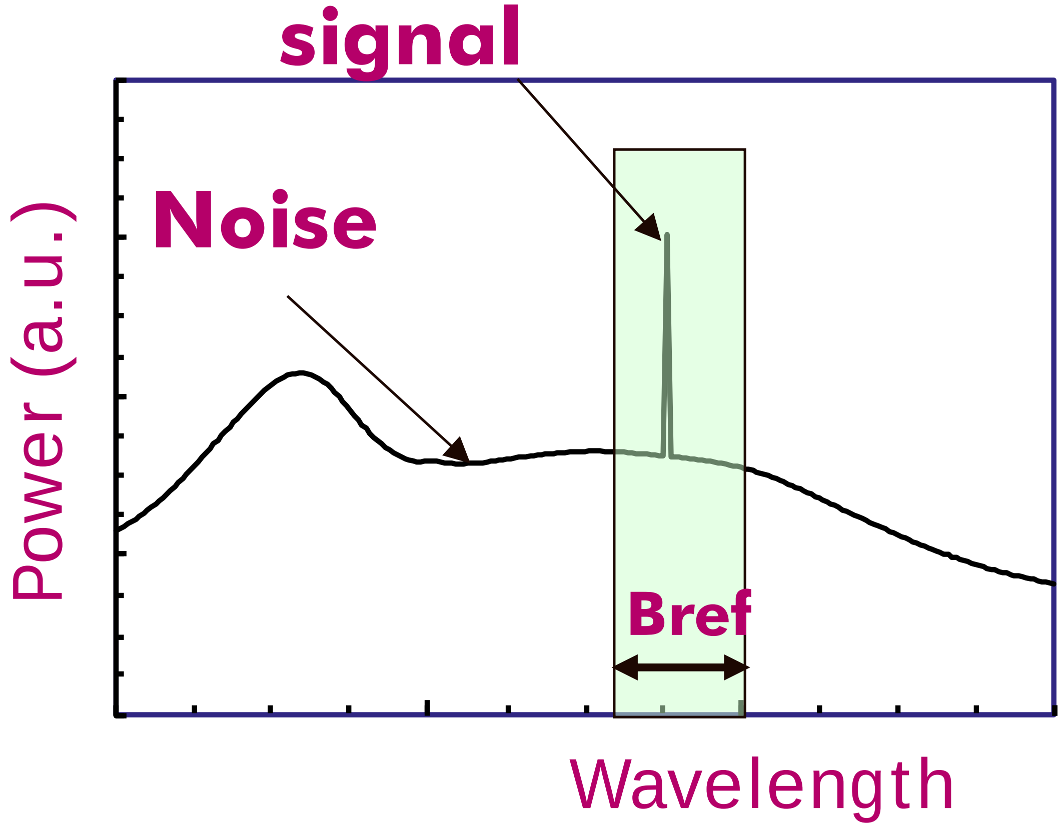
Amplified Spontaneous Emission (ASE)

- Additive Gaussian Noise
- Broadband noise: >4THz, 30nm

Optical Signal to Noise Ratio (OSNR)

$$OSNR_{B_{ref}} = \frac{P_{signal\ per\ channel}}{P_{noise,2\ polars,B_{ref}}}$$

Expressed in dB, generally w/in 0.1nm (12.5GHz)



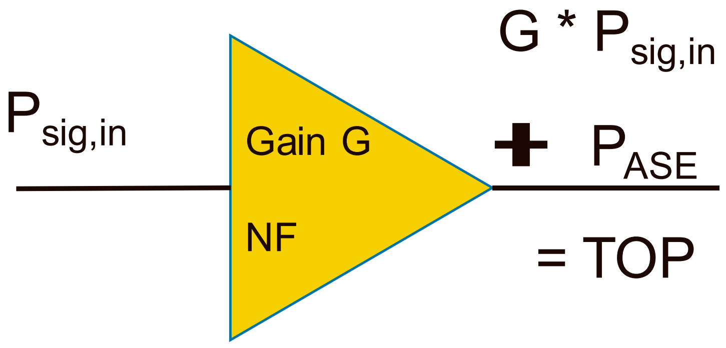
Amplifier characteristics:
Total Output Power (TOP), noise figure (NF)

- Generated ASE noise:
  - $P_{ASE,B_{ref}} = NF * G * \frac{hc}{\lambda} * B_{ref}$

    Noise Figure (ITU)

    Amplifier gain

    Photon energy



- OSNR after 1 amplifier
  - Depends on input power
  - $OSNR_{B_{ref}} = \frac{P_{in\ per\ channel}}{NF} * K, \quad with\ K = \frac{\lambda}{hc * B_{ref}}$

ALCATEL SUBMARINE NETWORKS

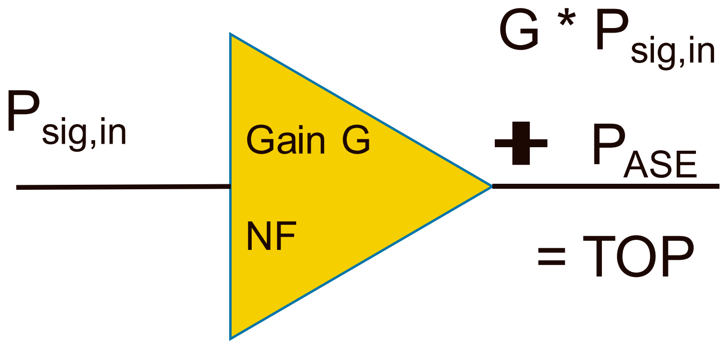
Amplifier characteristics:
Total Output Power (TOP), noise figure (NF)

- Generated ASE noise:
  - $P_{ASE,B_{ref}} = NF * G * \frac{hc}{\lambda} * B_{ref}$

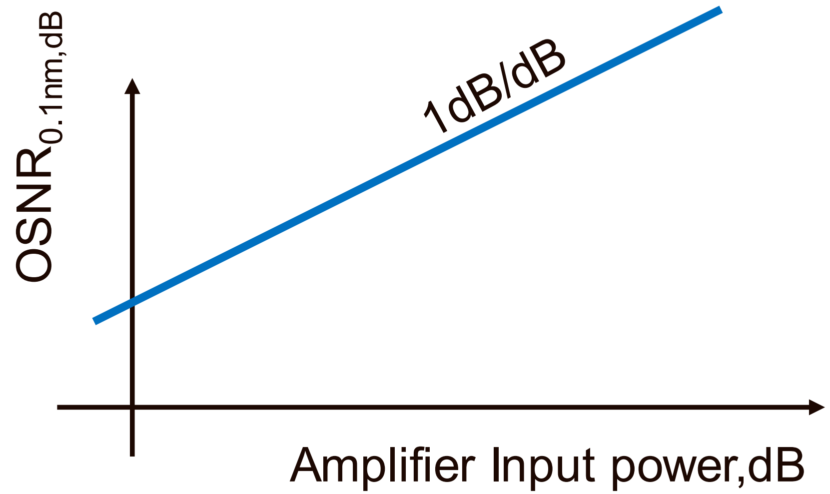
Noise Figure (ITU)

Amplifier gain

Photon energy

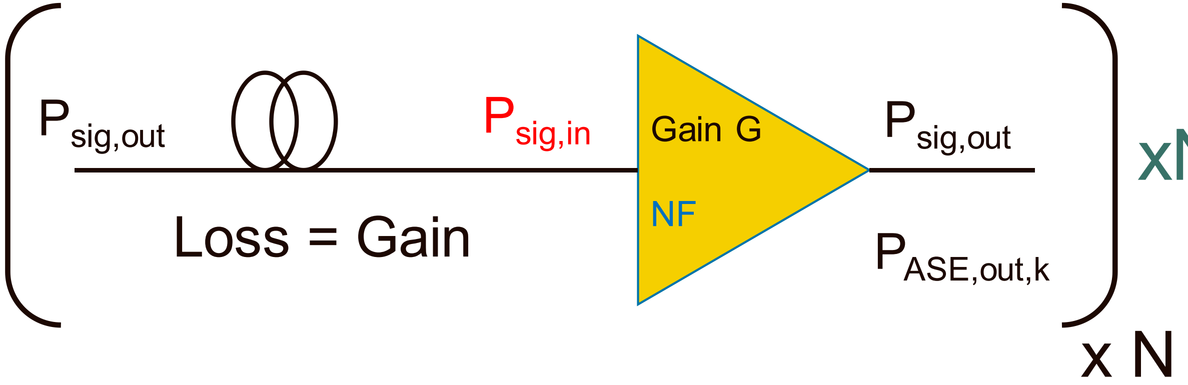


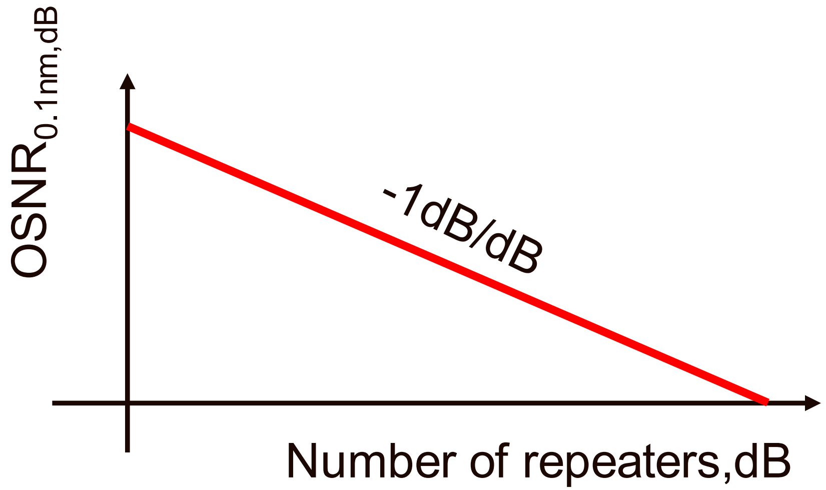
- OSNR after 1 amplifier
  - Depends on input power
  - $OSNR_{B_{ref}} = \frac{P_{in\,per\,channel}}{NF} * K, \quad with\ K = \frac{\lambda}{hc*B_{ref}}$
  - $OSNR_{0.1nm,dB} = 58 + P_{tot,in,dBm} - Nb_{channels,dB} - NF_{dB}$



Cascade of N identical repeaters

- Generated ASE noise:
    - * N
- OSNR after N amplifiers
    - Assuming same signal input power





- $OSNR_{dB,0.1nm} = 58 + P_{tot,out,dBm} - Loss_{dB} - Nb_{channels,dB} - NF_{dB} - N_{dB}$

Application : reach of terrestrial vs submarine systems

- $OSNR_{dB,0.1nm} \approx 58 + P_{out,total,dBm} - \#channels_{dB} - Loss_{dB} - NF_{dB} - N_{repeaters,dB}$
- SpanLoss$_{dB}$ = Attenuation$_{dB/km}$ * Repeater-spacing$_{km}$

	Terrestrial	Submarine
Amplifier spacing (km)	100	60
Attenuation (dB/km)	0.22	0.15
Amplifier total output power (dBm, 100ch)	20	15
Noise figure (dB)	6	4
Transmission reach (km)	2,000	12,000
Number of repeaters		
Amplifier output power per channel (dBm)		
Span loss (dB)		
OSNR (dB/0.1nm)		

OSNR in open cables: conventional vs natural bandwidth

- Convention: 0.1nm → OSNR depends on terminal (# channels)
- Natural: **channel spacing** → OSNR does not depend on terminal

$$SNR_{ASE} = \frac{P_{signal,channel}}{P_{noise,channel\ spacing}} = \frac{P_{signal,total}}{P_{noise,total}}$$

OSNR in open cables: conventional vs natural bandwidth

- Convention: 0.1nm → OSNR depends on terminal (# channels)
- Natural: **channel spacing** → OSNR does not depend on terminal
- Conversion:

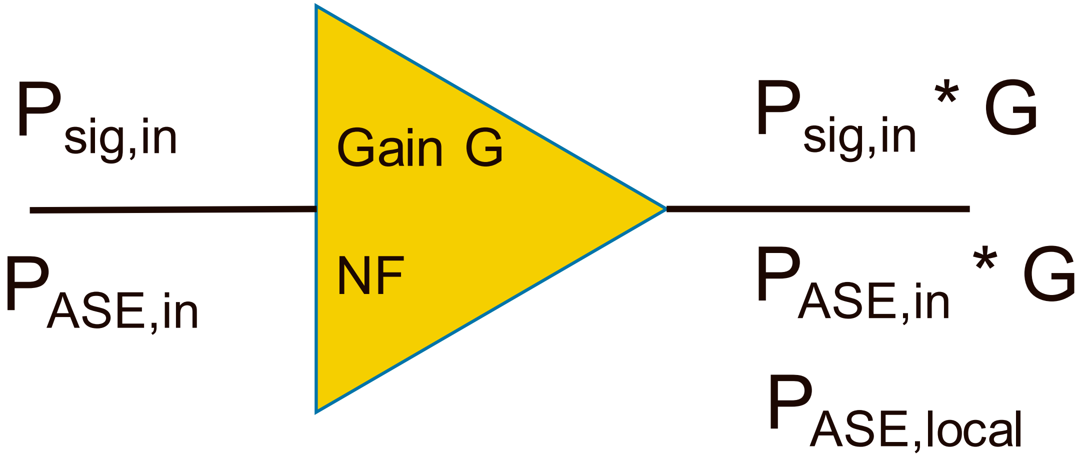
$$SNR_{ASE,dB} = OSNR_{ASE,B_{ref},dB} + 10 * \log_{10}\left(\frac{B_{ref}}{Channel\ spacing}\right)$$

or

$$SNR_{ASE,dB} \approx 38.9 + P_{out,tot,dBm} - Loss_{dB} - NF_{dB} - N_{rep,dB} - 10\log_{10}(Ampl.Band_{THz})$$

General formula of a cascade of amplifiers (1/3)

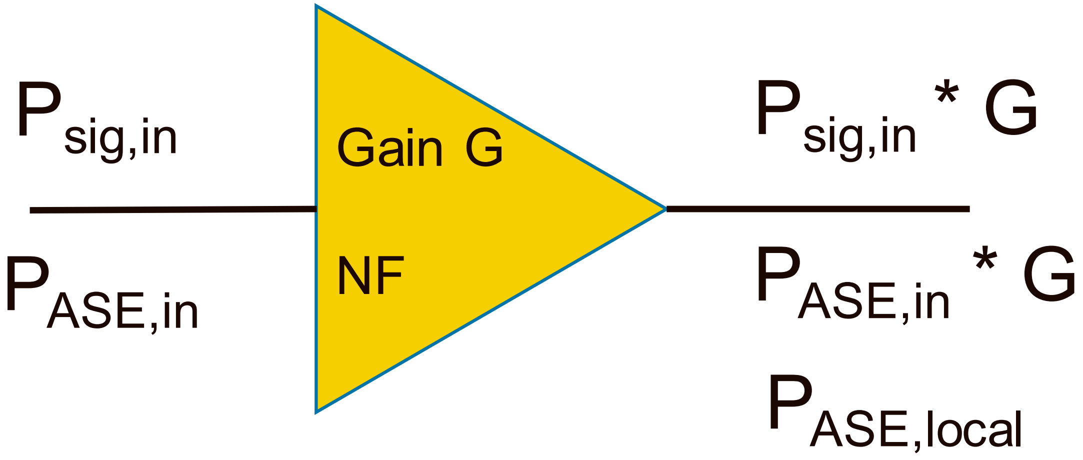
- OSNR degradation in presence of existing noise ($OSNR_{in}$)



$$\frac{1}{OSNR_{out}} = \qquad = \qquad +$$

General formula of a cascade of amplifiers (2/3)

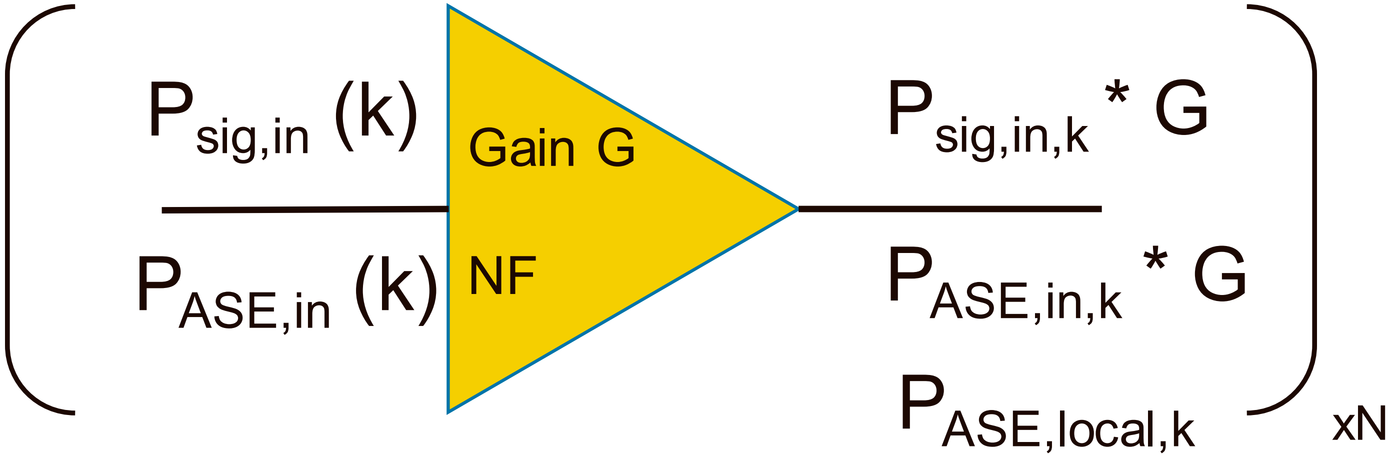
- OSNR degradation in presence of existing noise ($OSNR_{in}$)



$$\frac{1}{OSNR_{out}} = \frac{1}{OSNR_{in}} + \frac{1}{OSNR_{local}}$$

General formula of a cascade of amplifiers (3/3)

- OSNR degradation in presence of existing noise ($OSNR_{in}$)



$P_{sig,in}$ (k)

$P_{ASE,in}$ (k)

Gain G

NF

$P_{sig,in,k}$ * G

$P_{ASE,in,k}$ * G

$P_{ASE,local,k}$

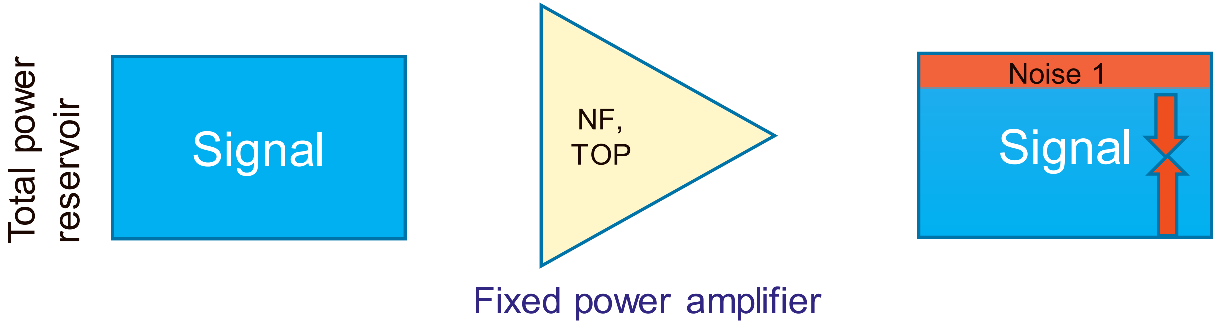
xN

$$\frac{1}{OSNR_{out}} = \sum_{k=1}^{N} \frac{1}{OSNR_{local,k}}$$

- Depends on $P_{sig,in,k}$

Exact OSNR with constant power amplifiers: signal & ASE droop

- Submarine repeaters = constant output power



Fixed power amplifier

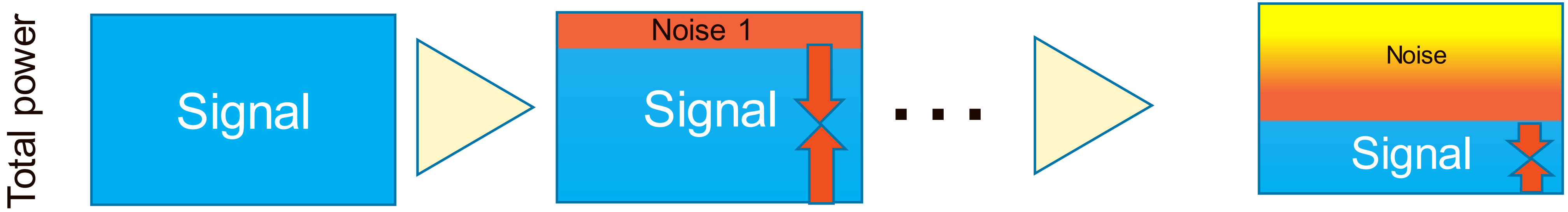
- A fraction of total power is converted into noise
- The proportion of input signal decreases ➔ attenuation / droop

$$\frac{P_{total}}{P_{signal}} = \frac{P_{signal}+P_{noise}}{P_{signal}} = 1 + \frac{1}{SNR_{ASE}}$$

(SNRs expressed in channel spacing band)

Exact SNR after a cascade of repeaters

[J.-C. Antona et al, Mo1J.6, OFC’19]



- Cascade of fixed power amplifiers: product of attenuations matters

$$1+\frac{1}{SNR_{ASE}}=\prod_k\left(1+\frac{1}{SNR_k}\right)$$

Individual theo. contributions

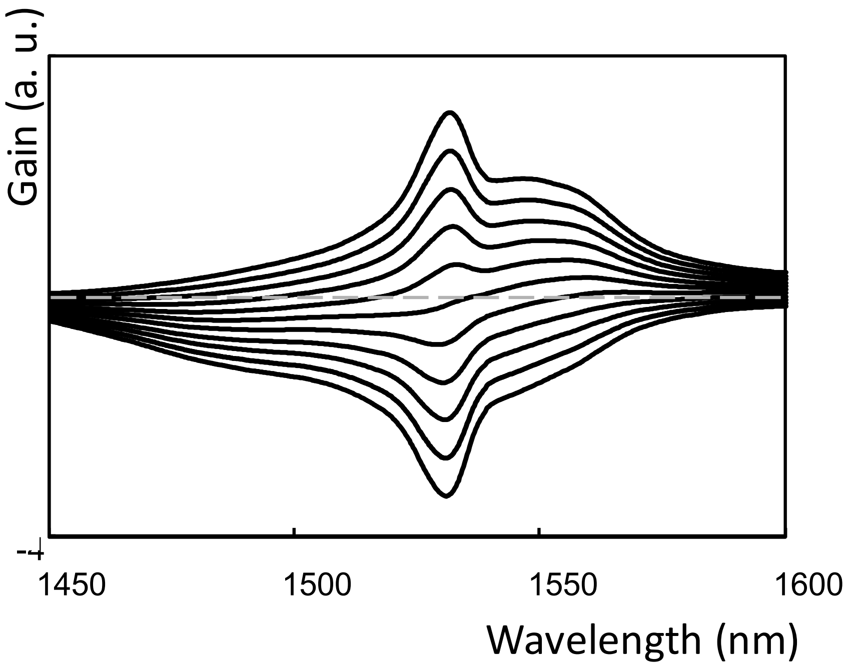
Generalized droop (of signal and ASE)

- 1st order approximation: $SNR_{Droop,1st\ order}=SNR_{theo}-\frac{1}{2}$ (for SNR>2dB)

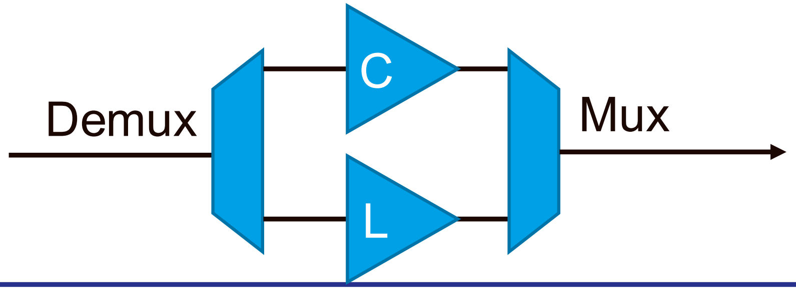
$$OSNR_{Droop,1st,B_{ref}}=OSNR_{theo,B_{ref}}-\frac{1}{2}*\frac{Ch.spacing}{B_{ref}}$$

C+L wide-band amplification

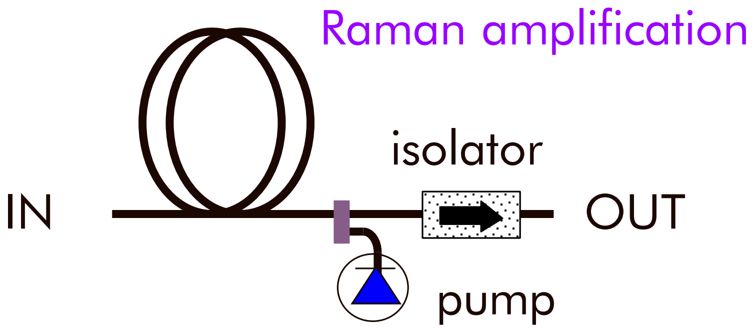
- Most amplifiers operate in the C-band
  - 1528-1570nm
  - High gain => short EDF



- Possible operation in the L-band
  - 1570-1610nm
  - Low gain ➔ long EDF
- Wideband C+L amplifiers
  - Separate amplifiers and band Demux/Mux
  - Higher bandwidth, with a price to pay…

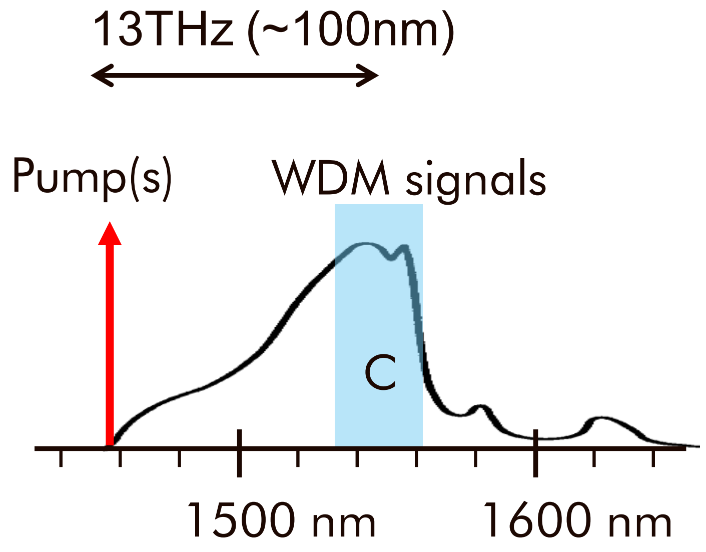


(Distributed) Raman amplification

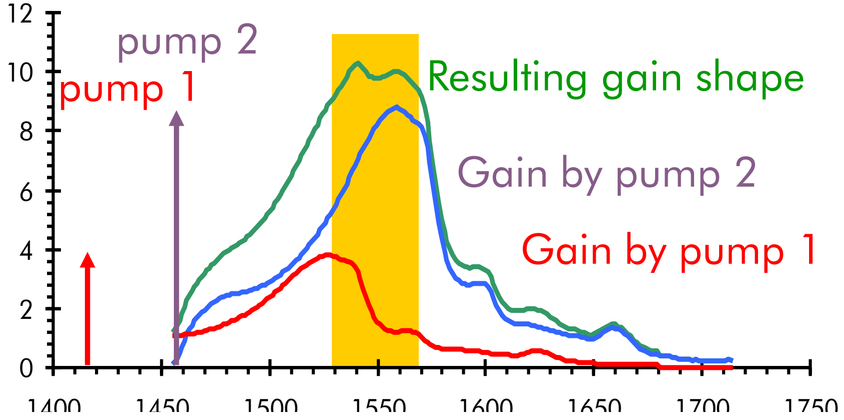


Stimulated process

Molecular vibrations of SiO_2



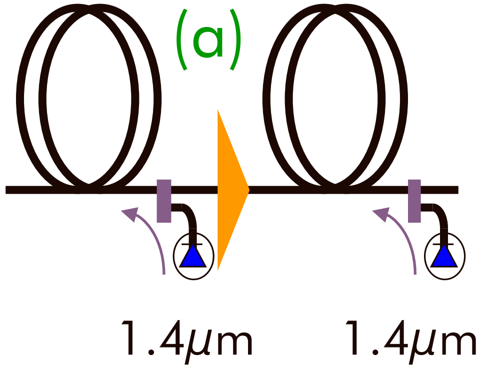
- Erbium process enables constant power operation
- Yet Raman amplification
  - bandwidth and gain shape are tunable
  - can be distributed along the line fiber → low NF



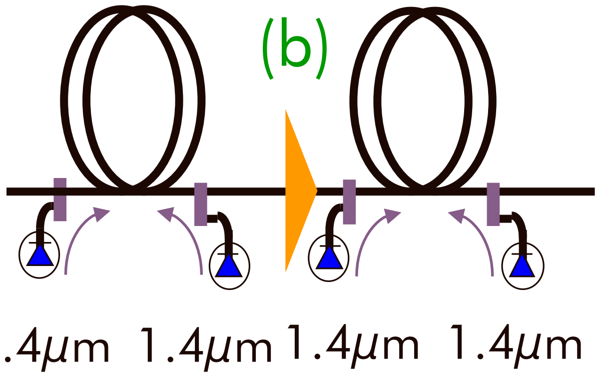
➔ (Dynamic) gain tilt management possible

Raman-assisted amplification schemes

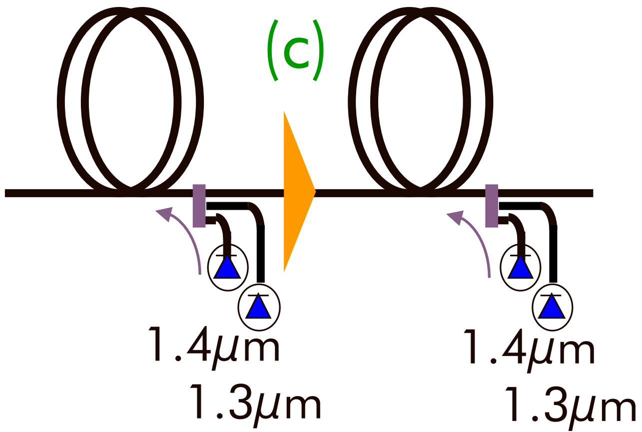
Conventional backward scheme



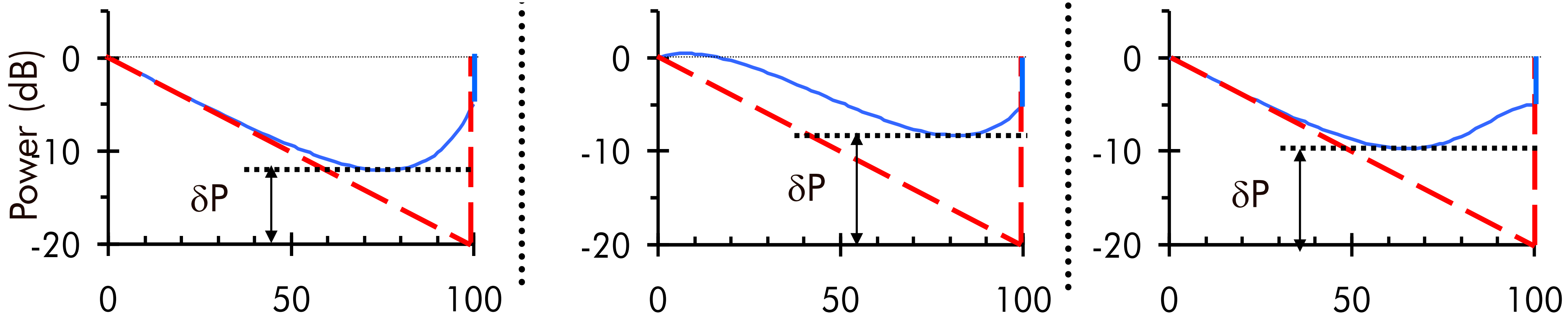
Bidirectional scheme



Second-order backward pumping

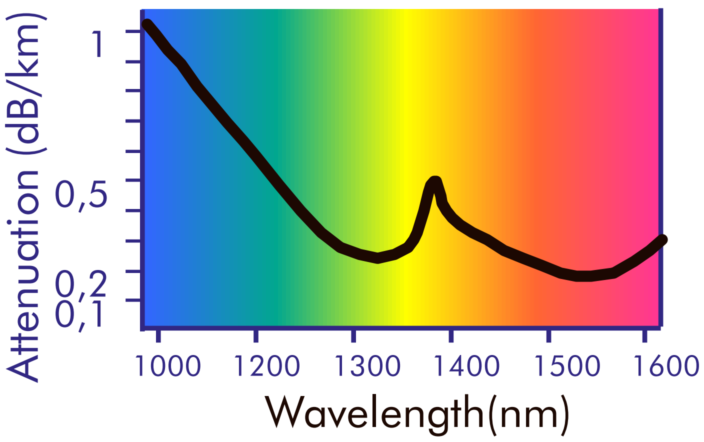


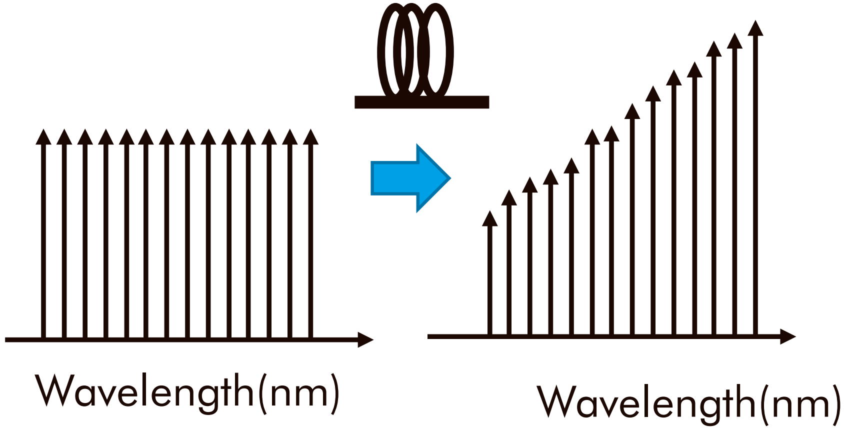
(Example: 15dB total Raman gain in all configurations)

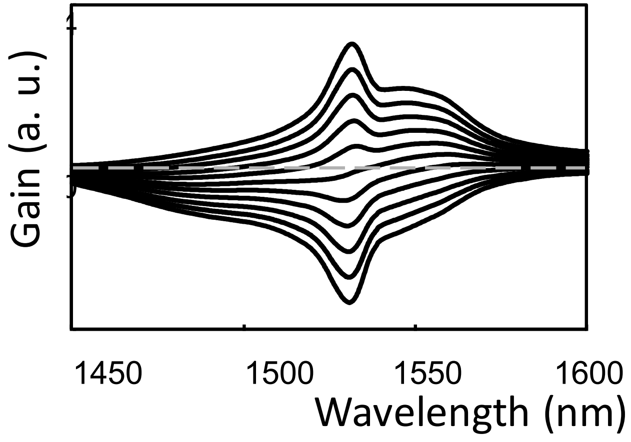


- ◆ Naturally, (b) and (c) may be combined…

Refinement: Wavelength dependence Gain

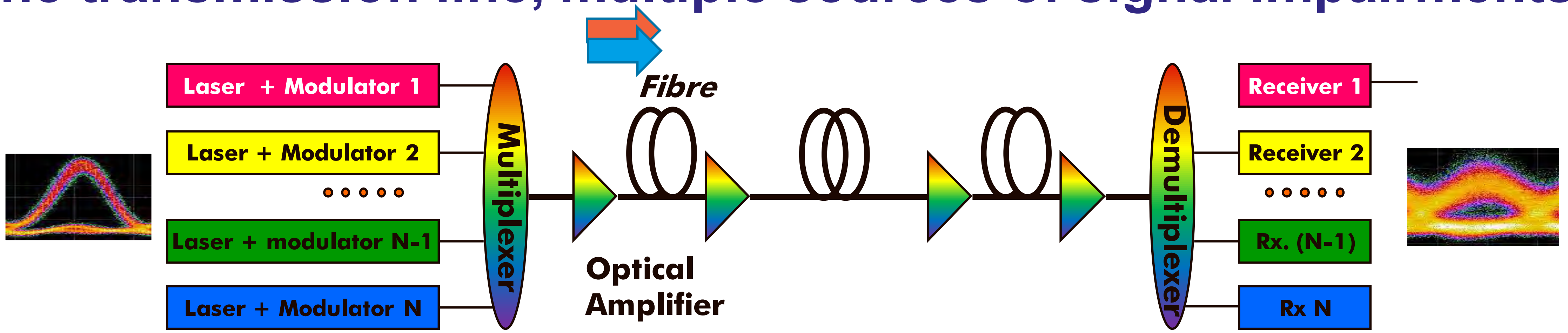

Fiber Attenuation


Stimulated Raman Scattering


EDFA gain

- Despite filter at amplifiers + periodic Equalizers along the line
- Wavelength-dependent OSNR ➔ reduction of average OSNR
- Coping with that:
  - Today: (O)SNR equalization by channel power adjustment (pre-emphasis)
  - Future ?: wavelength-dependent bit-rate

One transmission line, multiple sources of signal impairments



Physical effect	Impact	Mitigation	Limitations
Attenuation	Undetectable Signal	Optical amplification	Amplifier noise, SNR_{ASE}
Chromatic Dispersion Frequency dep. Speed	Pulse broadening	~~Inline optical~~ Electronic Dispersion compensation	Imperfect compensation

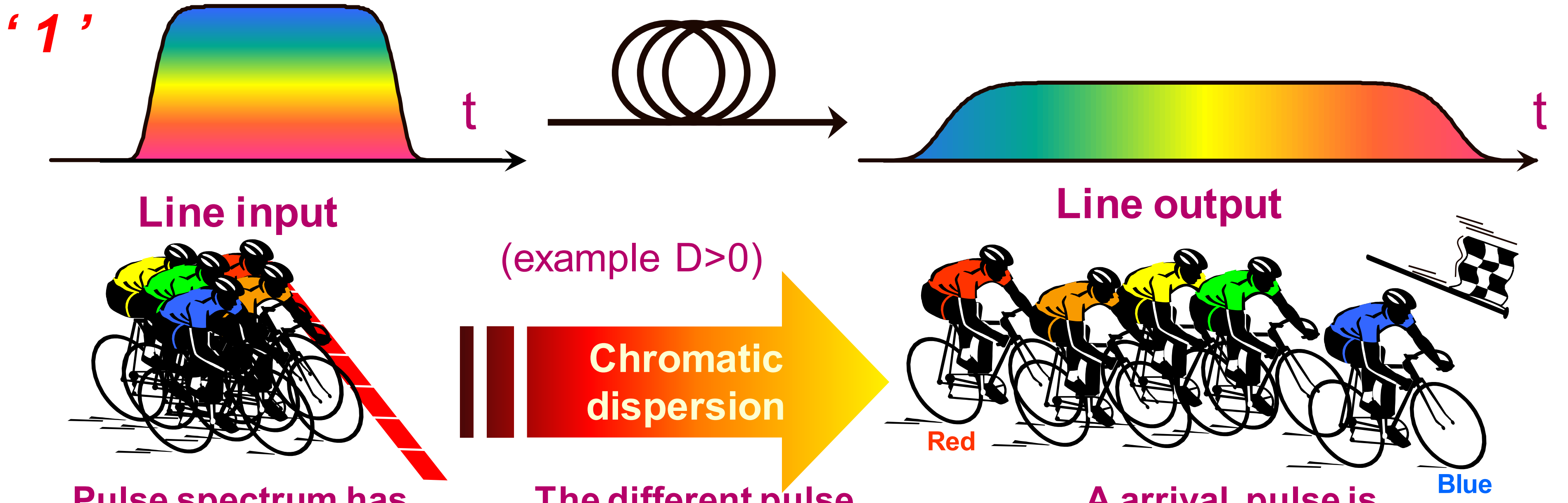
Chromatic dispersion (or Group velocity dispersion)

- Origin: wavelength dependence of refractive index
- Thus group velocity depends on wavelength
- Chromatic dispersion (or group velocity dispersion, GVD)

$$D = \frac{\partial}{\partial \lambda}\left(\frac{1}{v_g}\right)(ps/nm/km) \quad ou \quad \beta_2 = \frac{\partial}{\partial f}\left(\frac{1}{v_g}\right)(ps^2/km)$$

Notation from Optics world **Notation from Physics world**

Chromatic dispersion



Line input

(example D>0)

Line output

Pulse spectrum has a given bandwidth

The different pulse wavelengths travel at different group velocities

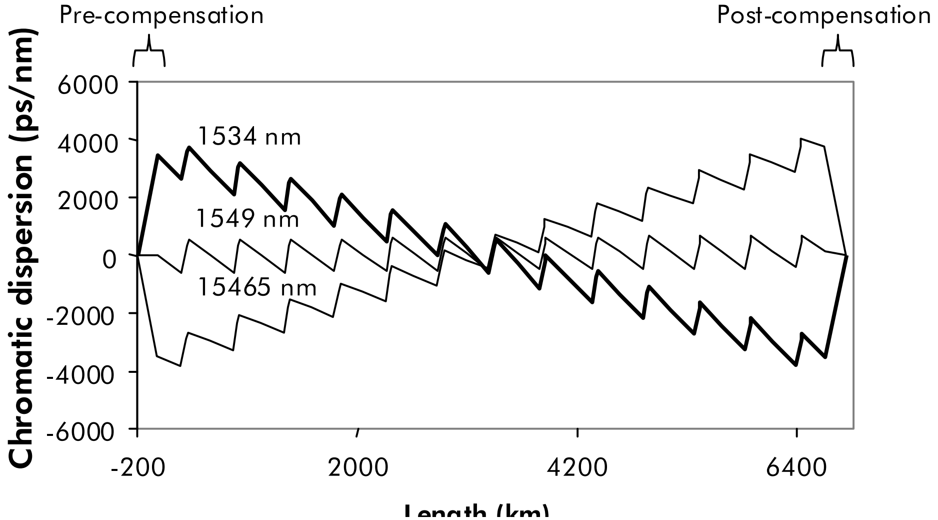
A arrival, pulse is broadened because of chromatic dispersion

- Dispersion D is expressed in (ps/(nm.km))

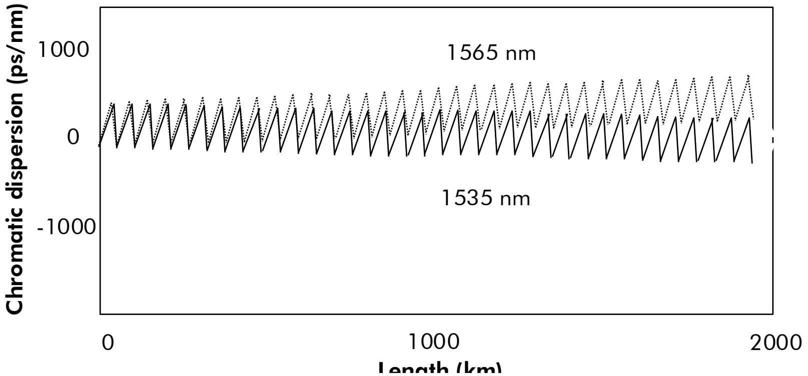
D gives the arrival time after 1km fiber between two 1nm-spaced spectral components.
From 10 to 100Gbaud: 100 times more stringent !!!

Evolution of dispersion maps in submarine cables

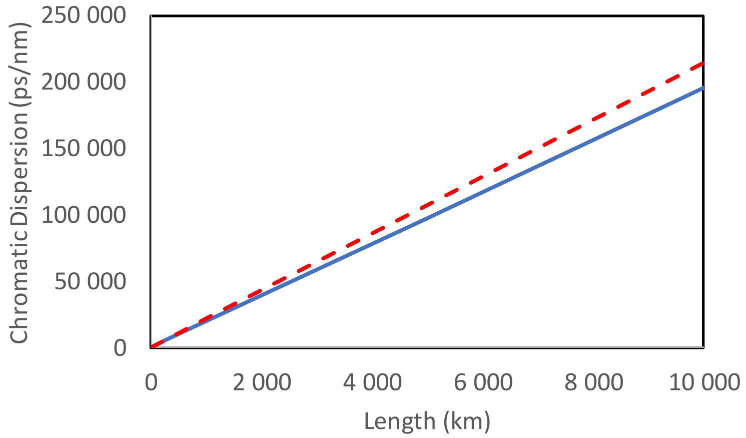
2000: NZDSF dispersion map



2005: DMF dispersion map

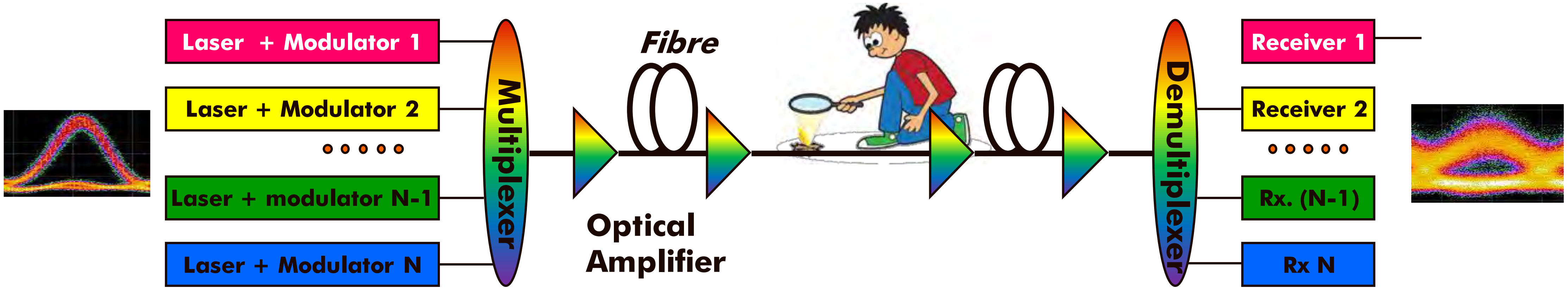


2010: Coherent dispersion map



- "Coherent" systems
  - Electronic mitigation
  - D+ fiber only:
    - Low attenuation, high effective area, high dispersion
    - ~ 0.15 dB/km 80-150μm^2 ~ 21 ps/nm/km

One transmission line, multiple sources of signal impairments

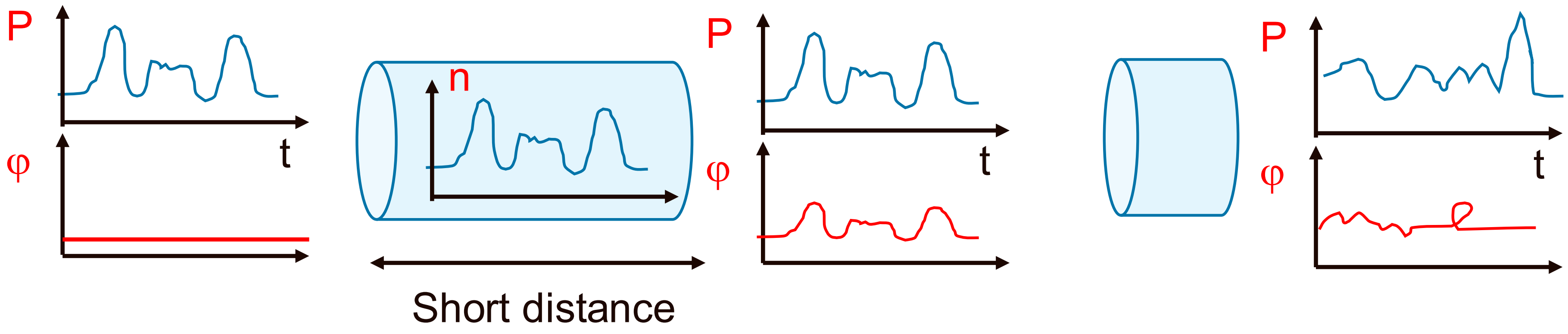


Physical effect	Impact	Mitigation	Limitations
Attenuation	Undetectable Signal	Optical amplification	Amplifier noise, SNR_{ASE}
Chromatic Dispersion Frequency dep. Speed	Pulse broadening	~~Inline optical~~ Electronic Dispersion compensation	Imperfect compensation
Kerr effect (power →phase)	Power-dep. distortions	~~Dispersion management,~~ electronic mitigation	Repeater count & power

Origin of Optical nonlinearities

- Main limitation = ASE noise ➔ need higher optical powers…
- But not too much, please
  - Low optical powers ~ 20dBm (100mW)
  - Low core effective area ~ 100µm²
  - ➔ High optical intensity: 1 billion W/m²
- 10 000 x solar radiation at top of Earth's atmosphere

Nonlinear Kerr effect



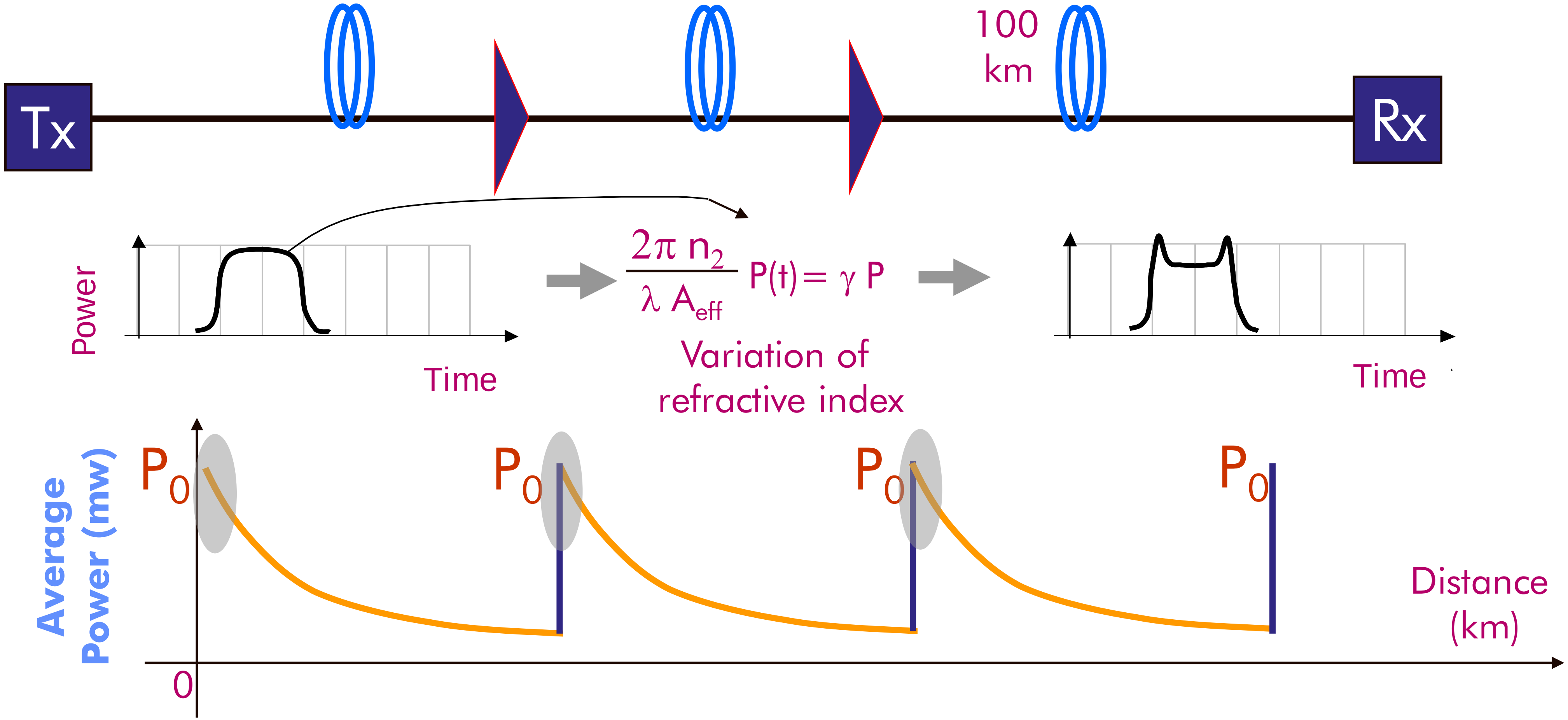
- 1/ High optical power variations modulate fiber refractive index
  - $n = n(\omega) + n_2 * P(t) / A_{eff}$

- 2/ the refractive index modifies the local phase of total optical field

- 3/ interplay with chromatic dispersion ➔ phase and intensity modulation ➔ mess

- Impact on one channel:
  - intra-channel or inter-channel effect, nonlinear signal noise interaction

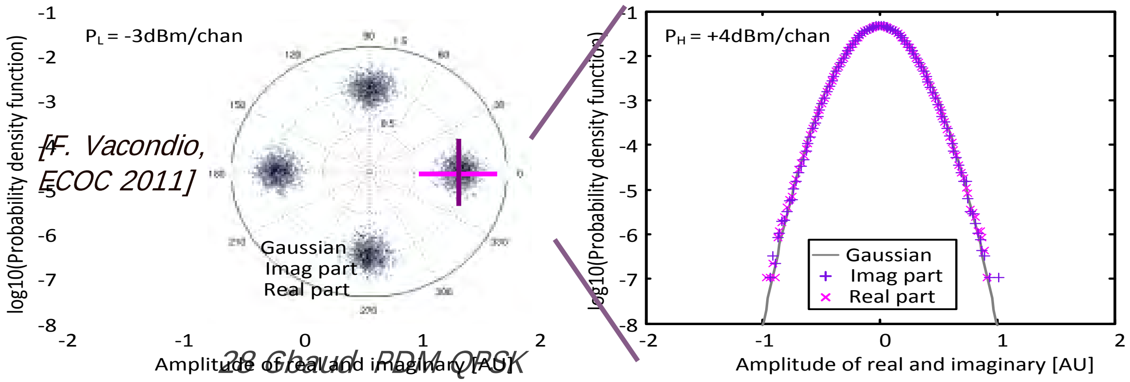
Nonlinear effects accumulation



- When P_0 or distance (N) increase, non-linear effects increase and degrade signal.
- Accumulation depends on cumulated dispersion at each section input… Non obvious.

Nonlinear impairments as an additive Gaussian noise

- With current systems
  - High modulation rate
  - Complex modulations
  - Coherent detection



[F. Vacondio, ECOC 2011]

28 Gbaud PDM QPSK

Measured PDF of Kerr induced distortions

After 15x100km SSMF WDM Dispersion Unmanaged experiment.

Additive Gaussian noise ➔ noise variance, (O)SNR$_{NL}$ matter

$$\text{Variance} \propto N_{spans}^{1+\epsilon} * \left(\frac{P_{span\ input}}{A_{eff}}\right)^2 P_{Rx}$$

$\epsilon \sim 0$ for coherent dispersion maps, ~1 when inline dispersion compensation

$\propto$: analytical derivation in perturbative models (GN model…)

Practical cases

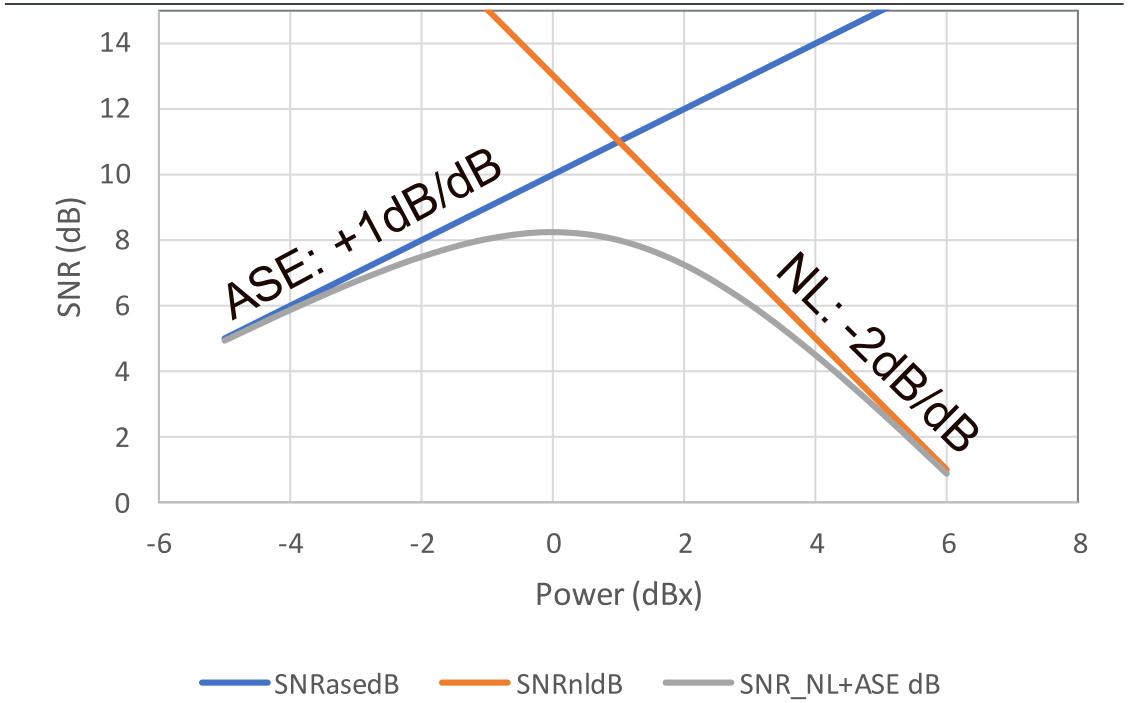
$$SNR_{NL} \propto \frac{1}{N_{spans} * P_{ch}^2}$$

i.e.

$$SNR_{NL,dB} = K - N_{spans,dB} - 2 * P_{ch,dBm}$$

Combined with (O)SNR$_{ASE}$

$$P_{ASE+NL} \approx P_{ASE} + P_{NL}$$



Optimum power: ASE noise = 2x NL noise

Practical cases

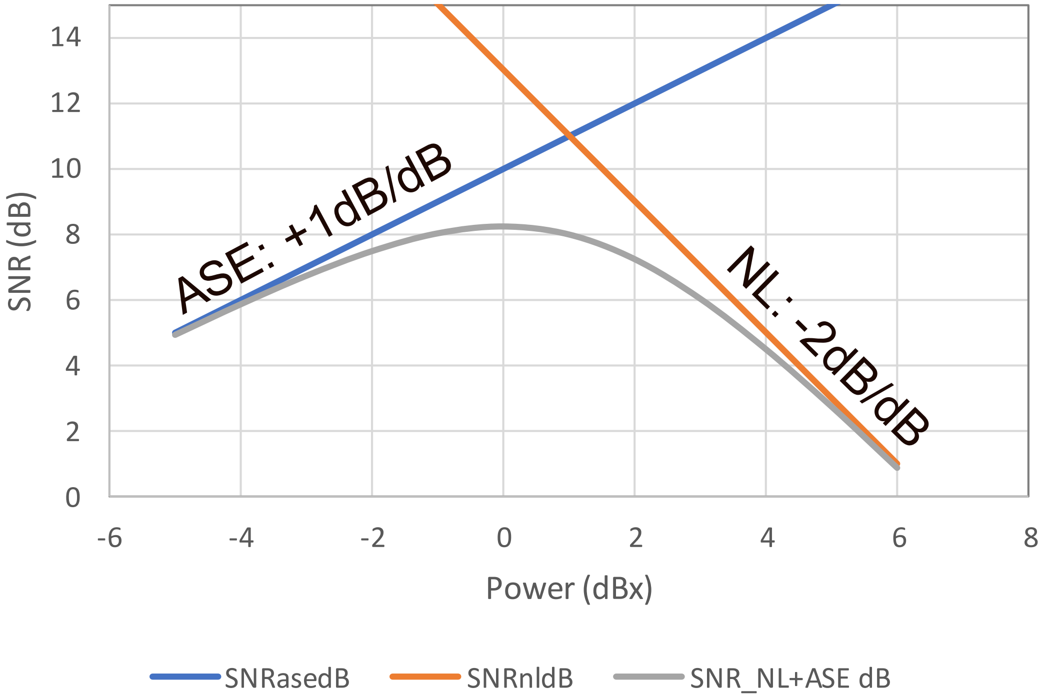
$$\boldsymbol{SNR_{NL} \propto \frac{1}{N_{spans} * P_{ch}^{2}}}$$

i.e.

$$SNR_{NL,dB} = K - N_{spans,dB} - 2 * P_{ch,dBm}$$

Combined with (O)SNR$_{ASE}$

$$\boldsymbol{\frac{P_{ASE+NL}}{P_{signal}} \approx \frac{P_{ASE}}{P_{signal}} + \frac{P_{NL}}{P_{signal}}}$$



Optimum power: ASE noise = 2x NL noise

Practical cases

$$\boldsymbol{SNR_{NL} \propto \frac{1}{N_{spans} * P_{ch}^2}}$$

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Combined with (O)SNR$_{ASE}$

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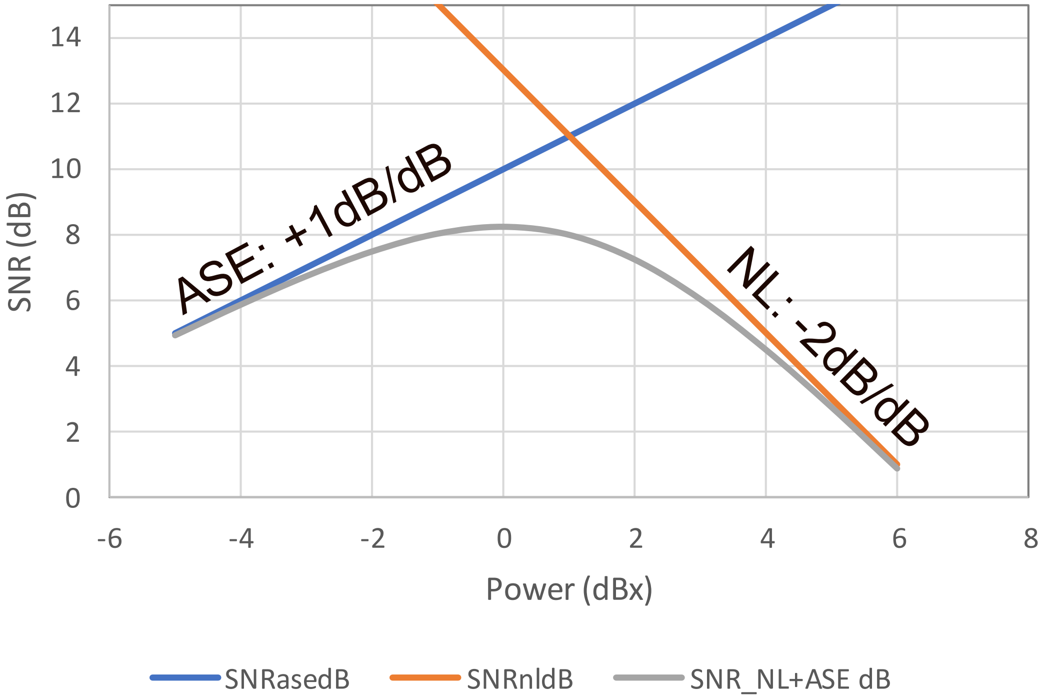


Optimum power: ASE noise = 2x NL noise

Application : reach of terrestrial vs submarine systems

- $OSNR_{dB,0.1nm} \approx 58 + P_{out,total,dBm} - \#channels_{dB} - Loss_{dB} - NF_{dB} - N_{repeaters,dB}$
- $SpanLoss_{dB} = Attenuation_{dB/km} * Repeater\text{-}spacing_{km}$

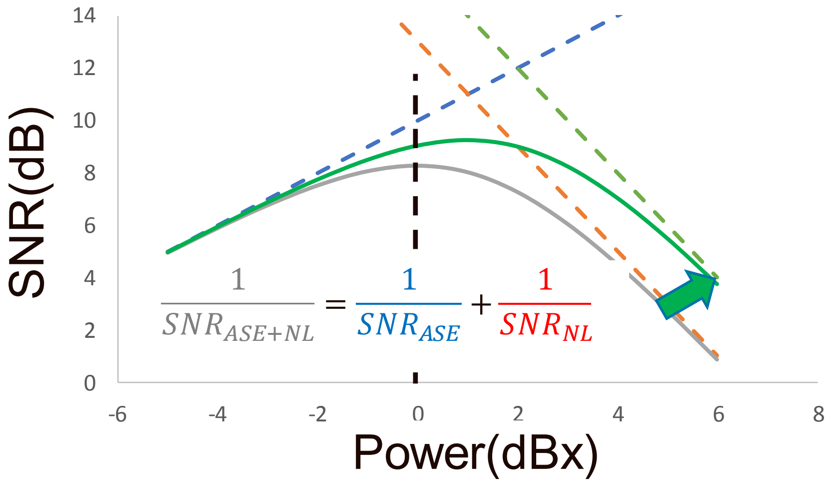
	Terrestrial	Submarine
Amplifier spacing (km)	100	60
Attenuation (dB/km)	0.22	0.15
Amplifier total output power (dBm, 100ch)	20	15
Noise figure (dB)	6	4
Transmission reach (km)	2,000	12,000
Number of repeaters	20	200
Amplifier output power per channel (dBm)	0	-5
Span loss (dB)	23	9
OSNR (dB/0.1nm)	17	17
Nonlinear noise: $N_{dB} + 2P_{dBm}$		

Signal impairments in the cable: Additive Gaussian noise models

- 2. Nonlinear (NL) noise due to high power density: (< 30% of impairments)

$$SNR_{NL} \approx \frac{K_{models} * A_{eff}^2}{N_{spans}^{\epsilon}} * \frac{\mathbf{1}}{\boldsymbol{N_{spans}} * \boldsymbol{Power^2}} - 1$$

often neglected

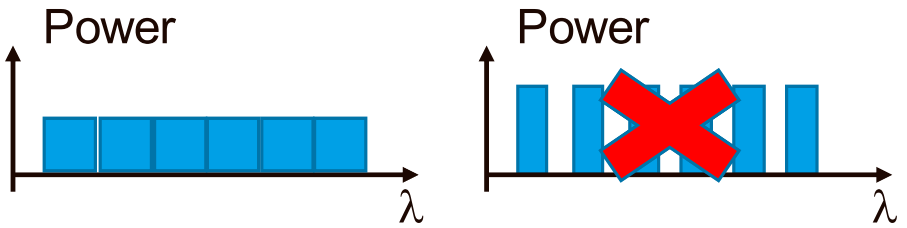


$$\frac{1}{SNR_{ASE+NL}} = \frac{1}{SNR_{ASE}} + \frac{1}{SNR_{NL}}$$

- Coming: partial mitigation of NL at transceiver

Signal impairments in the cable: Additive Gaussian noise models

- More on Nonlinear (NL) noise
  - **The higher the chromatic dispersion, the better**
  - **The flatter the power spectral density, the better**
    - Why ? Peaks of power (in time / frequency) are detrimental
    - Channel rate as close as possible to channel spacing

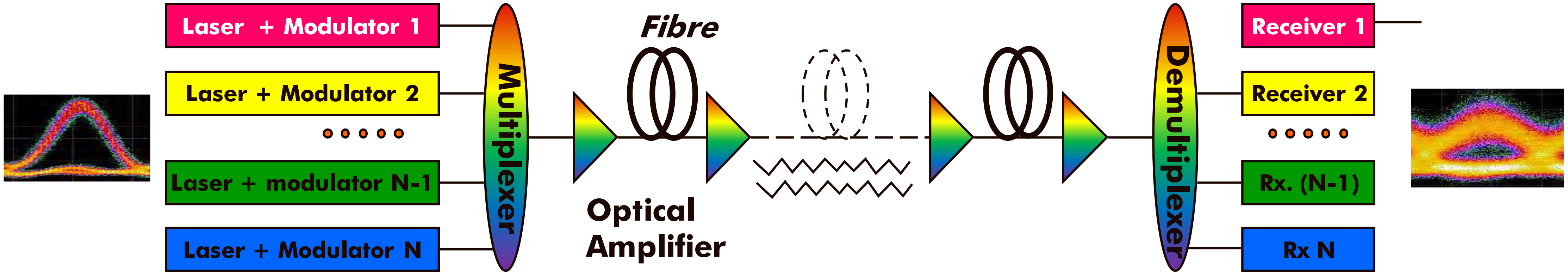


- Details: NL noise seen by a channel stems from intra- and interchannel nonlinear effects, following:
- $\sigma^2_{NL,tot}(ch\ \#i) = A_{NL} * P^2_{ch\ \#i} + B_{NL} * \sum_{ch\ \#j\neq i} \frac{P^2_{ch\ \#j}}{|\lambda_j-\lambda_i|}$ ➔ Less channels @ constant TOP and channel type = ☹

Power channel i

Difference in wavelengths/frequencies

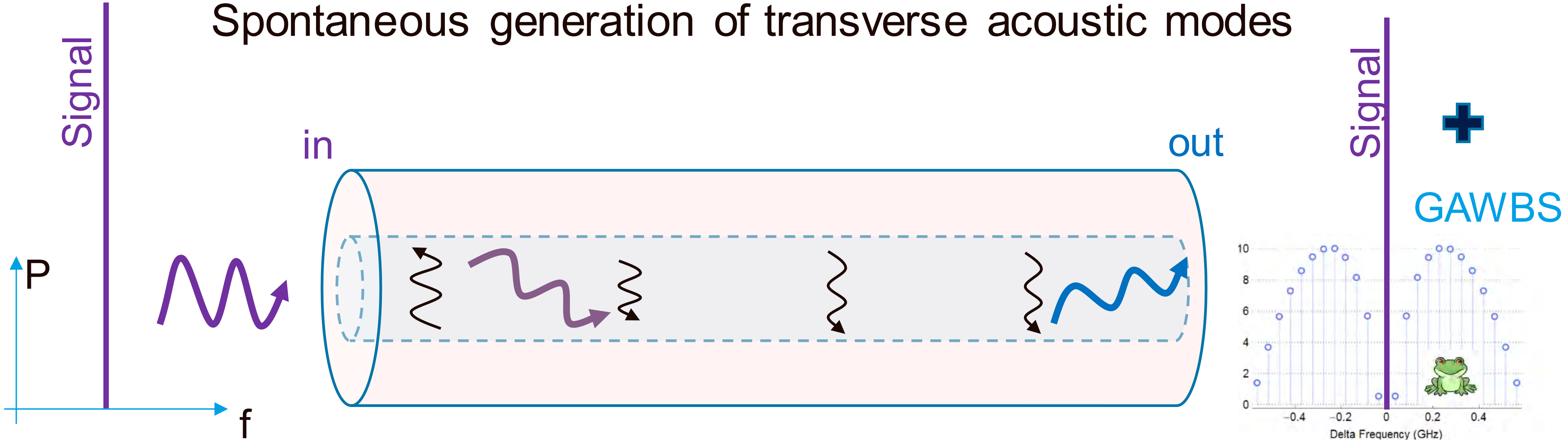
One transmission line, multiple sources of signal impairments



Physical effect	Impact	Mitigation	Limitations
Attenuation	Undetectable Signal	Optical amplification	Amplifier noise, SNR_{ASE}
Chromatic Dispersion Frequency dep. Speed	Pulse broadening	~~Inline optical~~ Electronic Dispersion compensation	Imperfect compensation
Kerr effect (power →phase)	Power-dep. distortions	~~Dispersion management,~~ electronic mitigation	Repeater count & power
GAWBS: acoustic waves	Phase & polar shifts		Length, Effective area

Guided Acoustic Wave Brillouin Scattering (GAWBS)

[M. Bolshtyanski et al, M4B.3, OFC'18]



Scatters incoming light in the forward direction, with small frequency shifts

➔ Crosstalk noise

$$P_{GAWBS} \propto \frac{Distance}{A_{eff}^{x}} * P_{ch}$$

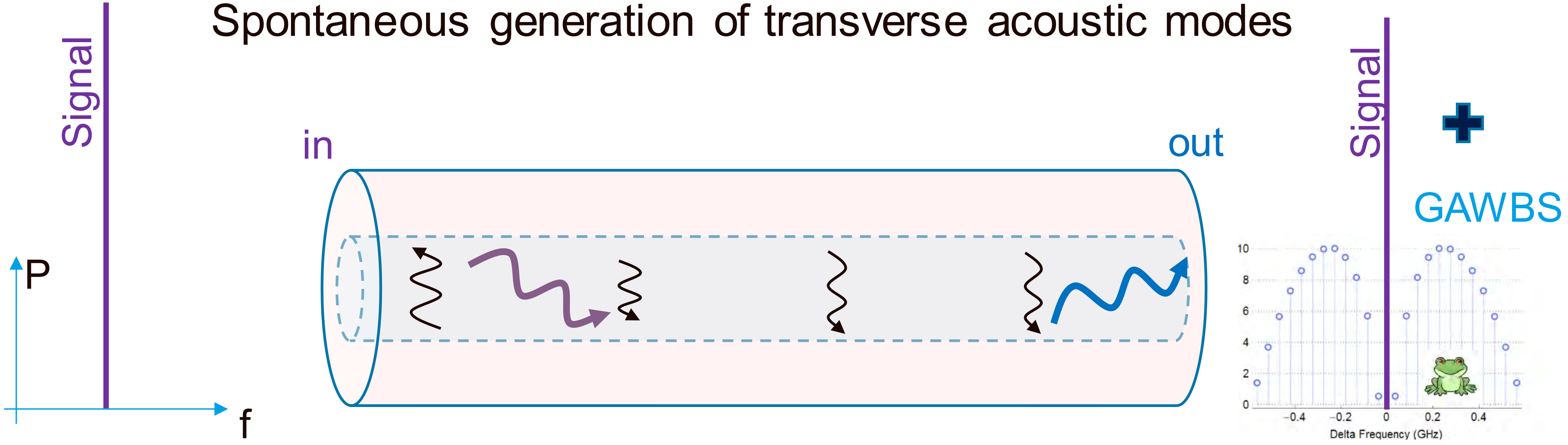
characterized in M4B.3, OFC'18

X ~ 1

Guided Acoustic Wave Brillouin Scattering (GAWBS)

[M. Bolshtyanski et al, M4B.3, OFC'18]

Spontaneous generation of transverse acoustic modes



Scatters incoming light in the forward direction, with small frequency shifts

➔ Crosstalk noise

$$SNR_{GAWBS} \propto \frac{A_{eff}^{x}}{Distance}$$

characterized in M4B.3, OFC'18

Joint SNR, Line SNR, Gaussian SNR, Generalized SNR

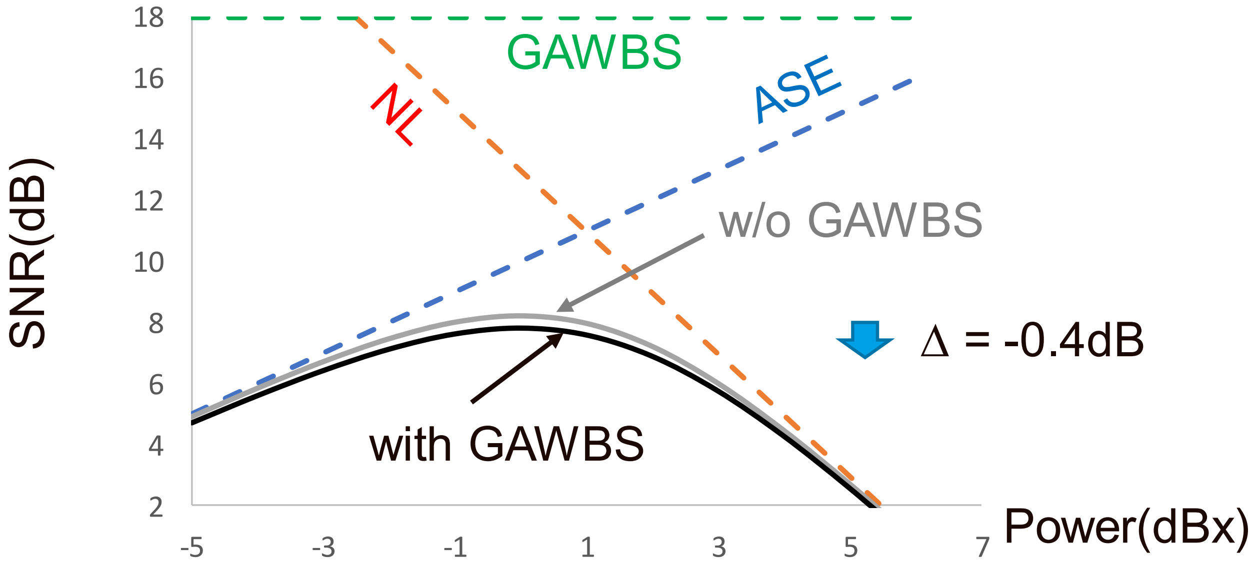
- Most signal distortions coming from the line can be captured by the joint G-SNR:

$$\frac{1}{G-SNR}=\frac{1}{SNR_{ASE}}+\frac{1}{SNR_{NL}}+\frac{1}{SNR_{GAWBS}}$$

- We expect here that chromatic dispersion and PMD are compensated by transceiver

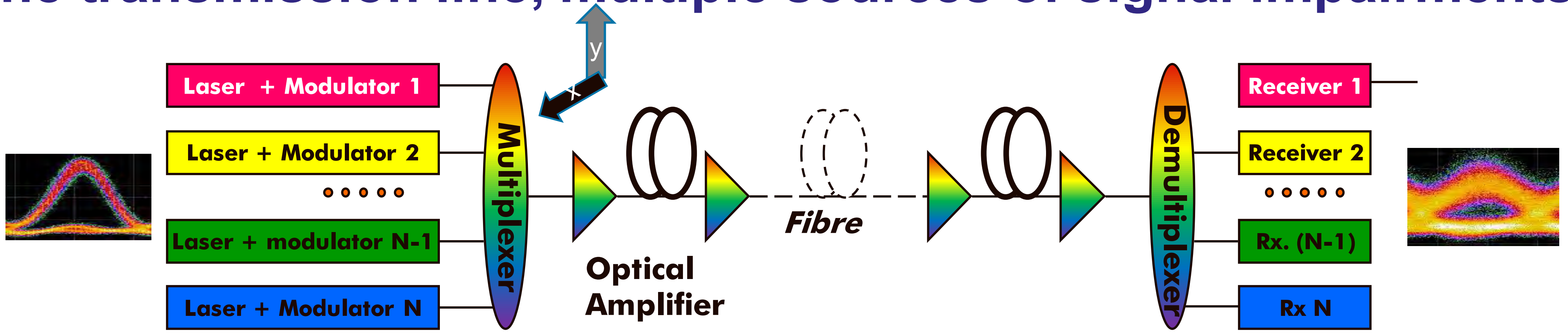
Aggregation of impairments: Cable SNR, GSNR

$$\frac{1}{GSNR} \approx \frac{1}{SNR_{ASE}(P)} + \frac{1}{SNR_{NL}(P)} + \frac{1}{SNR_{gawbs}}$$



Optimum power P only depends on ASE and NL noises

One transmission line, multiple sources of signal impairments



Physical effect	Impact	Mitigation	Limitations
Attenuation	Undetectable Signal	Optical amplification	Amplifier noise, SNR_{ASE}
Chromatic Dispersion Frequency dep. Speed	Pulse broadening	~~Inline optical~~ Electronic Dispersion compensation	Imperfect compensation (ASIC)
Kerr effect (power →phase)	Power-dep. distortions	~~Dispersion management,~~ electronic mitigation	Repeater count & power
GAWBS: acoustic waves	Phase & polar shifts		Length, Effective area
PMD (polar. dep. speed)	Time-varying distortions	Electronic mitigation	ASIC implementation

Polarization Mode Dispersion (PMD)

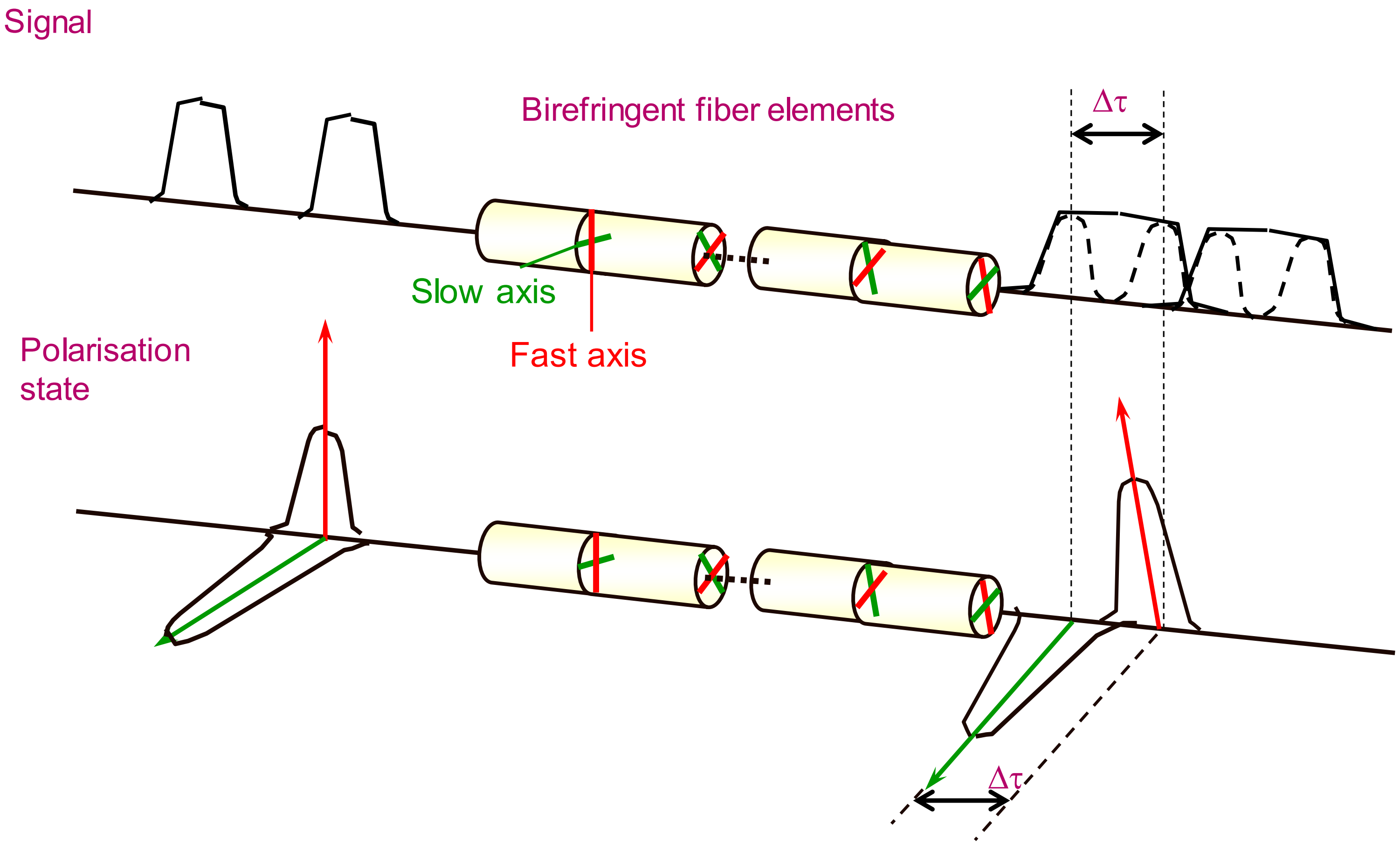
- Origin:
  - Fibre is a cylindrical medium with a quasi-circular section
  - Small imperfections from construction and conditions of deployment (torsions, pressure, trains…)

- 3 consequences
  - 1. Slight birefringence.
  - 2. This birefringence evolves along fiber line
  - 3. and with time

- Which impact over signal ?

Polarization Mode Dispersion (PMD)

- Fiber can be seen as a cascade of birefringent sections



In summary: transmission line = multiple sources of impairments modeled as Additive Gaussian noises

- 1. Amplifier noise (> 60% of impairments)
  - $SNR_{ASE,dB} \approx 38.9 + P_{out,tot,dBm} - Loss_{dB} - NF_{dB} - N_{rep,dB} - 10\log_{10}(Ampl.Band_{THz})$
  - Correction with constant output power repeaters: -1/2 in linear scale
  - Extra-penalty expected with line non flatness
- 2. Nonlinear noise due to high power density: (< 30% of impairments)
  - At optimized power (max QoT), ASE noise = 2 x Nonlinear noise power
- 3. GAWBS: (< 10% of impairments)
- 4. Plus other sources of degradations, minor or signicantly mitigated by transceiver
- Aggregation into a line SNR: $\frac{1}{GSNR} \approx \frac{1}{SNR_{ASE}} + \frac{1}{SNR_{NL}} + \frac{1}{SNR_{gawbs}}$

Next: Design of an end to end system

- End to end performance model including transceiver
- Typical experiments to validate models / systems
- Power budget table
- Design of standard / SDM systems

Thank you

ALCATEL
SUBMARINE
NETWORKS

Cable Powering

Yoshihisa INADA
NEC Corporation

Contents

Contents

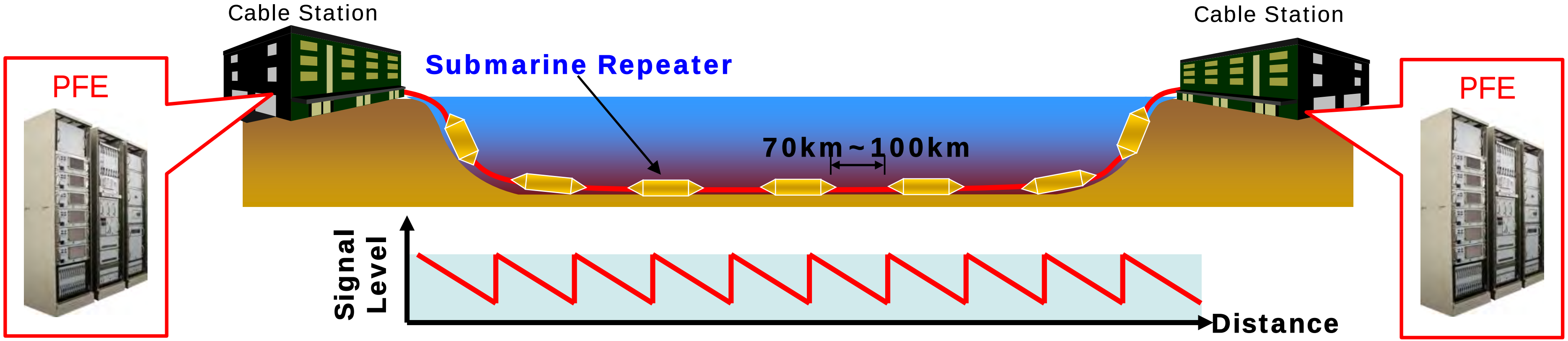
Powering Method

Purpose of Powering Feeding

To supply stable power to submersible repeaters

General Requirement :

- Stable power supply and high voltage applied up to 15kV for trans oceanic application
- High reliable power feeding system for operate 25 years or more
- Safety operation to personnel and system
- Fault analysis in case of cable failure



Powering Method

AC or DC ?

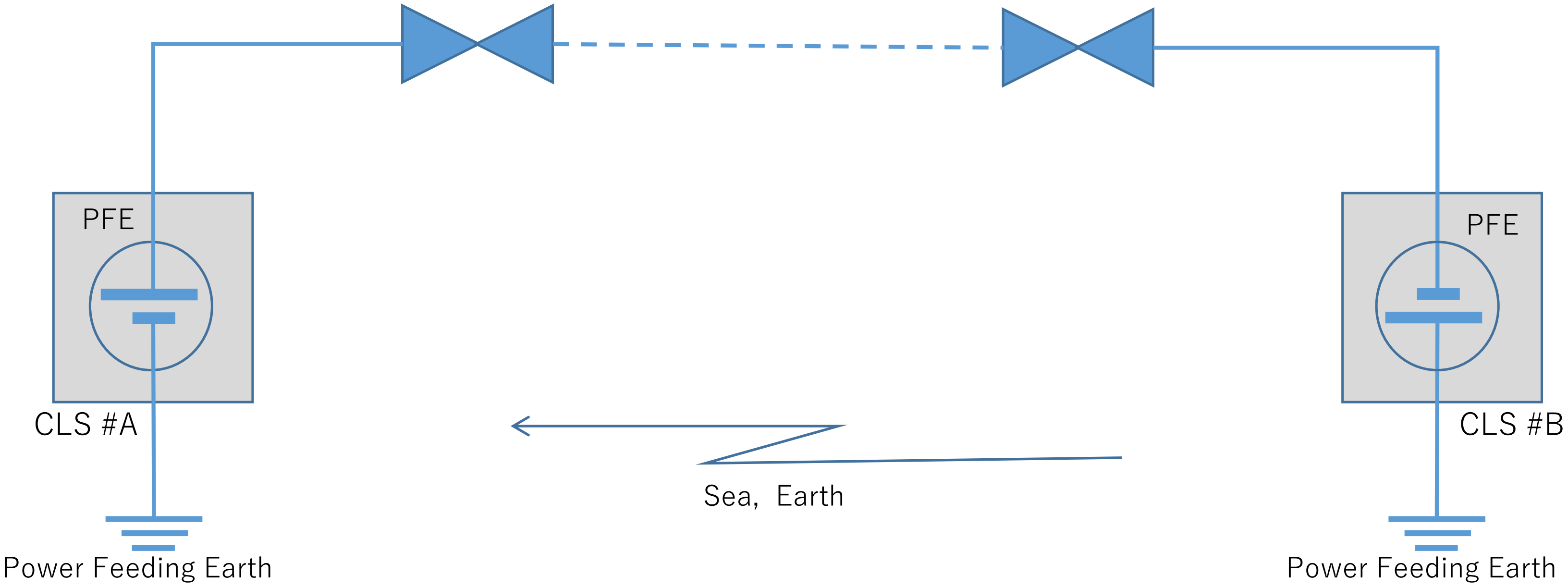
- AC
  - Easy for voltage conversion
    ➔ Flexible for voltage apply to repeater
  - Need transformer and rectifier in each repeaters
    ➔ complicated power circuit in each repeater, less reliability…

Parallel or Series?

- Parallel
  - Supply current becomes sum of each repeater's current
    - ➔leading huge current and voltage drop through cable …
    - ➔Receiving voltage at each repeaters becomes unstable…

Powering Method

- ✓ Direct Current and Series Circuit are applied for all submarine cable system



PFE : Power Feeding Equipment
CLS : Cable Landing Station

Powering Design

Power Feeding Design Parameters

Specification of Power Feeding Equipment (PFE)

- Specified to generate maximum voltage under constant current

Consideration;

- Power feeding configuration
- Power feeding budget
- Margin consumed by repair

Withstand voltage limitation : up to 15KV

- Taking into consideration all the devices; submersible plant, land/beach joint, land cable

$$\textbf{Constant} = \mathbf{V^{nt}}$$

where V : *apply voltage*
n : *device-specific parameter*
t : *elapsed time to failure of device*

- Maximum power feeding voltage must be less than the withstand voltage of all devices, reducing maximum voltage is more preferable to have an additional margin of safety

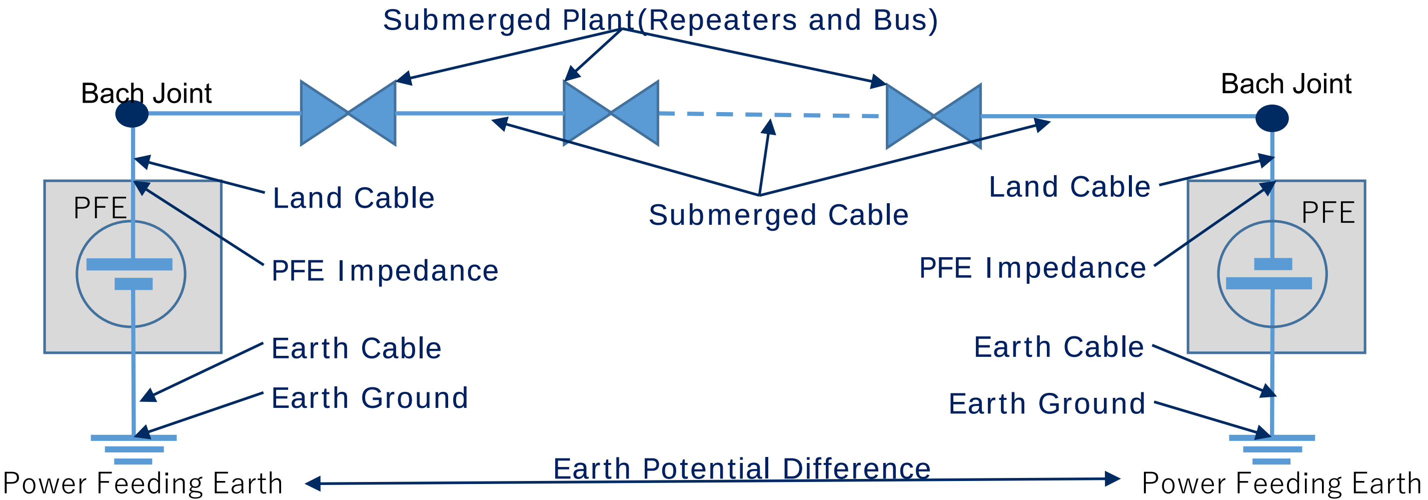
Power Feeding Budget

- ✓ Aggregate the effects of all components contributing to voltage drops along electrical path

$$\begin{aligned} V_{SYSTEM} &= V_{EARTH\_GROUND} + V_{EATH\_CABLE} + V_{PFE} + V_{LAND\_CABLE} \\ &+ V_{SUB\_PLANT} + V_{SUB\_CABLE} \\ &+ V_{EPD} + V_{REPAIR} \end{aligned}$$

where, $V_{SUB\_CABLE} = \text{Cable Resistance} \times \text{Cable Length} \times \text{Feeding Current}$

$V_{SUB\_PRANT} = \Sigma V_{REP} + \Sigma V_{BU}$



Power Feeding Current

Power feeding current is derived from repeater current requirement to maintain stable amplification characteristics

- Repeater optical output power
  - Power efficiency of Pump Laser Diode (LDs)
- Power consumption of control circuit
- Margin for electroding current

Current distribution in a repeater

Parameters	Proportion	Remarks
LD current for the specified optical output power	80%	Approx. 10% End Of Life margin
Current for LD control circuit	10%	
Electroding margin	10%	Nominally 80mA margin

Margin Design

Earth Potential Voltage (EPV)

- Potential difference between both PFE earths due to Earth’s magnetic field
- In general, earth potential changes is caused by movement of the Earth’s mantle.
- 0.1~0.3V/km (EPV) is considered based on historical experience.

System		PFE voltage		c) Earth Potential Difference	
Link	Length (km)	a) Calculation	b) Measured	Volts	V/km
Japan-Guam	3,743	4,404	4,352	-52	-0.01
Guam-Australia	7,130	7,296	7,189	-107	-0.02
Malaysia-China	2,632	4,339	4,469	130	0.05
Singapore-Phillippin	2,789	4,073	4,208	135	0.05
Japan-Taiwan	2,792	4,617	4,646	29	0.01

Repair Allowance

- Design life of 25 yeas, cable repair must be considered.
- Cable repair requires additional cable insertion, typically 2.5 times of water depth per repair. Additional cable insertion cause cable voltage drop.

Power Feeding Voltage and Max. Capacity

✓ For ultra-long system, maximum voltage of PFE limits the max. capacity

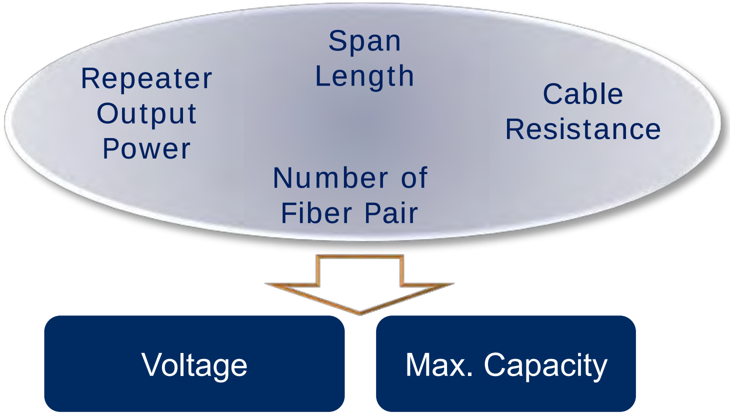
Cable Capacity

- Number of fiber pairs (N_{FP})
- Repeater Bandwidth (BW)
- Shannon SE [G-OSNR (N_{REP},ROP,Fiber,L,BW)]

Total Voltage

- Number of fiber pairs (N_{FP})
- Feeding current (L,ROP,BW)
- Cable resistance
- Number of repeaters (N_{REP})

Maximum Capacity per kV



Repeater Output Power

Span Length

Cable Resistance

Number of Fiber Pair

Voltage

Max. Capacity

Repeater Output Power (ROP), Span Length (L) and the number of fiber pairs (N) are free parameters defining total voltage entirely the Capacity optimization

✓ Fiber attenuation helps increasing span length (L), and reducing number of repeaters (N_{REP})
✓ Lower cable resistance of cable, but costly ➔ Apply Aluminum??
✓ Repeater efficiency improvements reduce feeding current

Example of line Design impact in powering

- Different line designs can provide the same capacity
- What is the best design in terms of power efficiency?

	High SE design	Large FP count design
Distance	9000	9000
Span Length	75km	100km
Repeater sharing index	4pumps/2FPs	4pumps/4FPs
Repeater Power [dBm]	19	15.1
Line Current [mA]	1000	750
Resistance [Ohm/km]	1.0	1.0
Repeater BW [THz]	4.5	4.5
Fiber Effective Area	150	110
OSNR/90carriers [dB]	20.2	14.3
GSNR [dB]	11.9	7.3
Capacity Shannon FP [Tb/s] *∝BWxlog2(1+GSNR)*	34.8	23.2
FPs	8	12
Capacity Shannon CABLE [Tb/s]	278	278
Voltage Cable [kV]	7.2	6.8
Voltage Repeaters [kV]	7.3	4.3
Voltage Cable+Reps [kV]	14.5	11.1

Capacity grows logarithmically with SNR and linearity with BW

Large SNR comes with Fiber Nonlinearity

⇩

Power efficient submarine networks operate al low OSNR and larger bandwidth (more fibers)

Powering Topology

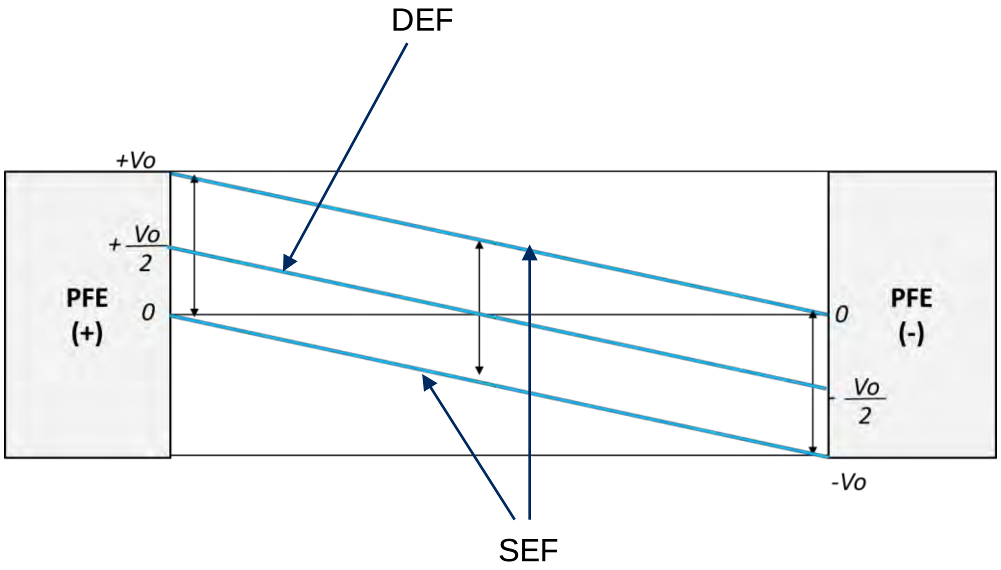
Powering Mode

Double-End-Feeding (DEF)

- Feeding power from both end station

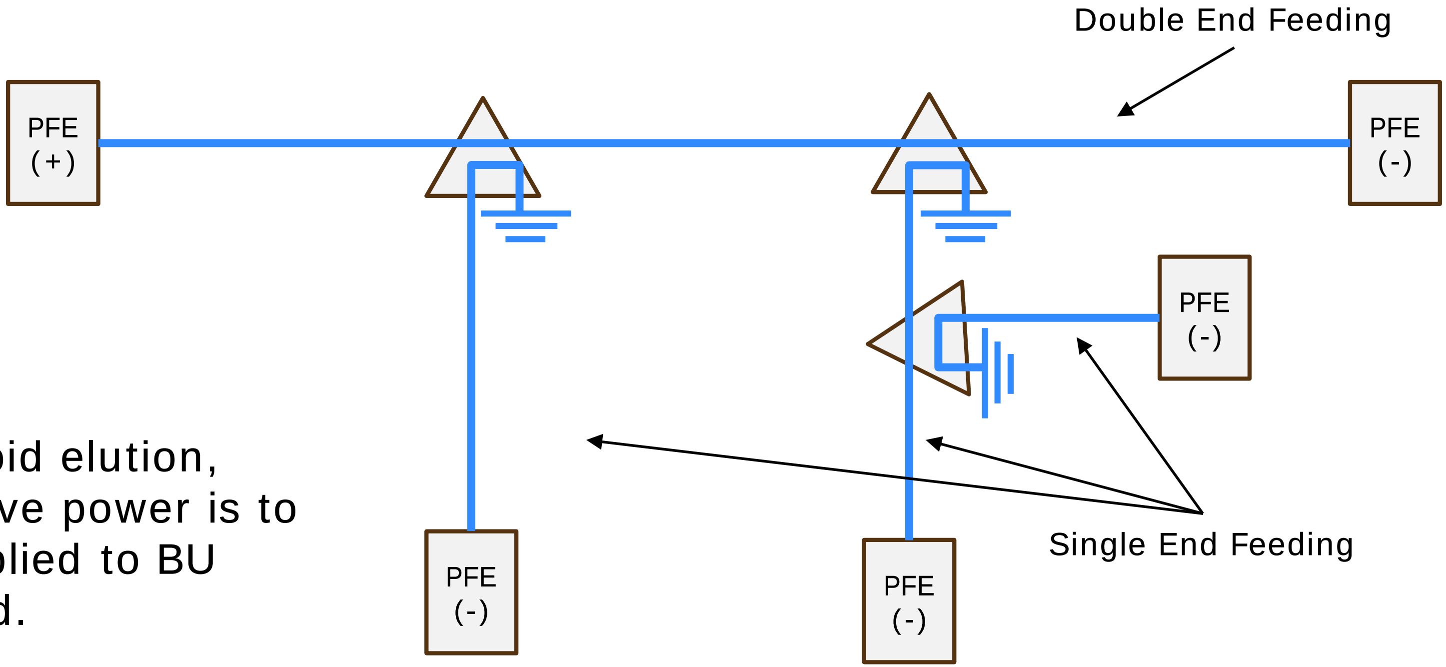
Single-End-Feeding (SEF)

- Feeding power from one end station



System Powering Example

- Trunk Segment : Double End Feeding
- Branch Segment : Single End Feeding



Note;

To avoid elution, negative power is to be applied to BU ground.

Contents

Power Feeding Equipment (PFE)

Power Feeding Equipment (1/4)

Major Functions

- Current control
  - Precise current control is required for stable system
- Polarity switching (when PSBU is deployed)
  - Polarity change is required for power re-configuration (detail to be discussed in Part III.)
- Voltage limitation
  - To avoid voltage generation beyond a specific value, the maximum output voltage is limited.
- Slow ramp up & down
  - To avoid large surge currents being injected into the line, the PFE controls the voltage ramp-up and ramp-down speeds.

Power Feeding Equipment (2/4)

Major Functions (cont.)

- Shutdown function
  - Auto-shutdown when high current, high voltage, and/or open circuit is detected
  - Auto-shutdown when operator access high voltage terminal
  - Emergency shutdown is provided for the event of an accident or other potential hazard

- Discharge function
  - Cable end stores electric charge due to cable capacitance
  - PFE provides discharge function
    - Resistive Mode
    - Short Mode

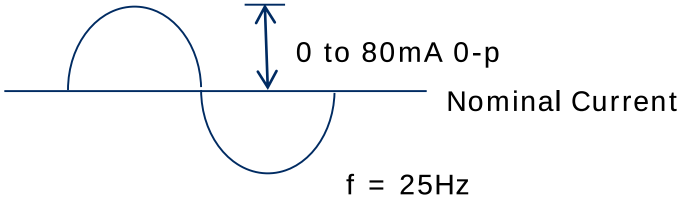
Power Feeding Equipment (3/4)

Major Functions (cont.)

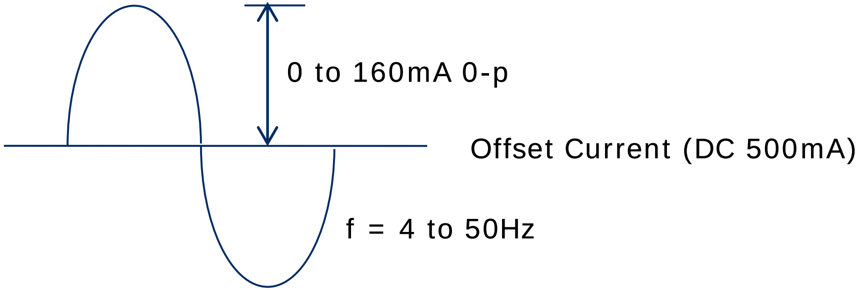
- Electroding
  - ✓ This function is used to identify the cable or cable fault location by cable ship
  - ✓ Electroding tone is detected by tone detector (magnetic sensor) equipped on cable ship

- Electroding tone (low frequency) is superposed on a nominal current or DC offset current

In-service Mode



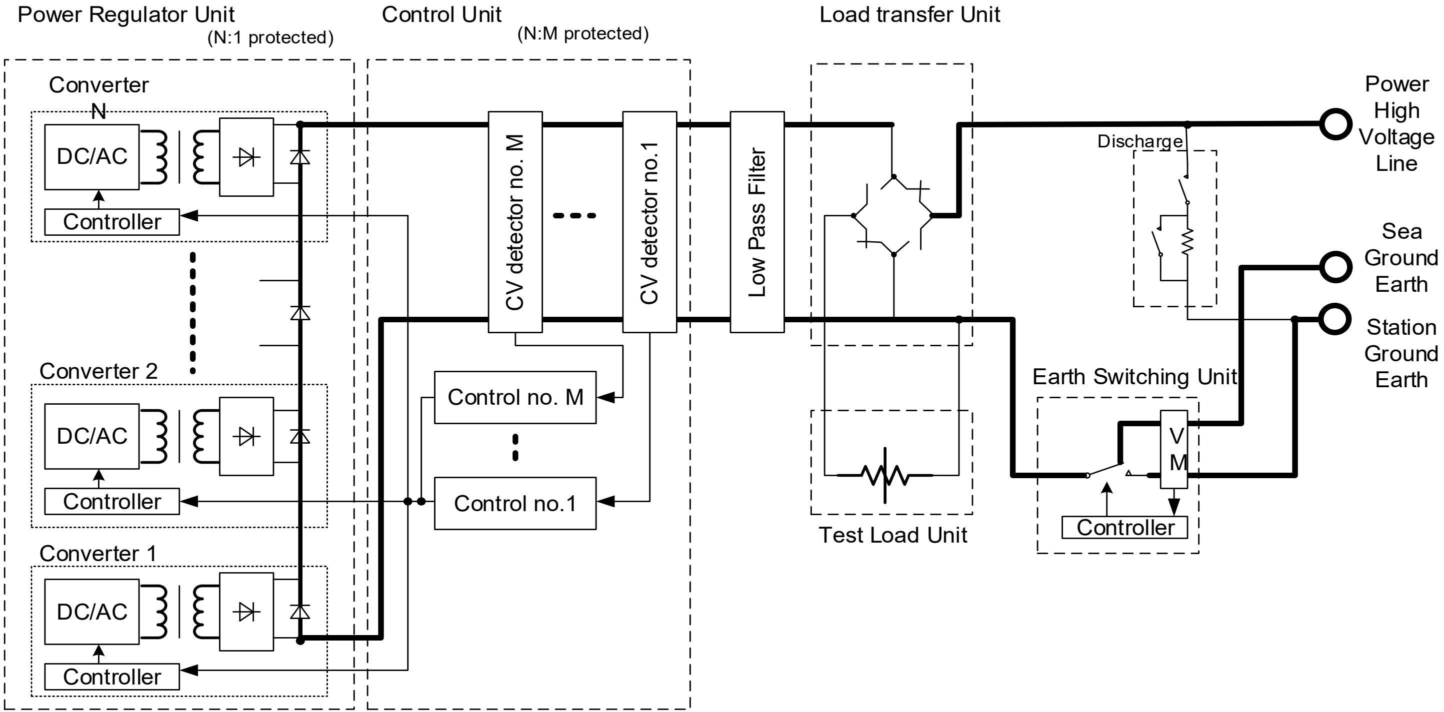
Out-of-service Mode



Electroding tone of 10mA can be detected;
- 300 km from PFE (In-service mode)
- 500 km from PFE (Out-of-service mode)

Power Feeding Equipment (4/4)

Configuration



Power Path Switchable BU (PSBU)

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Powering Switchable - Branching Unit (PSBU)

Branching Unit (BU)

- BU is laid underwater for the trunk and branch system
- BU provides routing both optical fiber and power feeding path to trunk and branch landing stations
- PSBU ➔ Power path switchable BU

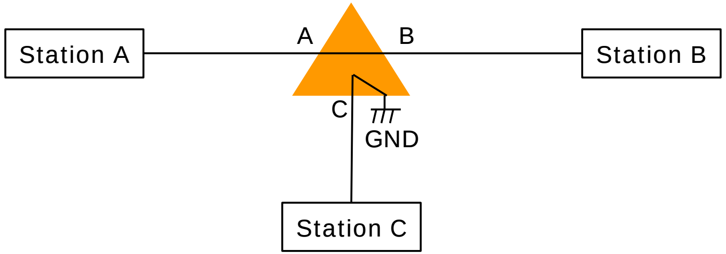
Key Features for Power Feeding Routing

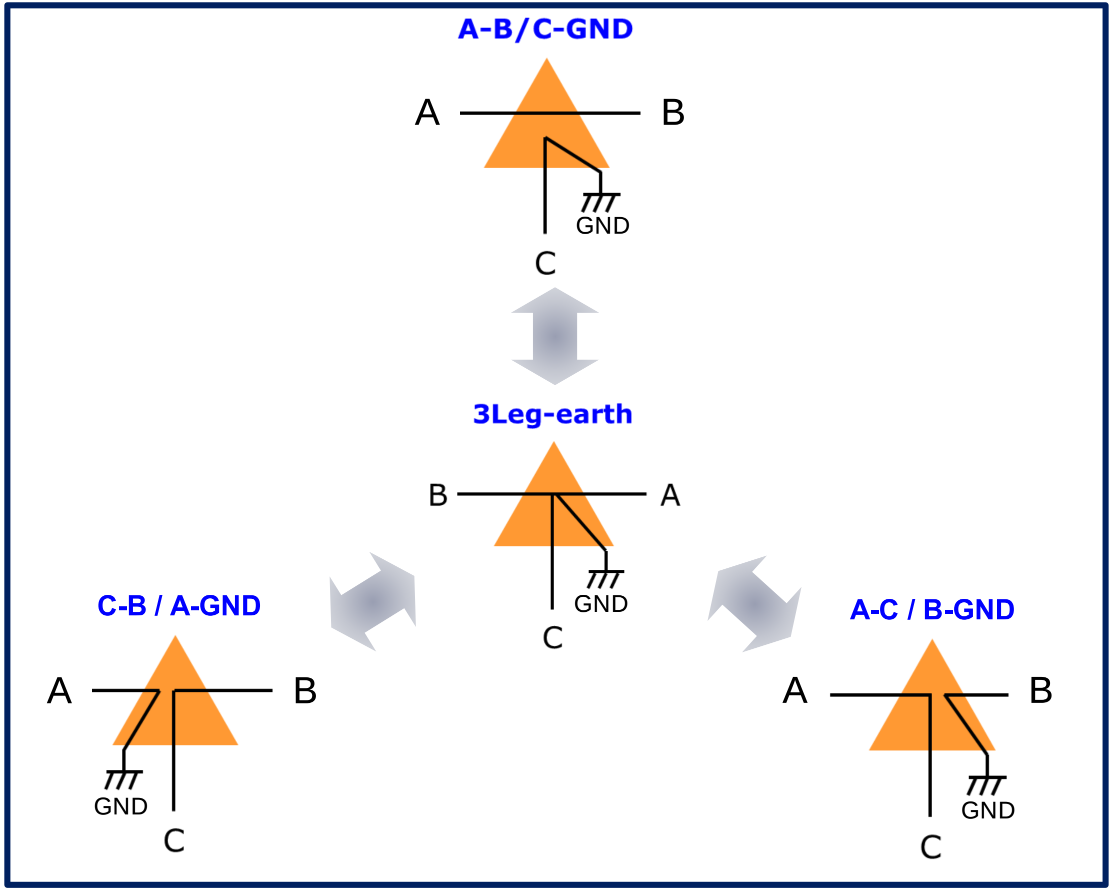
- Reconfiguration of PSBU status shall be performed by optical command
- Command operation shall be available as long as BU is powered any one of three leg, even branch power only
- Switch status is maintained even if the electric power is removed from the BU.
- “Hot switching” is feasible under single-end feeding ➔ Withstand up to 15KV

Powering Switchable - Branching Unit (PSBU)

Switch Status

Normal Configuration

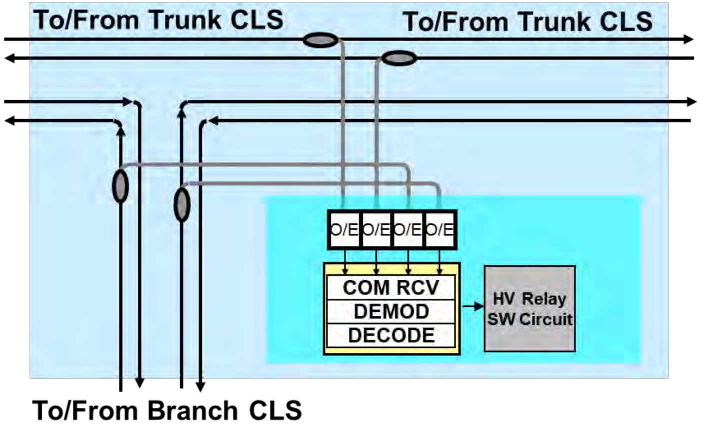




Powering Switchable - Branching Unit (PSBU)

Remote Control of PSBU

- High Voltage Circuit
  - Highly reliable SW part
- Command Control of BU Switch
  - Control Command to be sent as serial data including BU address
  - Only the BU assigned by the address responds to the command signal
- Multi Control Path
  - BU can be controlled through multiple fiber paths
- Self Holding
  - BU power path status configured by the command maintains even when power supply stops



Submarine Cable

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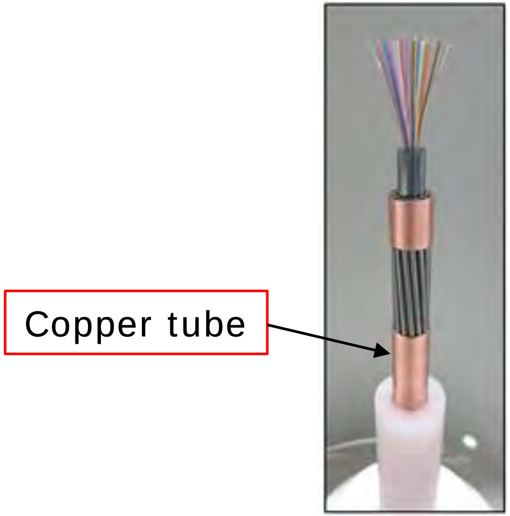
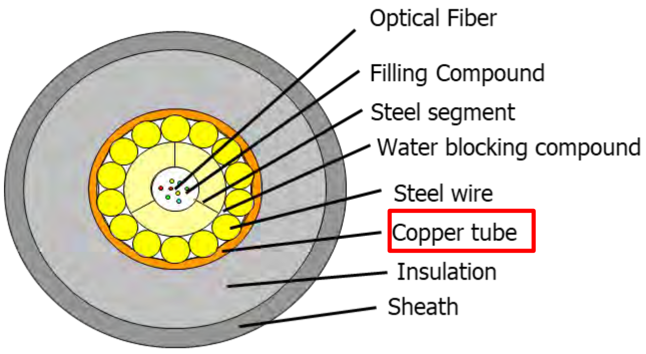
Submarine Cable Structure

- ✓ Power is fed through copper tube in submarine cable
- ✓ Cable resistance is depending on thickness of copper





LW (Light Weight)

Contents

System Powering and Redundancy

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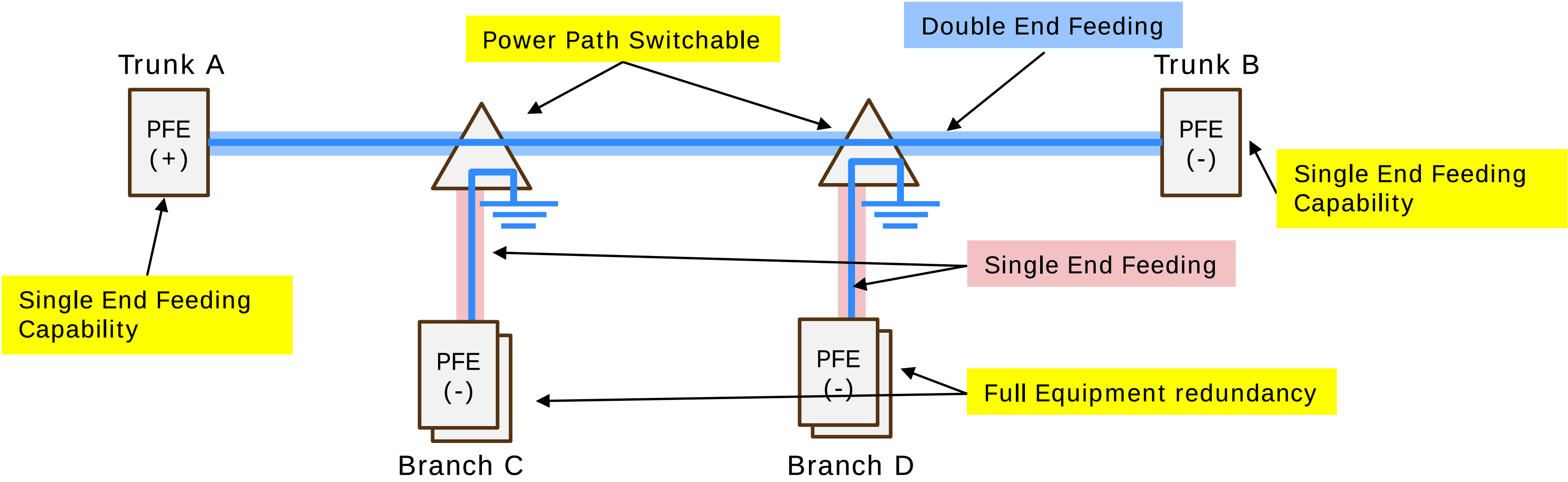
Normal Power Feeding Configuration

Features:

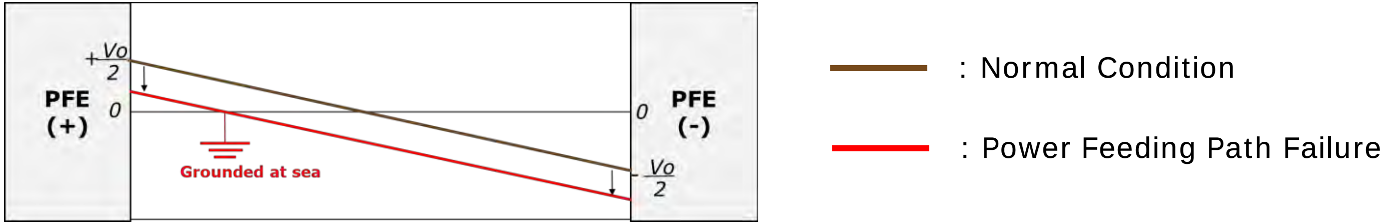
- Trunk Double End Feeding with Single End Feeding capability
- Branch : Full Equipment Redundancy
- BU : Power Path Re-configurable



System Redundancy

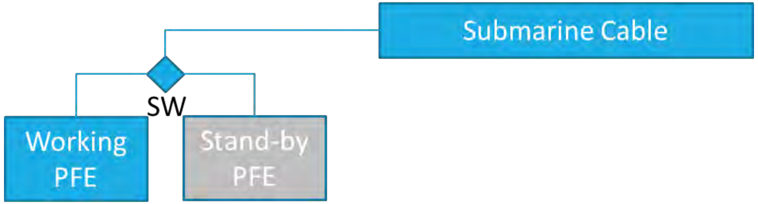
Trunk Power Feeding Path with Single End Feeding Capability

- Maintain power even if power path failure happens



Equipment Redundancy

- Full Equipment Redundancy



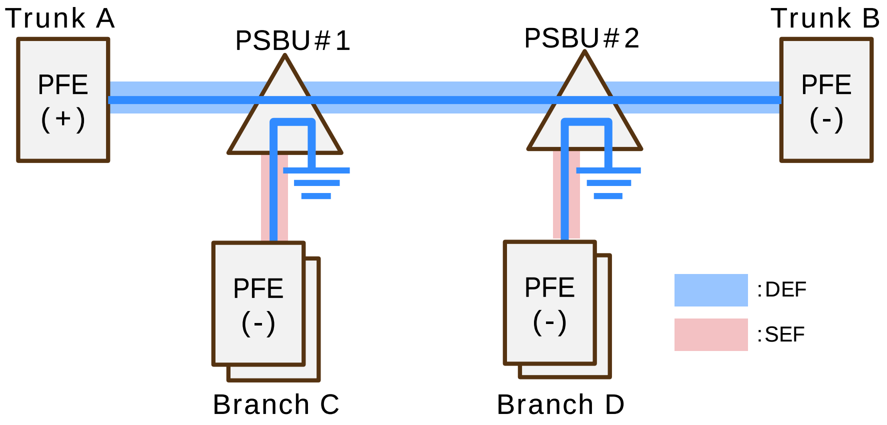
Power Path Switching

- Power Path Switching to restore power feeding path for un-failed segment

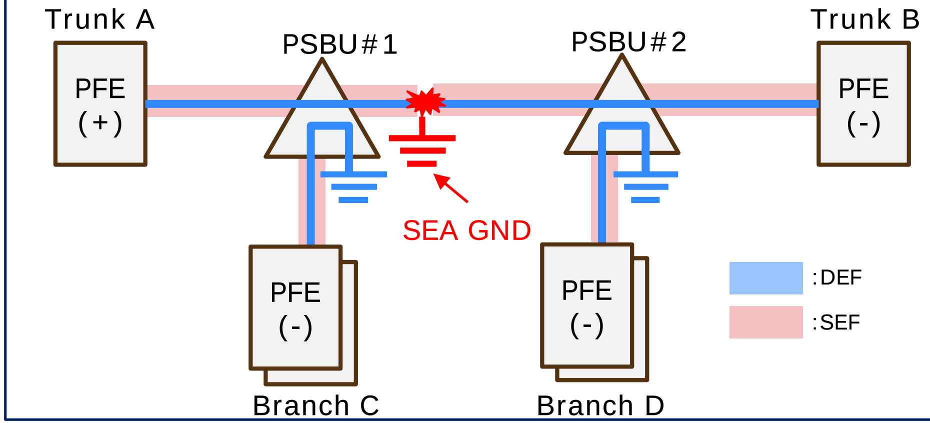
Power Path Re-Configuration

Power Feeding Path Re-Configuration -Trunk Failure (1/3)

Normal Configuration

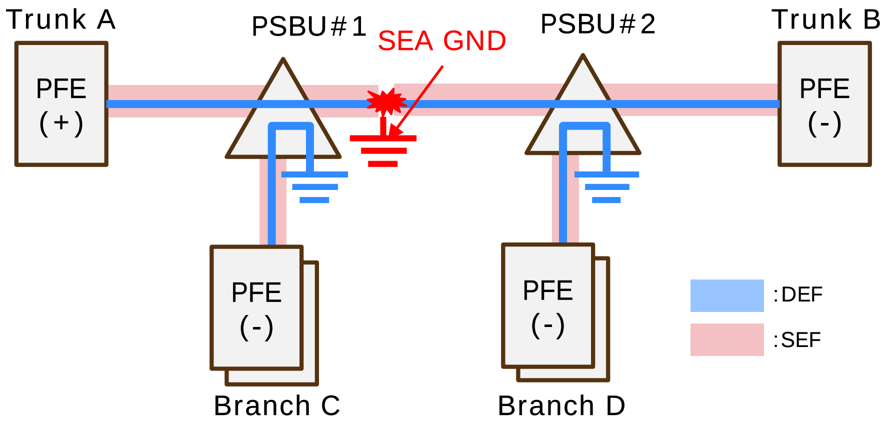


After trunk path failure

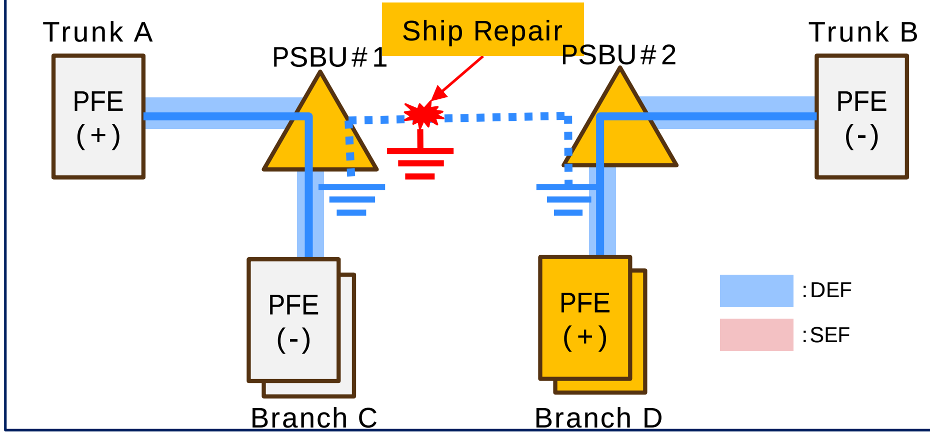


- ✓ Power feeding is **maintained** since PFEs in Trunk A and B feed power to sea ground under SEF
- ✓ Power re-configuration is not required until ship repair

Power Feeding Path Re-Configuration -Trunk Failure (2/3)



After trunk path failure



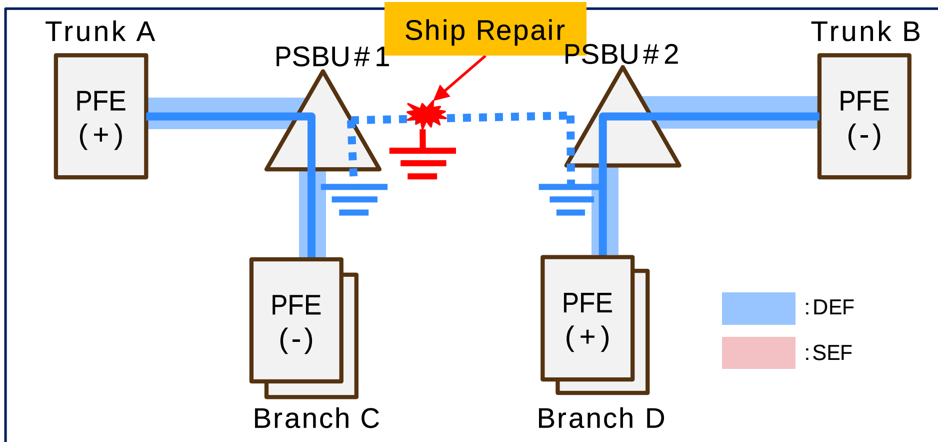
During Ship Repair

✓ Powering path is **re-configured** in order to isolate failure segment;

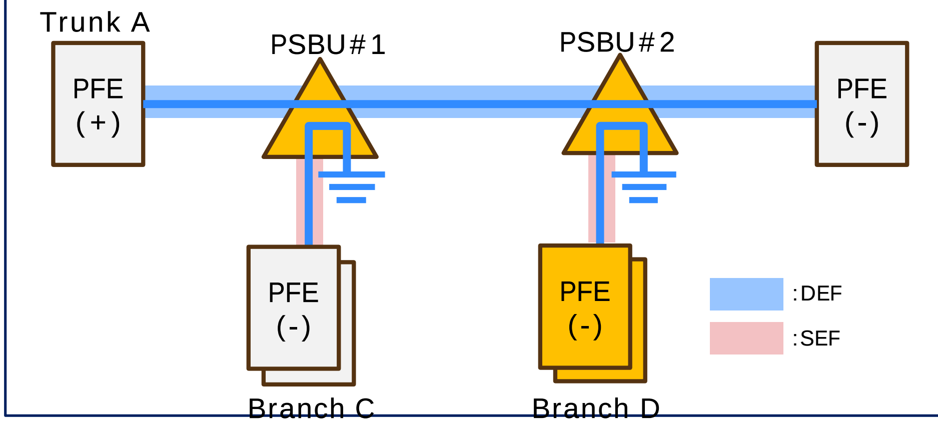
- Trunk A – Branch C (DEF)
- Trunk B – Branch D (DEF)

○ PSBU#1 and #2 are switched
○ Branch D polarity is changed

Power Feeding Path Re-Configuration -Trunk Failure (3/3)



During Ship Repair



After Ship Repair

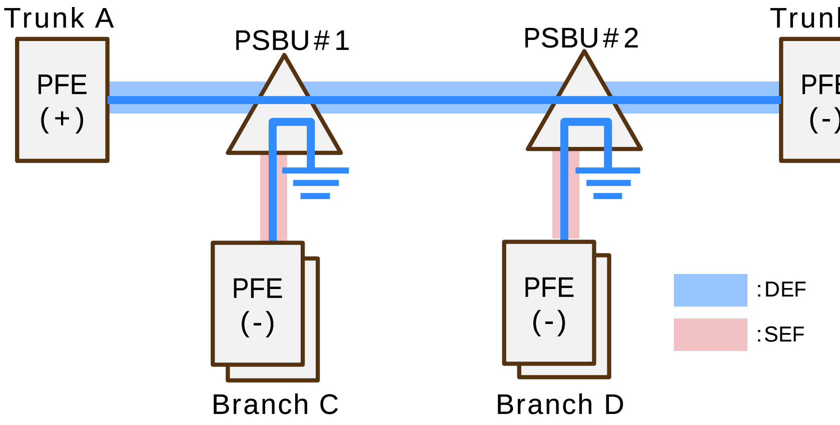
✓ Powering path is **normalized:**

- Trunk A – Trunk B (DEF)
- PSBU#1 – Branch C (SEF)
- PSBU#2 – Branch D (SEF)

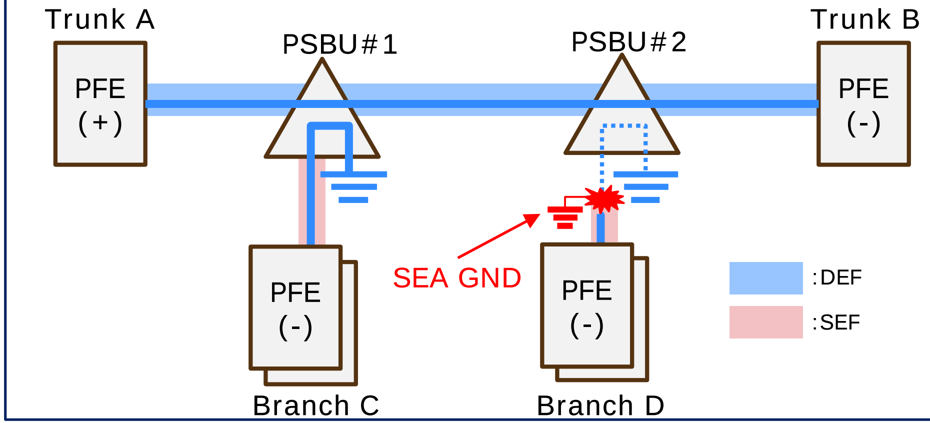
○ PSBU#1 and #2 are switched
○ Branch D polarity is changed

Power Feeding Path Re-Configuration -Branch Failure (1/4)

Normal Configuration

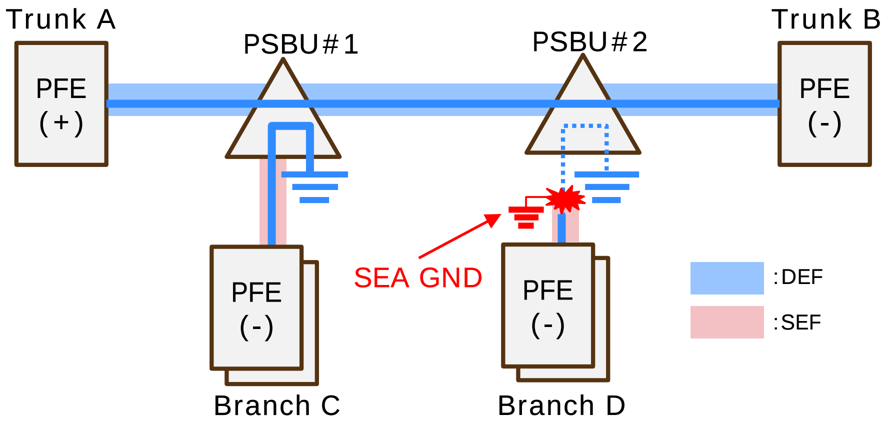


After branch path failure

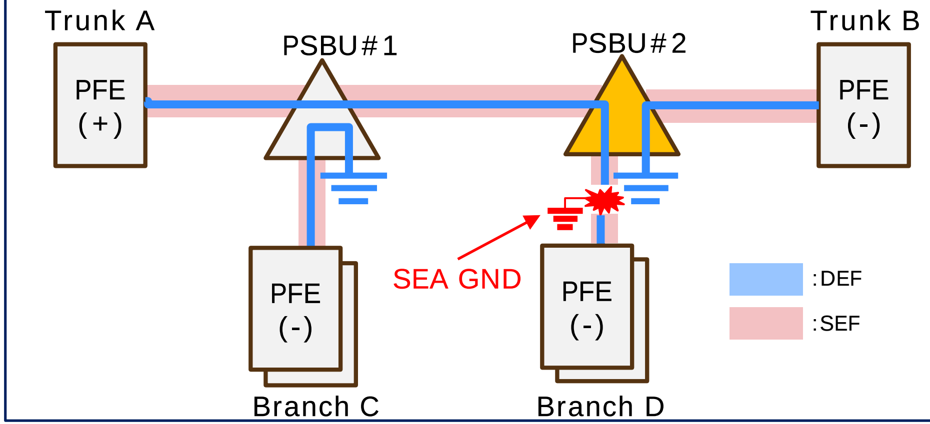


- ✓ PSBU#2 and failure point becomes **unpowered**.
- ✓ Un-failed segment does **not affected**.
  - •Trunk A-B,
  - •PSBU#1-Branch C

Power Feeding Path Re-Configuration -Branch Failure (2/4)



After branch path failure



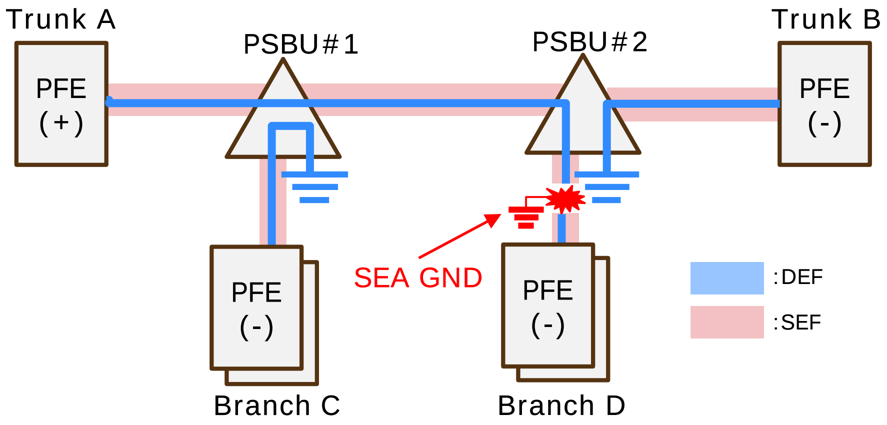
Before Ship Repair

✓ Power path is **re-configured** in order for failure segment to be **restored**.

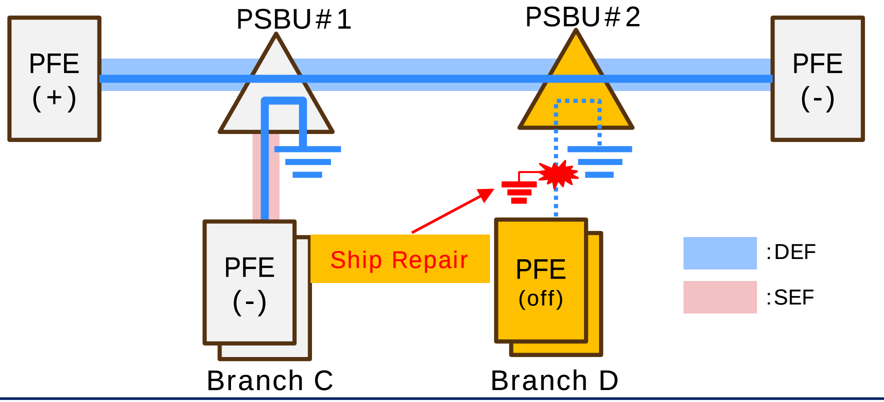
- Trunk A- Branch D fault Point (SEF)
- Trunk B- PSBU#2 GND (SEF)
- Branch C – PSBU#1 (SEF)
- Branch D – Failure point (SEF)

○ PSBU#2 is switched

Power Feeding Path Re-Configuration -Branch Failure (3/4)



Before Ship Repair



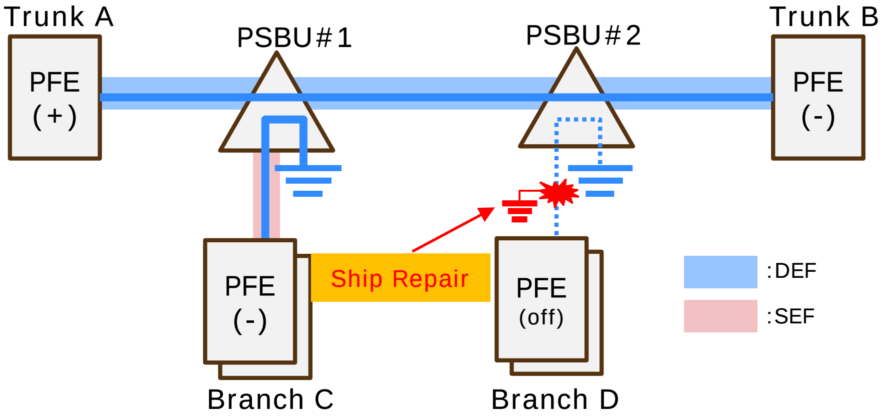
During Ship Repair

✓ Power path is **re-configured** in order to **isolate** failure segment;

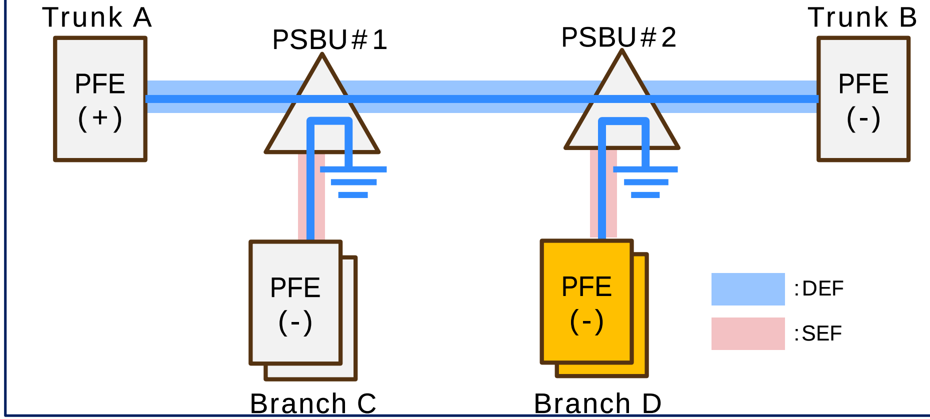
- Trunk A- B (DEF)
- Trunk B- PSBU#2 GND (SEF)
- Branch C – off

○ PSBU#2 is switched

Power Feeding Path Re-Configuration -Branch Failure (4/4)



During Ship Repair



After Ship Repair

✓ Powering path is **normalized:**
- Trunk A – Trunk B (DEF)
- PSBU#1 – Branch C (SEF)
- PSBU#2 – Branch D (SEF)

○ Branch D is just powered

Powering Management System

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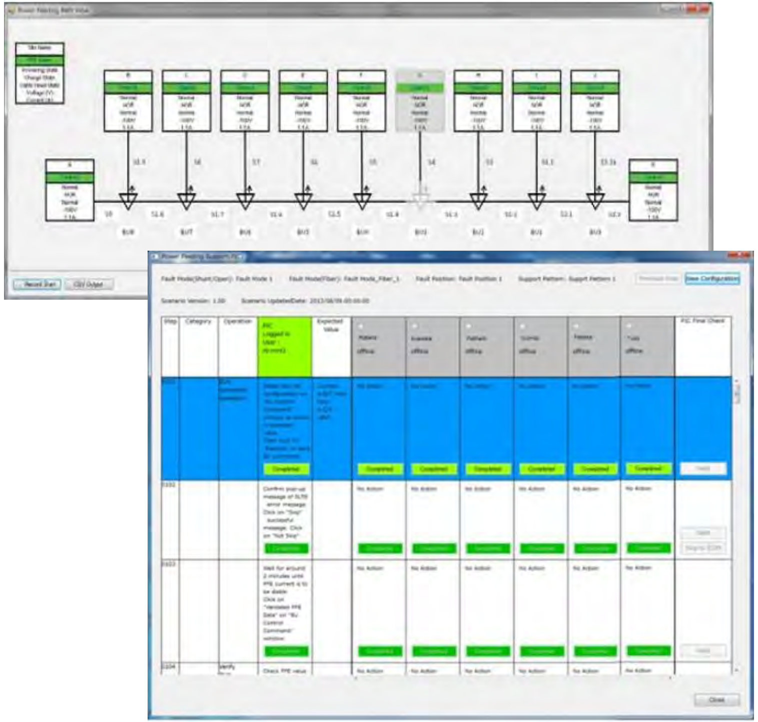
Power Feeding Management System

Functions

- Monitor power feeding current and voltage for every station
- Manage PFE status
- Control and manage Power-Path Switching in BU
- Display the power feeding configuration
- Support powering procedure among stations



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Optical Transmission – Lecture 3

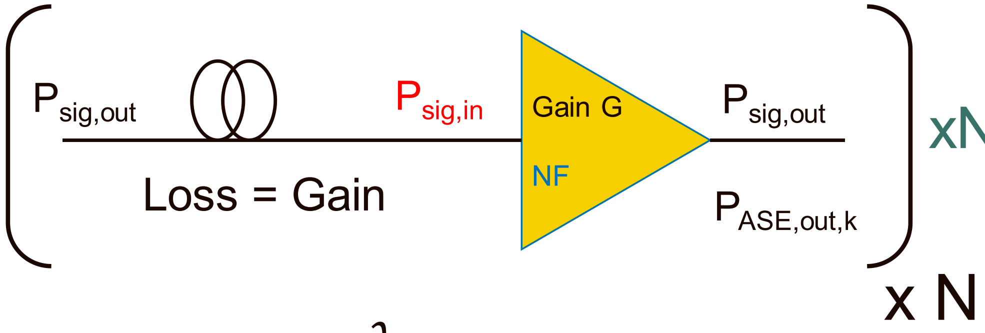
From physics to system design

ALCATEL
SUBMARINE
NETWORKS

Back to propagation effects in the cable

Signal impairments in the cable: Additive Gaussian noise models

- 1. Amplifier noise (ASE) (> 60% of impairments)



$$SNR_{ASE} \approx \frac{P_{out,tot}}{Gain * NF * N_{rep} * Amplifier\ Band} * \frac{\lambda}{hc}$$

(within channel spacing band)

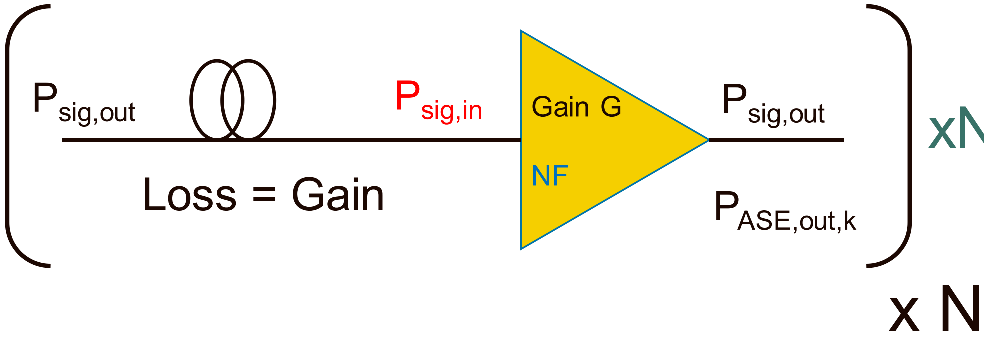
- Concatenation :

$$\frac{1}{SNR_{1\rightarrow N,lin}} \approx \frac{1}{SNR_{1,lin}} + .. + \frac{1}{SNR_{N,lin}}$$

- Refinements
  - Constant total output power : $SNR_{signal\ droop,lin} - SNR_{basic,lin} \approx -\frac{1}{2} * \frac{Ch.spacing}{Ref.Band_{SNR}}$
  - Extra-penalty expected due to spectral non flatness

Signal impairments in the cable: Additive Gaussian noise models

- 1. Amplifier noise (ASE) (> 60% of impairments)



$$SNR_{ASE,dB} \approx 38.9 + P_{out,tot,dBm} - Gain_{dB} - NF_{dB} - N_{rep,dB} - 10 * \log_{10}(Bandwidth_{THz})$$

(within channel spacing band)

From $OSNR_{0.1nm,dB}$ to SNR_{dB}:

$$SNR_{dB} = OSNR_{dB,0.1nm} + 10 * \log\left(\frac{12.5\ GHz}{Channel\ spacing}\right)$$

12.5GHz corresponds to 0.1nm at 1550nm

Signal impairments in the cable: Additive Gaussian noise models

- 2. Nonlinear (NL) noise due to high power density: (< 30% of impairments)

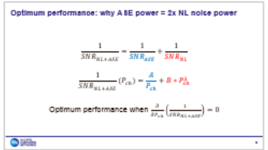
$$SNR_{NL} \approx \frac{K_{models} * A_{eff}^{2}}{N_{spans}^{\epsilon}} * \frac{\mathbf{1}}{\boldsymbol{N_{spans}} * \boldsymbol{Power^{2}}} - 1$$

often neglected

- At optimized power (max Quality of Transmission),

ASE noise = 2 x Nonlinear noise power

$SNR_{ASE,dB}$ = $SNR_{NL,dB}$ – 3dB

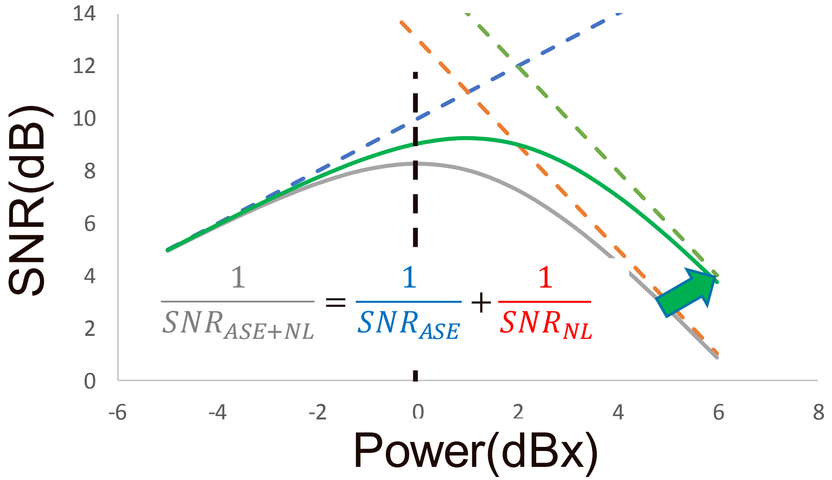


Optimum performance: why ASE power = 2x NL noise power

$$\frac{1}{SNR_{NL+ASE}} = \frac{1}{SNR_{ASE}} + \frac{1}{SNR_{NL}}$$

$$\frac{1}{SNR_{NL+ASE}}(P_{ch}) = \frac{A}{P_{ch}} + B * P_{ch}^{2}$$

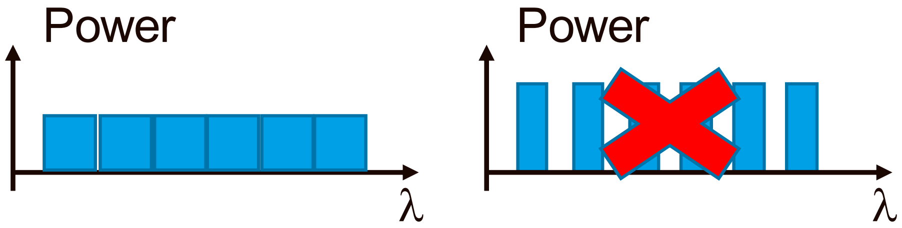
Optimum performance when $\frac{\partial}{\partial P_{ch}}\left(\frac{1}{SNR_{NL+ASE}}\right) = 0$



- Coming: partial mitigation of NL at transceiver

Signal impairments in the cable: Additive Gaussian noise models

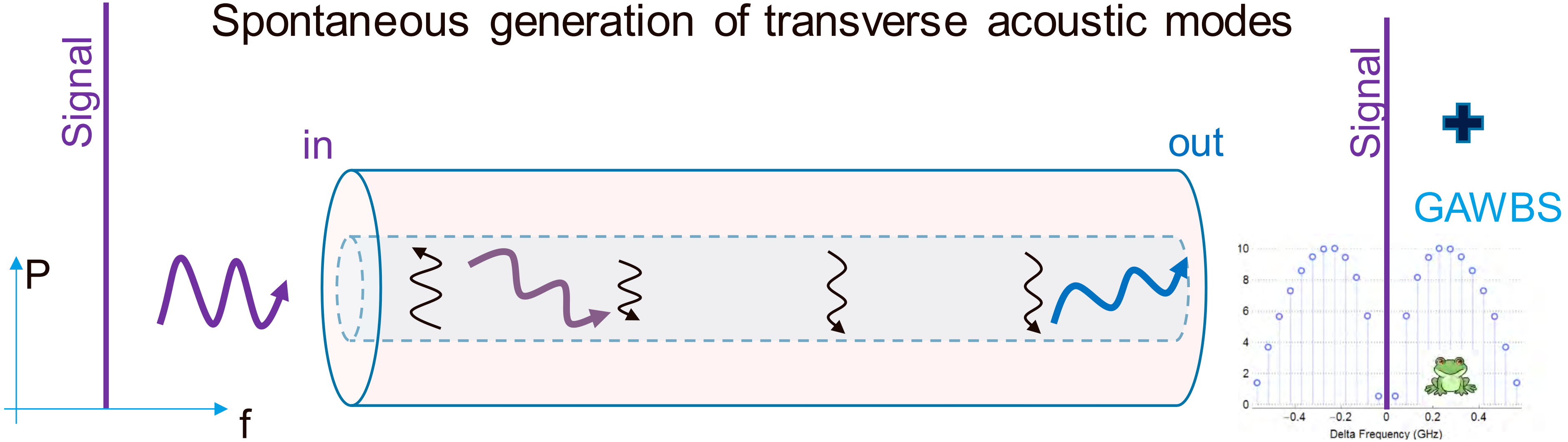
- More on Nonlinear (NL) noise
  - **The higher the local chromatic dispersion, the better**
  - **Increases with high cumulated chromatic dispersion, with quick saturation**
  - **The flatter the power spectral density, the better**
    - Why ? Peaks of power (in time / frequency) are detrimental
    - Channel rate as close as possible to channel spacing



Guided Acoustic Wave Brillouin Scattering (GAWBS)

[M. Bolshtyanski et al, M4B.3, OFC’18]

Spontaneous generation of transverse acoustic modes



Scatters incoming light in the forward direction, with small frequency shifts

➔ Crosstalk noise

$$P_{GAWBS} \propto \frac{Distance}{A_{eff}^{x}} * P_{ch}$$

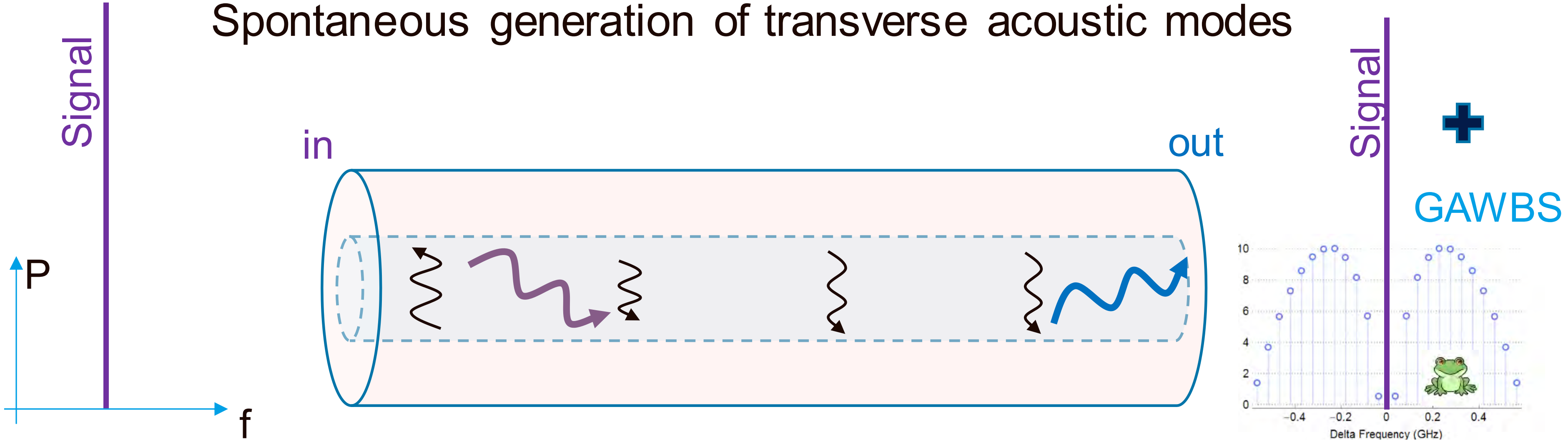
characterized in M4B.3, OFC’18

X ~ 1

Guided Acoustic Wave Brillouin Scattering (GAWBS)

[M. Bolshtyanski et al, M4B.3, OFC’18]

Spontaneous generation of transverse acoustic modes



Scatters incoming light in the forward direction, with small frequency shifts

➔ Crosstalk noise

$$SNR_{GAWBS} \propto \frac{A_{eff}^{x}}{Distance}$$

characterized in M4B.3, OFC’18

Joint SNR, Line SNR, Gaussian SNR, Generalized SNR

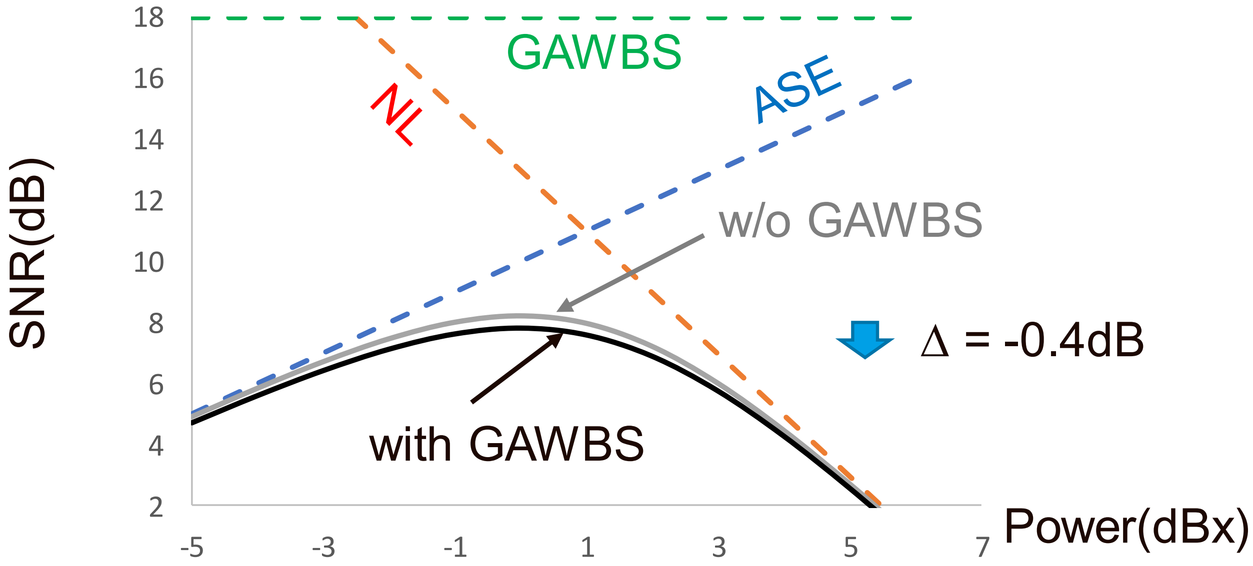
- Most signal distortions coming from the line can be captured by the joint G-SNR:

$$\frac{1}{G-SNR}=\frac{1}{SNR_{ASE}}+\frac{1}{SNR_{NL}}+\frac{1}{SNR_{GAWBS}}$$

- We expect here that chromatic dispersion and PMD are compensated by transceiver

Aggregation of impairments: Cable SNR, GSNR

$$\frac{1}{GSNR} \approx \frac{1}{SNR_{ASE}(P)} + \frac{1}{SNR_{NL}(P)} + \frac{1}{SNR_{gawbs}}$$



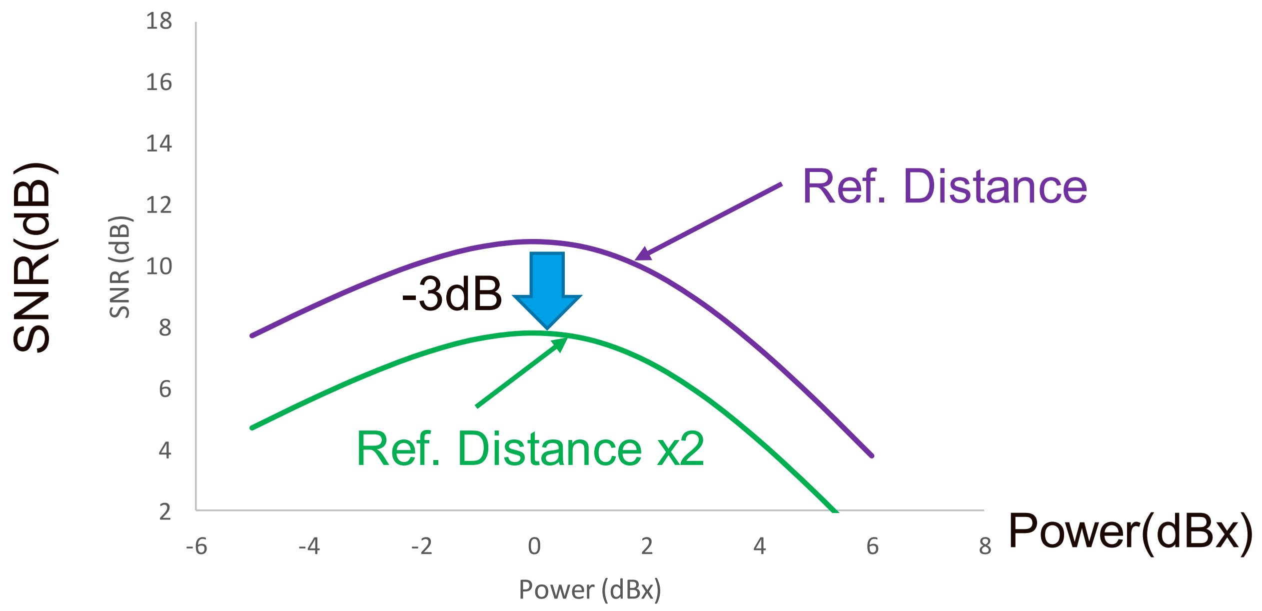
Δ = -0.4dB

Optimum power P only depends on ASE and NL noises

GSNR and distance   (constant repeater spacing)

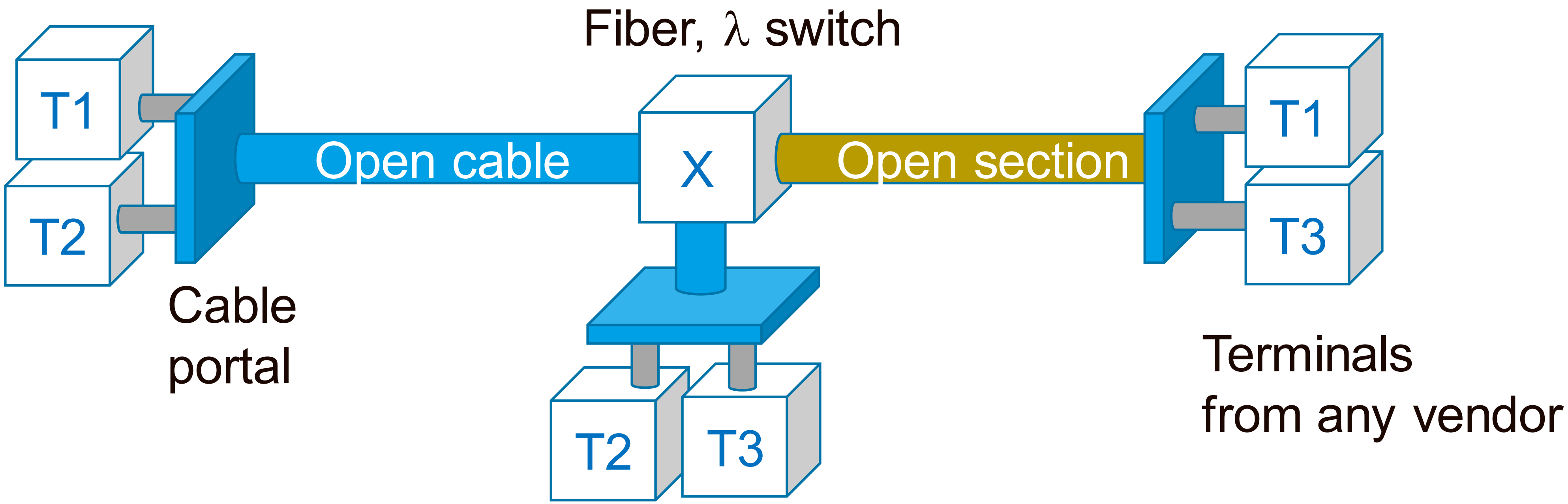
$$\frac{1}{GSNR} \approx \frac{1}{SNR_{ASE}} + \frac{1}{SNR_{NL}} + \frac{1}{SNR_{gawbs}}$$

All the terms are almost proportional to distance



GSNR scales like 1/distance (-1dB/dB), with almost same optimum power

From GSNR to end to end performance



- Possible interconnection of cables with terrestrial sections, terminals through portals
- Same physics applies:
  - model impairment as an equivalent SNR, sum the inverse (G)SNRs…

Quality of Transmission (QoT) between 2 transceivers

- A usual metric is the Bit Error Rate (BER) before FEC decoding
  - or its translation into Q-factor, more precisely $Q_{dB}^2 = 10 * \log_{10}(Q^2)$
    - With Q defined from relation: $BER = \frac{1}{2}\operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right)$
    - Interest: Q^2 is usually proportional to electrical SNR
- BER is a function of the electrical SNR integrated in receiver band

$$BER \approx x * \operatorname{erfc}(\sqrt{K * SNR_e})$$

x,K depend on the modulation

Physical limitations at modem side

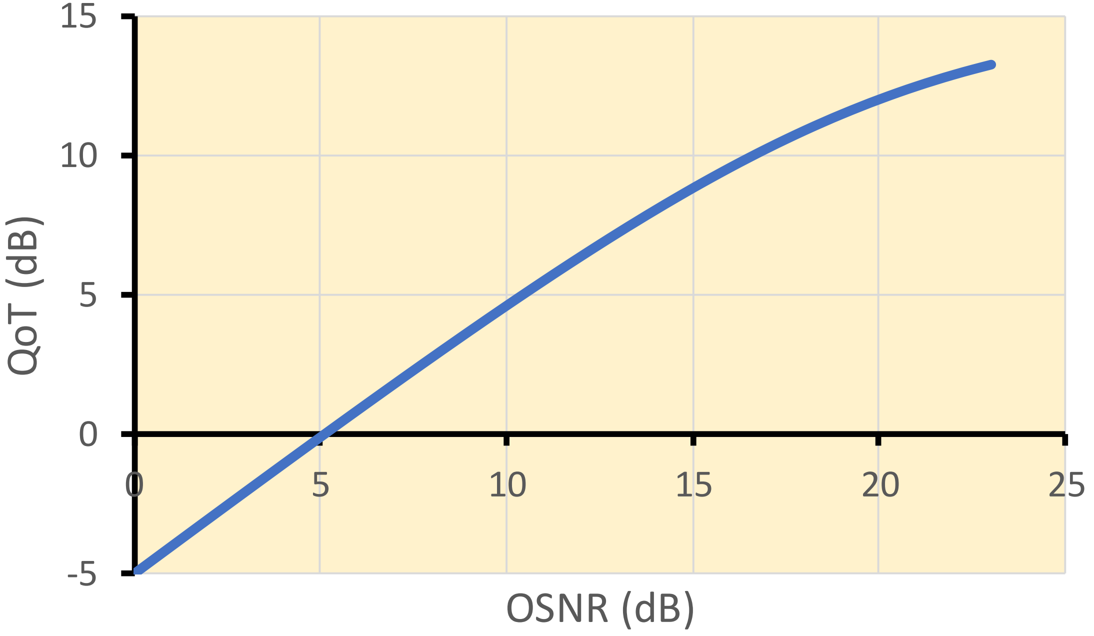
Transmission independent

- Thermal, shot noises
- Bandwidth of E/O components
- Assembly / alignment

Model: Additive Gaussian noise

Back to back measurements:

QoT vs external source of SNR

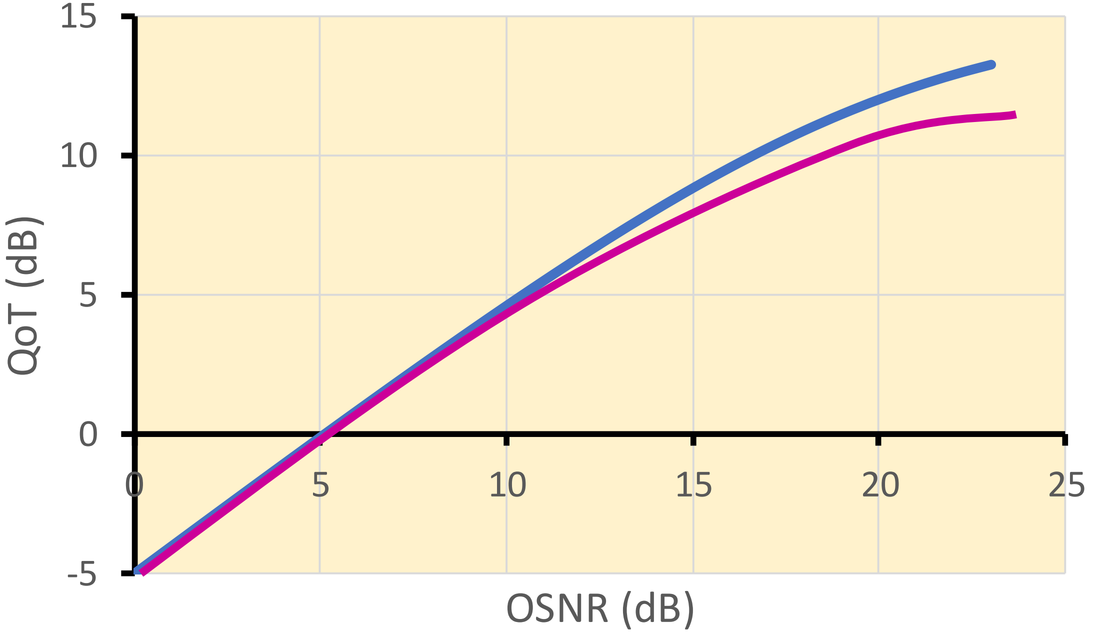


Physical limitations at modem side

Transmission dependent

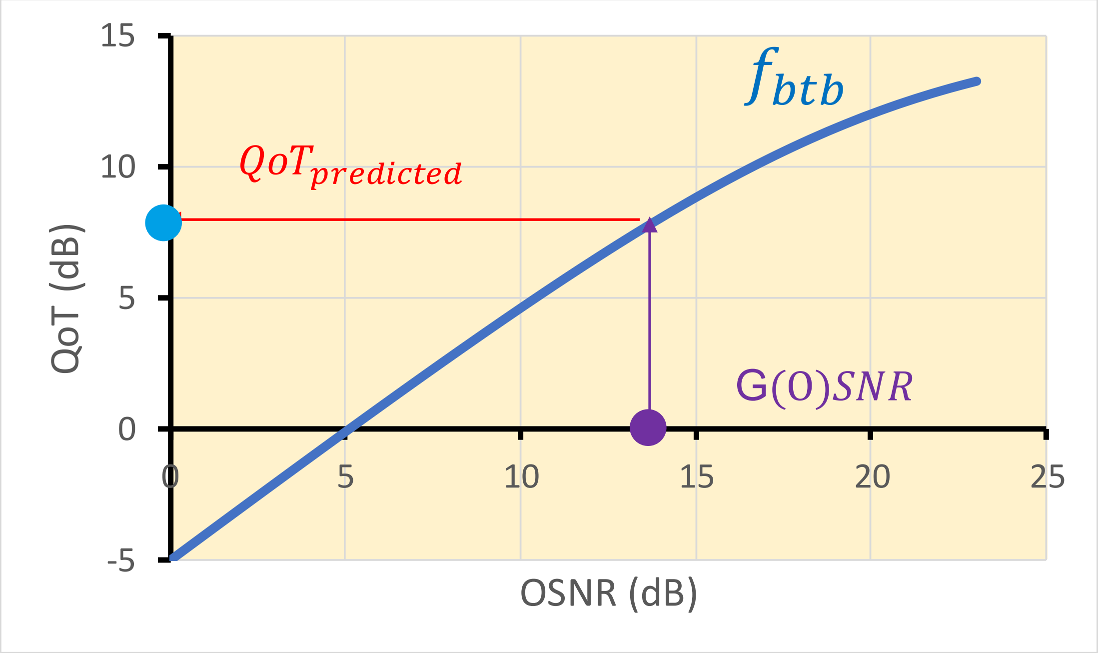
- Av. impact of PDL / PMD
- Imperfect mitigation of chromatic dispersion due to
    - Resolution of implemented DSP
    - Laser linewidth

Characterization requires reliable emulation of impairment / model / simulations



Basic fit for QoT=Q² or SNR$_e$: $\frac{\eta}{QoT} = \frac{1}{SNR_{line}} + \frac{1}{SNR_{TRx}}$

End to end Gaussian noise model



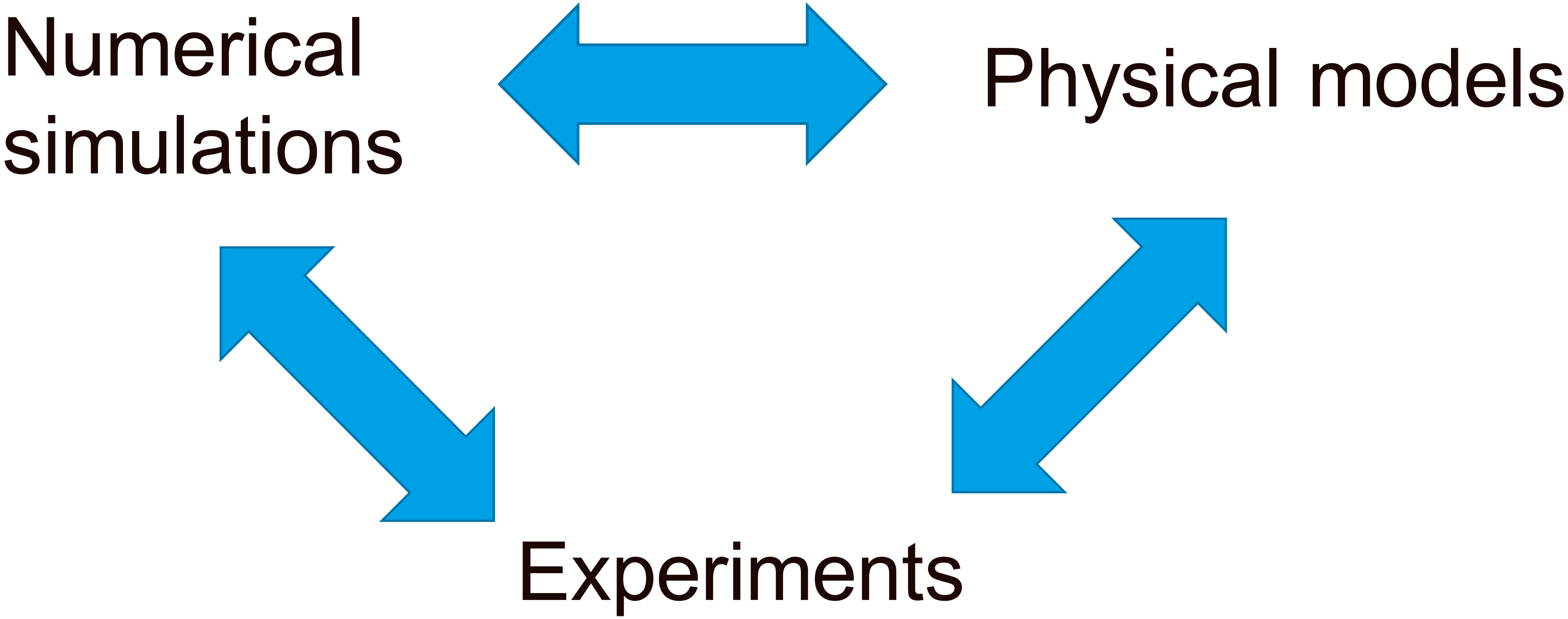
- 1. Back to back characterization
  - Transponder tolerance to Gaussian noise (ASE noise)

$$QoT = f_{btb}(O{-}SNR)$$

    - With possible refinements
- 2. Model transmission impairments as Gaussian noises
    - ASE noise, nonlinear effects, GAWBS,
    - G-(O)SNR matters
- 3. Infer end to end QoT using the back to back calibration

$$QoT_{predicted} = f_{btb}(GOSNR)$$

Performance prediction relies in three pillars



Numerical simulations

Physical models

Experiments

SubOptic2019
TO THE BEACH AND BEYOND
RETHINKING GLOBAL NETWORKS

Performance of Open Cable: From Modeling to Wide Scale Experimental Assessment

Name: Jean-Christophe ANTONA
Company: Alcatel Submarine Networks

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NETWORKS

Parametric study

Experimental set-up

- 36nm loop testbed
  - CSF1 (110µm² fiber)
- Real-time tribs,
calibrated in back to back
- Various configurations :

Pulse shaping
RRC 0.1, 0.2

Channel spacing
33.3, 37.5, 50GHz

Baud Rates
31, 34Gbaud

Modulation
PDM-PSK, 8QAM

Distance
1 500→12 000 km

Power
16, 18, 20dBm

➡

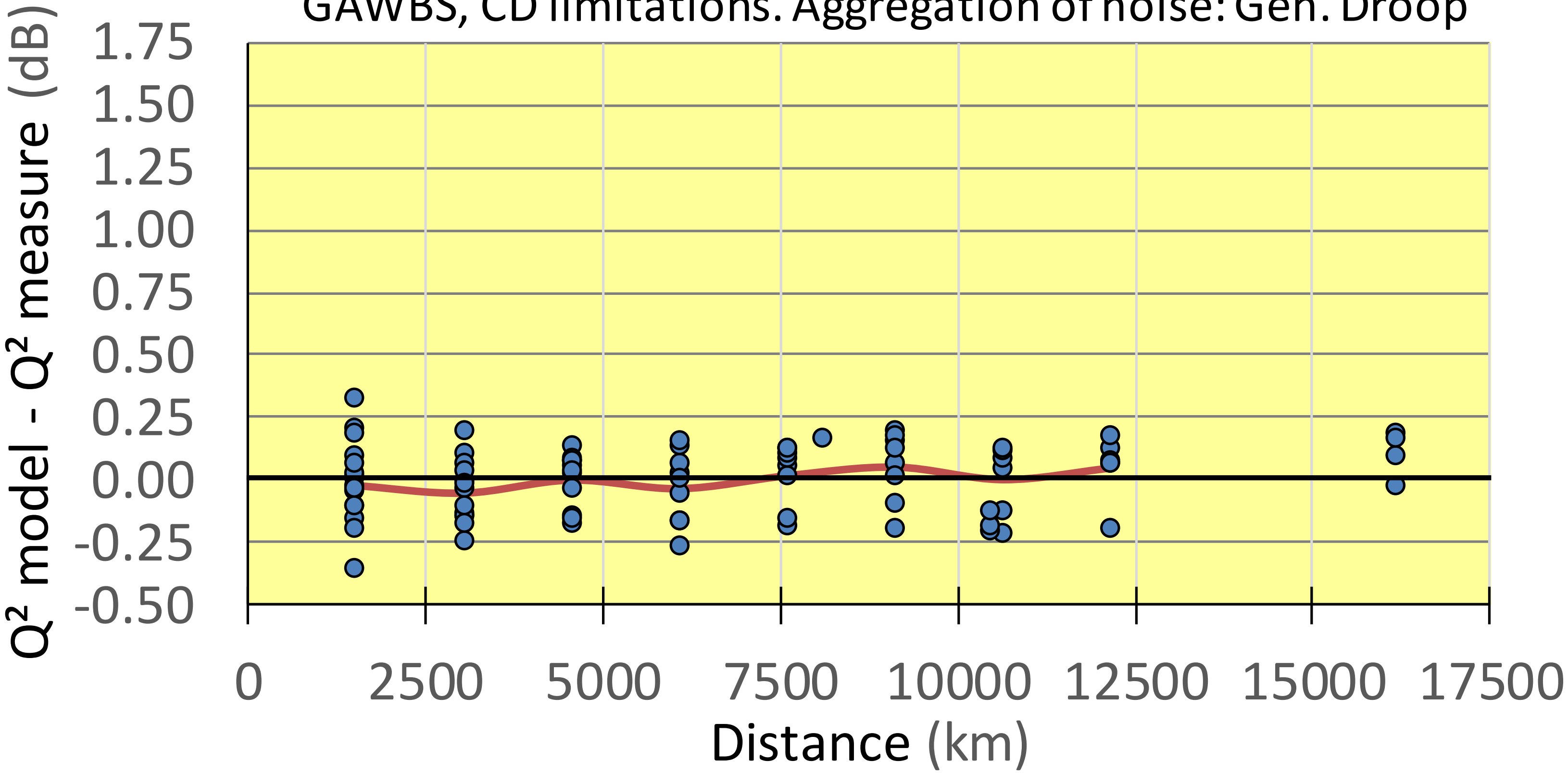
- Measurements of average OSNR_{ASE} and Q² factor over the full C-band
- Comparisons with Q² factor predictions, aware of OSNR_{ASE} measures

Performance prediction accuracy

SubOptic2019 TO THE BEACH AND BEYOND RETHINKING GLOBAL NETWORKS

+ Additional cases: 45, 69Gbaud, QPSK, TPCS, 16 000km

Nonlinear noise: coherent GN model, signal depletion GAWBS, CD limitations. Aggregation of noise: Gen. Droop



Accurate prediction whatever the configuration

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Enough models and labs, let’s design a cable

Main expectations from a customer

Turn-key system

Guarantee capacity “per fiber” over 25 years

Incl. manuf. Margins, time-fluctuations, repairs, customer margins

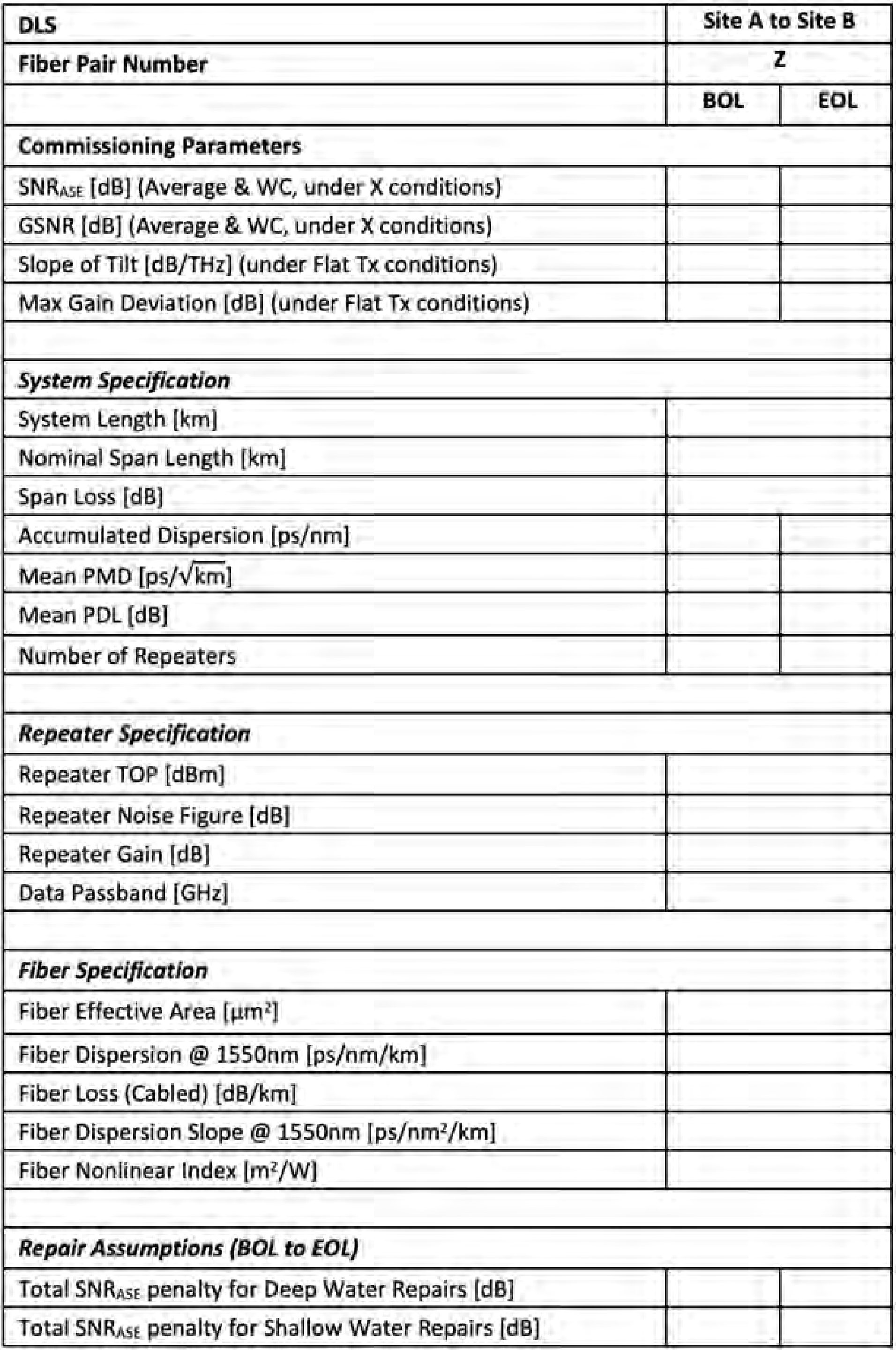
Demonstrate capacity at commissioning, with terminals

Open cable

Commit on agreed cable characteristics that will enable further interconnection with SLTE: OSNR_{ASE}, GOSNR (NL?), flatness, expectable capacity over time

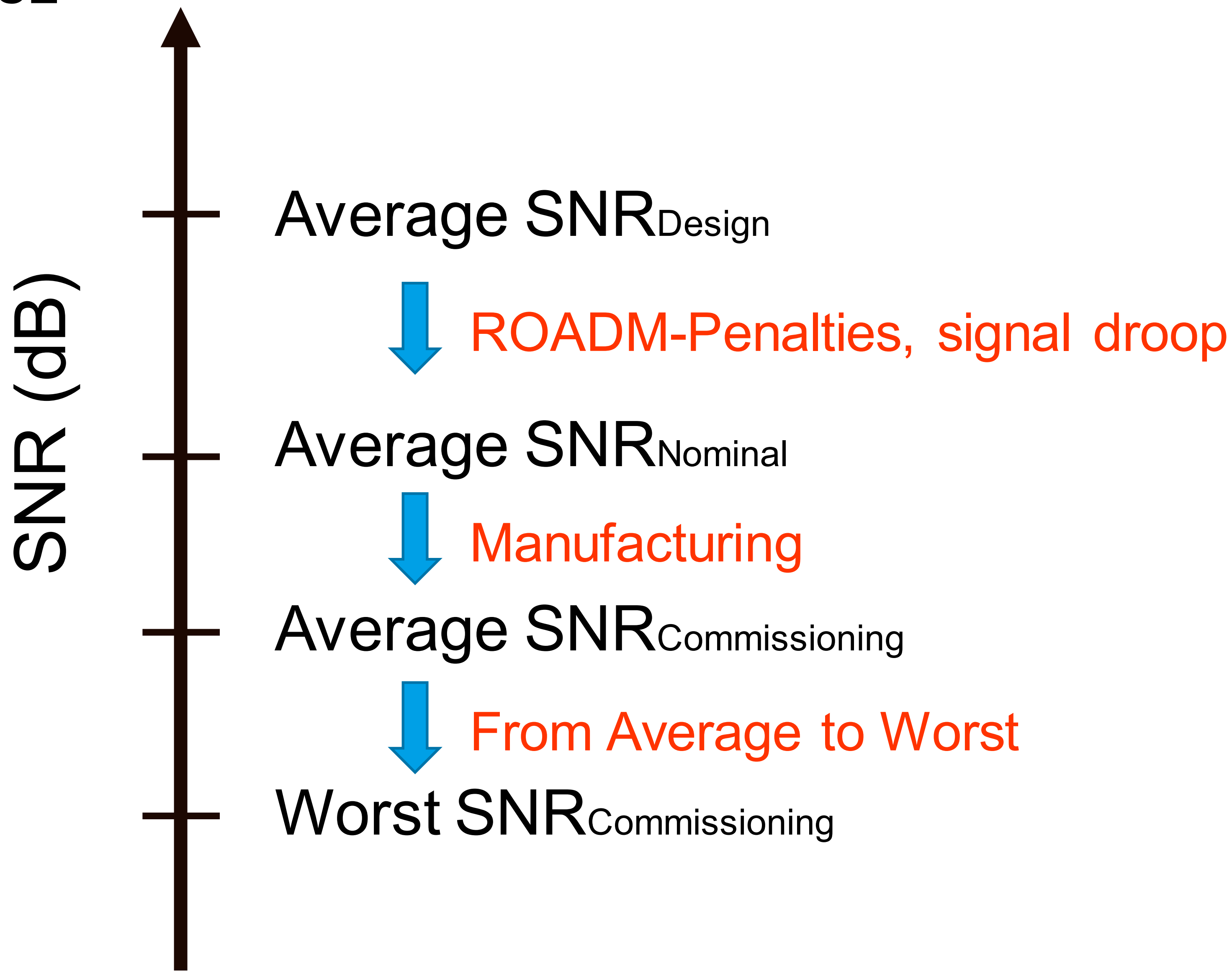
Demonstrate OSNR / GOSNR at commissioning

Examples of characteristics to provide



DLS	Site A to Site B	
Fiber Pair Number	Z	
	BOL	**EOL**
Commissioning Parameters		
SNR_{ASE} [dB] (Average & WC, under X conditions)		
GSNR [dB] (Average & WC, under X conditions)		
Slope of Tilt [dB/THz] (under Flat Tx conditions)		
Max Gain Deviation [dB] (under Flat Tx conditions)		
System Specification		
System Length [km]		
Nominal Span Length [km]		
Span Loss [dB]		
Accumulated Dispersion [ps/nm]		
Mean PMD [ps/$\sqrt{km}$]		
Mean PDL [dB]		
Number of Repeaters		
Repeater Specification		
Repeater TOP [dBm]		
Repeater Noise Figure [dB]		
Repeater Gain [dB]		
Data Passband [GHz]		
Fiber Specification		
Fiber Effective Area [μm^2]		
Fiber Dispersion @ 1550nm [ps/nm/km]		
Fiber Loss (Cabled) [dB/km]		
Fiber Dispersion Slope @ 1550nm [$ps/nm^2/km$]		
Fiber Nonlinear Index [m^2/W]		
Repair Assumptions (BOL to EOL)		
Total SNR_{ASE} penalty for Deep Water Repairs [dB]		
Total SNR_{ASE} penalty for Shallow Water Repairs [dB]		

Different SNR_{ASE}



SNR (dB)

Average $\text{SNR}_{\text{Design}}$

ROADM-Penalties, signal droop

Average $\text{SNR}_{\text{Nominal}}$

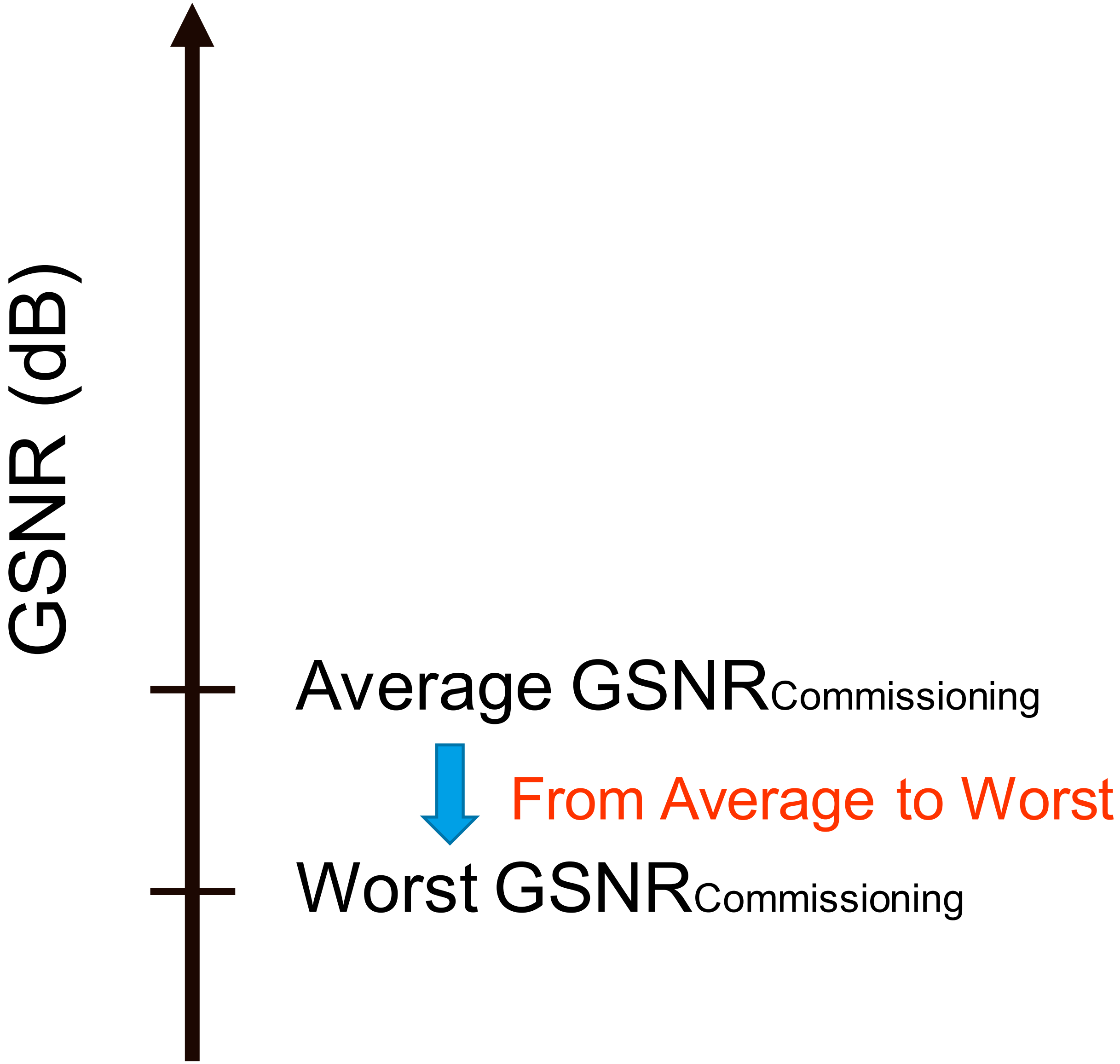
Manufacturing

Average $\text{SNR}_{\text{Commissioning}}$

From Average to Worst

Worst $\text{SNR}_{\text{Commissioning}}$

Different GSNR



Average $\text{GSNR}_{\text{Commissioning}}$

From Average to Worst

Worst $\text{GSNR}_{\text{Commissioning}}$

End of life considerations

- Possible SNR_{ASE} degradations due to
  - Fiber ageing: typ. 0.002dB/km over 25 y
  - Pump failure:
    - Typ. 5% repeaters
    - 2pumps / FP => 3dB extra loss
  - Repairs
    - Deep sea: one repair every 1000km: splice loss + 2-3 times water-depth * attenuation
    - Shallow water: one repair every … 20km. Typical 0.5dB loss.

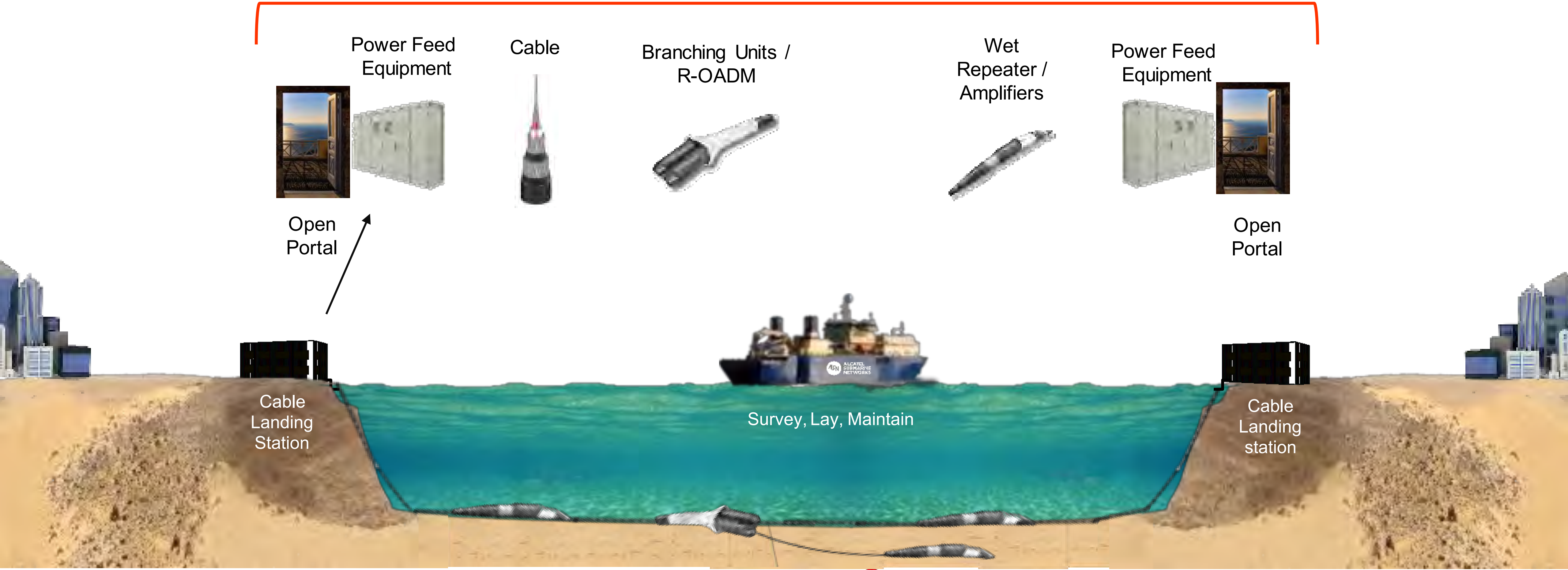
SubOptic2019
TO THE BEACH AND BEYOND
RETHINKING GLOBAL NETWORKS

MASTERCLASS: OPEN SUBMARINE NETWORKS

Name: Brian LAVALLEE, Pascal PECCI
Company: Ciena, Alcatel Submarine Networks

ciena
ALCATEL SUBMARINE NETWORKS

OPEN system



Power Feed Equipment

Cable

Branching Units / R-OADM

Wet Repeater / Amplifiers

Power Feed Equipment

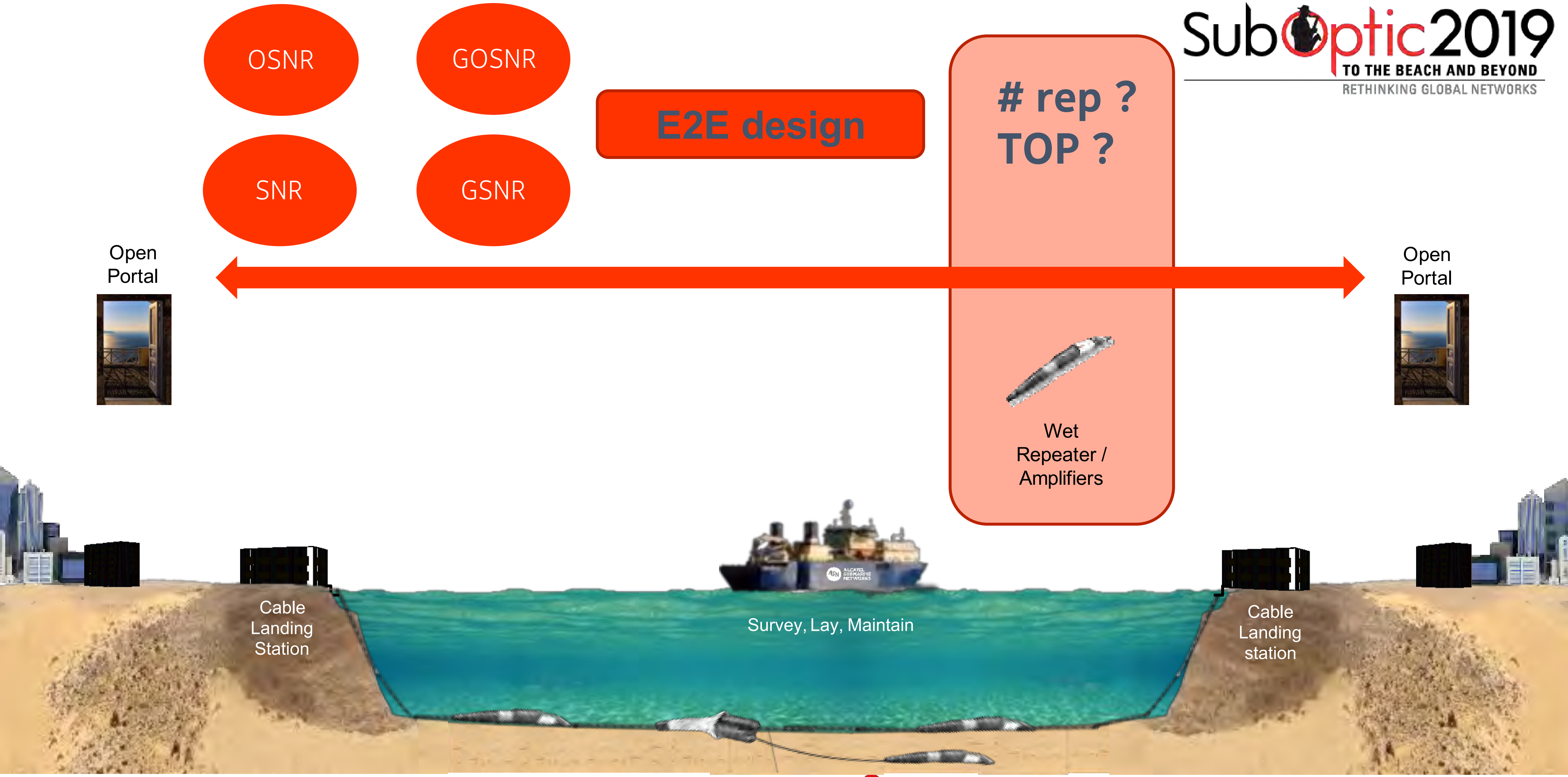
Open Portal

Open Portal

Cable Landing Station

Survey, Lay, Maintain

Cable Landing station



OSNR

GOSNR

SNR

GSNR

E2E design

 # rep ?
TOP ?

Open
Portal

Open
Portal

Wet
Repeater /
Amplifiers

Cable
Landing
Station

Survey, Lay, Maintain

Cable
Landing
station

OUTLINES

OSNRASE
Upper bound
limit

GOSNR
Lower bound
limit

SDM

-Many solutions to reach it
-SNRASE
  -Capacity upper bound limit

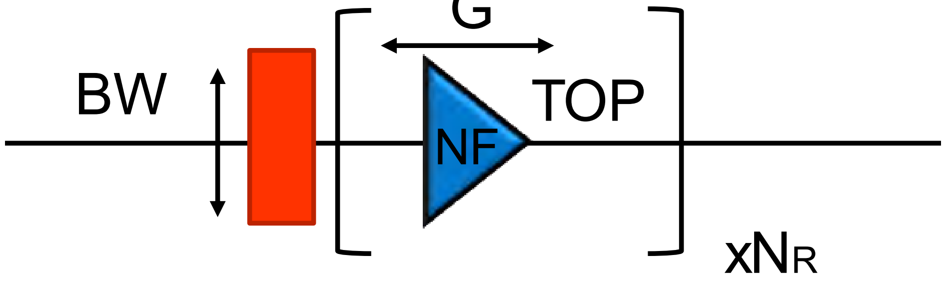
-Definition
-Comparison of 3 solutions
-Optimums

Fibre capacity

-Fibre
-Repeaters
-Conductor

Cable capacity

OSNR$_{ASE}$ and SNR$_{ASE}$



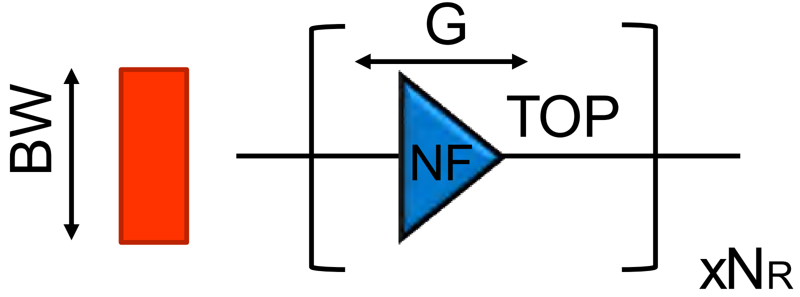
OSNR$_{ASE}$ targeted: $OSNR_{ASE}$ =18.0 dB/0.1nm for 120ch

↓ -10.Log(37.5/12.5)

SNR_{ASE} =13.2 dB

BW is chosen to be 4500 GHz or 36nm

SNR_{ASE}: Capacity upper bound limit



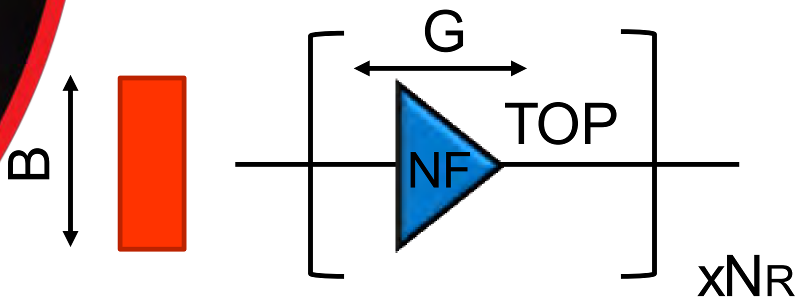
$$C_{upperbound}(Tb/s) = 2.B(THz).log_2[1 + SNR_{ASE}(lin)]$$

with $SNR_{ASE}(dB) = 38.9 - 10 \times Log(BW_{THz}) + TOP - G - NF - N_R$

0.1nm = 12.5GHz @ 1550nm

All WET parameters considered in the upper bound capacity : TOP, G, N_R, NF, BW

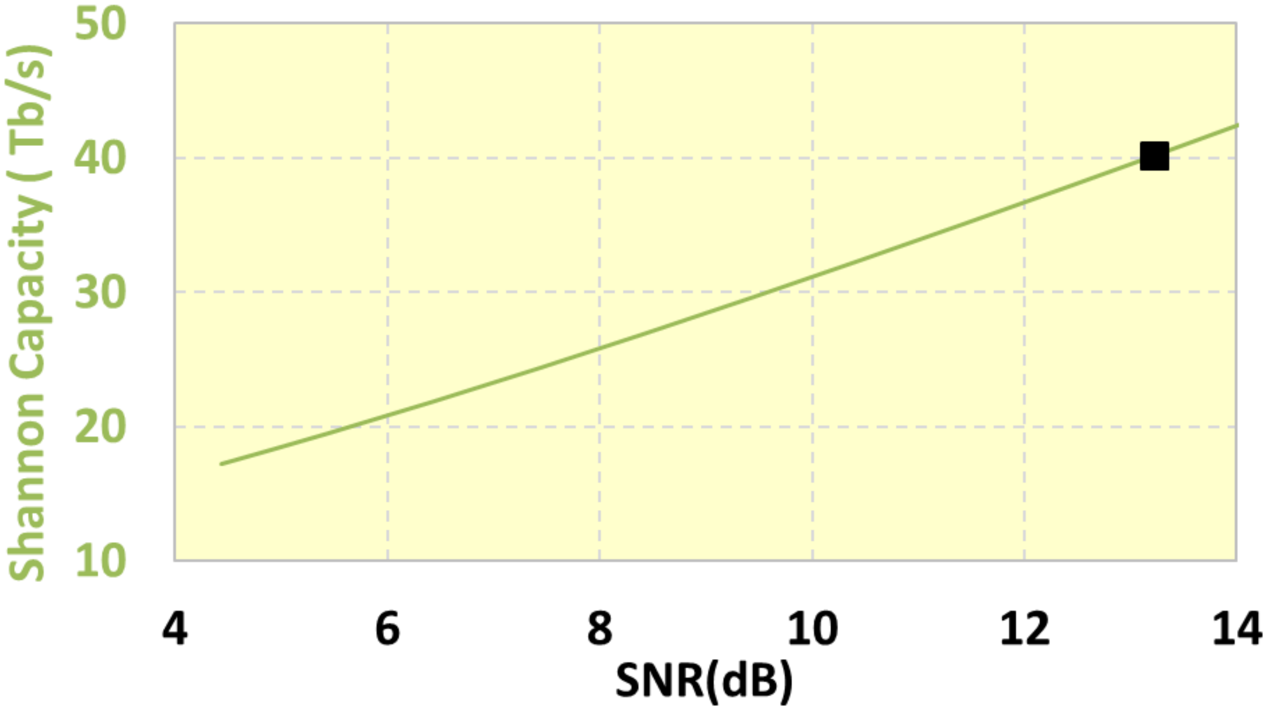
SNR_{ASE}: Capacity upper bound limit



$$SNR_{ASE} = 13.2\ \text{dB}$$

$$C_{upperbound} = 40.2\ \text{Tb/s per fiber}$$

SE=C/BW=8.9 b/s/Hz



Different solutions to reach the same SNRASE

$$SNR_{ASE}(dB) = 38.9\text{-}10\text{xLog}(BW_{THz}) + TOP\text{-}G\text{-}NF\text{-}N_R$$

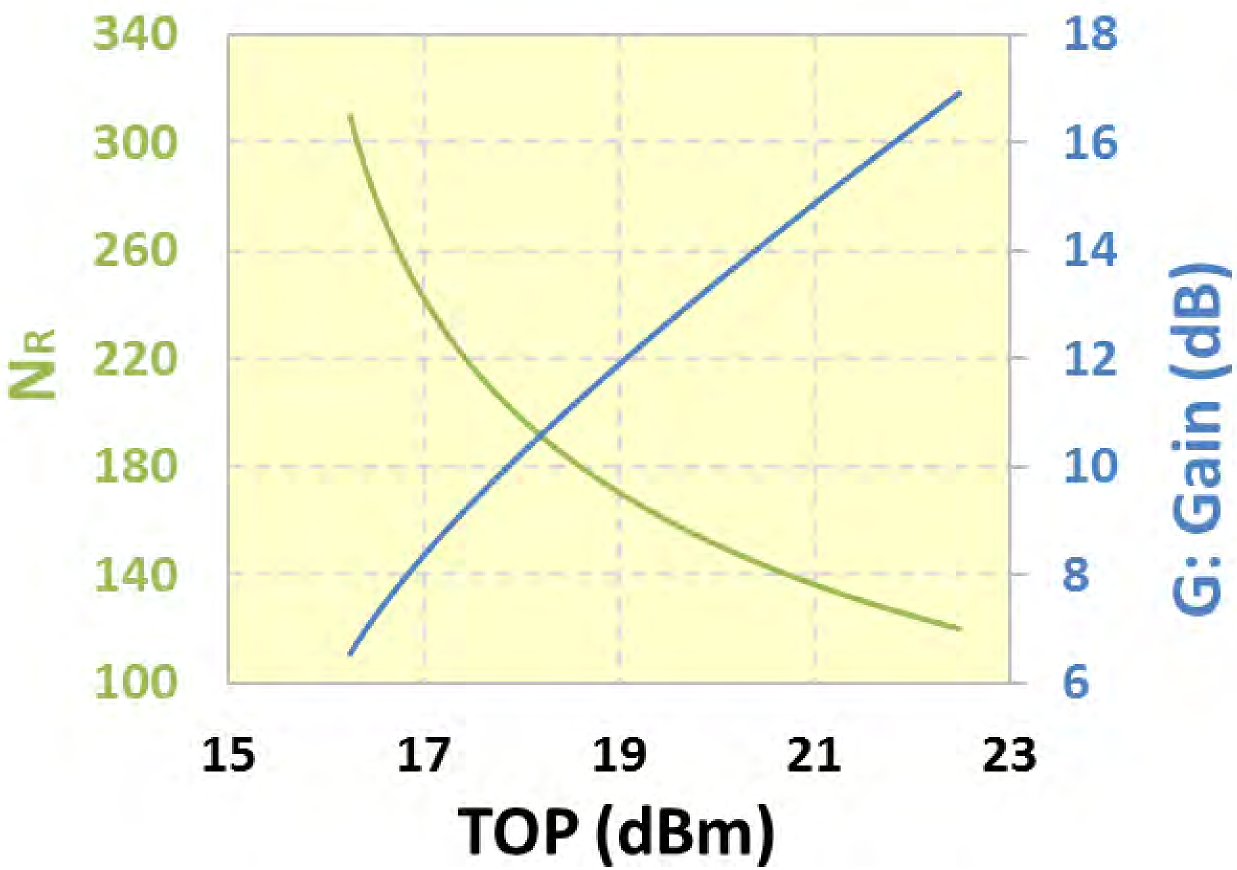
$SNR_{ASE}(dB)$13.2 dB

Distance = 13 000 km

Fibre losses = 0.156 dB/km

16.0 dBm < TOP < 22.5 dBm

NF = 4.0dB (constant)

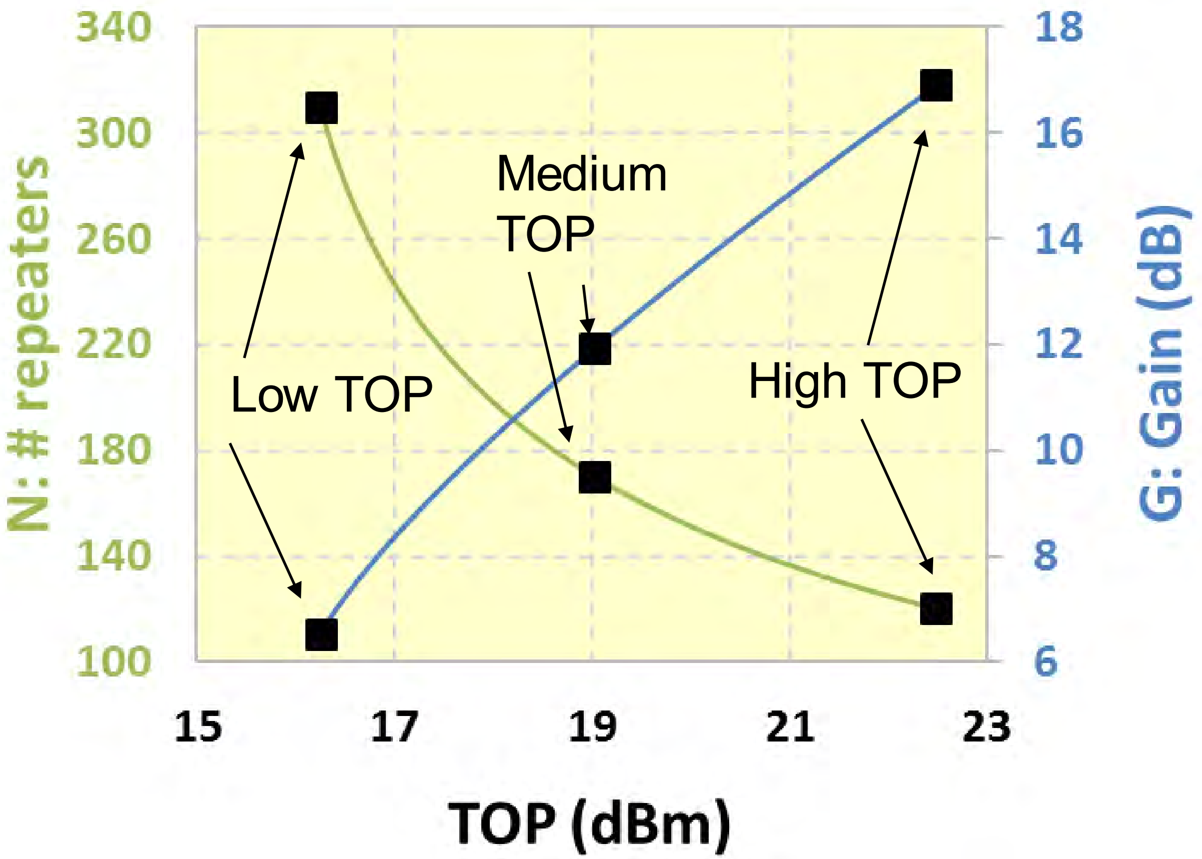


Many solutions: 120<N<310 & 6.5<Gain<17.0 dB

Different solutions to reach the same SNRASE

$$SNR_{ASE}(dB) = 13.2$$

	TOP (dBm)	# rep	Gain (dB)
High TOP	22.5	120	16.9
Medium TOP	19.0	170	11.9
Low TOP	16.2	310	6.5



3 solutions will be studied. How can we differentiate them ?

OUTLINES

OSNR$_{ASE}$
Upper bound limit

GOSNR
Lower bound limit

SDM

- -Many solutions to reach it
- -SNR$_{ASE}$
  - -Capacity upper bound limit

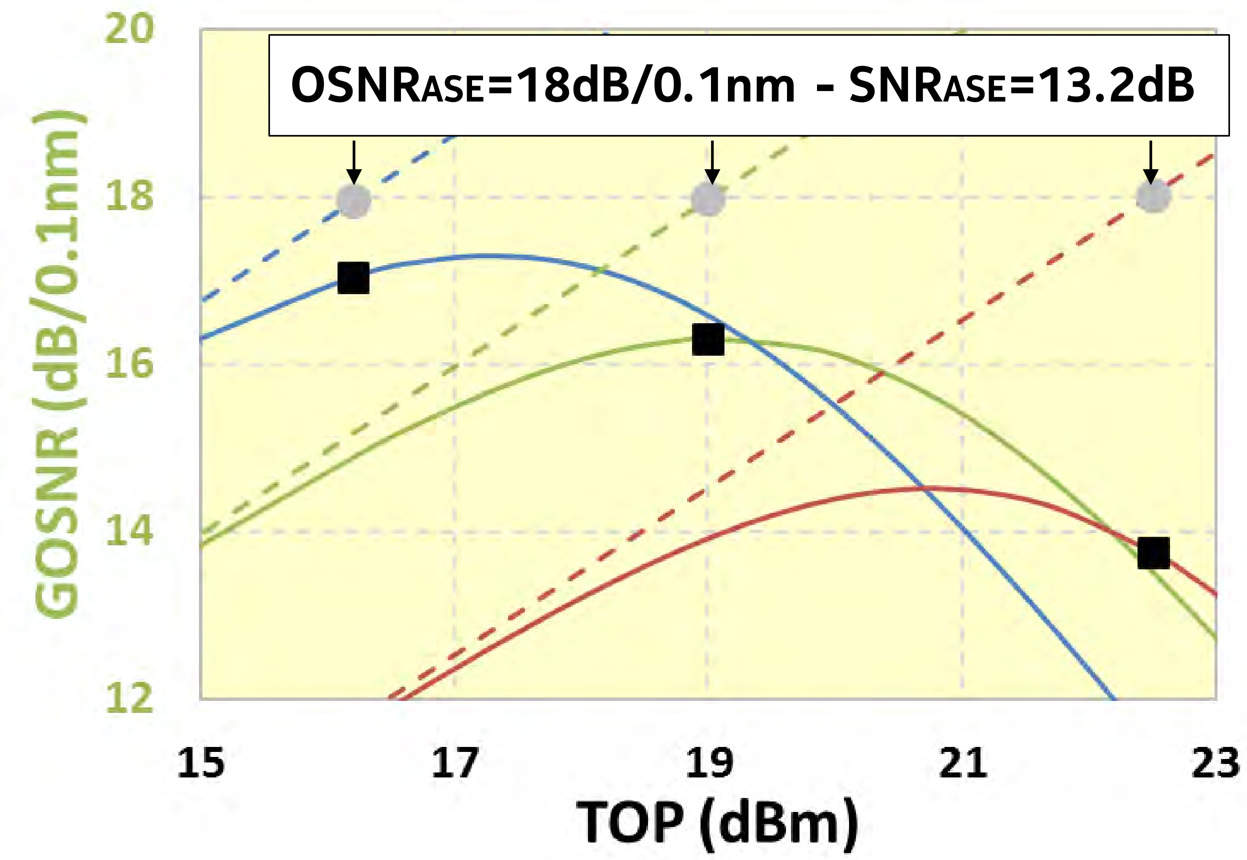
- -Definition
- -Comparison of 3 solutions
- -Optimums

- -Fibre
- -Repeaters
- -Conductor

Fibre capacity

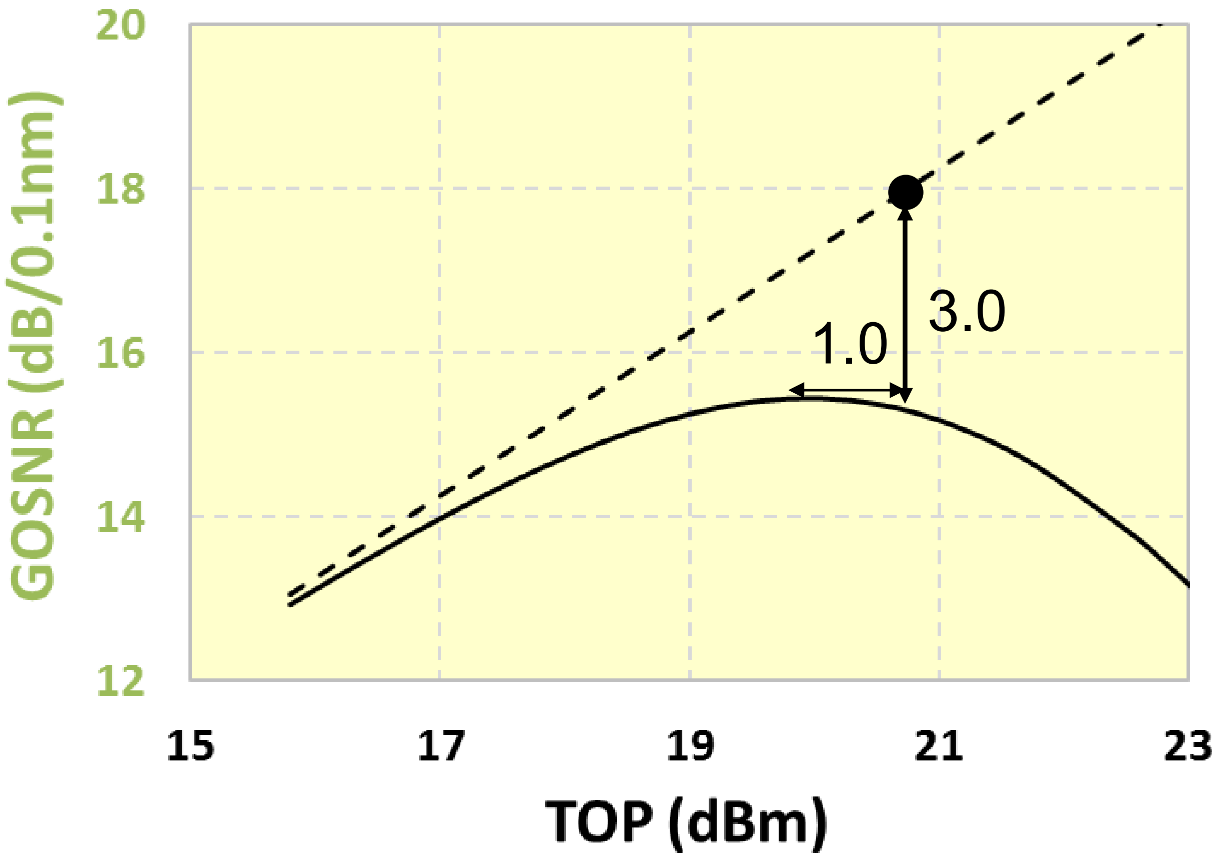
Cable capacity

Different solutions to reach the same SNRASE



[illegible]	TOP (dBm)	# rep	Gain (dB)
High TOP	22.5	120	16.9
Medium TOP	19.0	170	11.9
Low TOP	16.2	310	6.5

Design rule

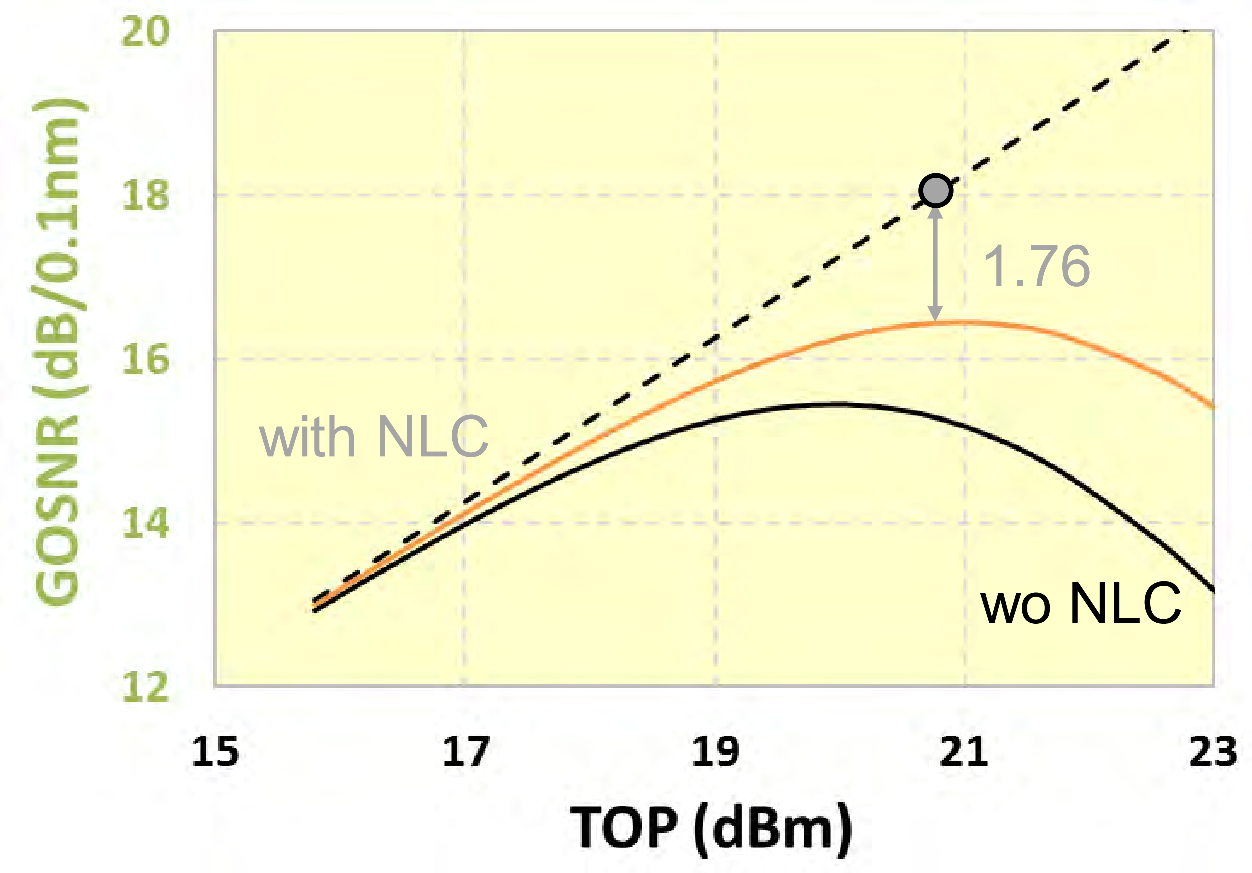


Define a SNRASE

Define the max amount of NLE based on the amount of NLE that transponders will compensate in X years

-> Only one solution

Design r



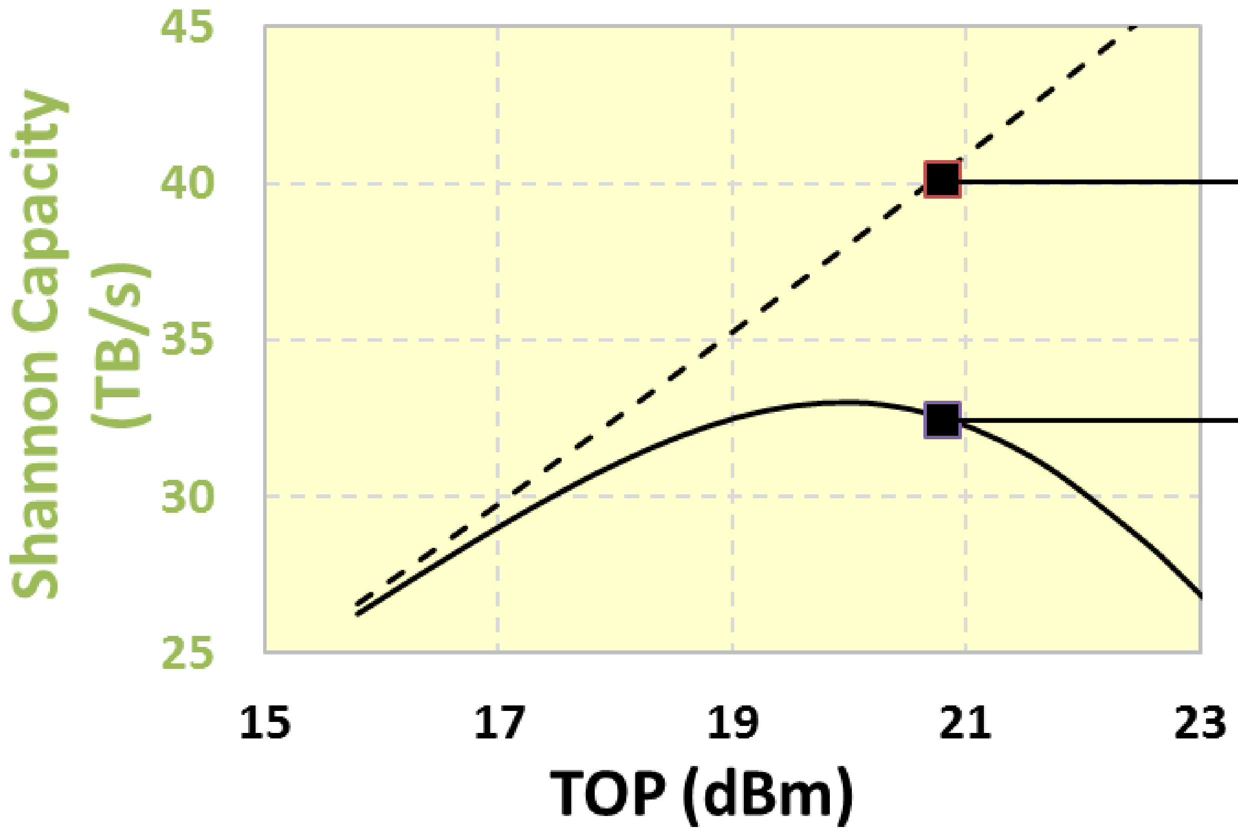
Define an SNRASE

Define the max level of NLE

-> Only one solution

13.2 dB	TOP (dBm)	N	Gain (dB)
Opt TOP	20.8	140	14.5

Shannon capacity: Lower and upper bounds



$C_{upperbound}(Tb/s)$=2.B.$log_2[1 + SNR_{ASE}]$

$C_{lowerbound}(Tb/s)$=2.B.$log_2[1 + GSNR\ ]$

$GSNR$ =GOSNR+10.Log(12.5/37.5)

Upper and lower capacities can characterize the WET part of submarine network

Optical Design reached

Inputs:

- 13 000 km
- SNR_{ASE}=13.2 dB
- BW=4500 GHz or 36nm
- Max level of NLE=3dB
- 150µm² / 0.156 dB/km

Outputs:

- 140 repeaters
- TOP=20.8dBm
- Gain=14.5dB
- Capacity per FP=32.4 Tb/s

Hypothesis:

Today's SLTE can reach 60% of Shannon capacity.

Our cable is a 5FP cable.

Cable capacity:

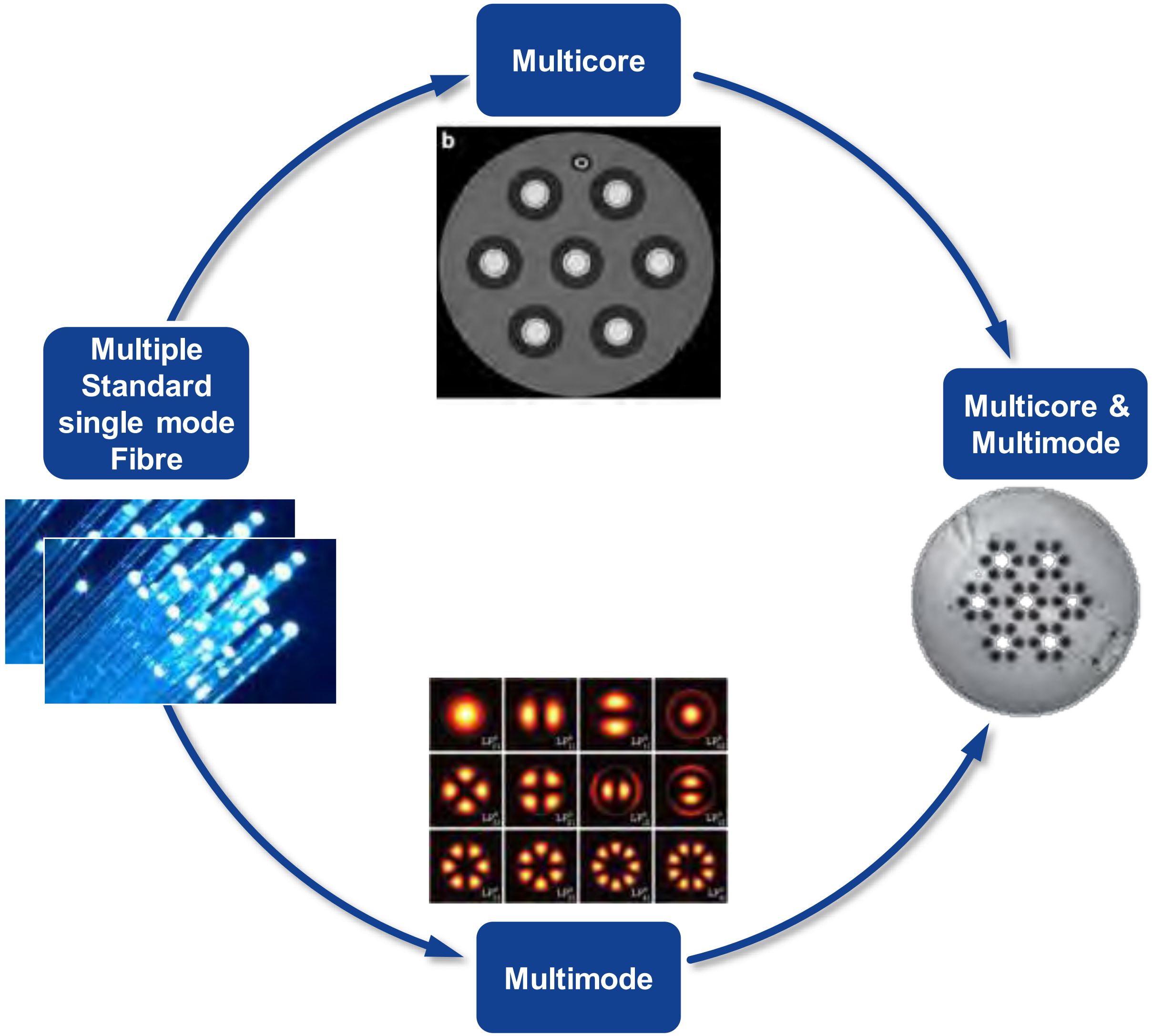
Cable capacity=5 x 60% x 32.4T

Cable capacity~100 Tb/s

What about power efficiency ?

INCREASING SYSTEM CAPACITY & EFFICIENCY WITH SDM

How can SDM be achieved?



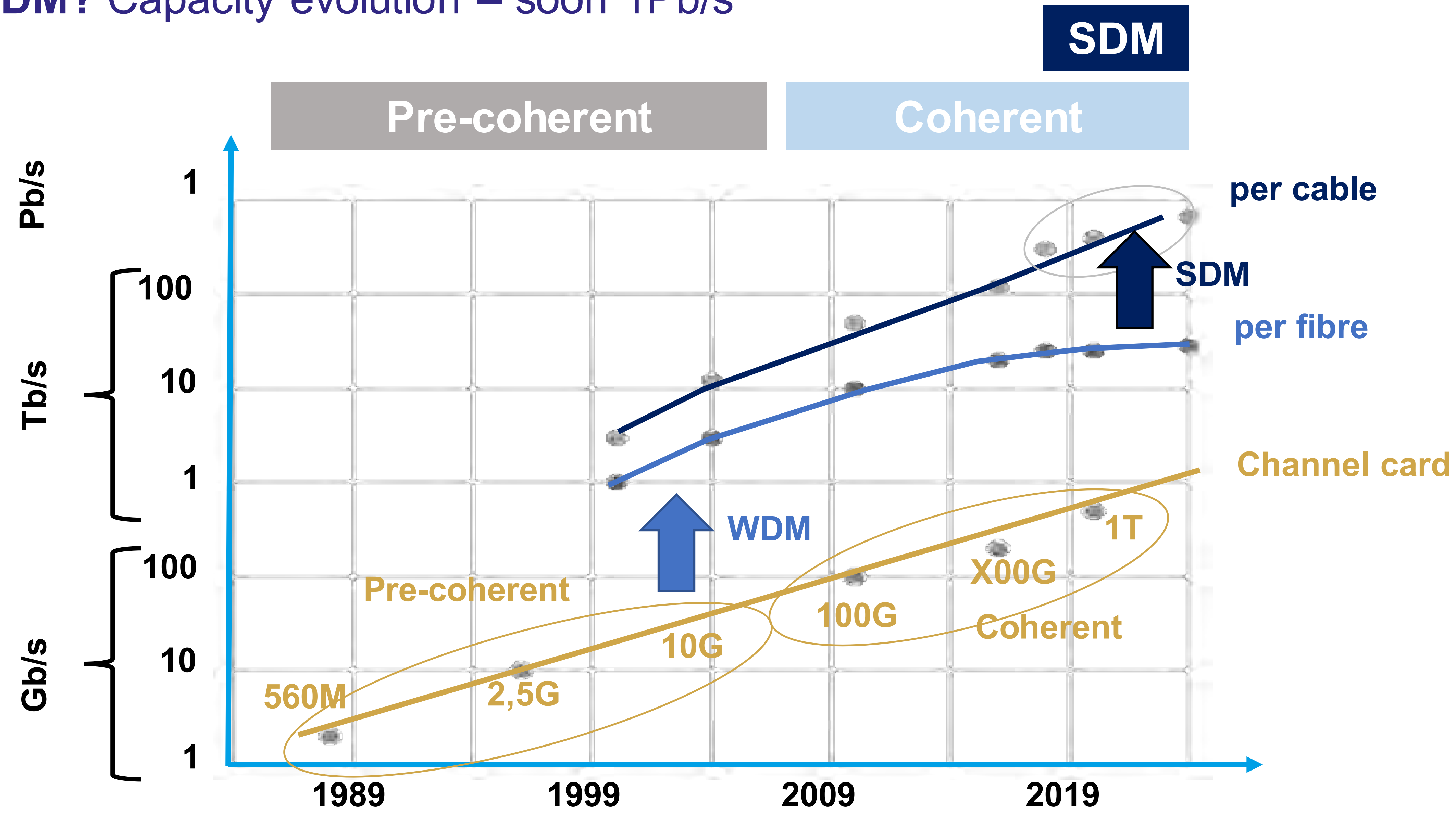
Multicore

Multicore & Multimode

Multimode

Multiple Standard single mode Fibre

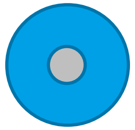
WHY SDM? Capacity evolution – soon 1Pb/s



WHY SDM?

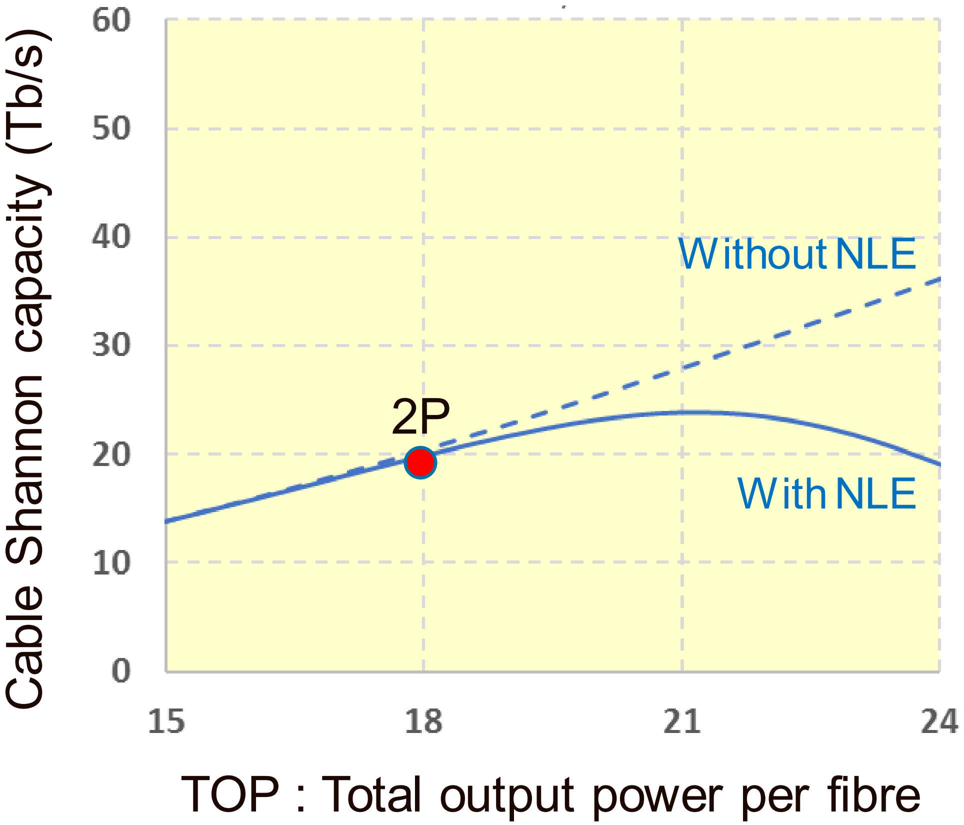
Higher capacity for the same power

Cable with
1 fibre pair



A_{eff} 150µm²

● 20Tb/s



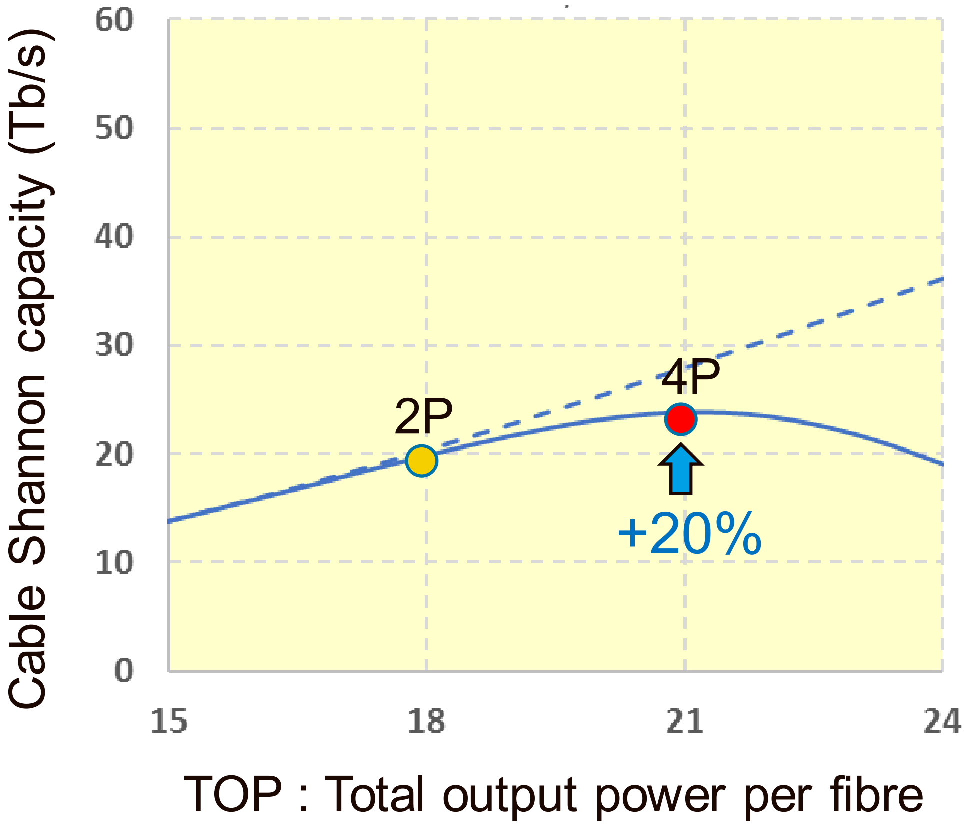
What are the options to increase capacity by doubling the # of pumps ?

WHY SDM?

Higher capacity for the same power

Cable with
1 fibre pair

● 24Tb/s



Option 1:

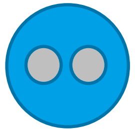
Increase the Power (TOP, $OSNR_{ASE}$)

→ +20% fibre capacity (best case)

WHY SDM?

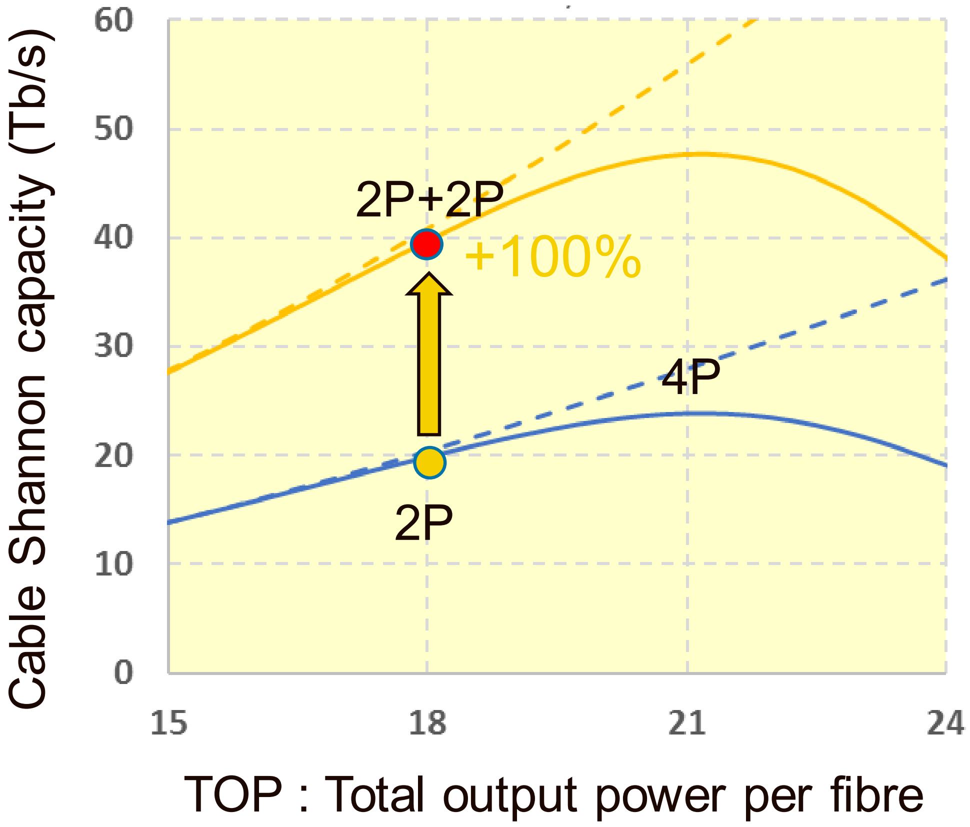
Higher capacity for the same power

Cable with
2 fibre pairs



A_{eff} 150μm^2

● 40Tb/s



Option 2a:

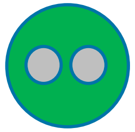
+ Add a fibre

→ +100% fibre capacity (best case)

WHY SDM?

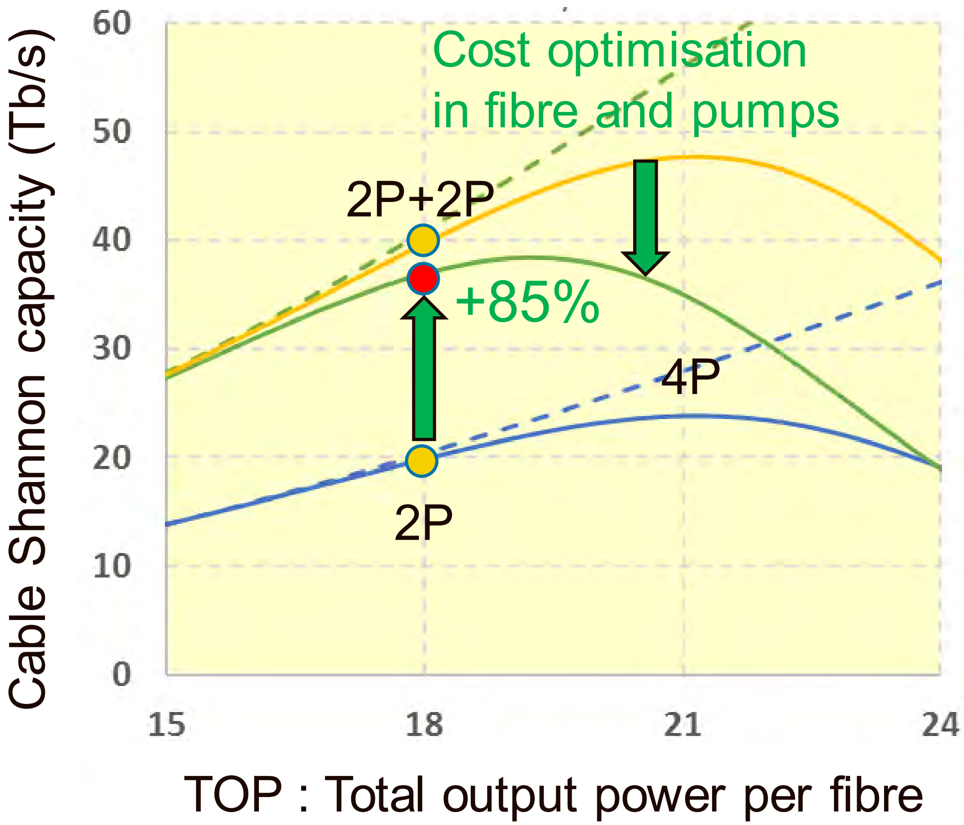
Higher capacity (+50%) for the same power

Cable with
2 fibre pairs



A_{eff} 80µm^2

● 37Tb/s



Option 2b:

+ Add a fibre

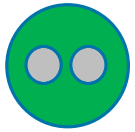
+ Change type of fibre

→ +85% fibre capacity (best case)

WHY SDM?

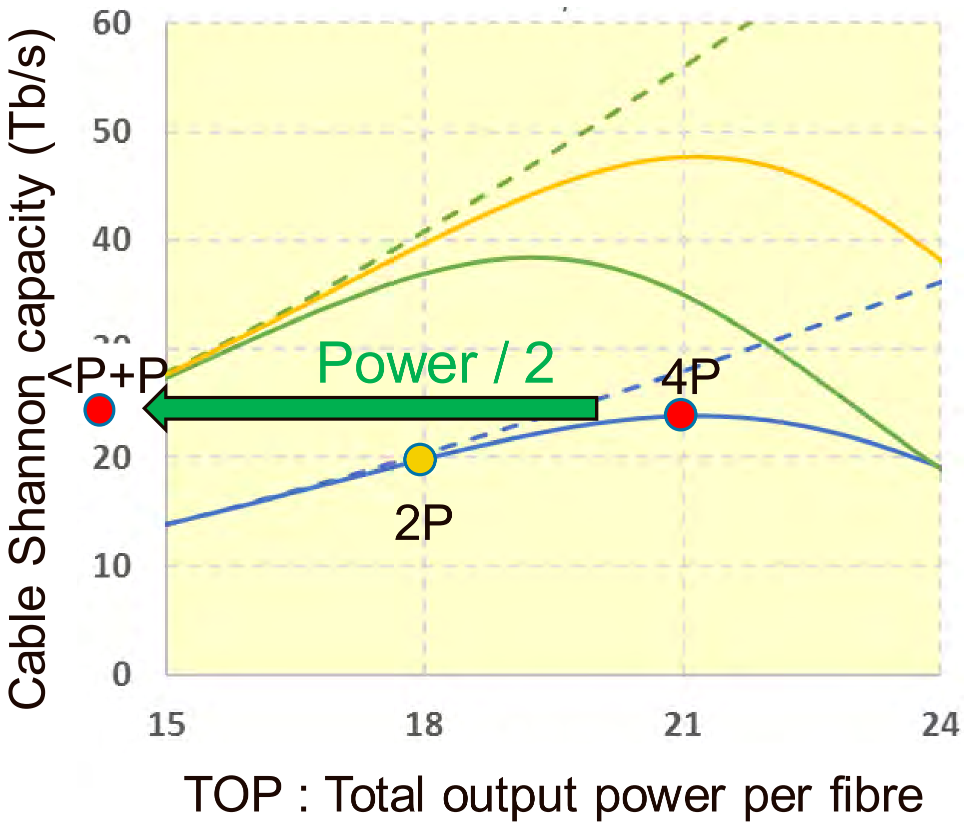
Same capacity for lower power (-50%)

Cable with
2 fibre pairs



A_{eff} 80µm^2

● 24Tb/s



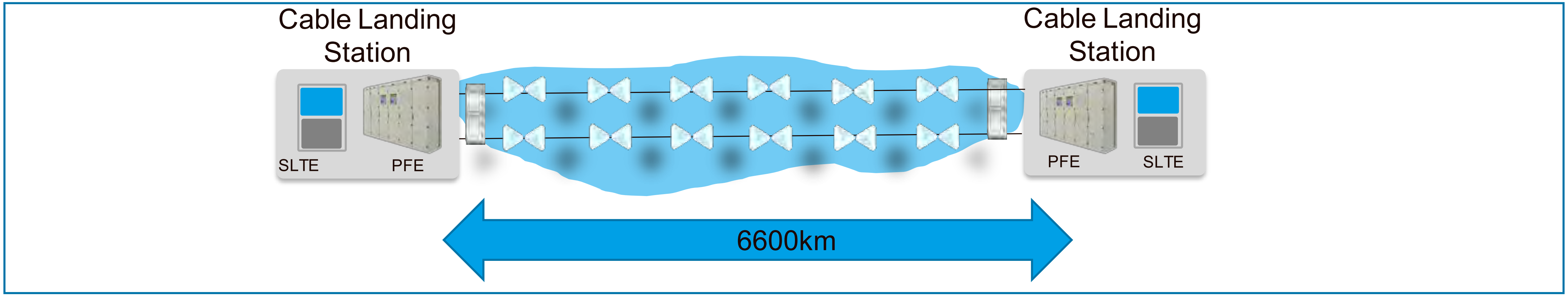
Option 3:

- \+ Add a fibre
- \+ Change type of fibre
- \+ Share the pump power
- \+ Reduce the current
- → same cable capacity

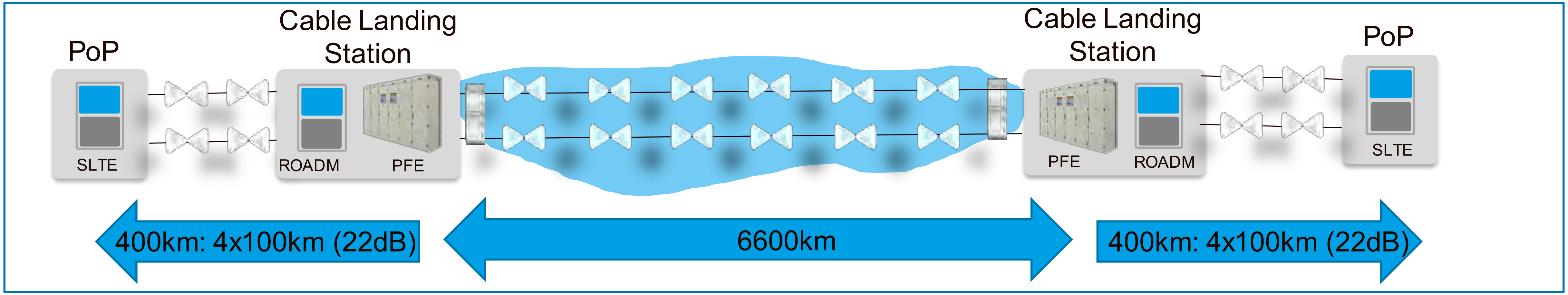
WHY SDM?

Extension to POP

Standard - 8FP – 160 T cable



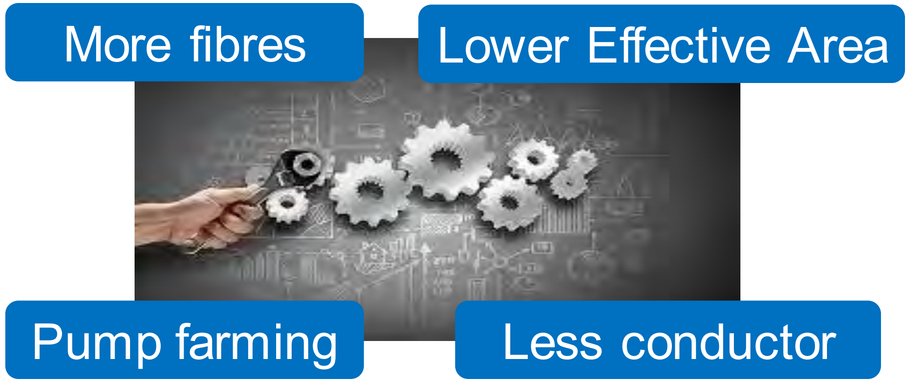
SDM - 12FP – 160 T cable



SDM Benefits

- Optimised $/bit compared to traditional approach (max OSNR per fiber pair)

- Technical: Extend the limit of traditional approach
  - Cable capacity increase
  - Higher reachable distance
  - Increase speed of manufacturing



More fibres

Lower Effective Area

Pump farming

Less conductor

- Business
  - Fiber pair as a new granularity: Easier to swap/sell/manage
  - POP to POP connectivity

Future challenges of subsea optical cables

- Higher and higher capacities
- At reduced cost / bit
- Power efficiency
- Spatial parallelism
- Integration
- More monitoring and automation

Zero loss “fibers”
Zero margin operation
Zero nonlinearities

- Global optimization: wet + dry + marine + …

Thank you

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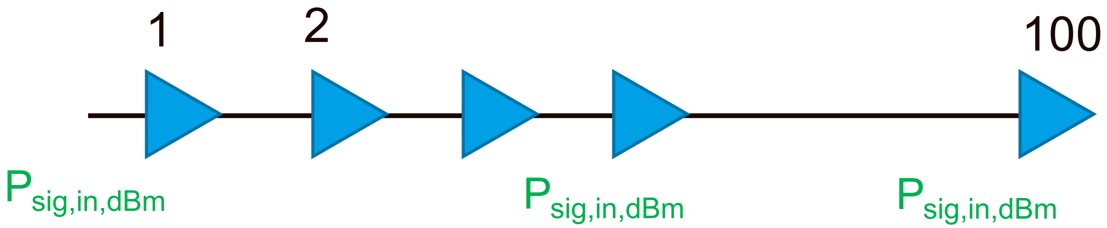
Constant total power vs constant gain amplifiers

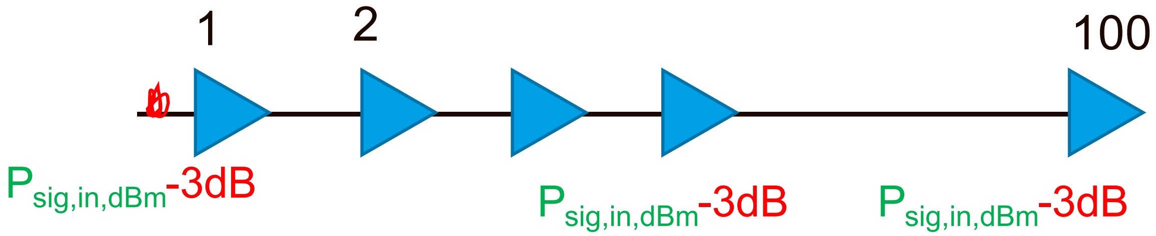
Case study: 100 repeated sections, 3dB extra loss at first section

Gain mode amplifiers

- Nominal :
  - Constant signal power
  - $SNR_{ref,dB} = K + P_{dBm} - 20dB$



- Degradation at span 1
  - Signal power -3dB at each span
  - Doubled noise per span
  - SNR penalty = 3dB



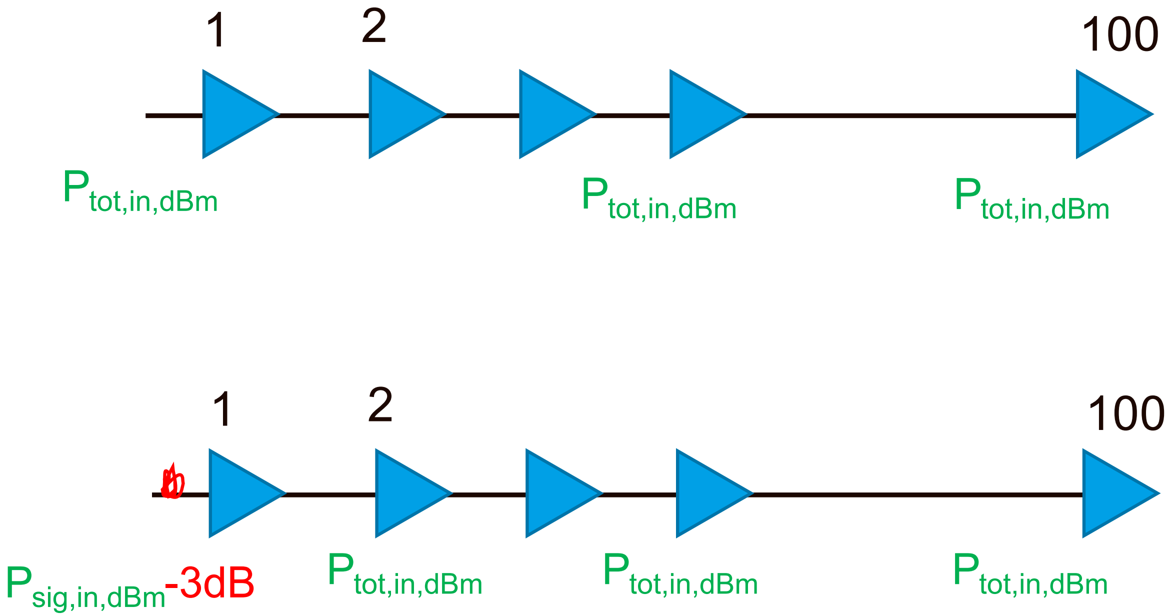
Constant total power vs constant gain amplifiers

Case study: 100 repeated sections, 3dB extra loss at first section

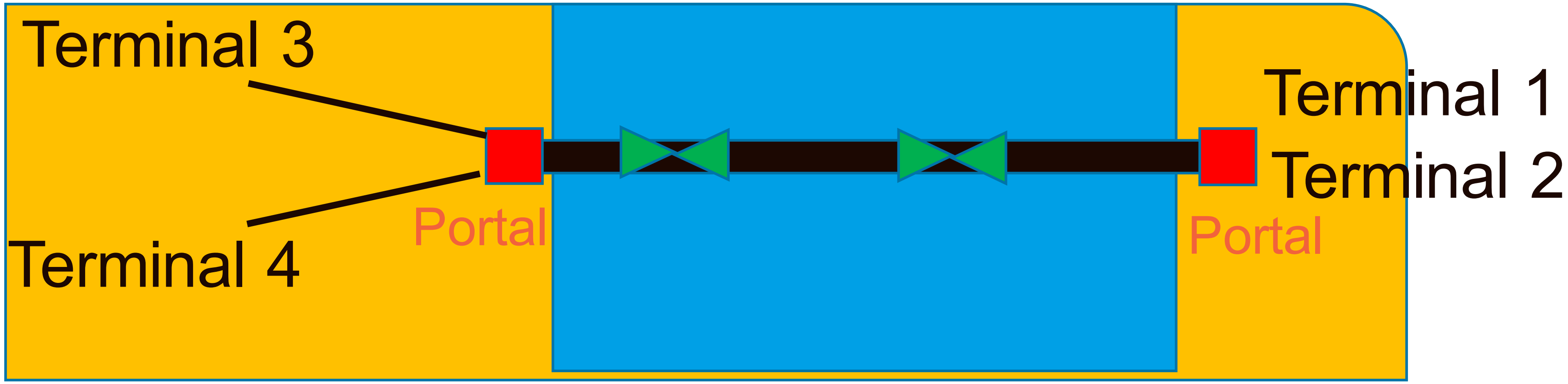
Gain mode amplifiers

- Nominal :
  - Slight signal + ASE droop
  - $SNR_{power} = SNR_{gain} - 0.5$
  - Typically 0.1dB penalty

- Degradation at span 1
  - Signal power -3dB at 1st ampli
  - Equivalent to 1 more section
  - $Pen = 10 * \log\left(\frac{101}{100}\right) = 0.04dB$



Submarine portal



The portal is the frontier between the open cable from one vendor
And terminals, extensions from other vendors

Primary mission: supervision of the cable, (band loading with ASE)
Can be adapted to multi-terminals per cable/fiber, extensions

System Planning in Developing Markets

Table on Contents - System Planning in Developing Markets

Market Analysis Today and in 10 years

1. GDP trends
    a. Be aware of any technology, demographic, legal changes that can change your model.
    b. Trends linear or polynomial?
2. STEM graduates per annum
    a. University expense per anticipated income trends
    b. Innovation from technology or demographics that can change your model.
3. Mobile broadband available to population*
4. Kms of fiber per person ratio
5. Internet exchange maturity, traffic ratio per population, traffic ratios in country vs. international.

Market Analysis Today and in 10 years - cont.

1. Carrier Neutral Data Centers
   a. Amount of critical IT load (MWs) available in country trend
   b. Power sustainability (% renewable and green)
   c. Power availability (timelines and MTBF)
   d. Land ownership
   e. Geography, environmental, weather, sustainability
2. Literacy rates
   a. Reading literacy rate
   b. Rate graduating with at least a grade 12 education
   c. Coding literacy rate*
3. Existing cable market
   a. Price trends per 10G / 100G / 1T
   b. Telcos willing to swap and trade

Market Analysis Today and in 10 years - cont.

Do the previous two slides with your futures hat on - how will this country / region change in 10 years?

- Trendline from previous data.
- Inject strategic initiatives discounting for probability of success.
- Run Monte Carlo simulations to narrow down your assumptions.

Cable Station Design - Developing Markets

Site Selection and Land Choice

a. Zoning
b. Ownership
c. At coast or PFE at coast with CS inland?
    i. $150,000 / km for concrete encased conduit x two paths
    ii. $50,000 / km for direct burial but this is a risk for critical infra.
    iii. ROW fees.
d. Expansion space around your cable station for future use.
e. BMH and conduits to your station / PFE
f. Access to skilled labor
g. Diversity from other assets
h. Minimize distance to continental shelf and BU
i. Insurance on the property and annual cost

Cable Station Design - Developing Markets Cont

Electrical

a. Deviation and trend of power costs.
b. Availability of high voltage feeds.
    i. HV via tower tends to have higher reliability than LV delivered by pole.
    ii. Timing for construction of the substation
c. Substation (build yourself or have power company manage - trade-offs)*
d. Genset (minimum dual gensets - N+N / Active + Active)
e. Power storage
    i. Two tanks if possible to clean old fuel while still providing protection.
    ii. Determine tank size by fuel consumption rate over 96 hours + buffer.
    iii. Filtering/warming if needed.
    iv. Choose gensets that have trained local experts + supply chain for parts.
f. Power distribution
    i. Battery strings should be available for 8 hours
    ii. N+N

Cable Station Design - Developing Markets Cont

Mechanical

a. Choose a cooling technology for the market
    i. DX for high humidity markets
    ii. Chillers can be used for medium to low humidity markets.
    iii. Choose technology based on the environment (sand, humid, dry, artic)
    iv. Building Management System (BMS) should be tied into OSS if possible.

b. Seismic zone considerations, engineer based on the zone

c. Install and monitor leak detection sensors around electrical gear inclusive of roof.

d. Choose materials to match the useful life of the asset and environment

e. Ensure your drainage can move water away from the site at 1.25x peak historical amounts.

f. Be aware of climate change - PFE / CS should be a few meters above sea level if possible and engineered to withstand more dramatic temperature / weather shifts than historical.

g. Local permitting should be studied.
    i. The best designs sometimes cannot be implemented because of construction code challenges.
    ii. Choose architecture of sites that match the environment or have positive historical significance.

Cable Station Design - Developing Markets Cont

Security

a. Have a physical perimeter around the site.
    i. Concertina wire / barbed tape on top of a two meter high fence.
    ii. Automobile blocking bollards
    iii. Motion sensors around the security perimeter.
    iv. Mantraps to control entry
    v. Biometrics for recording
b. Cloud based security system with local backup.
    i. Cameras should not have any non-monitored areas.
    ii. Cameras should be hard wired to a security office.
c. Use a cloud based OSS to prevent cyber attacks.

Cable Station Design - Developing Markets Cont

Local Telecoms Considerations

1. Have 8 x 4” / 100mm duct times two diverse paths to the property boundary
    a. Insert pull ropes / lines for ease of install later
    b. Build a large lockable vault near the cable station property line and near telecoms ROW.
2. Site should be carrier neutral for anyone to pull fiber into
3. Dual right of way (ROW) for local telcos to enter (road, rail, gas pipe, or OPGW)
4. Call before you dig and/or civil penalties for fiber disturbance should be sponsored and/or advocated for with government.
5. Fiber should be sourced / placed to other cable stations in market for backup and restoration.

Cable Station Design - Developing Markets Cont

Seaward telecoms considerations

1. Maintain route position lists and marine maps.
2. Liaise with fisherman in market.
3. Audit and maintain BMH, ROW, and any HDD
4. Armoring considerations

Cable Station Operations

1. Operations support software should be in the cloud with a local backup
2. Security (physical and cyber) should be audited annually.
3. Training courses should be recorded for future new employees.
4. Mechanical, Electrical, and Telecoms equipment should follow regular maintenance schedules.
5. Attend supplier training and be tested on operations & maintenance. Have a succession management plan.
6. CAD / Document building allocations, as-builts, and designs.

Cable Station Operations - Cont

1. Own methods and procedures for the site.
2. AIS monitoring for marine outages
3. Monitor backhaul fiber (either via OTDR or Acoustic sensing)
4. Maintain outage escalation list as well as methods and procedures.
5. Audit outside plant (BMH, beach erosion, backhaul) regularly.
6. Maintain, test, and replenish spares. If supply chain is lengthy, maintain a spare of all critical components on site.
7. Train on any power work with the marine NOC as well as supplier trainers.
8. Each station should maintain a power safety officer as well as deputy PSO.

Government, Licensing Analysis

1) How many telcos and wireless operators, what are the barriers to entry?
2) How has the regulator made decisions over the past 10 years? What is the head of the regulators CV / Resume?
3) What are the government's goals now and in 10 years?
4) What are societal goals now and in 10 years?
5) What are import / export laws and supply chain health?
6) Meet with the local economic development ministry / bureau.
7) What is the history of nationalization of cables or default on sovereign debt?
8) What is the mean time between coups (ie non peaceful transitions of power)?
9) What is the process to receive a new license (if needed)

Marine Maintenance

1. AIS monitoring for marine outages
2. Maintain outage escalation list as well as methods and procedures.
3. Audit outside plant (BMH, beach erosion, backhaul) regularly.
4. Distribute accurate route position list / coastal marine maps once per year.
5. Develop relationship with marine NOC, monitor utilization, location of repair vessels, DMOQ with repair vessels using AIS.
6. Monitor marine laws (especially for Cabotage / flagging regulations). Be aware of marine permitting process for survey, build, and repair).
7. Monitor environmental laws (sea bed, coastal, and any time of year restrictions). Which agencies need to be notified and which timelines are needed.

System Design

1. Single landing or dual landing
    a. Do you have two in country players who want the cable to land in their CS?
    b. Can you build a “Y” landing for increased protection?
2. Cable armoring
    a. Plough / bury where possible within budget
    b. Repair with armor (what has been cut likely to be cut again)
3. Type of landing or branch?
    a. Full landing
    b. Full BU
    c. Full BU with ROADM / WSS (part of a fiber)
    d. Fiber switched BU (can route around a shore end cut)

SUBCOM

Submerged Plant Equipment

Lecture I

Georg Mohs

August 6, 2019

Submerged Plant Equipment Characteristics

High performance:

- Ultra-long transmission distance up to 14,000 km!!
- High data capacity: 250 Tb/s across the Atlantic!

Space & Power Limitations:

- All functionality must fit inside an undersea body.
- Equipment must be powered from shore through the cable conductor.

Reliability for a 25 year lifetime in the undersea environment:

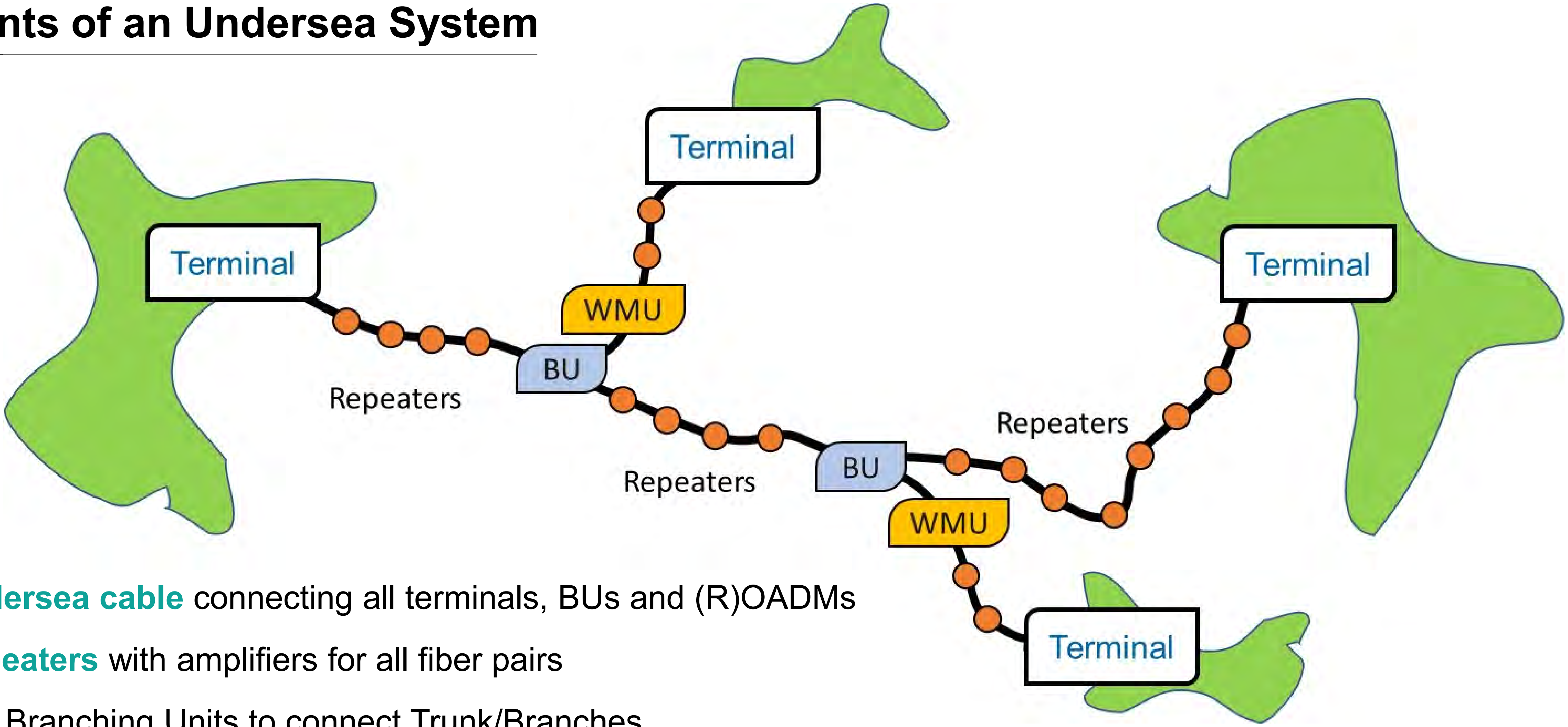
- Water-proof and pressure-stabilized body
- High reliability optics/electronics.

Deployment:

- Equipment must support shipboard storage, deployment, and retrieval for repairs.

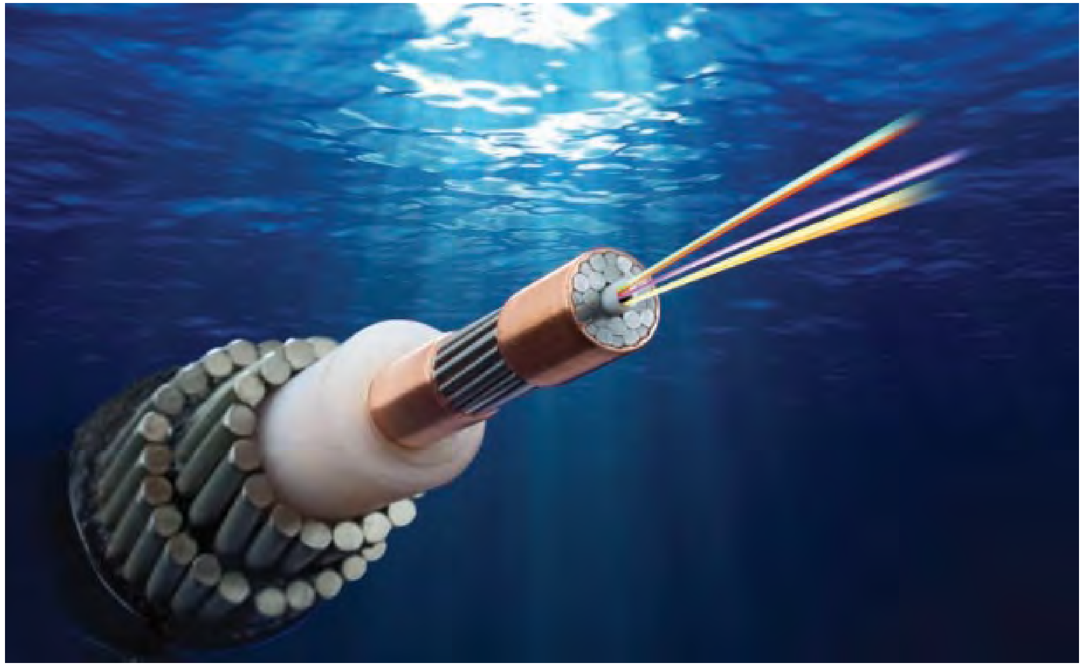
Unique technology for a unique environment

Elements of an Undersea System



- **Undersea cable** connecting all terminals, BUs and (R)OADMs
- **Repeaters** with amplifiers for all fiber pairs
- **BU**: Branching Units to connect Trunk/Branches
- **WMU:** Wavelength Management Units – (R)OADM

Outline



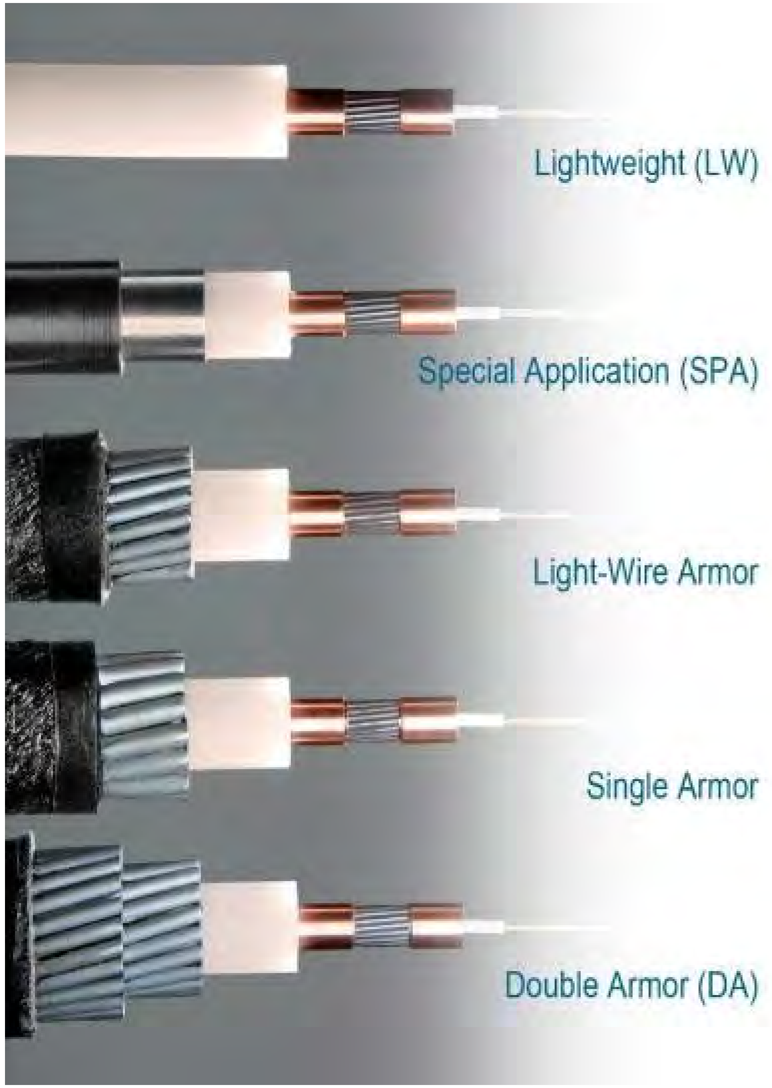
- Cable
- Repeaters
  - Amplification and gain equalization
  - Self-healing of a chain of amplifiers; gain tilt
  - Pump manifold and reliability
  - Line Monitoring and High Loss Loopbacks (HLLBs)
  - L-band amplification
  - The pressure vessel
- Branching Units
  - Fiber routing and optical switches - Why only one branch leg (3 port BUs)?
  - Electrical reconfiguration – Recovering from shunt faults
- Wavelength Management Units: (Reconfigurable) Optical Add Drop Multiplexing
- System Reliability

Undersea Fiber-Optic Cable

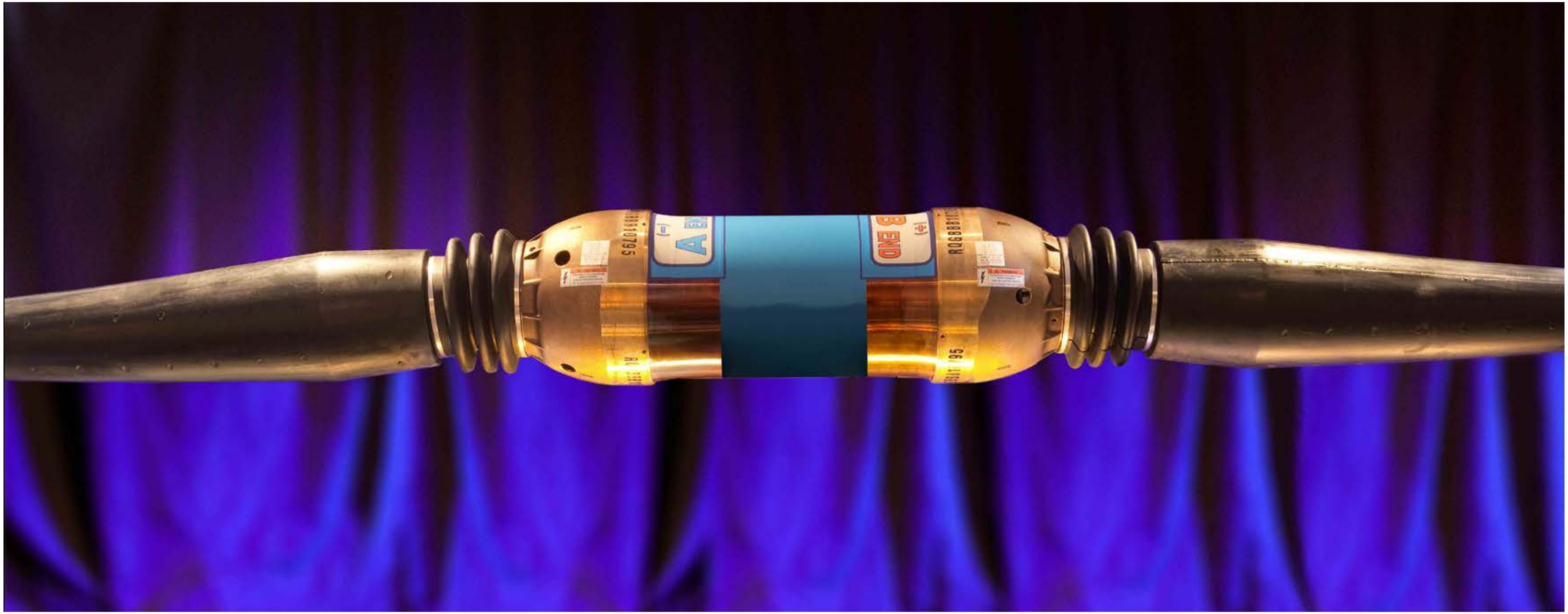
Cable Characteristics:

- **Fibers:** Benign environment for optical fibers
- **Strength:** For deployment and retrieval
- **Electrical:** Power for repeaters and network elements
- **Armoring:** Protection against external aggression

More on cable next by Marsha!

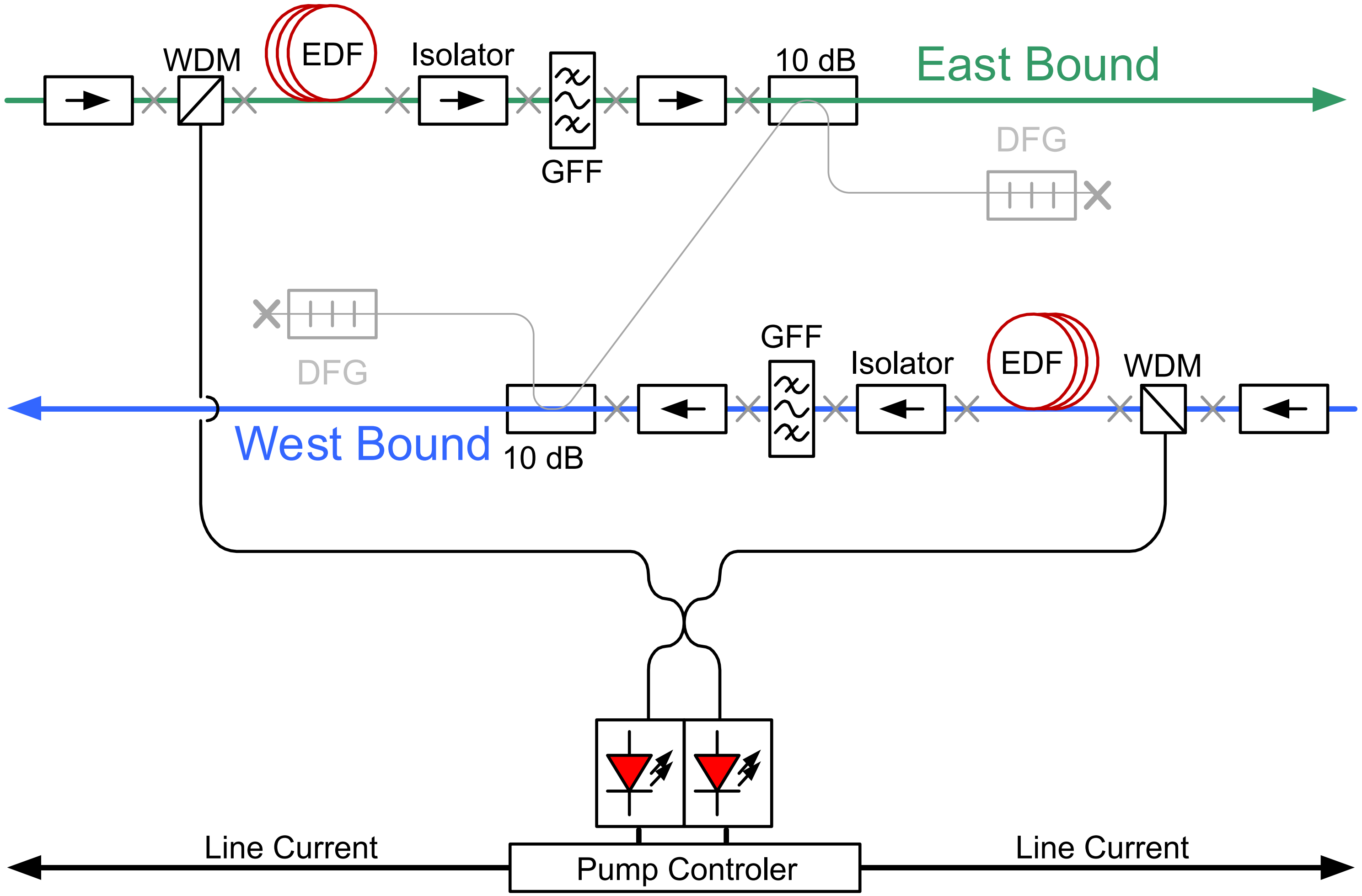


Repeater



The Repeater

- The modern repeater is an amplifier for the optical data signals on the fiber
- Amplification for fiber pairs
    - both directions of traffic: east and west bound
- High performance design for ultra-long distance transmission
    - Forward pumping for low noise figure
    - Single stage design
- 25 year design life
    - High reliability components
    - Higher order pump manifold
- COTDR path for fault localization



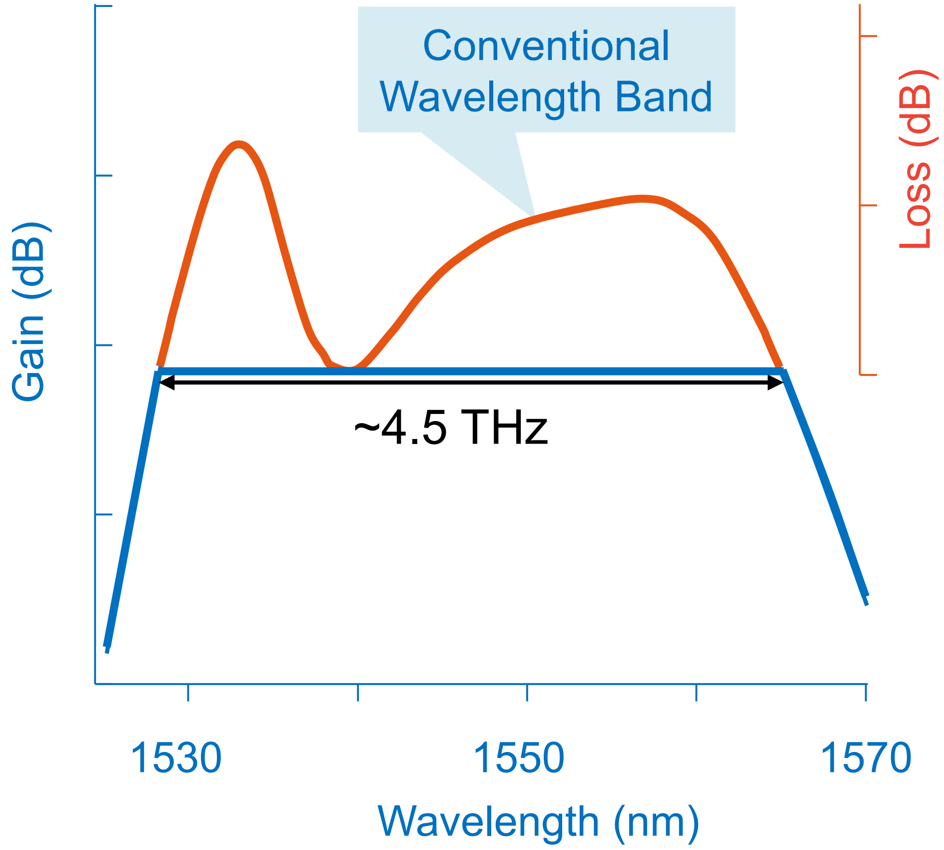
Amplification

Erbium Doped Fiber (EDF):

- Amplification around 1550 nm
- Bandwidth around 4.5 THz (1529 – 1565 nm)
- Optical pumping near 980 nm
- Significant gain variation across the amplification bandwidth (gain shape)

Gain Flattening:

- Gain flattening filter (GFF) to minimize gain variation across the amplification band
  - GFF is typically a Fiber Bragg Grating (FBG)
  - FBG reflection tuned to follow the EDF shape
  - Optical isolators suppress reflections and avoid lasing of the amplifier
- 0.1 dB gain variation leads to 10 dB across 100 repeaters (ignoring spectral-hole burning – more later)

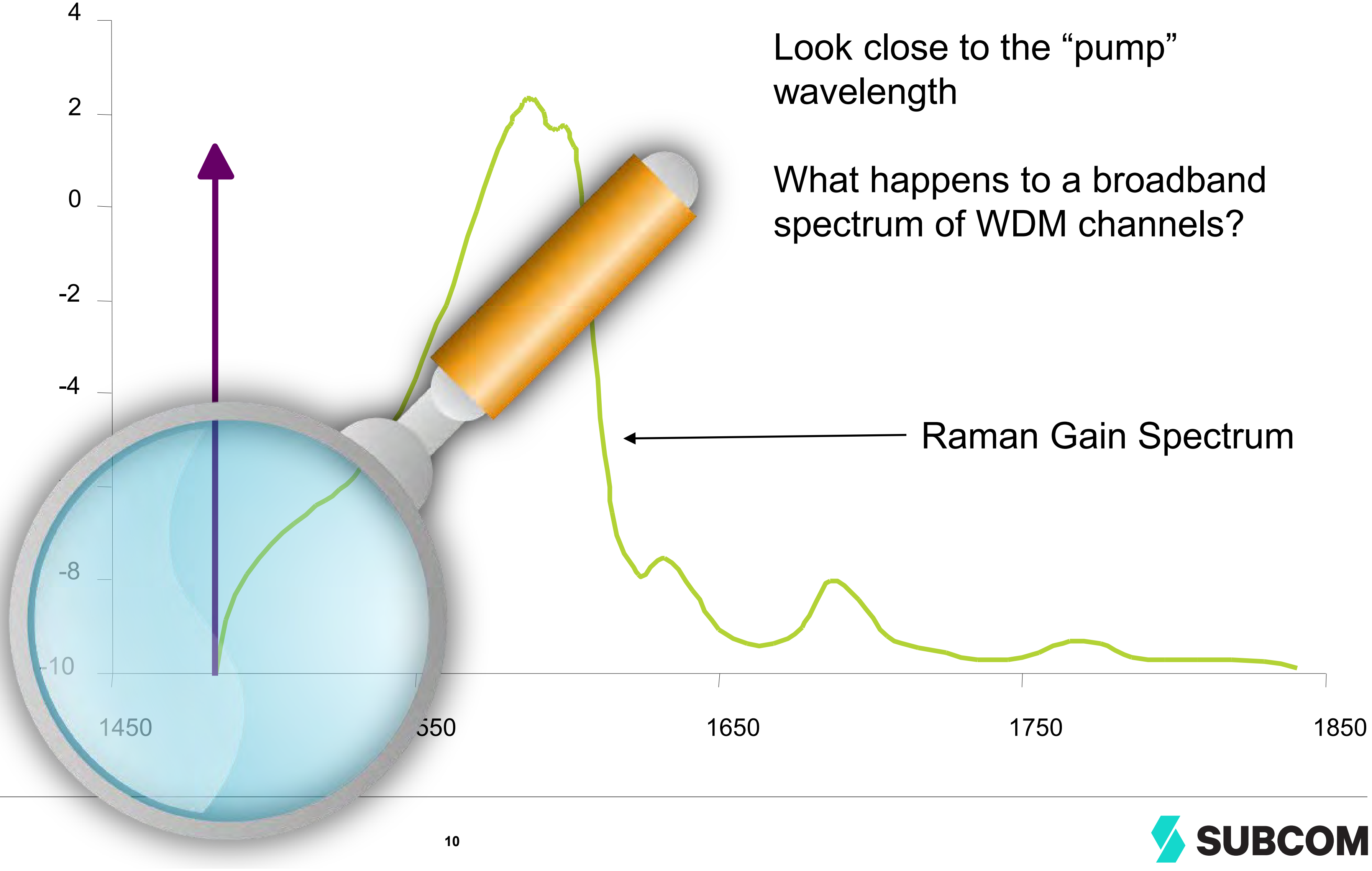


Gain Equalization

- EDF Shape
- Fiber Loss Shape
- Raman Gain
- Spectral-Hole Burning

Stimulated Raman Scattering

- Nonlinear scattering of light with optical phonons (lattice vibrations)
- A higher energy photon is scattered creating a phonon and lower energy photon

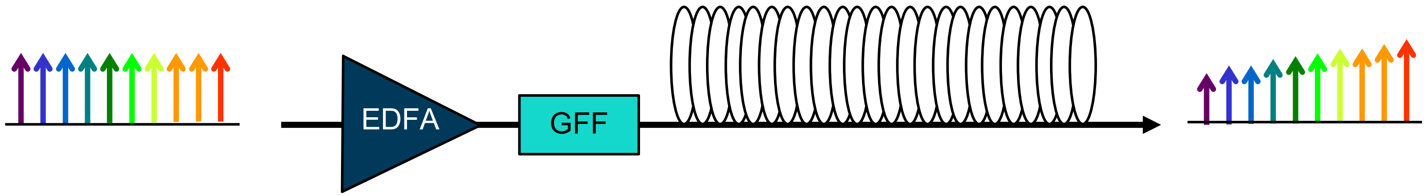


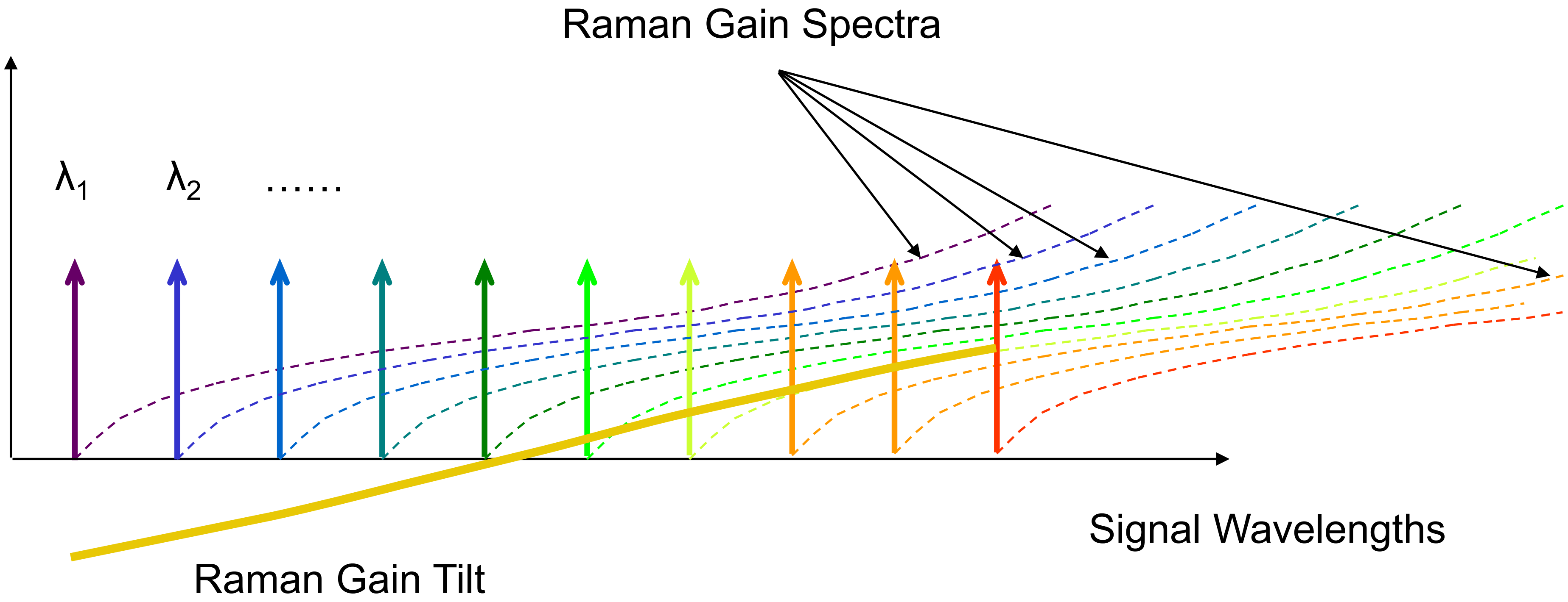
Raman Gain Spectrum

Look close to the “pump” wavelength

What happens to a broadband spectrum of WDM channels?

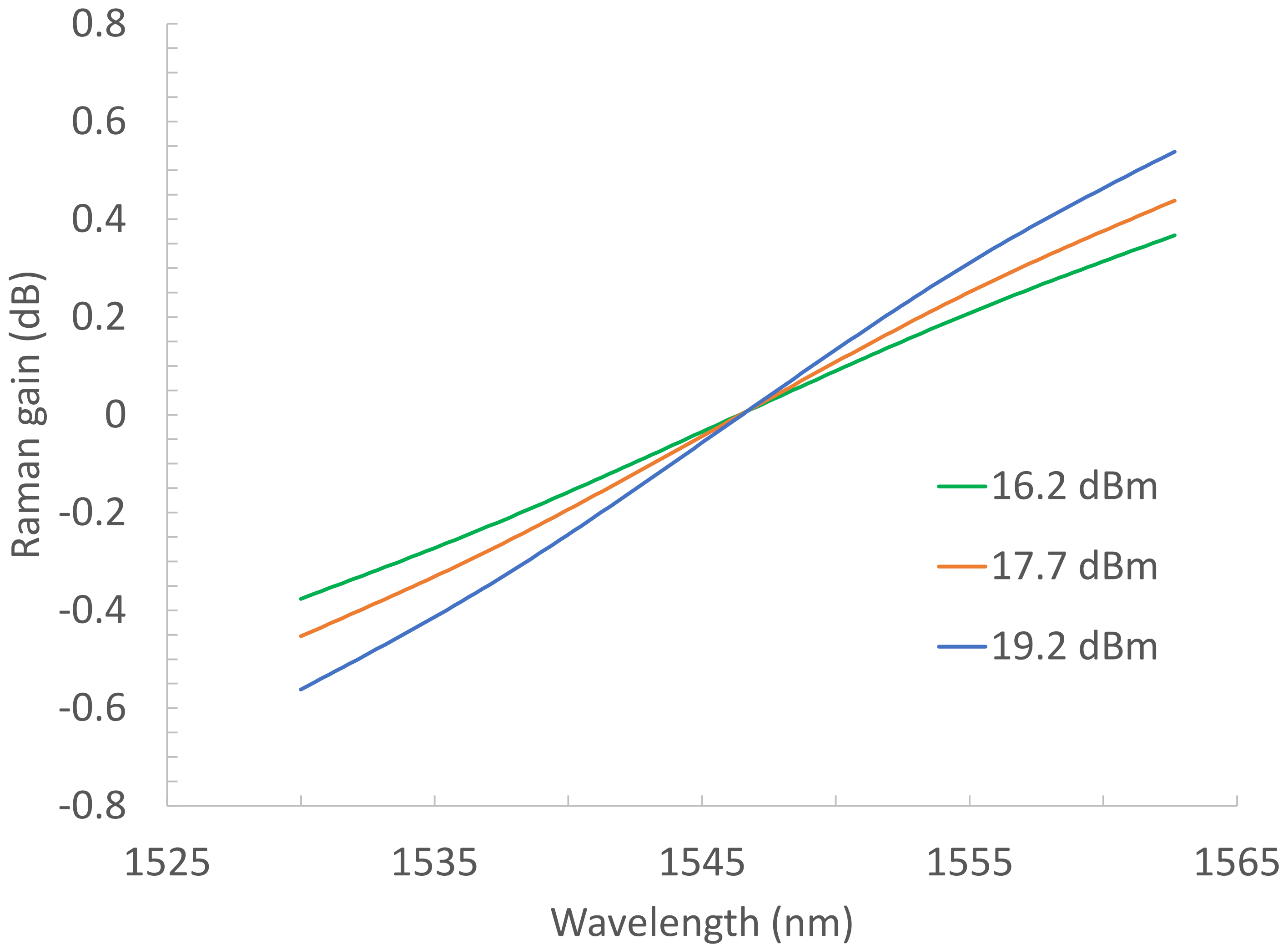
Intra-Band Raman Effect





Raman Gain Tilt

- Power transfer from short to long wavelengths
- Amount of power transfer depends on
    - Repeater power level (nonlinear)
    - Fiber (effective area)
    - Span length



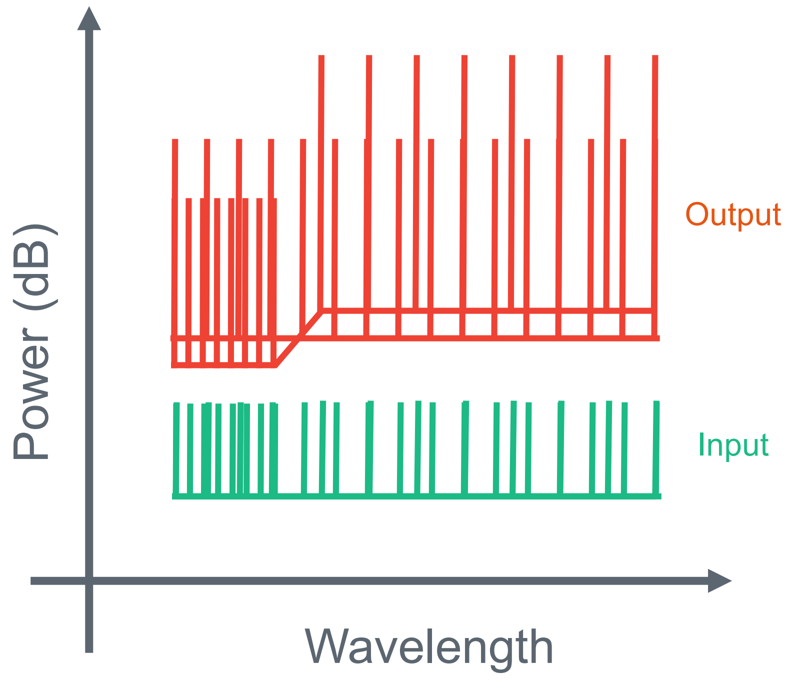
Gain Equalization

- EDF Shape
- Fiber Loss Shape
- Raman Gain
- Spectral-Hole Burning

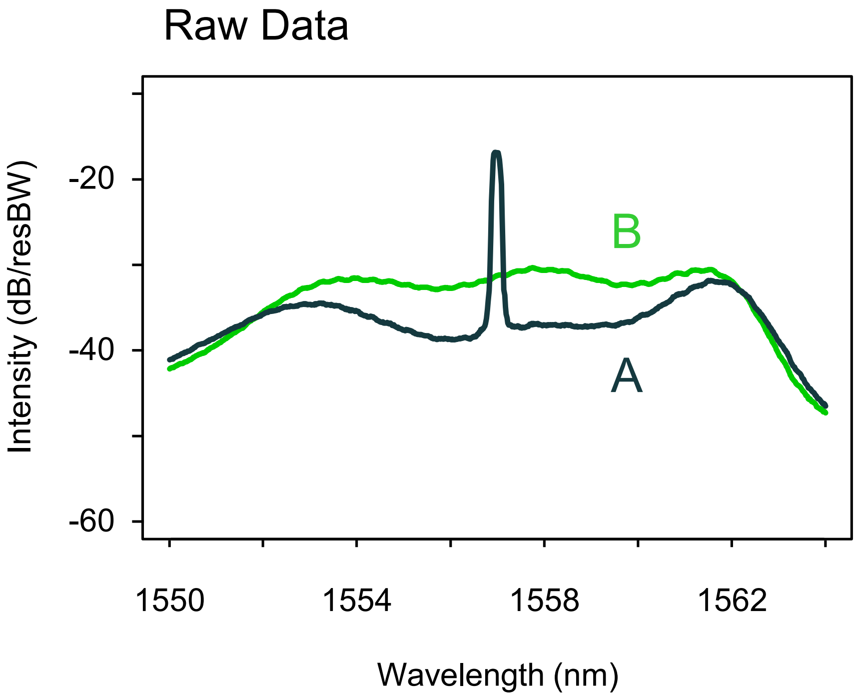
Spectral-Hole Burning

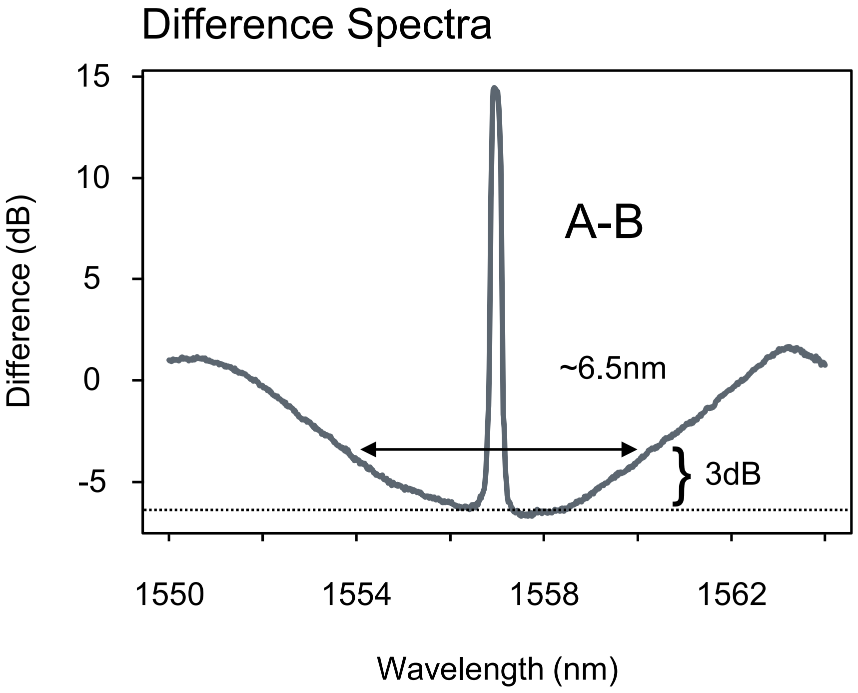
EDFAs tend to equalize power spectral density across the band

- Amplification depends on spectral loading of the EDFA
- Lower amplification where the power is high and higher amplification where the power is low
- Nonlinear effect
- Must be included when designing the gain management
- Tends to mitigate any residual gain error
- Tends limit effectiveness of pre-emphasis



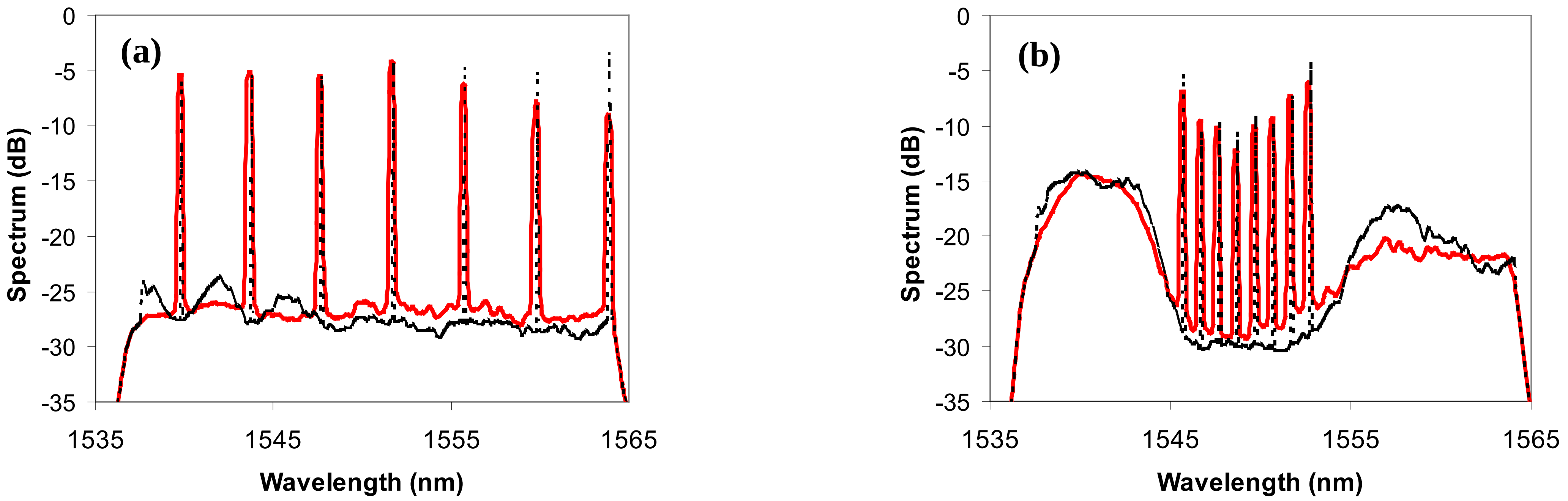
Spectral Hole-Burning in a 5,000km Amplifier Chain





Spectral Hole-Burning in WDM Systems*

Measured and simulated gain vs. wavelength using an installed 6,650km undersea cable system



* A. N. Pilipetskii et al., OFC’03

Gain Management in System Assembly

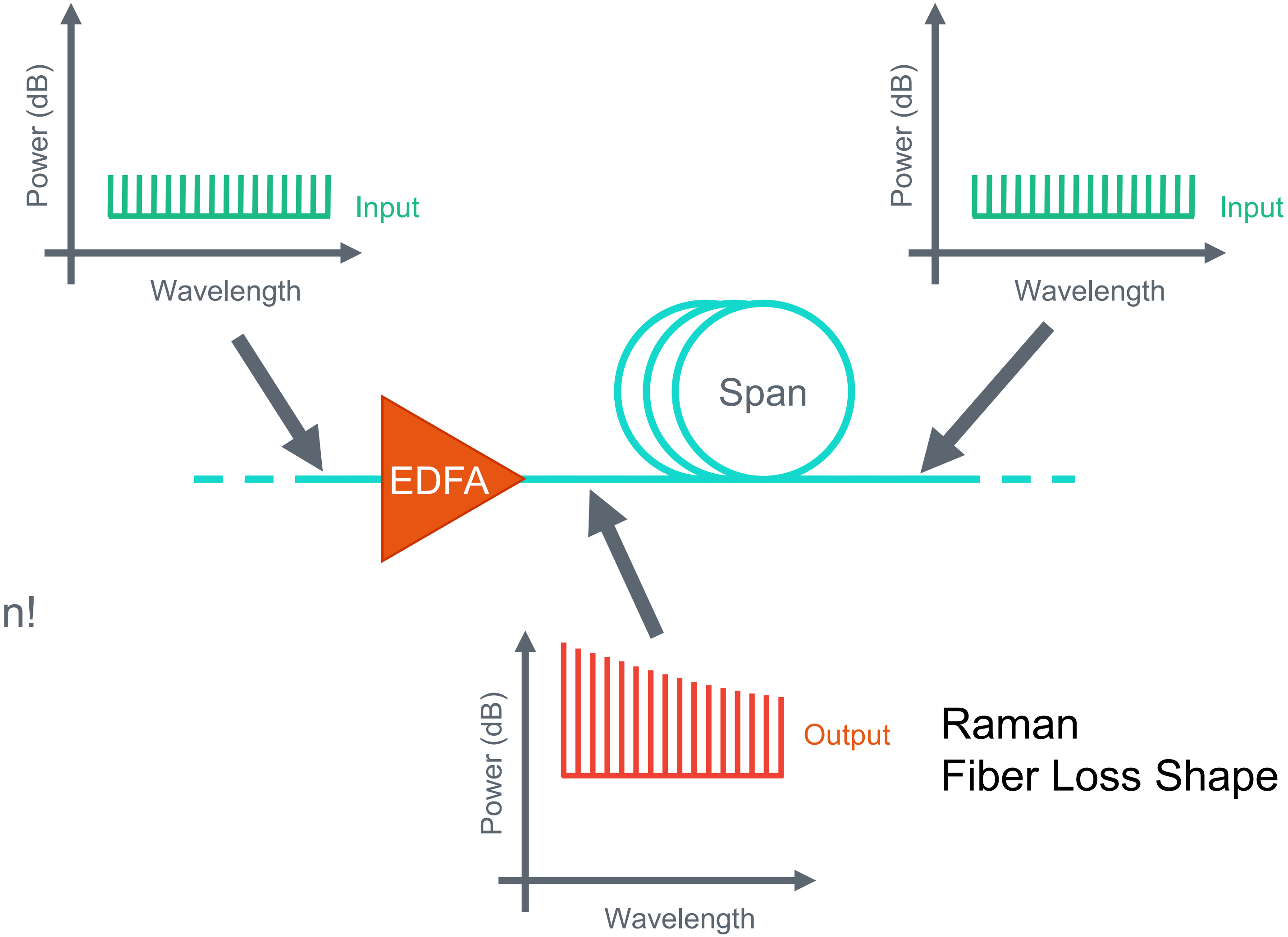
Repeater Design

Main Contributors to Gain Variation

- EDF shape
- Fiber loss shape (see Marsha)
    - Fiber loss minimum near 1565 nm
- Intra-band Raman effect
- Spectral-hole burning

Gain Equalization for amplifier/span combination!

- Precise characterization and custom gain flattening filter for each system design
- Results in nominal amplifier design



Raman
Fiber Loss Shape

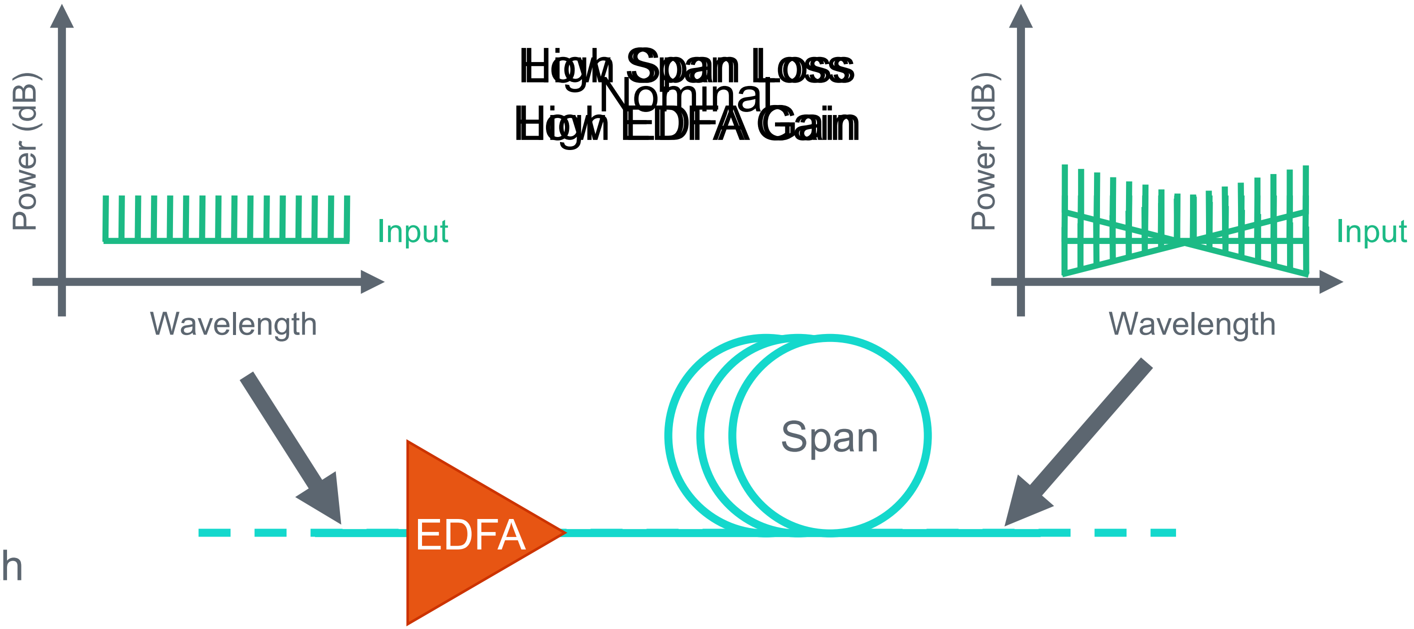
Gain and Loss

What happens with manufacturing variations?

- Span loss is higher/lower than nominal
- EDFA gain is higher/lower than nominal

Repeaters run is constant pump power mode

- Output power set by pump power
- Nominal gain set by EDF length
  - Average inversion determines optical bandwidth

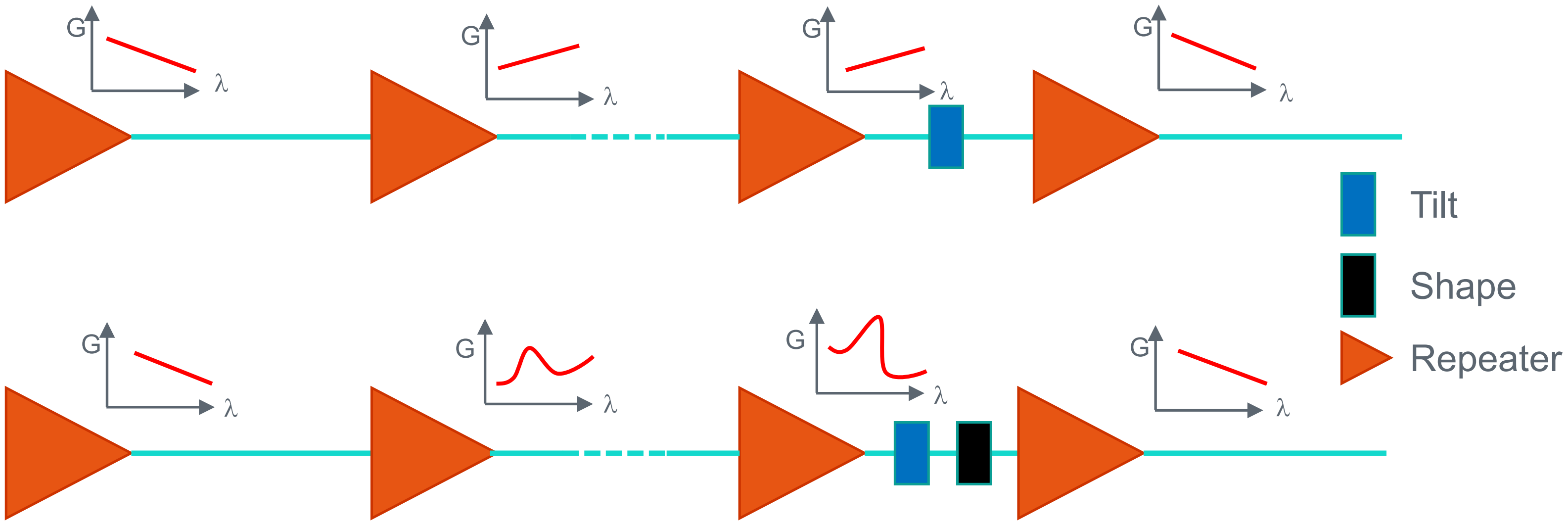


Spectral Tilt

- Deviation from nominal gain and/or loss leads to a spectral tilt (first order, also some shape)

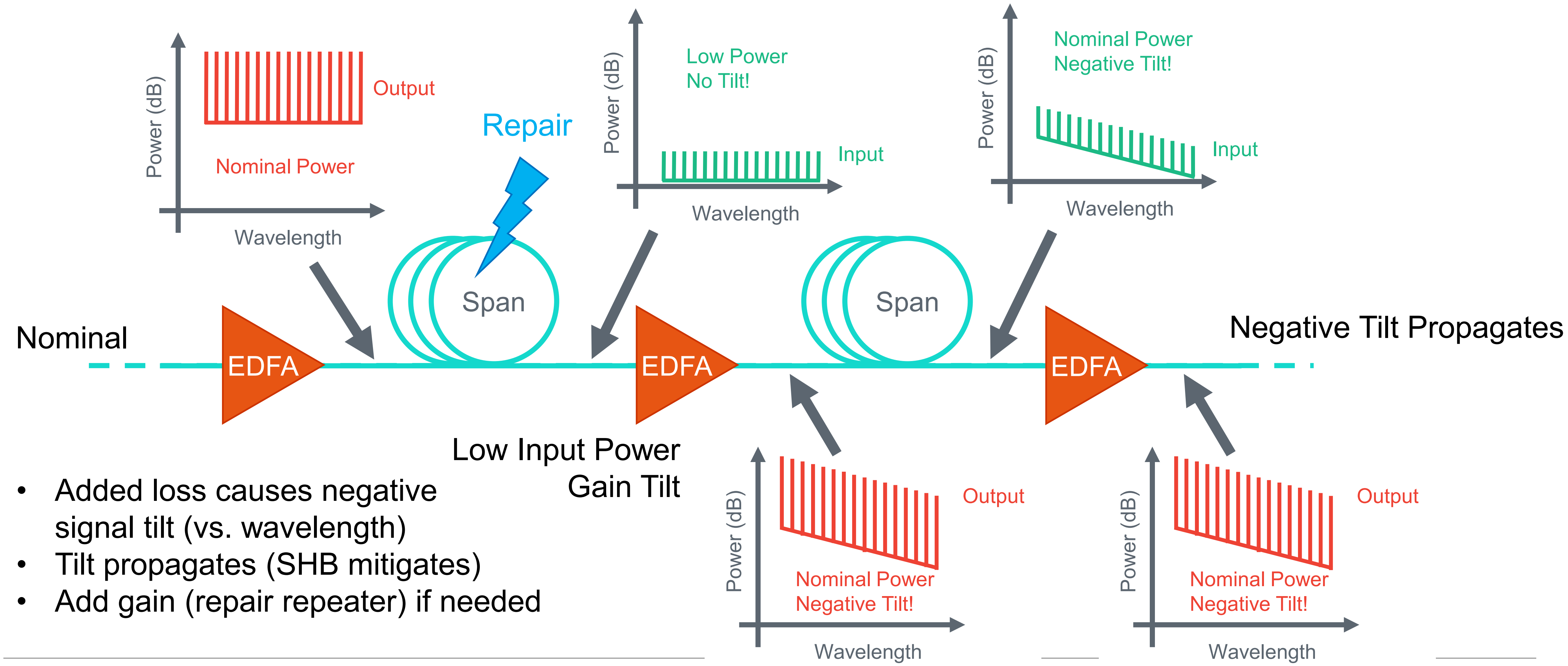
Gain Management

1. Gain equalization per amplifier/span combination
   - Gain flattening filter (GFF) – Typically a Fiber Bragg Grating
2. Gain tilt equalization
   - Adjustable (during system assembly) loss point (Loss Build Out – LBO) every several spans
3. Second order gain shape correction to address systematic GFF shape error
   - Shape Correction Unit (custom gain equalization filter)



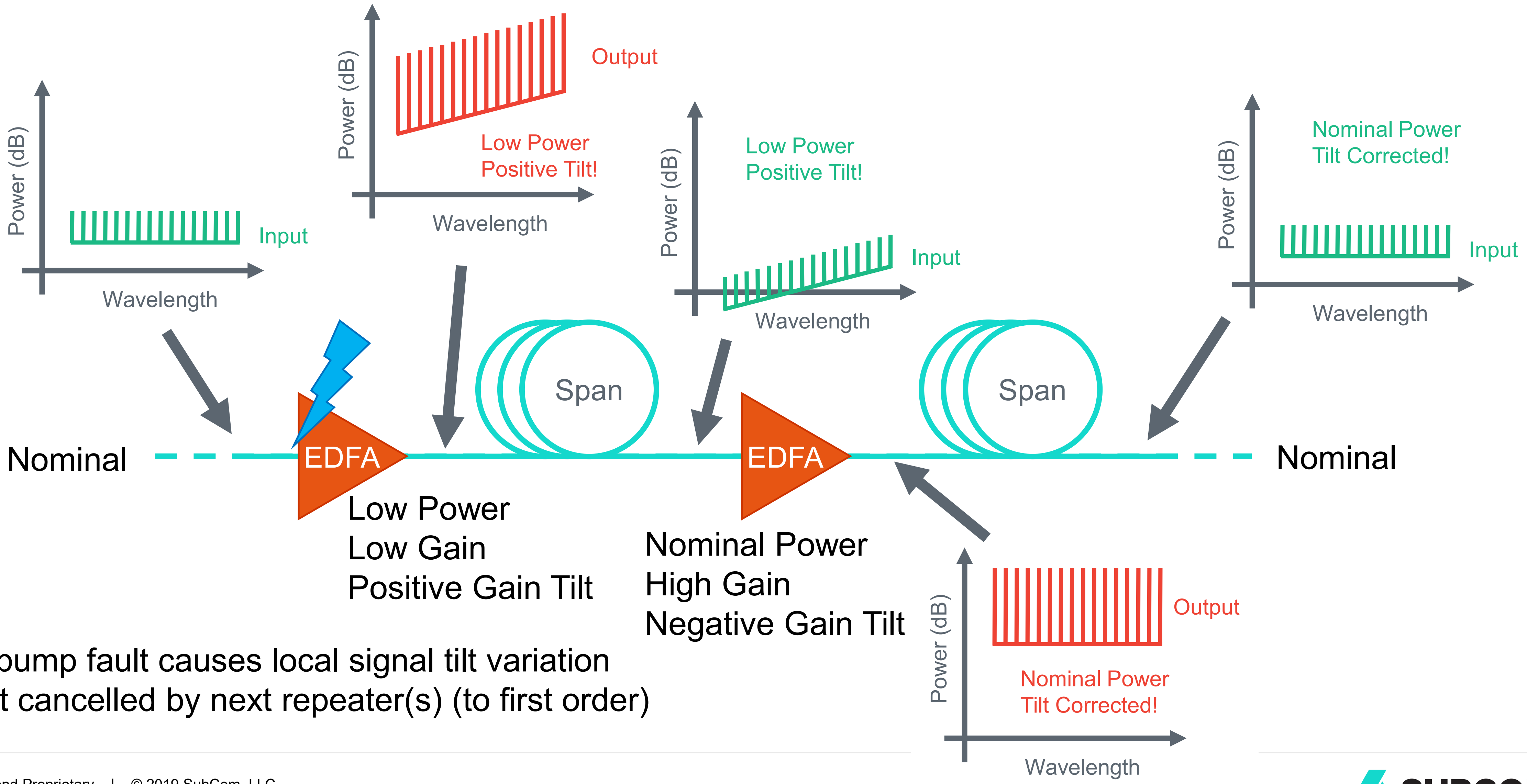
Gain Management During System Life

Loss Fault



- Added loss causes negative signal tilt (vs. wavelength)
- Tilt propagates (SHB mitigates)
- Add gain (repair repeater) if needed

Pump Fault in a Chain of Repeaters

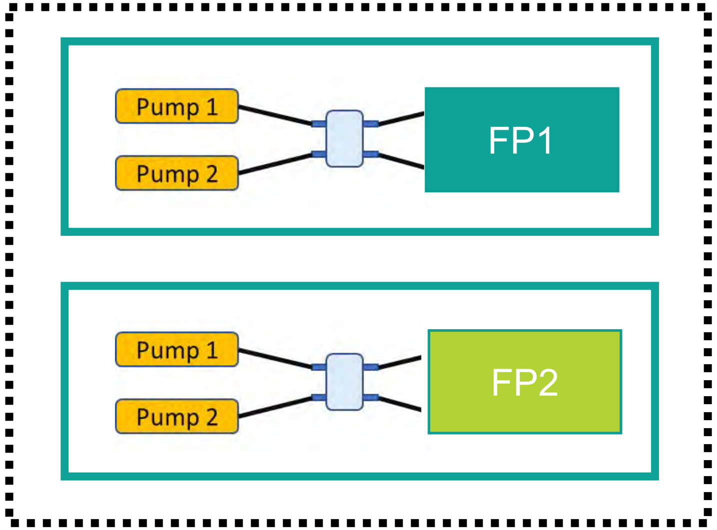


- A pump fault causes local signal tilt variation
- Tilt cancelled by next repeater(s) (to first order)

Repeater Pump Manifold

Pump Sharing: Higher Reliability

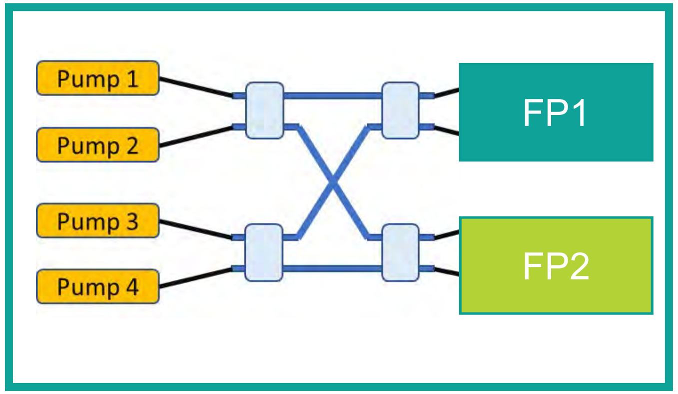
2 FPs = 2 Sets of “2 pumping 2 Fibers”:



Traditional:

“Fiber Pair Independence”
(One pump-pair per FP)
(2.6 FIT per FPs)

2FP = 1 set of “4 pumping 4 Fibers”:



New “Pump Sharing / Farming”

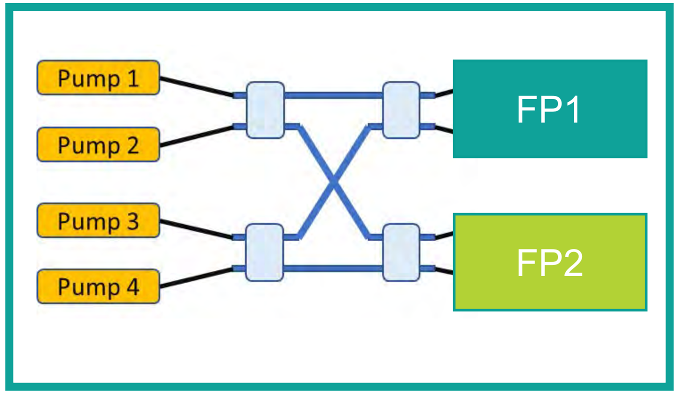
(Power shared over 2 FPs)
(0.001 FIT per FP)

Higher Reliability

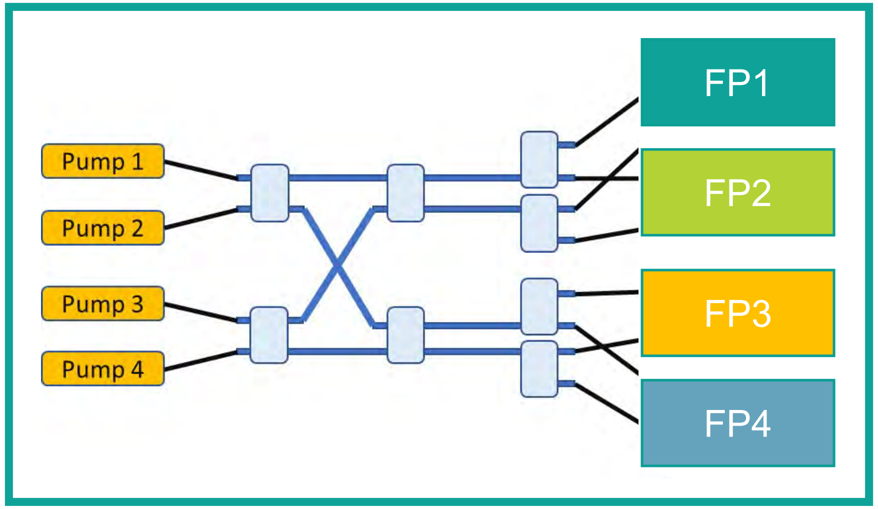
Pump Sharing: SDM / More Fiber Pairs

Pump Lasers are combined and shared in sets of four

“4 pumping 4 Fibers”



“4 pumping 8 Fibers”:



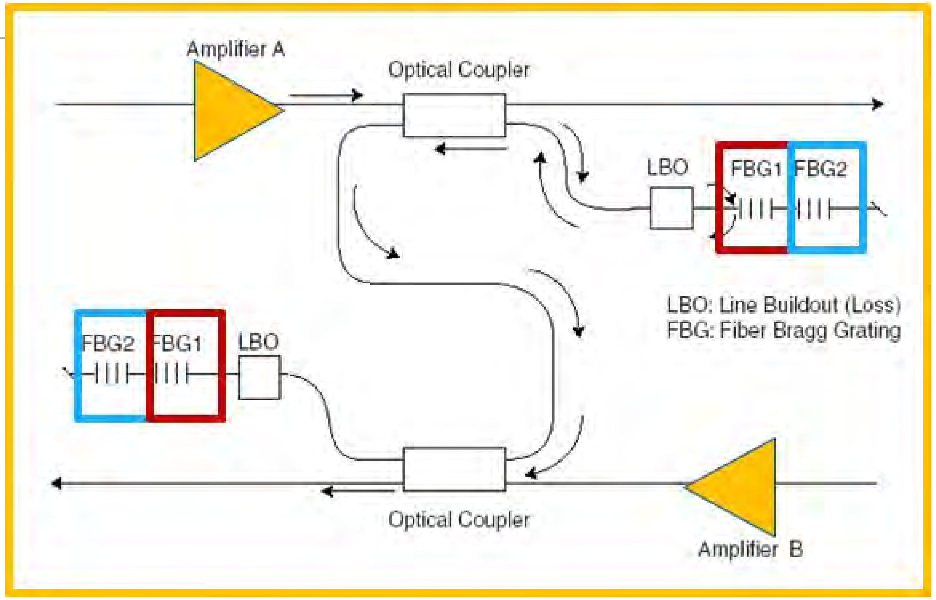
Support for twice as many FPs, with higher reliability

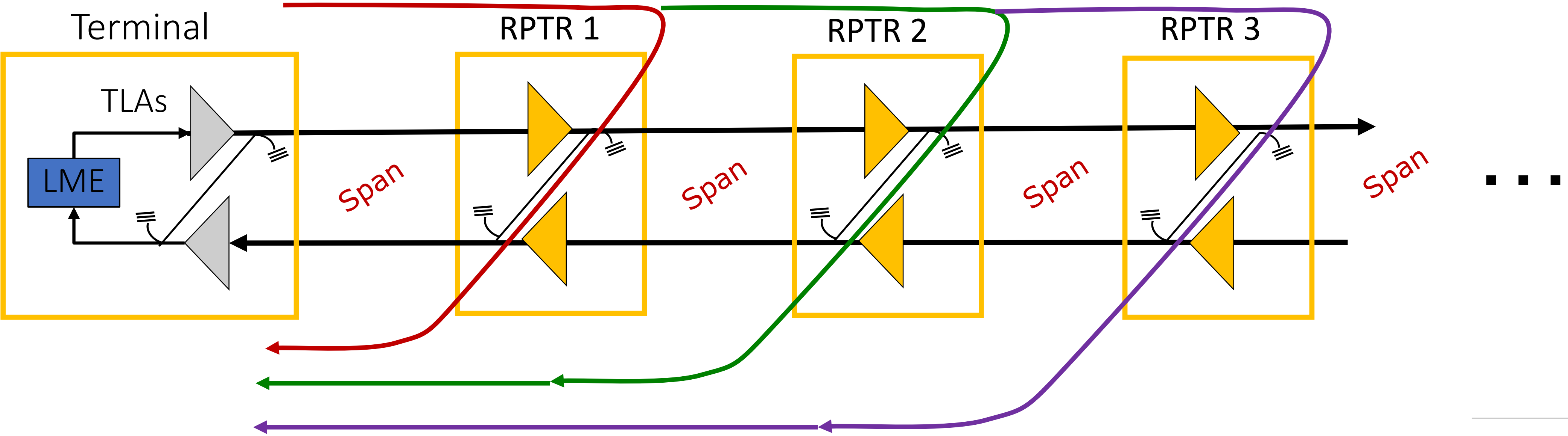
Line Monitoring System

Line Monitoring System

- Provides Undersea Monitoring and Fault Detection
- All optical principle, no active components in the repeaters
- Two operating modes: HLLB mode and COTDR mode

High-Loss Loopback Circuit
For one Amp-Pair





In-Service Line Monitoring

Line Monitoring System Signals

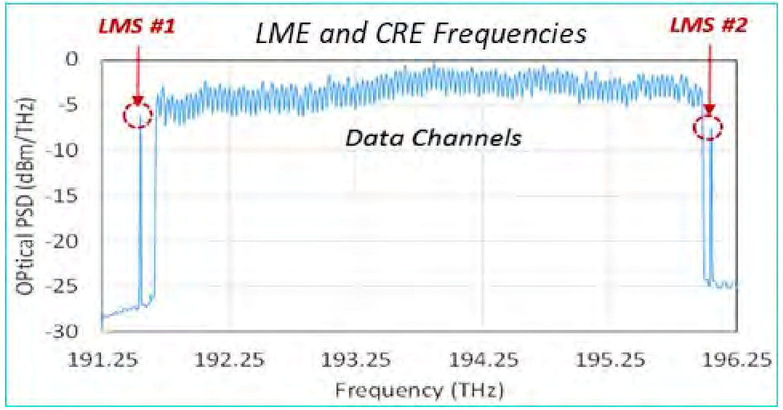
- LMS tones on the short and long wavelength side of the data transmission band

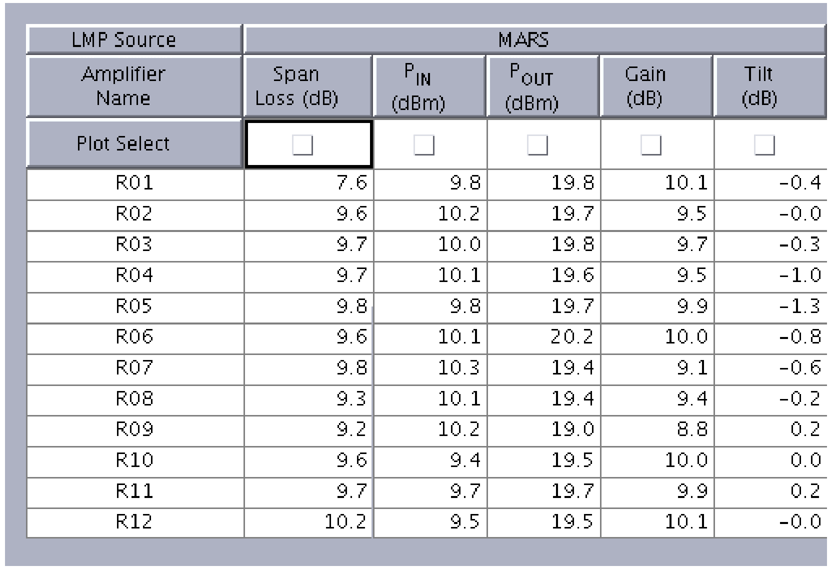
Automated Signal Interpretation

- Automatic Signature Analysis detects changes in loop gain and extracts span loss and repeater output powers.
- Reported parameters include span length, span loss, repeater input and output power levels, and tilt

Active Line Monitoring Systems are also in use

- Input and output power levels detected with photodiodes and reported to shore via command channel





LMP Source	MARS				
Amplifier Name	Span Loss (dB)	P_{IN} (dBm)	P_{OUT} (dBm)	Gain (dB)	Tilt (dB)
Plot Select	☐	☐	☐	☐	☐
R01	7.6	9.8	19.8	10.1	-0.4
R02	9.6	10.2	19.7	9.5	-0.0
R03	9.7	10.0	19.8	9.7	-0.3
R04	9.7	10.1	19.6	9.5	-1.0
R05	9.8	9.8	19.7	9.9	-1.3
R06	9.6	10.1	20.2	10.0	-0.8
R07	9.8	10.3	19.4	9.1	-0.6
R08	9.3	10.1	19.4	9.4	-0.2
R09	9.2	10.2	19.0	8.8	0.2
R10	9.6	9.4	19.5	10.0	0.0
R11	9.7	9.7	19.7	9.9	0.2
R12	10.2	9.5	19.5	10.1	-0.0

Example RPT for One Traffic Direction

Out-of-Service COTDR Measurements

Rayleigh Scattering

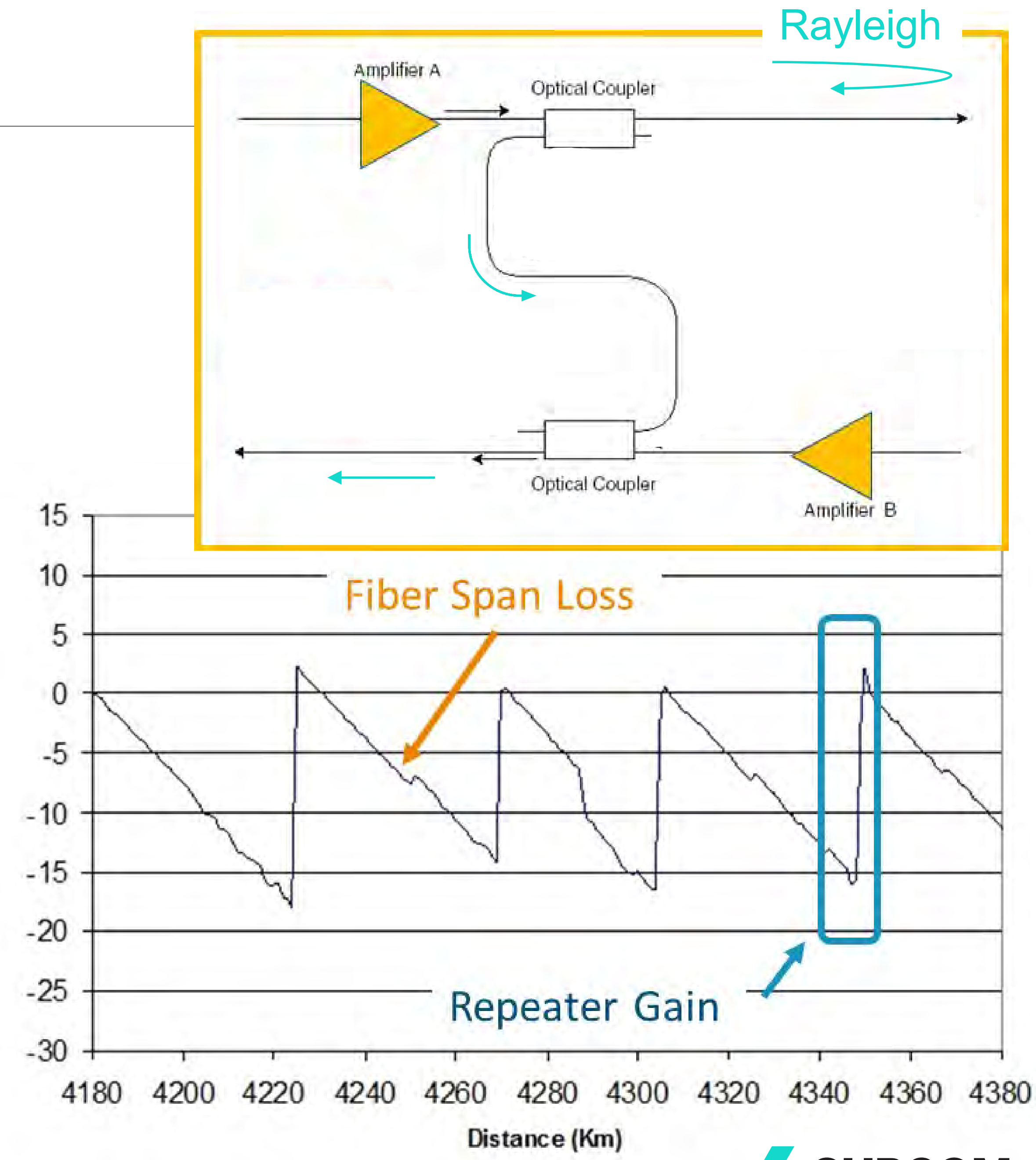
- Fiber reflects optical power back towards the transmitter (< -30 dB)

Optical Time Domain Reflectometry (OTDR)

- Send pulse, look for reflected signal

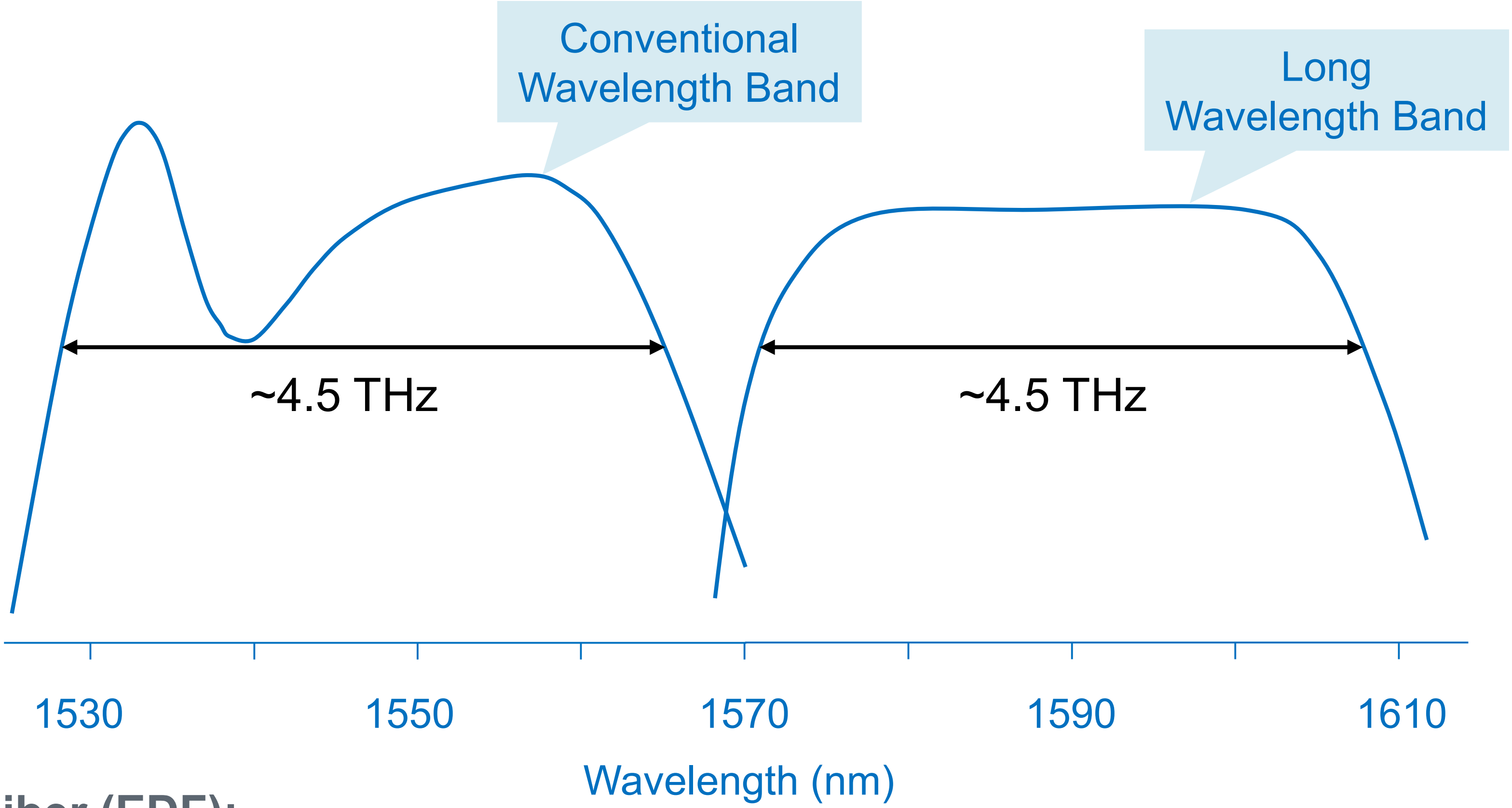
Coherent (Correlation) OTDR (COTDR)

- Send pulse (pattern) on outbound path, look for reflection on inbound path through High-Loss Loopback
- Works over multiple spans for >10,000 km
- **Locate faults with <1km accuracy**



C+L

C+L: Doubling Fiber Pair Bandwidth

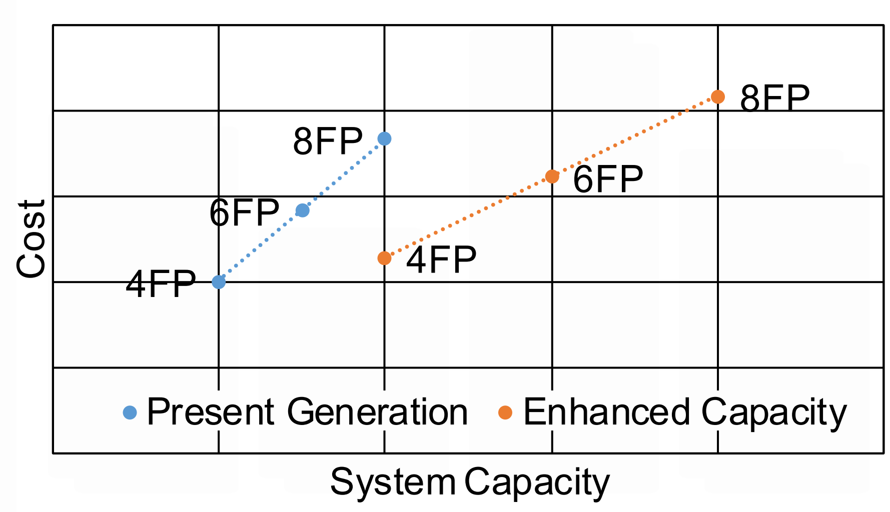


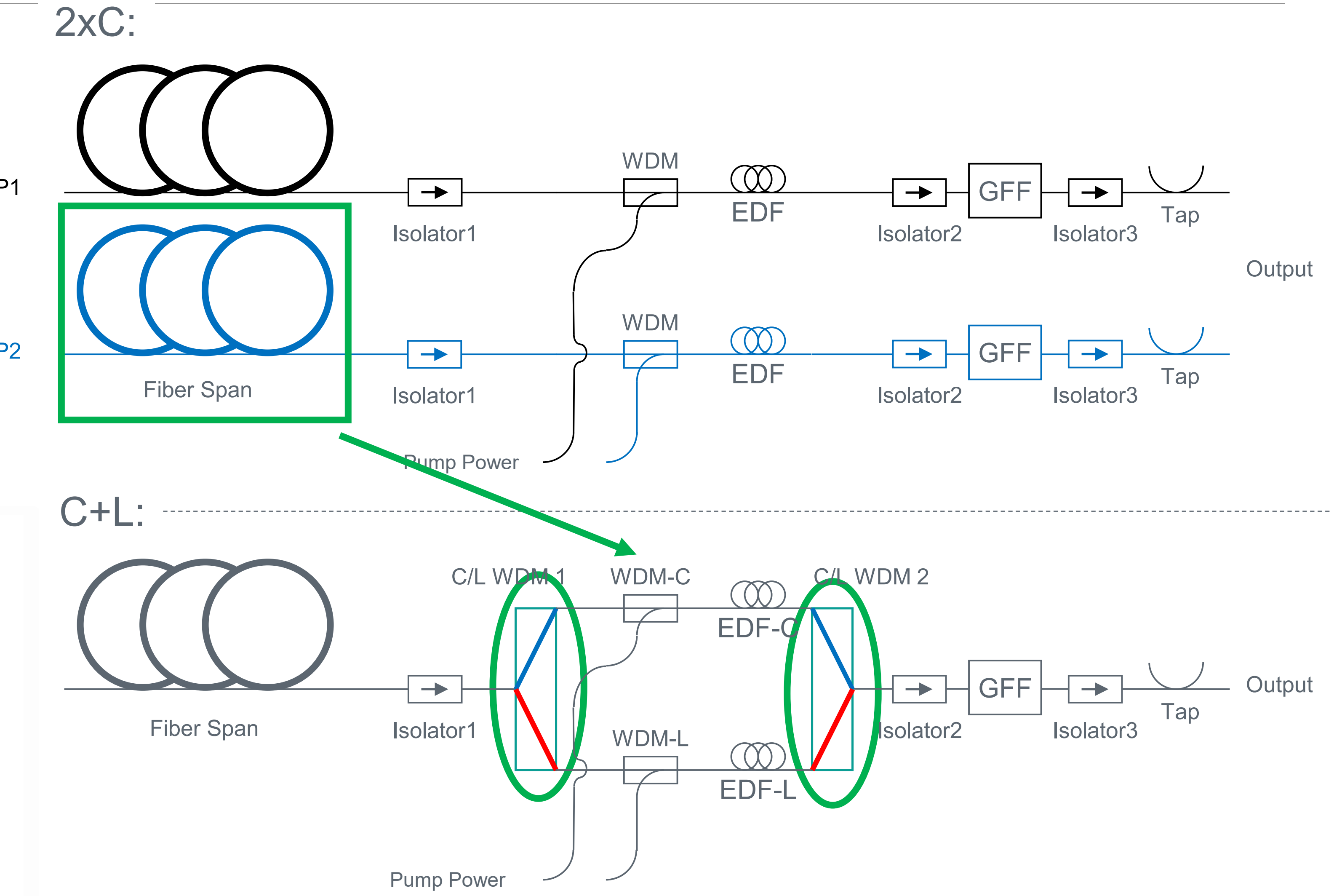
Erbium Doped Fiber (EDF):

- Amplification in the C-band (1529 – 1565 nm)
- Amplification in the L-band (1570 – 1608 nm) (if no light in C-band)

C+L Architecture

- Nearly double the capacity per fiber pair
- Enables compact cable designs with fewer fiber pairs for the same capacity





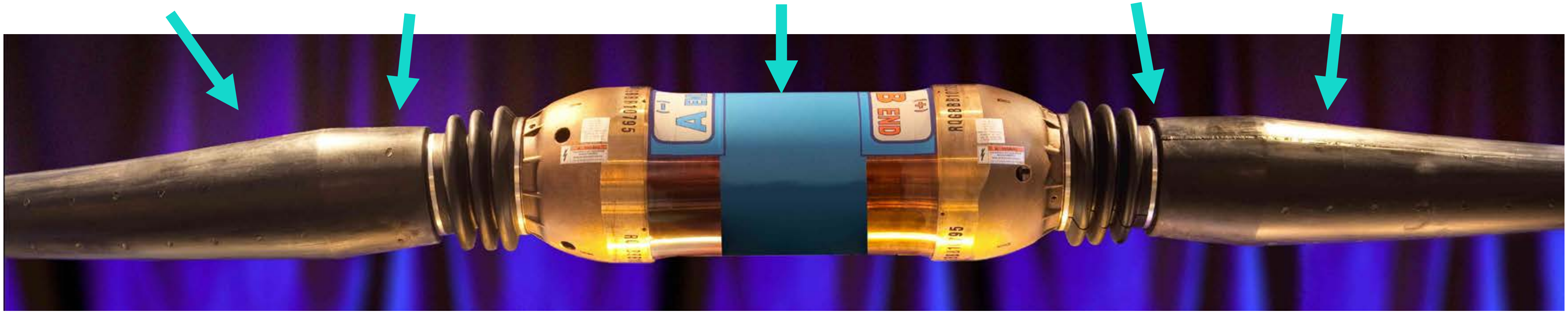
Repeater Mechanical

Pressure Vessel

- Cylindrical shape
- Material: BeCu

  (also Stainless Steel or Titanium)
- Good to 8000m

Feature	Nominal Value
Overall Length	498 cm (196 in.) w bend limiting boots
Diameter (largest)	33 cm (13 in)
Design Depth/Pressure	8000 m (~ 12000psi)
Approximate Weight Body with cones	225 kg (493 lb)



Cable Bend Limiter

Coupling

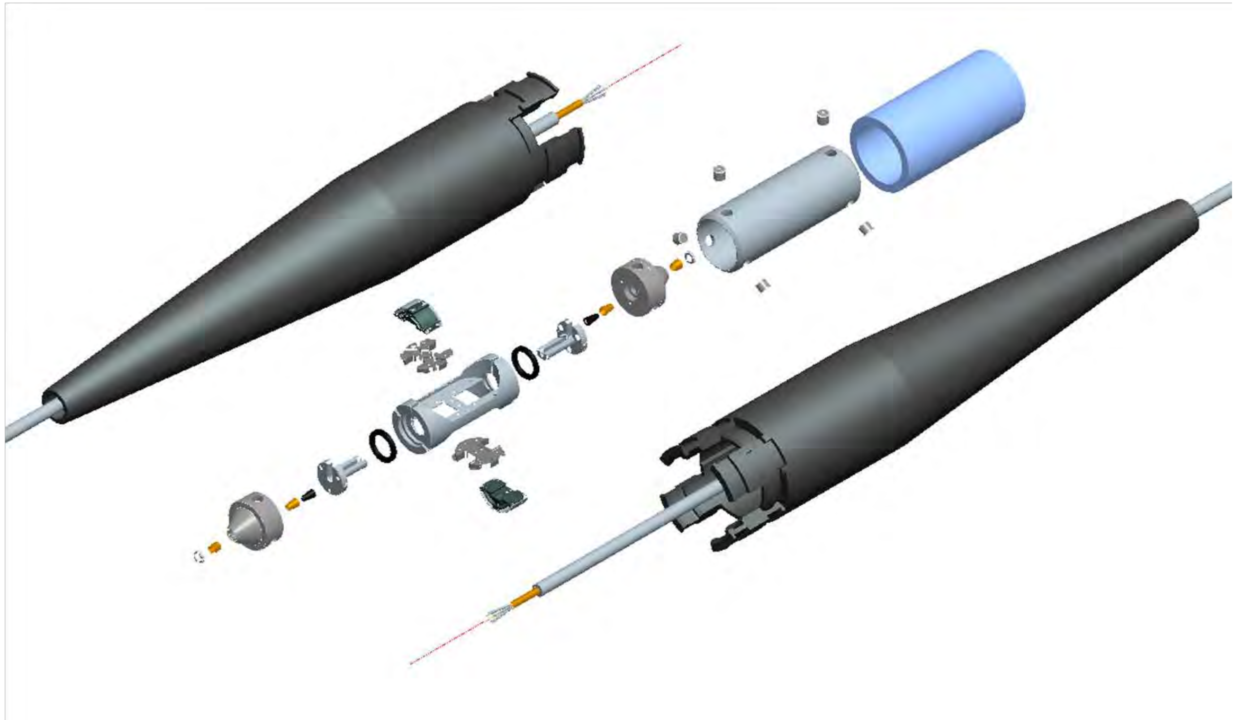
Pressure Vessel

Coupling

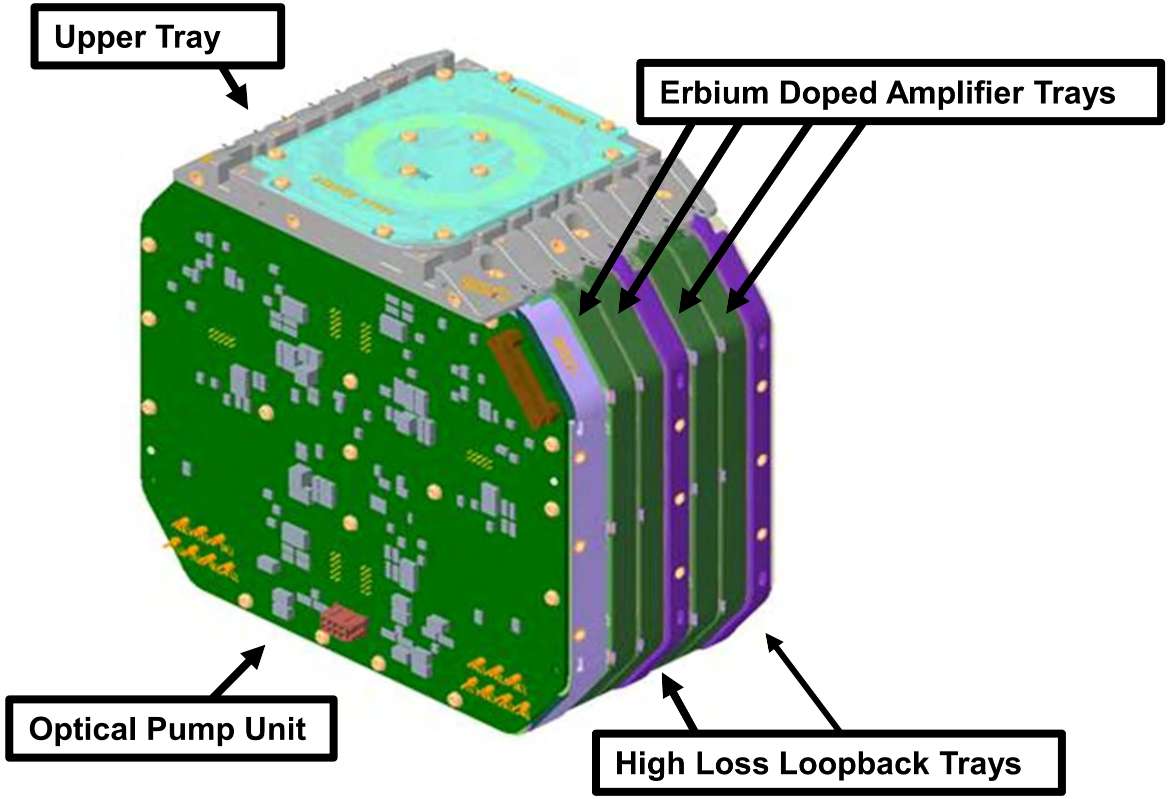
Cable Bend Limiter

Cable to Repeater Coupling

Millennia Joint



Repeater Mechanical Design – 16 FP Repeater

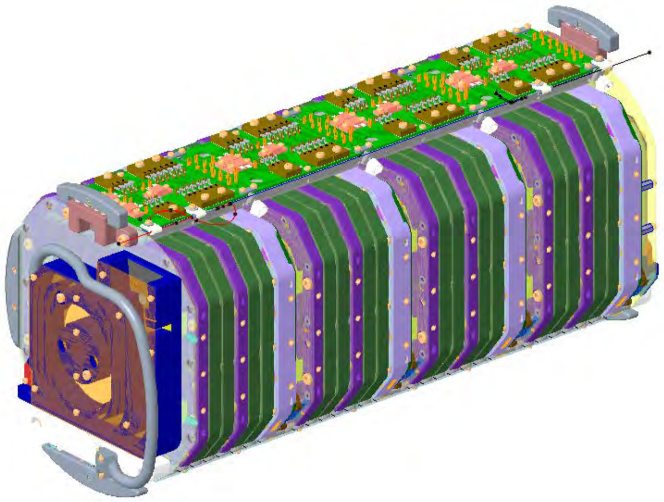

Upper Tray

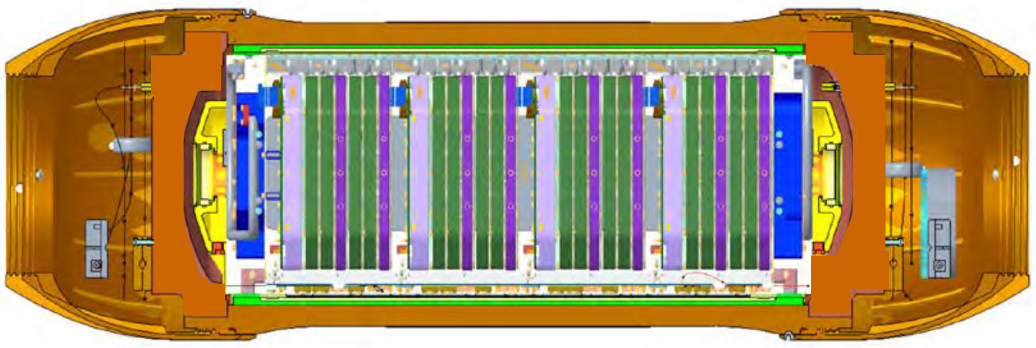
Erbium Doped Amplifier Trays

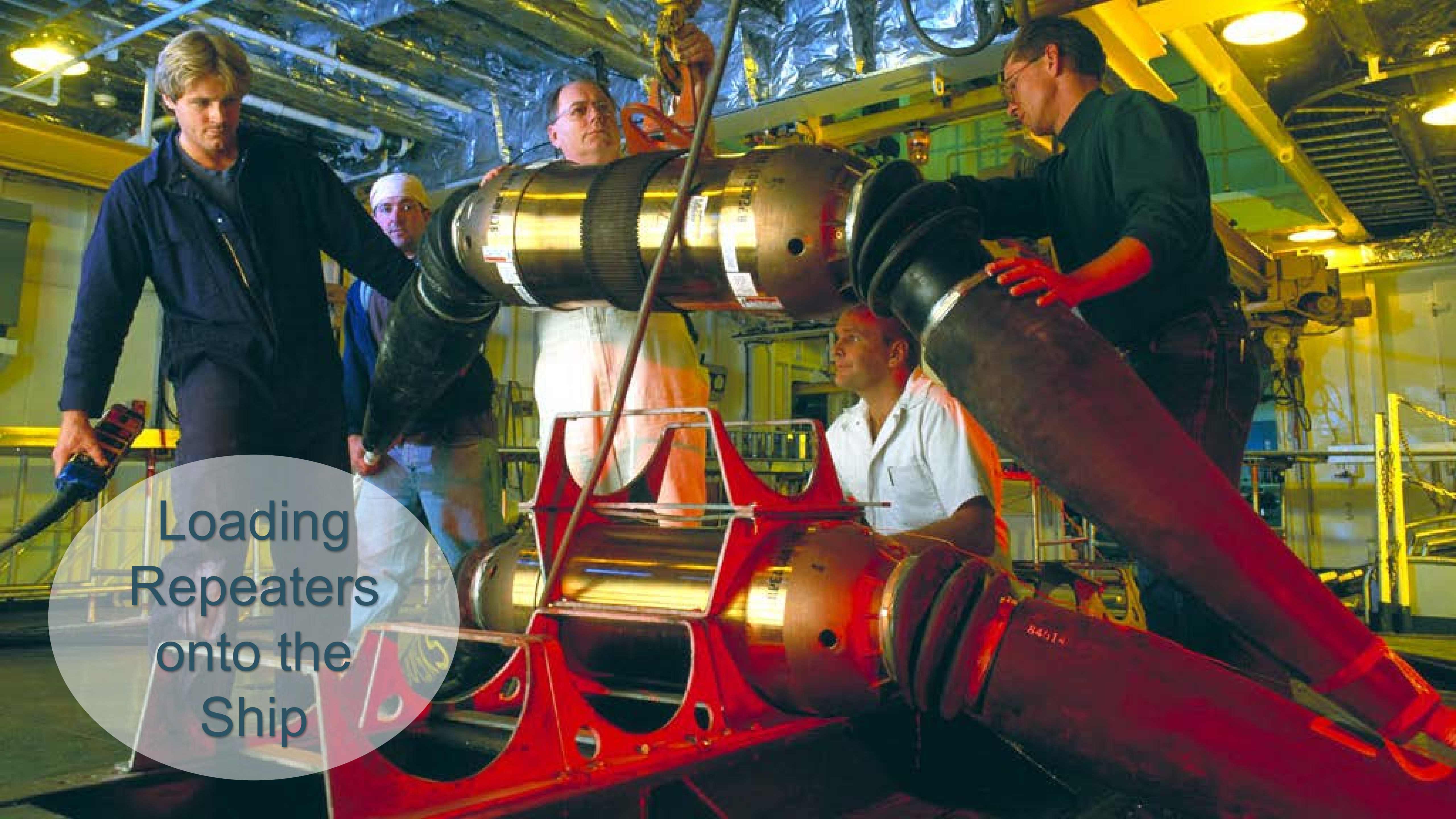
Optical Pump Unit

High Loss Loopback Trays

Dual Amplifier Quad Supports 4 Fiber Pairs


Up to Four Dual Amp Quads in a Network

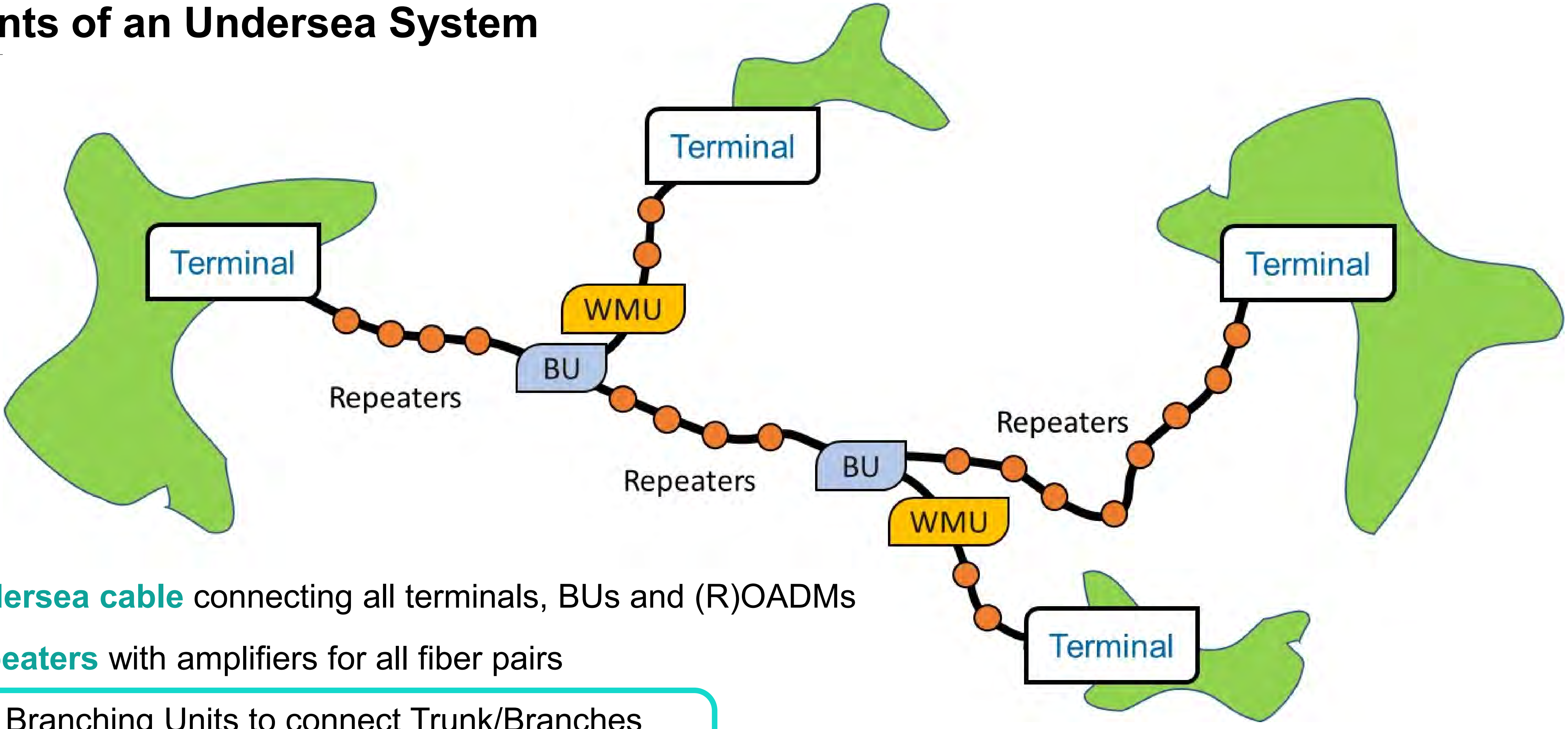

16 FP Repeater Network in Type 300 Repeater Housing



Loading Repeaters onto the Ship

Repeaters on Board Ship Ready for Deployment

Elements of an Undersea System



- **Undersea cable** connecting all terminals, BUs and (R)OADMs
- **Repeaters** with amplifiers for all fiber pairs
- **BU**: Branching Units to connect Trunk/Branches
- **WMU: **Wavelength Management Units – (R)OADM

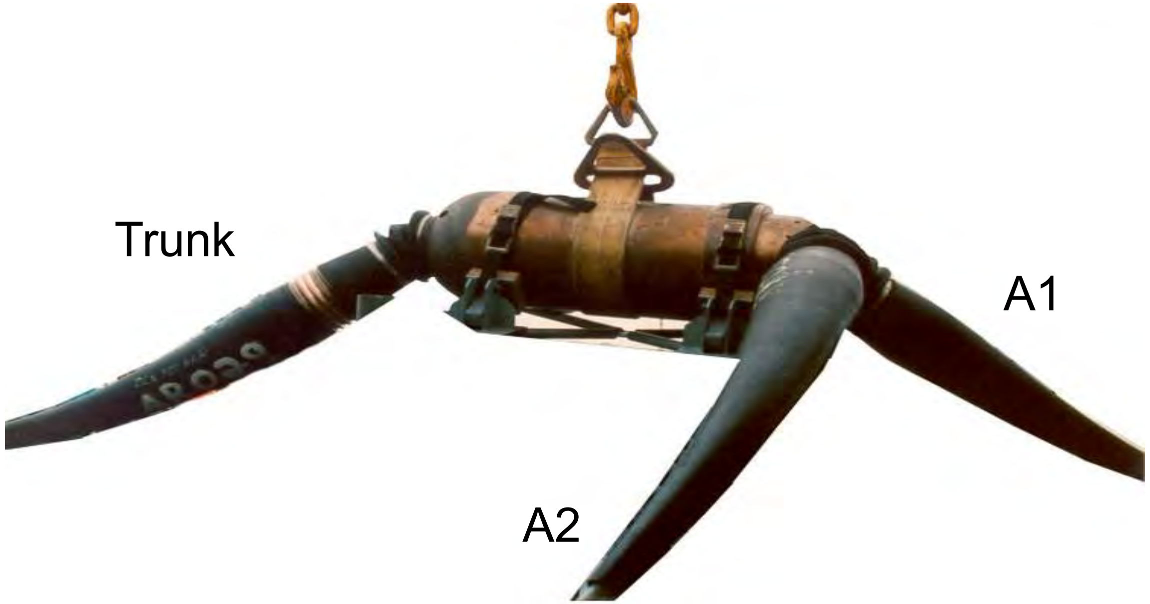
Branching Units

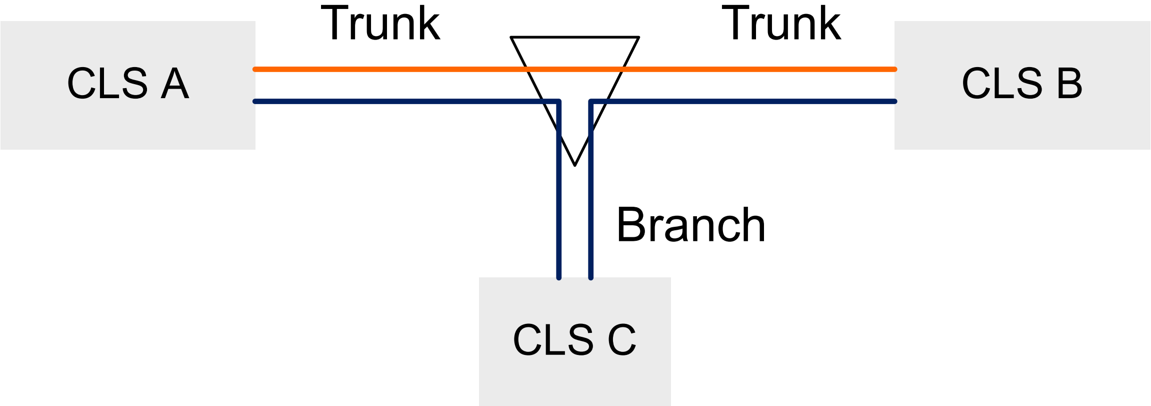
Branching Unit – Fiber Routing

The branching unit (BU) enables connections other than simple point to point

The Branching Unit

- A 3-port device: Trunk, A1 and A2
- Enables the creation of a branch of the main trunk
- Provides fiber routing and optical connectivity between 3 points
- Enables later network expansion



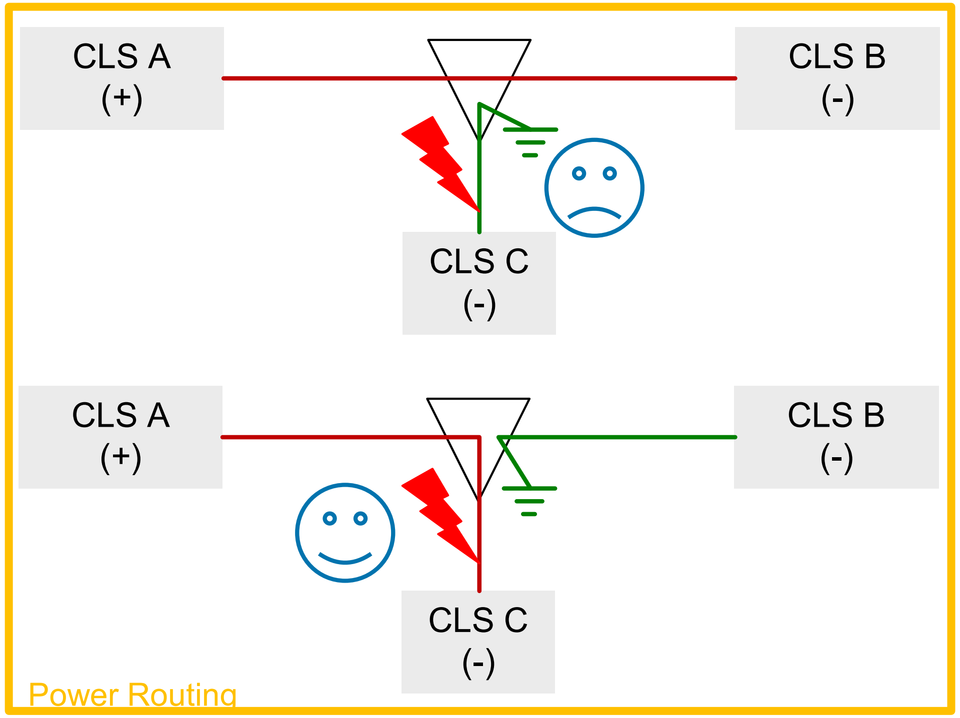

Trunk
Trunk
CLS A
CLS B
Branch
CLS C

Power Switched Branching Unit

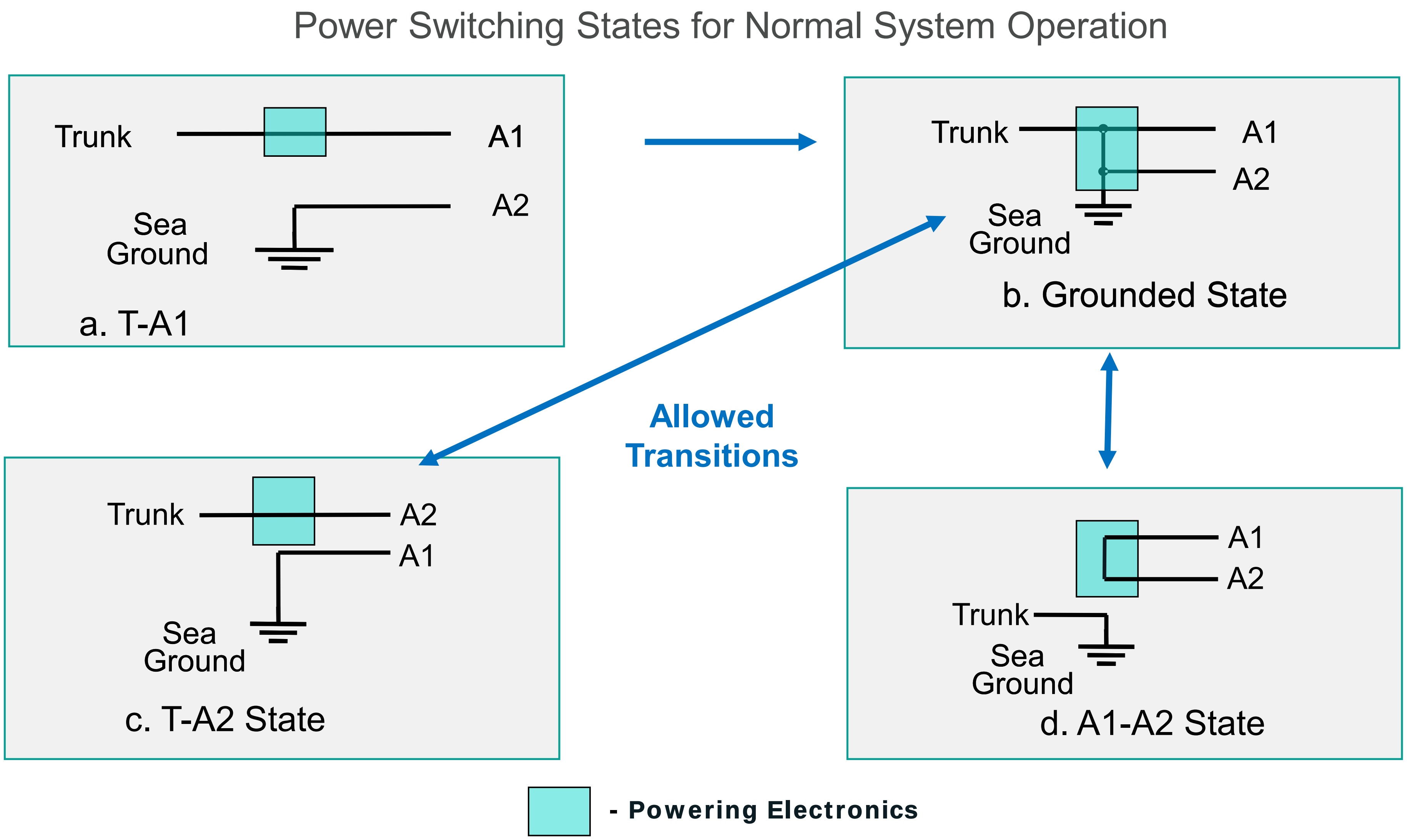
The branching unit can also contain remote controlled high voltage relays to enable switching of the power path

Cable Fault Recovery and Isolation:

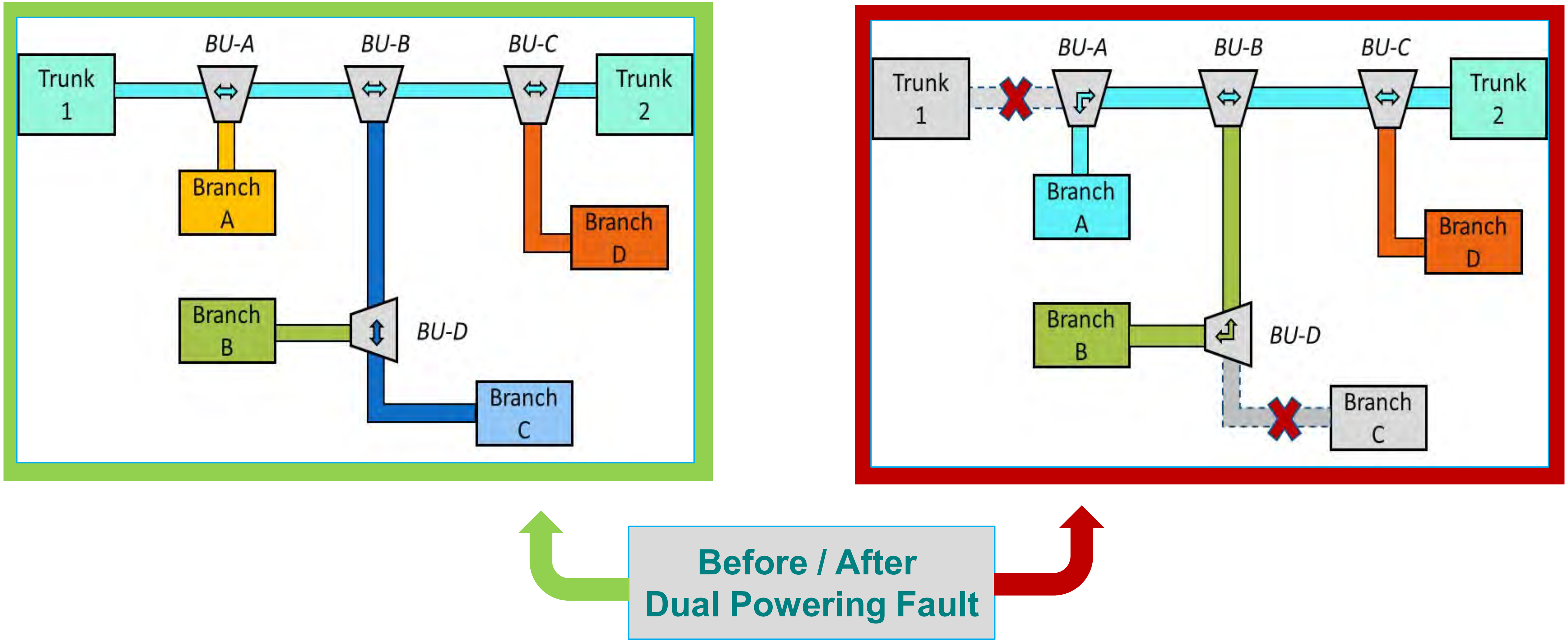
- Recover from shunt faults (see also lectures by Katsuji Yamaguchi)
- Maintain traffic on unaffected segments during a ship repair
- Optical command control from shore



Power Switching States in the eBU



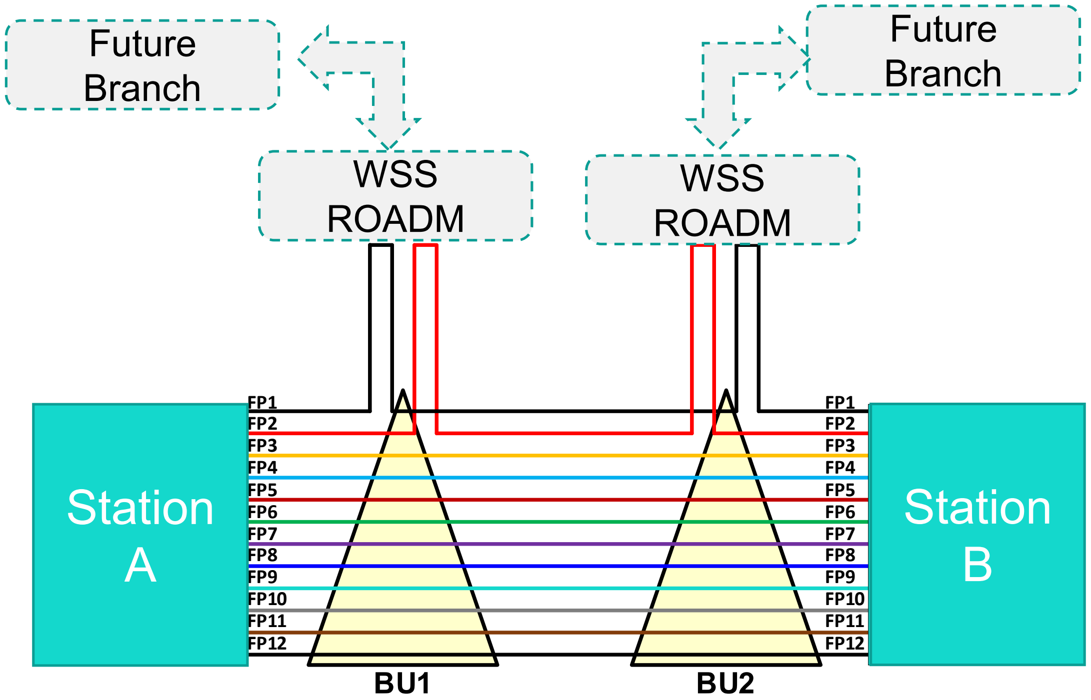
Submarine System Powering with Branches



Before / After
Dual Powering Fault

Powering submarine systems also requires creative architectures.

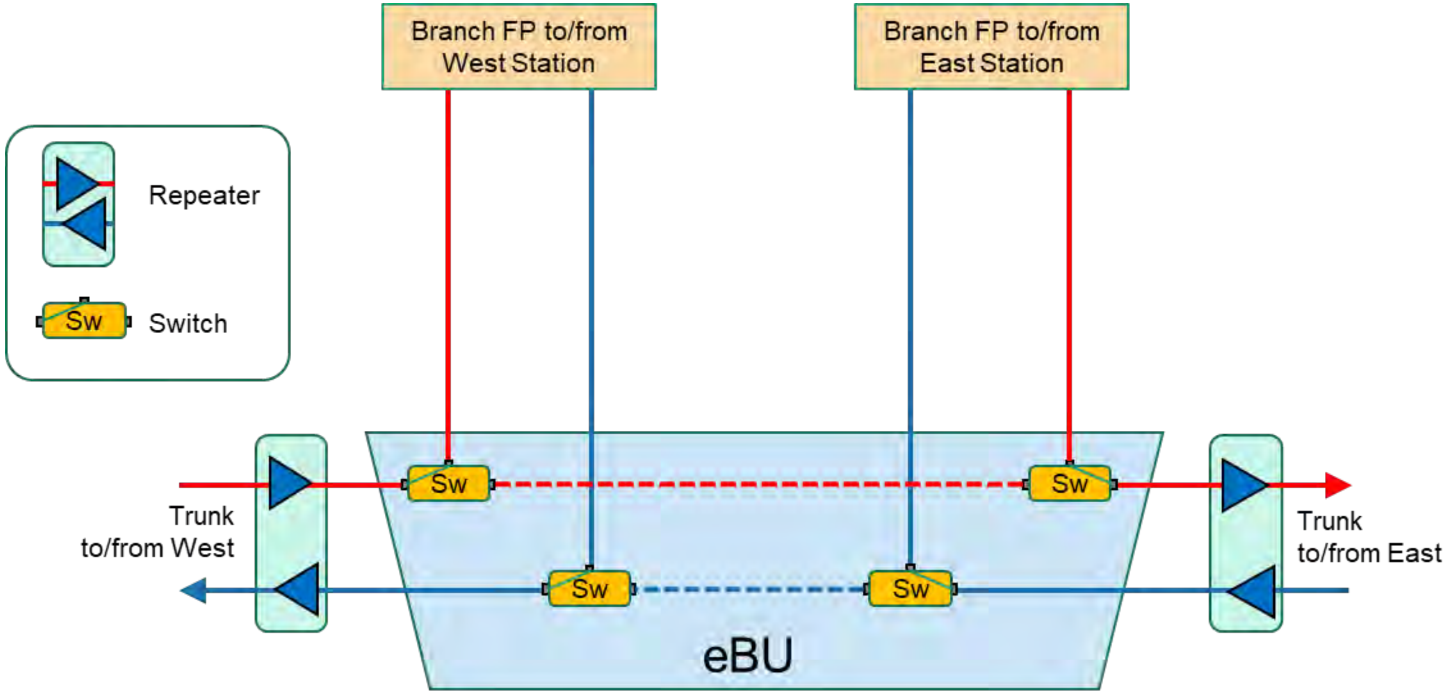
Future Network Expansion



- BUs with stubs can be inserted into a cable to enable future connectivity without cutting into the trunk cable
- Any number of trunk FPs can be accessed for connection to a branch state
- Stubs can also support later addition of WSS ROADM or Dry ROADM.

Branching Unit – Fiber Switching

Today's branching units also contain remote controlled optical switches for even more functionality



User configurable remote fiber switching allows

- Autonomous or/and manual fault recovery
- Isolating the branch for a repair or later network expansion
- Adding and/or re-routing traffic in a branch

Cross-Cable Architectures

Fiber Switched BUs can provide intra-cable connectivity.

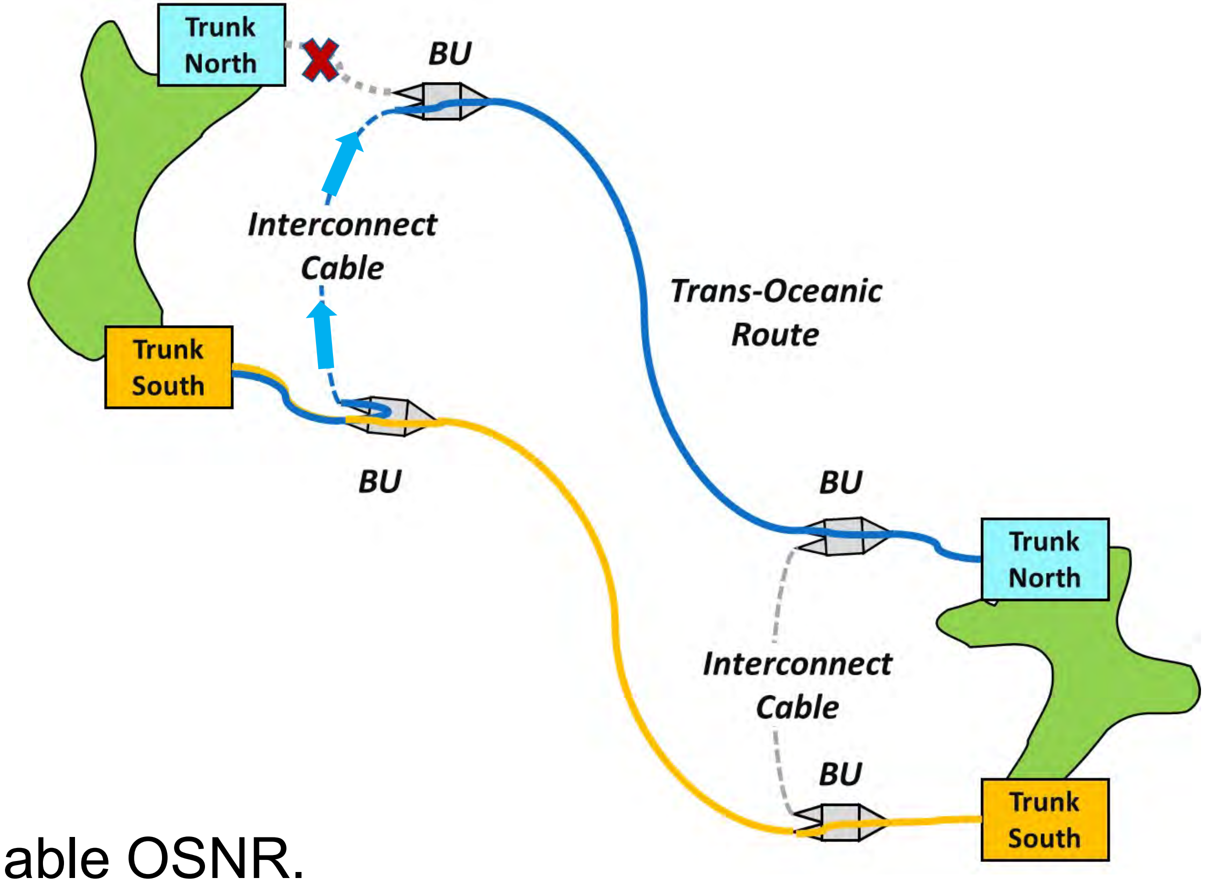
- Use for fault recovery, or for capacity routing flexibility.

Increases overall network availability.

- Protect on a FP basis, or use ROADMs to prioritize spectrum.

Increases path length:

- Could adjust channel data rates to match available OSNR.



Why Only 3-Port BUs?

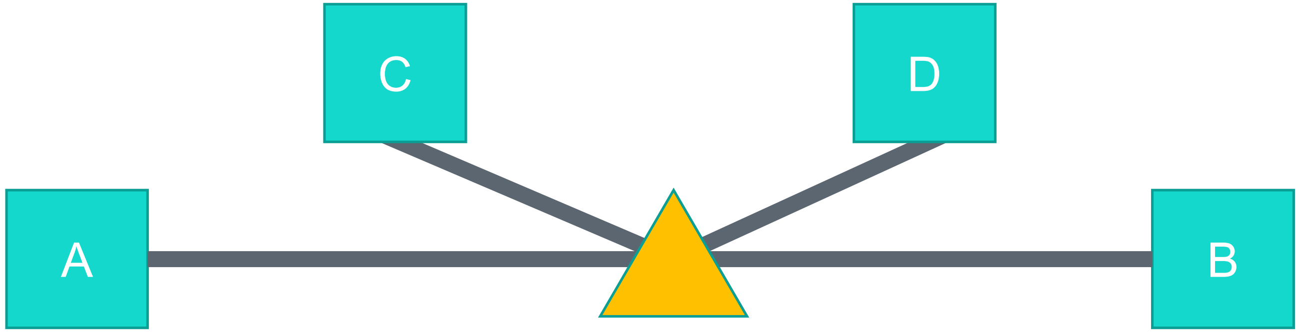
BU placement is typically optimized for overall cable length

- Lower cost
- Lower latency

There are additional marine considerations to best protect the BU

- Seafloor conditions

(4-Port BUs exist for special applications)



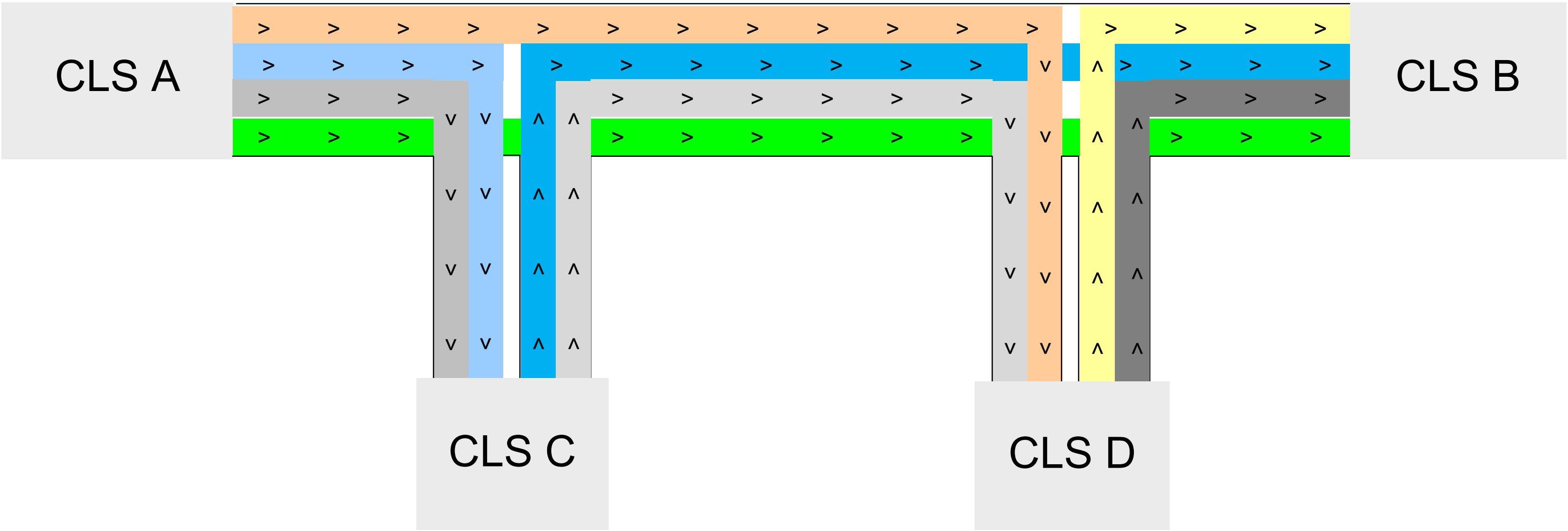
4-Port BU

Optical Add Drop Multiplexing

Undersea Optical Add Drop Multiplexing (OADM)

Enhanced Connectivity options

Multiple DLS on a single fiber pair



Wavelength Re-use

Bandwidth on a trunk fiber pair can be used for multiple DLS

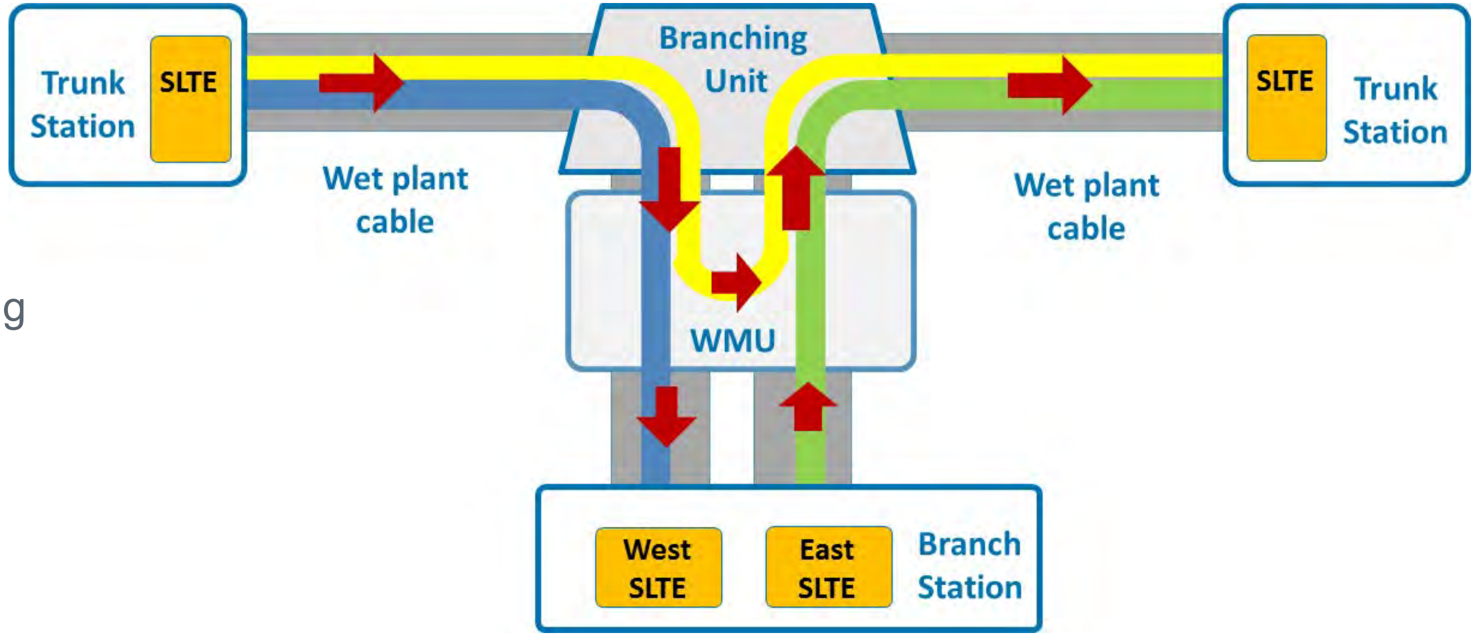
Optical Add/Drop Multiplexing (OADM) Node

Components in an OADM Node include:

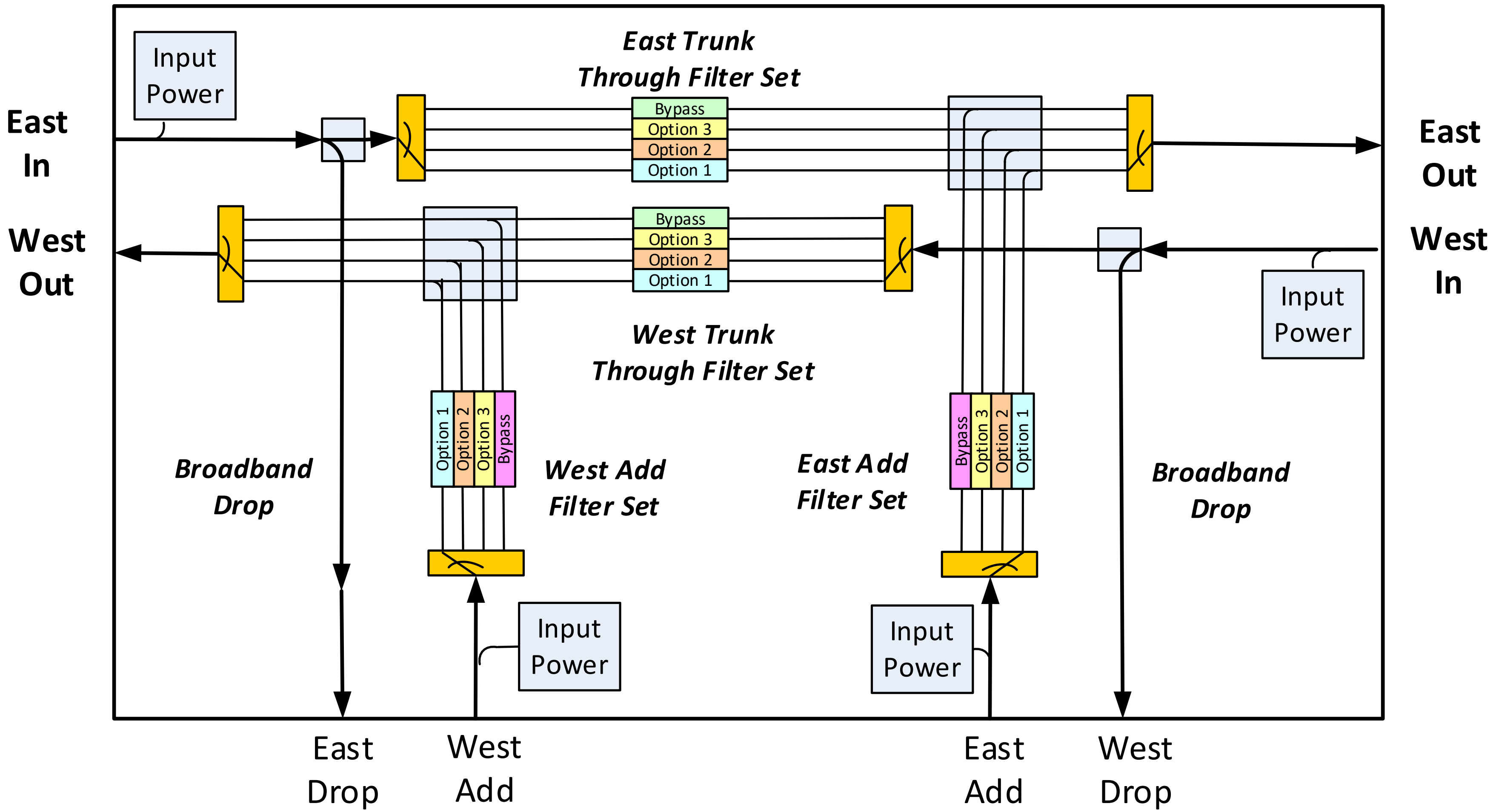
- Branching Unit
- OADM Unit:
  - Passive fixed filtering
  - Switchable filtering
  - Wavelength Selective Switch based filtering

Modular OADM options:

- OADM unit can be deployed when the branch is landed
- Simplified sparing (universal spare for BU)
- Repair operation does not affect express fiber pairs



Switched Filtering

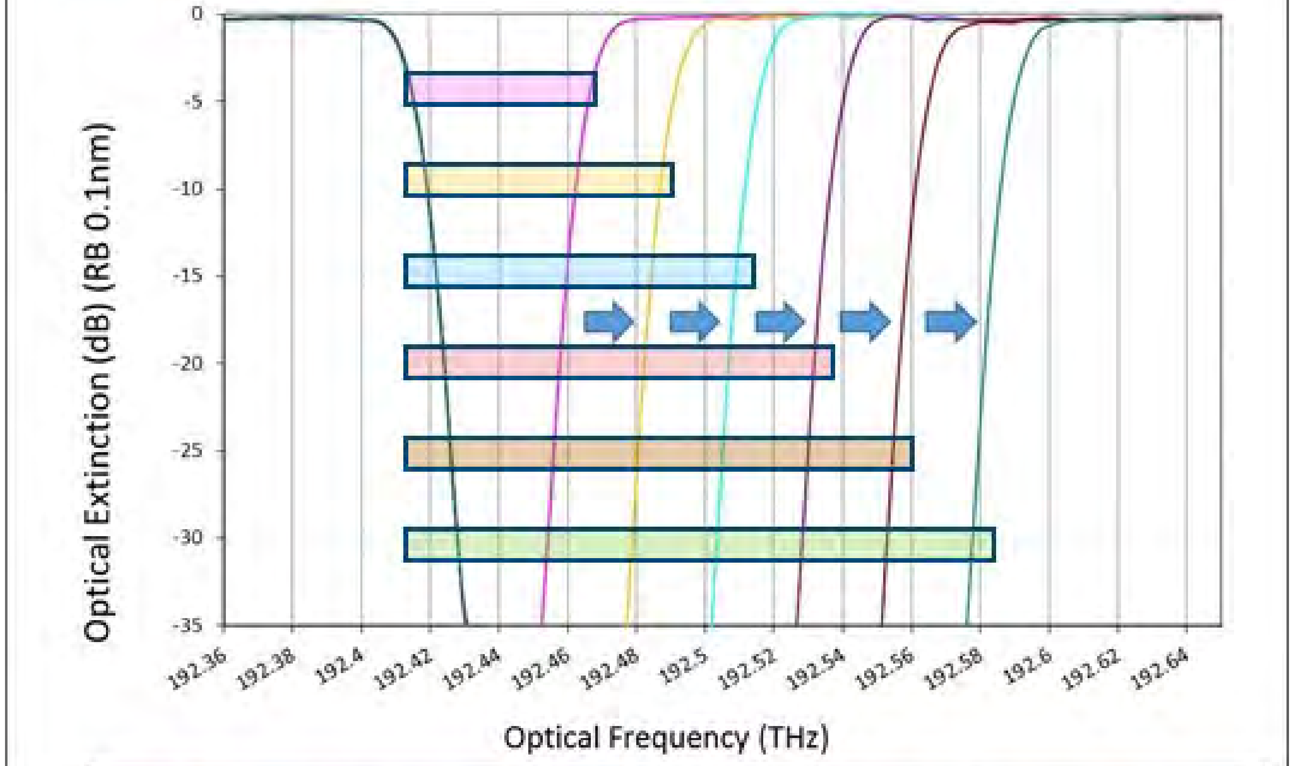


Wavelength Selective Switch

The Wavelength Selective Switch (WSS) is a pixelated device that supports reconfigurable filtering

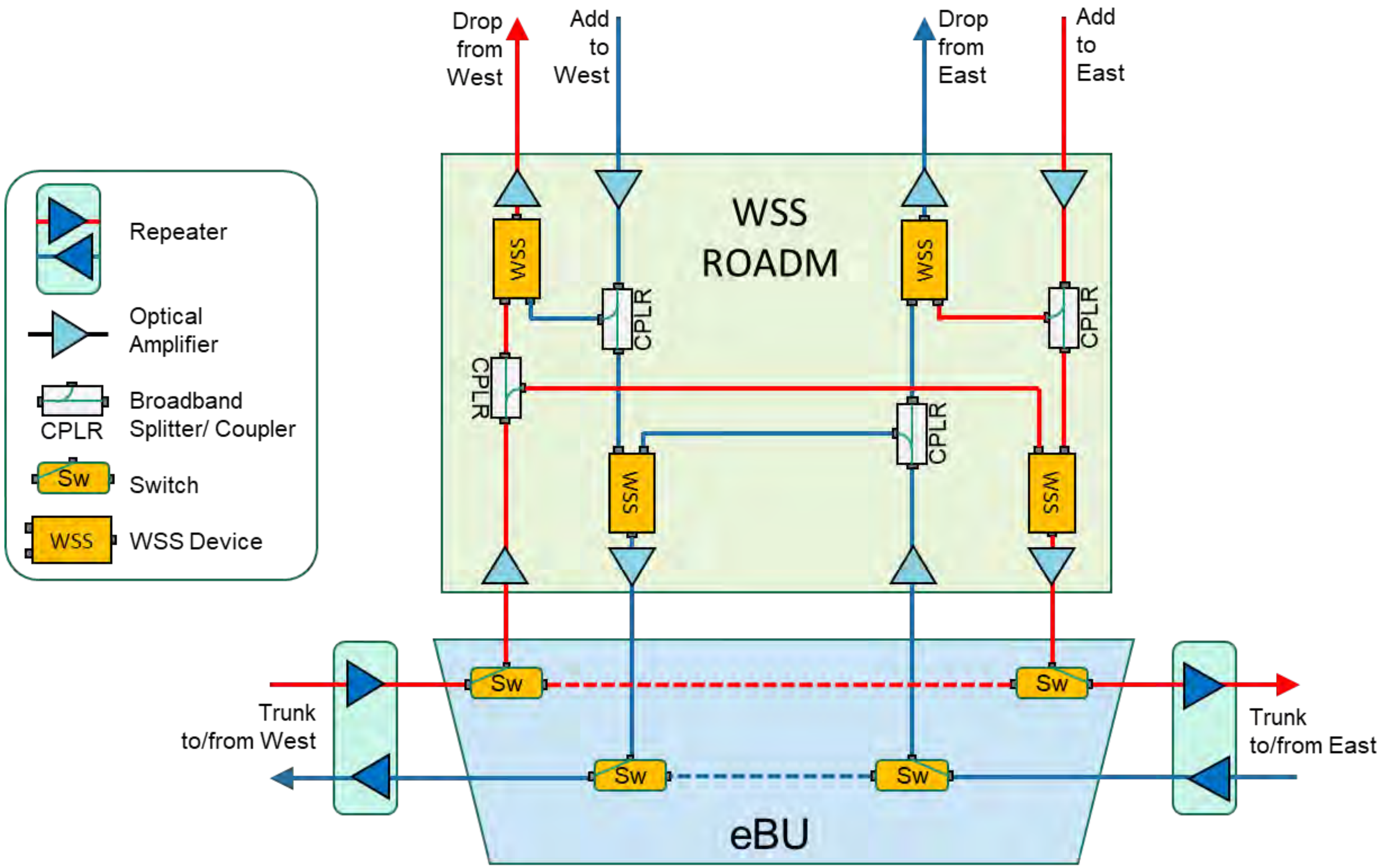
- Key specifications:
  - Grid-flexible channel plan with a fine granularity e.g. 6.25 GHz
  - Very steep filter edges
    30 dB transition in approximately 20 GHz

Band edge shape is independent of passband width



WSS transmission notch with increasing bandwidth.

Branching Node Example: PSBU + WSS ROADM

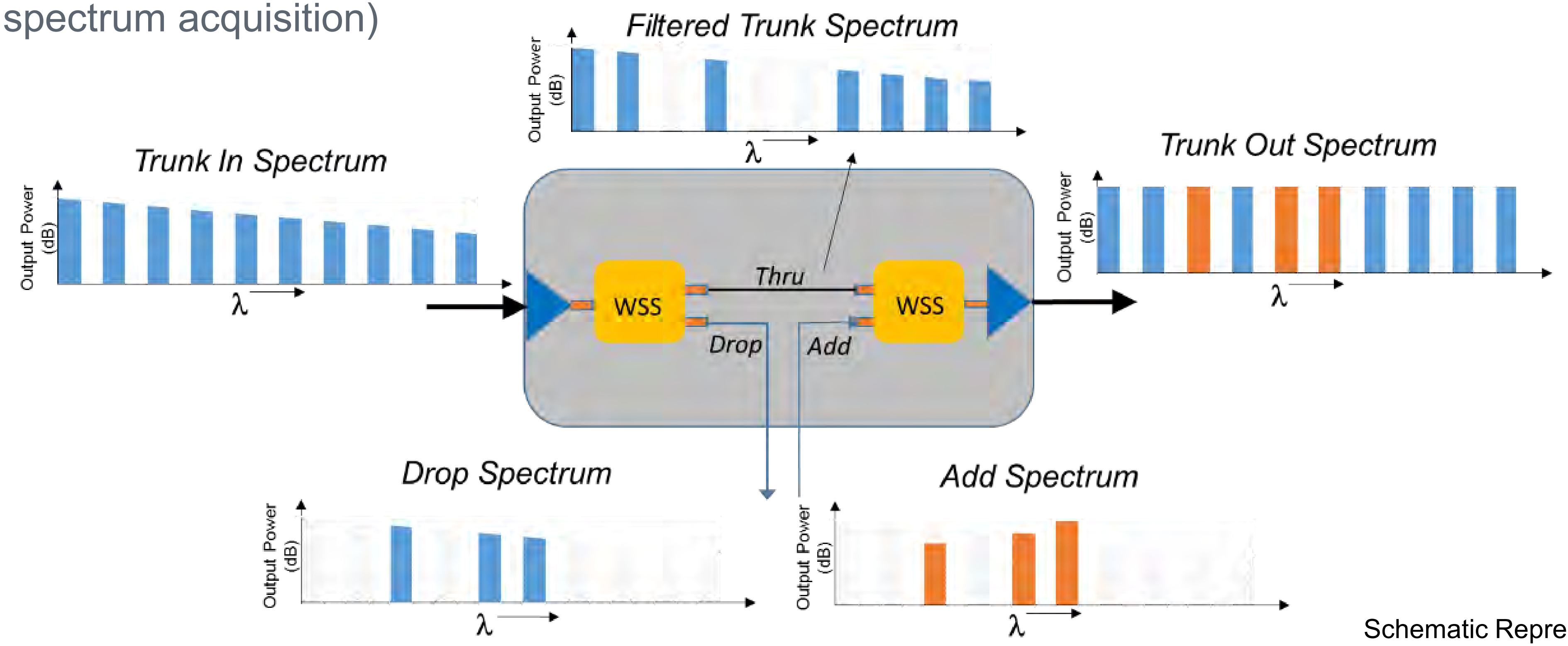


- Bi-directional Branch Access
- WSS Filtered Add/Drop
- Automatic bypass switching provided by eBU

Reconfigurable Optical Add Drop Multiplexing

Wavelength Selective Switch based OADM nodes support

- In service, gridless capacity reallocation
- Inline dynamic gain equalization
- (Optical spectrum acquisition)



Schematic Representation

* Schematic representation

System Reliability

System Reliability

System Design Life is typically 25 years

Transmission affecting failures require ship intervention

- Costly
- Takes time

Design for reliability

- High reliability components
- Redundancy

Expected number of ship repairs due to intrinsic failures is in the range of 0-3 depending on system size and complexity

Failures in Time

Failure Rate

- A common measure for failure rate is FIT, defined as the number of failures in 10^9 device hours (114,046 years).
- Use average failure rate λ
- Probability of failure is

$$\boxed{P_{fail} = 1 - e^{-\lambda t_{System}}},$$

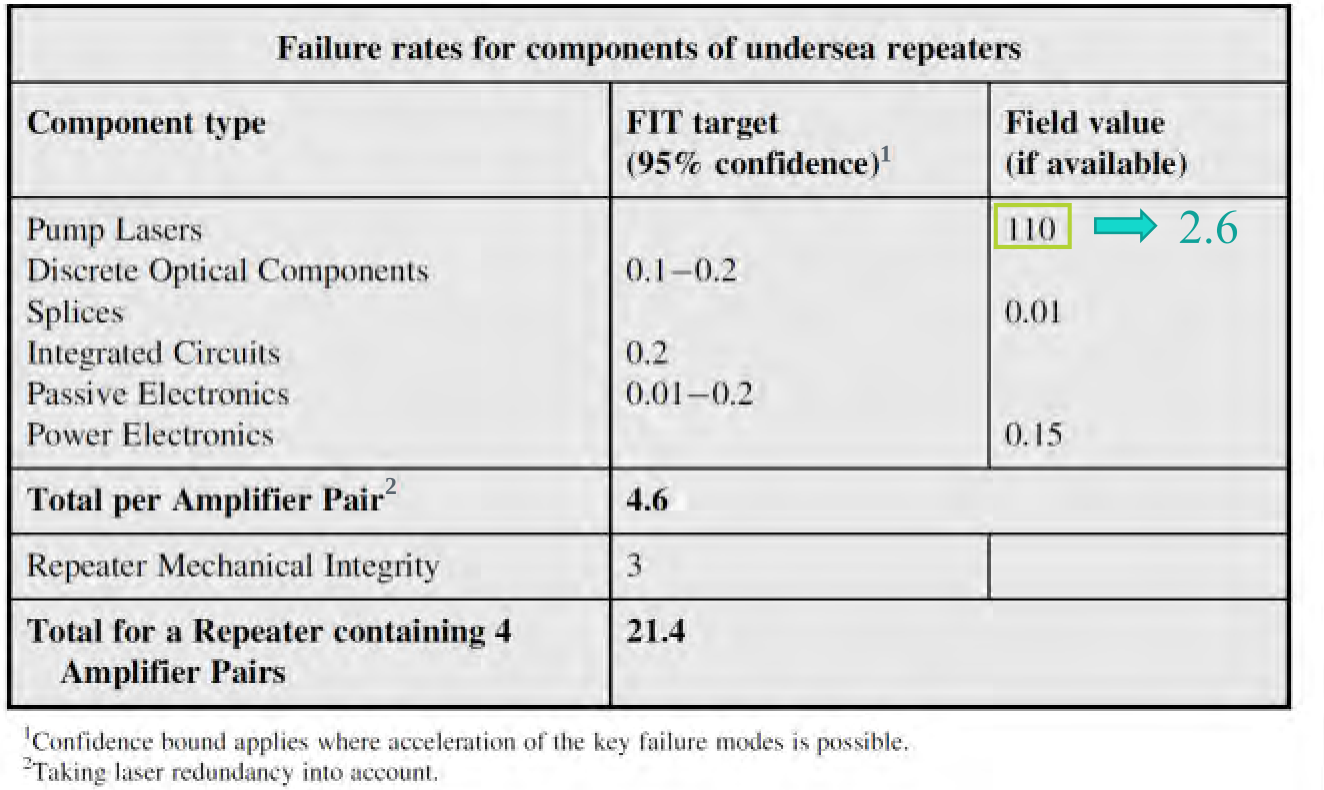
where t_{System} = 25 years

- Effective failure rate for redundant components (n=2 for 1x1)

$$\lambda_{effective} = \frac{-\ln(1 - P_{fail}^{n})}{t_{System}}$$

- Total FIT is the sum of all single points of failure (including effective FIT rate from redundancy)
  - Reliability: R=1-P_{fail}

110 FIT means 2.4% will fail in 25 years



Failure rates for components of undersea repeaters		
Component type	**FIT target (95% confidence)[1]**	**Field value (if available)**
Pump Lasers		110 → 2.6
Discrete Optical Components	0.1–0.2	
Splices		0.01
Integrated Circuits	0.2	
Passive Electronics	0.01–0.2	
Power Electronics		0.15
Total per Amplifier Pair[2]	**4.6**	
Repeater Mechanical Integrity	3	
Total for a Repeater containing 4 Amplifier Pairs	**21.4**	

[1] Confidence bound applies where acceleration of the key failure modes is possible.

[2] Taking laser redundancy into account.

From *Undersea Fiber Communication Systems* 2nd Edition
by Jose Chesnoy (Editor), Academic Press ISBN: 978-0128042694

Ship Repairs

- Failures are Poisson distributed.
- The expectation value of the distribution is the number of ship repairs.
- For Poisson the expectation value corresponds to the failure rate

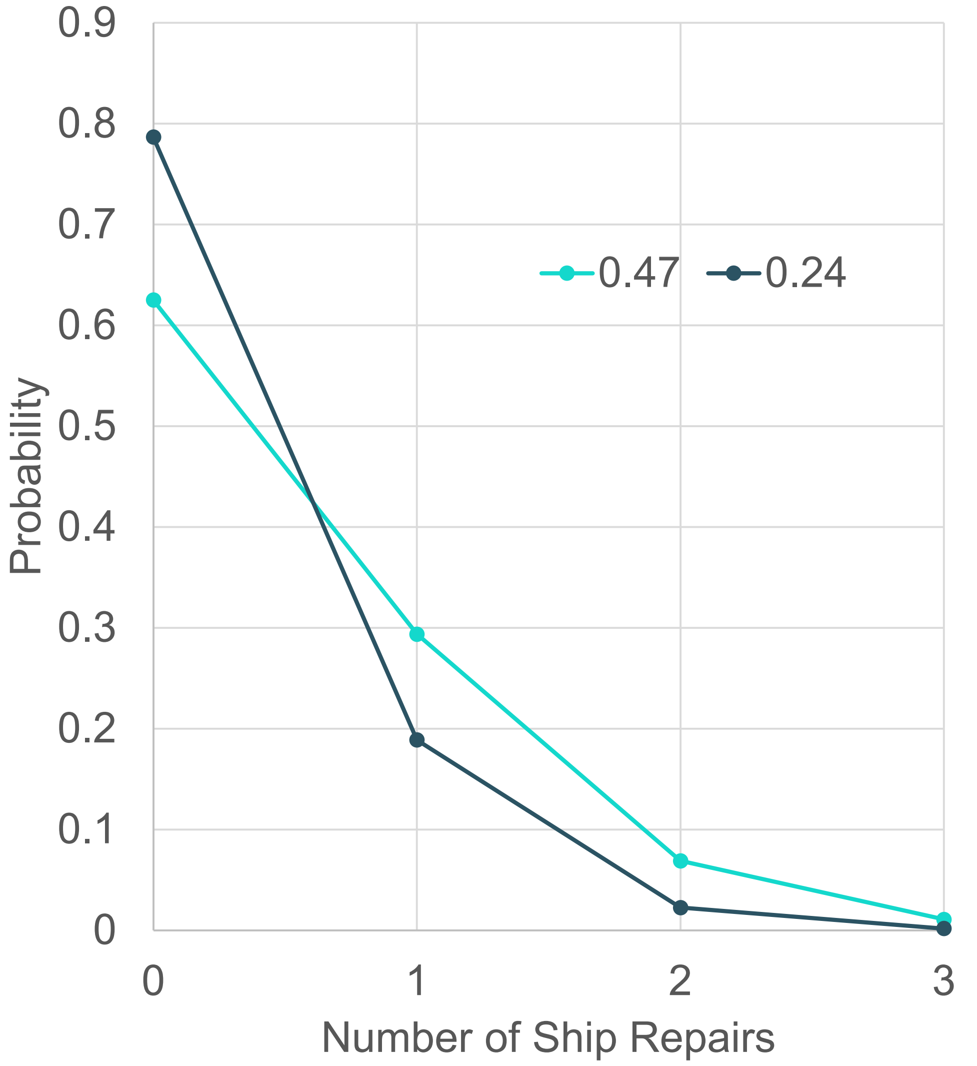
Example

- 100 Repeaters
- 4 Fiber Pairs

Example for Repeaters Only

- 800 Pumps (110 FIT)
- 19 Pump failures in 25 years
- 4x4 pump redundancy: no repeater failure due to pump failure

- Repeater: 11 FIT
- Expected number of ship repairs in 25 years: 0.24



External Aggression

Majority of cable failures are due to external events:

- Ship anchors
- Earthquakes and mud slides
- Abrasion

Good reasons to armor or bury cable near shore.

Summary

- Cable
- Repeaters
  - Amplification and gain equalization
  - Self-healing of a chain of amplifiers; gain tilt
  - Pump manifold and reliability
  - Line Monitoring and High Loss Loopbacks (HLLBs)
  - L-band amplification
  - The pressure vessel
- Branching Units
  - Fiber routing and optical switches
  - Electrical reconfiguration – Recovering from shunt faults
- Wavelength Management Units: (Reconfigurable) Optical Add Drop Multiplexing
- System Reliability

SUBCOM

Thank You

Subsea Terminal

Elizabeth Rivera Hartling

August, 2019

Outline

- DAY 4: Submarine Terminal
  - Submarine Line Terminal Equipment (SLTE)
    - Functions, Features, Equipment & the Real Thing
  - Advanced Modems & Features
    - The evolution of modem technology for Subsea cables

First: A Career in Subsea

My Career – There are many Roles in Subsea!

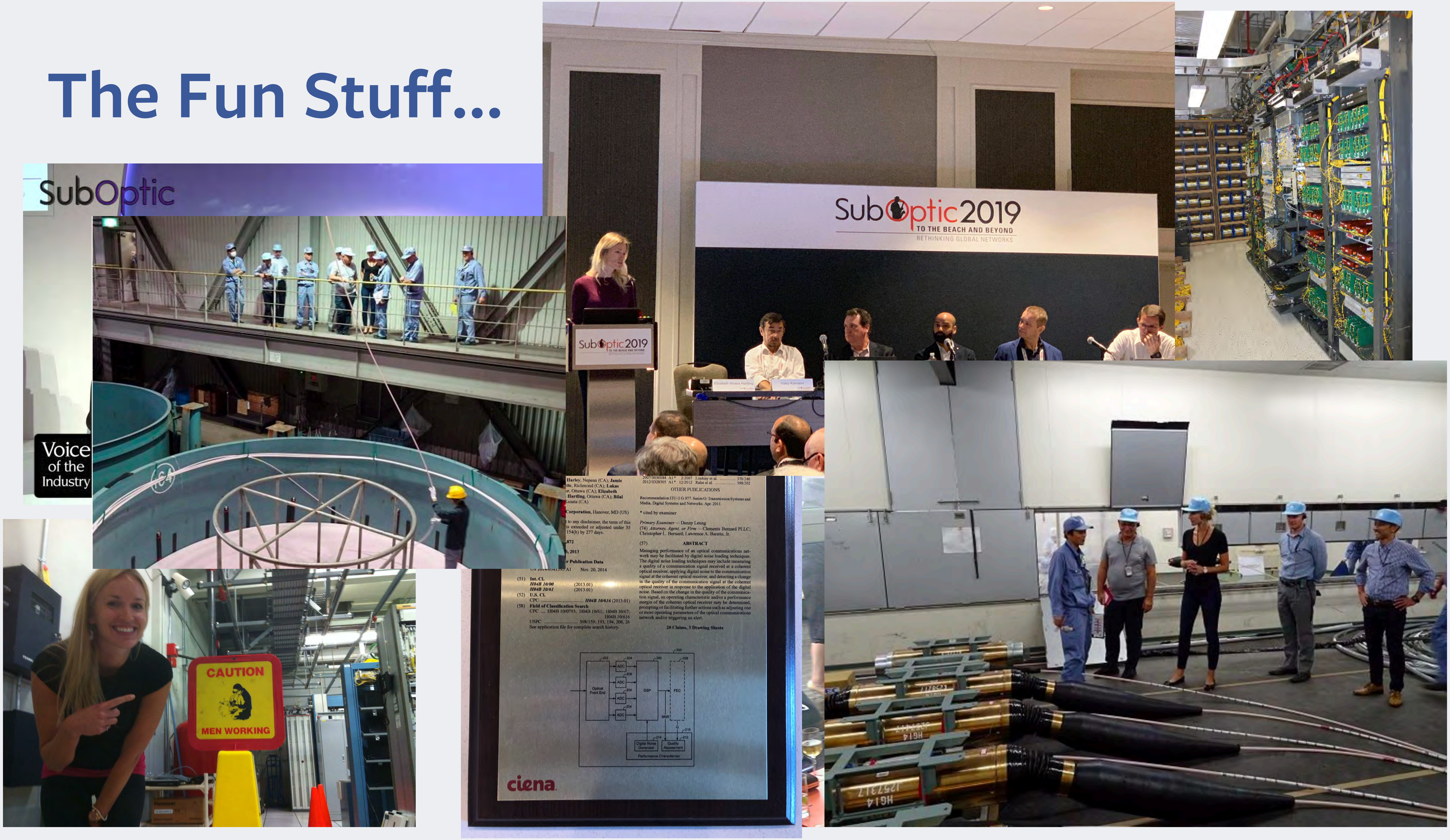
10 Years @ Ciena:

- Subsea R&D - Simulation & Modeling (SLDs, MATLAB) – 2 yrs
- Subsea R&D - Lab Work & Field Trials! Building lab test beds and testing product on real cables all over the world – 3 yrs
- Systems Engineering (SE) – Talking SLTE Technology – 4 yrs
- Product Line Management (PLM) – Product Decisions – 1yr

1 Year @ Facebook (and counting):

- Subsea Network Architecture & New Cable Builds

The Fun Stuff...



Harley, Nepean (CA); **Jamie**
tte, Richmond (CA); **Lukas**
r, Ottawa (CA); **Elizabeth**
Hartling, Ottawa (CA); **Bilal**
Kanata (CA)

Corporation, Hanover, MD (US)

to any disclaimer, the term of this is extended or adjusted under 35 154(b) by 277 days.

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(52) **U.S. Cl.**
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(58) **Field of Classification Search**
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USPC 398/159, 193, 194, 208, 26
See application file for complete search history.

2007/0036084 A1* 2/2007 Lindsay et al. 370/246
2012/0328305 A1* 12/2012 Rahn et al. 398/202

OTHER PUBLICATIONS

Recommendation ITU-T G.977. Series G: Transmission Systems and Media, Digital Systems and Networks. Apr. 2011.

* cited by examiner

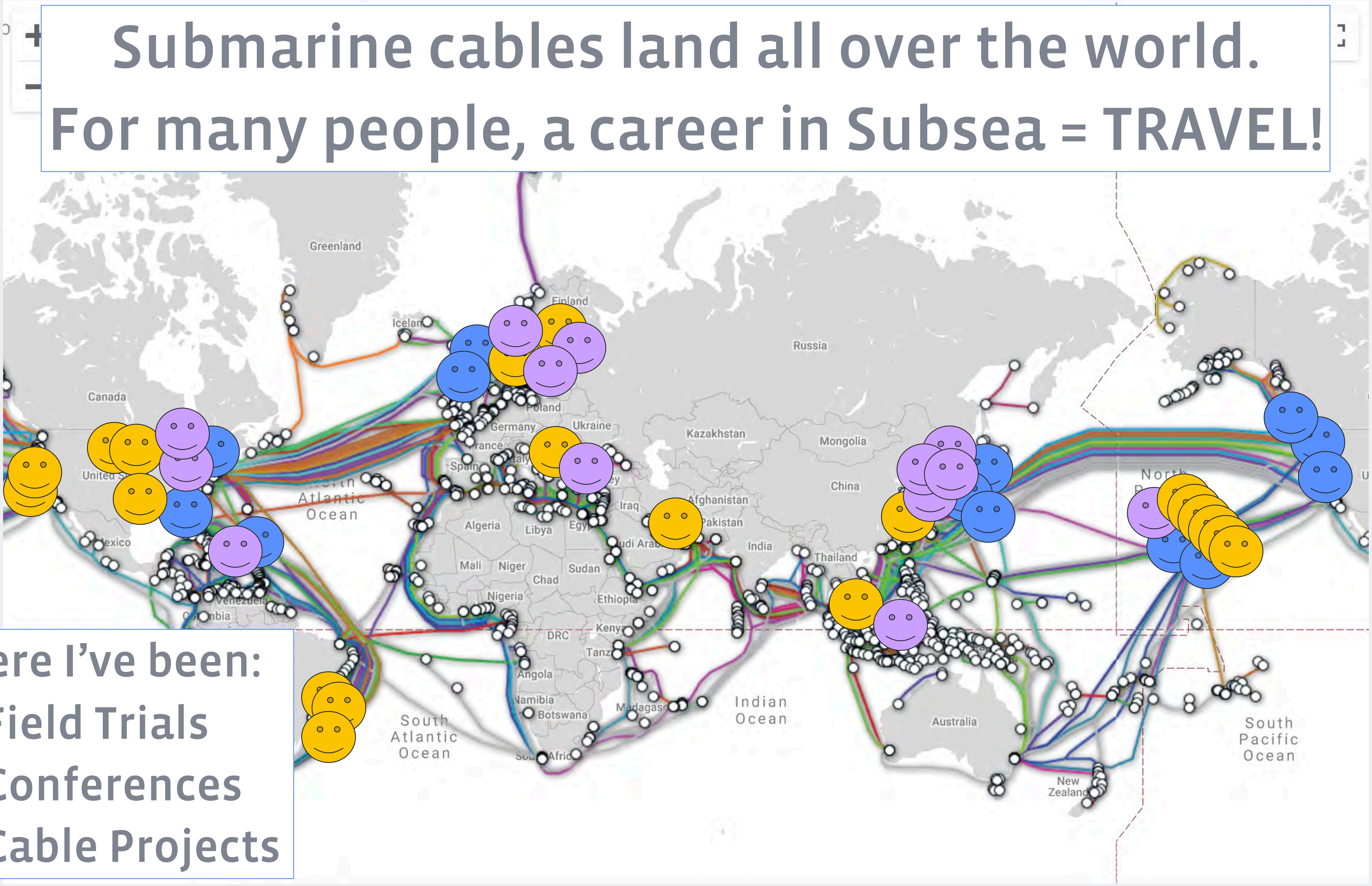
Primary Examiner — Danny Leung
(74) *Attorney, Agent, or Firm* — Clements Bernard PLLC; Christopher L. Bernard; Lawrence A. Baratta, Jr.

(57) **ABSTRACT**

Managing performance of an optical communications network may be facilitated by digital noise loading techniques. The digital noise loading techniques may include measuring a quality of a communication signal received at a coherent optical receiver, applying digital noise to the communication signal at the coherent optical receiver, and detecting a change in the quality of the communication signal at the coherent optical receiver in response to the application of the digital noise. Based on the change in the quality of the communication signal, an operating characteristic and/or a performance margin of the coherent optical receiver may be determined, prompting or facilitating further actions such as adjusting one or more operating parameters of the optical communications network and/or triggering an alert.

20 Claims, 3 Drawing Sheets

Submarine cables land all over the world.
For many people, a career in Subsea = TRAVEL!



Where I've been:

- 🔵 Field Trials
- 🟡 Conferences
- 🟣 Cable Projects

More than 2.7 Billion users across the Facebook family of apps
including **Facebook , Instagram, WhatsApp, Messenger**

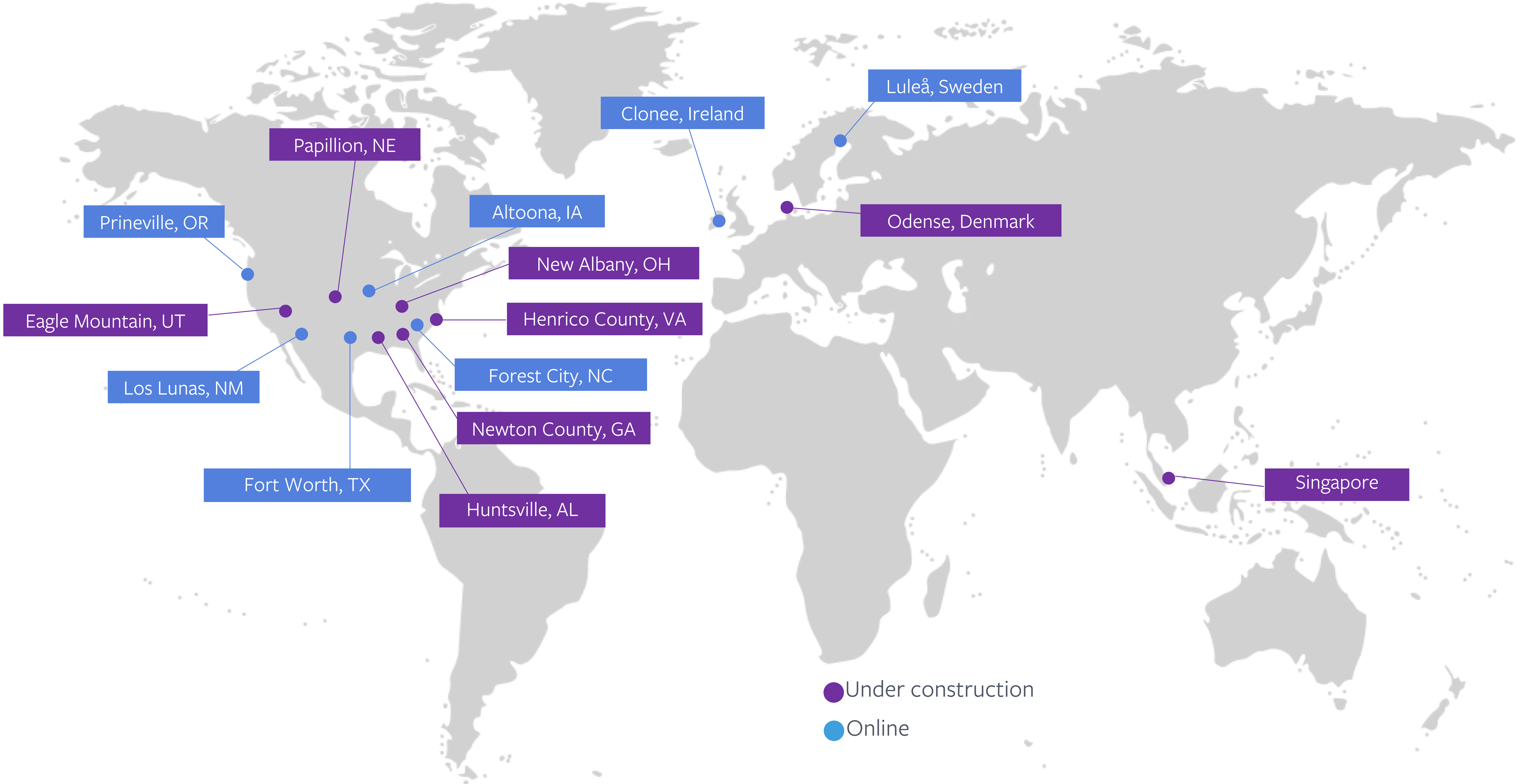
>85% of users are outside of the U.S


2018 This Is What Happens In An Internet Minute
facebook
973,000 Logins
18 Million Text Messages
YouTube
4.3 Million Videos Viewed
Google play
App Store
375,000 Apps Downloaded
174,000 Scrolling Instagram
481,000 Tweets Sent
1.1 Million Swipes
tinder
187 Million Emails Sent
936,073 Views
twitch
67 Voice-First Devices Shipped
amazon echo
38 Million Messages
25,000 GIFs Sent via Messenger
2.4 Million Snaps Created
$862,823 Spent Online
NETFLIX
266,000 Hours Watched
Google
3.7 Million Search Queries
60 SECONDS
Created By:
@LoriLewis
@OfficiallyChadd


2019 This Is What Happens In An Internet Minute
facebook
1 Million Logging In
18.1 Million Texts Sent
YouTube
4.5 Million Videos Viewed
Google play
App Store
390,030 Apps Downloaded
347,222 Scrolling Instagram
87,500 People Tweeting
1.4 Million Swipes
tinder
188 Million Emails Sent
1 Million Views
twitch
41 Music Streaming Subscriptions
180 Smart Speakers Shipped
amazon echo
4.8 Million Gifs Served
GIPHY
41.6 Million Messages Sent
Facebook Messenger
WhatsApp
2.1 Million Snaps Created
$996,956 Spent Online
NETFLIX
694,444 Hours Watched
Google
3.8 Million Search Queries
60 SECONDS
Created By:
@LoriLewis
@OfficiallyChadd

Data Centers

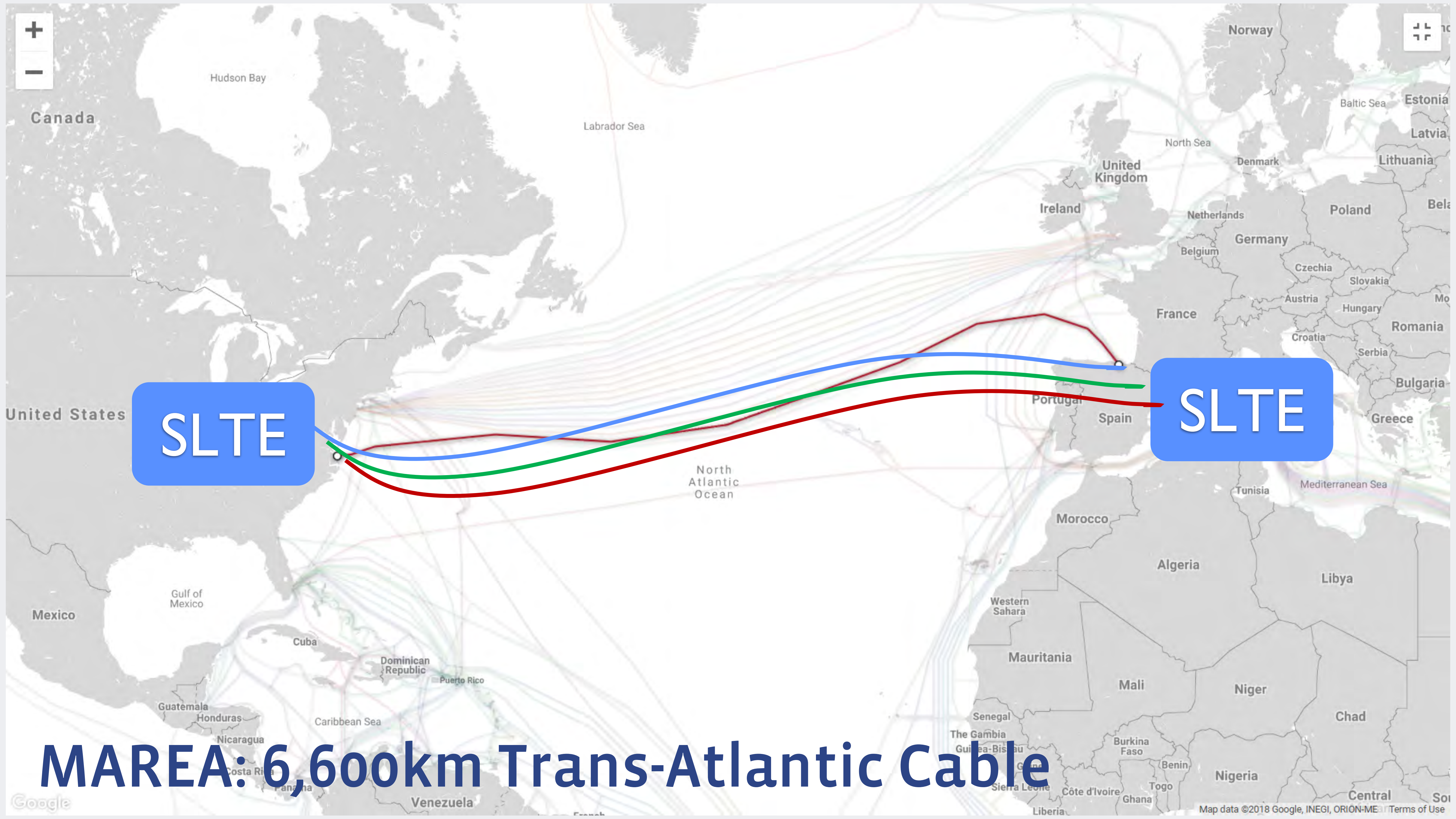
Facebook Data Center Locations



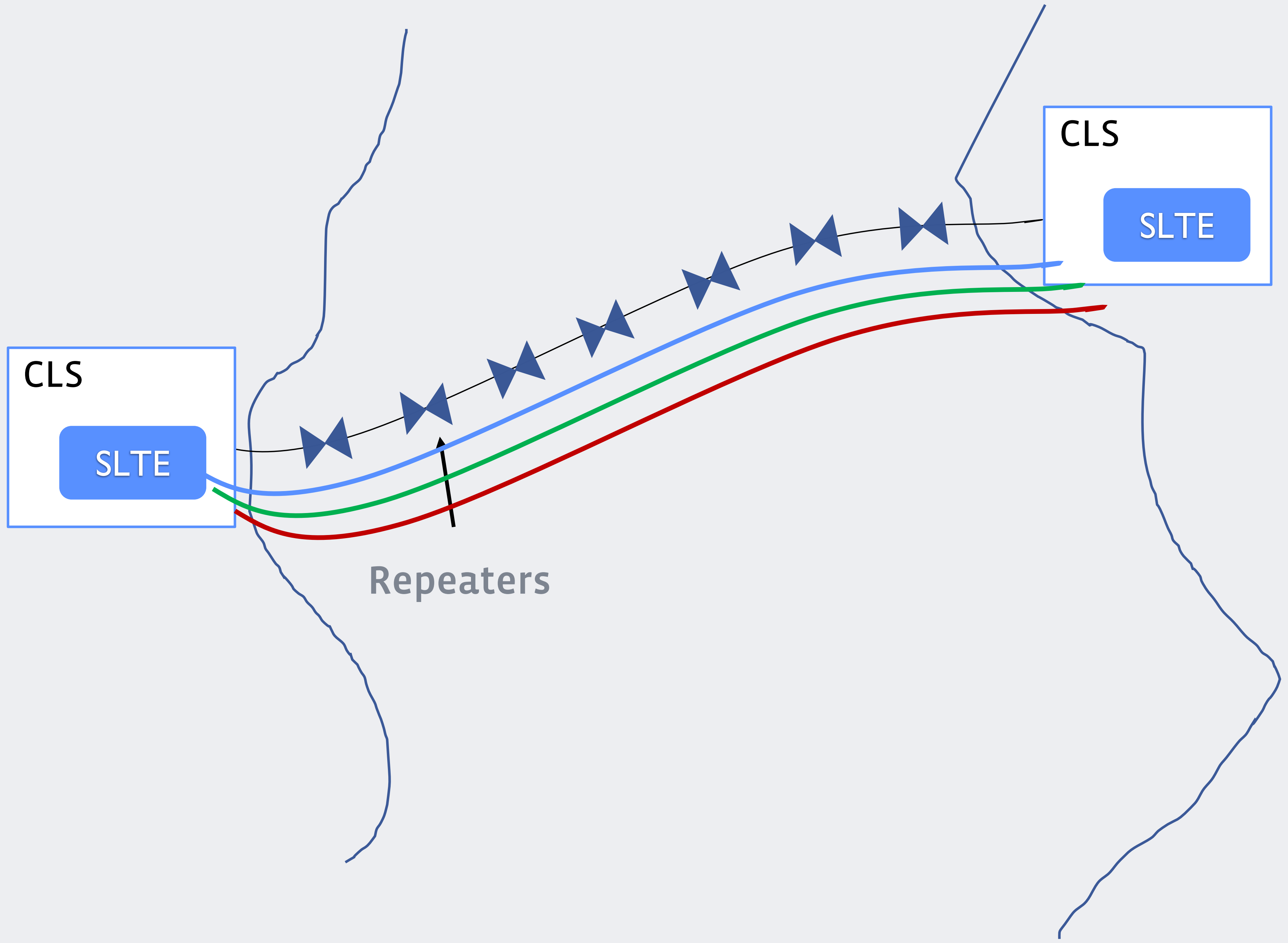
Submarine Line Terminal Equipment (SLTE)

What is SLTE & What Does it Do?

SLTE is what gets your data from one side of the ocean to the other with as few errors as possible (or with only as many as are correctable 😉)!



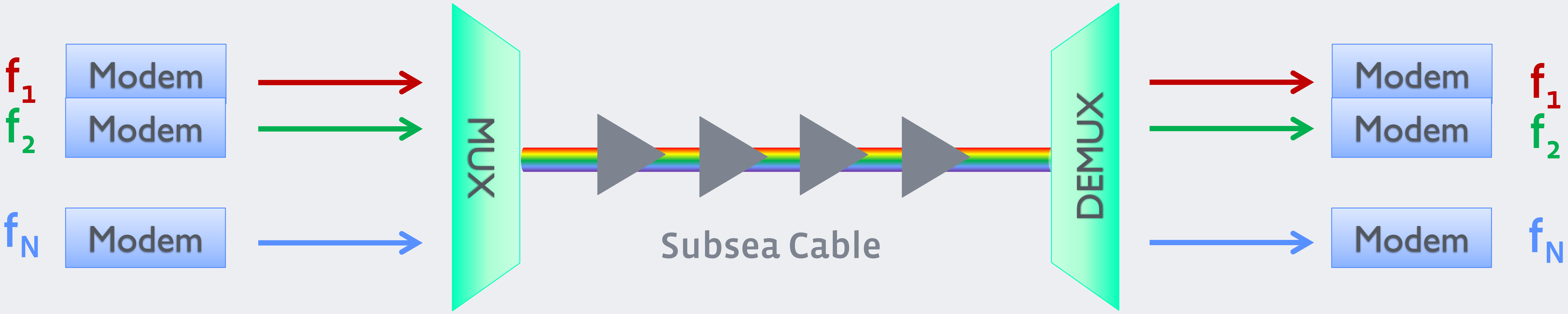
MAREA: 6,600km Trans-Atlantic Cable



WDM Transmission

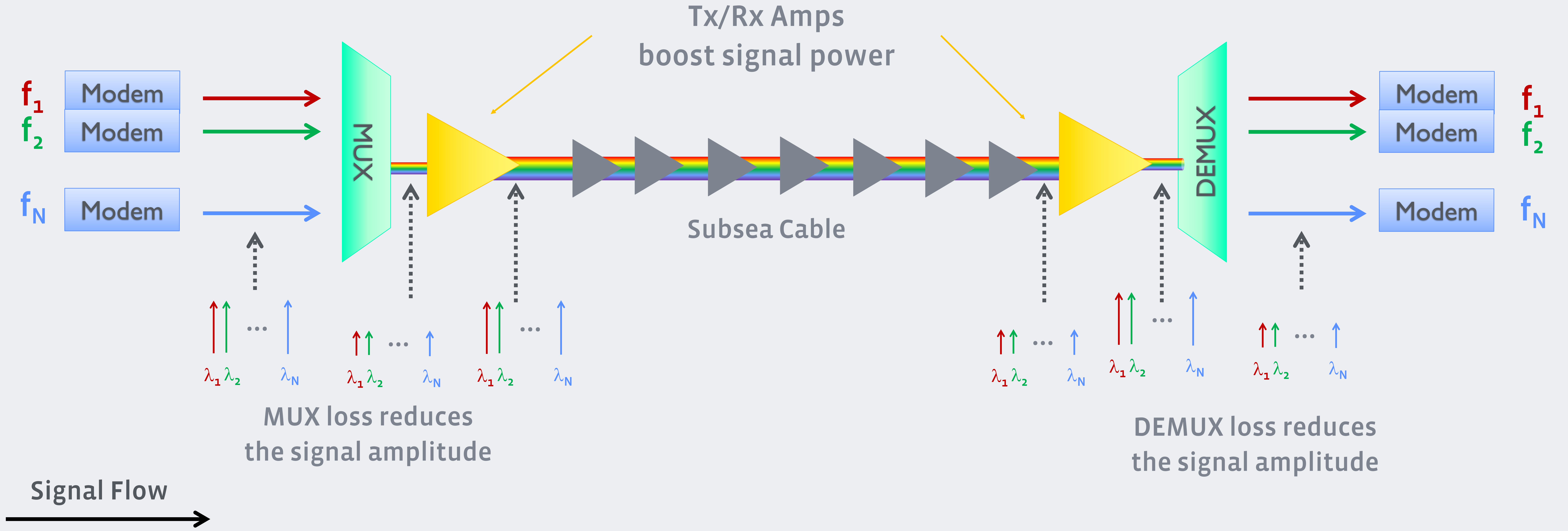
WDM transmission relies on optical multiplexers (MUX) and de-multiplexers (DEMUX) to seamlessly combine and split the waves for propagation.

Modems
a.k.a.
Transponder
Transceiver
Line Card
…all the same!



Optical Amplification

Most multi-span links amplify the waves before they enter the fiber, and after they exit, to ensure the best SNR possible for the wavelengths when they hit the optical receivers!

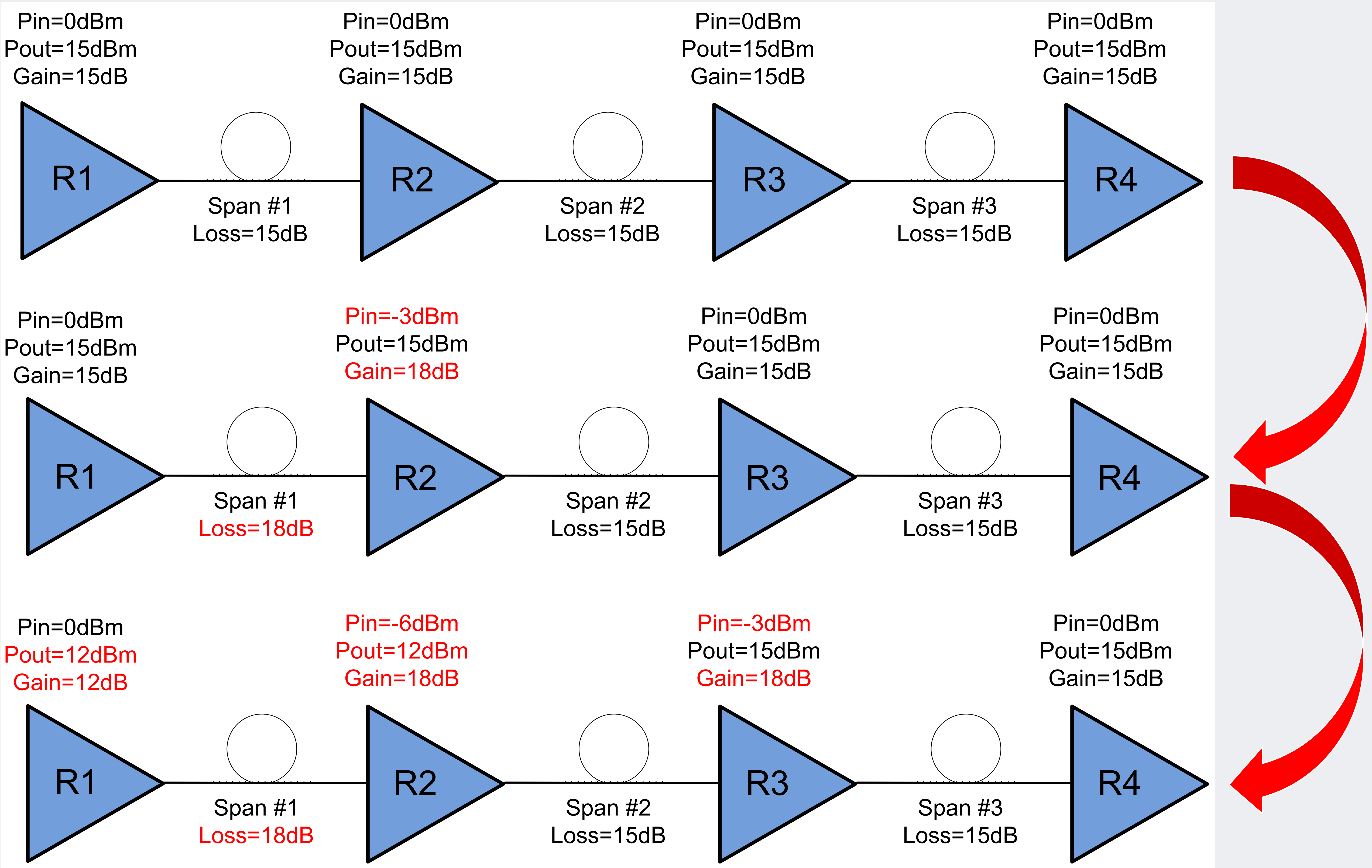


Courtesy of: ciena

Submarine Repeaters – Why TOP Mode?

Submarine repeaters are designed for low noise figures, high reliability and for system fault recovery, all with a 25 year lifetime. This is why submarine repeaters operate in Total Output Power mode.

- Cable repairs "recover" but often with some residual tilt
- Pump failures "self-correct" during their recovery due to SHB



Cable repair on Span #1:

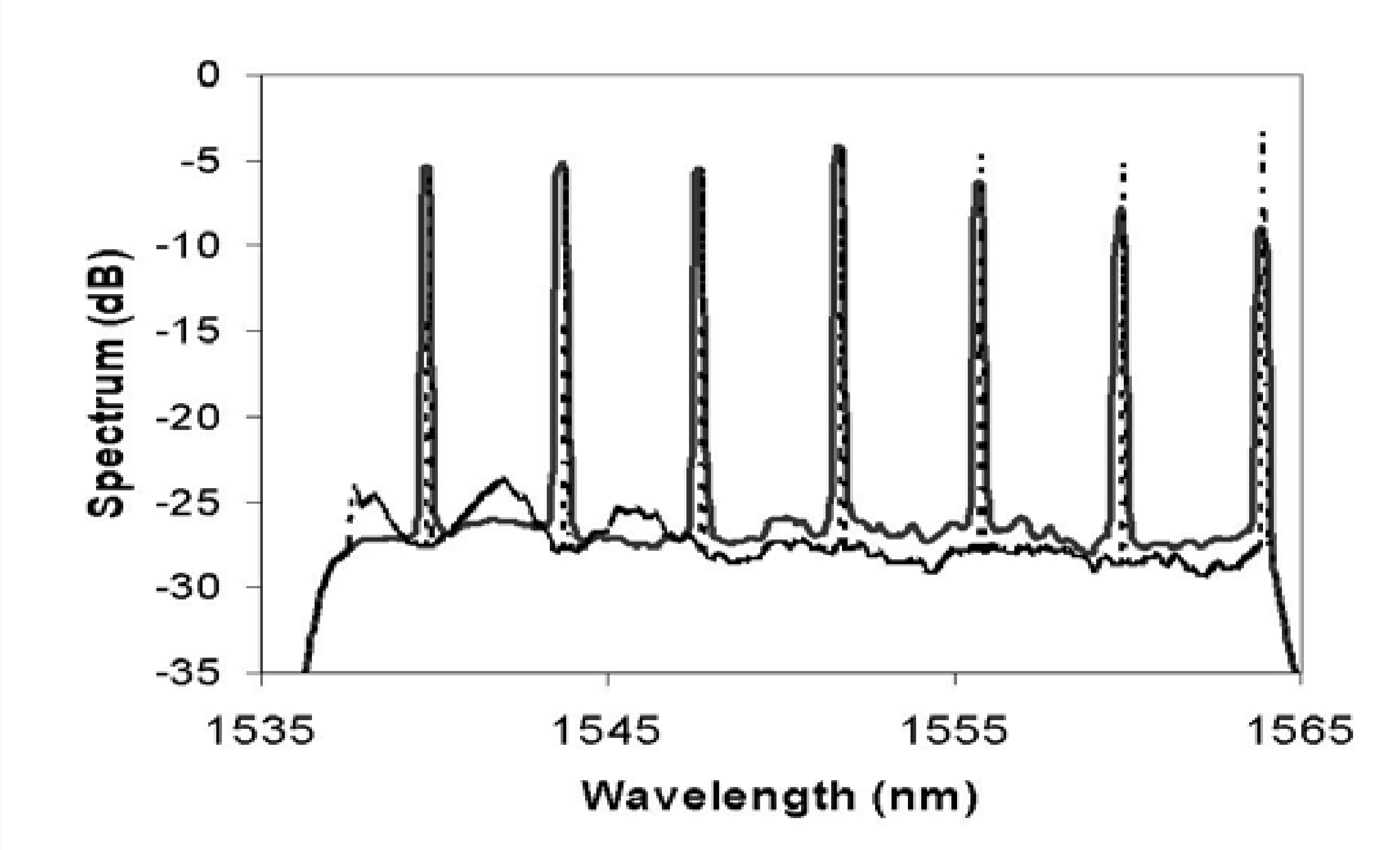
- 3dB increase in span loss
- R2 gain increases 3dB to compensate
- R3 sees no change

Pump failure on R1:

- 3dB reduction in output power
- R2 is already at max gain
- R3 sees 3dB lower input power, increases gain 3dB to compensate
- R4 sees no change

The Need for Dummy Lights in Subsea

- So, if subsea amps always run at the same TOP setting, that means if you have one wavelength, it gets all the power! And If you have 100 wavelengths, they each get 1/100th of the power (approximately)
  - The performance of any wavelength on a given optical link is highly dependent on it being propagated at or near it's optimal power (i.e. optimal balance of linear & nonlinear noise)
- Thus, Subsea systems uses "dummy" wavelengths (waves that don't carry any real data, but consume excess repeater power), to ensure all waves stay at their optimal power all the time.
  - Recall: the distribution of gain across the spectrum is highly dependent on how the power of the wavelengths is balanced, particularly in TOP mode ("waterbed" analogy!)



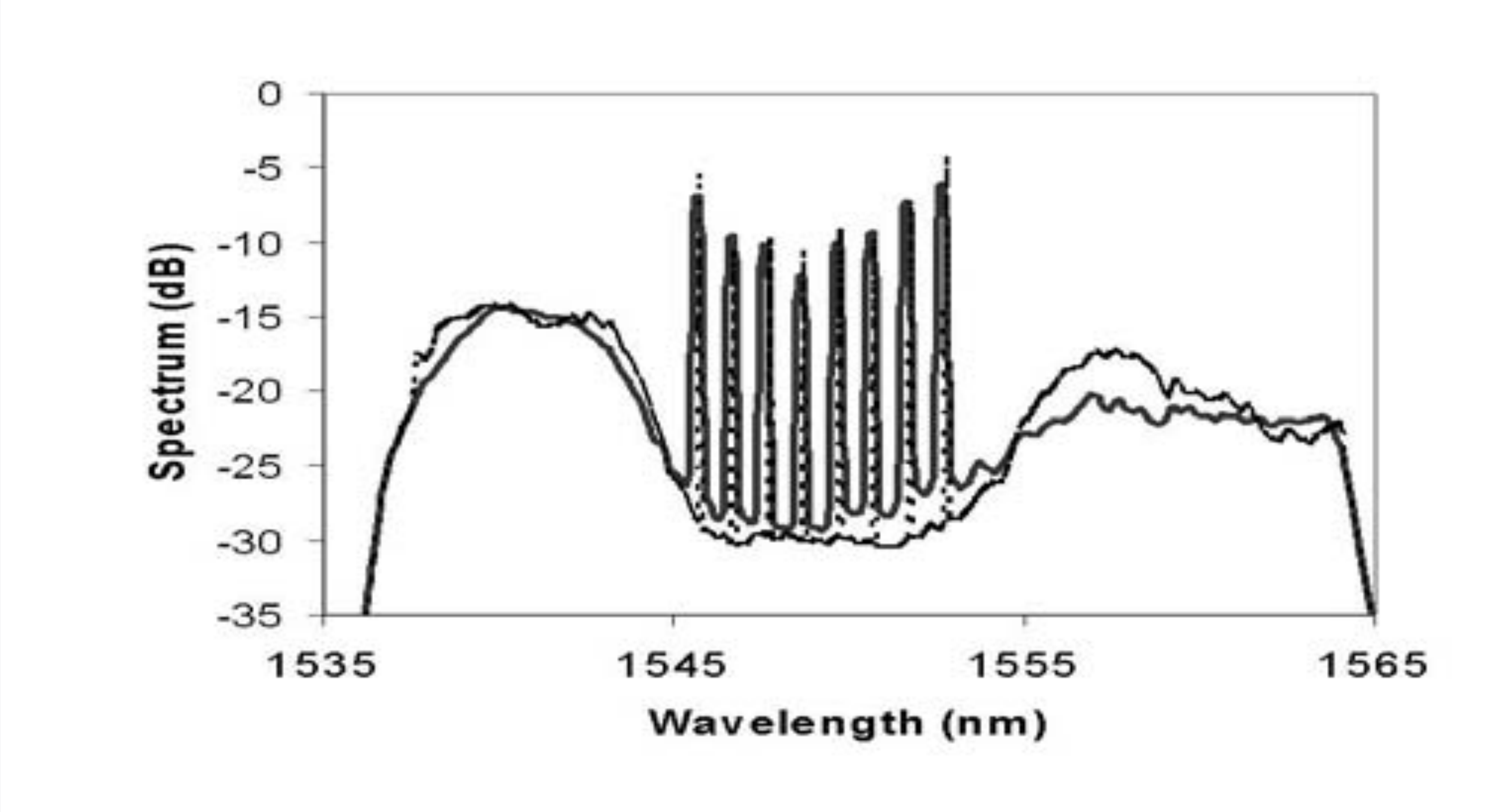
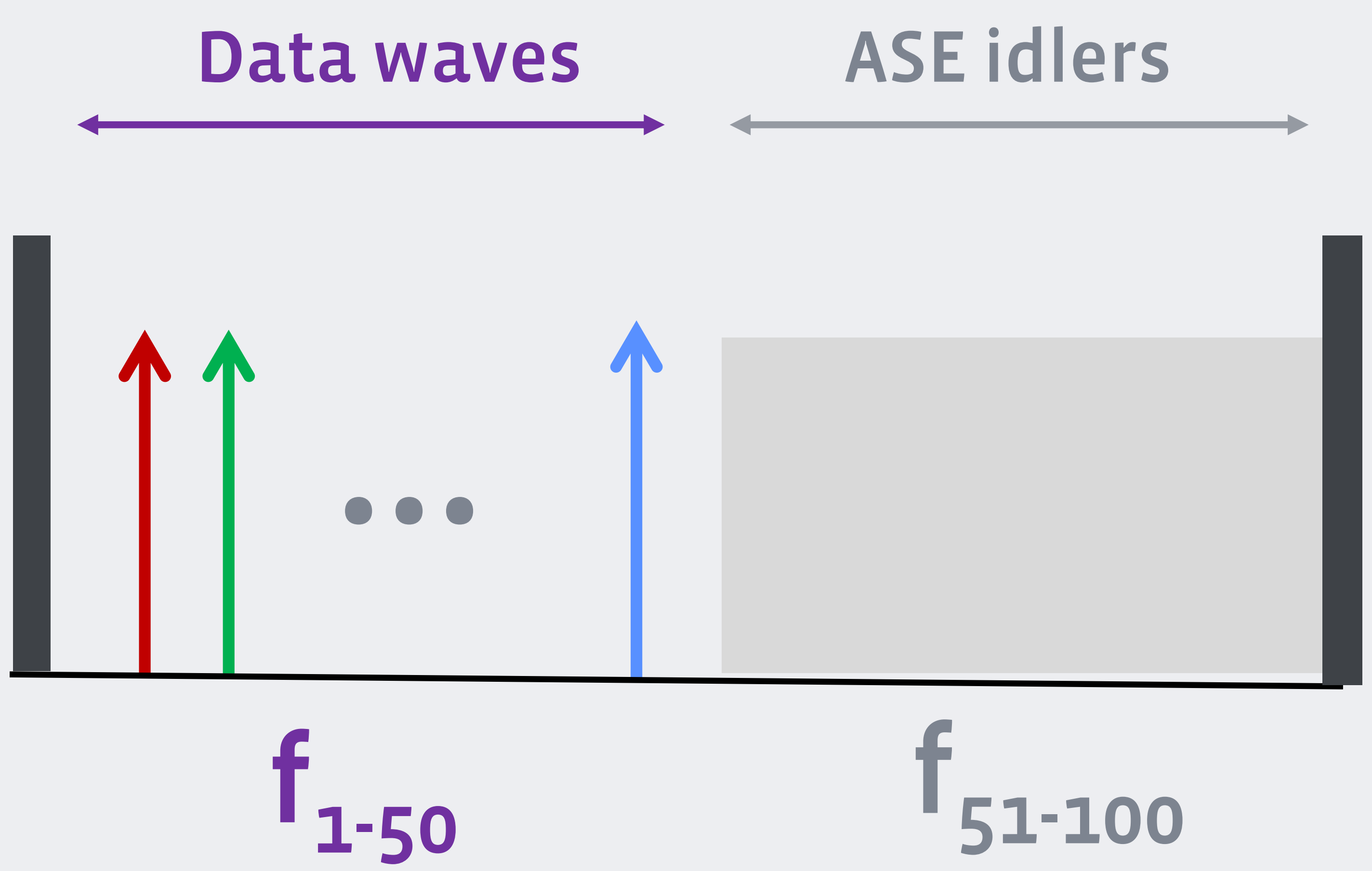


Figure Ref: JLT Invited Tutorial: Wavelength Division Multiplexing in Long-Haul Transoceanic Transmission Systems, Neal S. Bergano, *Fellow IEEE, Fellow OSA*

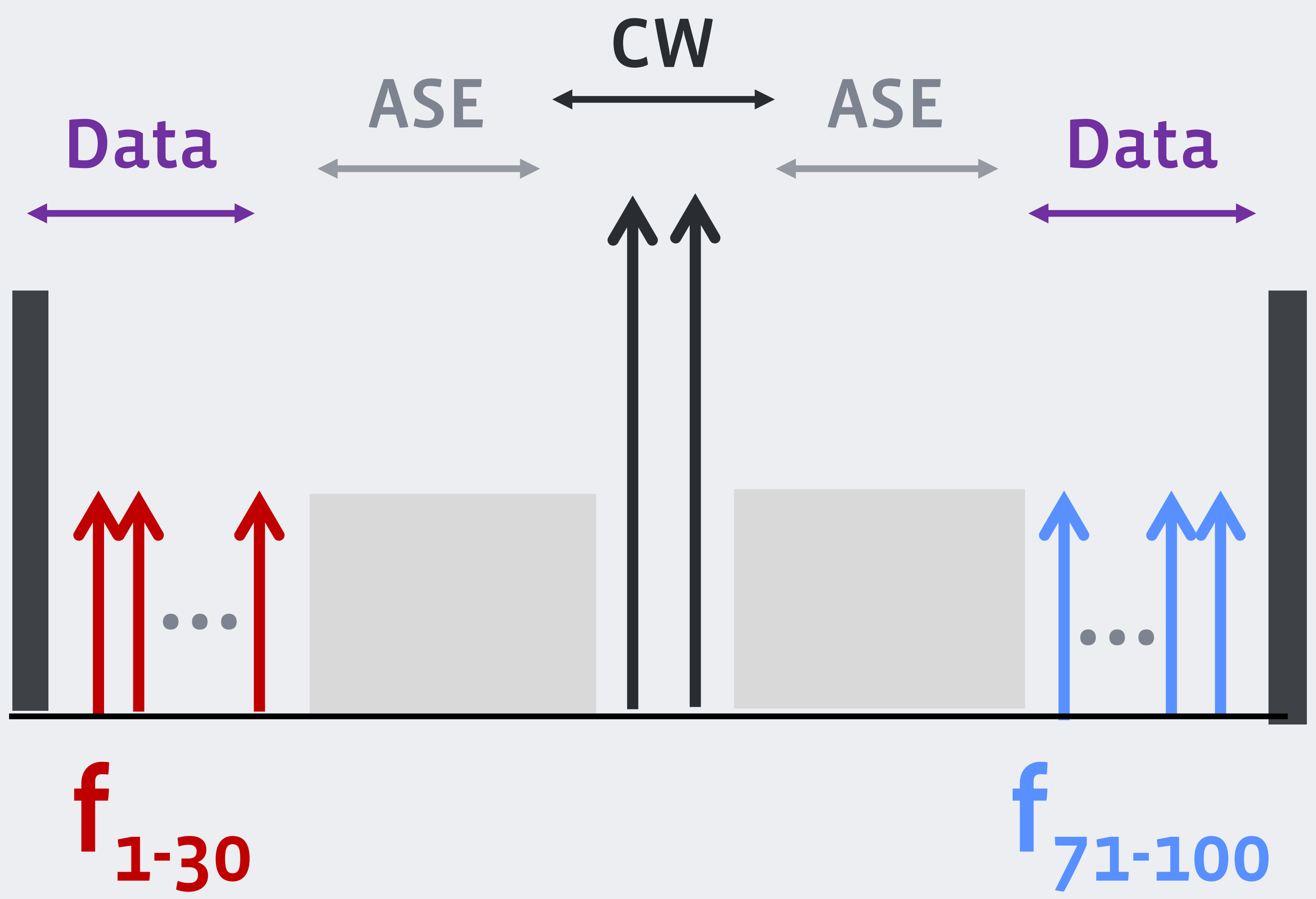
Not all Dummies are Created Equal…

- There are two kinds of dummy lights used in Subsea:
  - ASE based idlers (banded or channelized)
  - Continuous Wave (CW) idlers (unmodulated lasers)

Typical of D+ Cables:



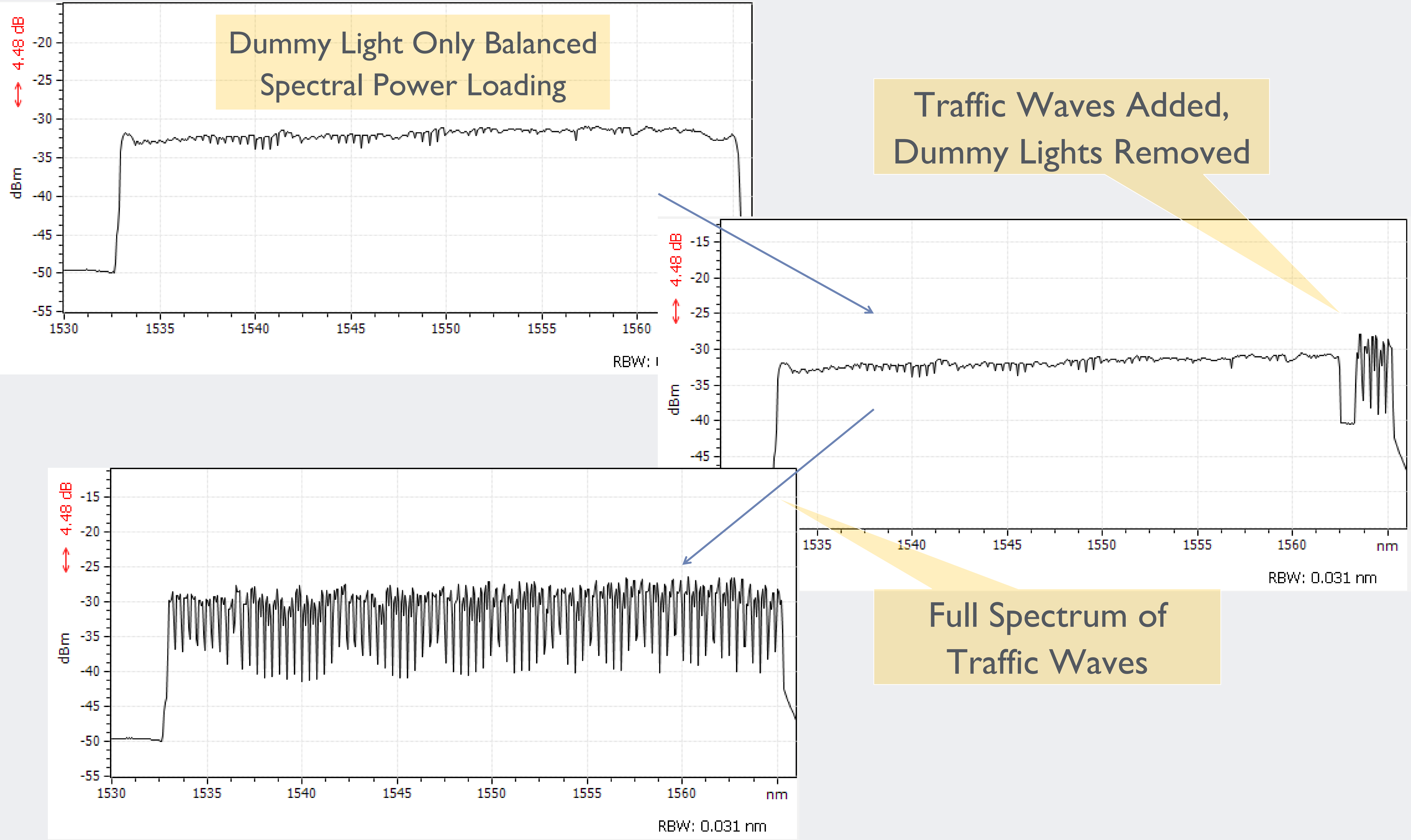
Typical of Legacy Cables:



We will discuss more tomorrow on when and how each are used in upgrades and deployments!

Courtesy of: ciena

Spectrum Power Management with Dummy Lights



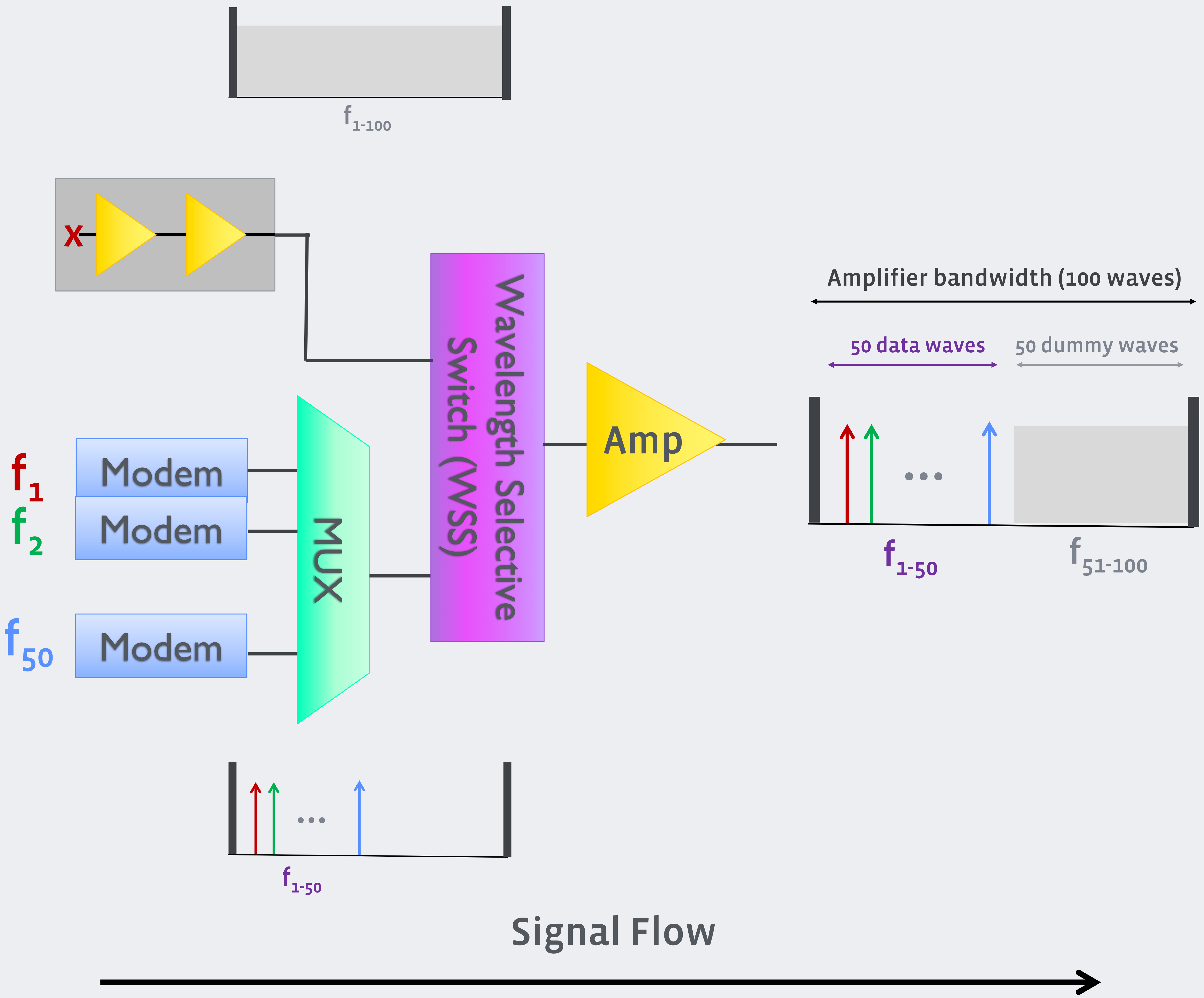
Dummy Light Only Balanced Spectral Power Loading

Traffic Waves Added, Dummy Lights Removed

Full Spectrum of Traffic Waves

Creating & Managing Dummy Waves

- Dummy Waves ideally need to be cheap, so ASE idlers are preferred, and are typically just generated as broadband noise
  - Can be generated very simply with cascaded amps
- With multiple signals from multiple sources (dummy waves & traffic waves), more advanced multiplexing / de-multiplexing is needed
- Wavelength Selective Switches (WSS) are used to enable source selection from a number of inputs, slice up the broadband ASE into desired sizing AND perform power control on a per wave basis

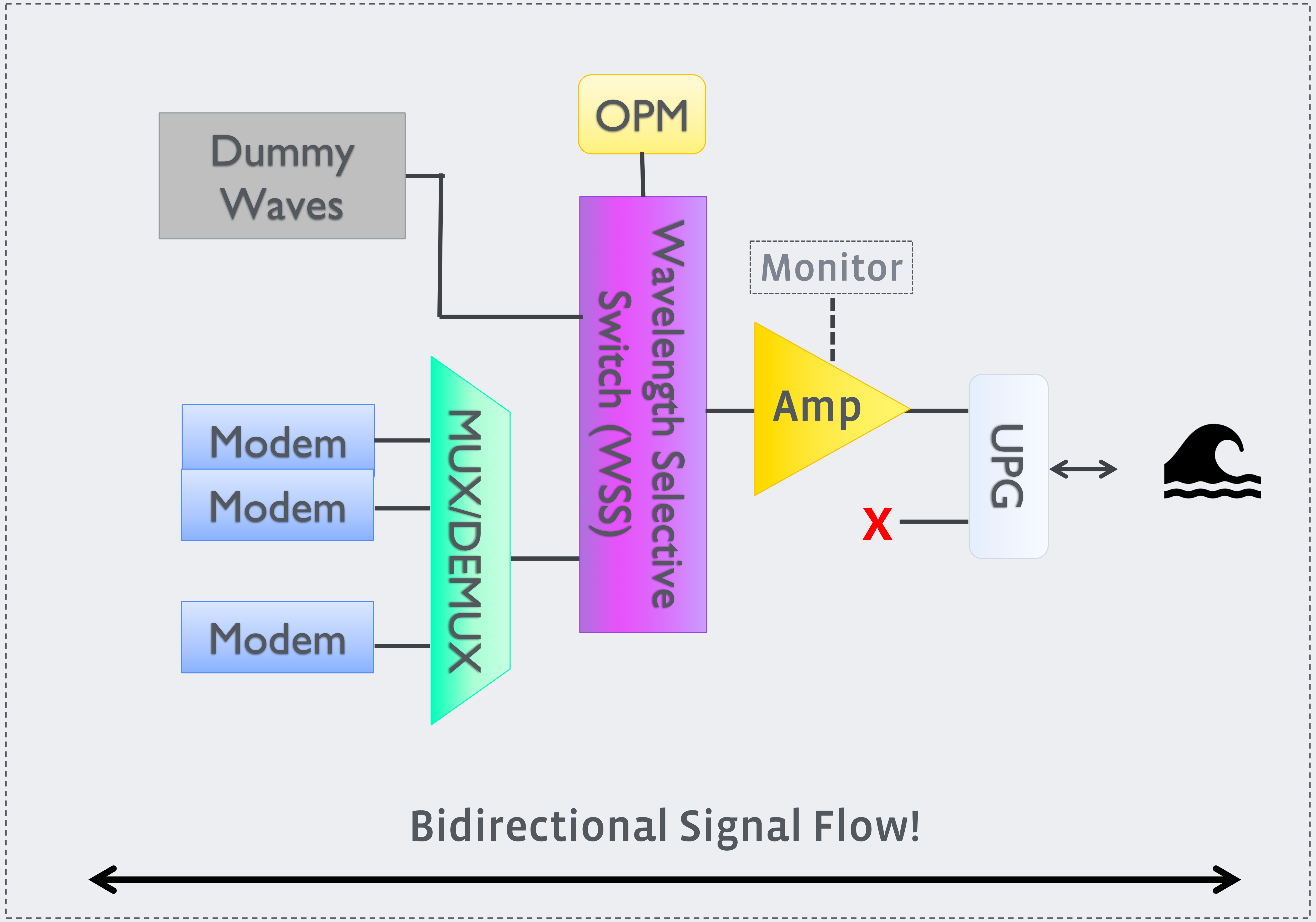


Submarine Line Terminating Equipment (SLTE)

We have now discussed the key functional building blocks of SLTE!

In reality, there are a few extra bits added:

- Optical Power Monitoring (OPM), which allows us to measure the optical spectrum (power vs frequency)
- Upgrade Couplers, which leave an open port for added equipment insertion in case you ever want to replace your equipment without traffic interruption
- Monitor Points, allowing you debugging capabilities at different points if anything ever goes wrong
- All these components are designed bidirectionally with dual fibers for management of each flow



Courtesy of: ciena

SLTE – A Real Example

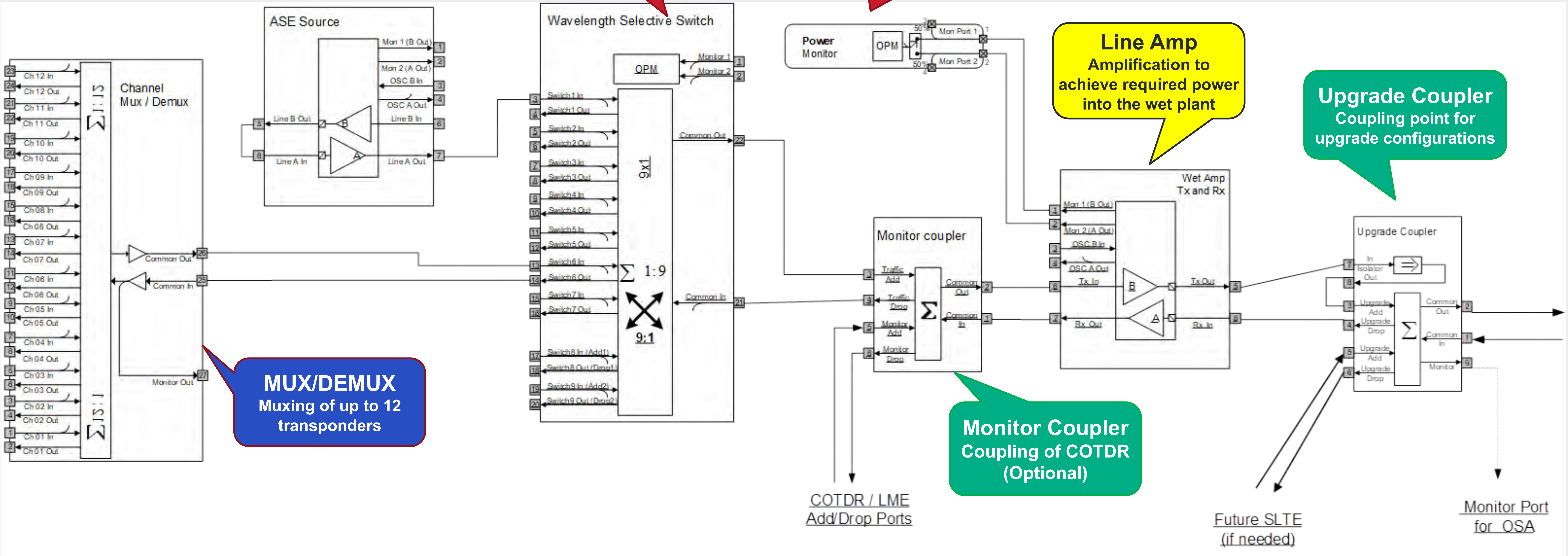
A Typical SLTE includes:

- Transponders Mux/Demux stage
- Dummy Waves
- SLTE Core Control
- Amplification Stage
- Open Coupling & Monitoring Points

ASE Source
Generation of amplified spontaneous emission (ASE) dummy waves

WSS
Spectral selection and spectral attenuation of signals present on one or more of the input ports

OPM
Spectral power measurement



Line Amp
Amplification to achieve required power into the wet plant

Upgrade Coupler
Coupling point for upgrade configurations

MUX/DEMUX
Muxing of up to 12 transponders

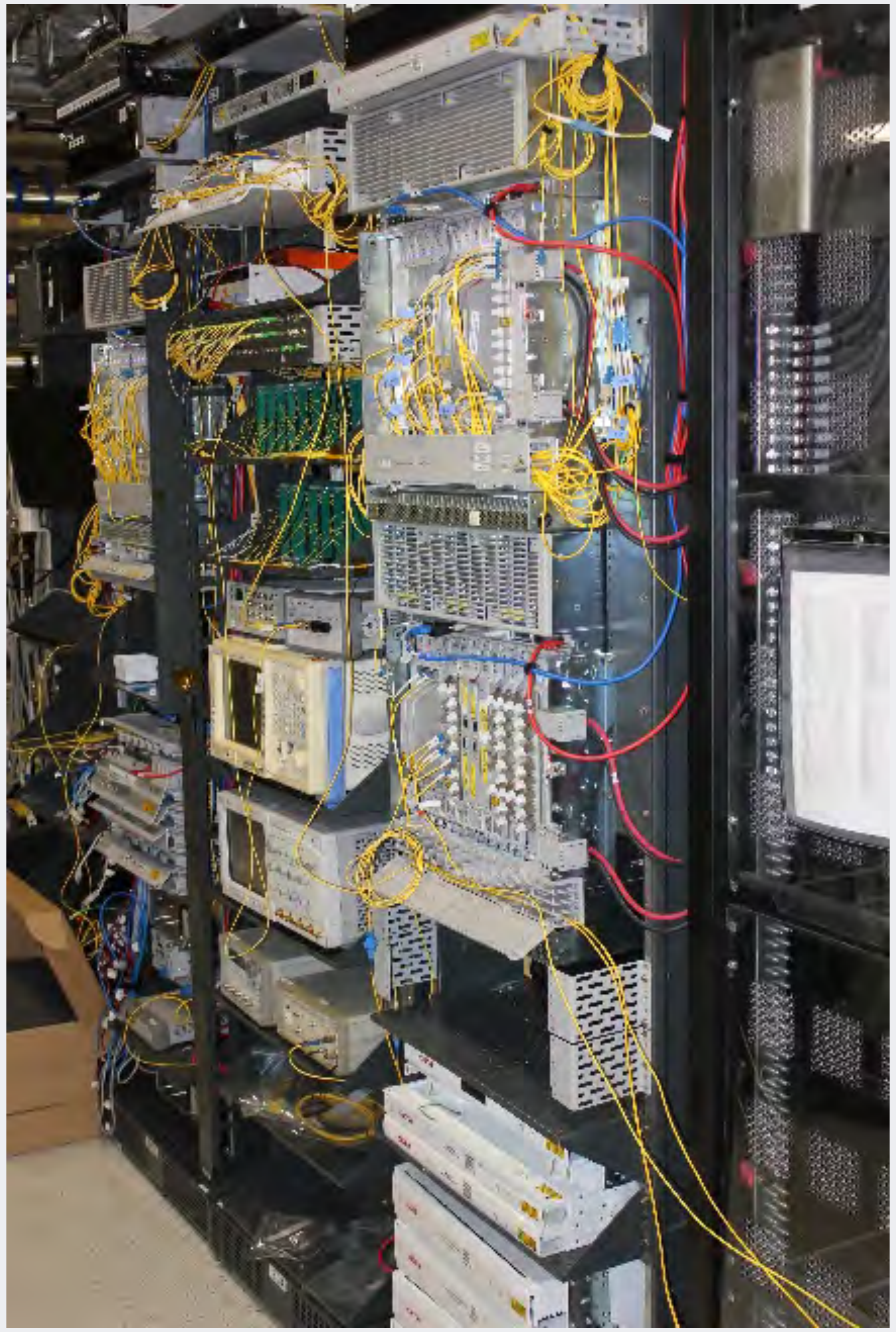
Monitor Coupler
Coupling of COTDR (Optional)

Courtesy of: ciena

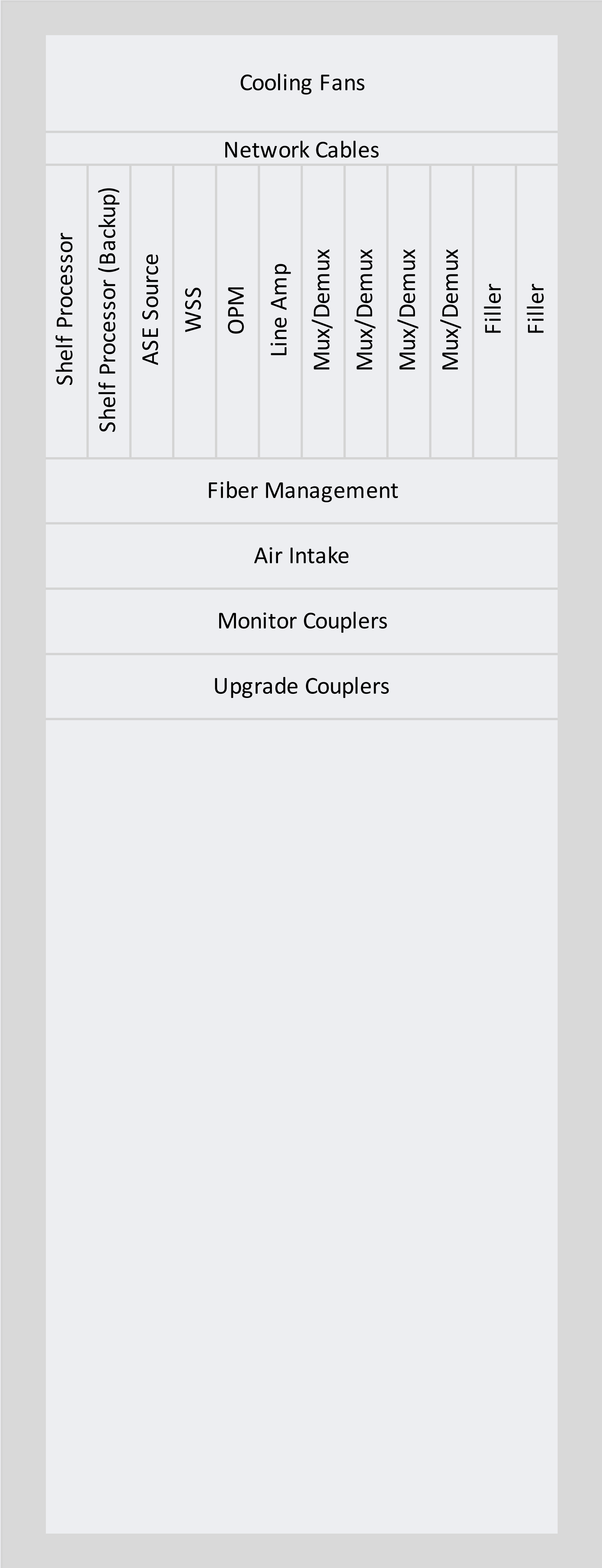
SLTE – A Real Example

Portable SLTE – For Field Trials!

Permanent SLTE – For Lab Tests!



Permanent SLTE Rack Diagram



Cooling Fans

Network Cables

Shelf Processor
Shelf Processor (Backup)
ASE Source
WSS
OPM
Line Amp
Mux/Demux
Mux/Demux
Mux/Demux
Mux/Demux
Filler
Filler

Fiber Management

Air Intake

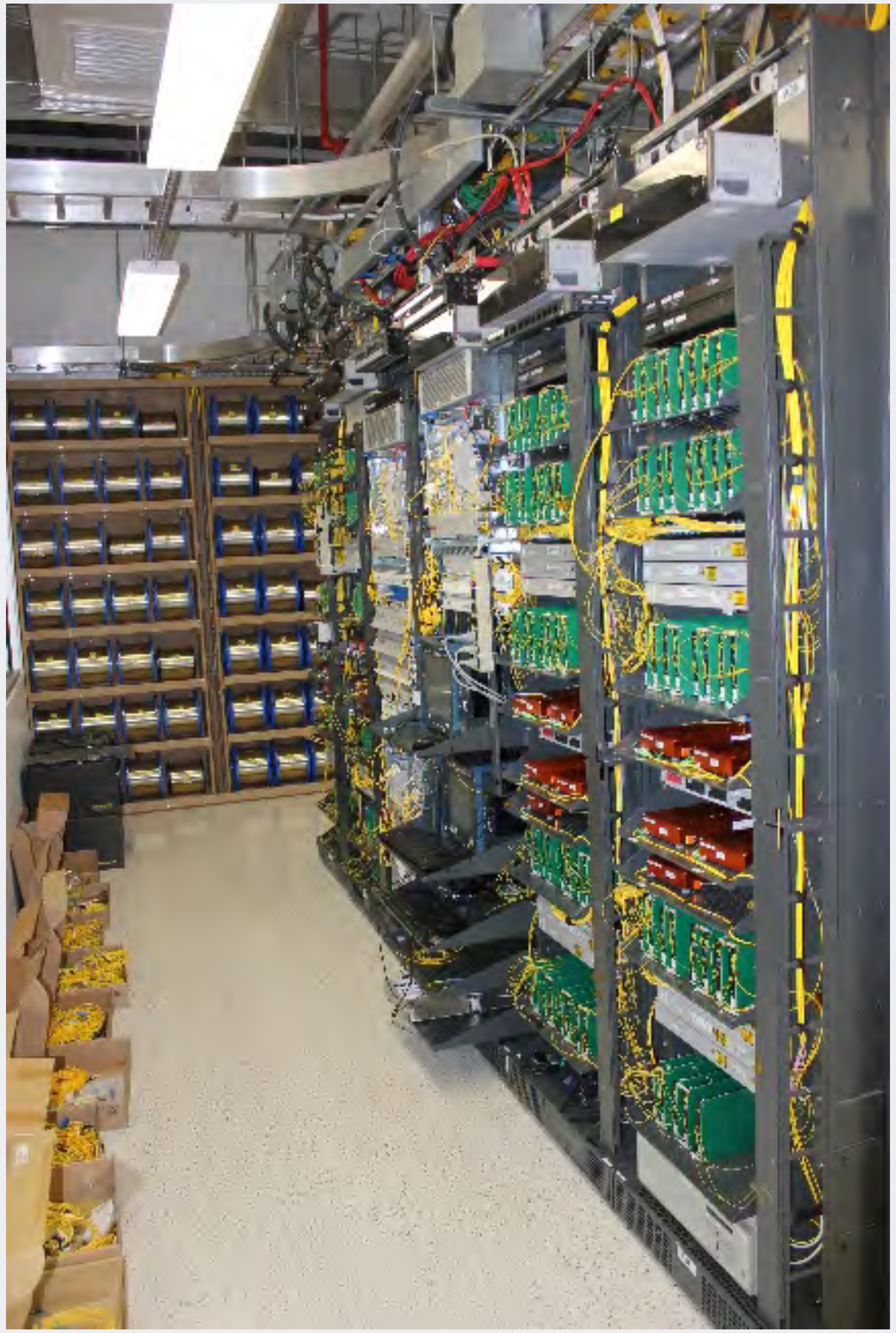
Monitor Couplers

Upgrade Couplers

Courtesy of: ciena

A Submarine Line System in a Lab

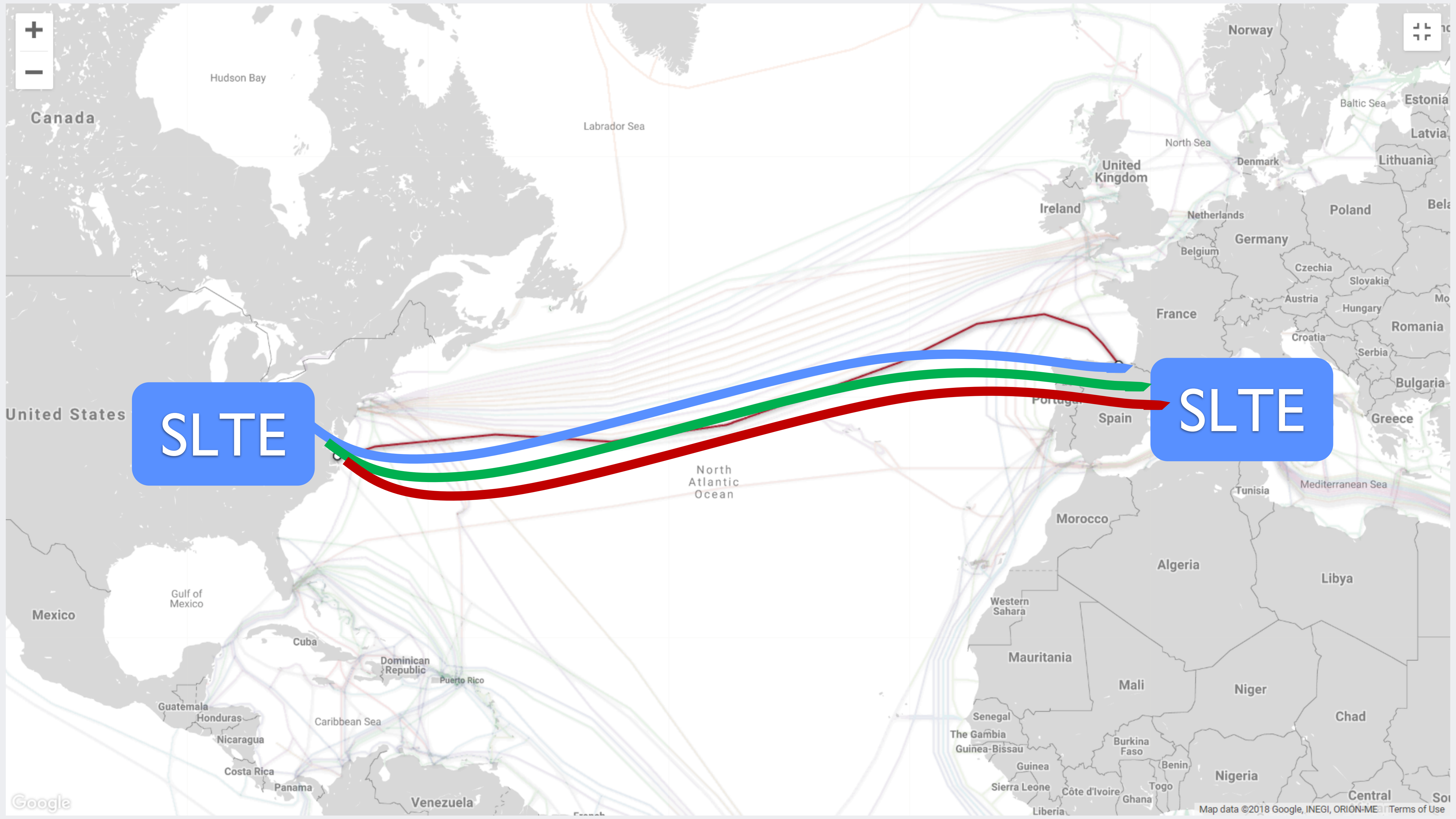
Spools of Submarine Fiber

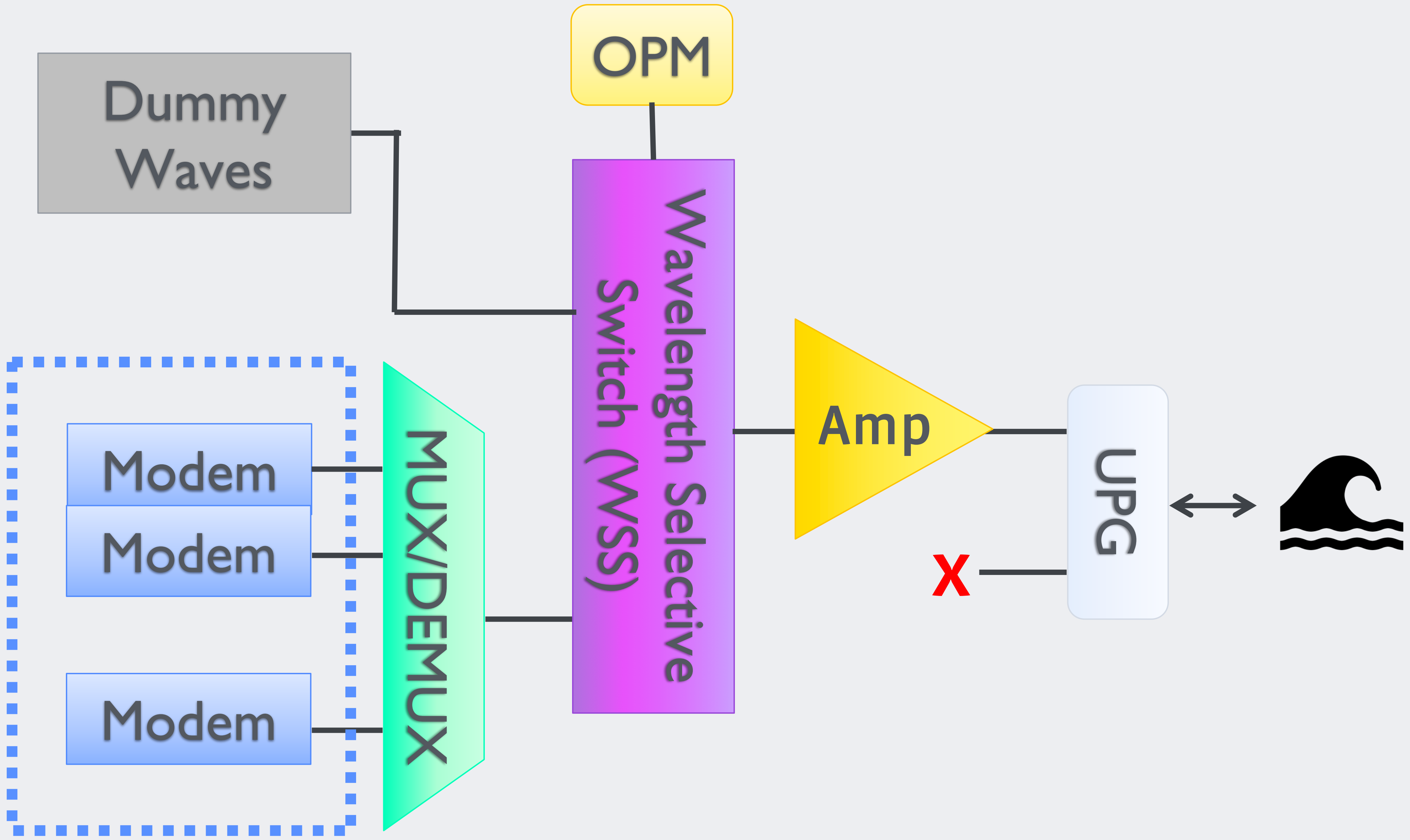


Banks of EDFAs & Equalizers

Summary of SLTE & on to Advanced Modems!

We’ve covered the functions and building blocks of an SLTE. Now let’s go into the many features of advanced modems: past, present and future!





Advanced Modems & Features

Courtesy of: ciena

Coherent Modems – Quick Recap!

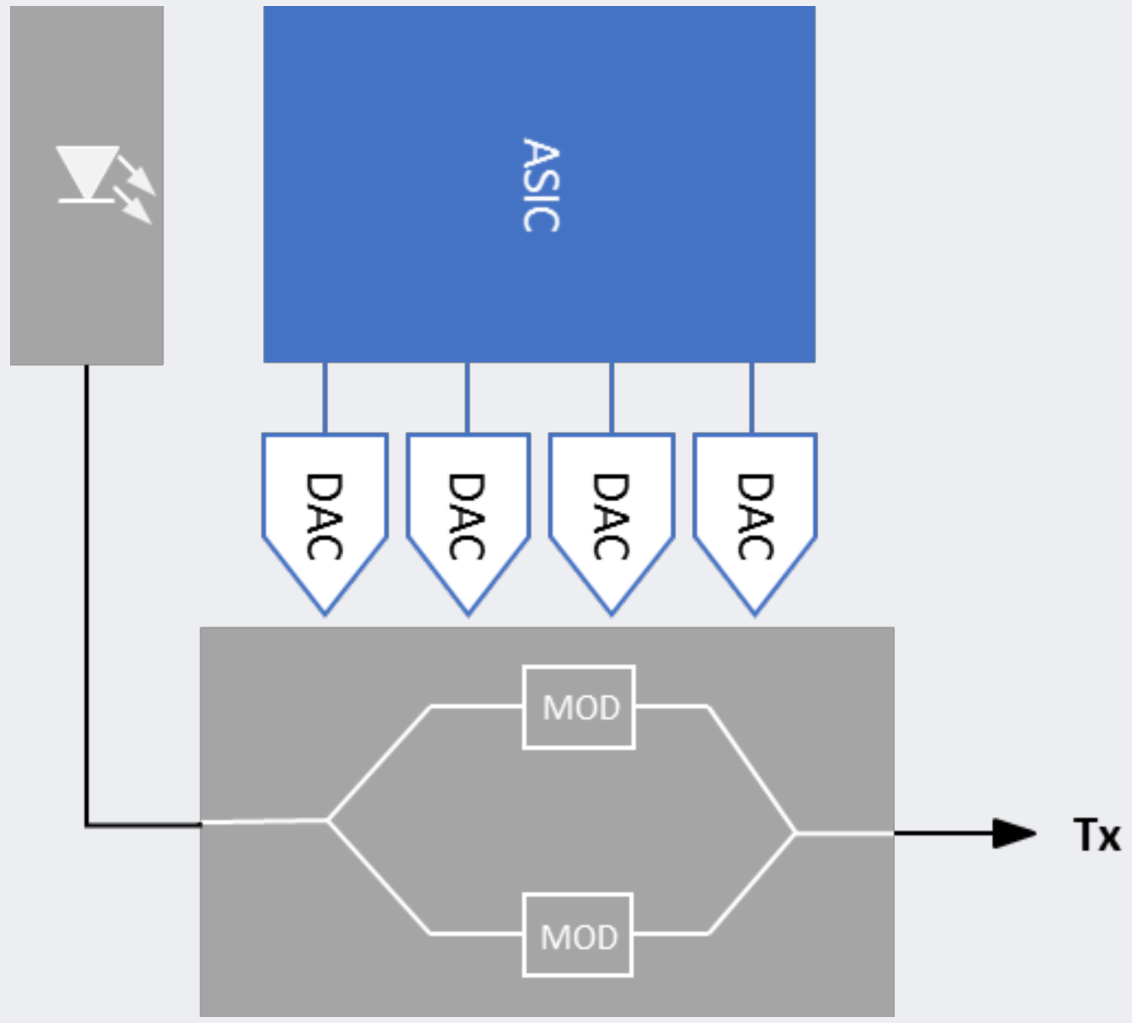
Key components – Transmit Side

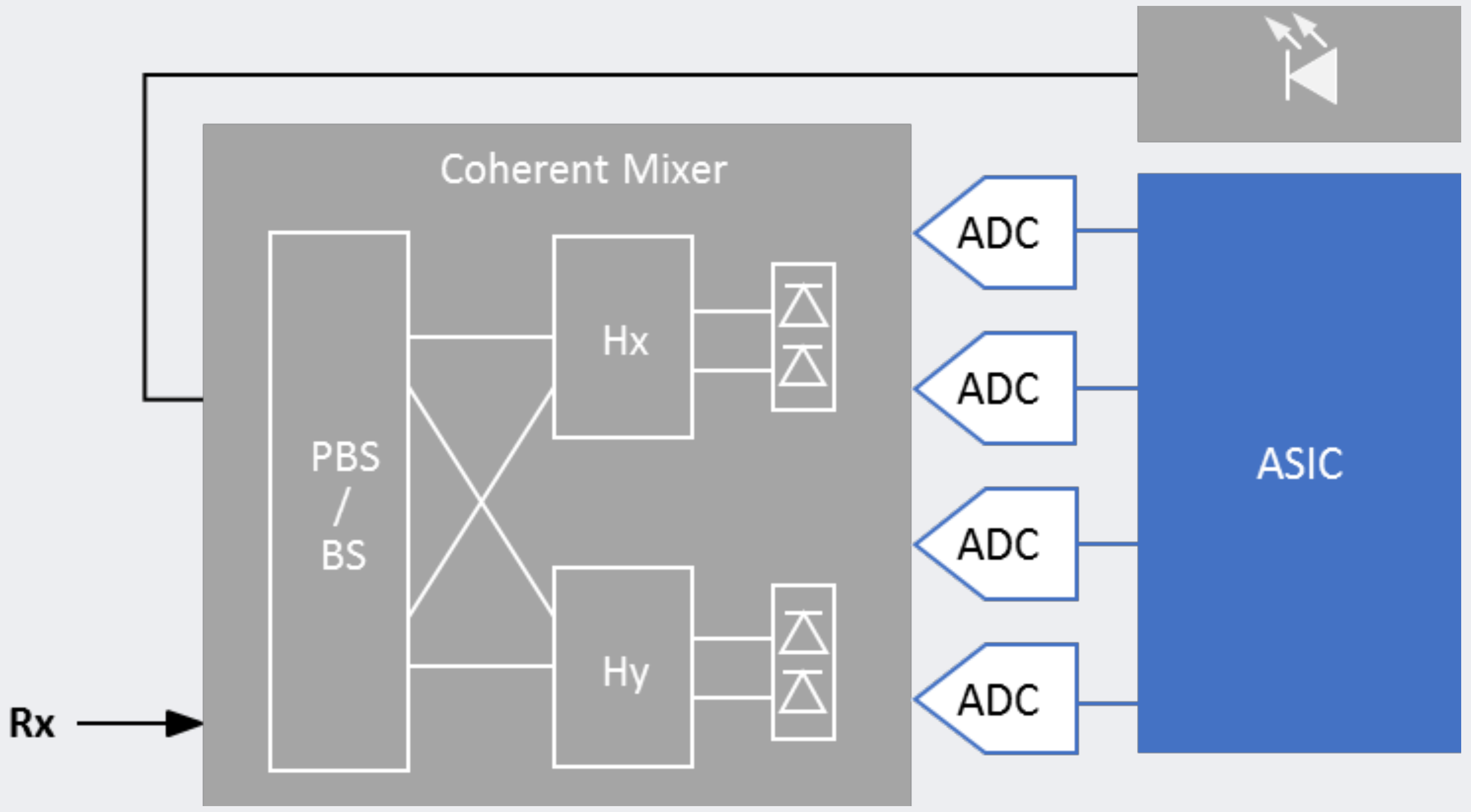
- Tx Laser (analog)
- Coherent Modulator (analog)
- DACs (mixed – digital to analog)
- ASIC (digital)

$$$

Key components – Receive Side

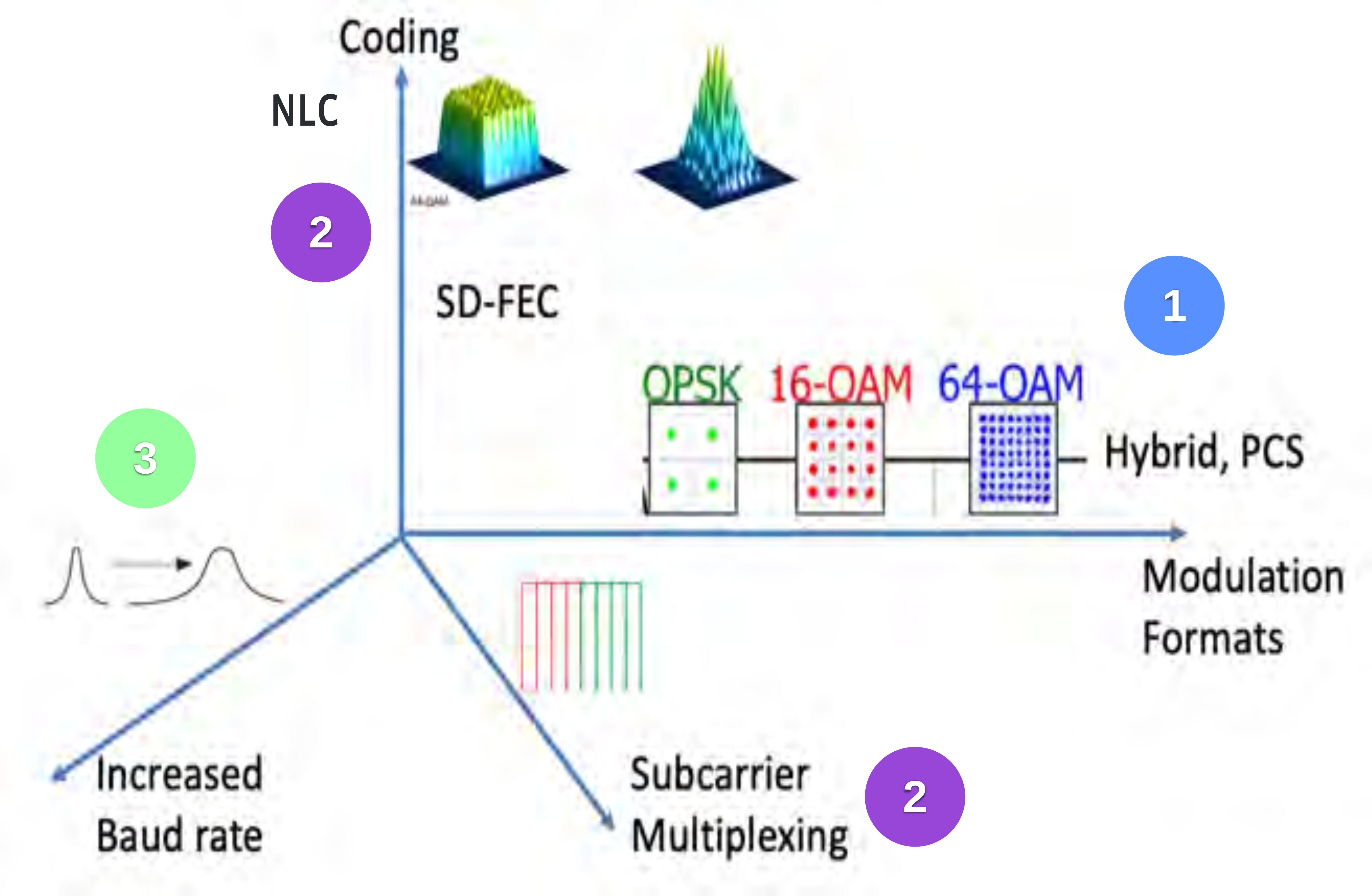
- Rx Laser or Local Oscillator (analog)
- Coherent Mixer (analog)
- ADCs (mixed – analog to digital)
- Electro-optics (analog)
- ASIC (digital)





Coherent Modems – The Workhorse

Advances in coherent modems have been THE core technology driver in the past decade to increasing capacity of fiber optic systems worldwide!



Improvements have been made along a few key axes, each enabling us to do one or more of the following things:

1 – Increase the number of bits sent with each symbol (how many bits/symbol)

2 - Improve the performance, or noise tolerance, at a given capacity per wave (how far those bits can travel)

3 – Increase the capacity on a single wave using the same modulation (how many symbols/s) → more on this later!

Coherent SLTE Technology Generations

	1st Gen Coherent	2nd Gen Coherent	3rd Gen Coherent	4th Gen Coherent
Year	2010	2012-2015	2016-2019	2020+
Data Rate	40G	50G / 100G / 150G / 200G	100G – 400G	200G – 800G
Baud Rate	~11 Gbaud	~28-35 Gbaud	~40-60 Gbaud	~62-95 Gbaud
Highest Order Modulation	QPSK (& BPSK)	16QAM (&BPSK, QPSK, 8QAM)	32QAM (& below)	64QAM (& below)
Key New Technologies	Coherent CD & PMD Comp	1st Gen Features plus: SD-FEC Tx CD pre-dispersion	2nd Gen Features plus: 4D/8D mod formats, custom modulations, Nyquist shaping Improved FEC NCG	3rd Gen Features plus: Const. Shaping (PCS) improved FEC NCG, variable baud rates, Nonlinear comp (NLC), more…
Silicon Process	90nm	28-64nm	16-28nm	7nm

Question:

On a given link, will you get more capacity out of 200G or 300G waves?

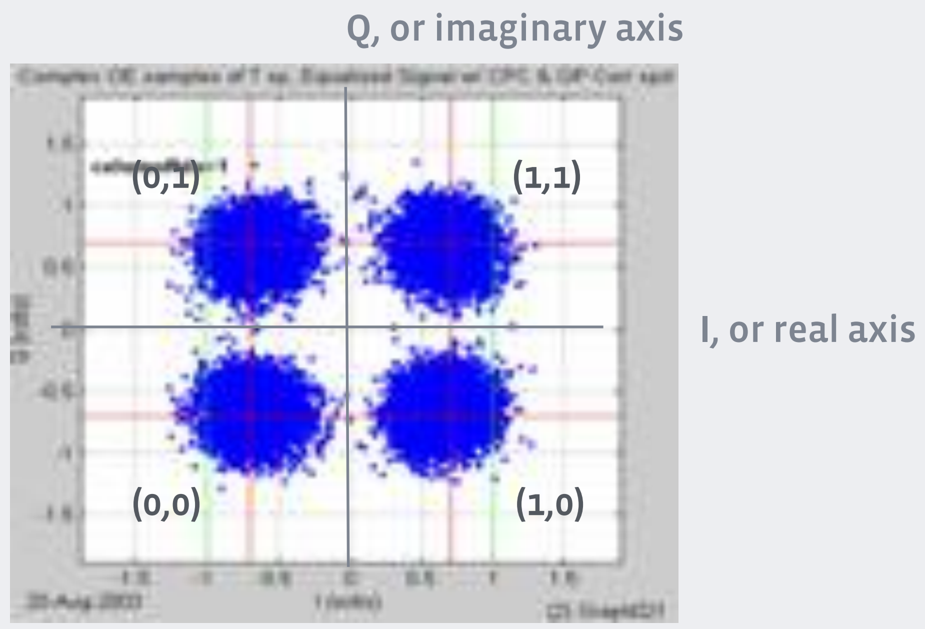
It's a trick question 🙄

- 200G could mean 33 Gbaud 16QAM, which might give you 24Tb/s of capacity (120 x 37.5GHz = 4.5THz)
- 200G could also mean 66 Gbaud QPSK, which would give you 12Tb/s of capacity (60 x 75GHz = 4.5THz)

Per wavelength capacity does not tell the whole story!!

Spectral efficiency is the key capacity metric.

Bits, Bauds & Modulations



33 Gbaud Wave, QPSK

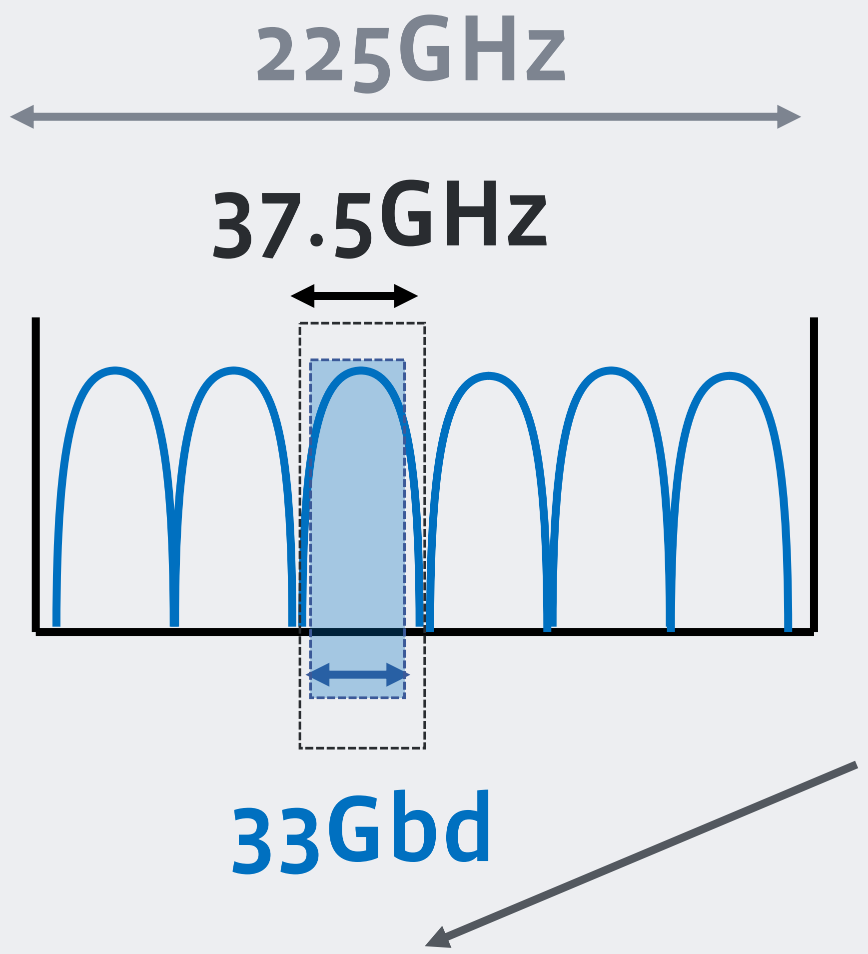
- 33GHz channel, occupying 37.5GHz
- 25 Gsymbols/s for data, plus 32% OH
- QPSK constellation enables 2 bits/symbol
- 25 Gsymbols/s * 2 bits/symbol * 2 pols
- Channel capacity of 100 Gb/s in 37.5GHz
- Spectral Efficiency of 2.67 b/s/Hz

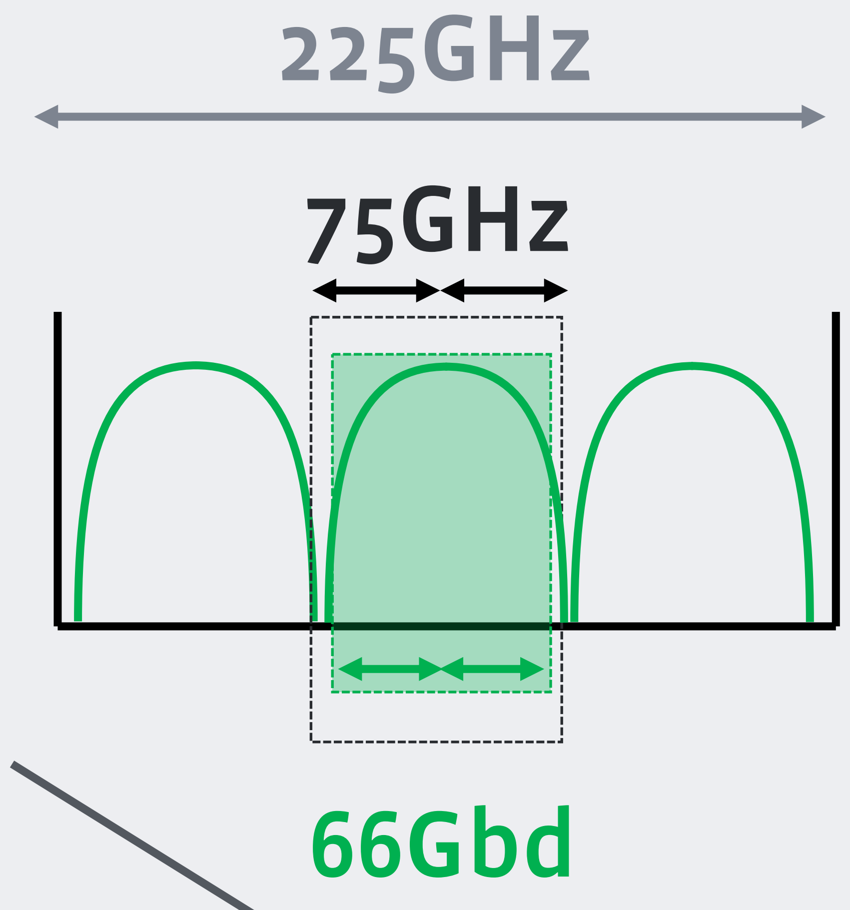
66 Gbaud Wave, QPSK

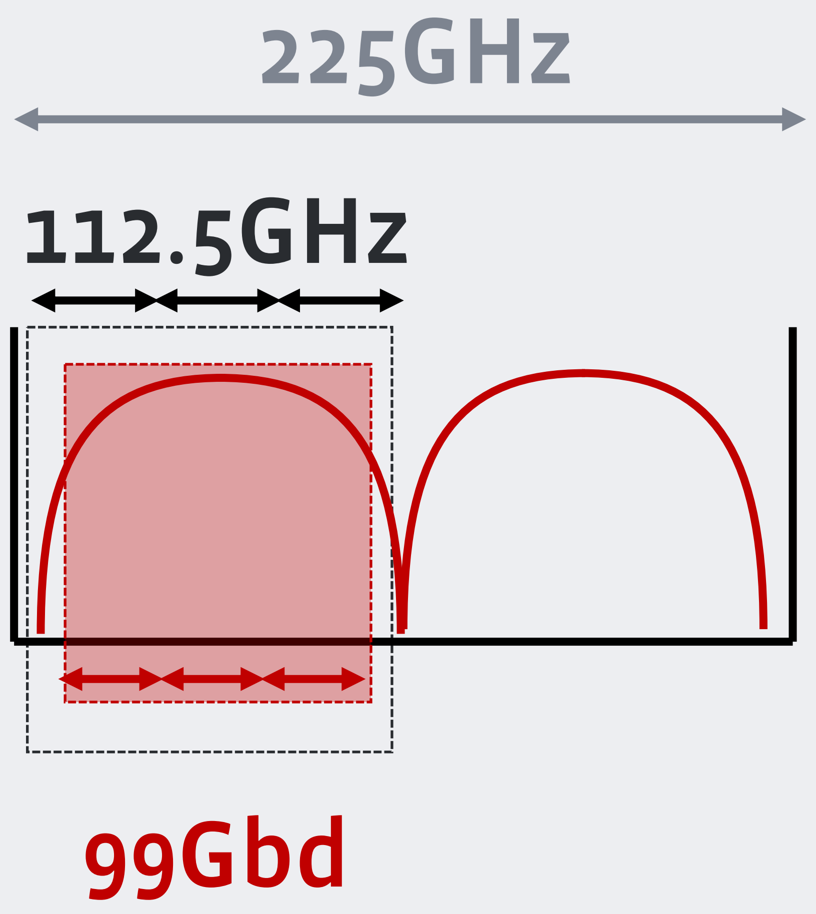
- 66GHz channel, occupying 75GHz
- 50 Gsymbols/s for data, plus 32% OH
- QPSK constellation enables 2 bits/symbol
- 50 Gsymbols/s * 2 bits/symbol * 2 pols
- Channel capacity of 200 Gb/s in 75GHz
- Spectral Efficiency of 2.67 b/s/Hz

99 Gbaud Wave, QPSK

- 99GHz channel, occupying 112.5GHz
- 75 Gsymbols/s for data, plus 32% OH
- QPSK constellation enables 2 bits/symbol
- 75 Gsymbols/s * 2 bits/symbol * 2 pols
- Channel capacity of 300 Gb/s in 112.5GHz
- Spectral Efficiency of 2.67 b/s/Hz







Per wavelength data rate is often used when comparing technology…but it can be deceiving!

6 x 100G QPSK
2.67 b/s/Hz

3 x 200G QPSK
2.67 b/s/Hz

2 x 300G QPSK
2.67 b/s/Hz

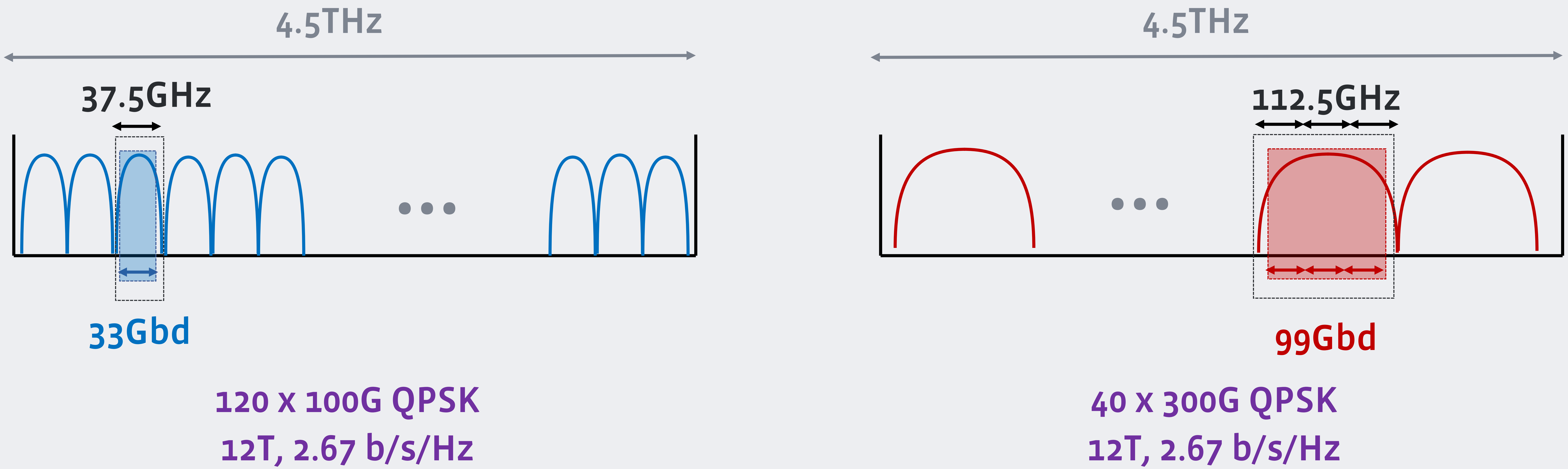
Higher data rate does not always mean higher fiber capacity!

Spectral efficiency is the best way to accurately compare technology!

So Wait…What's the Point of Increasing Baud?

Reason #1: Cost

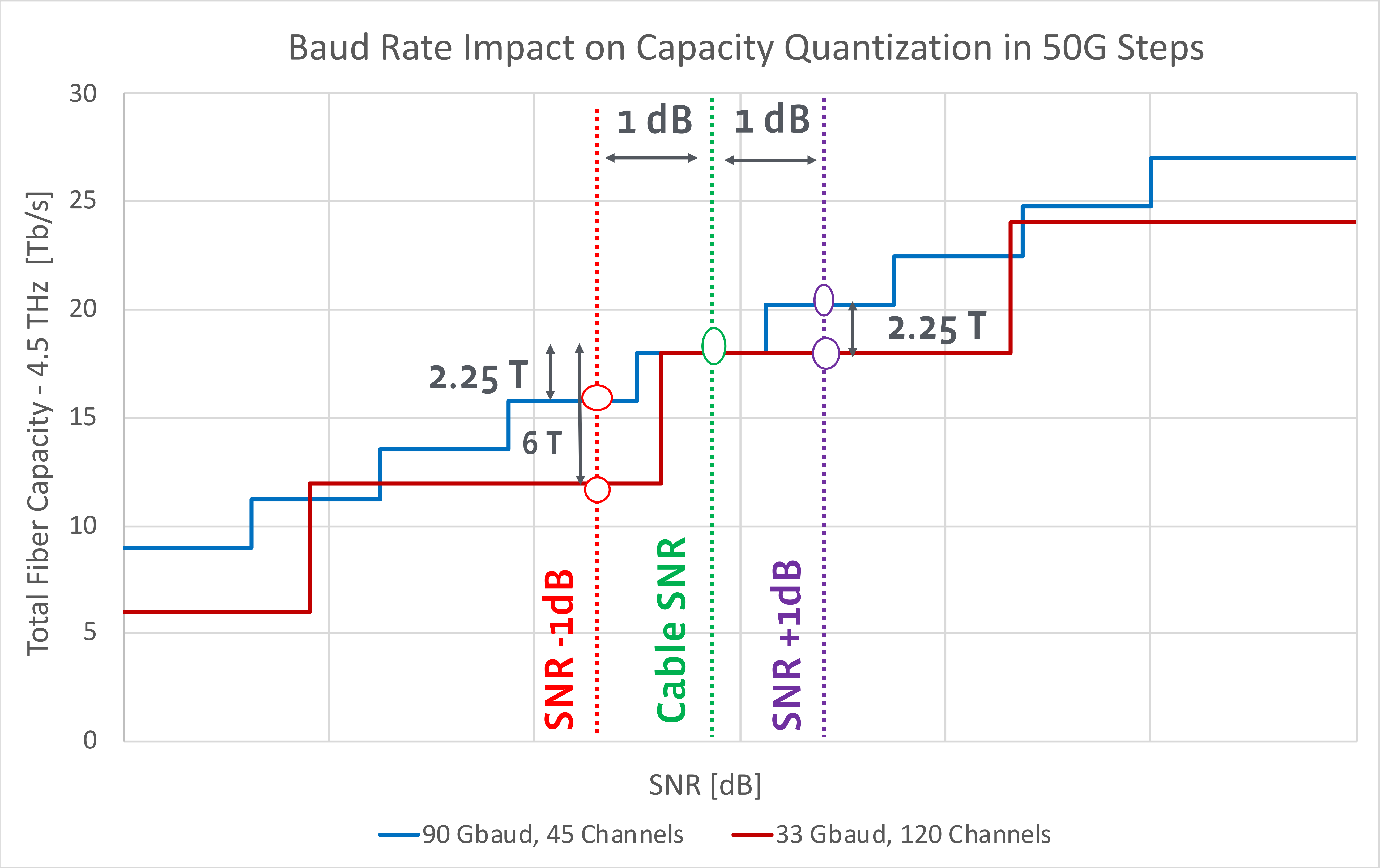
- ASIC development is the most expensive part of the coherent transponder
- High speed optics are challenging, but carry a smaller relative cost
- So, ***with the same DSP***, fewer transponders at higher baud should result in a lower total cost of capacity



Maximizing Capacity with High Baud Multi-Rate Modems

Reason #2: Capacity (Wait, what?)

High baud, multi-rate modems have smaller required SNR step sizes between data rates, offering more granularity in extractable spectral efficiency on any given cable (and can easily mix data rates)



@ Cable SNR +1 dB:
High Baud = 20.25 Tb/s
Low Baud = 18 Tb/s

@ Cable SNR:
High Baud = 18 Tb/s
Low Baud = 18 Tb/s

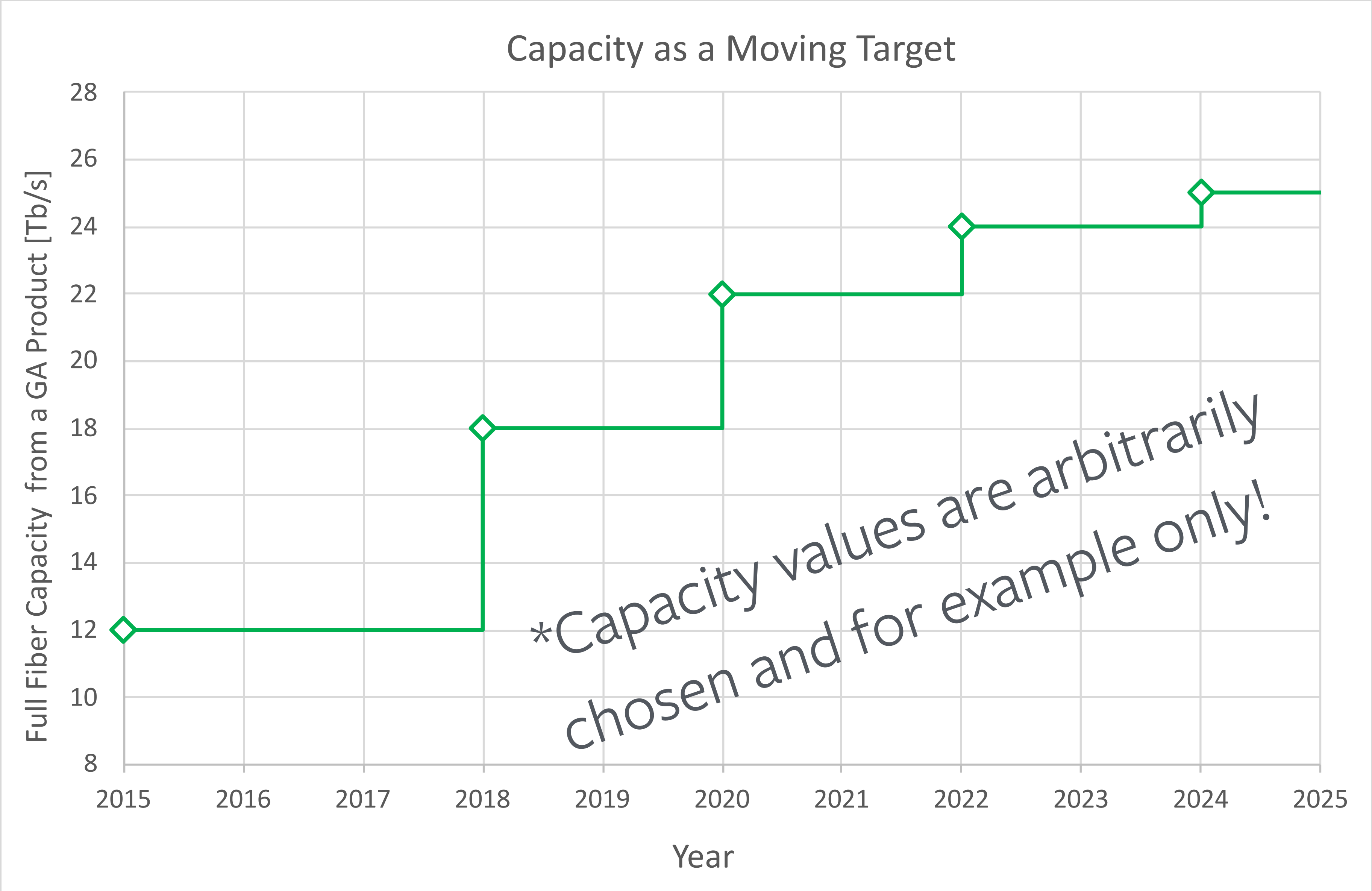
@ Cable SNR -1 dB:
High Baud = 15.75 Tb/s
Low Baud = 12 Tb/s

*Capacity values are arbitrarily chosen and for example only!

Capacity as a Moving Target

Capacity for a given subsea optical design, is a continually ***moving target*** with time

- In recent years, achievable capacity on a cable has been highly variable, with rapid changes in modem technology driving significant capacity improvements over original design capacities
- We have many vendors continually innovating and implementing new features & improvements, it is difficult to truly categorize "generations" of coherent – tech is constantly evolving!
- One thing remains consistent: the trend is compressing both as we approach Shannon's Limit and as we design more and more linear cables ("SDM")



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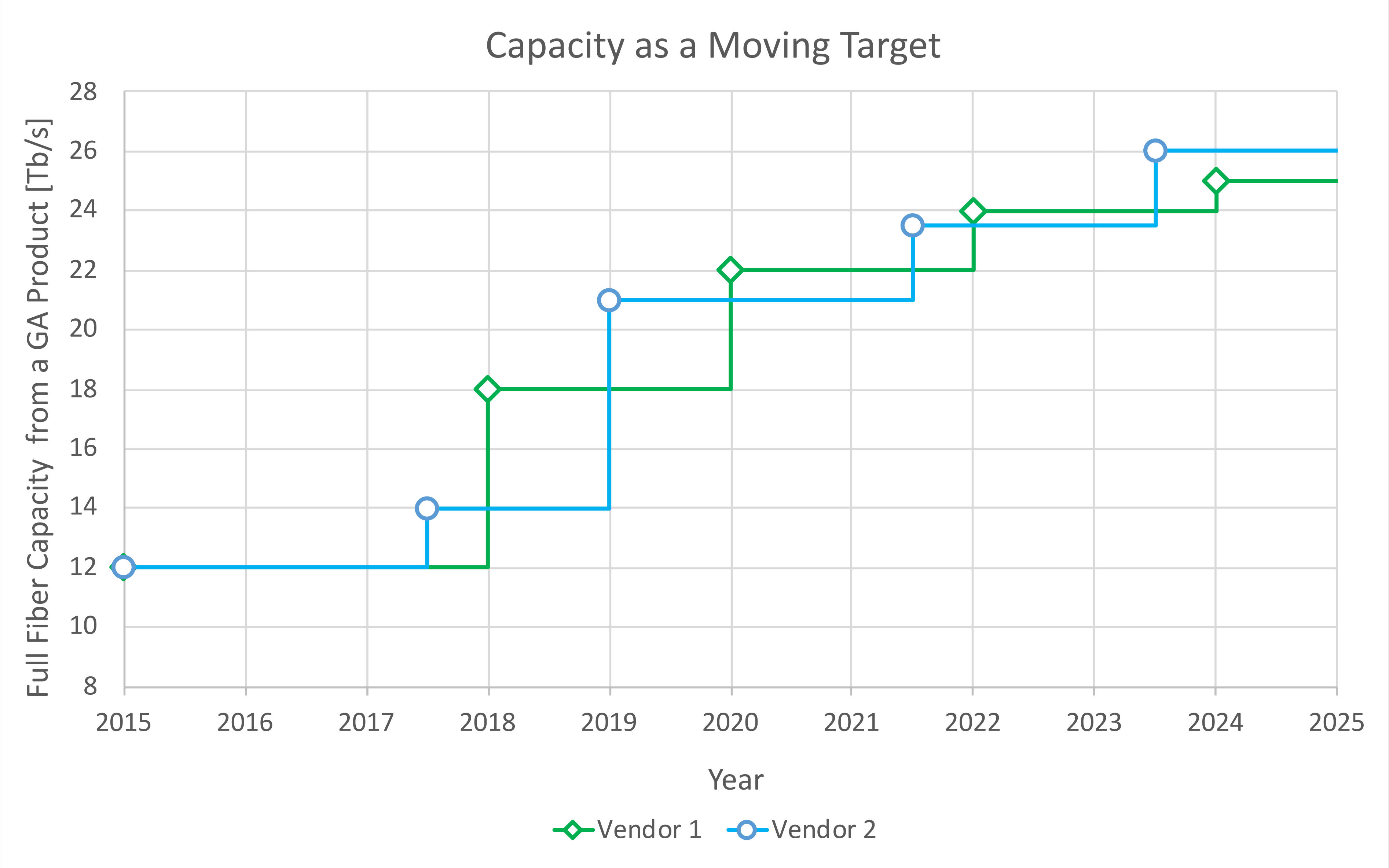


Coherent SLTE – Capacity Impact over the Years

	1st Gen Coherent	2nd Gen Coherent	3rd Gen Coherent	4th Gen Coherent
Year	2010	2012-2015	2016-2019	2020+
Data Rate	40G	50G / 100G / 150G / 200G	100G – 400G	200G – 800G
Baud Rate	~10 Gbaud	~28-35 Gbaud	~40-60 Gbaud	~62-95 Gbaud
"High Performance" D+ Trans-Atlantic (6,000km) *Example*	N/A *(D+ cables not common yet)*	100G QPSK 12 Tb/s	200G-250G Custom ~18 Tb/s	500G-600G PCS ~24 Tb/s
"High Performance" D+ Trans-Pacific (12,000km) *Example*	N/A *(D+ cables not common yet)*	100G QPSK 10 Tb/s	150G-200G Custom ~15 Tb/s	400G-500G PCS ~20 Tb/s

Subsea Performance Designs

Every submarine cable is uniquely designed to optimize performance, cost and availability at the required propagation distance:

1. Optical performance is primarily a balancing act of 2 important aspects:
    a. Linear performance (OSNR or $\mathrm{SNR}_{\mathrm{ASE}}$)
    b. Nonlinear performance (SPM/XPM/FWM/XPolM etc.)
2. More performance almost always equals more cost, so engineering trade-offs need to be made to find an optimal solution to the specific needs of the project
3. Availability drives many things, including marine routing (and as such distance)! There are some parts of the world where no subsea cable wants to go…

Like Here...

“Legacy” Submarine Wet Plant Designs

Fiber Type Acronyms

Dispersion Managed Cables:
“LEAF” Category – LCF, LMF, NZDSF
“LS” Category - RSF, HDF, NZDSF
“NDSF” Category - DCF, CMF, CSF
“DSF” Category – no aliases

Slope Matched Cables:
Positive – P, P-Type, D+
Negative – N, N-Type, D-

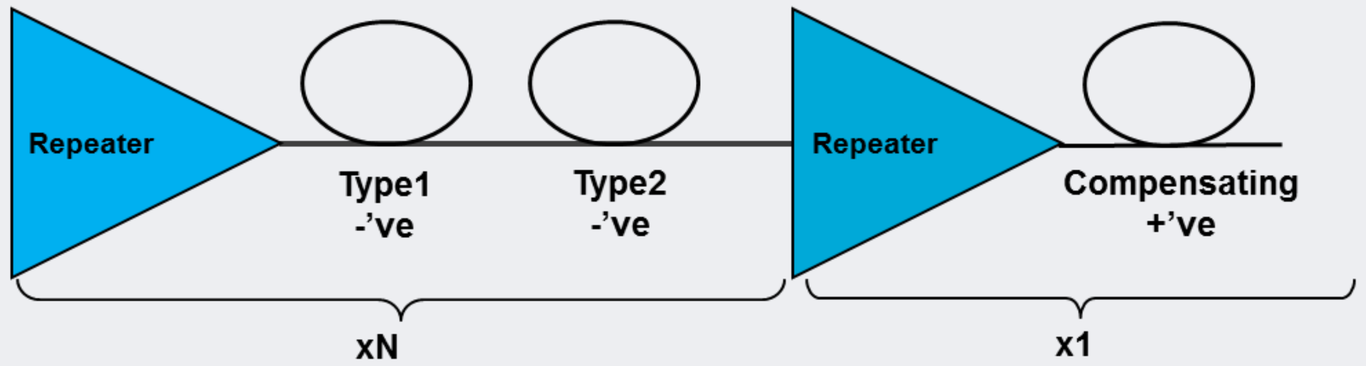
Dispersion Managed Cables

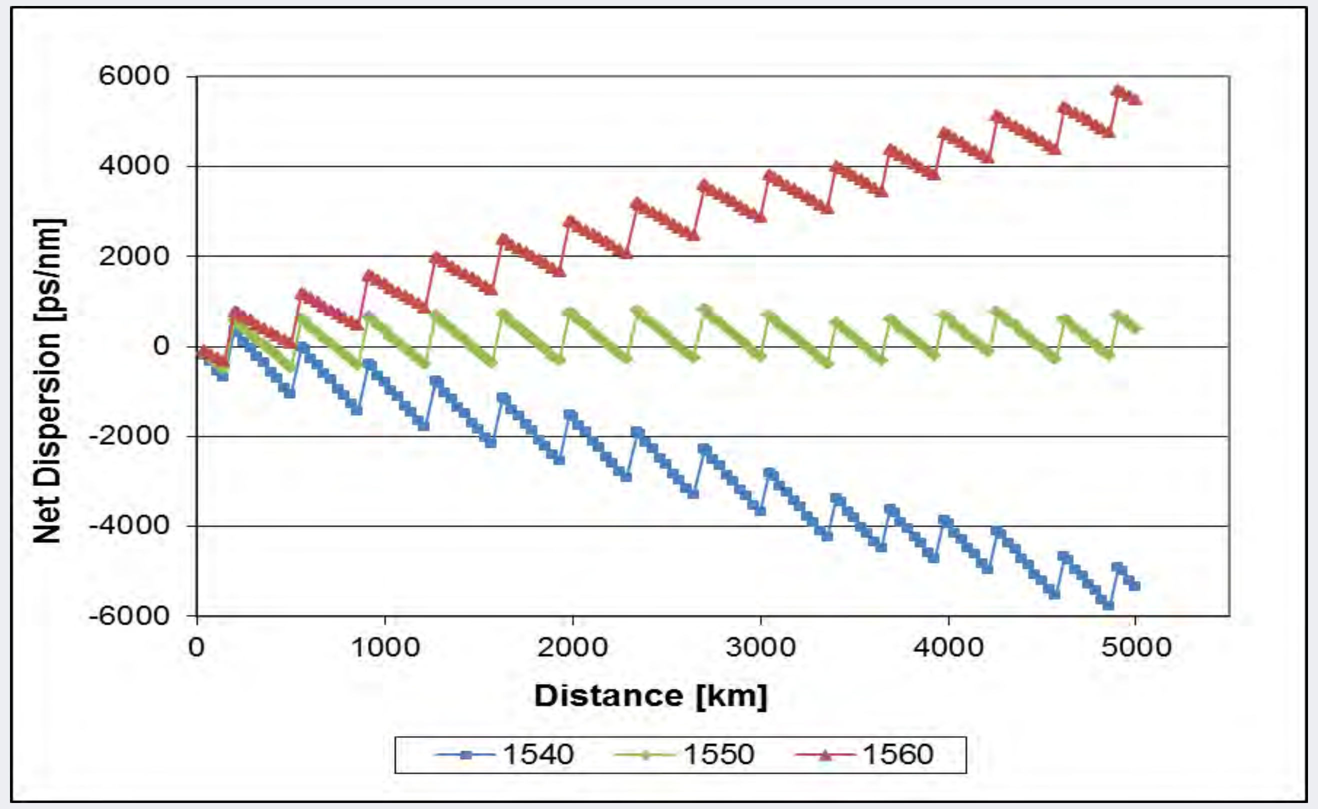
- Compensated systems used mixed fiber types to minimize dispersion & maximize performance of the target transmission technology of the time (Hint: it wasn’t coherent!)

- Two Primary Fiber Strategies on Legacy Cables:
  - Dispersion Managed, 3-Fiber Strategy
    - 2 primary propagation fibers
    - 1 compensating fiber
  - Slope Matched, 2-Fiber Strategy
    - 2 primary propagation fibers
    - 1 of the 2 fibers doubles for compensation

Standard Dispersion Managed 3-Fiber System

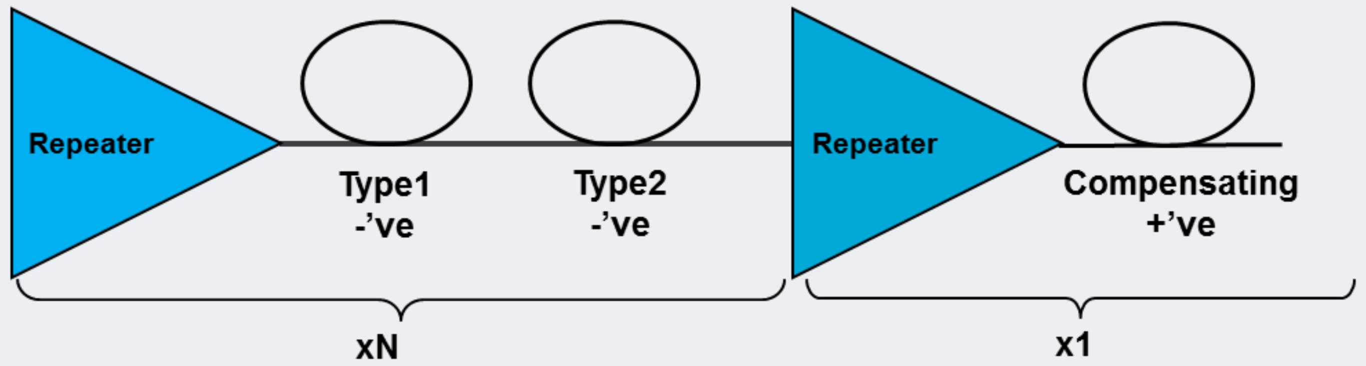
LEAF/LS + NDSF

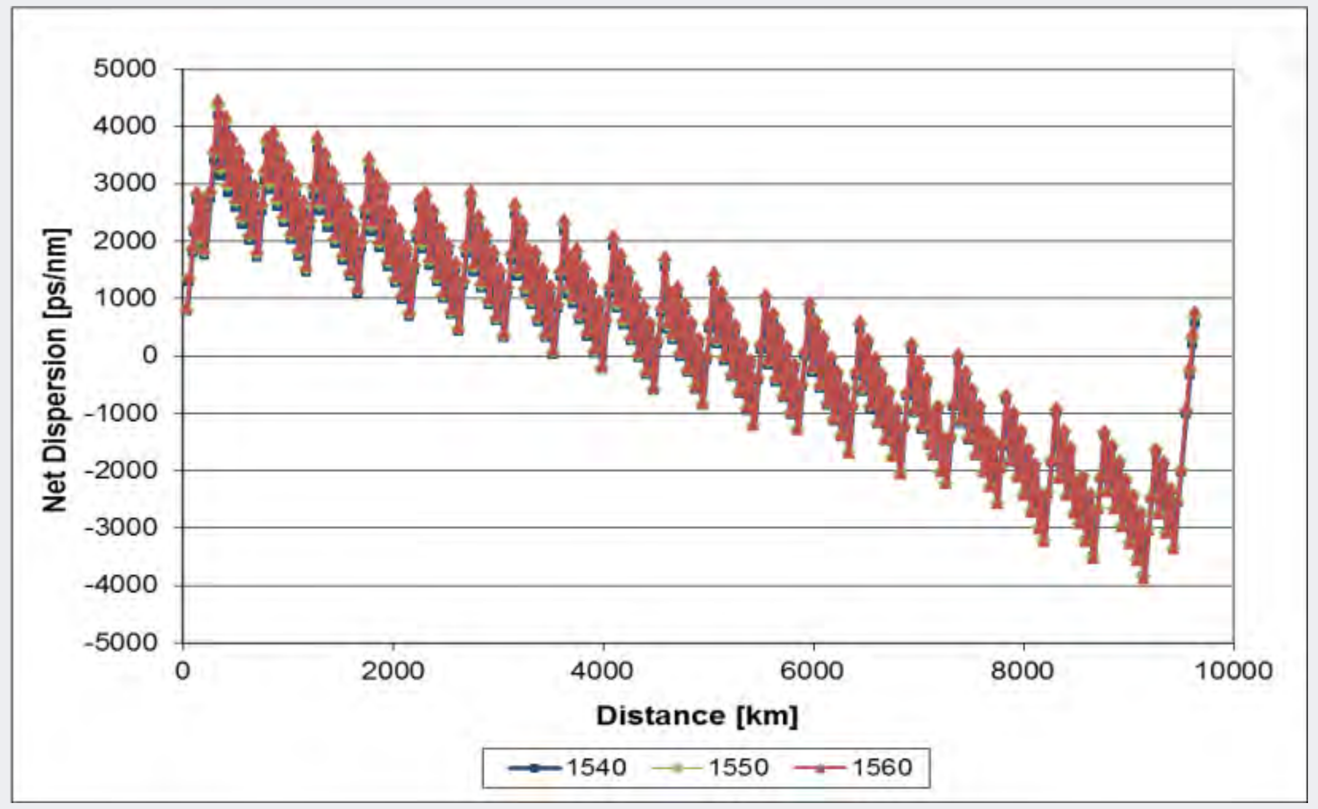




Standard Slope Matched 2-Fiber System

P/N + P

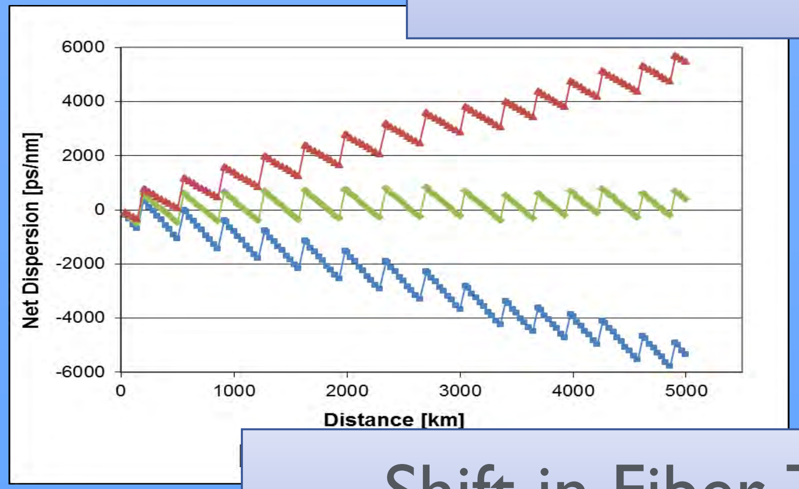
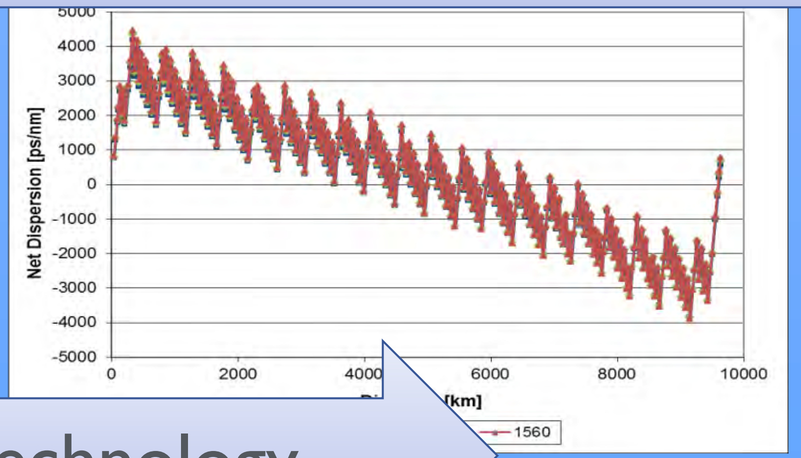
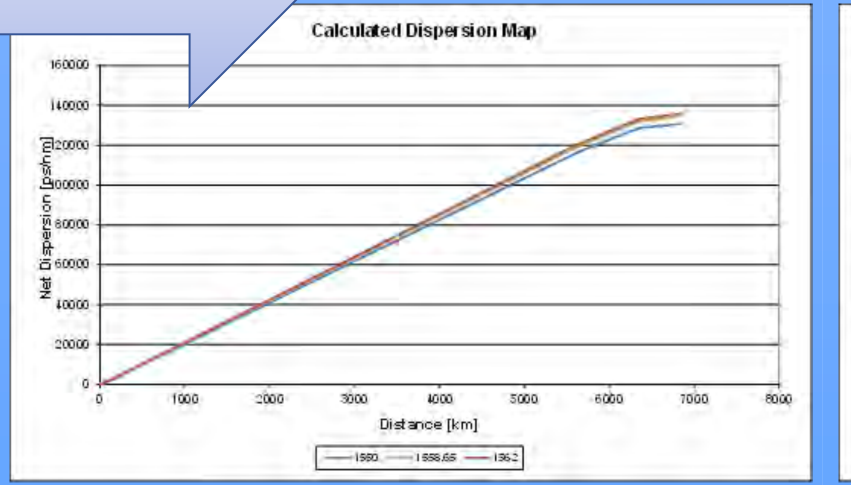
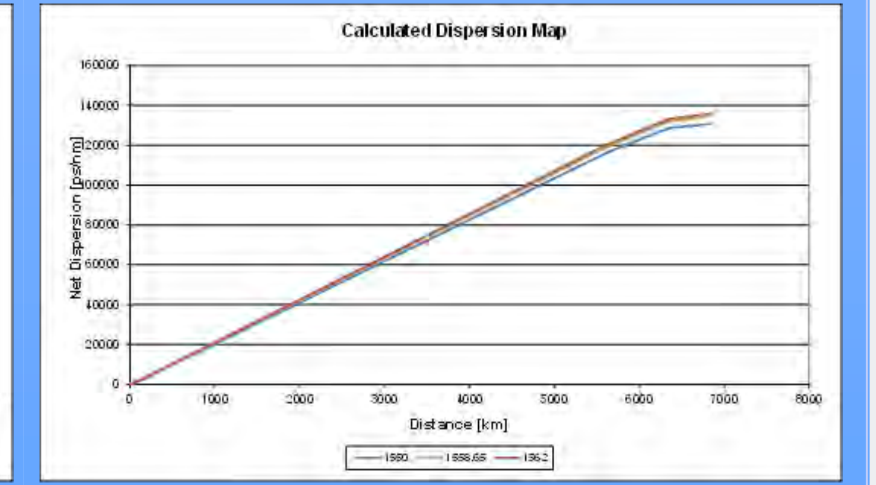




Evolution of Subsea Cable Designs

Limiter of Shannon Capacity

Limiter of Modem Gap to Shannon

	“Legacy Cables”		“New Builds” or “D+ Cables”	
	Dispersion Managed	**Slope Matched**	**Uncompensated (High TOP)**	**Uncompensated (SDM)**
Year of RFS	**2000 to 2008**	**2005 to 2012**	**2012 to 2020+**	**2021+**
Repeater BW	10nm to 27nm	27nm to 32nm	32nm to 40nm	36nm
Level of SNR	Low	Moderate	High	Moderate
Fiber A_{eff}	70 / 50	100 / 30	130 to 150	80 to 110
Degree of Nonlinearity	Ultra High	High	Low	Ultra Low
Max CD Excursion (Trans-Pacific)	+/- 8,000 ps/nm	+/- 1,000ps/nm	Up to +400,000 ps/nm	Up to +400,000 ps/nm
Typical CD Map				

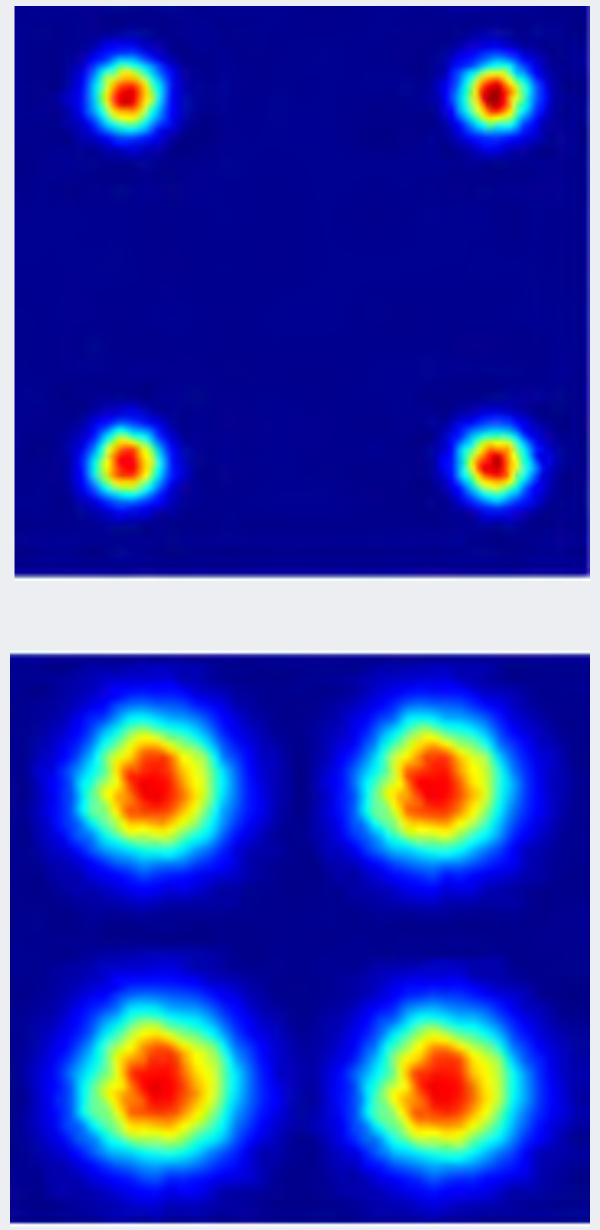
Shift in Transponder Technology: Coherent

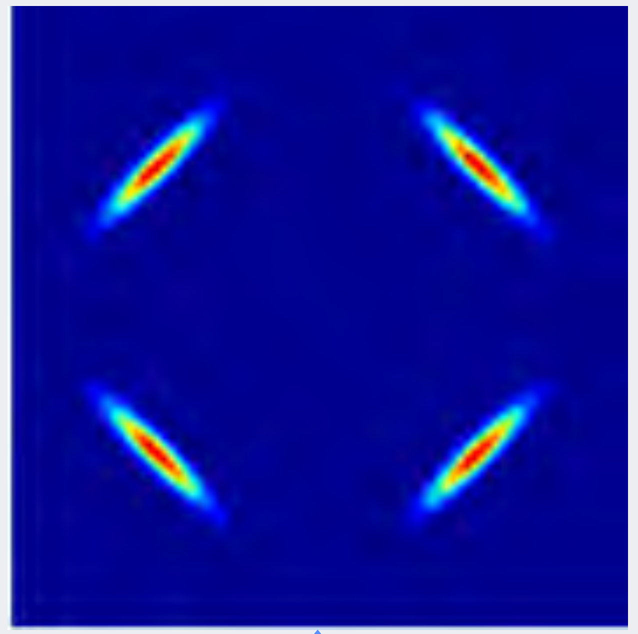
Shift in Fiber Technology

Courtesy of: ciena

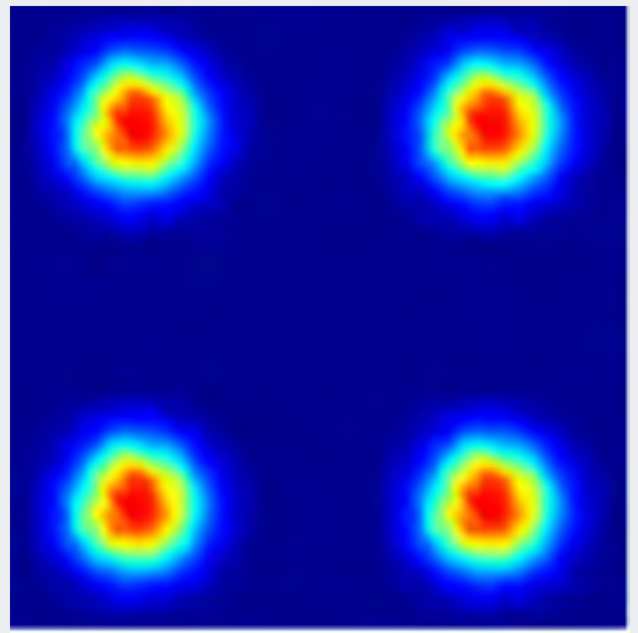
Noise Definitions

- Sources of noise:
  - Implementation Noise of the Transceiver SNR_{B2B}
    - DAC/ADC Quantization Noise
    - Thermal & Phase Noise
  - ASE from amplifiers SNR_{ASE}
    - Can be measured as OSNR via an OSA
    - Is AWGN (Additive White Gaussian Noise)
  - Non-Linear Interference SNR_{NLI}
    - Result of propagation in a non-linear medium
    - Kerr Effect: SPM, XPM, FWM, XPolM etc.
    - Not AWGN but with enough dispersion can be treated as AWGN



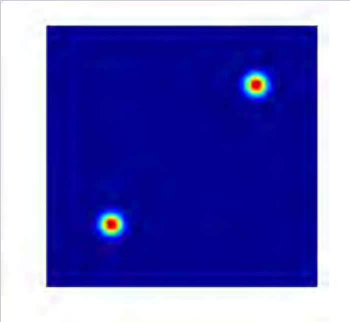
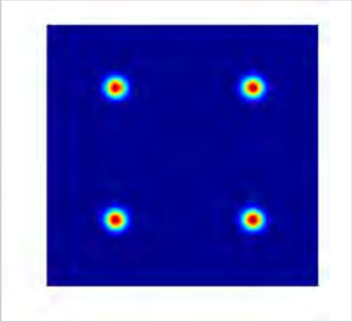
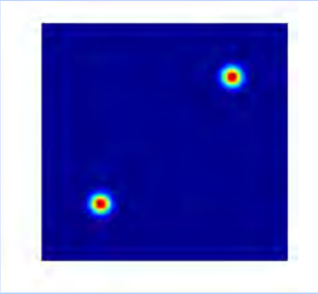
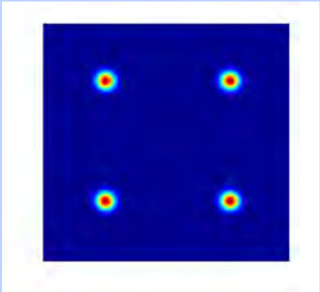
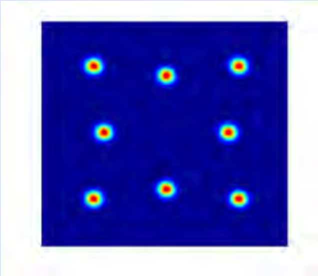
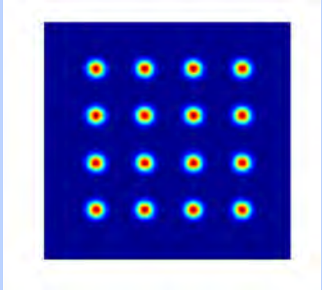
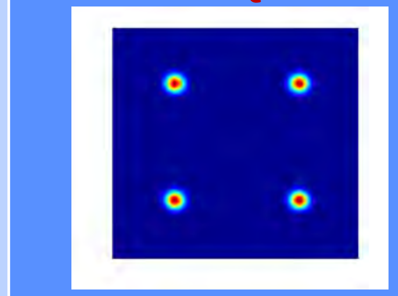
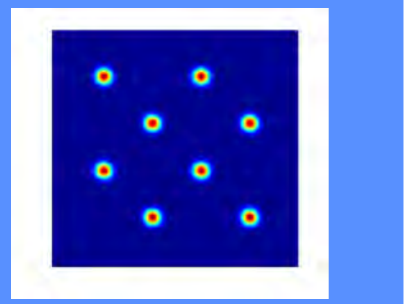
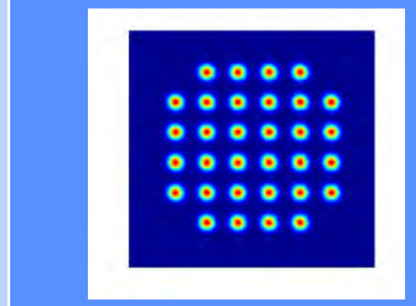
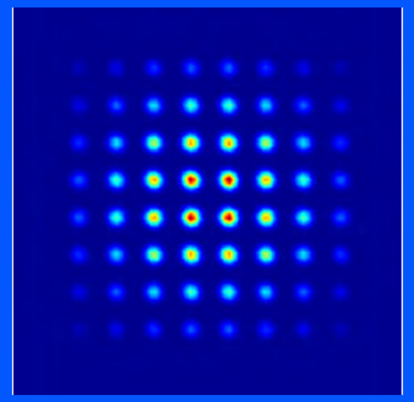
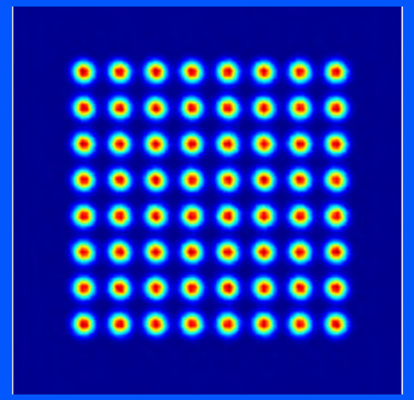


Dispersion Compensated or
“Nonlinear” Legacy System



High Dispersion D+
or “Linear” System

Evolution of Coherent Constellations

	1st Gen Coherent	2nd Gen Coherent	3rd Gen Coherent	4th Gen Coherent
Year	2010	2012-2015	2016-2019	2020+
Data Rate	40G	50G / 100G / 150G / 200G	100G – 400G	200G – 800G
Constellations	PM-BPSK  PM-QPSK 	PM-BPSK  PM-QPSK  PM-8QAM  PM-16QAM 	8D-2QAM  4D-PM-SP-QAM  PM-32QAM  + many more!	Shaped PM-64QAM  PM-64QAM  + many many more!

M.Reimer et al., Optimized 4 and 8 Dimensional Modulation Formats for Variable Capacity in Optical Networks, OFC 2016

Courtesy of: ciena

Multi-Dimensional Modulation Formats

Four available dimensions of the optical field:
In-phase (I) and quadrature (Q) components of two polarizations.

8D symbols are encoded across I and Q of two orthogonal polarizations of two time slots (or optical wavelengths, spatial modes, etc.)

M.Reimer et al., Prospects for real-time compensation of fiber nonlinearities, ECOC 2016

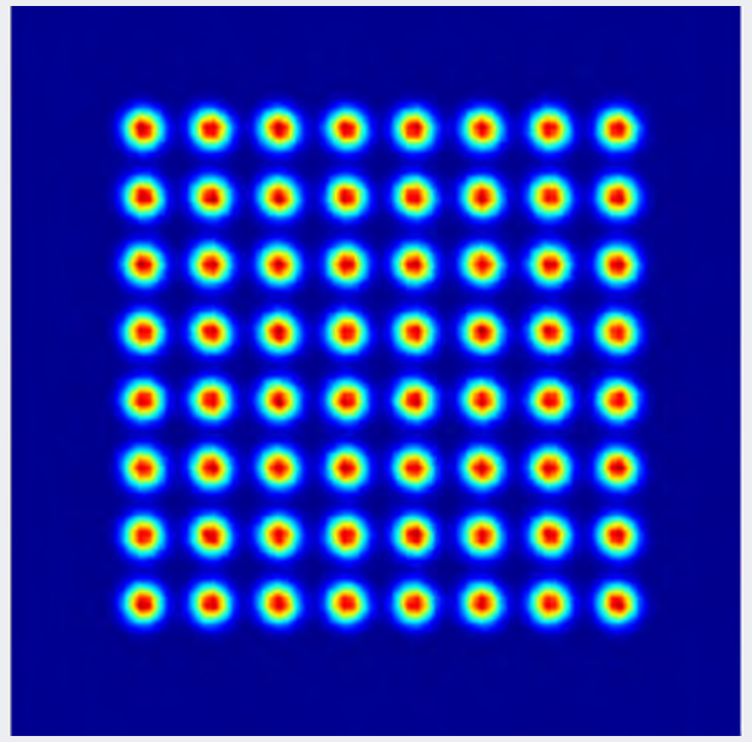
Courtesy of: Ciena & Nokia

Constellation Shaping

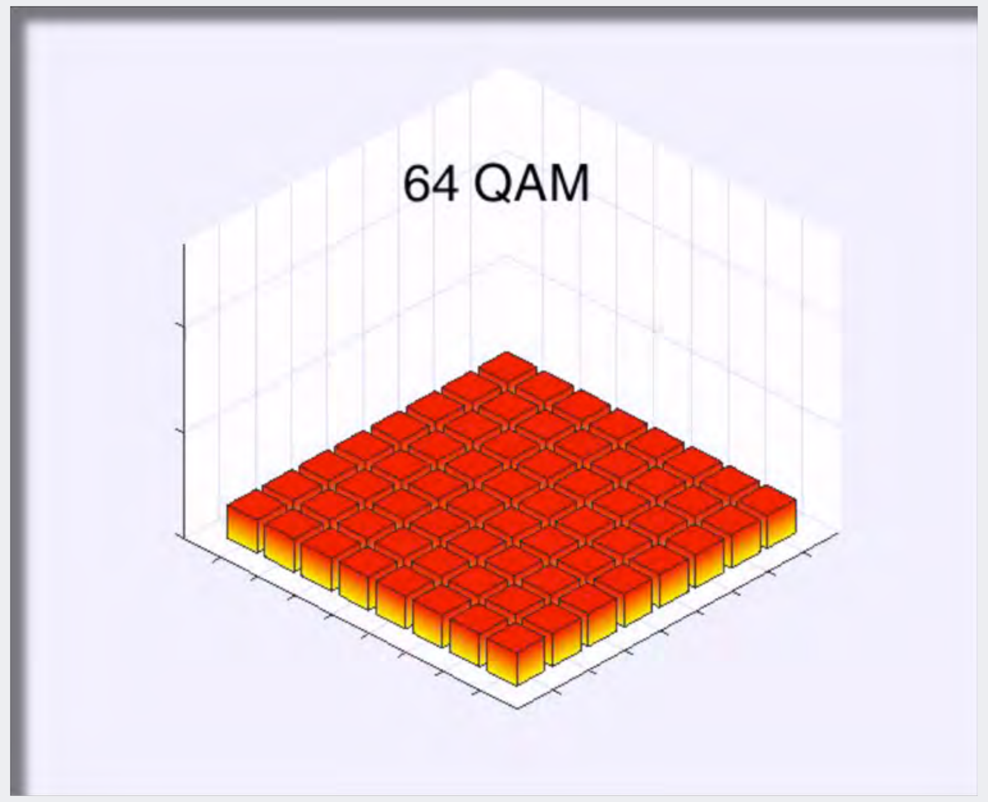
Constellation shaping builds on the traditional “square” constellations, and takes advantage of advanced DSP to optimize the constellation for the specific application to get the best performance and highest bit rate possible:

- Selected for type and quantity of noise present (fiber type, distance, channel powers, etc)

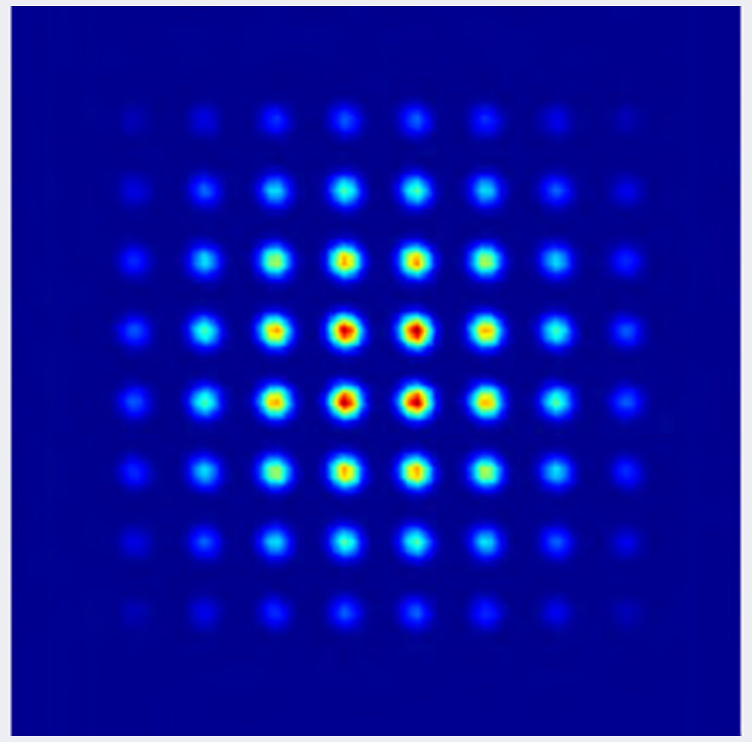
Without shaping
Every symbol sent equal # of times



Probabilistic Shaped (PCS)



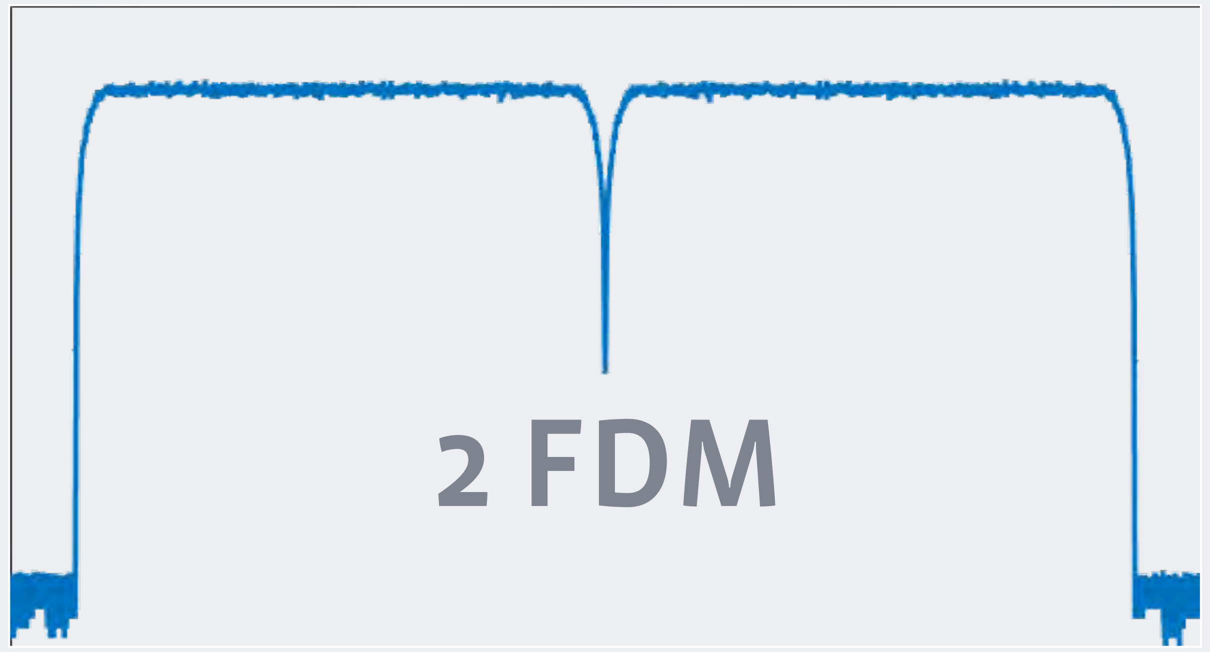
With shaping
Low energy symbols favored, sent more often

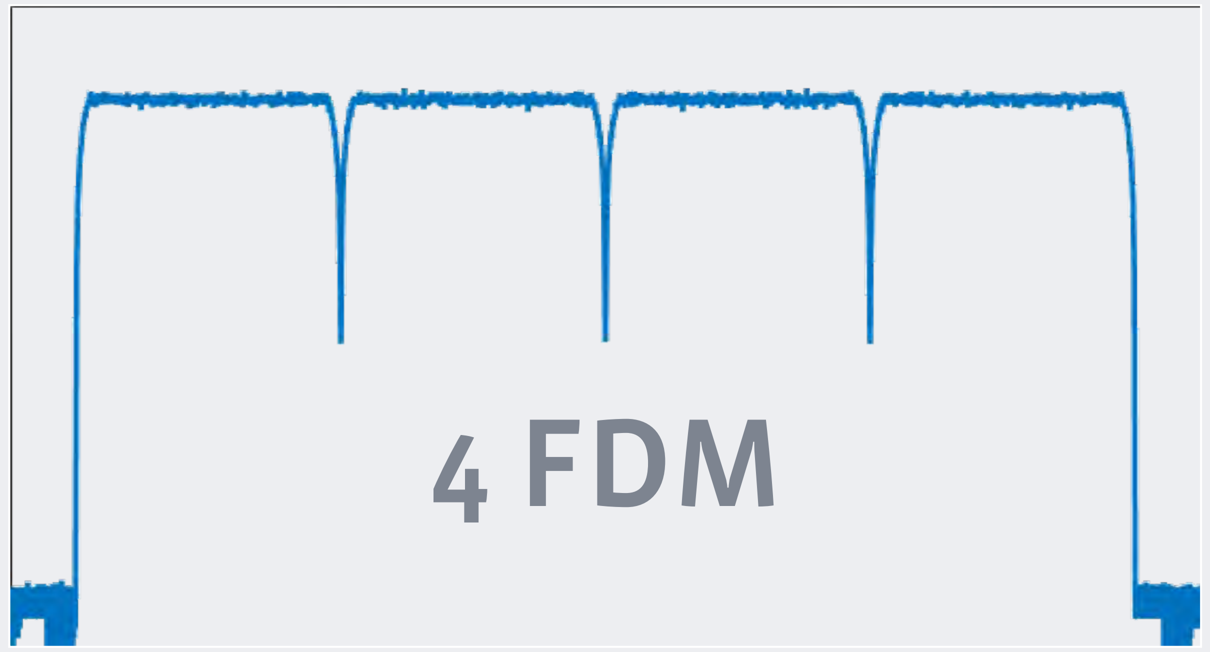


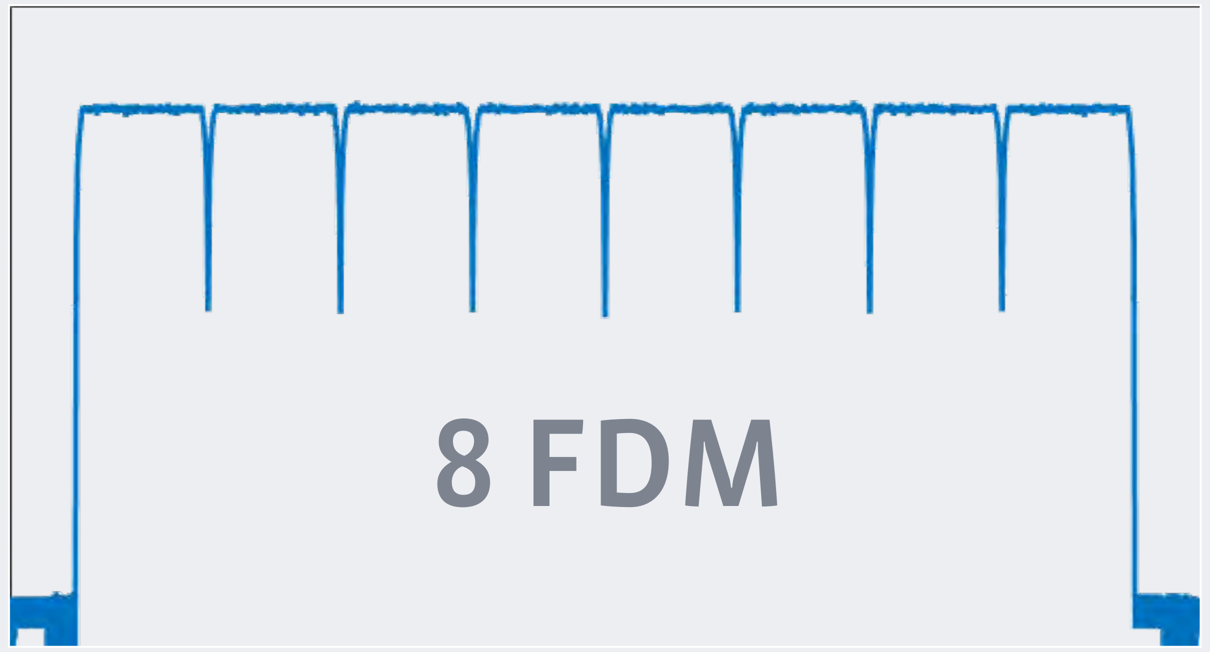
Courtesy of: ciena

Digital Subcarriers and Performance Impact

- Encoding data over multiple digital subcarriers <u>on a single optical wavelength</u>





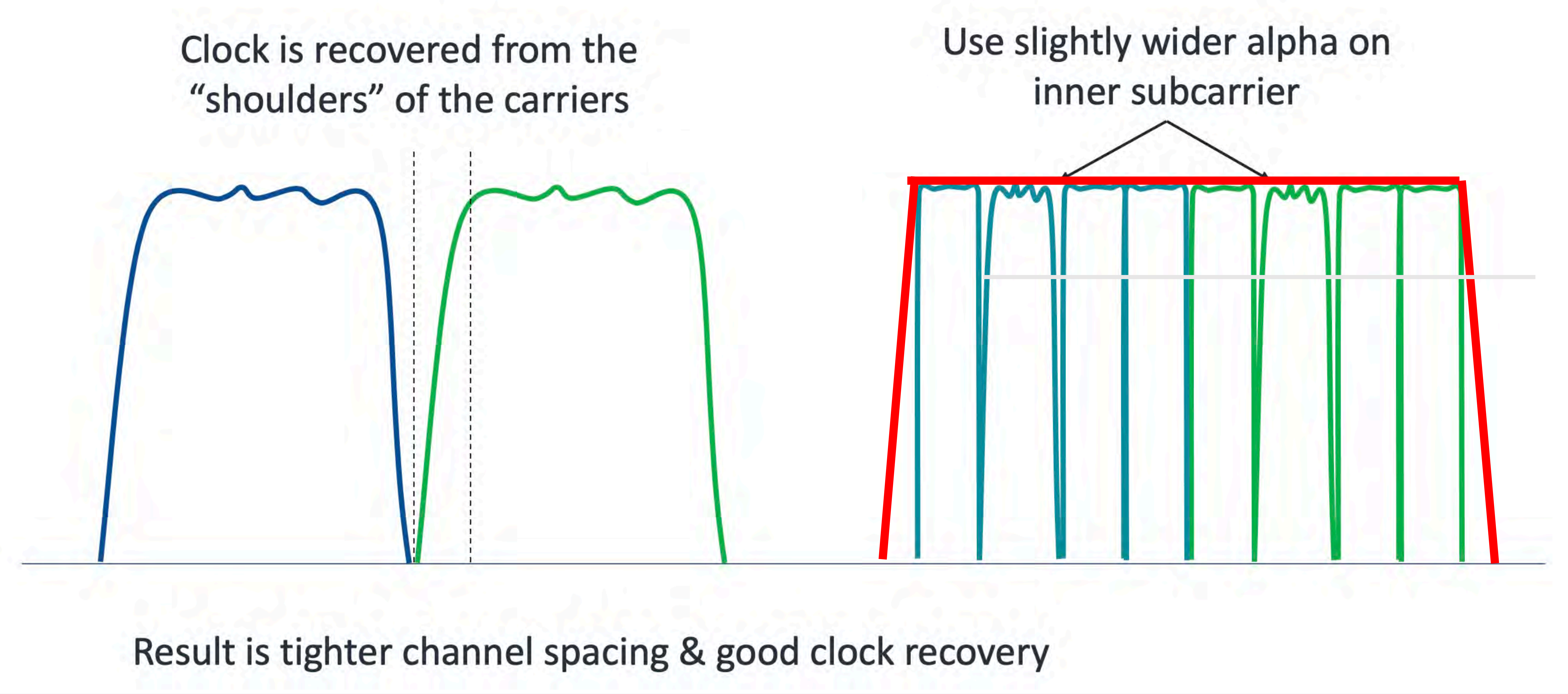


- Improves non-linearities in key applications
  - High residual net dispersion favors a larger number of subcarriers
    - E.g. uncompensated NDSF
  - Low residual net dispersion favors a single subcarrier
    - NZDSF (or dispersion managed/compensated cables)

Courtesy of: Infinera

Subcarriers within High Baud Signals

- Subcarriers shown to improve performance of high baud systems
- Demonstrated to reduce nonlinear effects
- Subcarriers can be coded individually
- Subcarriers can be used to make clock recovery more robust



Clock is recovered from the "shoulders" of the carriers

Use slightly wider alpha on inner subcarrier

Result is tighter channel spacing & good clock recovery

Courtesy of: ciena

Nonlinear Compensation

Nonlinear Compensation (NLC) is another technique used to improve the performance (or reach) of an optical signal

There are numerous proposed methods with extensive research and publications, many of which are highly complex (and Ph.D worthy!)

One of the biggest challenges we face today is reducing the complexity of computationally intensive NLC implementations in DSP

Field propagation equation: $\frac{\partial \vec{A}}{\partial z} = -\frac{\alpha}{2}\vec{A} + \frac{i\beta_2}{2}\frac{\partial^2 \vec{A}}{\partial t^2} - i\gamma\frac{8}{9}\left|\vec{A}\right|^2\vec{A}$

Perturbative nonlinear field: $\vec{A} \approx \vec{A}_{Linear} + \vec{a}_{NL}$

Dual polarization transmit symbols: $\vec{d}(k) = \begin{bmatrix} X(k) \\ Y(k) \end{bmatrix}$

Nonlinear optical field: $\vec{\boldsymbol{a}}_{NL} \approx \sum_{m,n=-M}^{M} C_{mn}\ \vec{\boldsymbol{d}}^{H}(m+n)\,\vec{\boldsymbol{d}}(n)\,\vec{\boldsymbol{d}}(m)$

C_{mn} parameterizes single channel nonlinear interactions including details of pulse shaping and dispersion map.

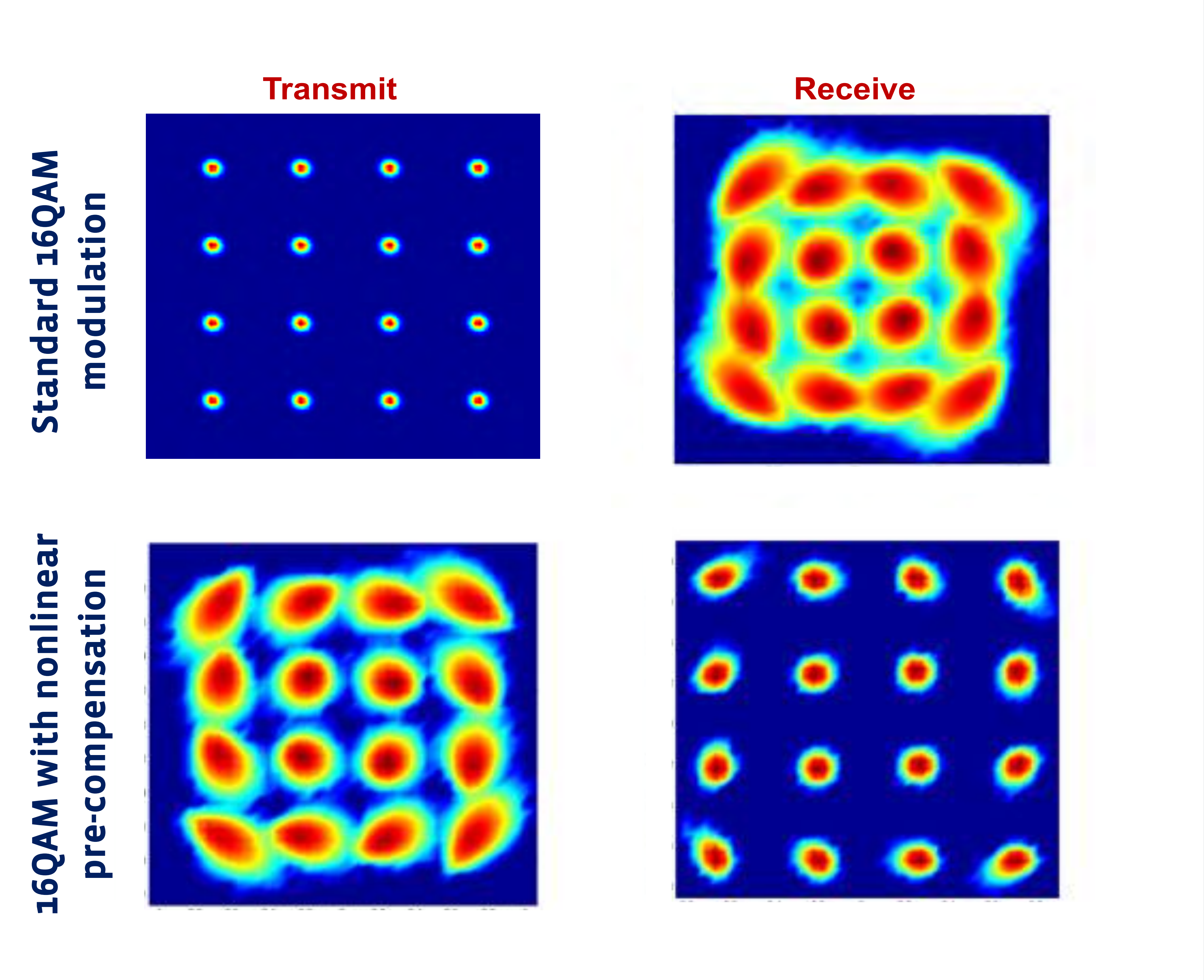
Z. Tao, et. al, Proc. SPIE (2013)
Z. Tao, et. al, J. Lightwave Technol. (2011)
Q. Zhuge, et. al, Proc. OFC (2014)
Y. Gao, et. al, Opt. Express (2014)

M.Reimer et al., Prospects for real-time compensation of fiber nonlinearities, ECOC 2016

Courtesy of: ciena

Nonlinear Pre-Compensation

Nonlinear pre-compensation techniques on single channels have proved highly effective, with multiple dBs performance improvements possible at low computational complexity



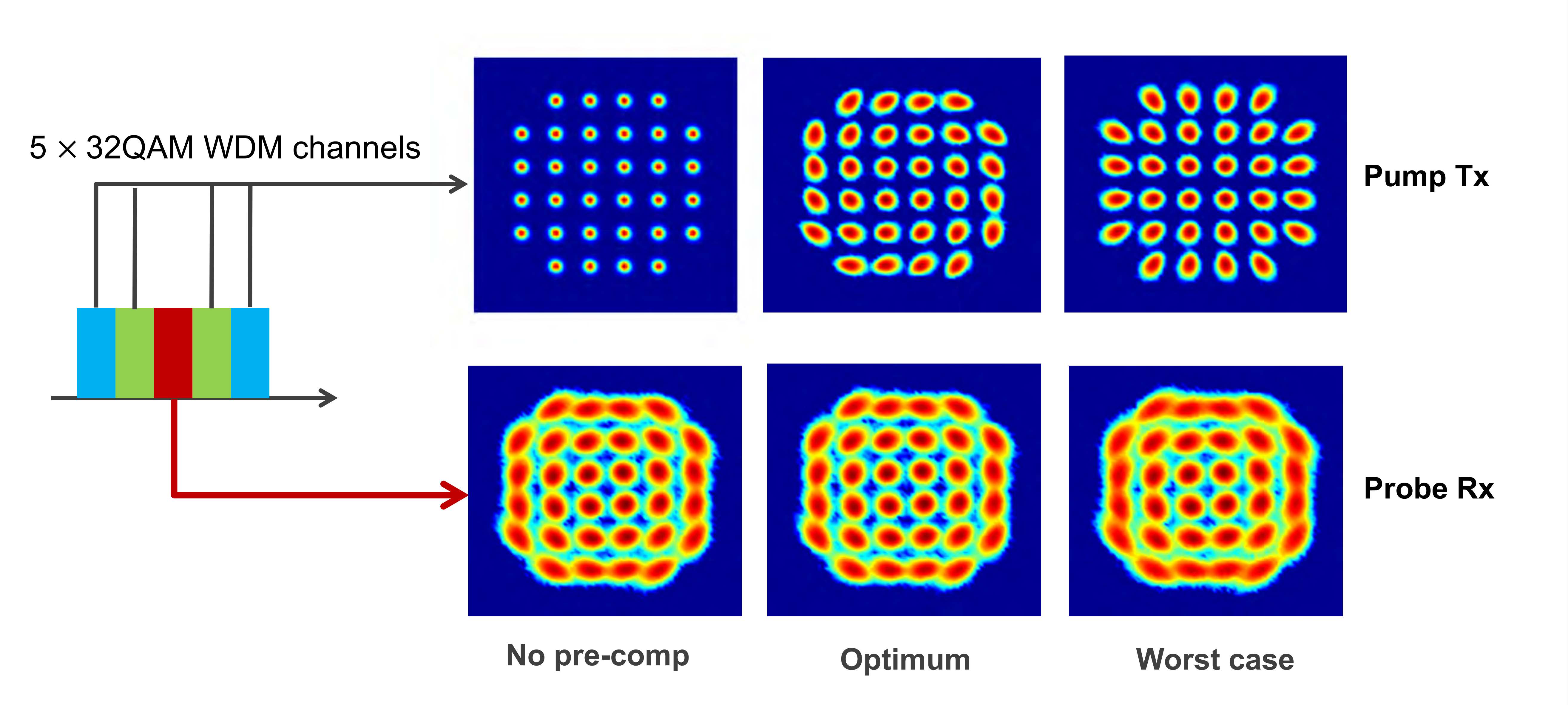
M.Reimer et al., Prospects for real-time compensation of fiber nonlinearities, ECOC 2016

Courtesy of: ciena

Nonlinear Pre-Compensation

However, WDM environments create additional complexities, in that nonlinear pre-compensation applied on one channel also couples to the nonlinear field of neighboring WDM channels.

This effect requires multi-channel consideration of nonlinear pre-compensation techniques, increasing the complexity of the required solution and reducing the benefits observed in single channel environments



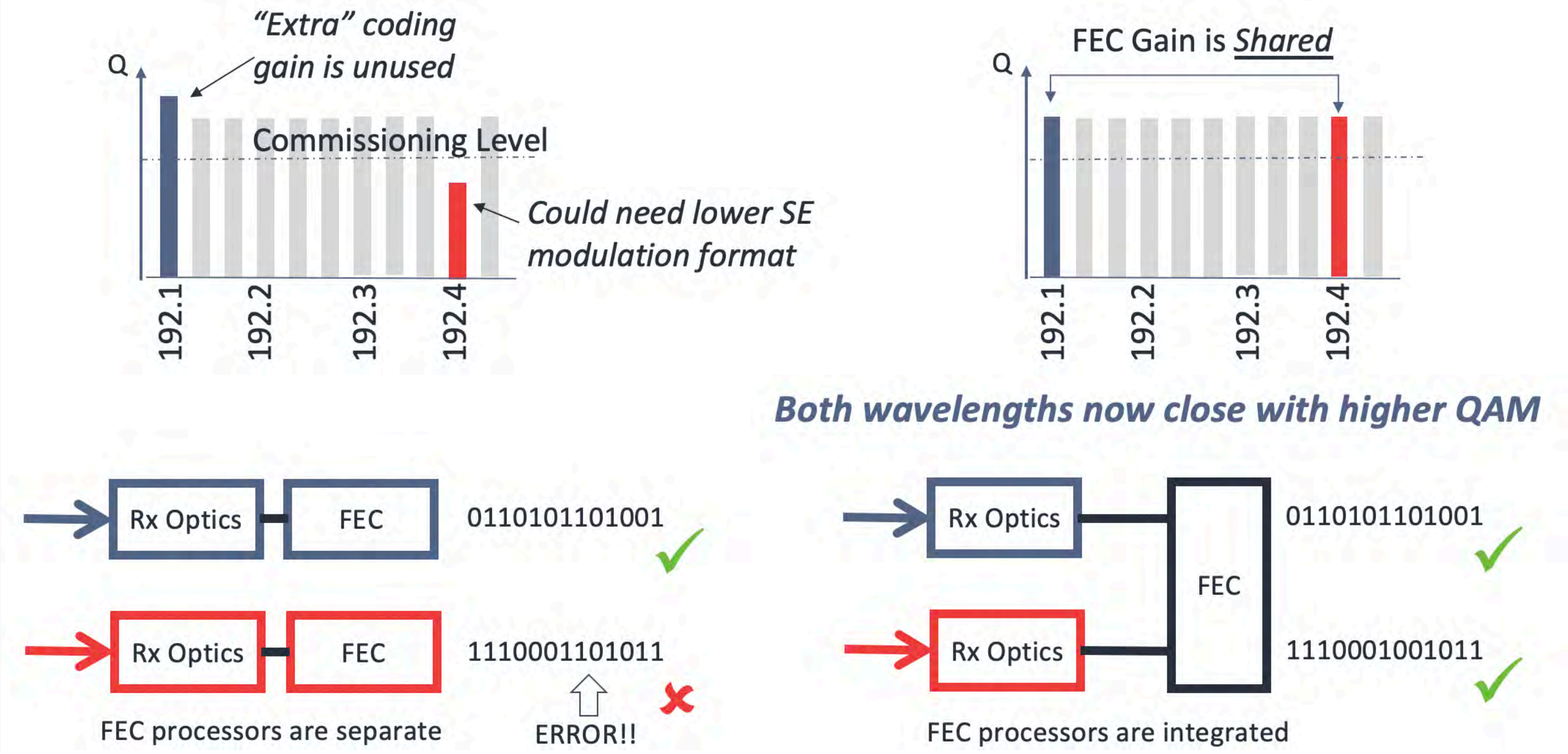
M.Reimer et al., Prospects for real-time compensation of fiber nonlinearities, ECOC 2016

Courtesy of: Infinera

Coding in Next Gen SLTE Transponders

Net Coding Gain (NCG) of modern and next gen FEC is around 13 dB in Gen 3-4 Coherent

- Overheads between 15-50%
- Advanced FEC should be able to reach with 1 dB of Shannon
- FEC can account for 25-35% of DSP gates in some implementations
- PCS can enable use of use lower overhead FEC of ~20%
- FEC gain sharing has been proposed for performance optimization in WDM environments



What is Soft FEC

- https://www.youtube.com/watch?v=81pTxPwB1Fw

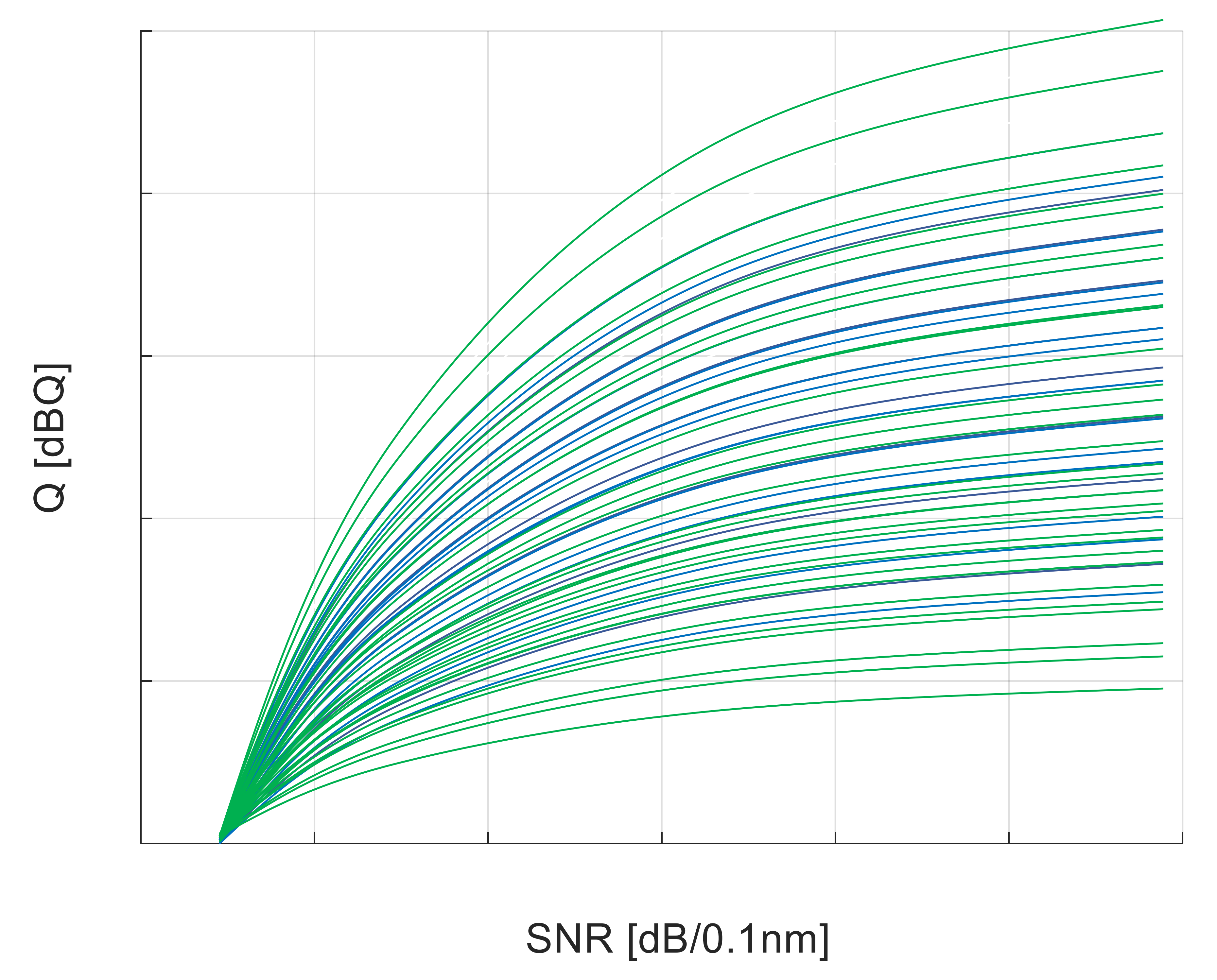
Summary

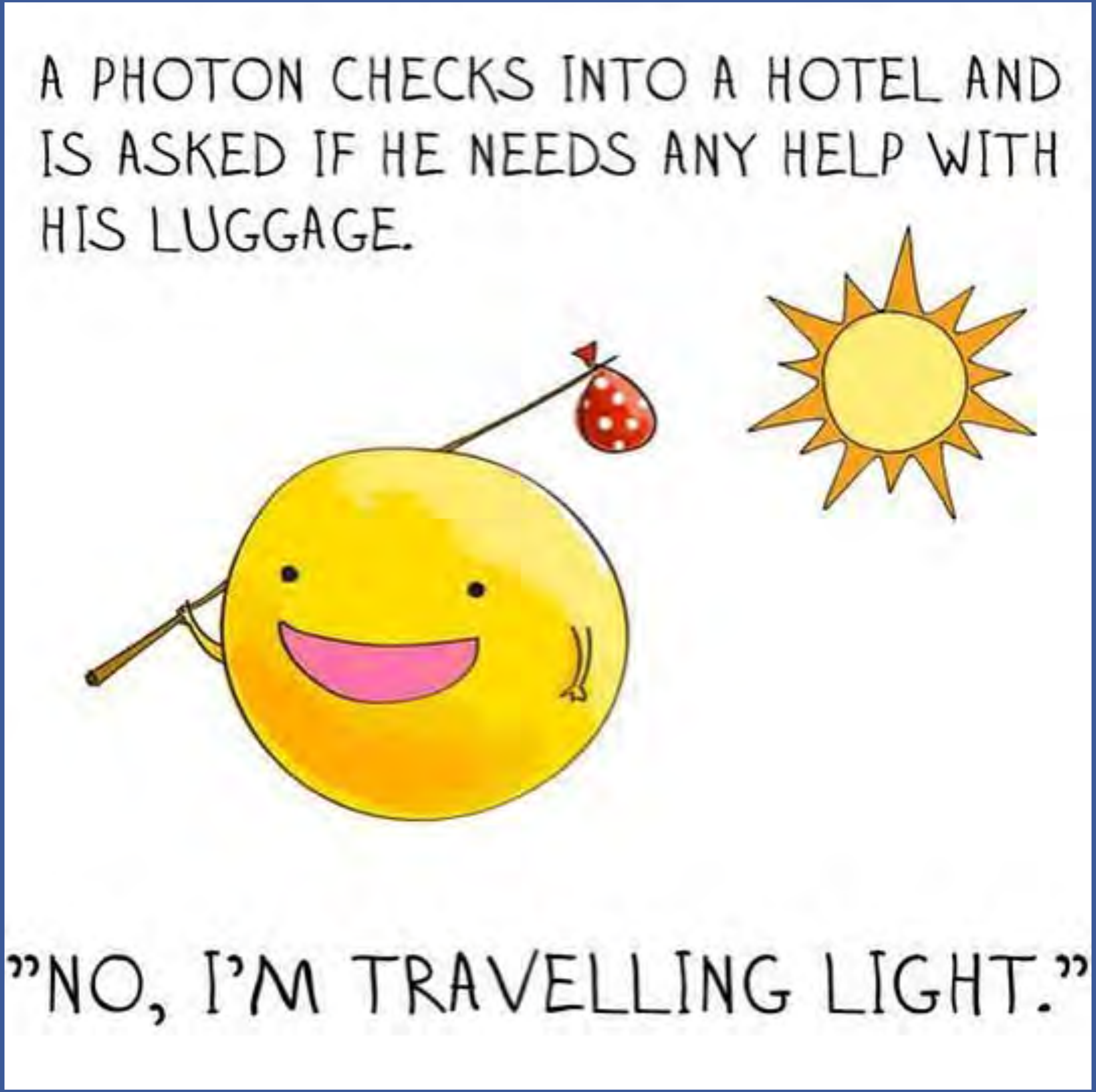
Modern day coherent modems have many tools to optimize performance for a given application:

- Probabilistic Constellation Shaping
- Multi-Dimensional Modulation Techniques
- Variable Baud & Bit Rates
- Soft FEC and FEC Gain Sharing
- Digital Subcarriers
- Nonlinear Compensation & Mitigation

Future modems will undoubtedly have even more degrees of freedom…but where are the limits?

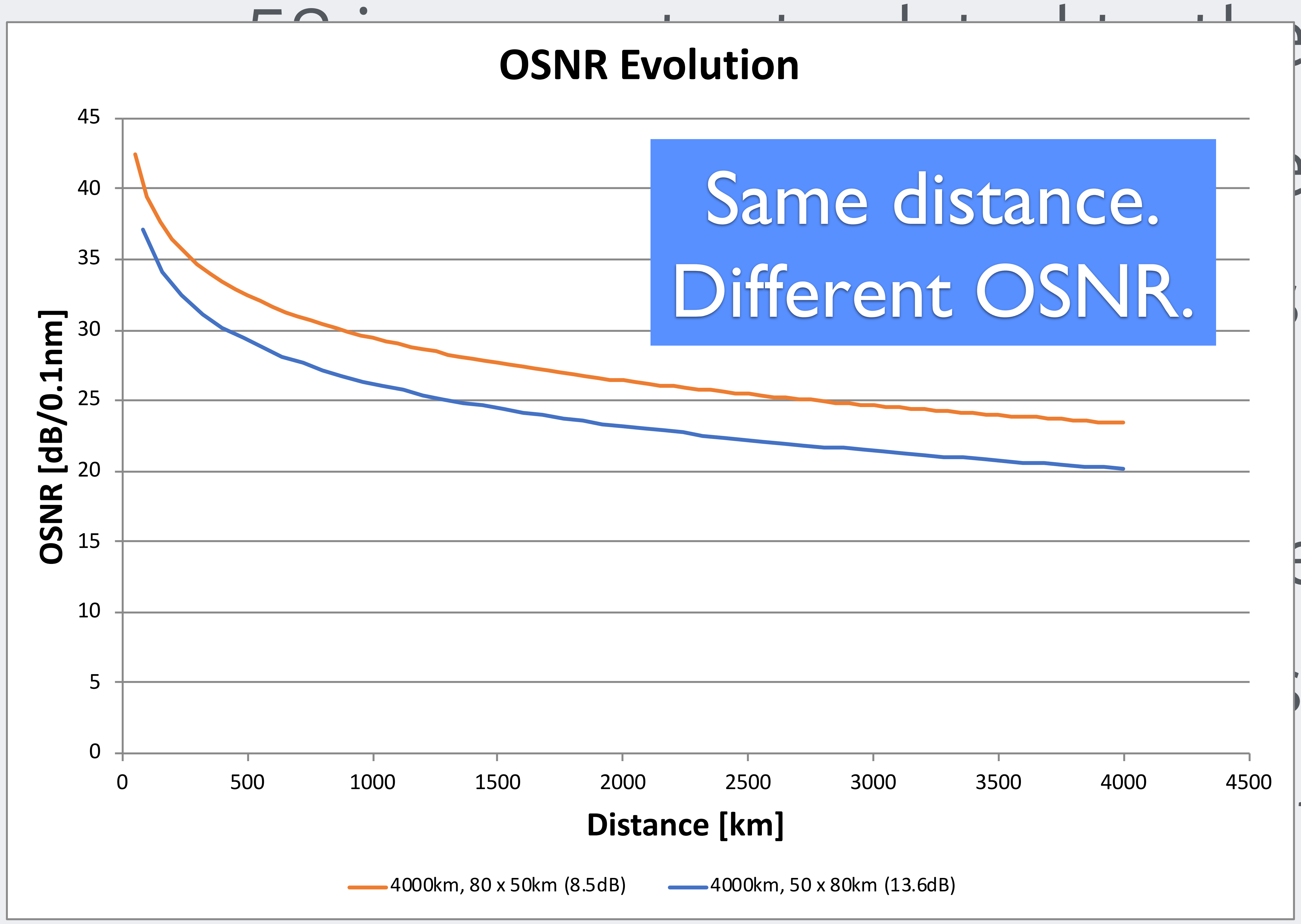
…We'll discuss that tomorrow!



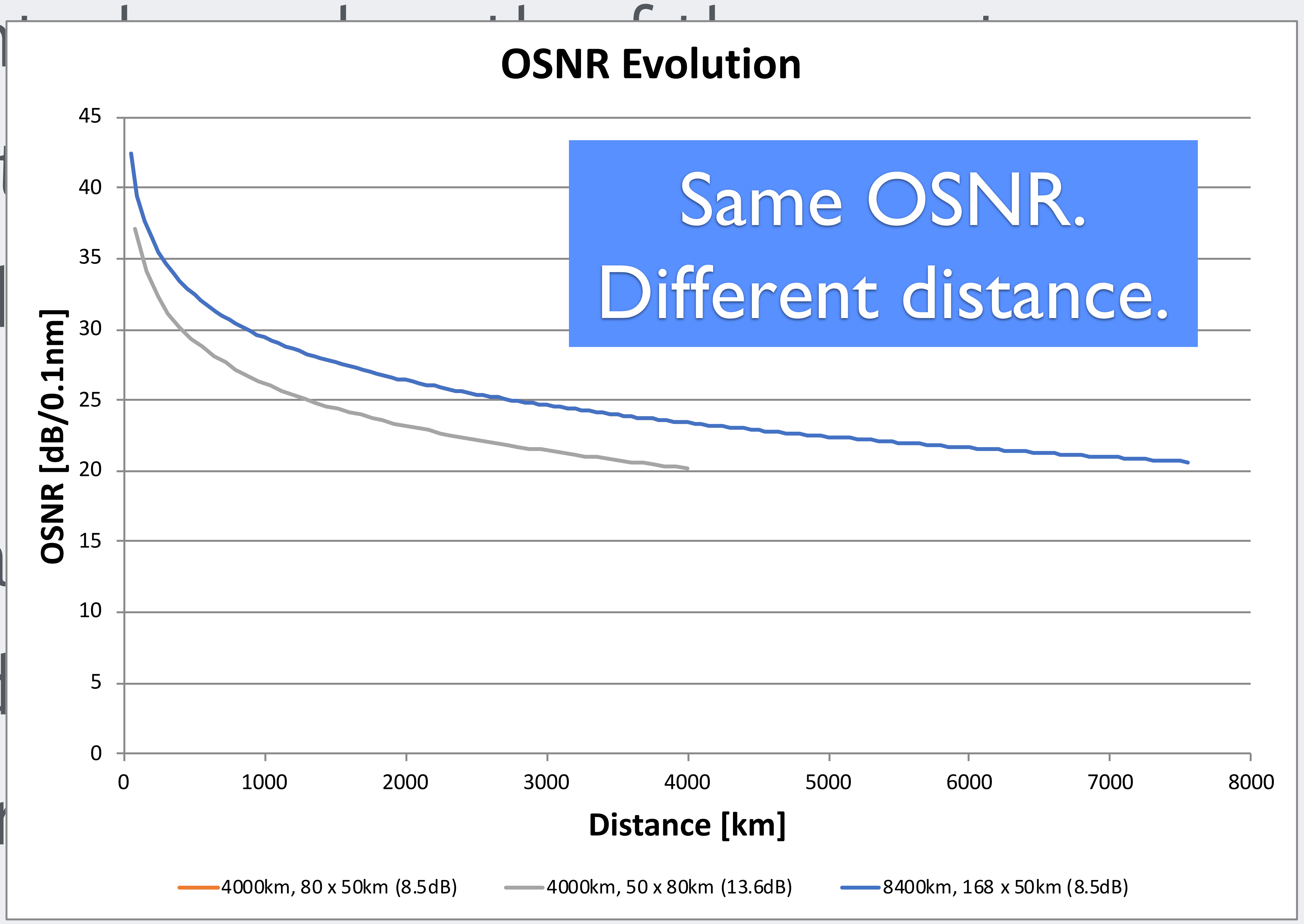

A PHOTON CHECKS INTO A HOTEL AND IS ASKED IF HE NEEDS ANY HELP WITH HIS LUGGAGE.
"NO, I'M TRAVELLING LIGHT."

OSNR vs Distance – Does Distance Really Matter?

$OSNR_{(dB/0.1nm)} = 58 + P_{TOP} - N_{Ch} - G - NF - N_R$ (*all in dB)



Same distance.
Different OSNR.



Same OSNR.
Different distance.

Same TOP, Nch, and NF for all examples! Only changing G and N_R

N_R is Distance / Span Length – 1 and G is Span Length * Fiber Loss per km

Lecture 11 -
System Deployment & Life of a Cable

Alan Cheung - Google Global Network Infrastructure (GNA APAC)

Subsea Optical Fiber Communication
Finland, 2019

Table of Contents - System Deployment & Life of a Cable

System Deployment - What do you need to know?

1. Contractual Documents
    a. Supply Contract
    b. Joint Build Agreement
    c. Landing Service Agreement
2. Purchasers Obligations
3. Supplier’s Obligations and Scope of Work
4. People

Supply Contract

Supply Contract generally consists of 6 Parts

Part 1 - Terms and Conditions of Contract
Part 2 - Technical Specifications
Part 3 - Price Schedule
Part 4 - Plan of Work
Part 5 - Billing Schedule
Part 6 - Supplier’s System Description

Supply Contract - Part 1 - Terms and Conditions of Contract

Key terms

1. Contract Price
2. Completion Date
3. Condition Precedent for Coming Into Force
    a. BM0 downpayment ?
    b. Government approval ?
    c. Letter of Performance Guarantee?
    d. Payment Assurance ?
4. Acceptance
5. No suspension rights by Supplier - Supplier cannot suspend work even though non-payment from any of the Purchasers
6. Permits: Scope of Contractor
7. Liquidated Damages

8. Liability
    a) Normally cap at contract price with exception of personal injury and death and environmental damage, etc.
    b) Not joint but several liability among Purchasers

9. Financial liability of each Purchaser

10. Payment term

11. Force Majeure - extension of time but no money

12. Warranty

13. Long term support

Supply Contract - Part 2 - Technical Specifications

Key terms

1. Configuration
    a. Main trunk and branches
    b. Locations of Cable Landing Station / Point Of Presence
    c. Locations of Beach Manholes
    d. Number of Fibre Pairs
    e. Power feeding configurations
    f. Add / drop capacity to branch landings (e.g. optical switch and/or WSS)
    g. Stubbed Branching Units, Optional landings if any
    h. etc.
2. Transmission design parameters (e.g. OSNR, design capacity, etc.)
3. Commissioning Limit
4. Burial depths / Horizontal Directional Drilling (HDD) requirements
5. Route Position List / Cable types
6. Training
7. etc.

Supply Contract - Permit Matrix

The Contractor shall identify, plan, obtain and procure the necessary licences, operational permits, work permits, permit-in-principle ("PIP"), authorisations from the appropriate authorities and pipelines/cable crossing agreements

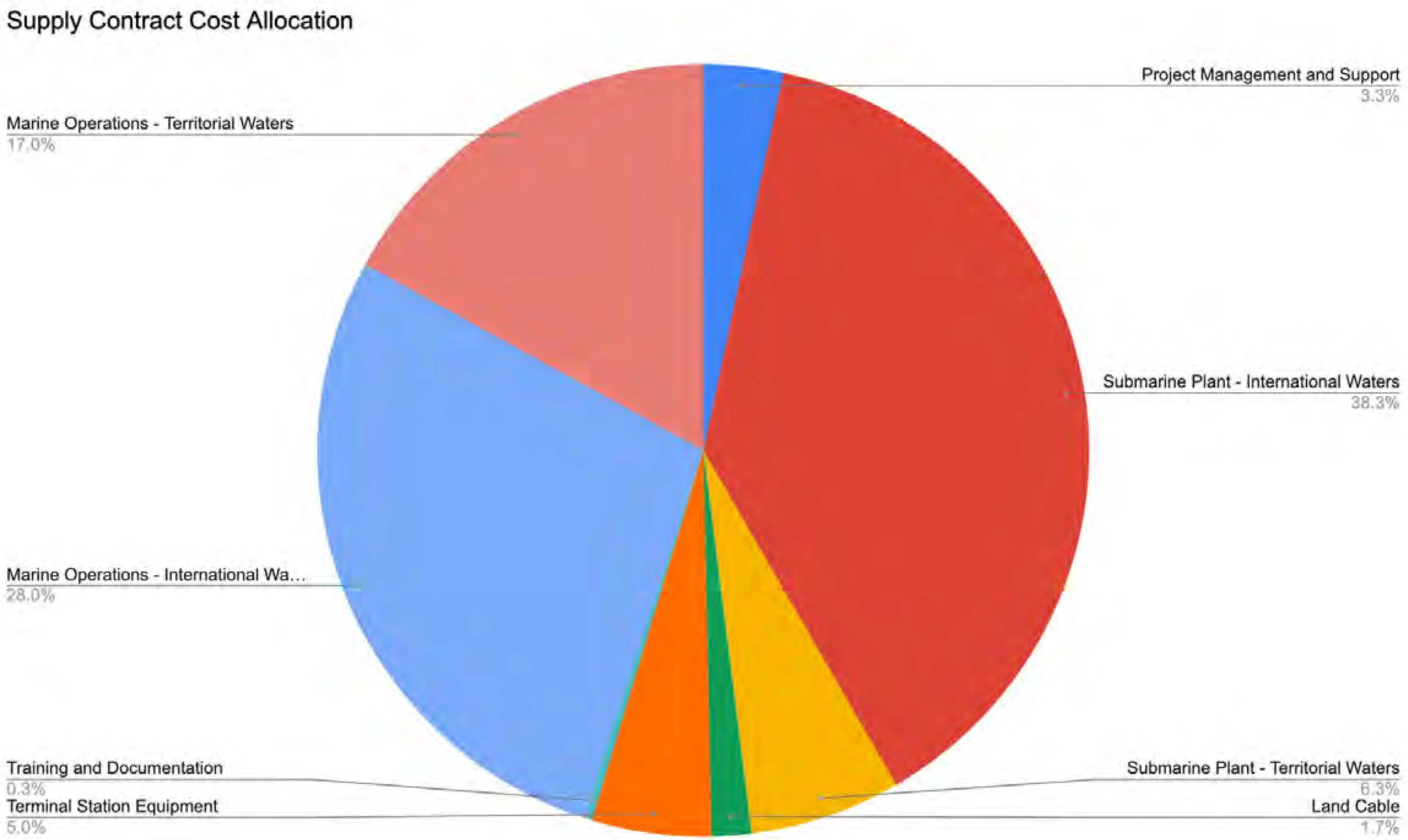
No.	Permit Name/Description/ Activity	Permit Granting Authority & Point-of-Contact Details	Responsible Party	PIPs/Ops
System Operating Permits				
1.1	Unified Carrier Licence	Office of the Communications Authority	Purchaser	PIP
Marine Route Survey Permits (inc survey vessel operational permits/notifications)				
2.1	Marine Department Notice (MDN) - Notice to Mariners	Marine Department	Supplier	OPS
2.2	Vessel Temporary Operating Licence - if non Hong Kong registered vessel	Marine department	Supplier	OPS
2.3	Personnel temporary working visas - all non Hong Kong residents	Immigration Department	Supplier - with Purchaser Support	OPS
Cable Station (CS) Permits				
3.1	Regulatory Permit	Local Gov. Authority	Purchaser	PIP
Outside Plant (OSP) Permits: includes land ducts, manholes and/or handholes between and exclusive of the cable station and Beach Manhole				
4.1	Land Use Approvals	Highways Department	Purchaser	PIP
4.2	Excavation permit	Highways Department	Supplier	PIP
Marine Installation Vessel(s) Permits/Notifications (i.e., Route Clearance, Pre-Lay Grapnel Run (PLGR), Main Lay, and Post-Lay Inspection & Burial (PLIB))				
8.1	Marine Department Notice (MDN) - Notice to Mariners	Marine Department	Supplier	OPS
8.2	Vessel Temporary Operating Licence - if non Hong Kong registered vessel	Marine department	Supplier	OPS
8.3	Constrcution Noise Permit	Environmental protection department (may be required for shore end operations)	Supplier	OPS
8.4	Marine Traffic Impact Assessment (MTIA)	Marine Department	Supplier	OPS
8.5	Personnel temporary working visas - all non Hong Kong residents	Immigration Department	Supplier - with Purchaser Support	OPS

Supply Contract - Part 3 - Price Schedule

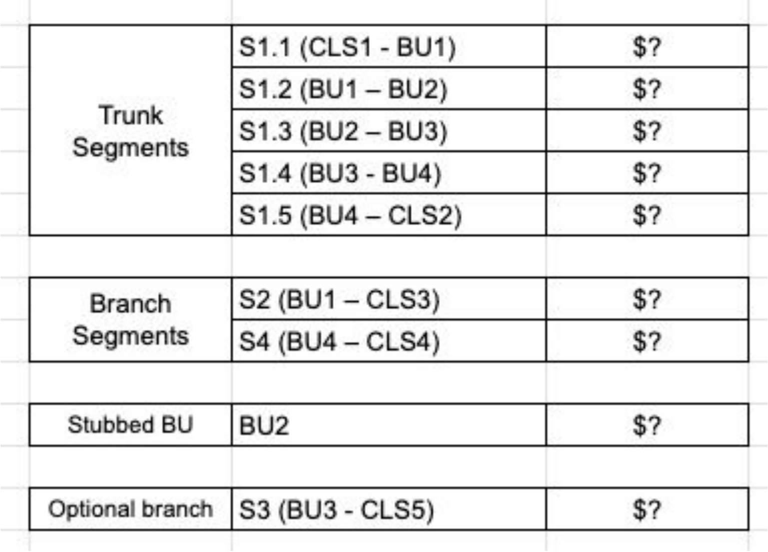
A spreadsheet detailing the Supply Contract Cost giving the below breakdown

1. Project Management and Support
2. Submarine Plant - International Waters
3. Submarine Plant - Territorial Waters
4. Land Cable
5. Terminal Station Equipment
6. Training and Documentation
7. Marine Operations - International Waters
8. Marine Operations - Territorial Waters

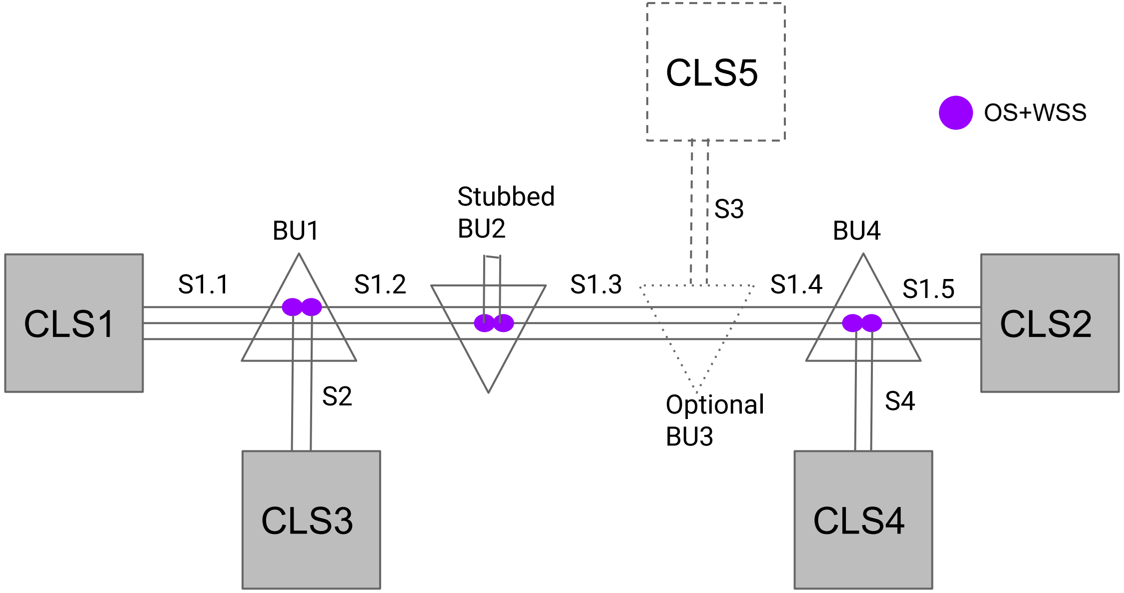
Supply Contract - Cost Allocation (Example)



Supply Contract - Price Breakdown



Trunk Segments	S1.1 (CLS1 - BU1)	$?
	S1.2 (BU1 – BU2)	$?
	S1.3 (BU2 – BU3)	$?
	S1.4 (BU3 - BU4)	$?
	S1.5 (BU4 – CLS2)	$?
Branch Segments	S2 (BU1 – CLS3)	$?
	S4 (BU4 – CLS4)	$?
Stubbed BU	BU2	$?
Optional branch	S3 (BU3 - CLS5)	$?



Supply Contract - Price Breakdown

	Cost
Power Switch Branching Unit	$?
Optical Switch	$?
Wavelength Selective Switch	$?

	Cable Type	Cable	Repeater	Shape Equaliser	Tilt Equaliser
4FP	LW	$?	$?	$?	$?
	SA	$?			
	DA	$?			
8FP	LW	$?	$?	$?	$?
	SA	$?			
	DA	$?			
12FP	LW	$?	$?	$?	$?
	SA	$?			
	DA	$?			
16FP	LW	$?	$?	$?	$?
	SA	$?			
	DA	$?			

Supply Contract - Part 4 - Plan of Work

Plan of Work to show the Milestones and Start / Finish date of each activity

	2019				2020				2021				2022			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Contract CIF			■													
Permit (Country X)			■	■	■	■	■	■	■	■	■					
Permit (Country Y)			■	■	■	■	■	■	■	■	■	■	■			
Desk Top Study			■	■												
Survey Permits				■	■											
Survey						■	■									
Cable Manufacture								■	■	■	■	■				
Repeater / BU Manufacturer								■	■	■	■					
Dry plant manufacturer								■	■	■						
Ready to Load											■					
Marine Lay											■	■	■	■	■	
Station Installation										■	■	■	■			
Training														■		
Testing and Commissioning															■	
Provisional Acceptance																■

Supply Contract - Part 4 - Plan of Work

Purchasers' Deliverables - Purchasers' critical delivery and option decision dates will be shown in the POW:

- Readiness of Beach Manhole
- Readiness of CLS
- Decision dates for options election (add / reduction of FP, branches, etc.)
- Finalisation of spares
- Finalisation of marine maintenance and depot storages
- NOC location
- Readiness of licence

Supply Contract - Part 6 - Supplier's System Descriptions

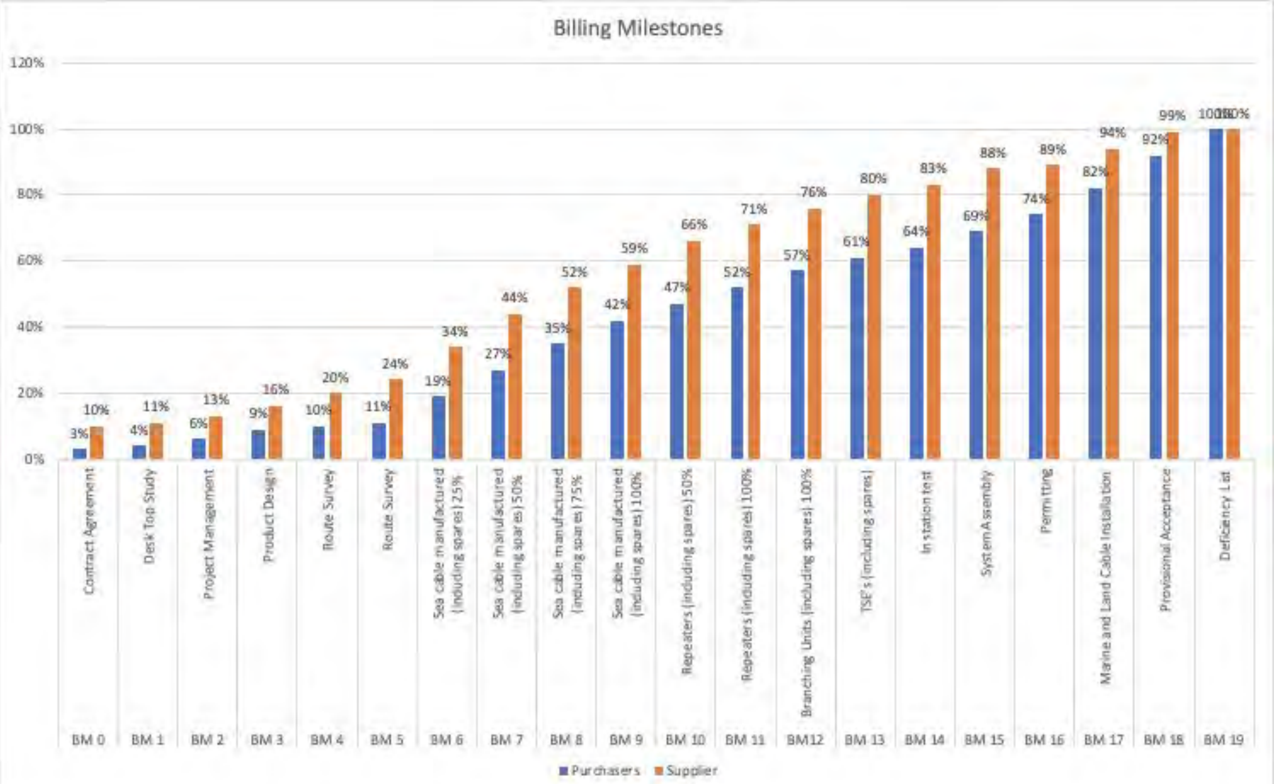
System Description is Supplier's document to specify how they implement the project so as to meet the Technical Specifications specified by the Purchasers.

1. Configuration and options
2. Optical connectivity
3. Power Configuration
4. Submerged plants
5. Terminal Station Equipment
6. System Performance
7. Acceptance test
8. Training
9. Documentations
10. Marine Descriptions
11. Permit Services Descriptions
12. Product descriptions
    a. Cable
    b. Repeaters
    c. Branching Units
    d. Management System
    e. Dry Plants
    f. SLTE, if applicable
    g. etc.

Supply Contract - Part 5 - Billing Schedule

Billing Milestones with criteria for achievement are well defined. The % allocation on each BM is mutually agreed prior to Contract CIF.

BM No.	Billing Milestone [BM]
BM 0	Contract Agreement
BM 1	Desk Top Study
BM 2	Project Management
BM 3	Product Design
BM 4	Route Survey
BM 5	Route Survey (Report)
BM 6	Sea cable manufactured (including spares) 25%
BM 7	Sea cable manufactured (including spares) 50%
BM 8	Sea cable manufactured (including spares) 75%
BM 9	Sea cable manufactured (including spares) 100%
BM 10	Repeaters (including spares) 50%
BM 11	Repeaters (including spares) 100%
BM12	Branching Units (including spares) 100%
BM 13	TSE's (including spares)
BM 14	In station test
BM 15	System Assembly
BM 16	Permitting
BM 17	Marine and Land Cable Installation
BM 18	Provisional Acceptance
BM 19	Deficiency List



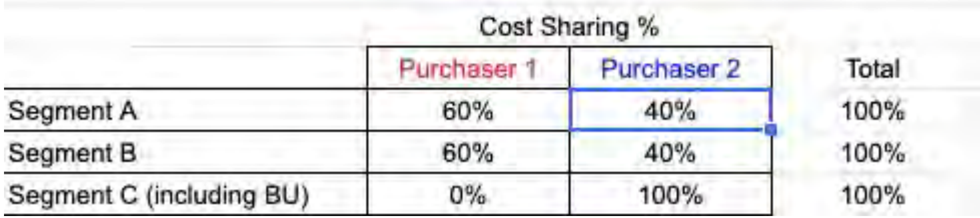
Joint Build Agreement

Key terms

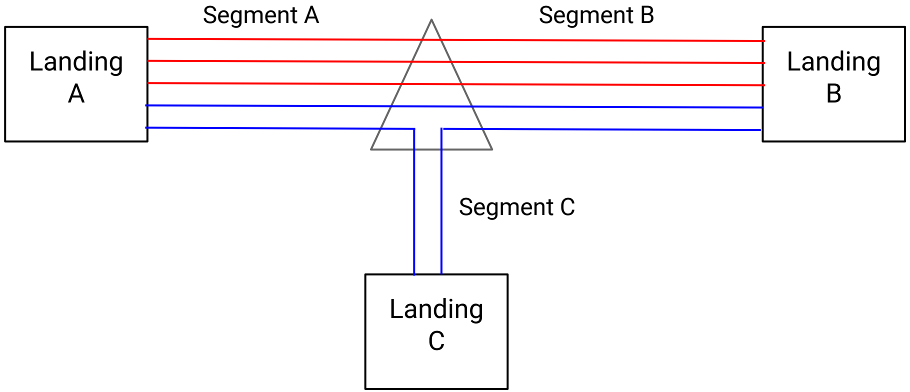
1. System Configuration
2. Investment Level and Cost sharing principles
3. Participating Interest and Voting Rights
4. Open access principles
5. Management Structure, Decision and Voting
    a. Management Committee
    b. Procurement Group
    c. Investment & Administrative SubCommittee
    d. O&M Working Group
6. Landing Parties / Service Providers Responsibility and Obligations
7. Decommissioning
8. Joint System Maintenance Document Key Terms
9. Terms of Reference for
    a. PG
    b. OMG
    c. NOC
    d. CBP

Joint Build Agreement - System Config & Cost Sharing

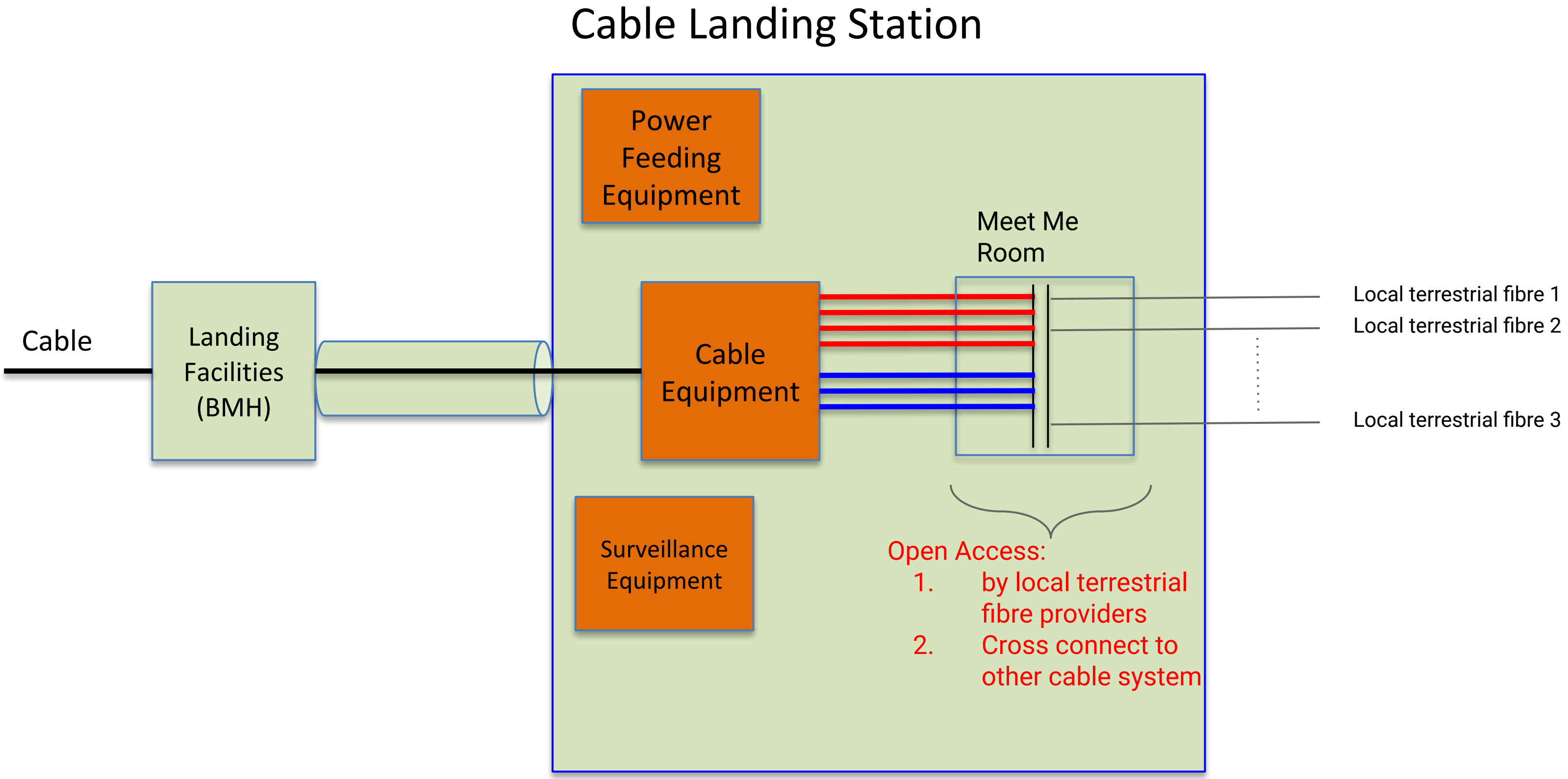
Trunk: Segment A & Segment B
Branch: Segment C
No. of FP: Trunk (5); Branch (2)
OSNR: XX dB
Design capacity: XX Tbps per FP



	Cost Sharing %		
	Purchaser 1	Purchaser 2	Total
Segment A	60%	40%	100%
Segment B	60%	40%	100%
Segment C (including BU)	0%	100%	100%



Joint Build Agreement - Open Access



Cable Landing Station

Power Feeding Equipment

Meet Me Room

Cable

Landing Facilities (BMH)

Cable Equipment

Local terrestrial fibre 1

Local terrestrial fibre 2

Local terrestrial fibre 3

Surveillance Equipment

Open Access:

1. by local terrestrial fibre providers
2. Cross connect to other cable system

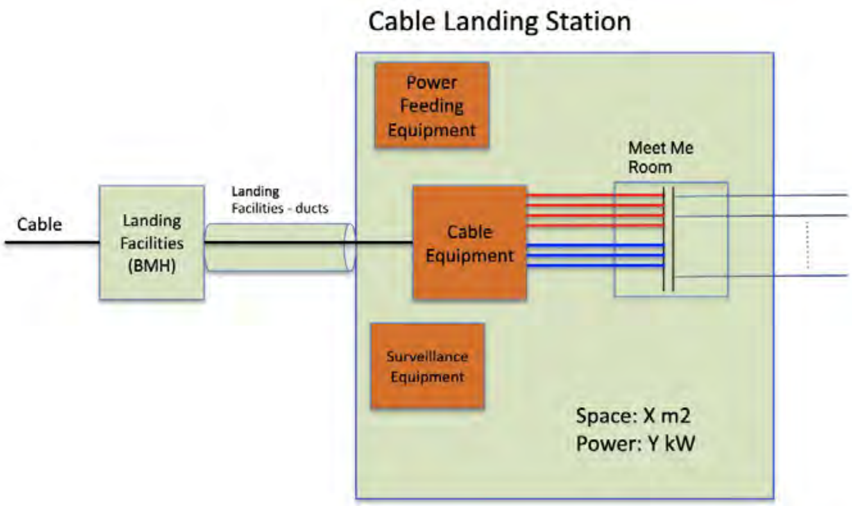
Landing Service Agreement

Key terms

1. Facilities / Services to be provided
   a. Beach Manhole (BMH)
   b. Land route from BMH to Cable Landing Station
   c. Cable Landing Station Space and power (X sq meters, Y kW)
   d. Permit application
   e. Negotiation and signing of any fishery agreement, pipeline agreement
   f. Manpower for Operations and Maintenance (O&M)
   g. Importer of Record

2. Non Recurrent Cost and Recurrent Cost

3. Open access



Purchasers’ Obligations

1. Provision of cable landing facilities (Cable Landing Station, Land route, Beach Manhole)
2. Make timely payments to Supplier
3. Obtain Purchasers’ permits
    a. submarine cable landing license (e.g. FCC license in USA)
    b. permits needed to operate the System

Supplier’ Obligations and Scope of Work

1. Design review and demonstration of technology
2. Route engineering to optimise the cable route
3. Complete the work on time
    a. Permits acquisition
    b. manufacturing
    c. Timely qualification for First Office Application (FOA)

4. Comply with laws and regulations
5. Meet technical specifications
6. Meet acceptance criteria
7. Mitigation of cost exposure

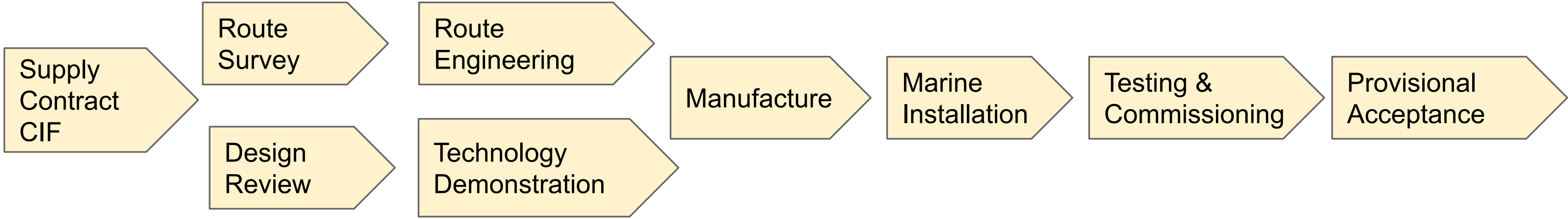
People You need to know

1. Project Team from Supplier
    a. Project Manager
    b. Contract Manager
    c. Marine Manager
    d. Quality Manager
    e. Escalation contact

2. Your own consortium members

Project Implementation and Management

Project Implementation



Supply Contract CIF

Route Survey

Design Review

Route Engineering

Technology Demonstration

Manufacture

Marine Installation

Testing & Commissioning

Provisional Acceptance

Project Management

1. Forming Subcommittees and Working Groups

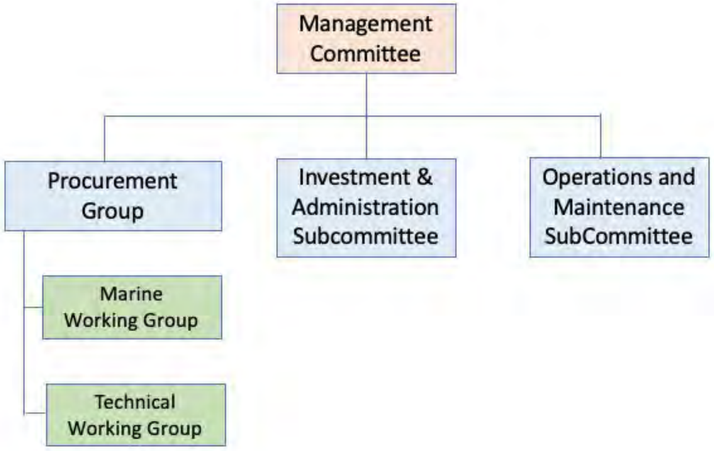
2. Meetings / Conference Calls
    a. Contractor Coordination meetings
    b. Purchasers' internal meetings

3. Quality checks / audits
    a. Factory audit

4. Factory Release Certificates

5. Sending Purchasers' shipboard representatives onboard vessels

6. Monthly Reports / Incident Reports



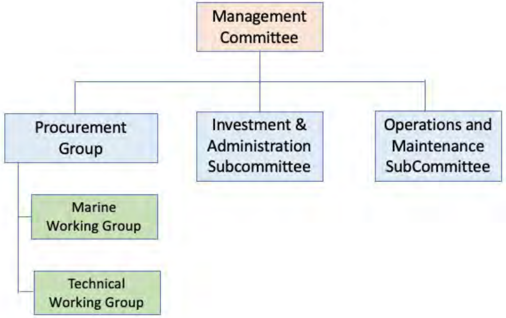
Committees / Meetings

Committees

1. Management Committee (MC) - decision making - exist throughout the cable life
2. Investment and Administrative SubCommittee (I&ASC) - deal with Joint Build Agreement / Landing Party Agreements - exist throughout the cable life
3. Procurement Group (PG) - deal with Suppliers
4. Technical Working Group (TWG) - assist PG on technical matters
5. Marine Working Group (MWG) - assist PG on marine matters
6. Operations and Maintenance SubCommittee Group (O&MSC) - Established ~9-12 months before Provisional Acceptance to deal with O&M matters

Meetings

1. MC / I&ASC - Bi-annually / Quarterly / Ad-hoc
2. PG Meeting / TWG / MWG / Contract Coordination Meetings - Quarterly / Bi-monthly / Ad-hoc
3. O&MSC Meeting - quarterly before PA; once annually after PA



Project Management - Reports

Monthly Report

1. Critical project risks
2. Update on Milestones
3. Near term decisions
4. Purchasers deliverables and due dates
5. Manufacturing status
6. Dry plant installation
7. Permit and license acquisition status
8. Installation Programs
9. New product development
10. Updated Plan of Work
11. Revised Billing Milestones and payment status

Marine Survey and Installation Report

Outside Plant Installation Report

Site Installation Report

Ship Representative Reports

Factory Release Certificate

Testing and Commissioning Report

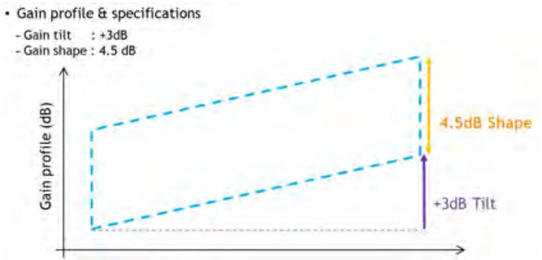
Commissioning

Commissioning

High Tech & High Reliability Systems

- Recommendation: thorough testing & controlling by supplier & qualified inspection authority at
  - Pre-manufacturing
    - Technology Demonstration
    - Qualification
  - Manufacture
    - Component supply
    - Factory test
    - Assembly tests
  - Installation
    - Load & lay tests
    - On-site equipment tests
    - System test

- Why so many tests ?
  - System shall perform 25 years !
  - Time-consuming now but time-saving later
  - Many functionalities
- Test examples
  - Optical power, spectrum, margins, etc
  - Confidence trials, software tests
  - OSNR, GOSNR, Gain Tilt and Gain Shape



- Test passed -> Get the cash and go to next one
- Test failed ->

Acceptance

Acceptance

1. Acceptance - rejection

2. Commercial Acceptance - commissioning test not fully satisfied -> accept part of the System for commercial traffic

3. Provisional Acceptance - commissioning tests satisfied. May have some minor deficiencies but the System is good for carrying traffic.

4. Final Acceptance - it is generally a 5-year period after PA to ensure the System is up and running before Final Acceptance.

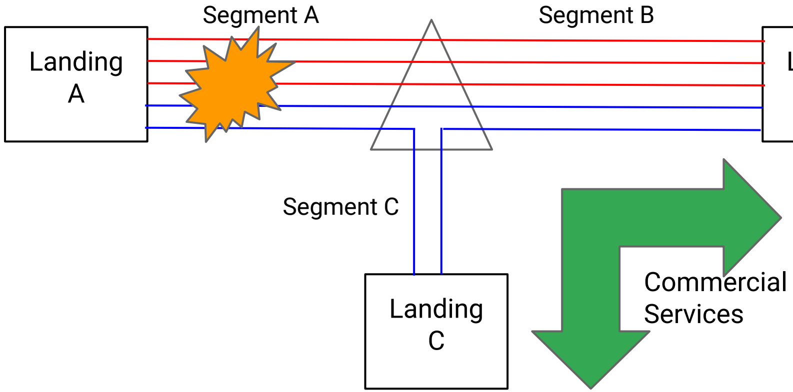
Commercial Acceptance

1. Purchasers are not satisfied with the results of the Acceptance Tests but wish to put a part of or all the System into Commercial Services.

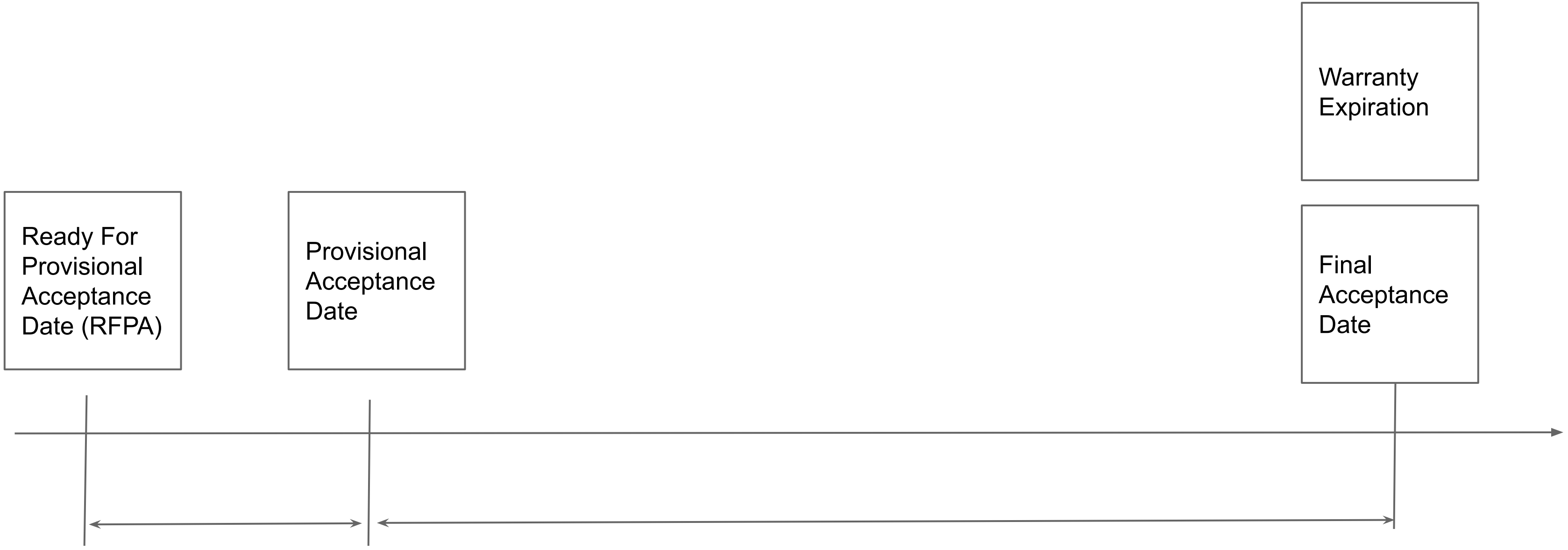
2. Terms and conditions to be mutually agreed between Purchasers and Supplier

3. Supplier shall continue to carry the risk of loss of the System or relevant Segments

4. Upon Supplier's remedy the deficiencies to meet full conformance of contract, Purchasers will issue a Certificate of Provisional Acceptance.



Provisional Acceptance / Final Acceptance



Ready For Provisional Acceptance Date (RFPA)

Provisional Acceptance Date

Warranty Expiration

Final Acceptance Date

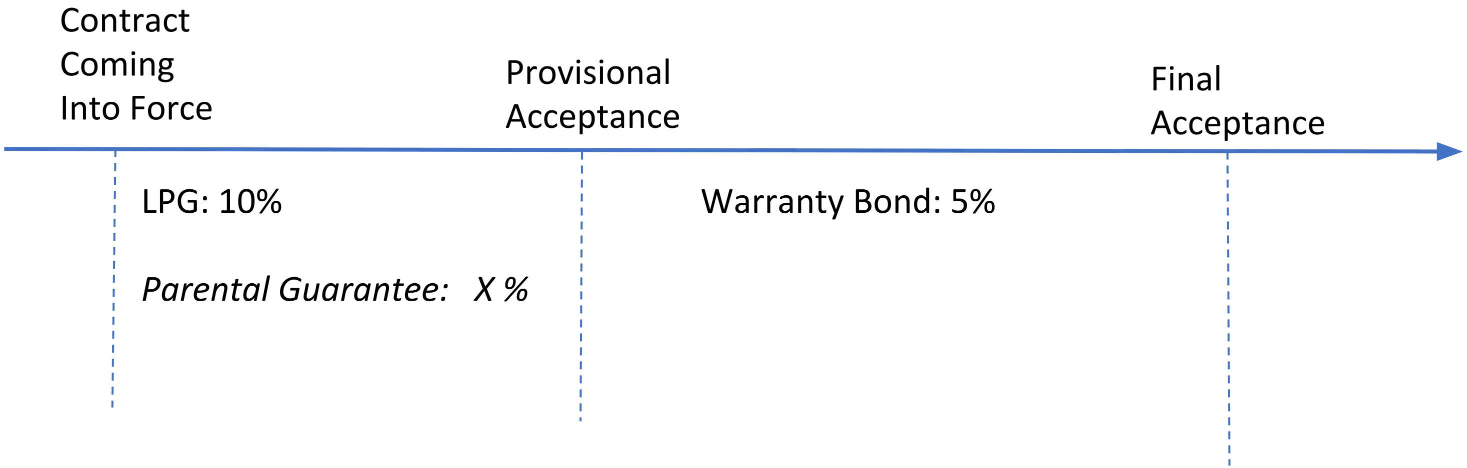
Purchasers review period for test results (e.g. 14 days)

Warranty period (e.g. 5 years)

Performance Bond

Performance Bonds

In order to guarantee the good and timely execution of all of the Contractor’s contractual obligations from the signature date of the Contract through Final Acceptance, Contractor shall provide a Letter of Performance Guarantee (LPG) for a value equal to 10% of the Contract Price, which shall be reduced to 5% of the Contract Price upon the Provisional Acceptance, in favour of the Purchasers and in the form of an irrevocable and unconditional Bank Guarantee issued by a bank approved by Purchasers.



Contract Coming Into Force

Provisional Acceptance

Final Acceptance

LPG: 10%

Parental Guarantee: X %

Warranty Bond: 5%

Construction Challenges

Construction Challenges

1. Permits / License - often on the critical path

- Survey Permit
- Permits In Principle
- Cable Laying Permits
- Operational Permits

2. National Security Agreement - Relevant authorities are increasingly more protective of its critical infrastructure.

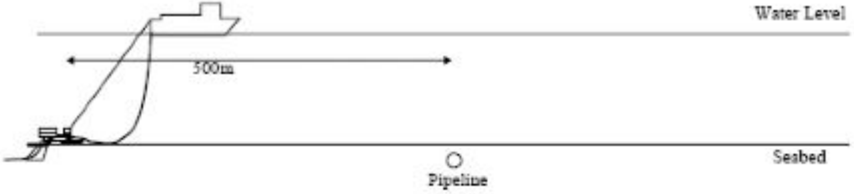
3. Environment Impact Assessment - increased durations and scopes

4. Fishery agreements

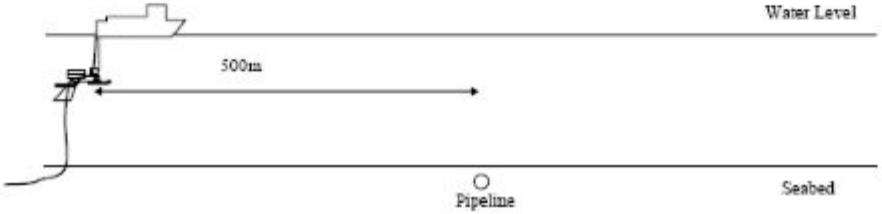
Construction Challenges

5. Pipeline / Cable crossing agreement

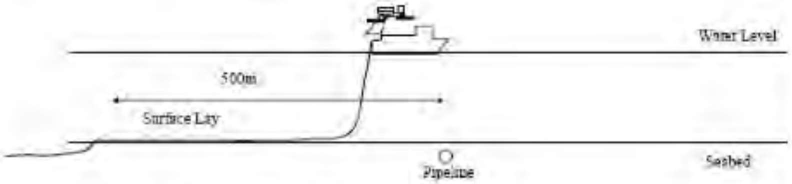
Phase-1 Cease Ploughing 500m before Crossing



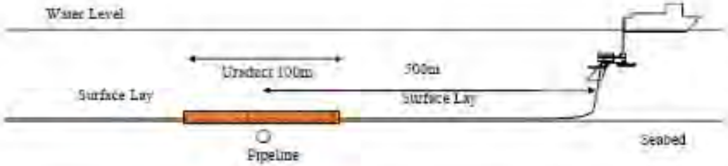
Phase-2 Plough Recovery to onboard Ship



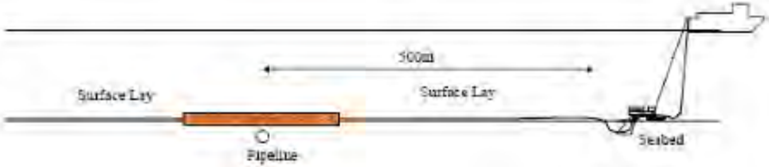
Phase-3 Surface Lay over Pipeline



Phase-4 Launch Plough after 500m from Crossing



Phase-5 Resume Ploughing



Construction Challenges

6. Weather delay - wind, weather, sea conditions and currents that would force curtailment of the work (“Unworkable Weather”).

7. Route engineering - route selection, cost versus quality.

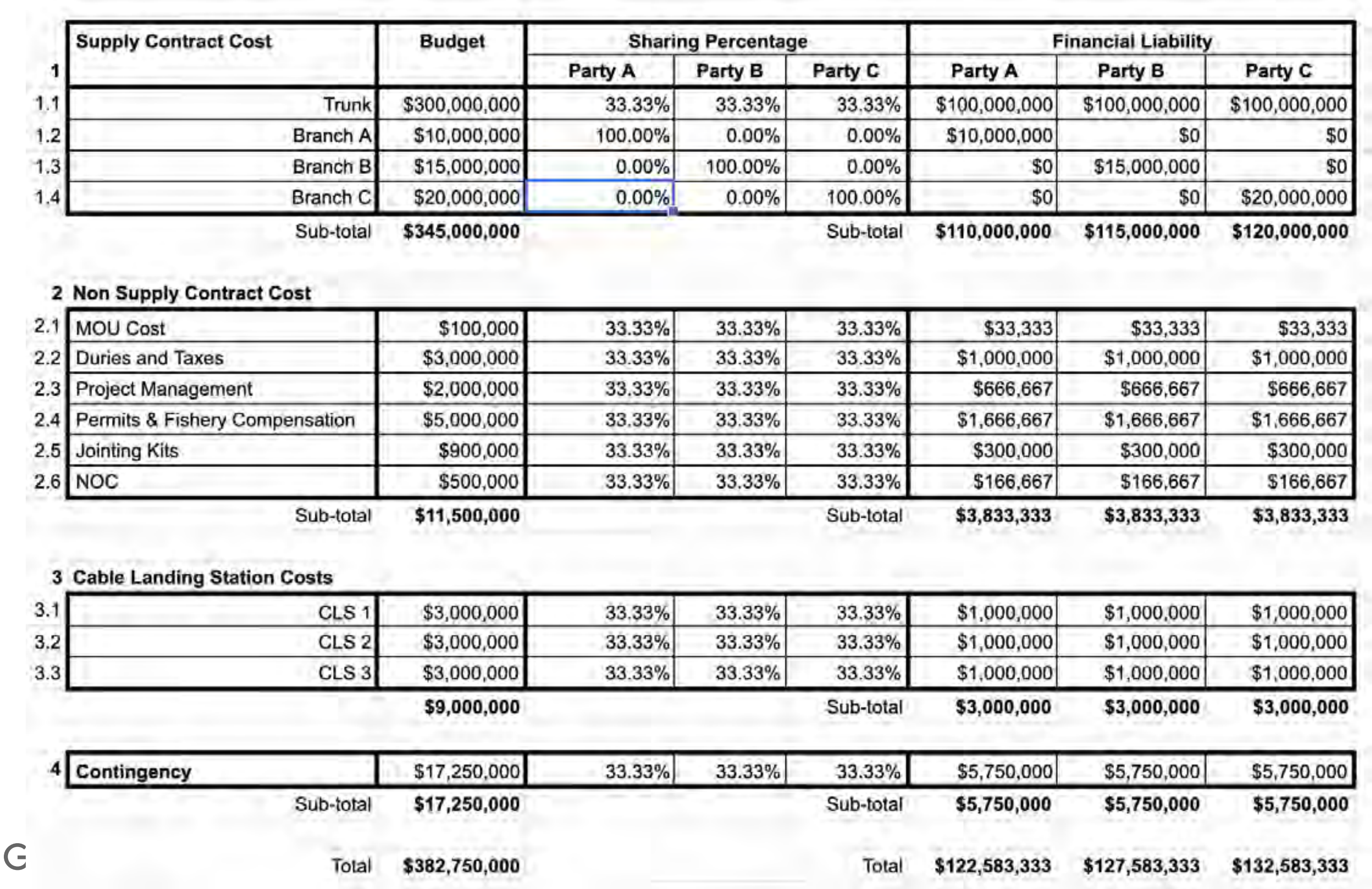
Delay in Completion

1. Liquidated Damages for late completion - the compensation imposed on Supplier due to the delay in completion caused by Supplier

2. LD structure
   a. Generally not exceeding 10% of the contract price
   b. 0.1% of contract price per calendar day of delay up to 10% cap.

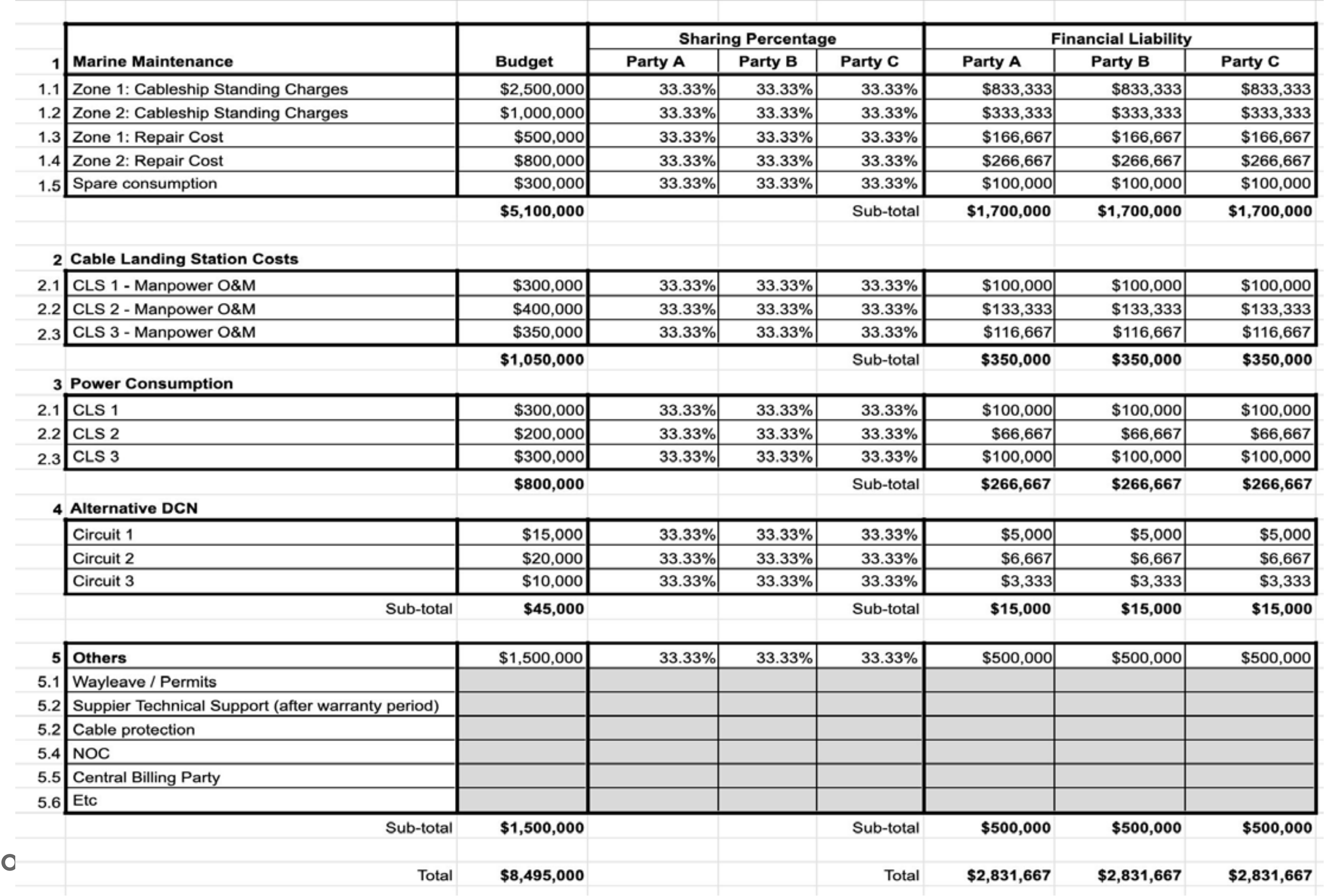
System Budget

System Budget (Capex)



	Supply Contract Cost	Budget	Sharing Percentage			Financial Liability		
1			Party A	Party B	Party C	Party A	Party B	Party C
1.1	Trunk	$300,000,000	33.33%	33.33%	33.33%	$100,000,000	$100,000,000	$100,000,000
1.2	Branch A	$10,000,000	100.00%	0.00%	0.00%	$10,000,000	$0	$0
1.3	Branch B	$15,000,000	0.00%	100.00%	0.00%	$0	$15,000,000	$0
1.4	Branch C	$20,000,000	0.00%	0.00%	100.00%	$0	$0	$20,000,000
	Sub-total	**$345,000,000**			Sub-total	**$110,000,000**	**$115,000,000**	**$120,000,000**
2	**Non Supply Contract Cost**							
2.1	MOU Cost	$100,000	33.33%	33.33%	33.33%	$33,333	$33,333	$33,333
2.2	Duries and Taxes	$3,000,000	33.33%	33.33%	33.33%	$1,000,000	$1,000,000	$1,000,000
2.3	Project Management	$2,000,000	33.33%	33.33%	33.33%	$666,667	$666,667	$666,667
2.4	Permits & Fishery Compensation	$5,000,000	33.33%	33.33%	33.33%	$1,666,667	$1,666,667	$1,666,667
2.5	Jointing Kits	$900,000	33.33%	33.33%	33.33%	$300,000	$300,000	$300,000
2.6	NOC	$500,000	33.33%	33.33%	33.33%	$166,667	$166,667	$166,667
	Sub-total	**$11,500,000**			Sub-total	**$3,833,333**	**$3,833,333**	**$3,833,333**
3	**Cable Landing Station Costs**							
3.1	CLS 1	$3,000,000	33.33%	33.33%	33.33%	$1,000,000	$1,000,000	$1,000,000
3.2	CLS 2	$3,000,000	33.33%	33.33%	33.33%	$1,000,000	$1,000,000	$1,000,000
3.3	CLS 3	$3,000,000	33.33%	33.33%	33.33%	$1,000,000	$1,000,000	$1,000,000
		$9,000,000			Sub-total	**$3,000,000**	**$3,000,000**	**$3,000,000**
4	**Contingency**	$17,250,000	33.33%	33.33%	33.33%	$5,750,000	$5,750,000	$5,750,000
	Sub-total	**$17,250,000**			Sub-total	**$5,750,000**	**$5,750,000**	**$5,750,000**
	Total	**$382,750,000**			Total	**$122,583,333**	**$127,583,333**	**$132,583,333**

System Budget (Opex)



			Sharing Percentage			Financial Liability		
1	**Marine Maintenance**	**Budget**	**Party A**	**Party B**	**Party C**	**Party A**	**Party B**	**Party C**
1.1	Zone 1: Cableship Standing Charges	$2,500,000	33.33%	33.33%	33.33%	$833,333	$833,333	$833,333
1.2	Zone 2: Cableship Standing Charges	$1,000,000	33.33%	33.33%	33.33%	$333,333	$333,333	$333,333
1.3	Zone 1: Repair Cost	$500,000	33.33%	33.33%	33.33%	$166,667	$166,667	$166,667
1.4	Zone 2: Repair Cost	$800,000	33.33%	33.33%	33.33%	$266,667	$266,667	$266,667
1.5	Spare consumption	$300,000	33.33%	33.33%	33.33%	$100,000	$100,000	$100,000
		$5,100,000			Sub-total	**$1,700,000**	**$1,700,000**	**$1,700,000**
2	**Cable Landing Station Costs**							
2.1	CLS 1 - Manpower O&M	$300,000	33.33%	33.33%	33.33%	$100,000	$100,000	$100,000
2.2	CLS 2 - Manpower O&M	$400,000	33.33%	33.33%	33.33%	$133,333	$133,333	$133,333
2.3	CLS 3 - Manpower O&M	$350,000	33.33%	33.33%	33.33%	$116,667	$116,667	$116,667
		$1,050,000			Sub-total	**$350,000**	**$350,000**	**$350,000**
3	**Power Consumption**							
2.1	CLS 1	$300,000	33.33%	33.33%	33.33%	$100,000	$100,000	$100,000
2.2	CLS 2	$200,000	33.33%	33.33%	33.33%	$66,667	$66,667	$66,667
2.3	CLS 3	$300,000	33.33%	33.33%	33.33%	$100,000	$100,000	$100,000
		$800,000			Sub-total	**$266,667**	**$266,667**	**$266,667**
4	**Alternative DCN**							
	Circuit 1	$15,000	33.33%	33.33%	33.33%	$5,000	$5,000	$5,000
	Circuit 2	$20,000	33.33%	33.33%	33.33%	$6,667	$6,667	$6,667
	Circuit 3	$10,000	33.33%	33.33%	33.33%	$3,333	$3,333	$3,333
	Sub-total	**$45,000**			Sub-total	**$15,000**	**$15,000**	**$15,000**
5	**Others**	$1,500,000	33.33%	33.33%	33.33%	$500,000	$500,000	$500,000
5.1	Wayleave / Permits							
5.2	Suppier Technical Support (after warranty period)							
5.2	Cable protection							
5.4	NOC							
5.5	Central Billing Party							
5.6	Etc							
	Sub-total	**$1,500,000**			Sub-total	**$500,000**	**$500,000**	**$500,000**
	Total	**$8,495,000**			Total	**$2,831,667**	**$2,831,667**	**$2,831,667**

Check-list before Provisional Acceptance

Check-list before Provisional Acceptance

1. Satisfactory acceptance test
2. List of deficiency items, if any
3. Record of permits / licenses
4. Marine maintenance in place
5. Spare submersible plants, jointing kits
6. Readiness of Network Operation Centre (NOC)
7. Appointment of Central Billing Party (CBP)
8. Completion Training (NOC, CLS, land cable, etc.)
9. Land cable maintenance
10. Test equipment (CLS and depot)
11. System Manuals / Handbooks, update of Route Position List (RPL)
12. Joint System Maintenance Document
13. Alternative Data Communications Network
14. Supplier’s issuance of performance bond from 10% of contract price to 5%
15. Check fulfilment of Terms of Reference of each SubCommittee and Working Groups
16. Press Release ?

Ready to Go !

Operations and Maintenance

Joint System Maintenance Document

JSMD sets out the agreed by all the Maintenance Authorities to be followed for all aspects concerning the maintenance and repair of equipment and facilities.

O&M Organisation, Maintenance Representatives and Contacts:

a) Maintenance Authority
b) Cable Landing Station contacts
c) Marine Maintenance arrangement
d) Land cable maintenance arrangement
e) NOC

Power Safety: provides procedures to handle electrical and optical power handling during normal operation and during repair. To define Power Safety Rules and Power Safety Rules:

Power Safety Officer (PSO)

a) Terminal Power Safety Office (TPSO)
b) Deputy Terminal Power Safety Office (Deputy TPSO)
c) Ship PSO

Joint System Maintenance Document (Cont'd/…)

Power Safety Message (PSM)

The purpose of power safety message (PSM) is to ensure the communication between cable stations and cableship during cable repair so as to avoid any misunderstanding among all the participants of the repair work and prevent any accident.

“One Action One PSM” is the fundamental rule and the most important for safety operation. The message to be used for the PSM must be as simple as possible so that cable stations and cableship can understand quickly and easily. Time to be used in PSM must be UTC in principle.

The exchange of PSM must be made on in a written form.

After receiving the PSM, recipient must be acknowledged by PSM.

Copies of PSMs must be retained in the submarine power safety logbooks.

Reference Number must be put on PSM.

Joint System Maintenance Document (Cont’d/…)

Power Safety Message (PSM) - <u>PROHIBITED ACTIONS FOR POWER SAFETY OFFICER</u>

- ☠ To omit the respective power safety procedures and to communicate other PSOs verbally without exchange of power safety messages (PSM).
- ☠ To prepare signed PSMs in advance of each process.
- ☠ To make judgments at the mere sight of situation without confirmation.
- ☠ Not to observe power feeding process step by step.
- ☠ To make other staff to sign the PSM.
- ☠ To send PSM other than PSO or deputy PSO.
- ☠ To accept the existence of plural power control at the stations or cableships, in case of simultaneous cable repairs in the same system (in terms of power feeding configuration) by plural number of cableships.

Joint System Maintenance Document (Cont’d/…)

Power Safety Message (PSM) - Sample

Cableship

PSM - ABC Cable Segment 1 Repair No. 1

Cableship to CLS PSM No. 1 **Date**

Cableship XX will arrive at repair ground at XX LT on DDMMYY. Cableship PSO is XXX, Deputy PSO is YYY.

Please nominate Terminal Station Power Safety Officer and your contact point and advise the PFE status.

Signature

PSM - ABC Cable Segment 1 Repair No. 1

Cableship to CLS PSM No. 2 **Date**

Your PSM No.1 is received. Please inform the power feeding (voltage and current) of your Power Feeding Equipment and transfer responsibility of power safety control from CLS to cableship.

Signature

CLS

PSM - ABC Cable Segment 1 Repair No. 1

CLS to Cableship PSM No. 1 **Date**

Your PSM No. 1 is received. Our TPSO and DPSO are XXX and YYY. Contact information is xxx.

Signature

PSM - ABC Cable Segment 1 Repair No. 1

CLS to Cableship PSM No. 2 **Date**

Your PSM No. 2 is received. Our PFE current status is:

V= XX Volt; Current = XX mA

The Power Safety Control is handed over to cableship

Signature

Marine Maintenance

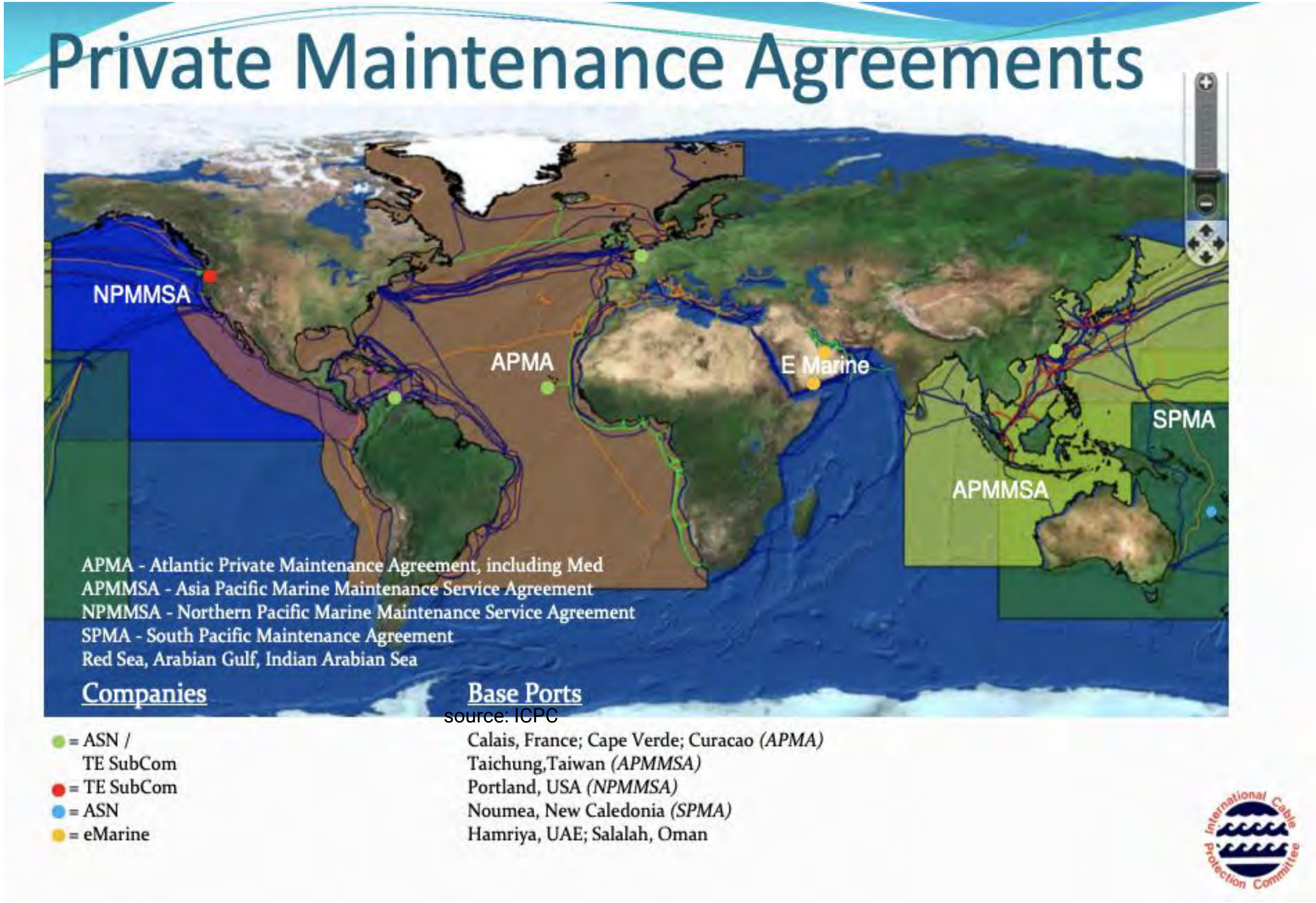
Zone Maintenance Agreements

NAZ - North America Zone
ACMA - Atlantic Cable Maintenance Agreement
MECMA – Mediterranean Cable Maintenance Agreement
SEAIOCMA – South East Asia and Indian Ocean Cable Maintenance Agreement
YZ - Yokohama Zone

Companies/Zones	Base Ports
● = Orange/GMSL *(ACMA)*	Brest, France; Portland, UK; Curacao
● = Orange/Elettra *(MECMA)*	La Seyne Sur Mer, France; Catania, Italy
● = Orange *(2OCMA)*	Cape Town, South Africa
● = GMSL *(NAZ)*	Victoria, Canada
● = KCS/KTS/SBSS (YZ)	Yokohama, Japan; Keoje, Korea; Wujing, China
● = ACPL/IOCPL/GMSL *(SEAIOCMA)*	Singapore; Colombo, Sri Lanka; Manila, Phillipines

source: ICPC

Marine Maintenance



Private Maintenance Agreements

APMA - Atlantic Private Maintenance Agreement, including Med
APMMSA - Asia Pacific Marine Maintenance Service Agreement
NPMMSA - Northern Pacific Marine Maintenance Service Agreement
SPMA - South Pacific Maintenance Agreement
Red Sea, Arabian Gulf, Indian Arabian Sea

Companies

🟢 = ASN / TE SubCom
🔴 = TE SubCom
🔵 = ASN
🟡 = eMarine

Base Ports

Calais, France; Cape Verde; Curacao *(APMA)*
Taichung,Taiwan *(APMMSA)*
Portland, USA *(NPMMSA)*
Noumea, New Caledonia *(SPMA)*
Hamriya, UAE; Salalah, Oman

source: ICPC

source: ICPC

Marine Maintenance

Considerations for selection of Marine Maintenance Providers:

1. Geographical coverage
2. Based ports and depots locations
3. Capability of cableships and ROVs
4. Service availability
5. Number of scheduled cables covered
6. Commercial (Standing Charges, Running Costs, Storage Charges)
7. Direct Measure of Quality (DMOQ)
    a. Time to mobilize Cableship
    b. Average transit speed
    c. Time to complete a cable repair
    d. Time to issue Completion Report after the repair

NOC

NOC & Network Administrator

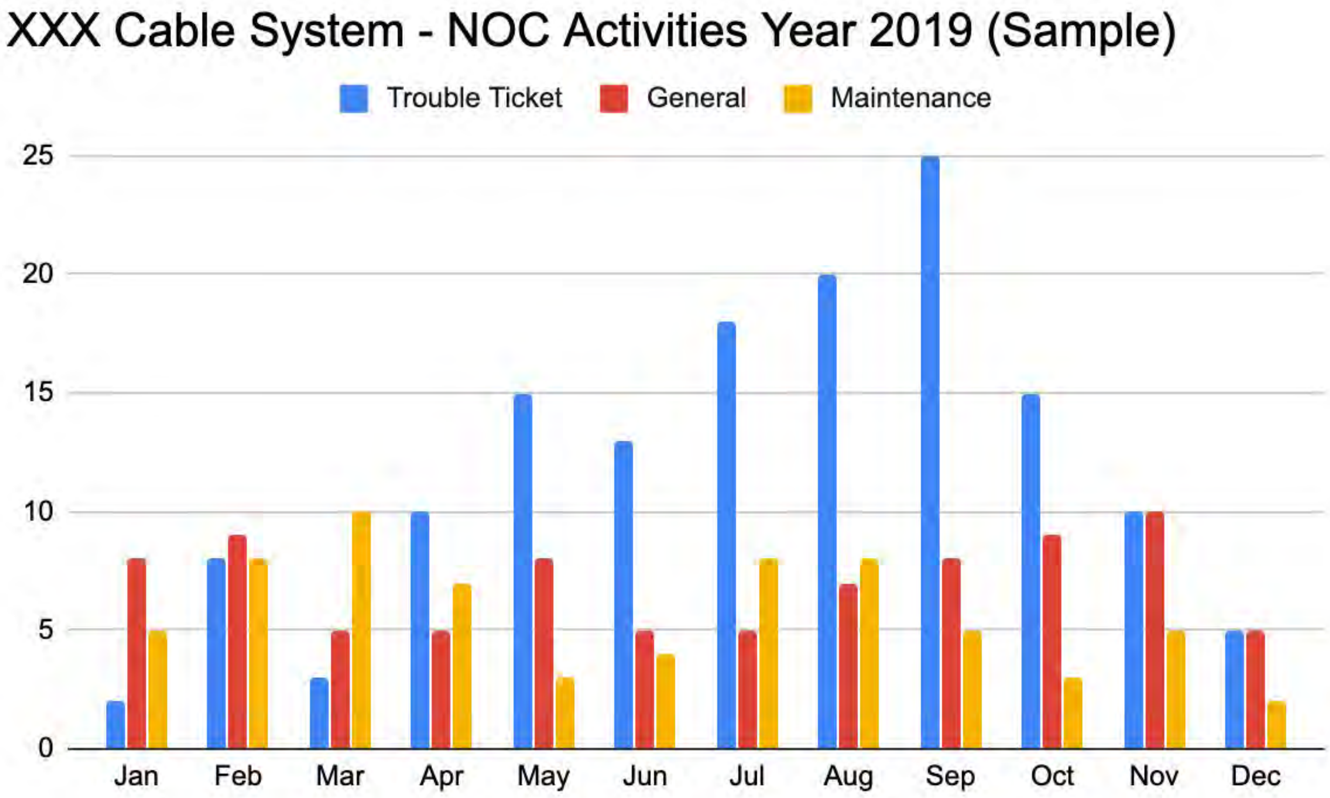
NOC = Network Operation Center

- Overall control of the System
- A 24/7 experienced team
- Location may be restricted due to licensing requirement

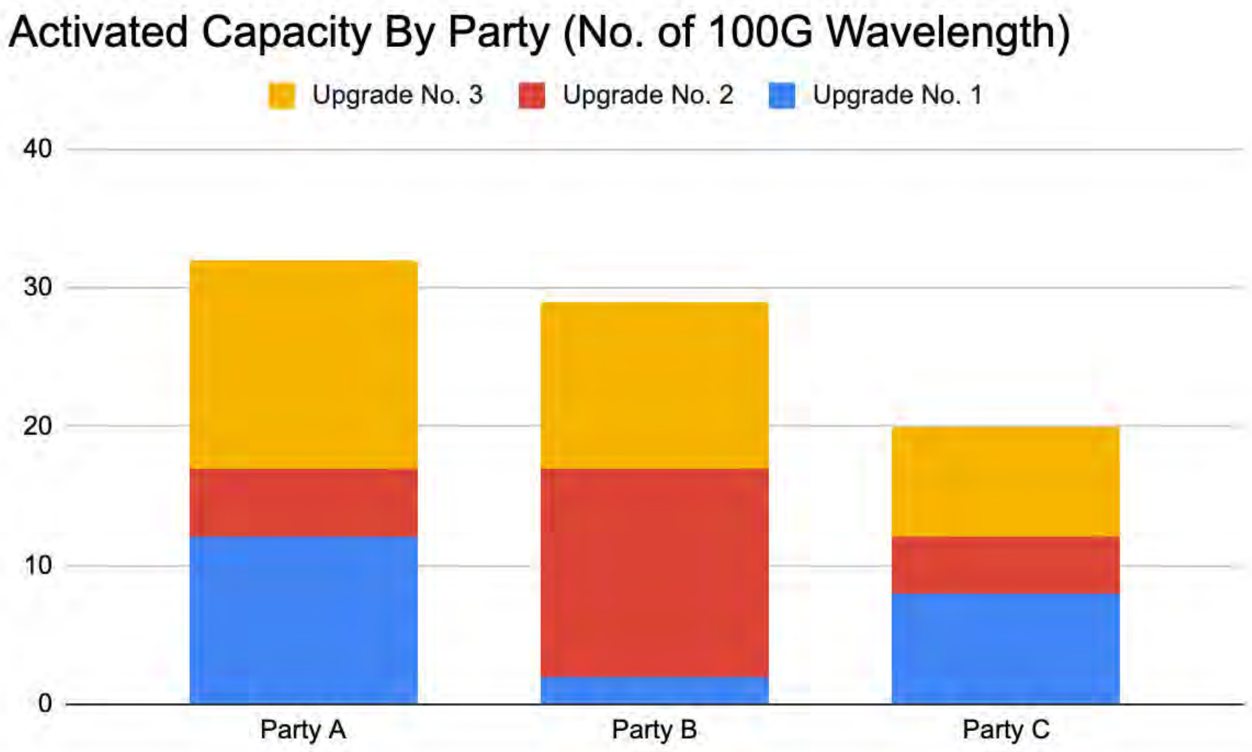
Tasks

- Monitor wet plant performance
- Coordinate fault localisation
- Coordinate cable repairs
- Coordinate planned maintenance
- Coordinate capacity upgrades
- Implement and supervise traffic
- Monitor traffic quality
- Generate capacity reports
- Keep logs of daily events (alarms, etc.)

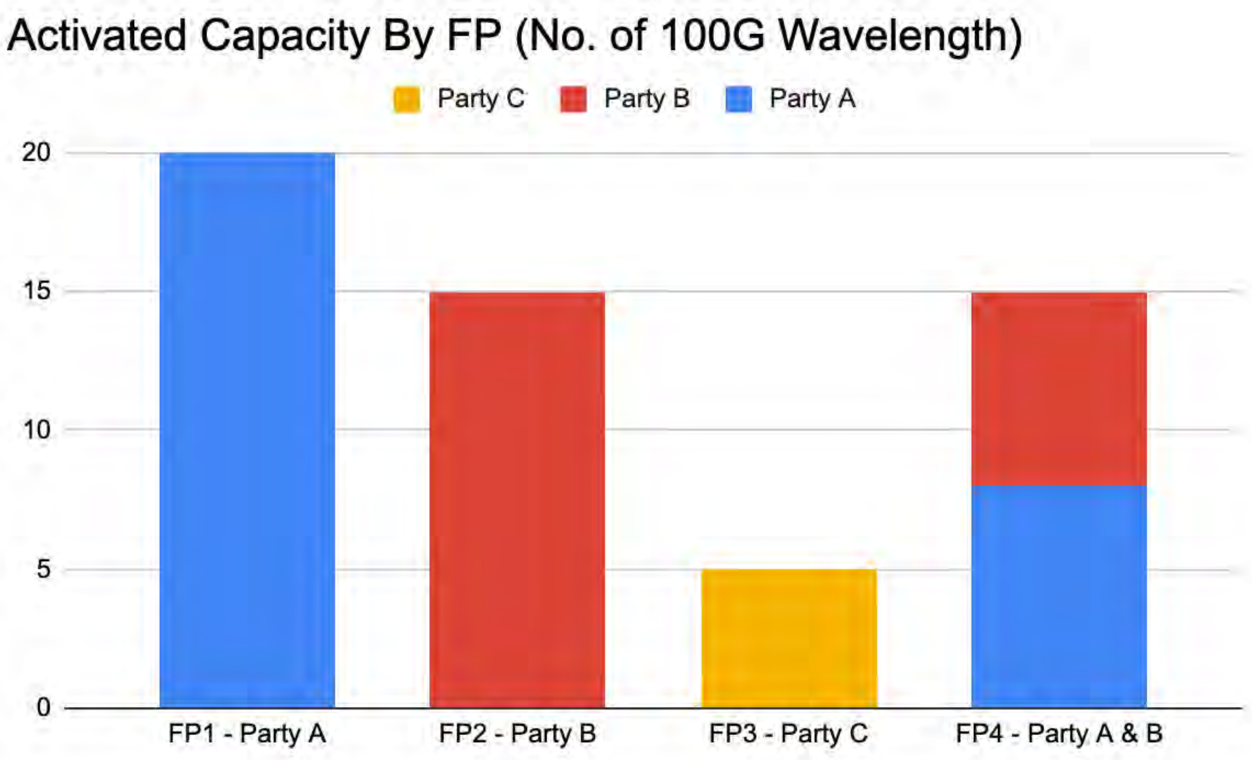
NOC & Network Administrator - Activities



NOC & Network Administrator - Report on Activated Capacity



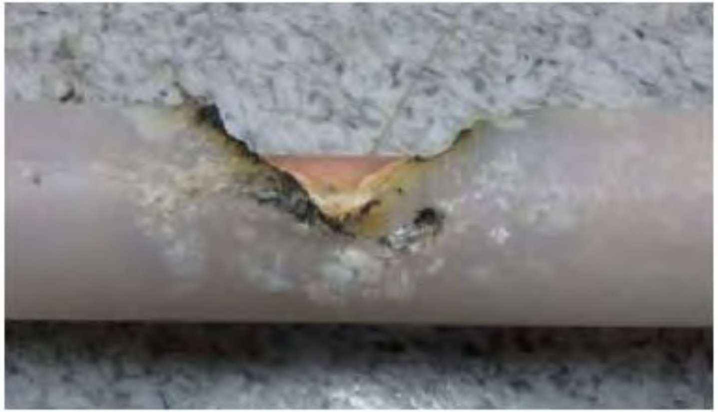
NOC & Network Administrator - Report on Activated Capacity



Life of a Cable

Life of a Cable

1. Cable Repairs
2. Update of JSMD, System Handbooks and maintenance procedures
3. Update of system parameters (SLD, RPL)
4. Marine Maintenance
5. Replenishment of spares
6. Renewal of licenses / permits
7. Compliance to regulations
8. Route diversions (land and subsea)



Life of a Cable

9. Cable Landing Station O&M

    a. Security
    b. Routine Maintenance
    c. Repair and return
    d. Land route patrol

10. Capacity Upgrades

11. Update of Mux Plan (channel assignment table)

12. Cable Protection / Awareness

13. Keeping of maintenance of records

14. O&M Budget Control

15. Annual O&M meeting

Capacity Upgrade

1. System is Dark on day-1. Need to augment capacity on a regular basis to meet demand
2. Open Cable: Purchasers can freely select any equipment suppliers
3. Consider individual upgrade versus consortium upgrade
4. Selection of upgrade supplier (cost, lead time, modulation formats, channel spacing, FEC limit, etc.)
5. Wavelength allocations / assignment
6. Guard band between spectrum from different suppliers and different technology
7. Ensure no interruption on existing capacity throughout the upgrade operations
8. Perform capacity upgrade during any maintenance window
9. Engage NOC to monitor traffic throughout the upgrade operation
10. Provide training to CLS and NOC if a new platform is introduced

Decommissioning

Decommissioning

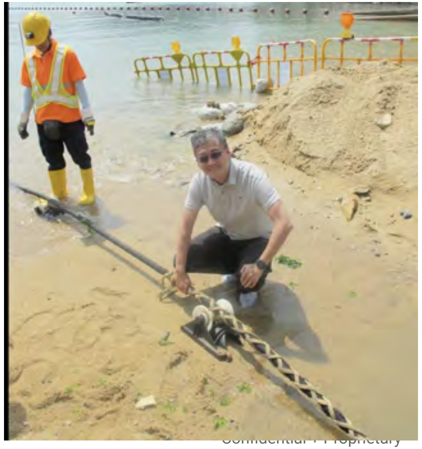
1. Decision on decommissioning or retirement shall be contemplated at JBA stage.

   For example:

      i. Design life is 25 years
      ii. Unanimous decision: early decommissioning or retirement if the cable is operated for less than 25 years
      iii. Simple Majority: if the System has been in operations for more than 25 years

2. Upon decommissioning, Parties shall:
   a. use all reasonable efforts to liquidate System
   b. The net proceeds or costs of decommissioning such as removal / recovery of plants shall be shared by the Parties.

Photos - Cable Landing



\Orchestrating a brighter world NEC

Alternative Applications and SMART Cables

Simon WEBSTER
NEC Europe Ltd.

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Acknowledgements

- Special thanks to the **ITU/WMO/UNESCO IOC Joint Task Force** (JTF), for providing much of the content on climate change and SMART Cables

- ··· particularly Bruce Howe, JTF Chair and Research Professor at University of Hawaii at Manoa

- SMART = **S**cientific **M**onitoring **A**nd **R**eliable **T**elecommunications

- The JTF is tasked with developing a **strategy and roadmap** that could lead to enabling the availability of submarine repeaters equipped with scientific sensors for ocean and climate monitoring and disaster risk reduction (tsunamis).

- https://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx

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Tsunamis

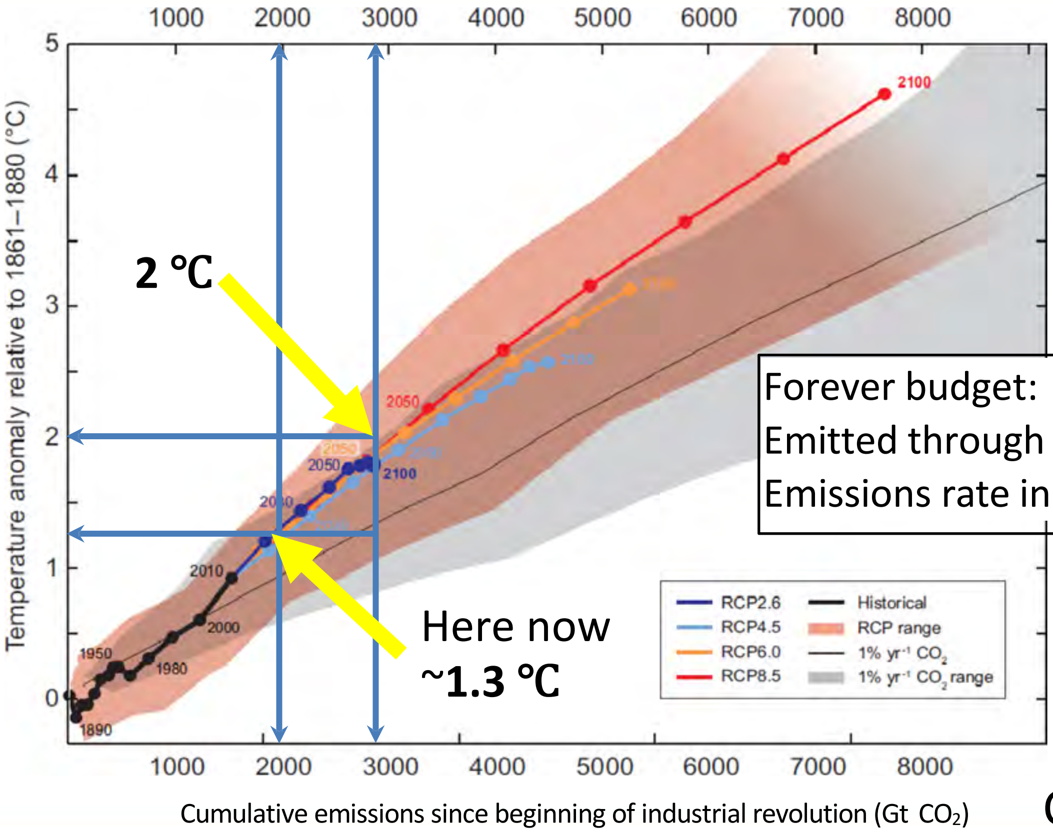

© BNPB

Place	Year	Mag	H(m)	Deaths
Chile	1960	9.5	25	6,000
Alaska	1964	9.2	30	132
Mindinao	1976	7.9	9	7,800
Tumaco	1979	8.1	6	350
Hokkaido	1993	7.8	30	250
Papua New Guinea	1998	7.1	15	2,200
Sumatra	2004	9.2	33	230,000
Solomon Islands	2007	8.1	12	52
Samoa	2009	8.1	14	192
Tohoku	2011	9.0	10	19,000
Palu	2018	7.5	7	1,703 +

Source: JTF

Climate – temperature vs cumulative CO_2

Temperature



2 °C

Here now

~1.3 °C

Sources:

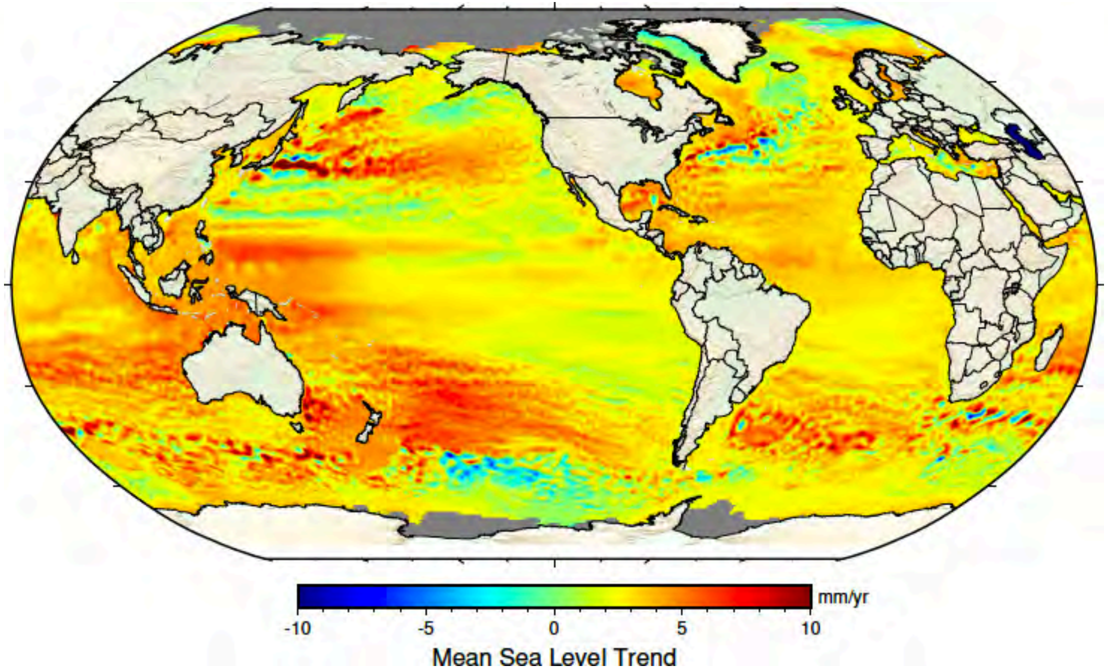
- IPCC, WG I, 2013
- JTF

Forever budget:	2900 Gt CO_2e for 66% prob. ≤ **2°C**
Emitted through 2016:	2133 Gt CO_2e
Emissions rate in 2016:	49.3 Gt CO_2e

→ ~15 years at present rate

Carbon burned

Sea level rise



Sea level rise is not uniform in time and space – it is accelerating

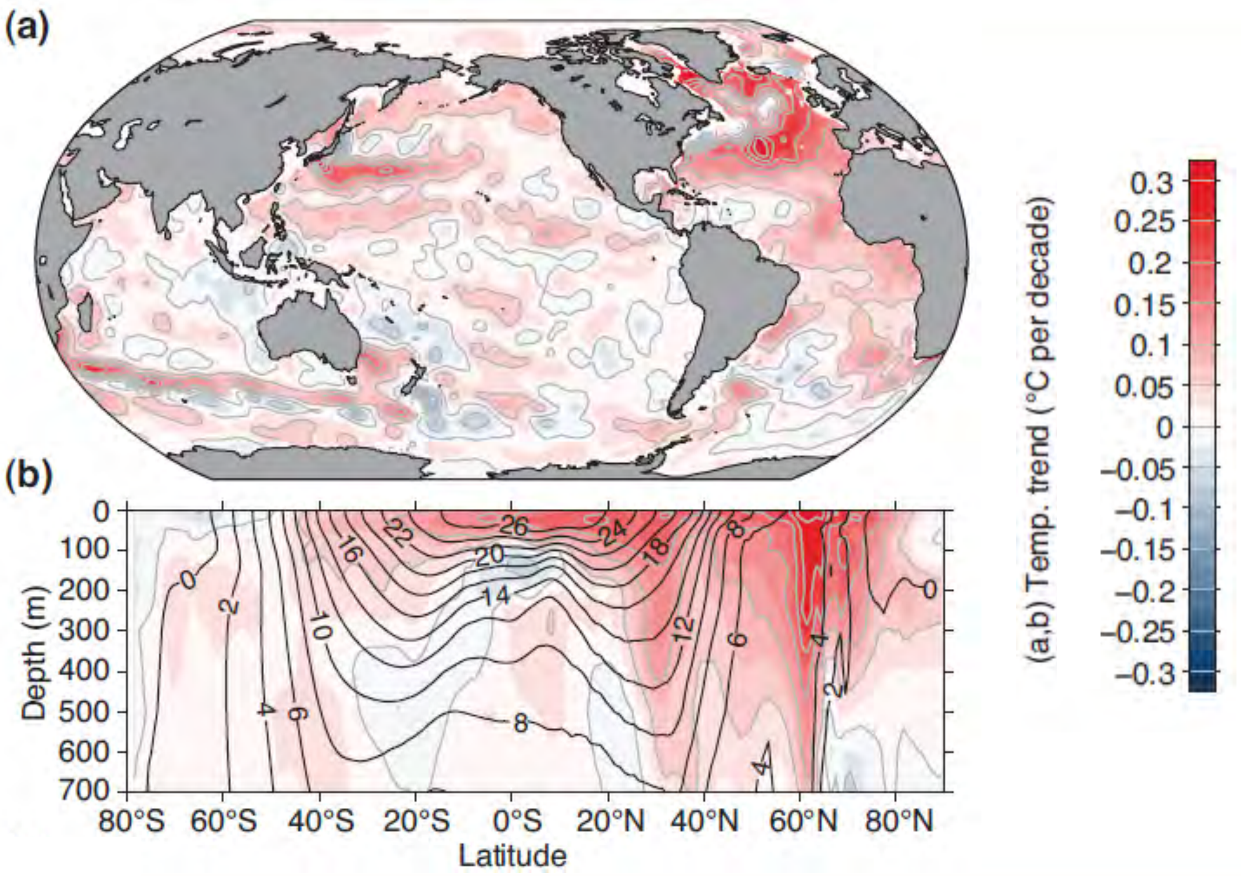
Now: globally 3.2 mm/y

By 2100: 8mm/y, +65cm since 2005

Sources:

- IPCC, WG I, 2013
- JTF
- J. T. Fasullo et al., Scientific Reports volume 6, Article number: 31245 (2016)

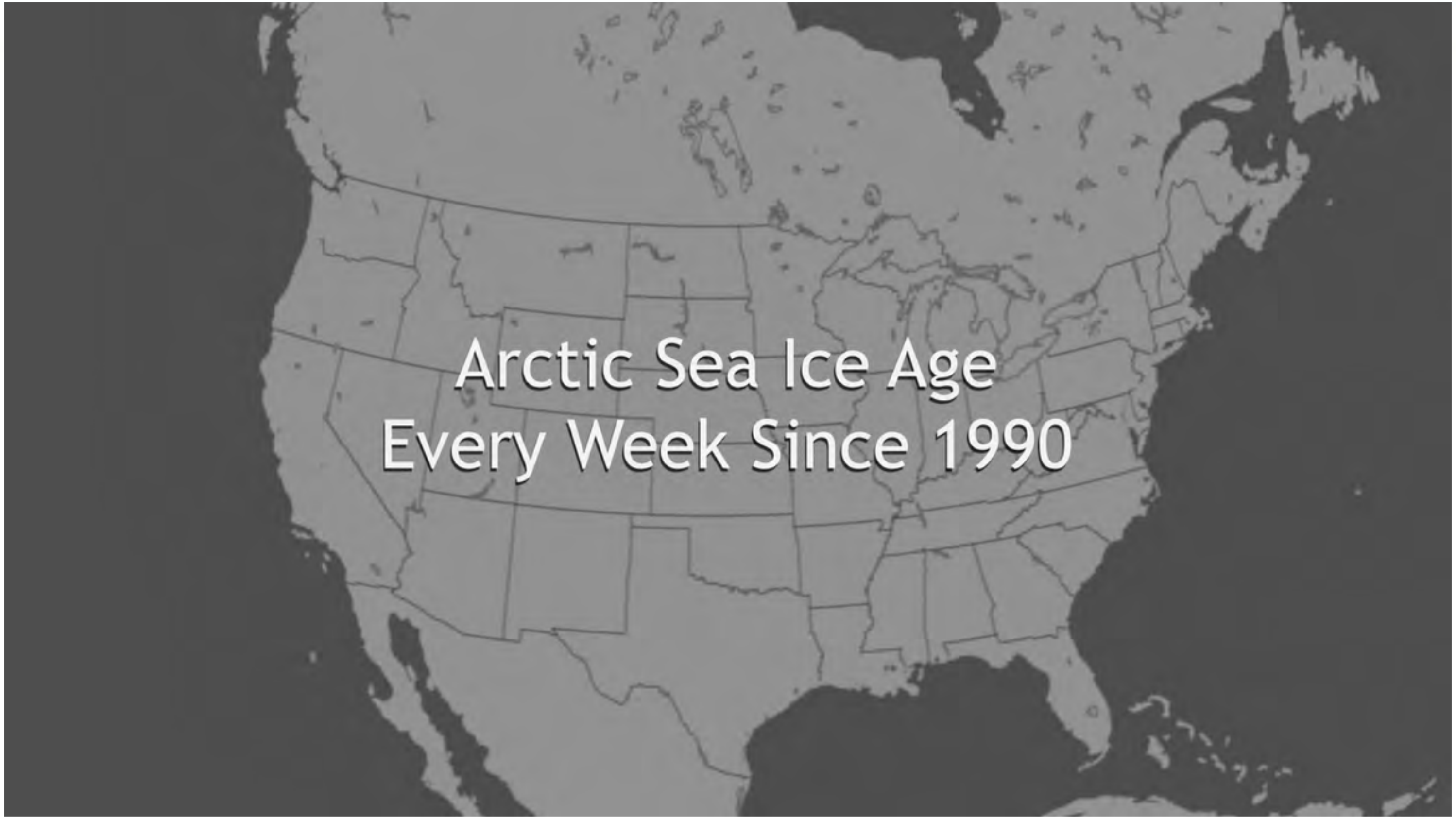
Ocean temperature rise



Few observations in deep water

Source:
- IPCC, WG I, 2013

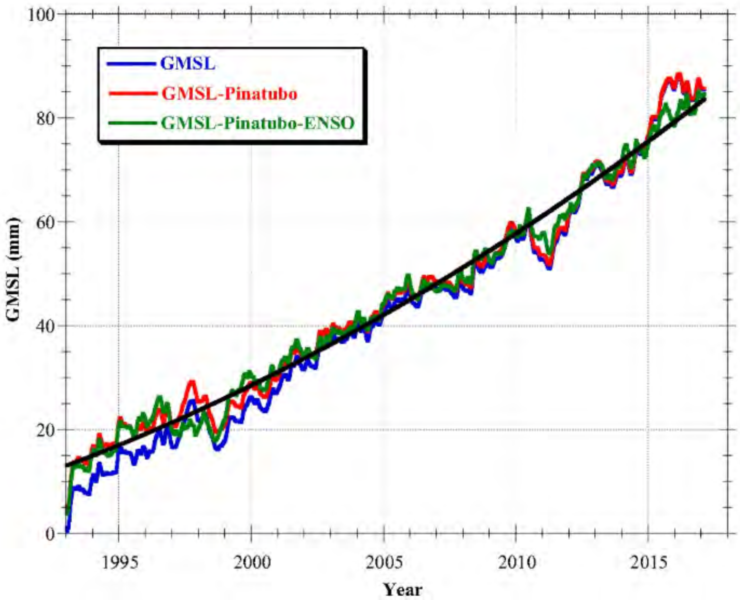
Declining sea ice extent and thickness



Source: NOAA, https://www.climate.gov/

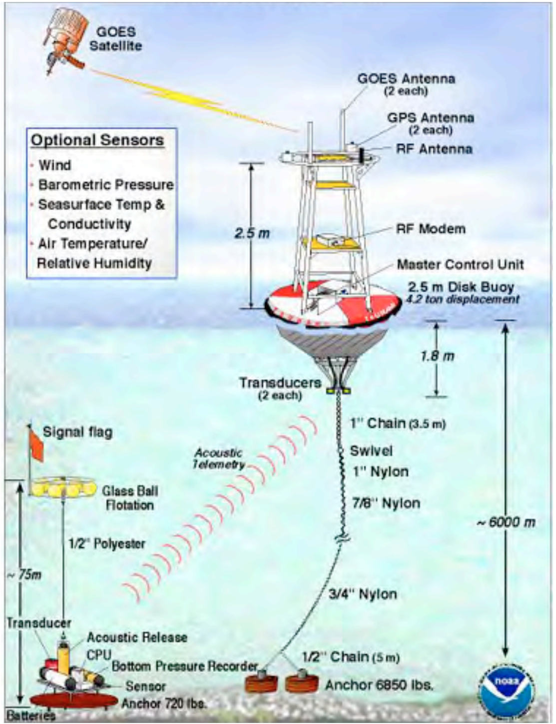
Techniques available

- Satellite altimetry shows Global Mean Sea Level rise



Source: R. S. Nerem et al., PNAS February 27,
2018 115 (9) 2022-2025

- DART buoys send bottom pressure data to satellites

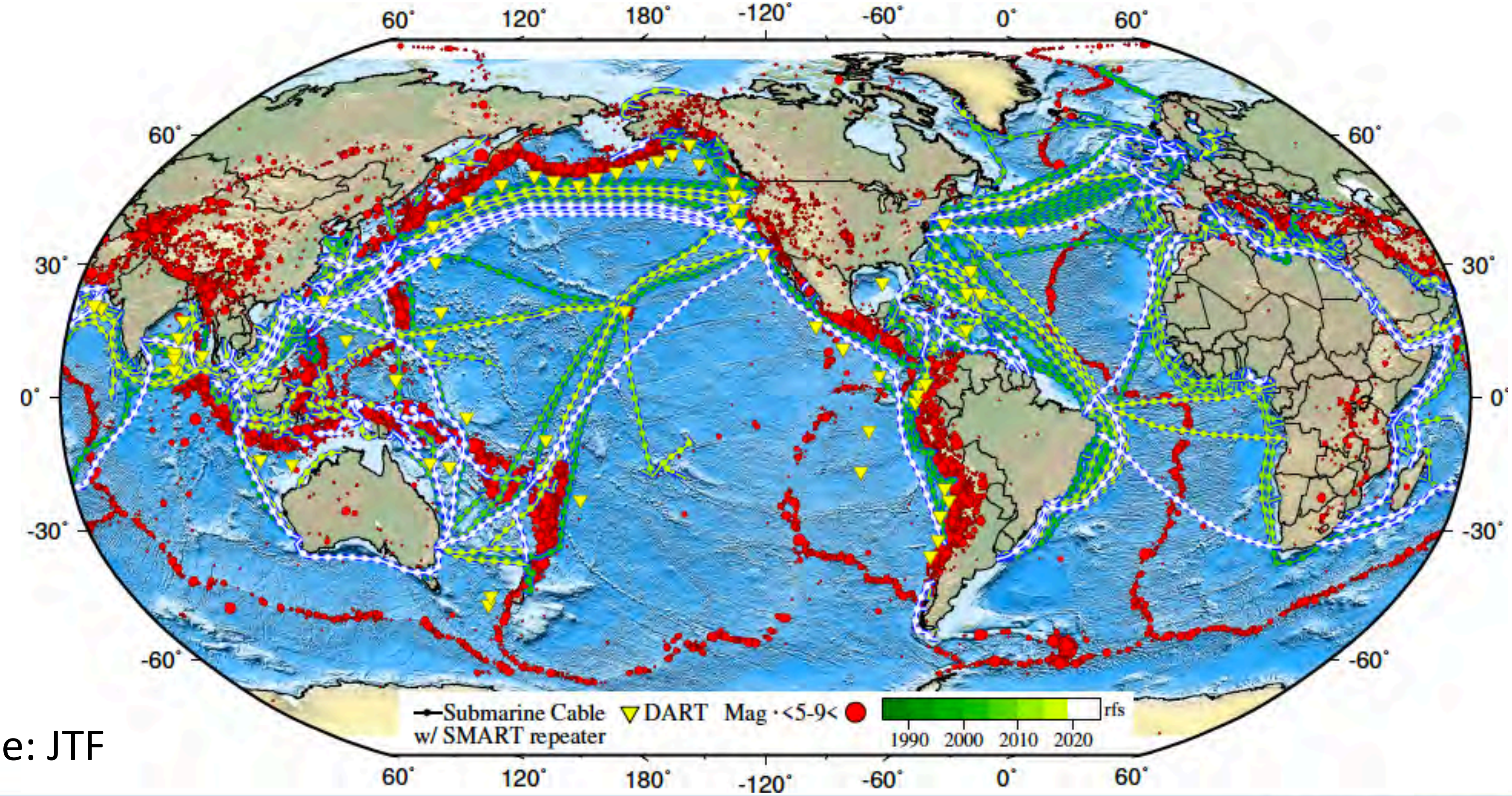


Source: NOAA

- Other basic methods

Tsunamis – where do we need to measure?

Comparing the locations of earthquakes, DART buoys and telecom cables



Source: JTF

Context – what could we gain from deep ocean measurements?

Ocean bottom observations of earthquake and tsunami effects offer:

- Longer-term understanding of submarine seismic activity and tsunamis, including the establishment an accumulated database for future reference
- Increased global coverage may lead to reduced location uncertainties, better seismic magnitude calculations, and reduced detection thresholds
- Prompt real-time monitoring for early warning to the public

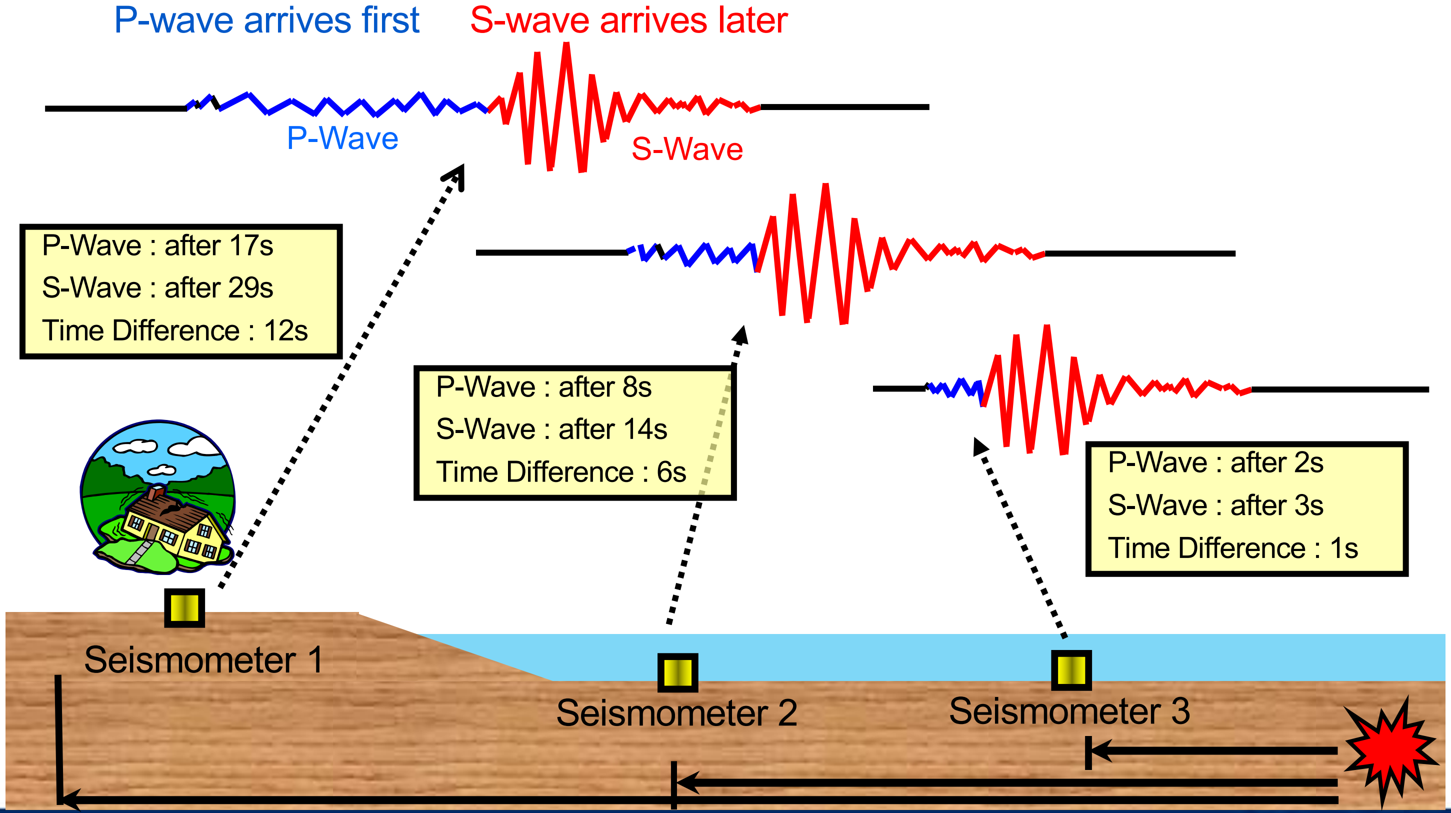
Ocean bottom observations of water temperature offer:

- Better understanding of global ocean currents
- Better models for climate science to refine predictions of climate change

How fast do seismic waves travel?

Seismic Wave Velocity: Primary Wave (P-Wave) ＝ 5 ~ 7 km/s

Secondary Wave (S-Wave) ＝ 3 ~ 4 km/s



P-Wave : after 17s
S-Wave : after 29s
Time Difference : 12s

P-Wave : after 8s
S-Wave : after 14s
Time Difference : 6s

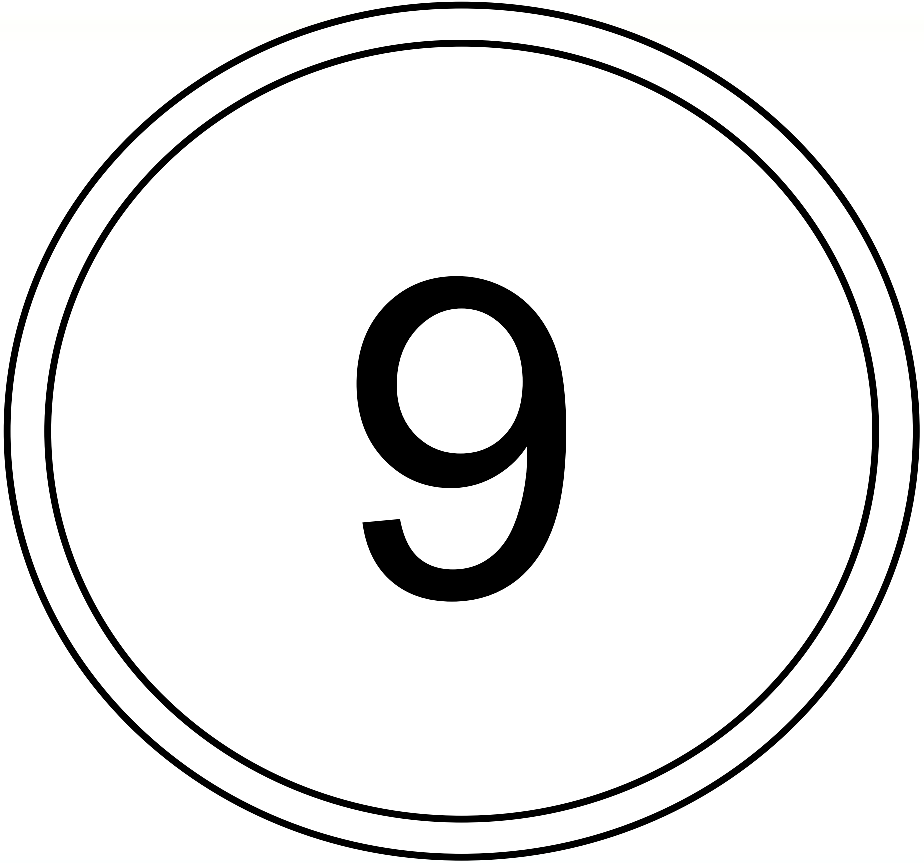
P-Wave : after 2s
S-Wave : after 3s
Time Difference : 1s

What can you achieve with advance earthquake warning?

What can you achieve with advance earthquake warning?

10

What can you achieve with advance earthquake warning?



What can you achieve with advance earthquake warning?

8

What can you achieve with advance earthquake warning?

7

What can you achieve with advance earthquake warning?

6

What can you achieve with advance earthquake warning?

What can you achieve with advance earthquake warning?

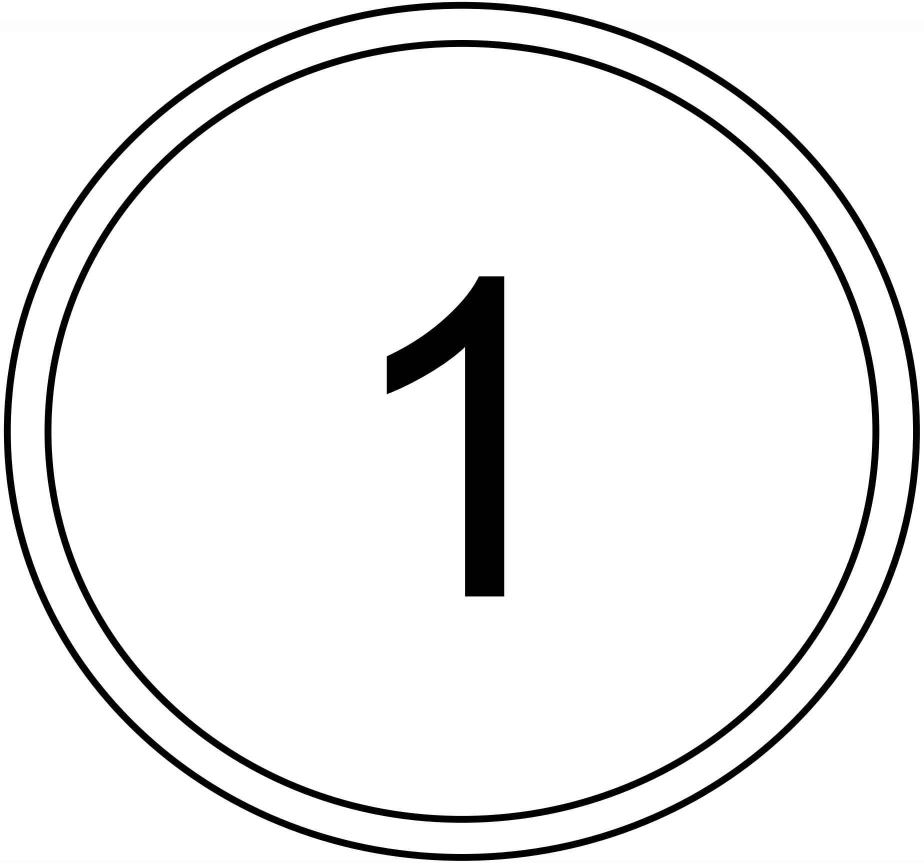
4

What can you achieve with advance earthquake warning?

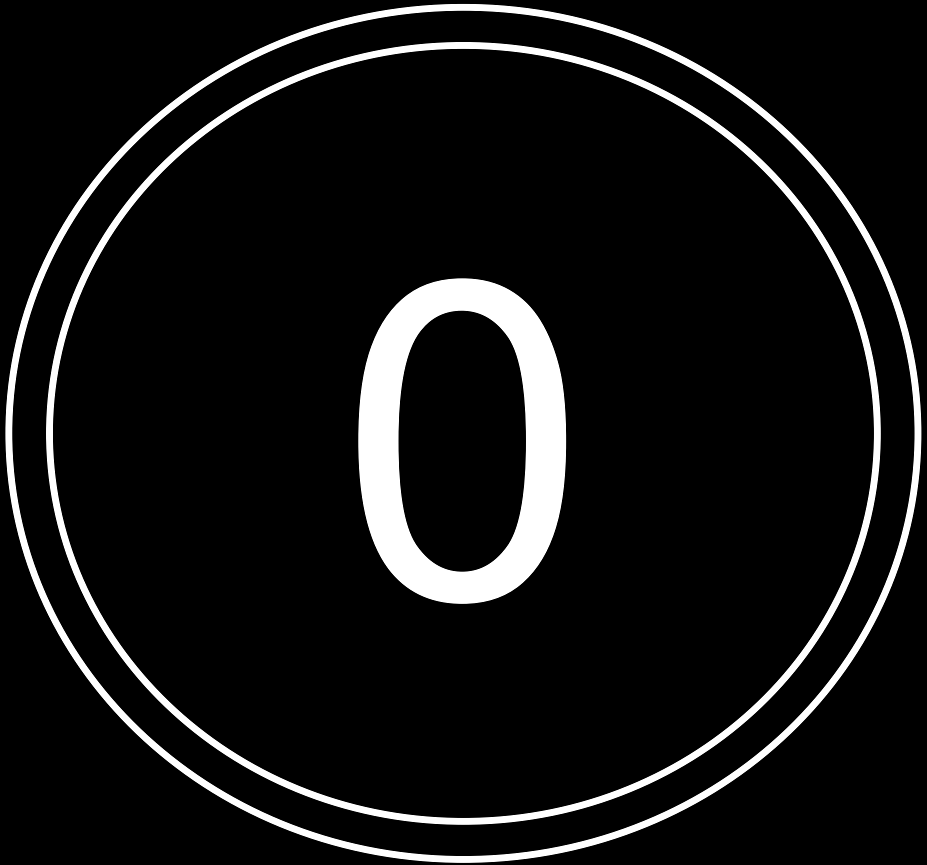
What can you achieve with advance earthquake warning?

2

What can you achieve with advance earthquake warning?

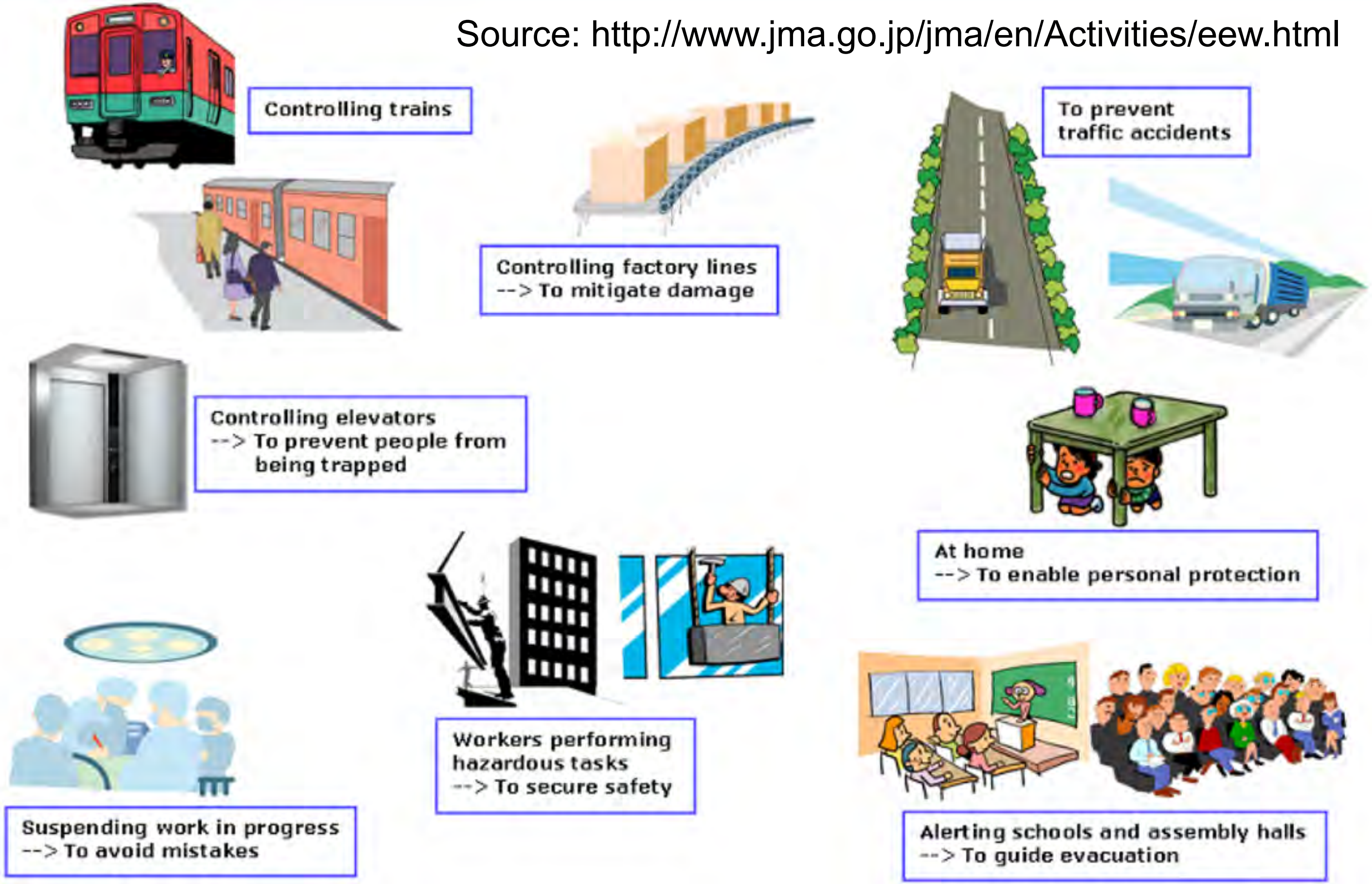


What can you achieve with advance earthquake warning?



What can you achieve with advance earthquake warning?

Source: http://www.jma.go.jp/jma/en/Activities/eew.html



Controlling trains

Controlling factory lines
--> To mitigate damage

To prevent
traffic accidents

Controlling elevators
--> To prevent people from
being trapped

At home
--> To enable personal protection

Workers performing
hazardous tasks
--> To secure safety

Suspending work in progress
--> To avoid mistakes

Alerting schools and assembly halls
--> To guide evacuation

Tsunami waves

- Mainly triggered by subsea earthquakes with large vertical seafloor displacement

Parameter	Normal waves	Tsunami waves*
Wavelength	100-200m	100-500km
Period	5-20s	10-120min
Amplitude	Metres	Metres

* in deep water

津波

Tsunami – “harbor wave”

Useful range of sensors

Earthquakes

- Small earthquakes: acceleration amplitudes as low as 10^{-9} ms^{-2}
- Large earthquakes: up to 20 ms^{-2}
- Observable earthquake frequencies cover a range from 0.02Hz to 100Hz
- Slow slip events may be observed on timescales such as days or months

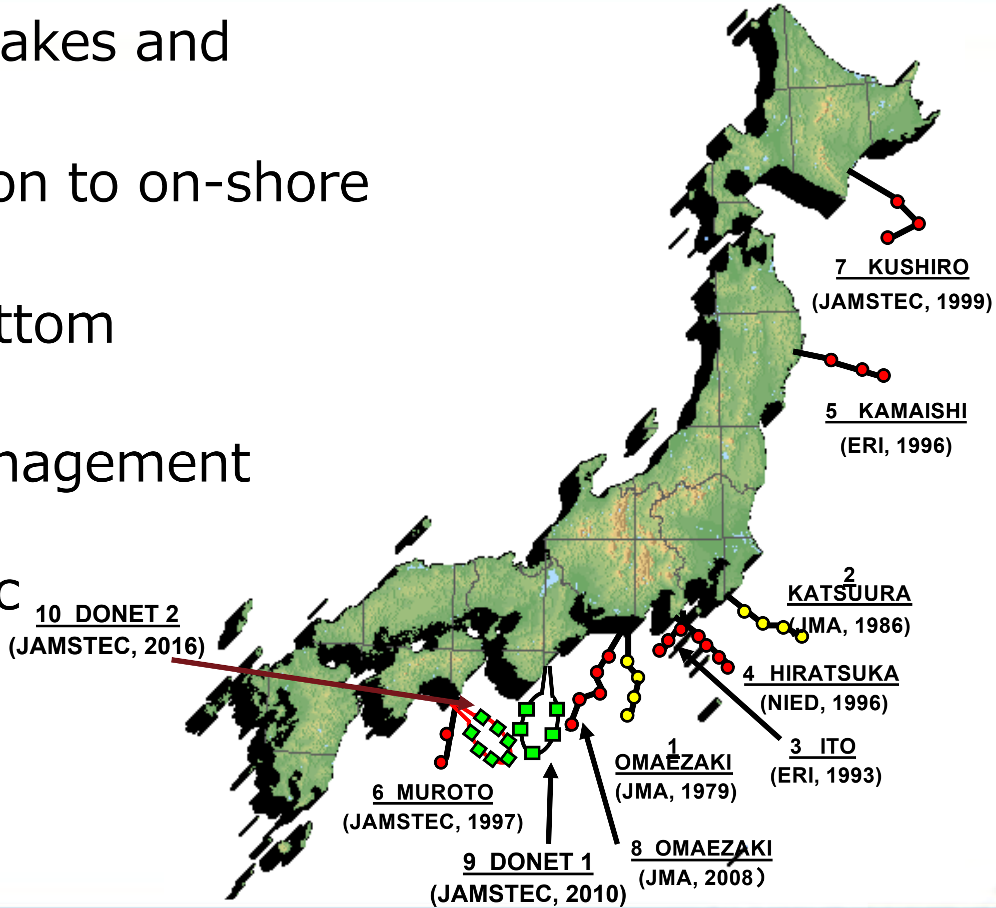
Tsunamis

- Absolute pressure gauges DC – 1Hz for tsunami monitoring
- Differential pressure gauges to observe broadband seismic waves 1/200 Hz to 20 Hz
- Measurement resolution as good as 1mm of water, operating down to 7700m WD

Date rate requirement is very low – can be measured in kbps or Mbps

Ocean Bottom Observation Networks (Japan)

- Early detection of earthquakes and tsunamis
- Real time data transmission to on-shore stations
- Long-term 24/7 ocean bottom observation
- Contribute to disaster management through early warning to the public



Legend

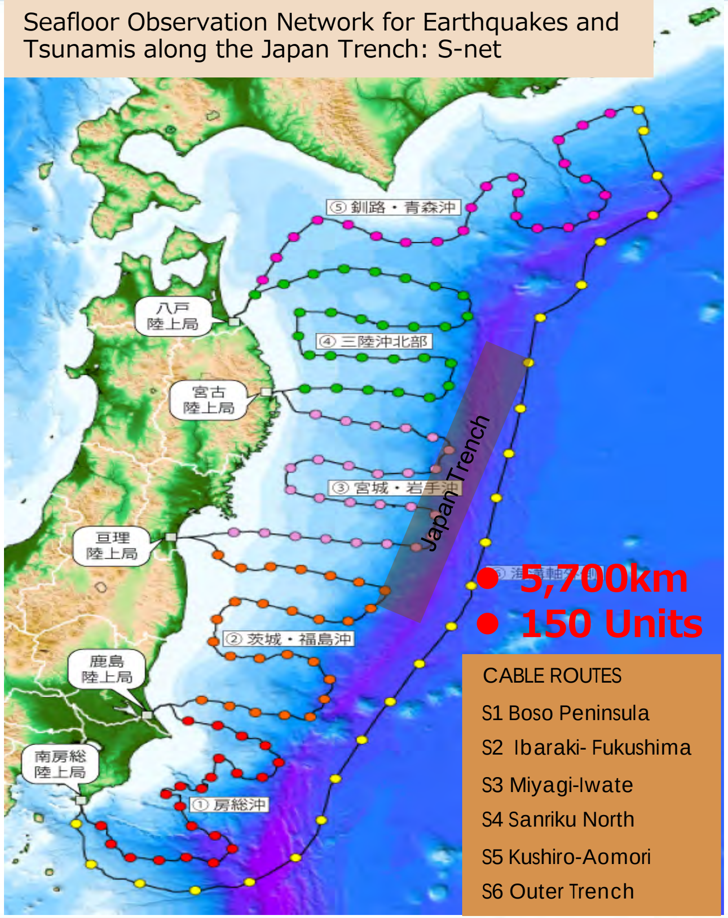
🔴 In-Line（Digital）

🟡 In-Line（Analog）

🟩 NODE（Digital）

New observation networks for eastern Japan

- Planned and owned by the Japanese Government
- Multi-year plan accelerated after 2011 East Japan earthquake and tsunami
- Completed in 2017 and now in use
- Used for real-time observation of earthquakes and tsunamis as well as long-term geophysical studies
- Over 5,700km of submarine fiber optic cable
- 150 undersea units with seismometers and tsunami sensors



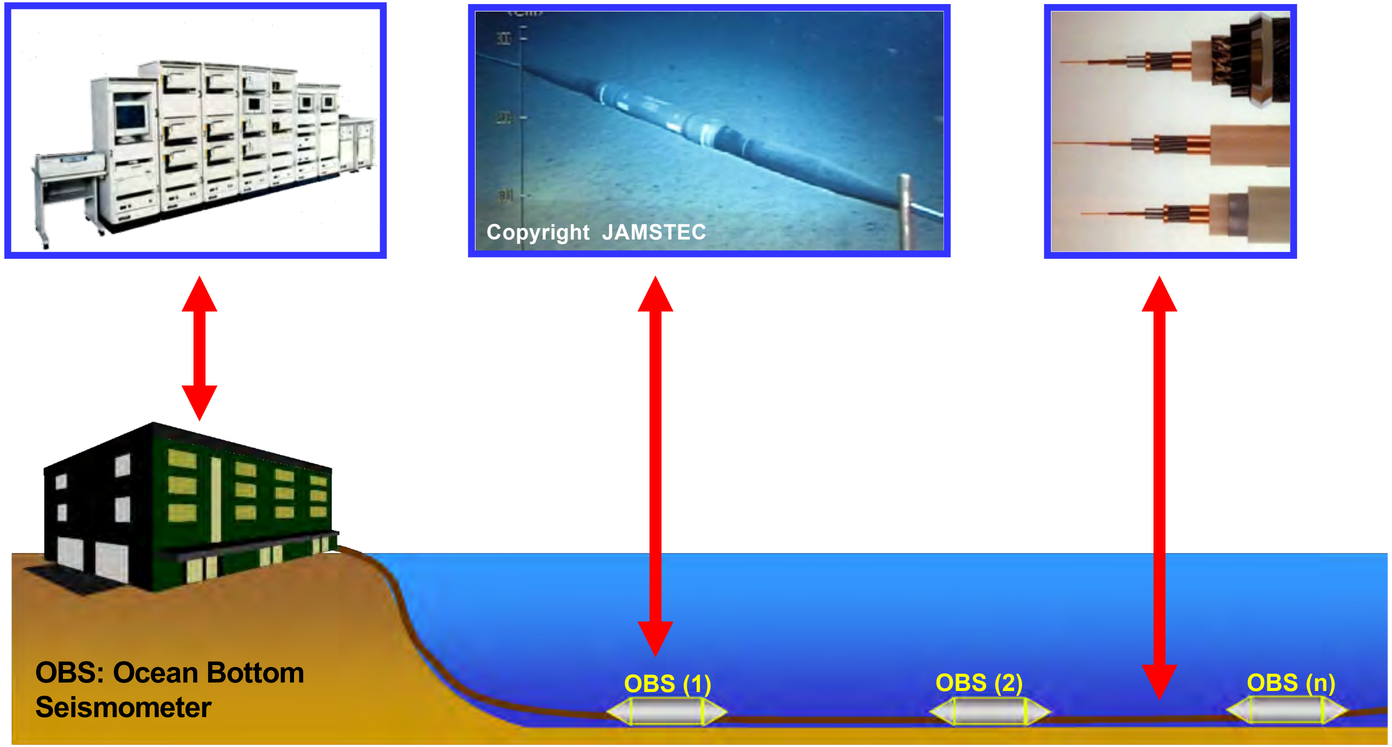
Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench: S-net

- 5,700km
- 150 Units

CABLE ROUTES

S1 Boso Peninsula
S2 Ibaraki- Fukushima
S3 Miyagi-Iwate
S4 Sanriku North
S5 Kushiro-Aomori
S6 Outer Trench

In-line systems



Terminal Equipment

Ocean Bottom Units

Cables & Fibres

Copyright JAMSTEC

OBS: Ocean Bottom Seismometer

Ocean Bottom Seismometer/Tsunami Sensors (2)

Ocean bottom observation units (in-line system)

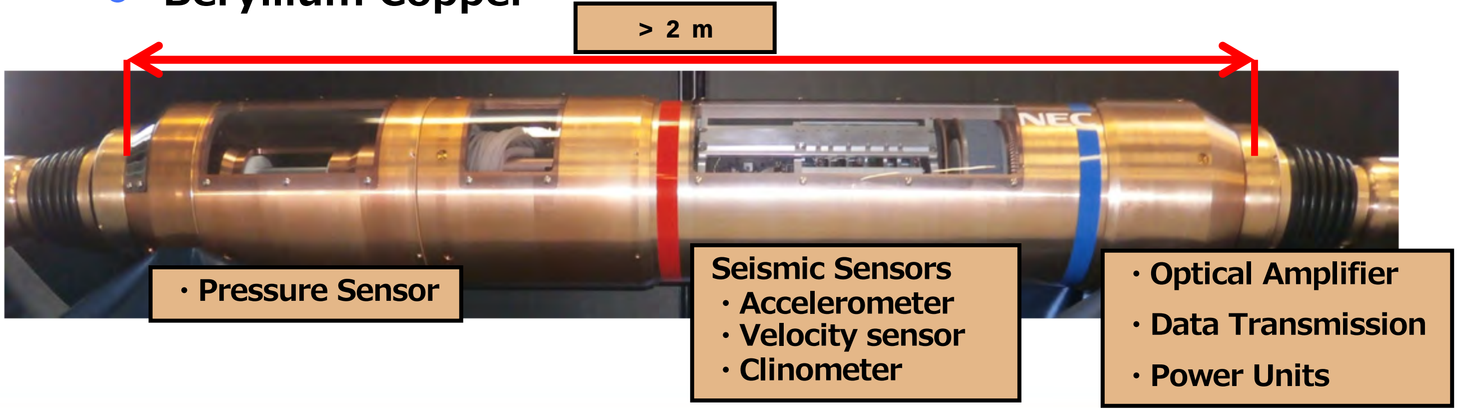
Ocean bottom sensor unit (example)

Unit Configuration

- Pressure Sensor（Tsunami Sensor)
- Seismometer （ACC/VEL)
- Clinometer
- Optical Amplifier
- Data Transmission
- Power Units

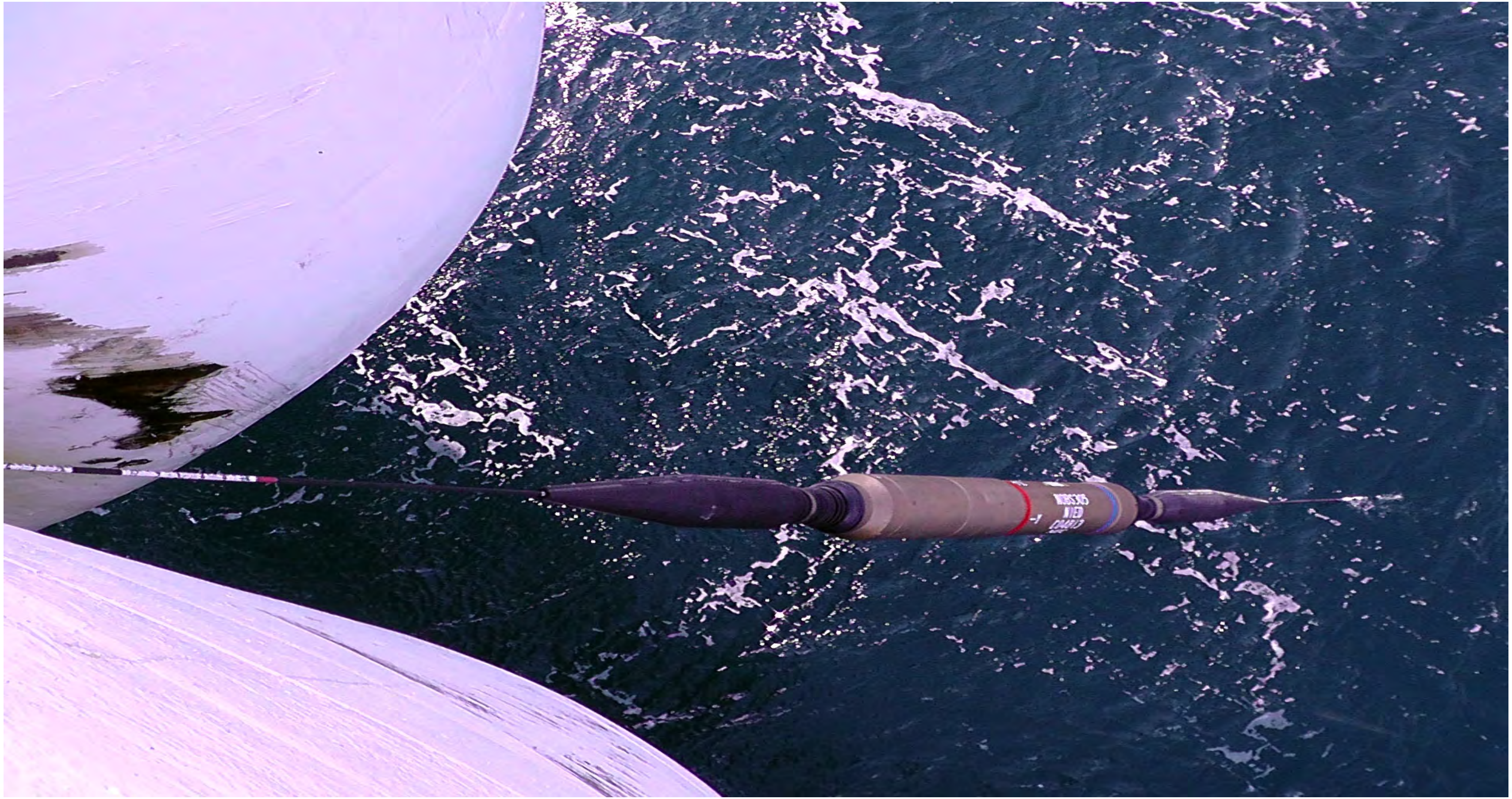
Pressure Tight Case

- Resistant to 8,000m depth
- Beryllium Copper



Installation vessel (example)

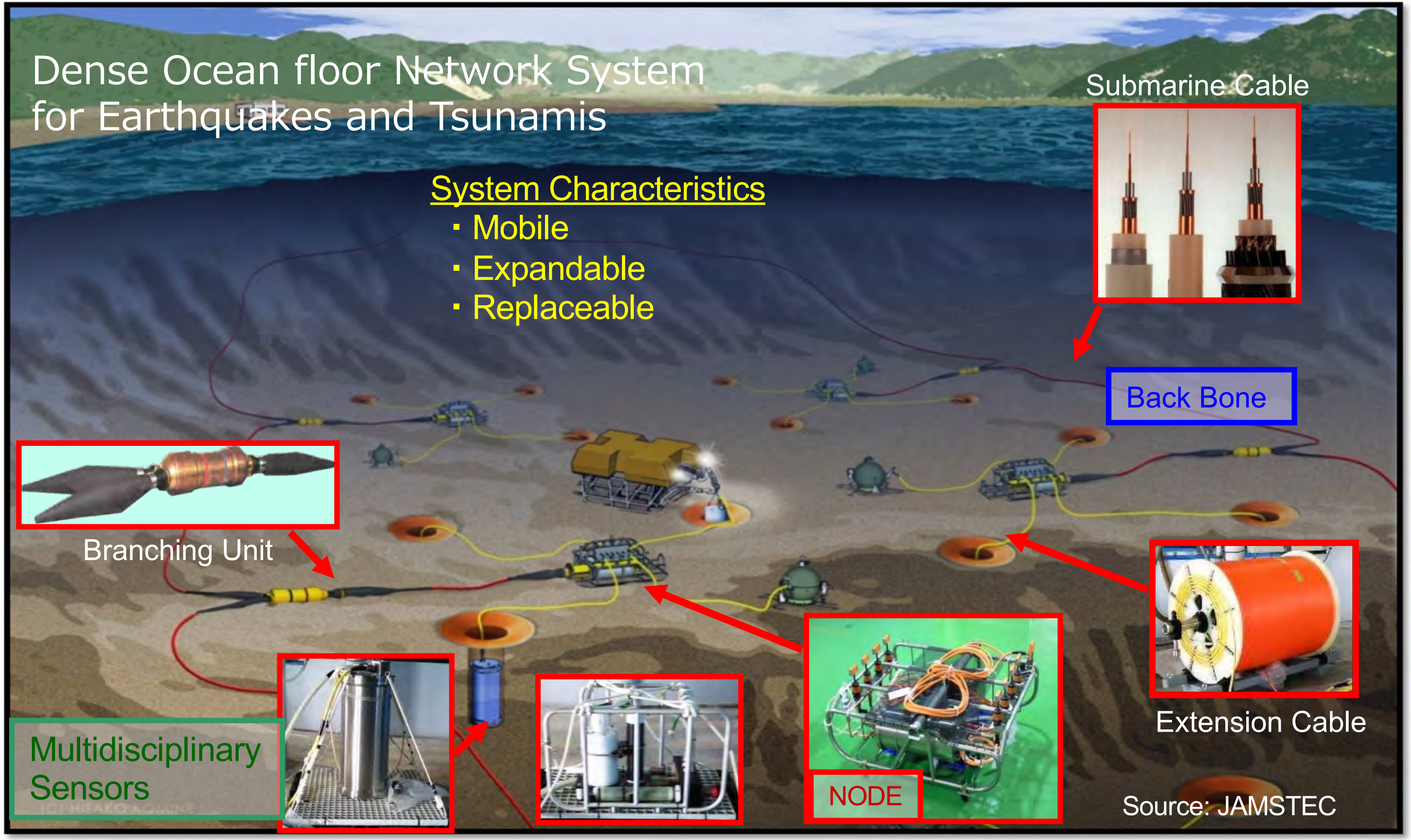
Laying operation



MBARI

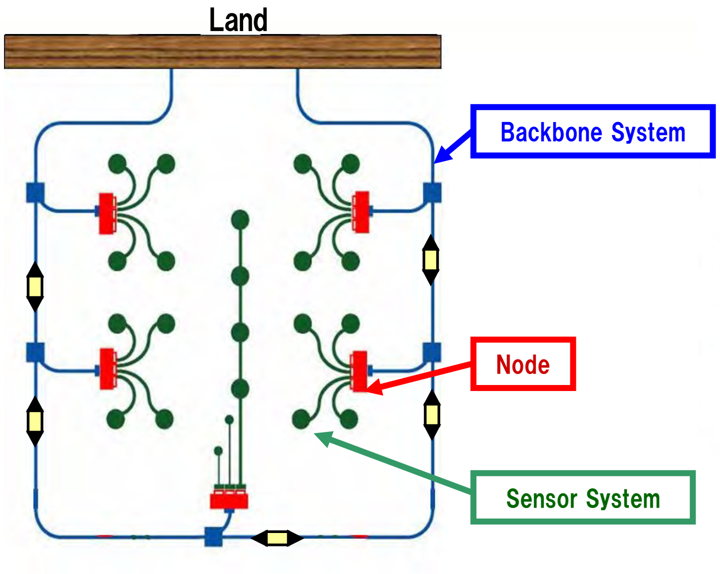
NEPTUNE

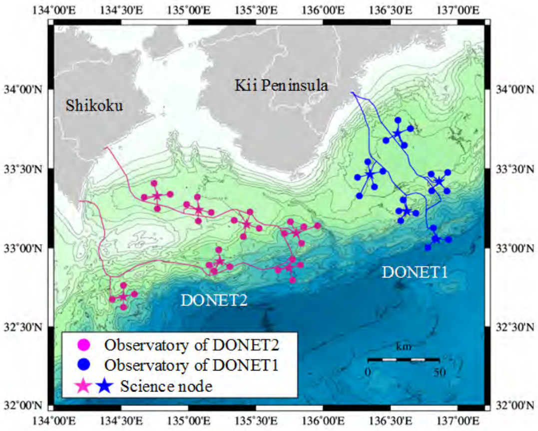
NODE System (DONET by JAMSTEC)

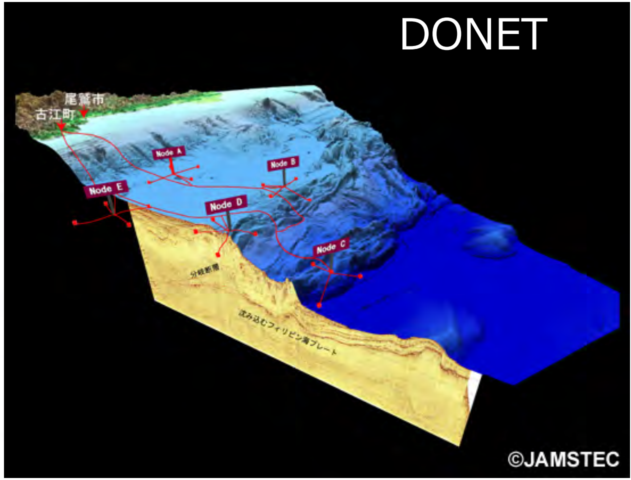


Source: JAMSTEC

DONET and DONET2







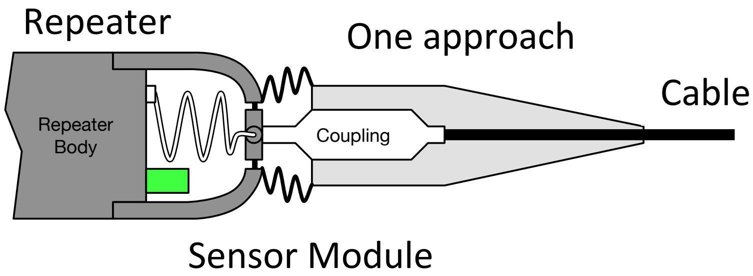
DONET: 5 nodes, 2000 - 4400m WD

DONET2: 7 nodes, 1400 - 2400m WD

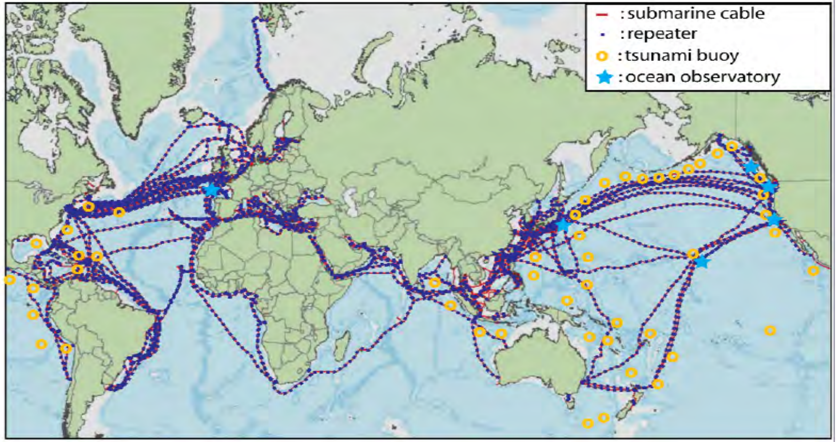
Source: JAMSTEC

SMART Cables - the idea

A global array of sensors spanning the oceans



Install routinely on new cables
Deploy by cable ship, no maintenance



- **Telecoms, plus science at low marginal cost**
- Cable repeaters host sensors, not to interfere
- Potential: trans-ocean, ~10,000 repeaters
- Initially: bottom pressure, temperature and acceleration

https://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx

John You, Nature, 2010 – Harnessing telecoms cables for science

Source: JTF

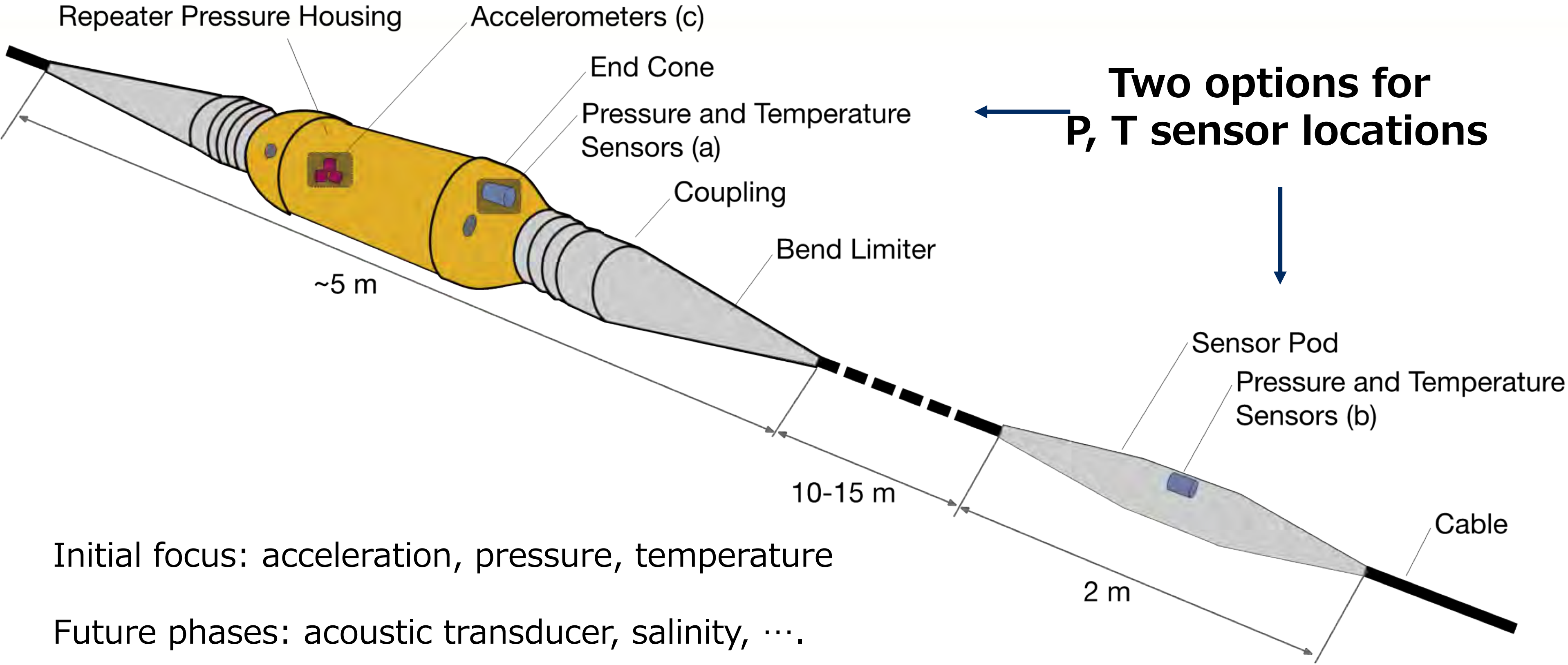
On-going discussion on use of telecom cables

Joint Task Force
ITU / UNESCO-IOC / WMO

- A Joint Task Force to investigate the potential of using submarine telecommunications cables for ocean and climate monitoring and disaster warning, initiated by;

Discussions continue to take place among the participants including cable system owners, academic institutions, national agencies, consultants and system suppliers.

SMART repeaters



Two options for P, T sensor locations

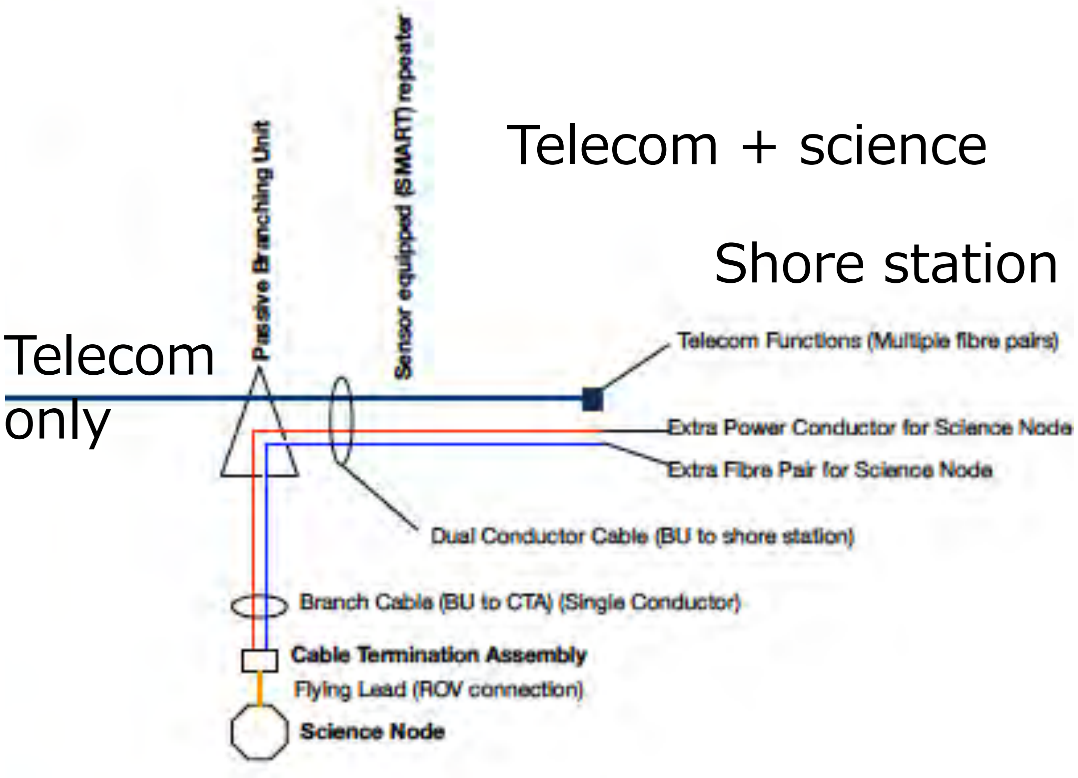
Initial focus: acceleration, pressure, temperature

Future phases: acoustic transducer, salinity, ….

Source: JTF

One step to a SMART repeater

- Wet demo – show science, mechanical packaging, ideally combine with telecom
- Branch unit on commercial cable
- May need dual conductor cable
- Could develop/qualify BU isolated power supply



Telecom + science

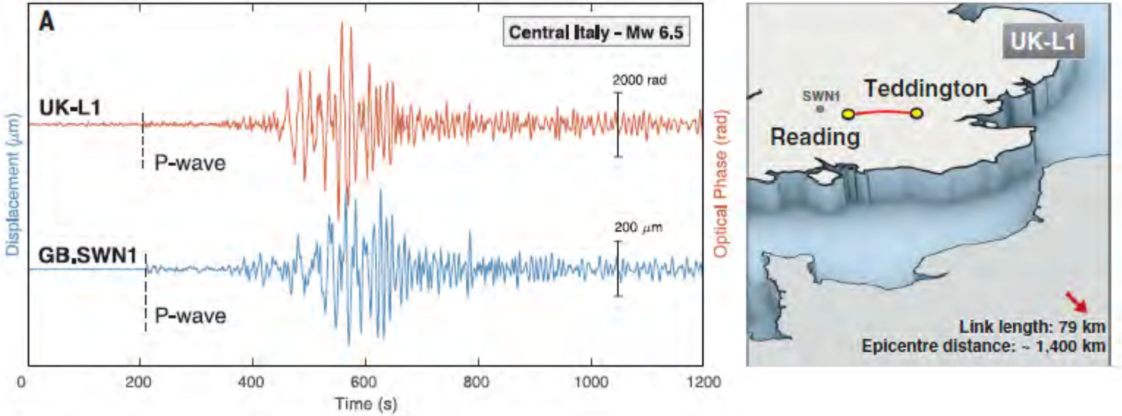
Shore station

Telecom only

Source: JTF

Fiber sensing (recent studies)

- Earthquakes detected by phase/length changes in fiber (ultra-stable laser)
- Good correlation with terrestrial seismometers
- Potentially low impact on commercial telecoms systems
- Results suggest earthquake events can be located using cable network



Source: G. Marra et al., *Science* 10.1126/science.aat4458 (2018)

SMART cables - the Idea

Ocean Science

Public Safety

nature

2010: SMART Cable

Synergy With Telecoms

Who Could Object?

SMART: Sensor Enabled Scientific Monitoring and Reliable Telecommunications

SMART Cables – The Pitch to the Board

Reasonable Questions

- Additional risks to my cable?
- How much commercial traffic I am sacrificing?
- Will my cable take longer to build?
- Additional CapEx costs?
- Additional OpEx costs?
- …

Qualitative Evaluation

Security impacts on Telecom System?

Marine installation impacts?

Independence of Systems?

Testing and Commissioning?

Design philosophy?

Permitting?

Quantitative Evaluation

Ship repair rate?

System Availability?

Backhaul Needs?

POW?

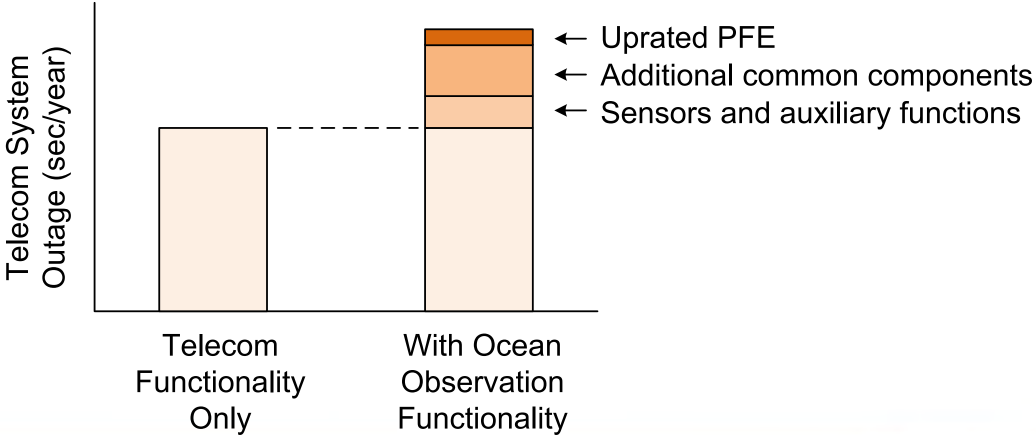
Space & Power?

CapEx vs. OpEx?

Example: System Availability

Reasonable Questions:

- Does the addition of sensors to a repeater increase its FIT rate?
- What about adding DC/DC converters to power a sensor pod?
- Is a higher voltage PFE needed to power the sensors?



Commercial Challenges - Summary

- Dedicated sensor cables are funded by governments / academia
- Telecom cables are funded by telcos and content providers
- SMART cables are··· more difficult (so far)

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\Orchestrating a brighter world

NEC

Subsea Upgrades

Elizabeth Rivera Hartling

August, 2019

Outline

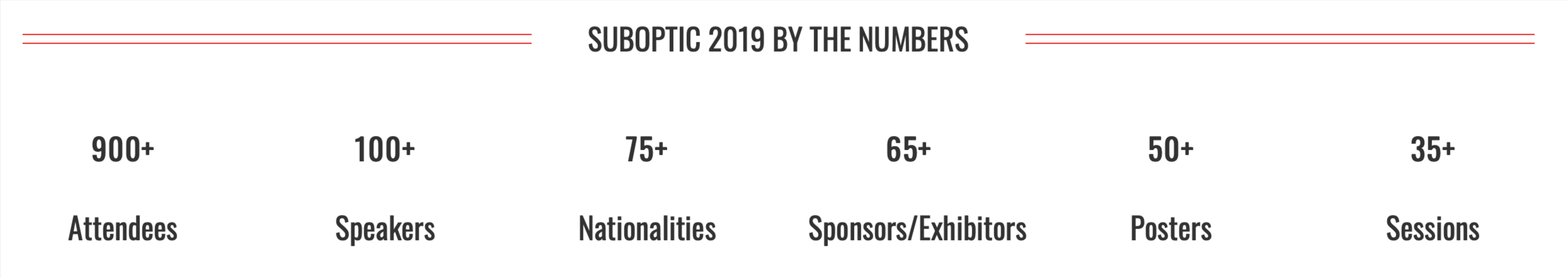
- Introduction to SubOptic

- DAY 5: Submarine Cable Upgrades
  - Upgrades on Legacy Cables
  - Open Cables & Convergence with Terrestrial
  - Open Cable Metrics - OSNR & GSNR
  - Open Cable Commissioning & Acceptance
  - Future Evolution

What is SubOptic?

- SubOptic is the premier technical conference for the Subsea industry!
  - Established in 1986, held only once every 3 years

- SubOptic 2019 was just held in New Orleans in April:



SUBOPTIC 2019 BY THE NUMBERS

900+	100+	75+	65+	50+	35+
Attendees	Speakers	Nationalities	Sponsors/Exhibitors	Posters	Sessions

- But SubOptic lives outside of the conference as well through it’s working groups!

Open Cables Working Group Team

Pascal Pecci
ASN

Priyanth Mehta
Ciena

Darwin Evans
Ciena

Elizabeth Rivera Hartling
Facebook (WG Chair)

Valey Kamalov
Google

Mattia Cantono
Google

Eduardo Mateo
NEC

Fatih Yaman
NEC

Alexei Pilipetskii
Subcom

Chris Mott
Telstra

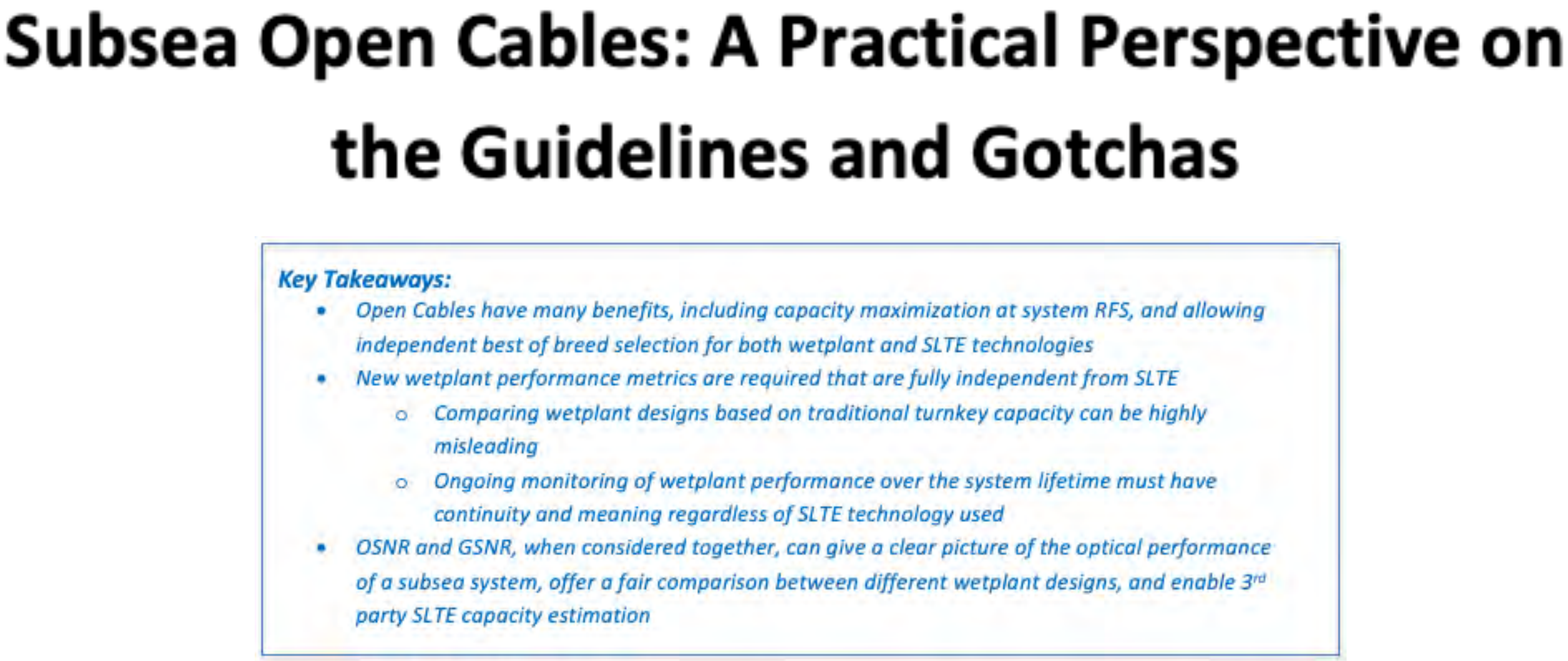
Philip Murphy
Telstra

Paul Lomas
Telstra

Open Cables Working Group Output

*We've been **BUSY**!*

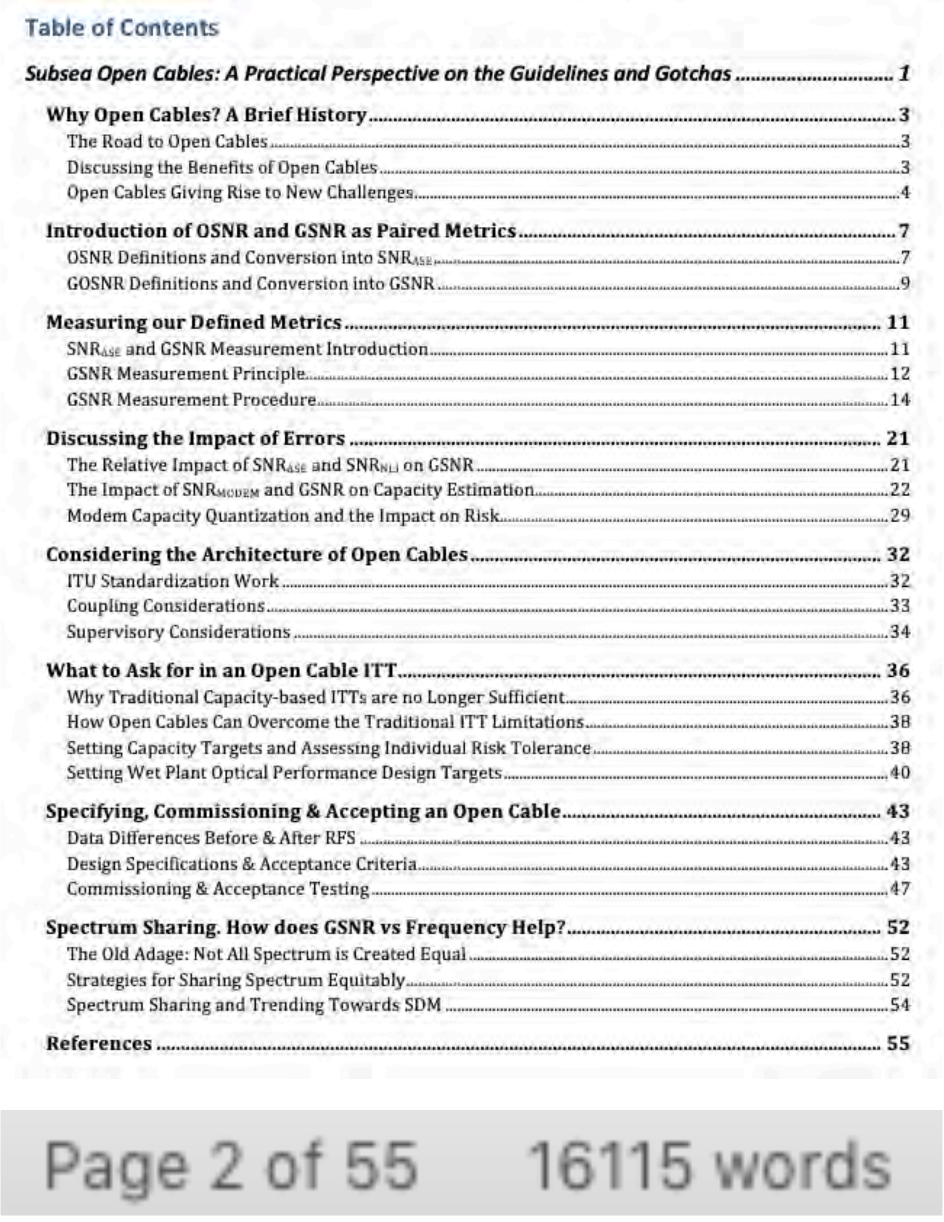
The team has generated a very extensive **white paper** (book?) detailing collectively agreed ideas and recommendations on Open Cables, that can be consumed by ***experts*** and ***non-experts*** alike!



Subsea Open Cables: A Practical Perspective on the Guidelines and Gotchas

Key Takeaways:

- *Open Cables have many benefits, including capacity maximization at system RFS, and allowing independent best of breed selection for both wetplant and SLTE technologies*
- *New wetplant performance metrics are required that are fully independent from SLTE*
    - *Comparing wetplant designs based on traditional turnkey capacity can be highly misleading*
    - *Ongoing monitoring of wetplant performance over the system lifetime must have continuity and meaning regardless of SLTE technology used*
- *OSNR and GSNR, when considered together, can give a clear picture of the optical performance of a subsea system, offer a fair comparison between different wetplant designs, and enable 3rd party SLTE capacity estimation*



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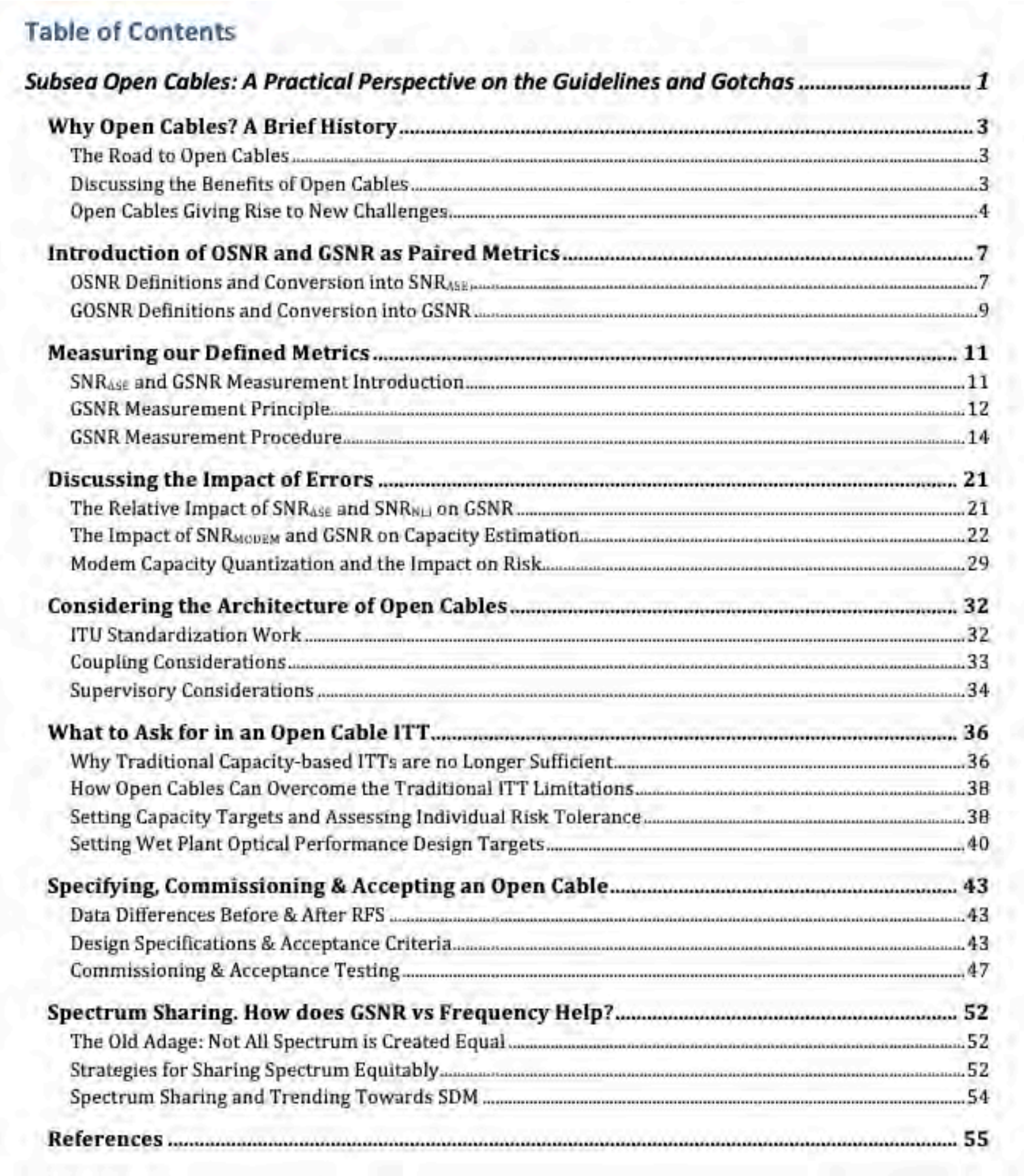
https://suboptic2019.com/suboptic-2019-papers-archive/



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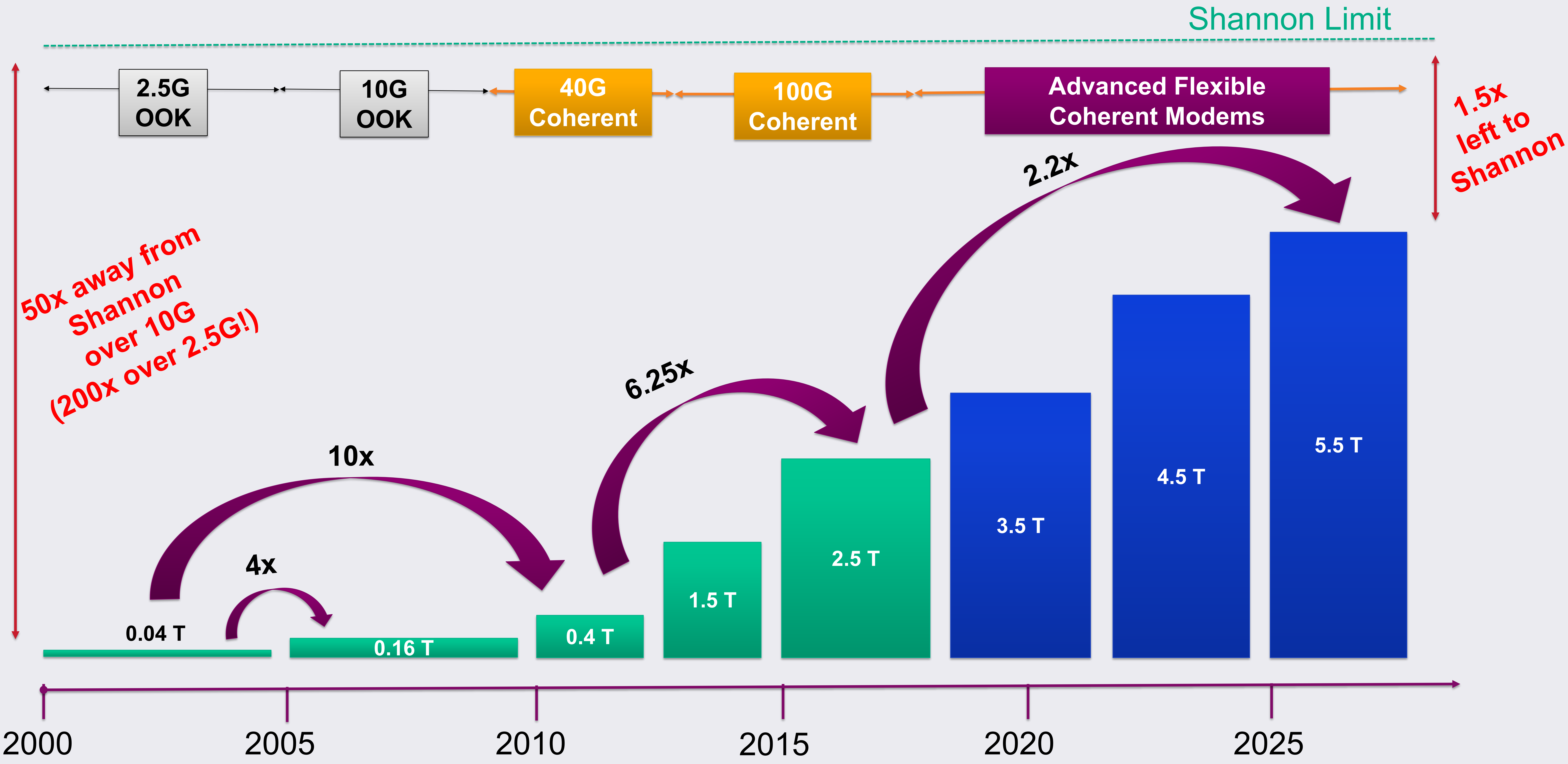
https://suboptic2019.com/suboptic-2019-papers-archive/

Subsea Upgrades

Shannon's Limit on Legacy Cables – Room to Grow with Coherent!



Enter: The “Upgrade Market”

“Dry Vendor”
Terrestrial Vendor
Upgrade Vendor
3rd Party
…all used the same!

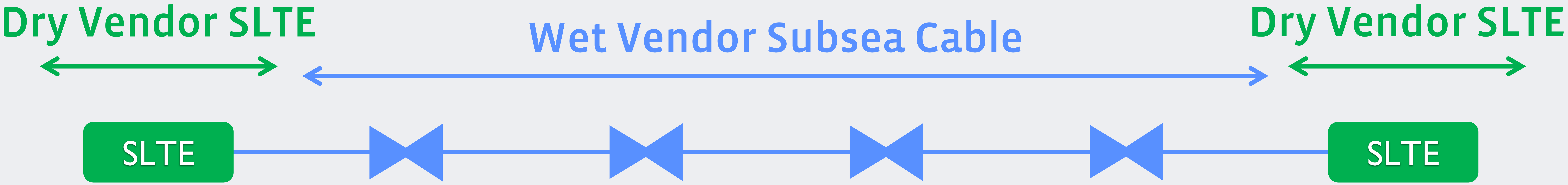
Traditional “Turnkey” Subsea Cable Capacity Model

Wet Plant Vendor Equipment End-to-End

SLTE

SLTE

Early “Upgrade” Subsea Cable Capacity Model



Dry Vendor SLTE

Wet Vendor Subsea Cable

Dry Vendor SLTE

SLTE

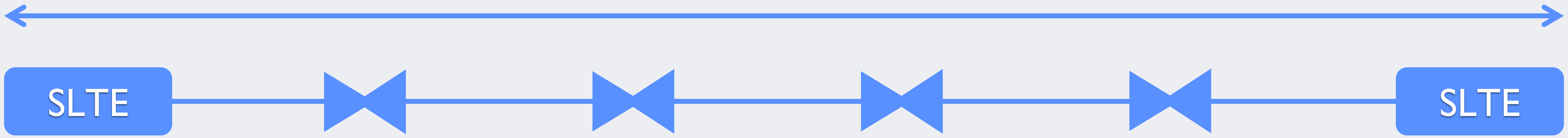
SLTE

Wait. But Why Terrestrial Vendors?

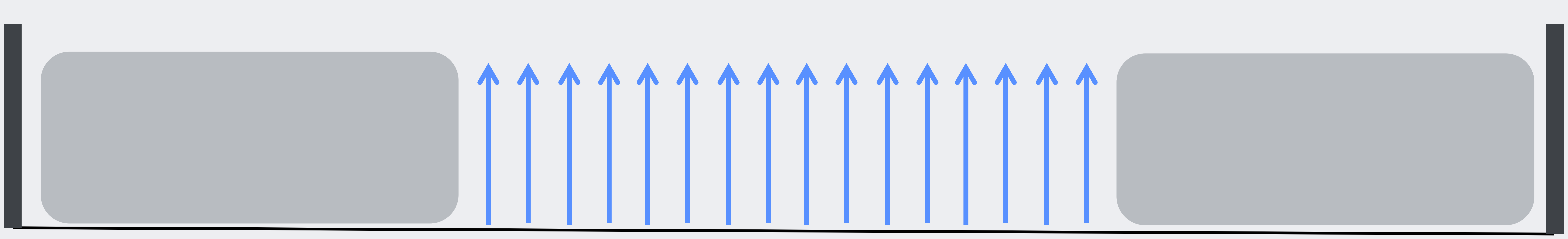
- Timing. It’s everything. That’s why.
- Terrestrial Optical companies were the first to develop and productize coherent technology and introduce it to the Subsea space.
- Some thought that coherent would never work in optical.
- And when it did. It happened FAST, and changed the course of the subsea industry!
- The benefits of coherent were so big, it was too expensive NOT to adopt it.

Many Ways to Upgrade Existing Cables

Option 1: Overlay New & Old Technology



Wet Plant Vendor Equipment End-to-End



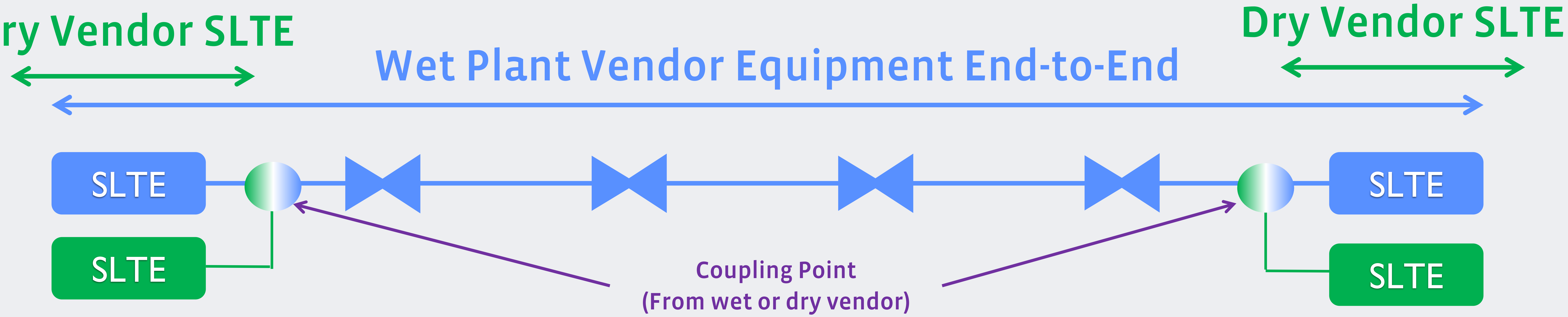
Banded dummy waves

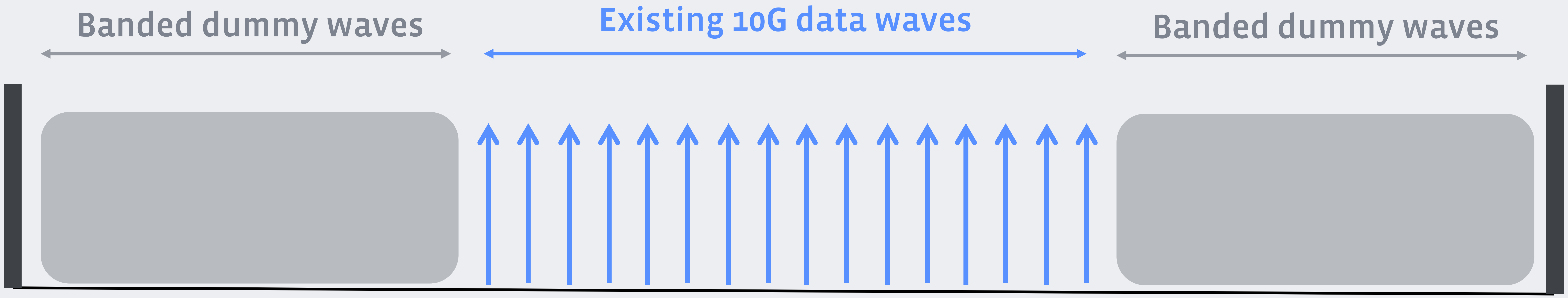
Existing 10G data waves

Banded dummy waves

Many Ways to Upgrade Existing Cables

Option 1: Overlay New & Old Technology



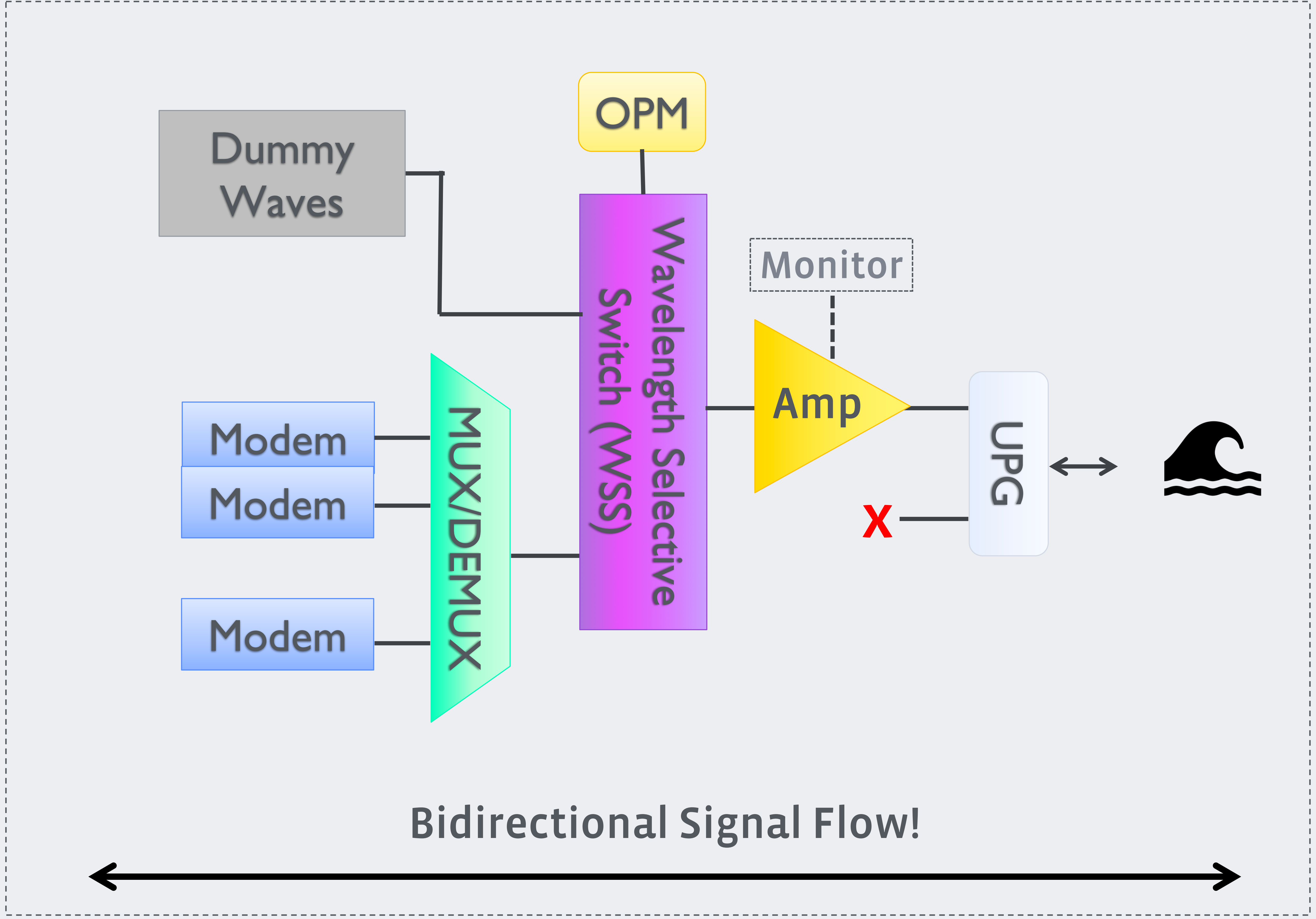


Recap from Yesterday: SLTE Coupling Point

Below are the key functional building blocks of SLTE from yesterday!

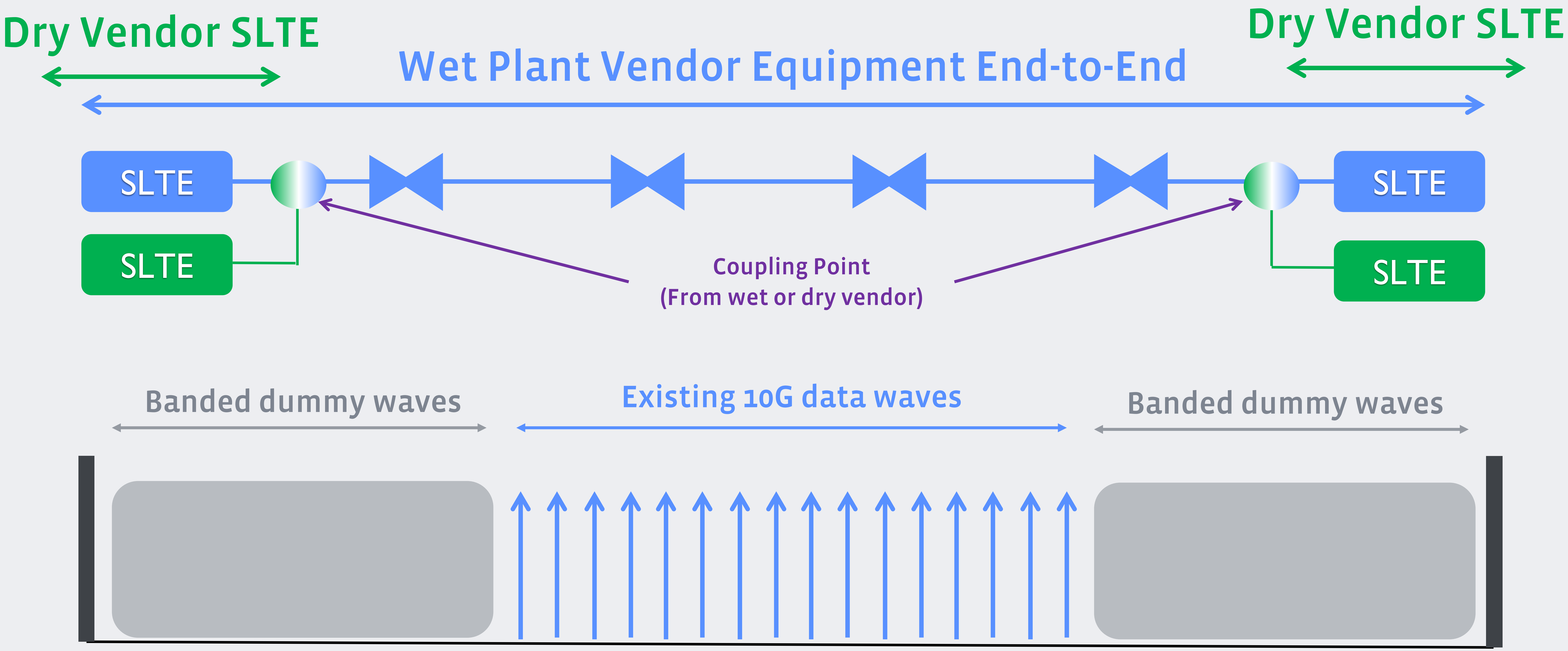
SO how do we couple 2x SLTE onto one fiber?

- Upgrade Couplers, which leave an open port for added equipment insertion in case you ever want to replace your equipment without traffic interruption
- HOWEVER, the traditional model didn't have upgrades in mind, so most SLTE before this time did not have upgrade couplers.
- So, an Upgrade coupler either needs to be inserted (interrupting traffic momentarily), or a non-ideal coupling point needs to be found
    - Note, older SLTE often did not use WSS either!



Many Ways to Upgrade Existing Cables

Option 1: Overlay New & Old Technology



Dry Vendor SLTE

Dry Vendor SLTE

Wet Plant Vendor Equipment End-to-End

SLTE

SLTE

SLTE

SLTE

Coupling Point
(From wet or dry vendor)

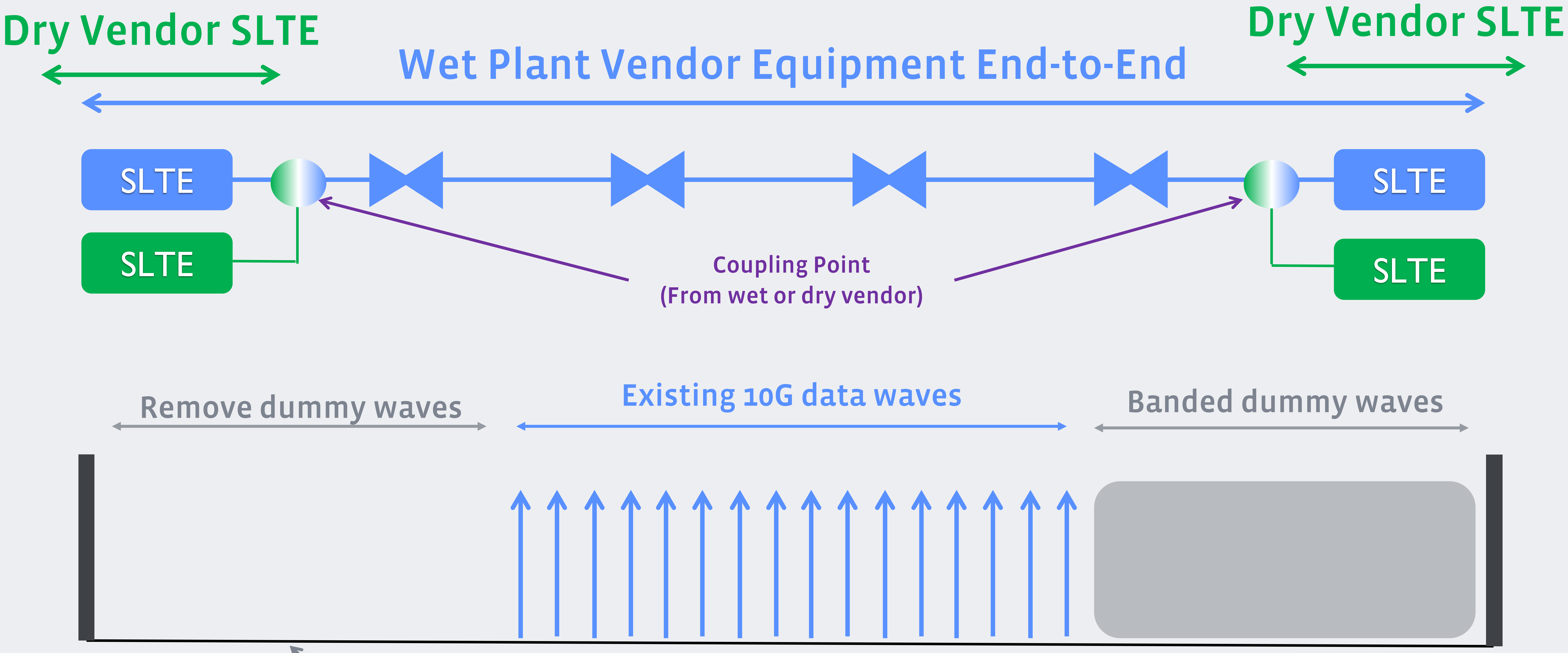
Banded dummy waves

Existing 10G data waves

Banded dummy waves

Many Ways to Upgrade Existing Cables

Option 1: Overlay New & Old Technology



Dry Vendor SLTE

Wet Plant Vendor Equipment End-to-End

Dry Vendor SLTE

Coupling Point
(From wet or dry vendor)

Remove dummy waves

Existing 10G data waves

Banded dummy waves

BUT: Removing large portions of power from Submarine line is not recommended, likely to be traffic affecting!

What Would Really Happen?

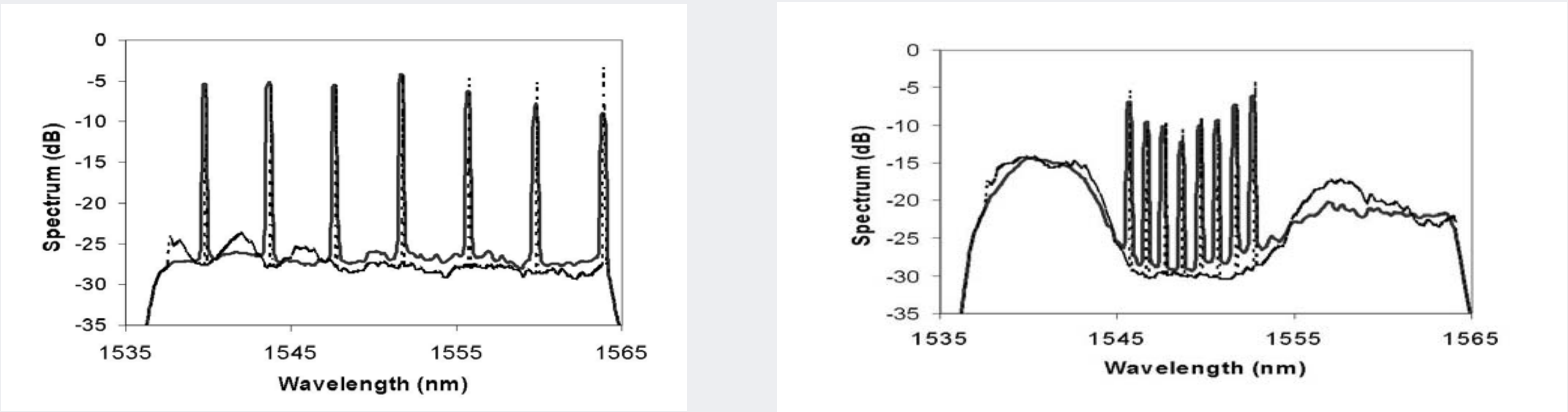
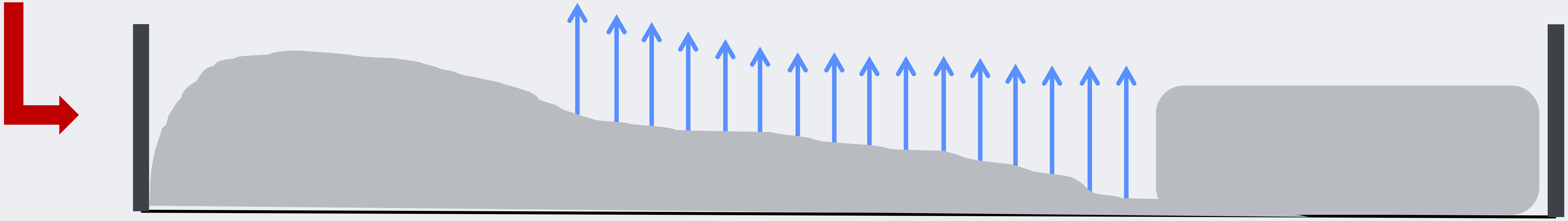


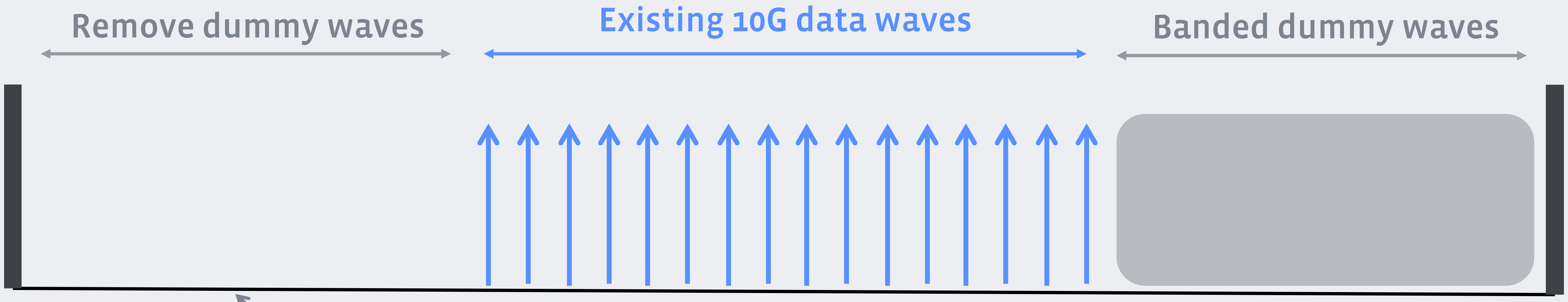
Figure Ref: JLT Invited Tutorial: Wavelength Division Multiplexing in Long-Haul Transoceanic Transmission Systems, Neal S. Bergano, *Fellow IEEE, Fellow OSA*

From Yesterday

Something along these lines:



Very Ideal Picture:



Remove dummy waves

Existing 10G data waves

Banded dummy waves

BUT: Removing large portions of power from Submarine line is not recommended, likely to be traffic affecting!

Many Ways to Upgrade Existing Cables

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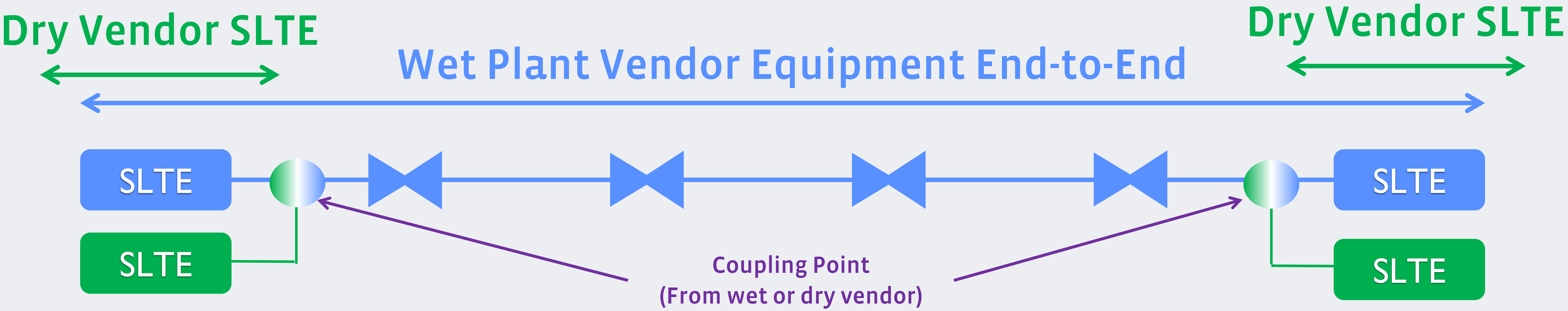


Dry Vendor SLTE

Dry Vendor SLTE

Wet Plant Vendor Equipment End-to-End

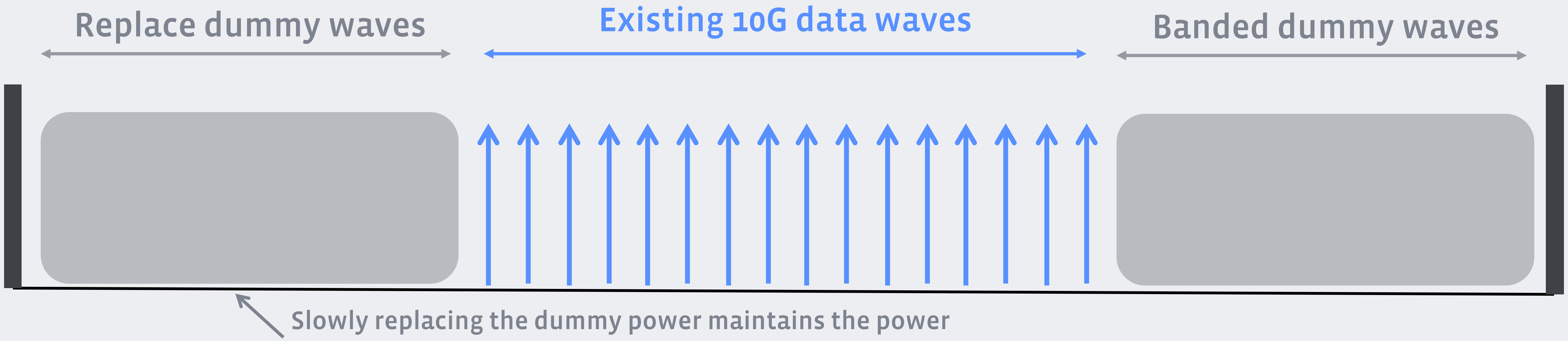
SLTE

SLTE

SLTE

SLTE

Coupling Point
(From wet or dry vendor)



Replace dummy waves

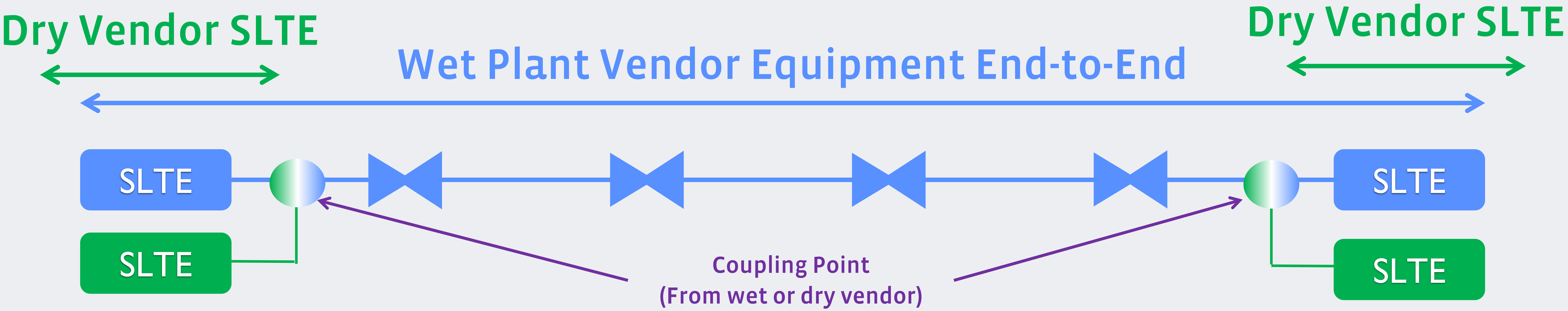
Existing 10G data waves

Banded dummy waves

Slowly replacing the dummy power maintains the power
(and thus performance) of existing traffic waves.

Many Ways to Upgrade Existing Cables

Option 1: Overlay New & Old Technology



Dry Vendor SLTE

Wet Plant Vendor Equipment End-to-End

Dry Vendor SLTE

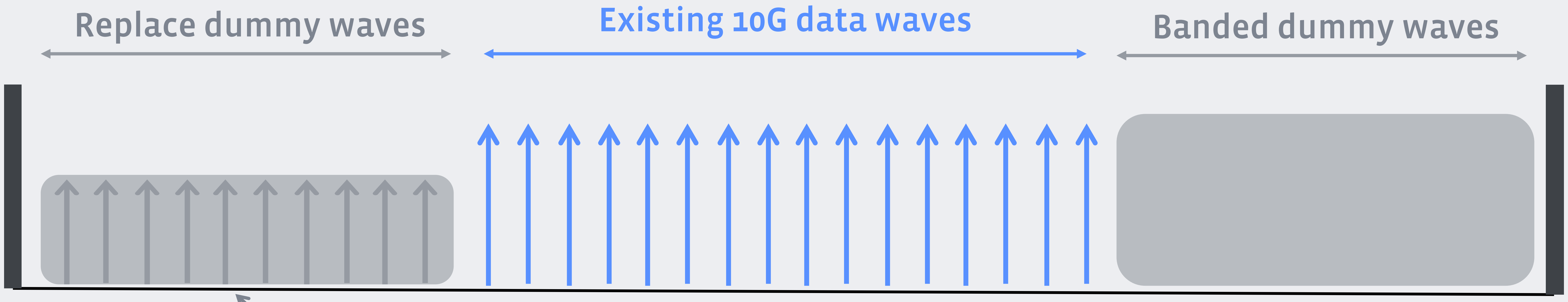
SLTE

SLTE

SLTE

SLTE

Coupling Point
(From wet or dry vendor)



Replace dummy waves

Existing 10G data waves

Banded dummy waves

Slowly replacing the dummy power maintains the power
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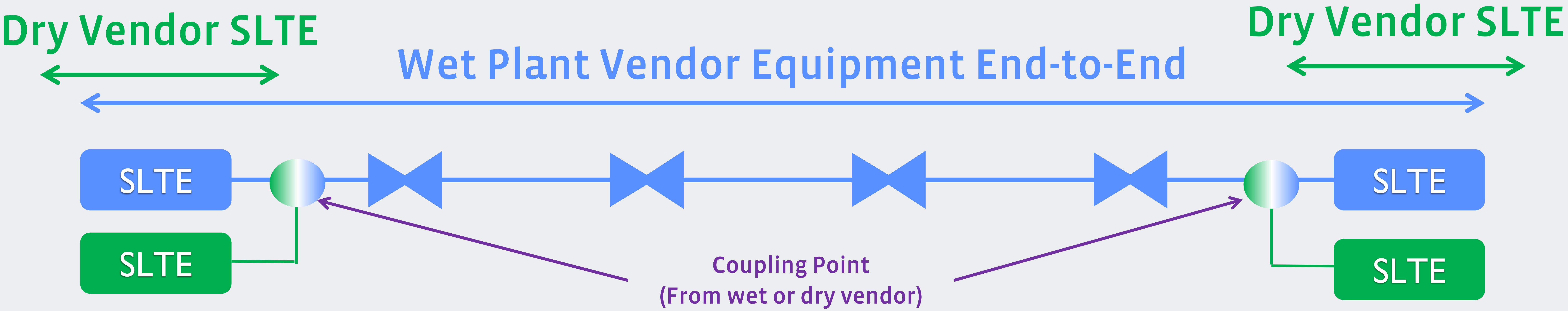
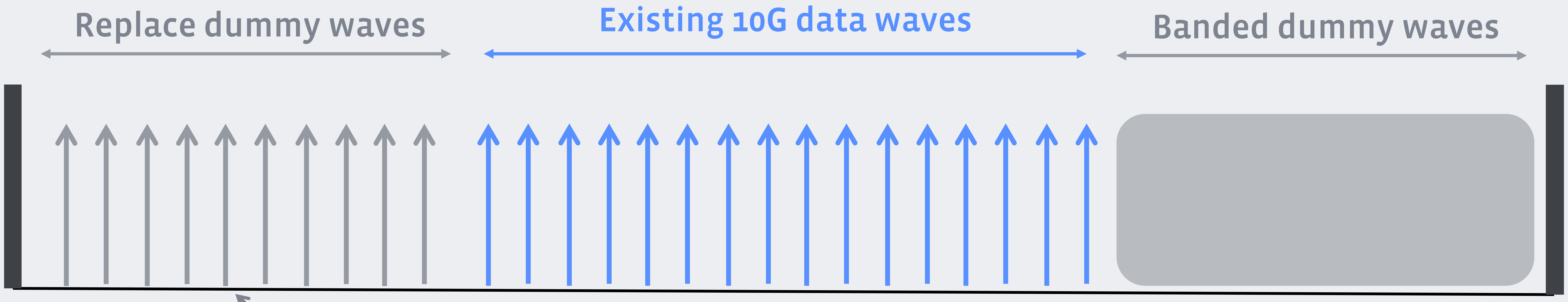
Many Ways to Upgrade Existing Cables

Option 1: Overlay New & Old Technology

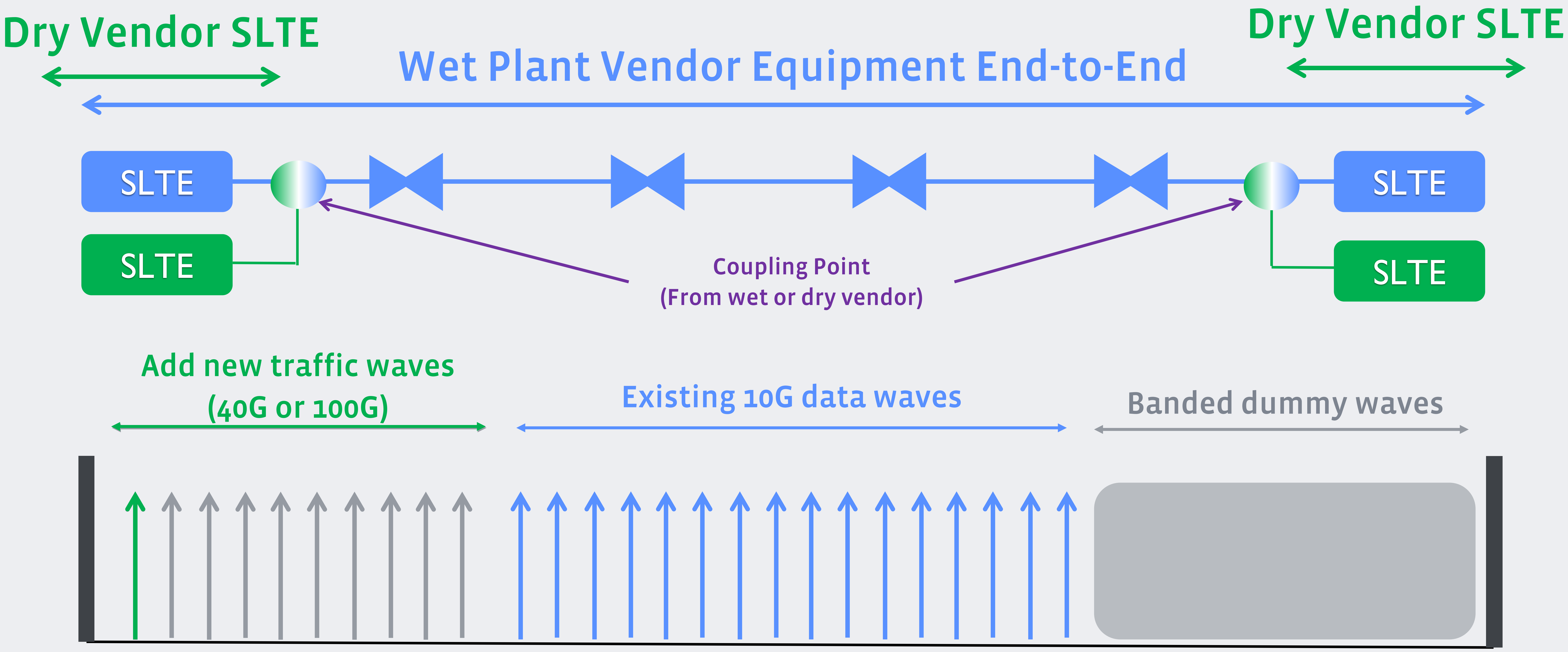




Once at full power, channelized dummy waves can be more easily replaced with new traffic waves.

Many Ways to Upgrade Existing Cables

Option 1: Overlay New & Old Technology



Dry Vendor SLTE

Dry Vendor SLTE

Wet Plant Vendor Equipment End-to-End

Coupling Point
(From wet or dry vendor)

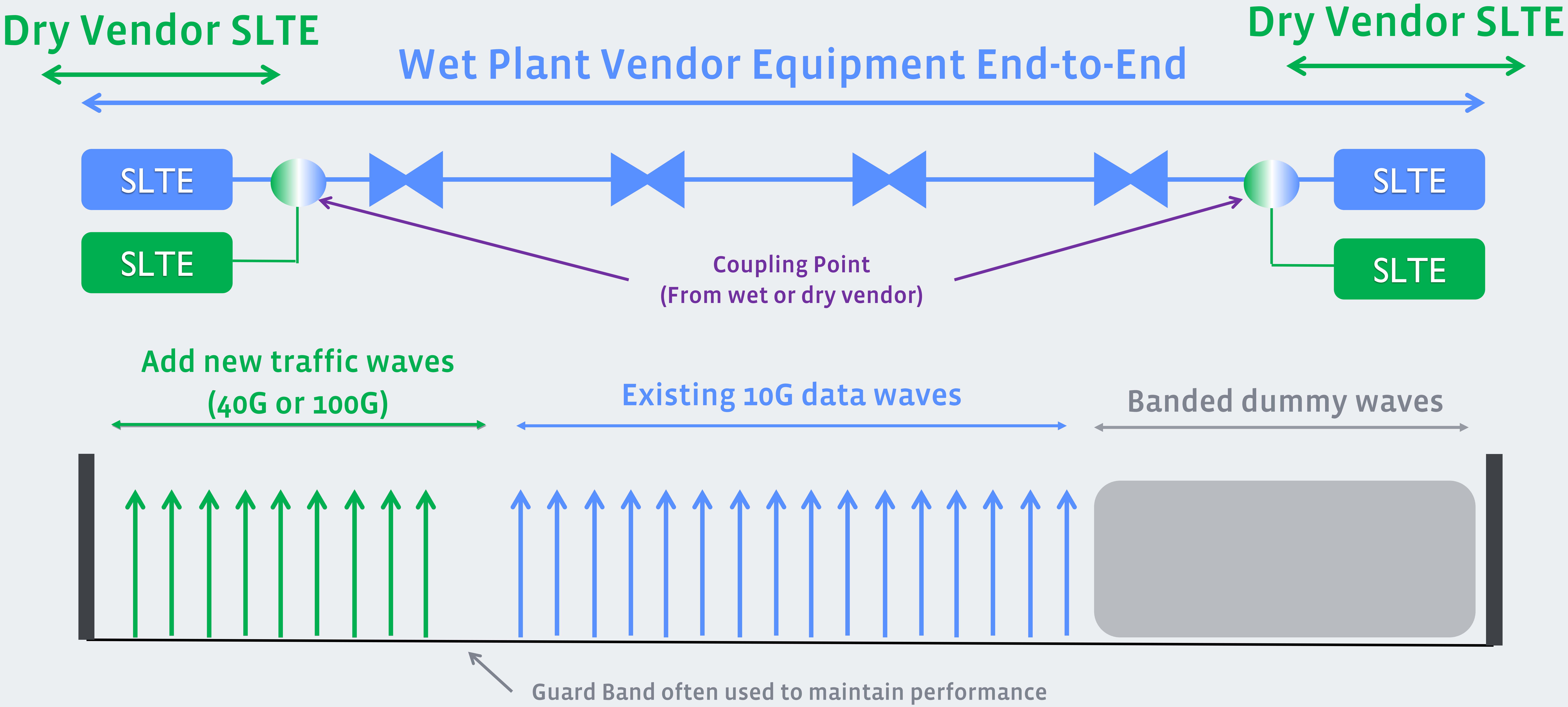
Add new traffic waves
(40G or 100G)

Existing 10G data waves

Banded dummy waves

Many Ways to Upgrade Existing Cables

Option 1: Overlay New & Old Technology



Dry Vendor SLTE

Wet Plant Vendor Equipment End-to-End

Dry Vendor SLTE

Coupling Point
(From wet or dry vendor)

Add new traffic waves
(40G or 100G)

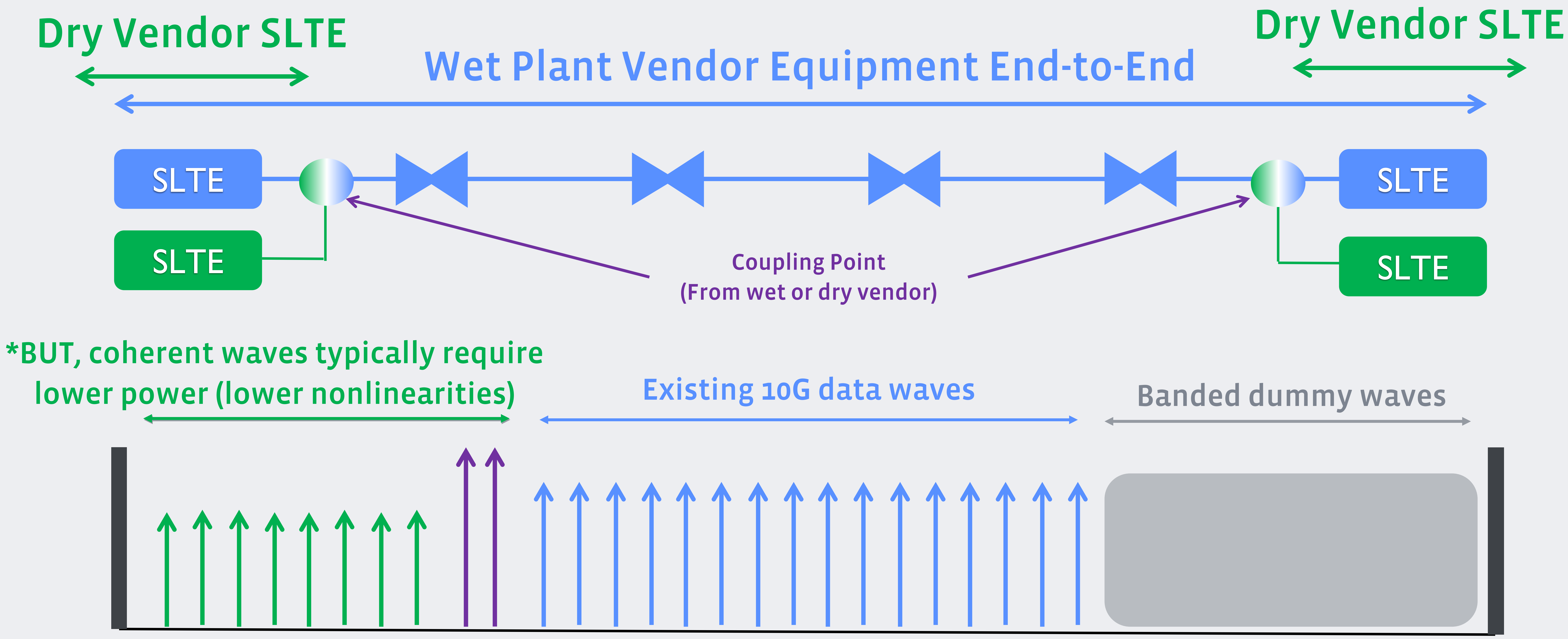
Existing 10G data waves

Banded dummy waves

Guard Band often used to maintain performance

Many Ways to Upgrade Existing Cables

Option 1: Overlay New & Old Technology



Dry Vendor SLTE

Wet Plant Vendor Equipment End-to-End

Dry Vendor SLTE

SLTE

SLTE

SLTE

SLTE

Coupling Point
(From wet or dry vendor)

*BUT, coherent waves typically require lower power (lower nonlinearities)

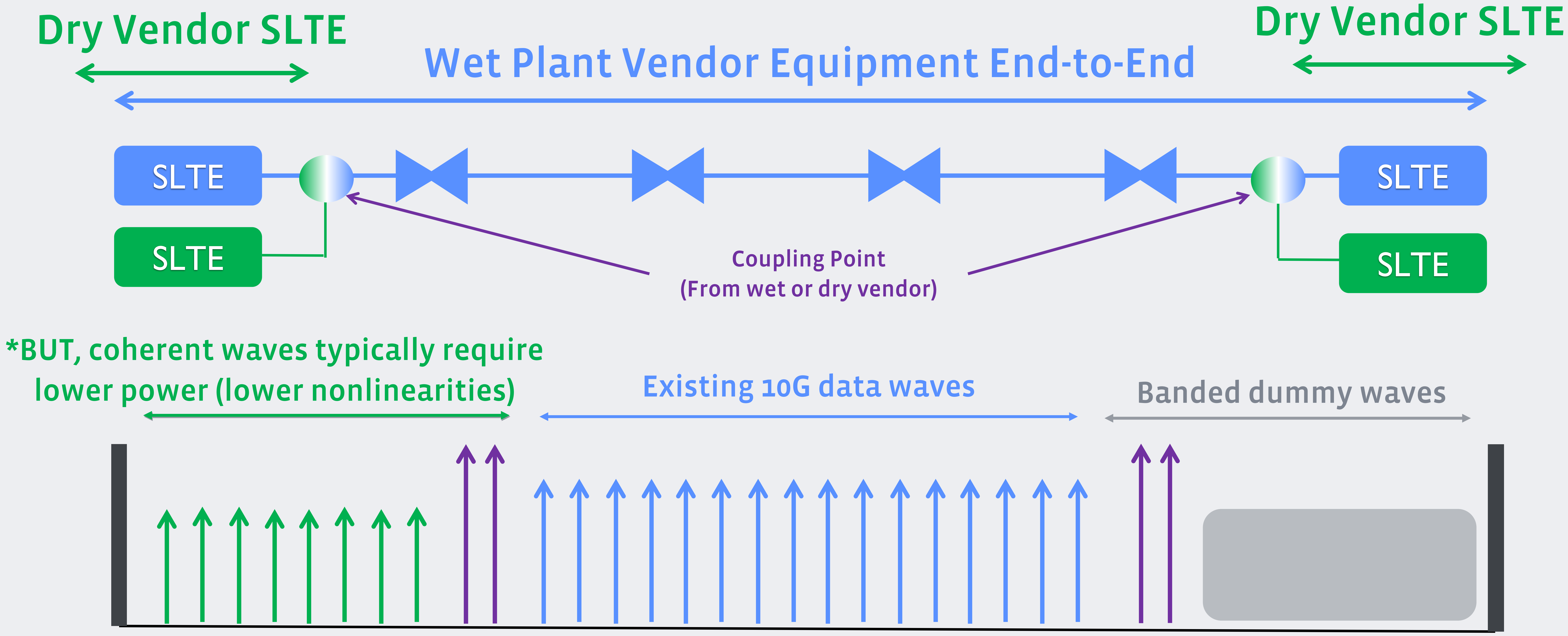
Existing 10G data waves

Banded dummy waves

Specialized CW dummy waves can be used to “hold” excess power to optimize performance of all waves, new and old.

Many Ways to Upgrade Existing Cables

Option 1: Overlay New & Old Technology



Dry Vendor SLTE

Wet Plant Vendor Equipment End-to-End

Dry Vendor SLTE

Coupling Point
(From wet or dry vendor)

*BUT, coherent waves typically require lower power (lower nonlinearities)

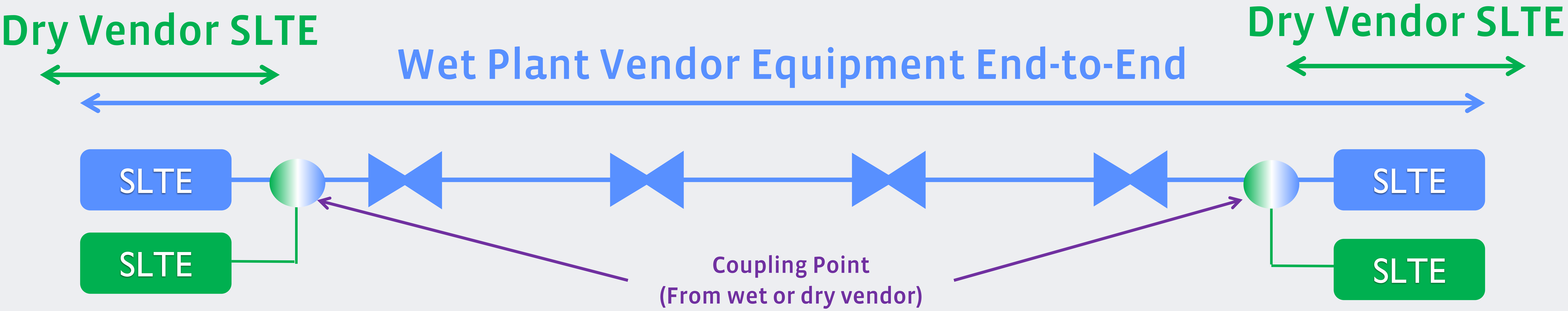
Existing 10G data waves

Banded dummy waves

But power must be balanced, so typically CW idlers are placed as symmetrically as possible, and in some cases are strategically placed to minimize the impact of tilt.

Many Ways to Upgrade Existing Cables

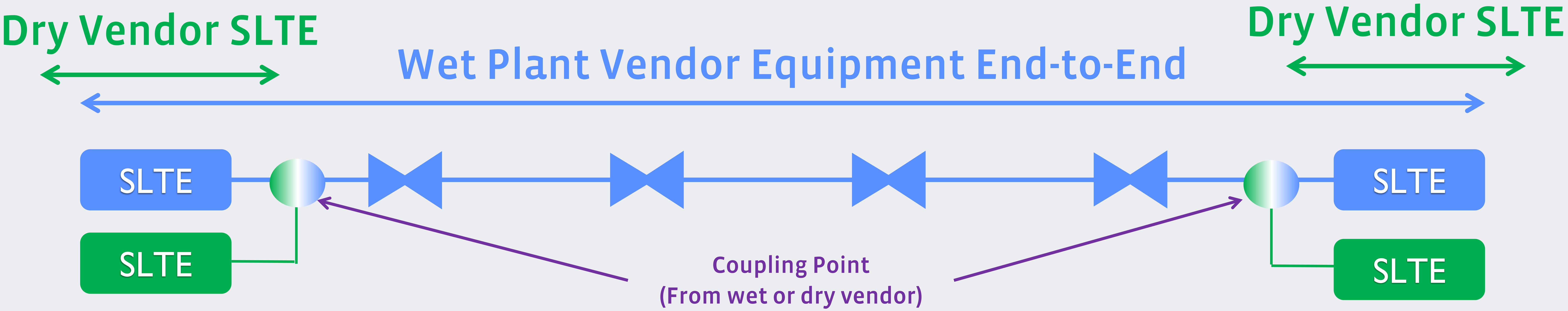
Option 2: Traffic Migration to New Technology



Sometimes, there is little or no open spectrum remaining on a fiber. Space is needed for a new wave.

Many Ways to Upgrade Existing Cables

Option 2: Traffic Migration to New Technology



Dry Vendor SLTE

Wet Plant Vendor Equipment End-to-End

Dry Vendor SLTE

SLTE

SLTE

SLTE

SLTE

Coupling Point
(From wet or dry vendor)

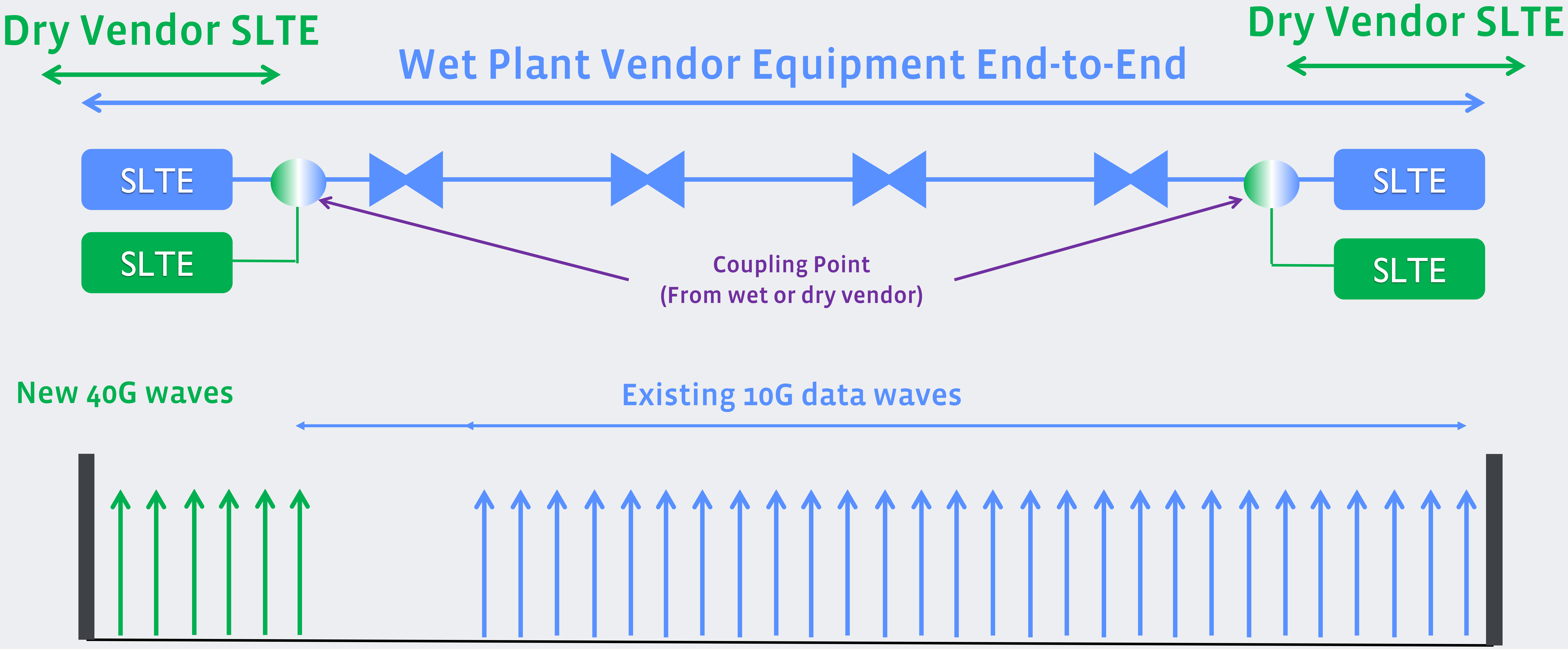
New 40G wave

Existing 10G data waves

New wave is higher bandwidth, and can replace older ones 4:1 (or 10:1 if 100G is used)

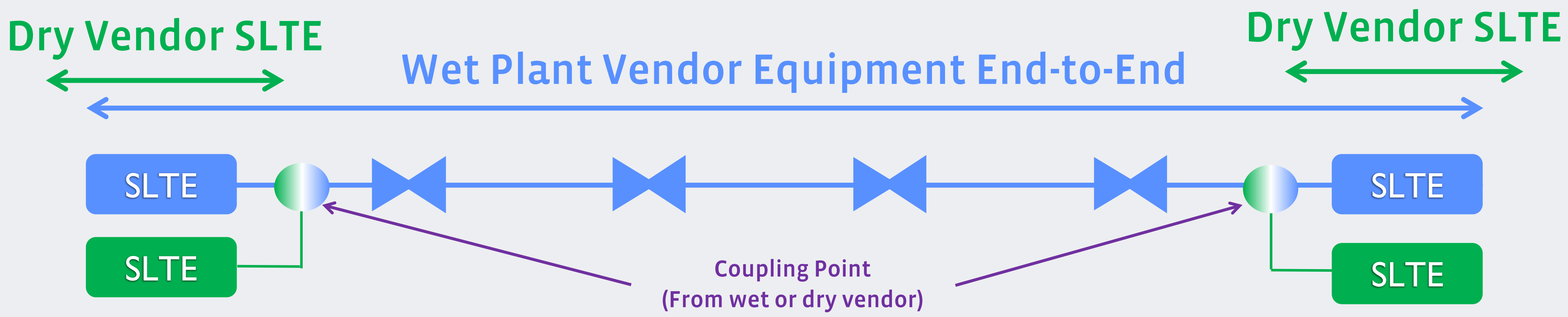
Many Ways to Upgrade Existing Cables

Option 2: Traffic Migration to New Technology



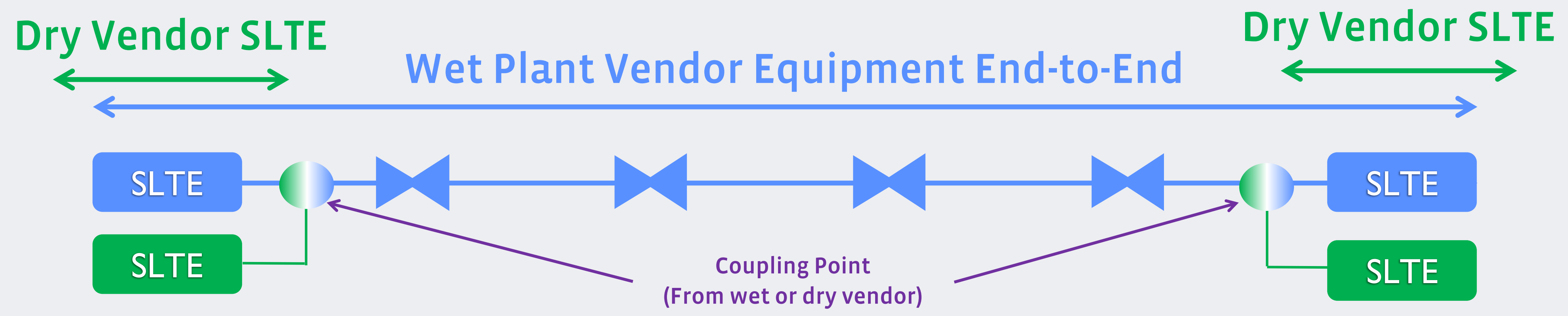
Process can be repeated until full spectrum is replaced or target capacity is achieved. Dummy lights will be needed at some point.

Upgrade Considerations



- Coupling Point:
  - Sometimes, existing SLTE has an open coupling point that is suitable for use
  - If not, new coupler must be inserted during a brief maintenance activity window, where traffic will be interrupted
- Dummy Replacement:
  - If banded dummy lights are used, new channelized dummy lights will be gradually inserted, maintaining the same power levels. Guard bands are often needed.
  - Traffic channels can then be inserted one by one using new dummy lights. CW idlers may also be needed if optimal channel power is lower than what is available
- Traffic Migration:
  - If there is no open spectrum available, then a single wave may need to be removed and replaced by a new, higher bandwidth wave. Sometimes though, we can find space for just one wave on the outer edges!
  - Then traffic can be migrated onto the new wave, and older waves can be removed in a 4:1 (40G upgrade from 10G) or 10:1 (100G upgrade from 10G) ratio (or more!)
  - Coherent DP-PSK technology overlays with single pol. IMDD waves on legacy cables requires very careful power control and guard band management. Traffic soaks are crucial to ensuring performance long term.

Field Trials

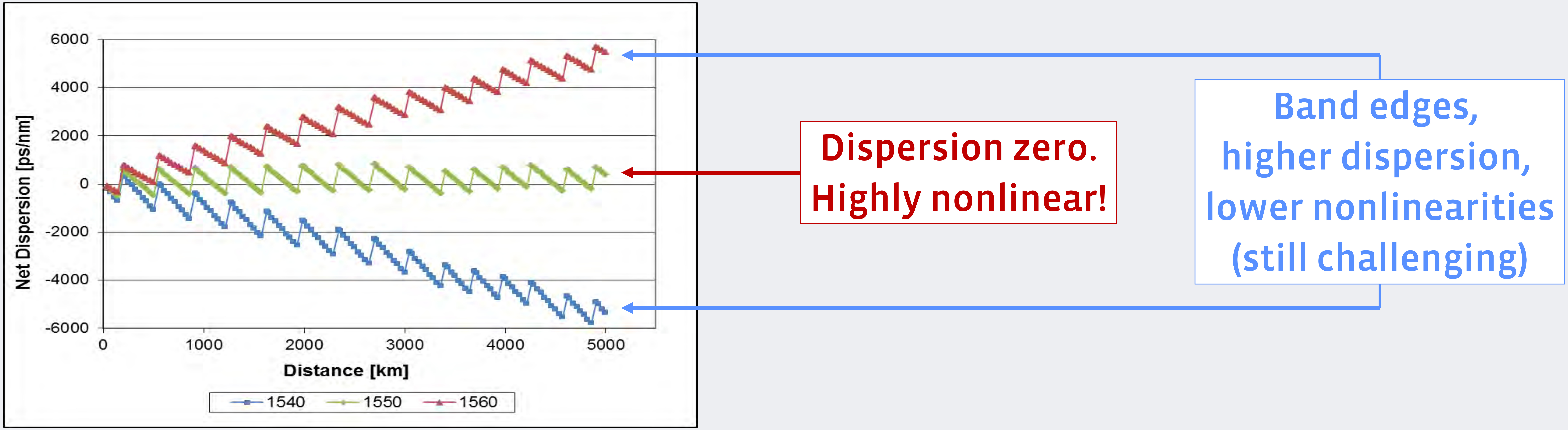


- How They are Done:
  - Field trials follow the same coupling and power replacement process as upgrades, however they are only temporary, and the steps need to be exactly reversed at the end of a field trial
  - Maintaining power and performance of existing traffic waves is highly critical, and not a trivial task!
- Why Field Trial?
  - Field trials are typically used to prove a new technology works as expected, but just as importantly, used to characterize the performance effect of the old technology on the new technology
  - In particular for coherent technology overlays on older cables and 10G waves, there are many nonlinear effects at play that must be carefully considered. These can be difficult to simulate, especially with so many unknowns about the actual propagation conditions (the "black box"). So field trials are typically the norm for these applications
- New "Coherent" cable designs have since changed the norms…

What About Greenfield on Legacy Cables?

There are many dimensions that can be used to optimize capacity on a legacy cable, with highly variable performance across the spectrum:

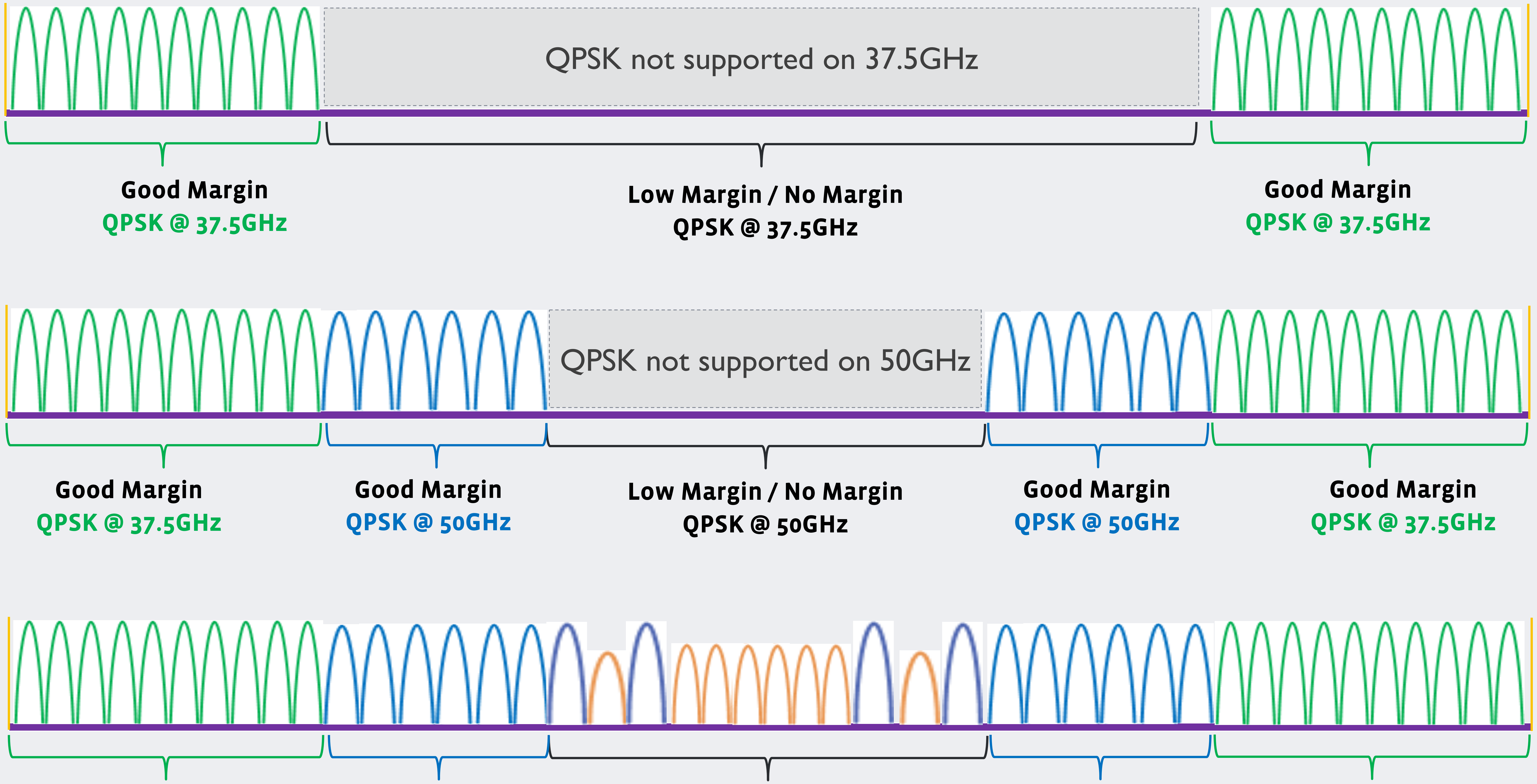
- Modulation formats, channel spacing, channel power, pre-dispersion, nonlinear mitigation & compensation techniques, carrier recovery techniques, etc.



Dispersion zero. Highly nonlinear!

Band edges, higher dispersion, lower nonlinearities (still challenging)

What About Greenfield on Legacy Cables?



100G QPSK @ 37.5GHz

Good Margin
QPSK @ 37.5GHz

Low Margin / No Margin
QPSK @ 37.5GHz

Good Margin
QPSK @ 37.5GHz

100G QPSK @ 37.5GHz & 50GHz

Good Margin
QPSK @ 37.5GHz

Good Margin
QPSK @ 50GHz

Low Margin / No Margin
QPSK @ 50GHz

Good Margin
QPSK @ 50GHz

Good Margin
QPSK @ 37.5GHz

Spectral Averaging

Good Margin
QPSK @ 37.5GHz

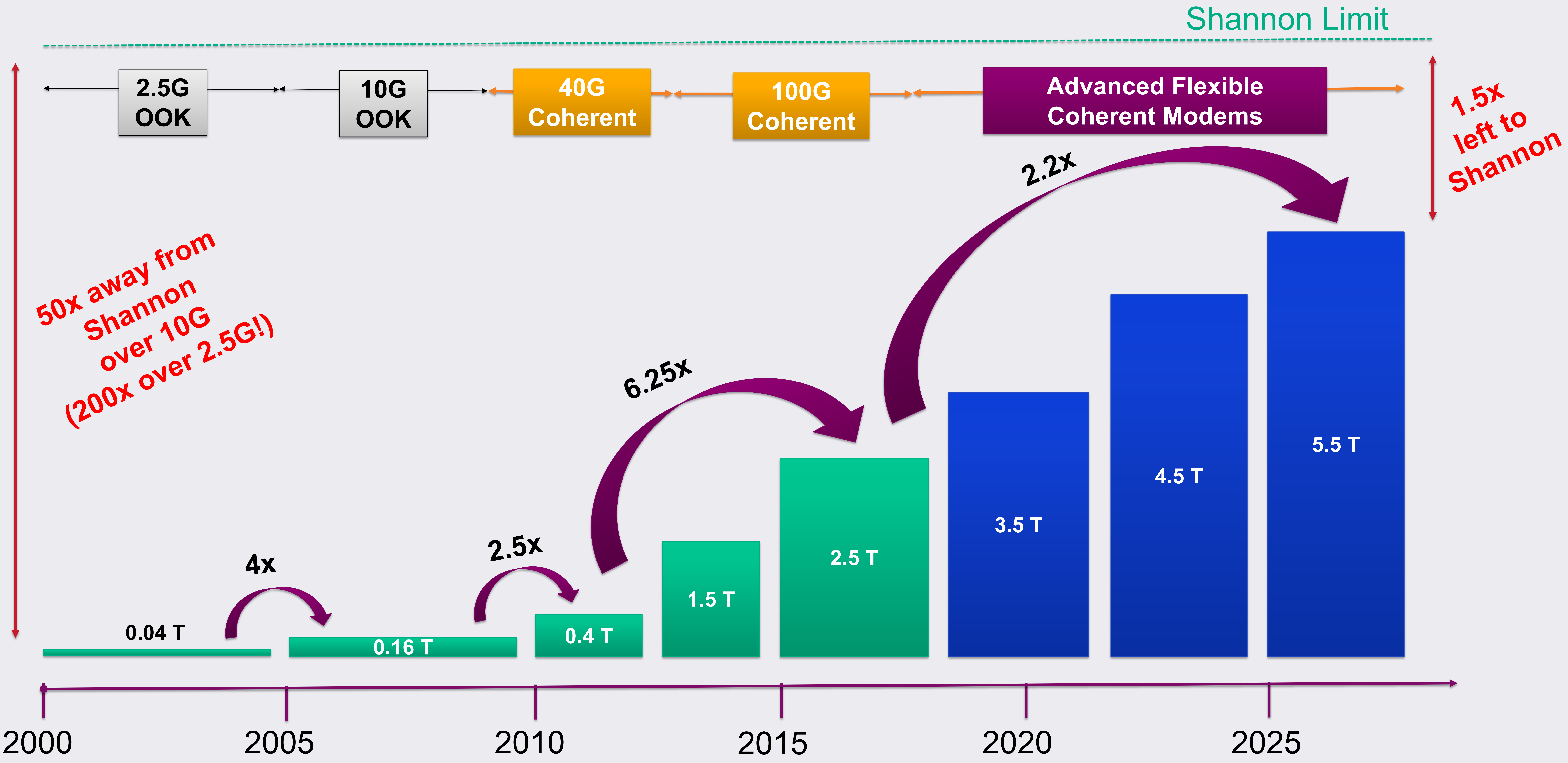
Good Margin
QPSK @ 50GHz

Good Margin
QPSK @ 100GHz
BPSK @ 37.5GHz

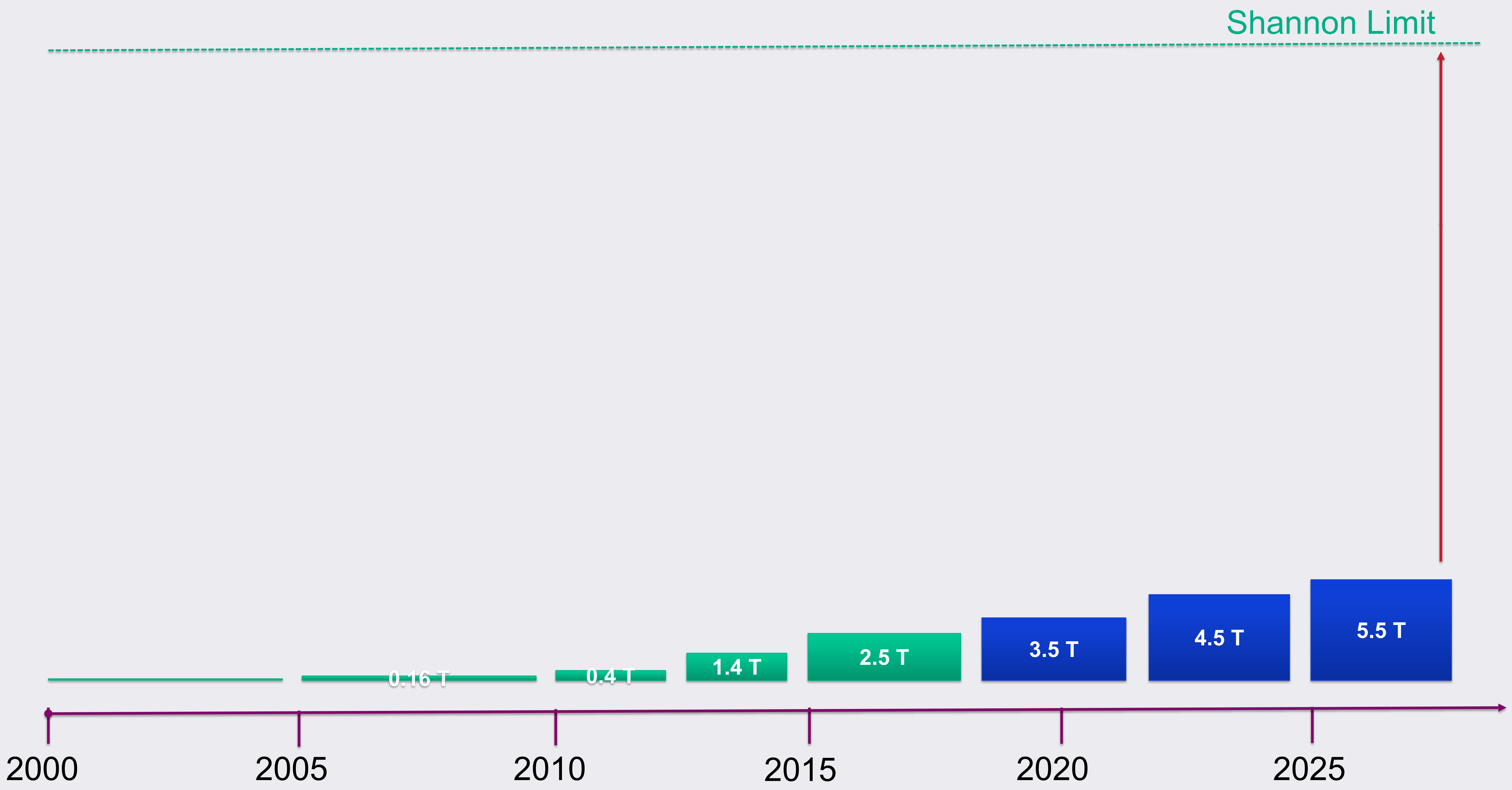
Good Margin
QPSK @ 50GHz

Good Margin
QPSK @ 37.5GHz

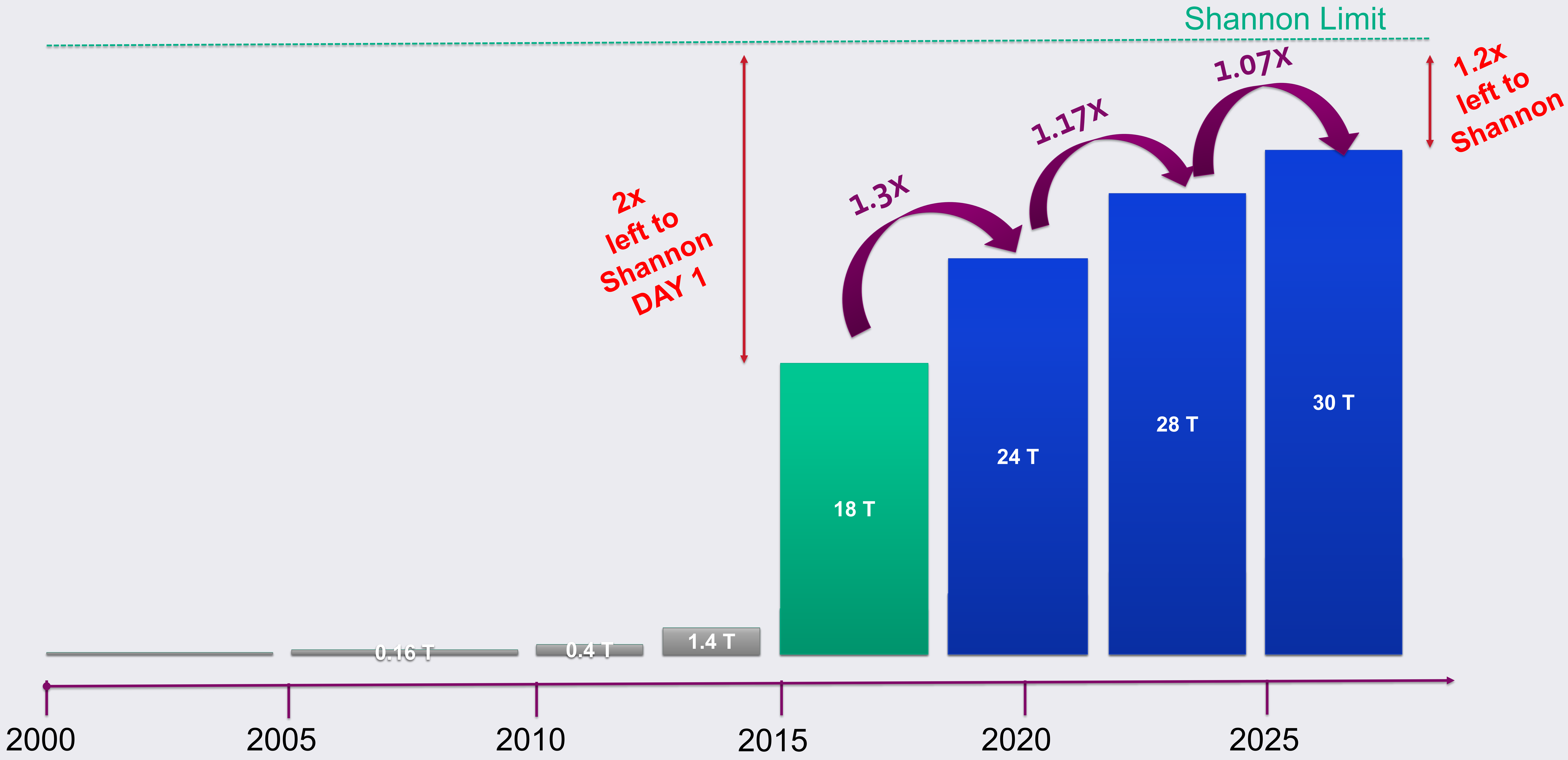
Shannon's Limit on Legacy Cables – Room to Grow with Coherent!



Shannon's Limit on New Coherent Cables!

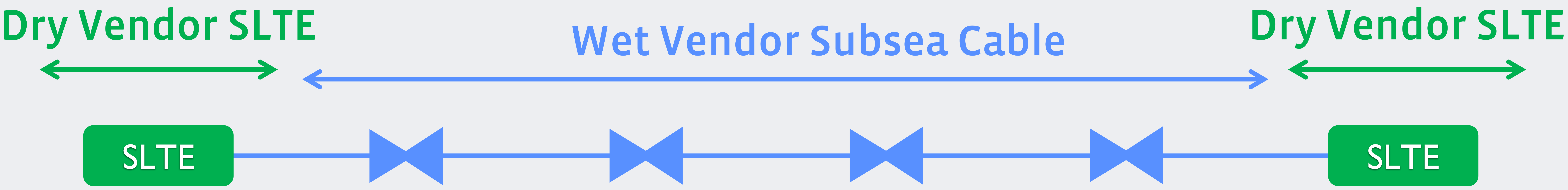


Shannon's Limit on New Coherent Cables!



Onto The “Open Cable Era”

Early “Upgrade” Subsea Cable Capacity Model



Dry Vendor SLTE

Wet Vendor Subsea Cable

Dry Vendor SLTE

SLTE

SLTE

Modern Subsea “Open Cable” Model (Designed to be Open from Day 1!)

ANY Vendor SLTE

Wet Vendor Subsea Cable + OCI

ANY Vendor SLTE

SLTE

OCI

OCI

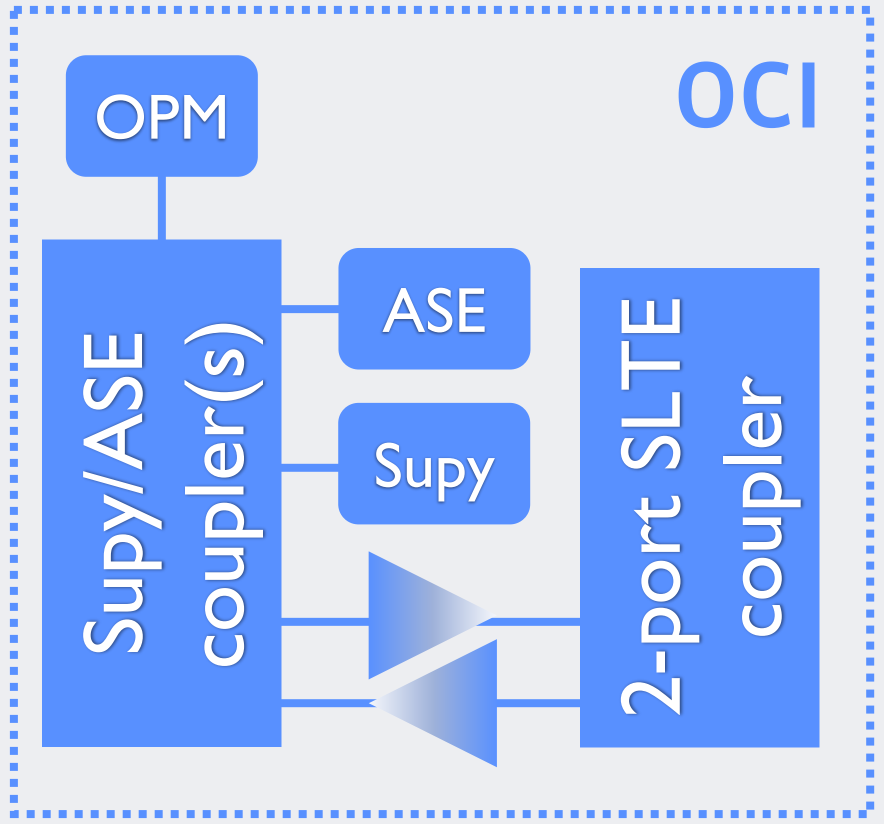
SLTE

Open Cables & Convergence with Terrestrial

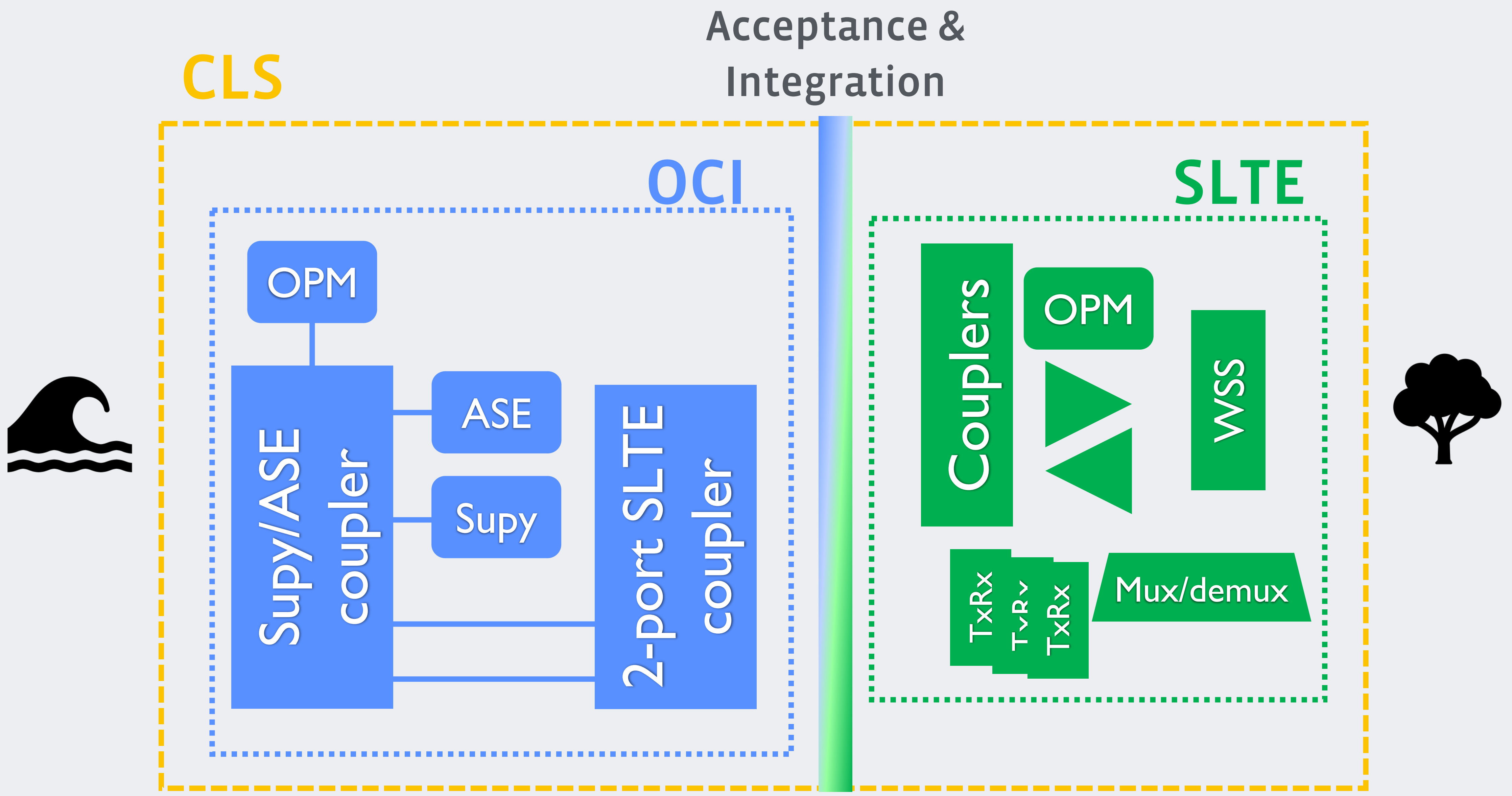
Basic OCI Requirements

An Open Cable Interface (OCI) is now defined as the boundary between wet plant and SLTE

- Line Amplifier:
  - Line amp should be only active element inline with traffic path. Must have reasonable gain and power ranges to allow efficient interop with 3rd party SLTE while maintaining optical performance levels.
- Supervisory:
  - Supervisory functions (monitoring & wet plant control) must be able to operate independent of 3rd party SLTE choice
- ASE:
  - ASE generation is required for acceptance & turn-up, dark fiber monitoring, and must not be inline with traffic path
- Optical Power Monitoring:
  - OCI must have OPM capabilities for direct Tx / Rx monitoring of wet plant. OPM needs to represent final spectral shape in and out of wet plant
- Open Coupling Ports:
  - Need open passive 3dB coupling ports for 2 x SLTE as the last element in Rx direction
  - Required coupling ports for COTDR to/from wet plant



Use Case 1: CLS to CLS, full termination

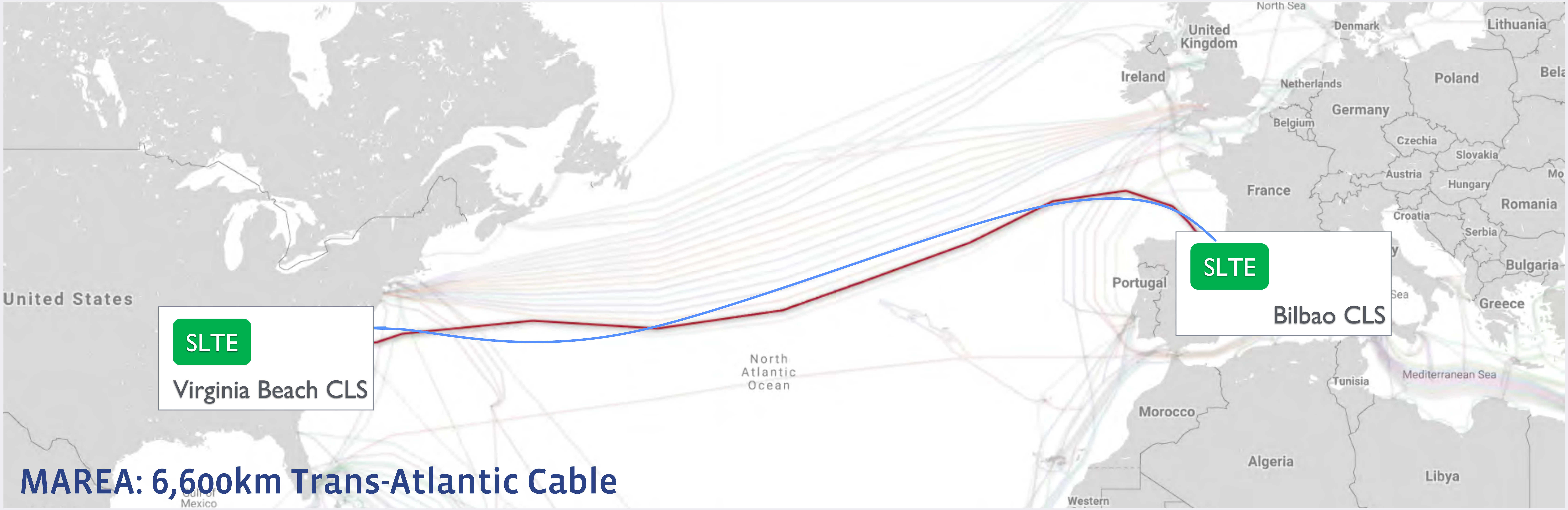


- Wet Vendor OCI:
  - ASE, Supervisory & OPM functions
  - Line amp replaced by SLTE amps
- Dry Vendor SLTE:
  - Gain controlled line amp(s), WSS, OPM, mux/demux, coupler(s)

Case	Use Case Description	Equipment at CLS	Equipment at PoP	Integration Point	Acceptance
1	**CLS to CLS, full termination**	Wet Vendor OCI Dry Vendor SLTE	N/A	Wet Vendor OCI in CLS	Acceptance is at CLS

CLS vs PoP and Why we Extend

Subsea cables land on the coast! (Near the sea...)

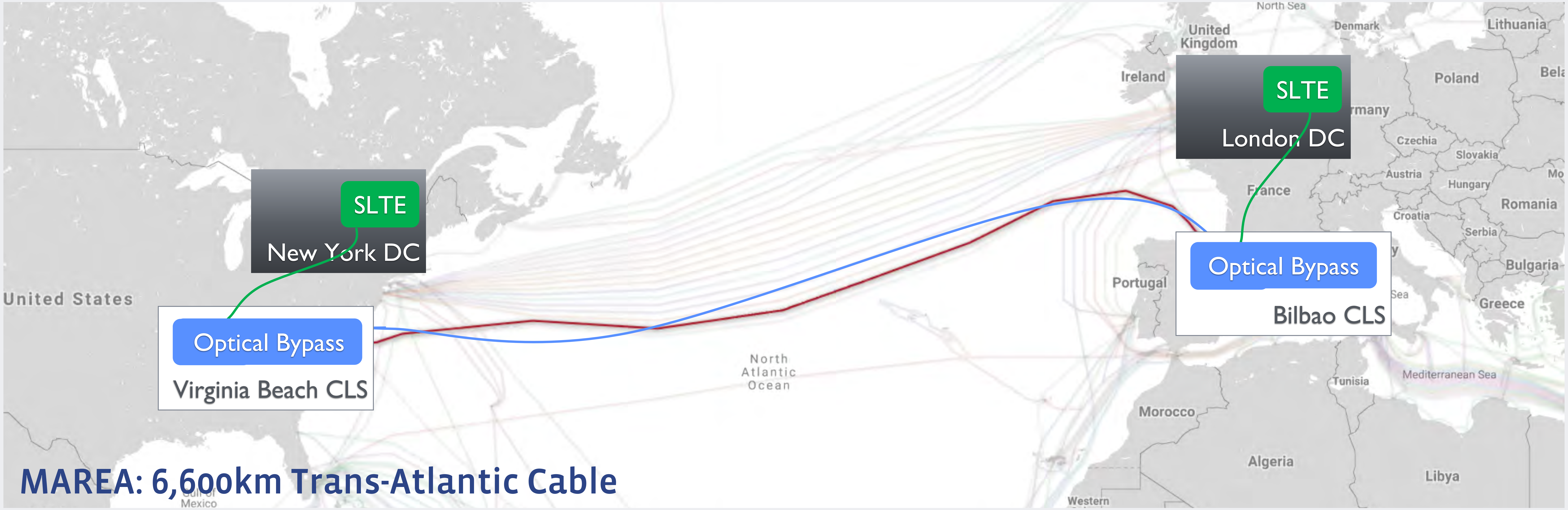


MAREA: 6,600km Trans-Atlantic Cable

CLS vs PoP and Why we Extend

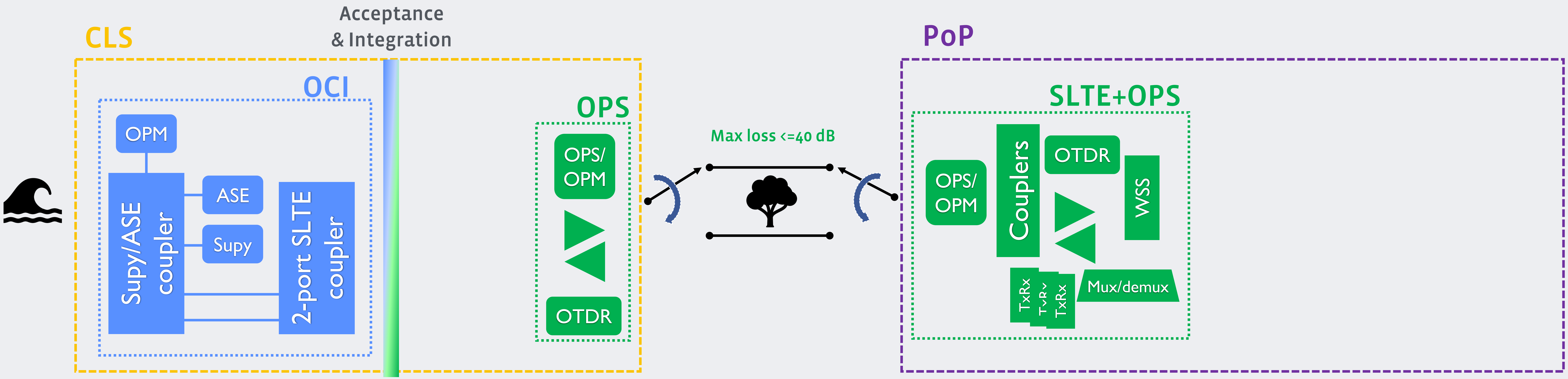
Subsea cables land on the coast! (Near the sea…)

- ***BUT*** that's not (usually) where the people are…and big data centers and fast internet want to be close to the densest populations of people!



MAREA: 6,600km Trans-Atlantic Cable

Use Case 2: CLS to PoP, single span, prot. SW

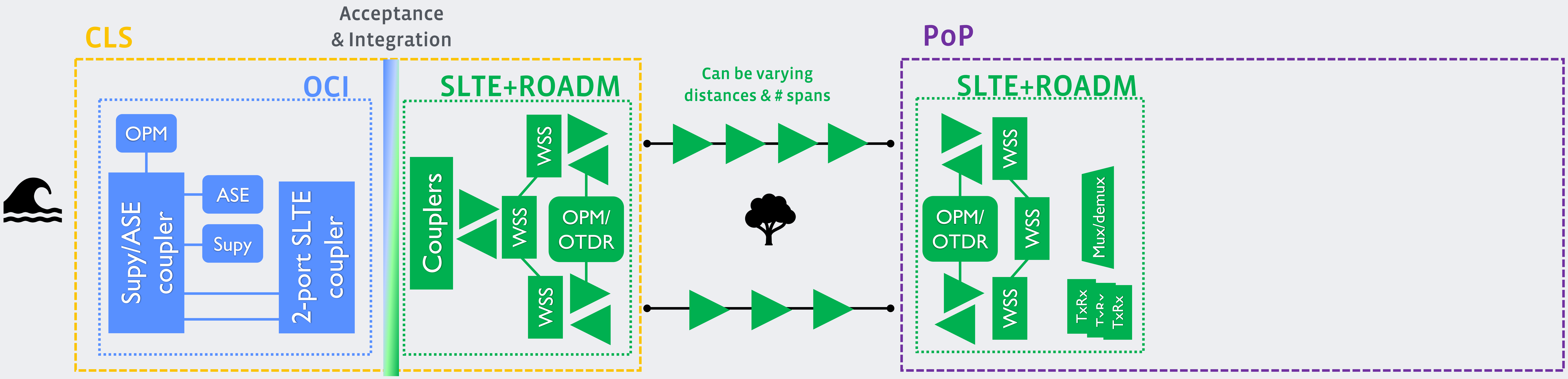


- Wet Vendor OCI:
  - ASE, Supervisory & OPM functions
  - Line amp replaced by SLTE amps
- Dry Vendor OPS:
  - OPS / coupler & line amp(s), OPM, OTDR

- Dry Vendor OPS + SLTE:
  - Converged solution
  - OPS / coupler & line amp(s), OPM, OTDR
  - Gain ctrl line amp(s), WSS, mux/demux, coupler(s)

Case	Use Case Description	Equipment at CLS	Equipment at PoP	Integration Point	Acceptance
2	**CLS to PoP, single span, protection switch**	Wet Vendor OCI Dry Vendor OPS	Dry Vendor OPS + SLTE	Wet Vendor OCI in CLS	Acceptance is at CLS

Use Case 3: CLS to PoP, multi-span, restoration



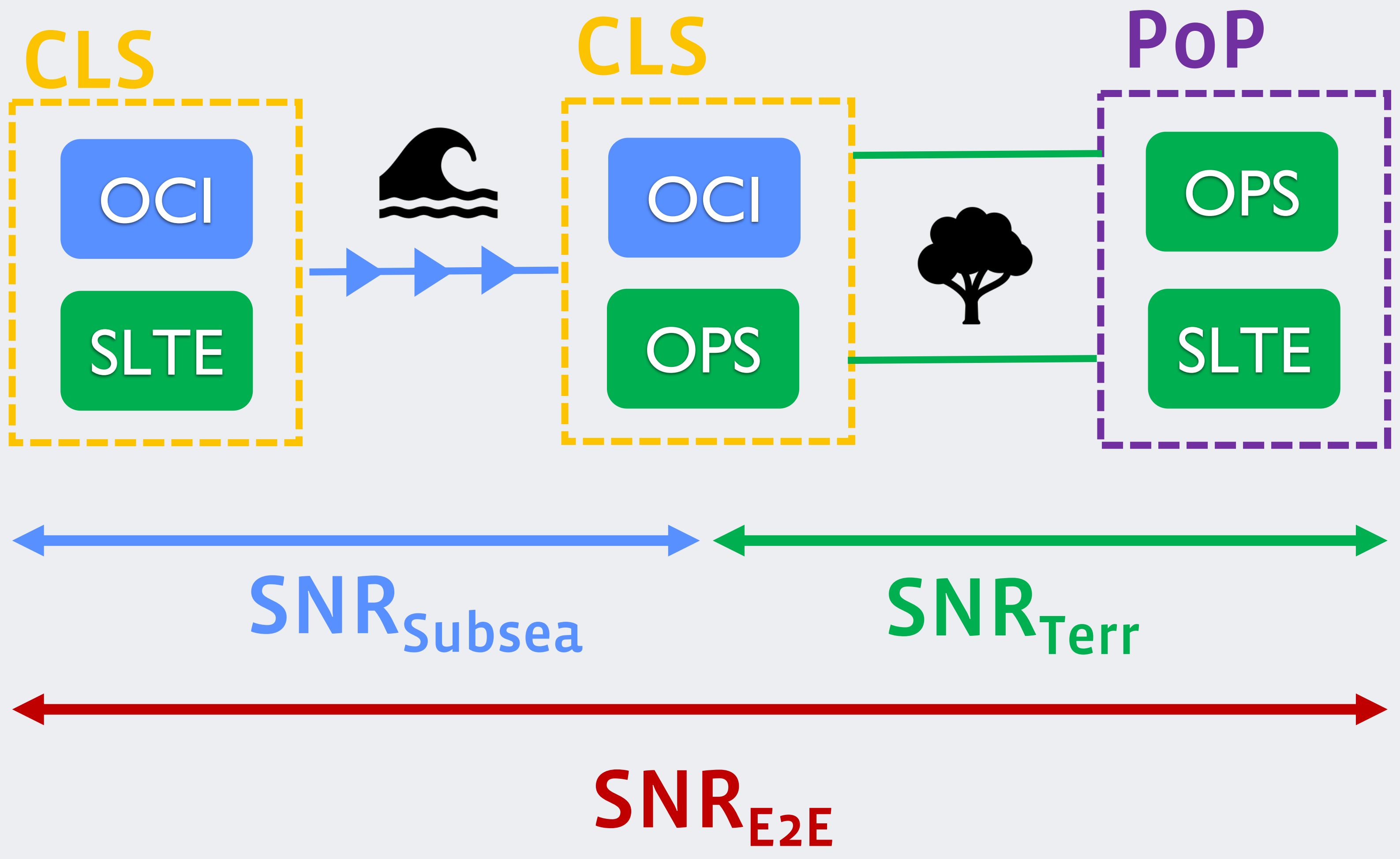
- Wet Vendor OCI:
  - ASE, Supervisory & OPM functions
  - Line amp replaced by SLTE amps
- Dry Vendor SLTE+ROADM:
  - Couplers, Gain ctrl line amp(s), multi-degree WSS', OPM/OTDR

- Dry Vendor SLTE + ROADM:
  - Gain ctrl line amp(s), multi-degree WSS', OPM/OTDR
  - Mux/demux

Case	Use Case Description	Equipment at CLS	Equipment at PoP	Integration Point	Acceptance
3	**CLS to PoP, multi-span, protection switch**	Wet Vendor OCI Dry Vendor SLTE + ROADM	Dry Vendor SLTE + ROADM	Wet Vendor OCI in CLS	Acceptance is at CLS

End-to-End Design Considerations

- We must be very careful when concatenating Subsea & Terrestrial links not to hurt the Subsea OSNR (it was expensive!)
- Recall that OSNRs are additive (1/SNR summation)
  - The higher the SNR of your subsea link, the larger the penalty it will take from a low SNR (high loss) terrestrial link.



$$\frac{1}{SNR_{E2E}} = \frac{1}{SNR_{Subsea}} + \frac{1}{SNR_{Terr}}$$

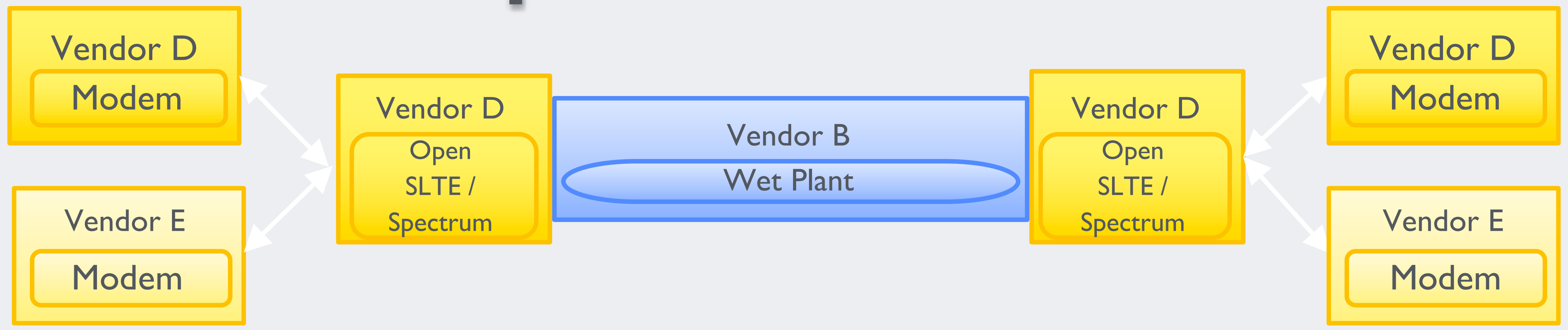
The *Benefits* of Open Cables

- Open Cables enable independent vendor selection for wet and dry technology, allowing ***best of breed*** utilization on two very critical pieces of a subsea cable

- Since SLTE technology cycles are typically faster than a Submarine cable build, and there are multiple DSP vendors with multiple chip generations, all with staggered availability over time, Open Cables also allow for **maximization of cable capacity at the time of cable RFS** (maximizing value)

- Open Cables allow the use of preferred SLTE vendors, which can be essential operationally when considering a ***global subsea & terrestrial mesh network***

Open Subsea Cable



The *Challenges* of Open Cables

- Comparing different wetplant designs by the traditional turnkey method, with each vendor proposing their own unique SLTE capacity can be highly misleading (and therefore costly!)
  - But how to compare different Open Cable wetplant designs and assess their performance?

- Industry standard wetplant **performance metrics** are needed that are *SLTE-independent*
  - OSNR and GSNR have been proposed. Higher OSNR generally equals higher capacity…as does higher GSNR
  - But neither tells the full story in isolation!!

- Ongoing monitoring of wetplant performance over the system lifetime must have continuity and meaning regardless of SLTE technology used
  - Upgrades that rip & replace press the reset button on Q-based performance tracking

Overcoming the *Challenges* and Reaping the *Benefits*

Open is being done today! On many cables…How?

- OSNR and GSNR, when ***carefully*** considered together, can:
  - Give a clear picture of the optical performance of a D+ subsea system
  - Offer a fair means of comparison between different wetplant designs
  - Enable 3rd party SLTE capacity estimation
  - Enable ongoing performance monitoring that is SLTE independent

- But, we **must** have consistency and industry agreed definitions and methodologies for measuring them (HINT: this was the goal of the SubOptic Working Group!)

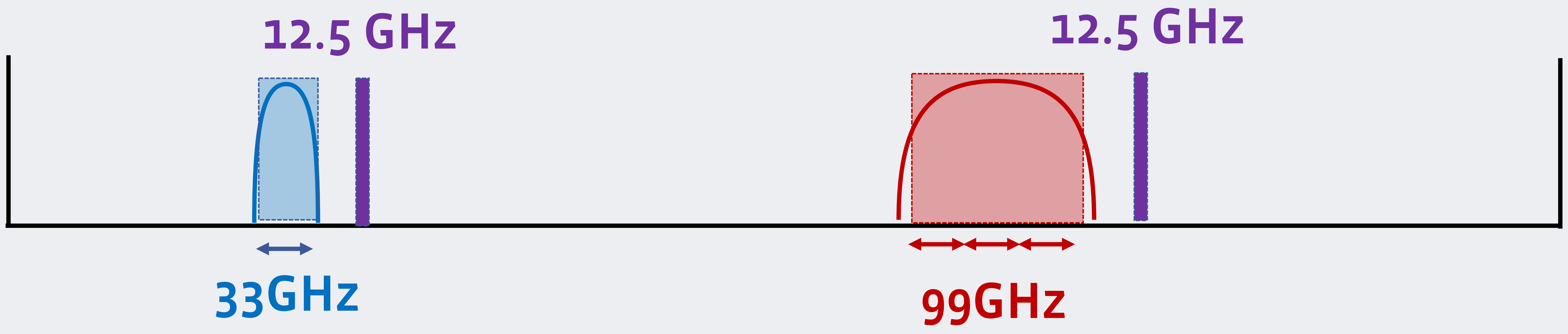
OSNR & GSNR

OSNR vs SNR

Definitions:

$OSNR = P_{sig,\Delta f}/N_{12.5GHz}$

$SNR = P_{sig,\Delta f}/N_{\Delta f}$



$OSNR_{33Gbd} = P_{sig,33GHz} / N_{12.5GHz}$

$OSNR_{99Gbd} = P_{sig,99GHz} / N_{12.5GHz}$

$OSNR_{33Gbd} \neq OSNR_{99Gbd}$

$SNR_{33Gbd} = P_{sig,33GHz} / N_{33GHz}$

$SNR_{99Gbd} = P_{sig,99GHz} / N_{99GHz}$

$SNR_{33Gbd} = SNR_{99Gbd}$

OSNR without context is not meaningful! We must know the conditions for it to be relevant.

As baud rates in the industry change, using SNR becomes critical to make meaningful comparisons.

Defining GSNR

- The validity of GSNR is predicated on the assumption that in D+ cables, linear (ASE) and nonlinear (NLI) noise look the same (both are Gaussian)

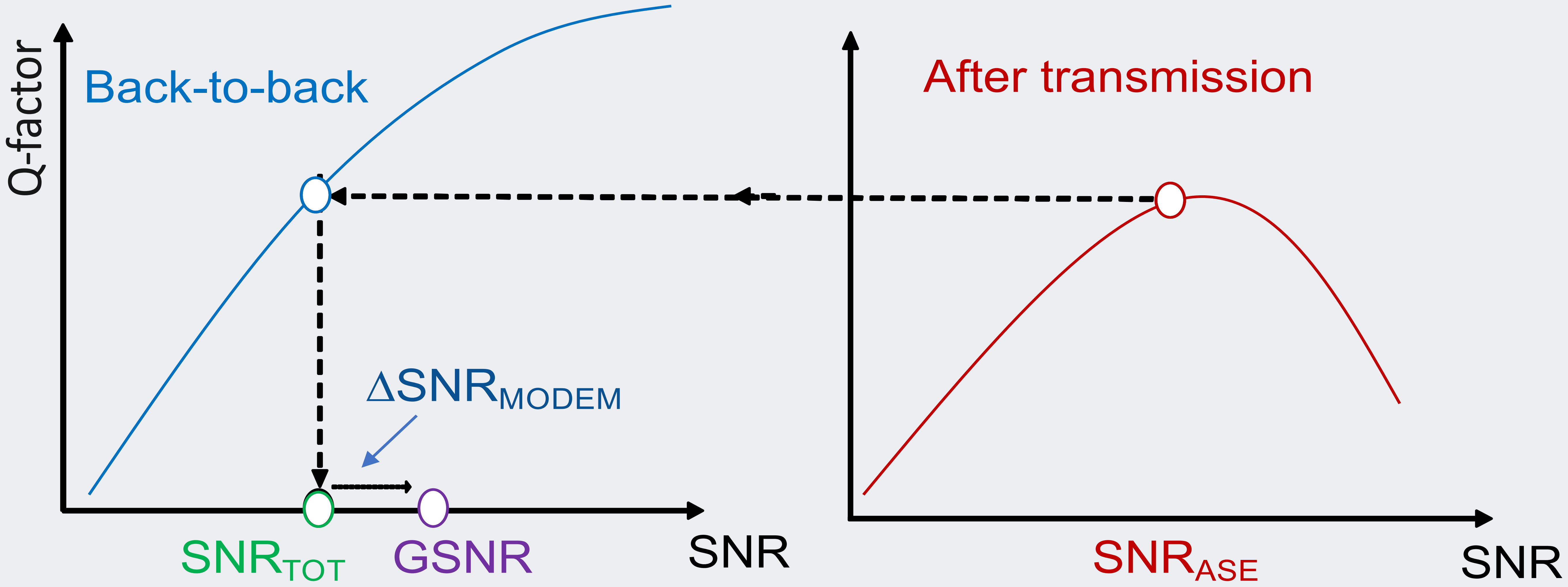
$$\frac{1}{GSNR} = \frac{1}{SNR_{ASE}} + \boxed{\frac{1}{SNR_{NLI}}}$$

SNR_{ASE} – GSNR (in dB)

- SNR_{ASE} is a direct measurement via an OSA of the linear noise only (OSNR)
- GSNR typically must be derived via a Q measurement from a (typically) QPSK transponder, which incorporates both linear and nonlinear noise
  - BUT also includes some modem impairments…more on this next…
- The delta between SNR_{ASE} and GSNR is the best indicator of degree of nonlinearity of the open cable

How to Measure GSNR

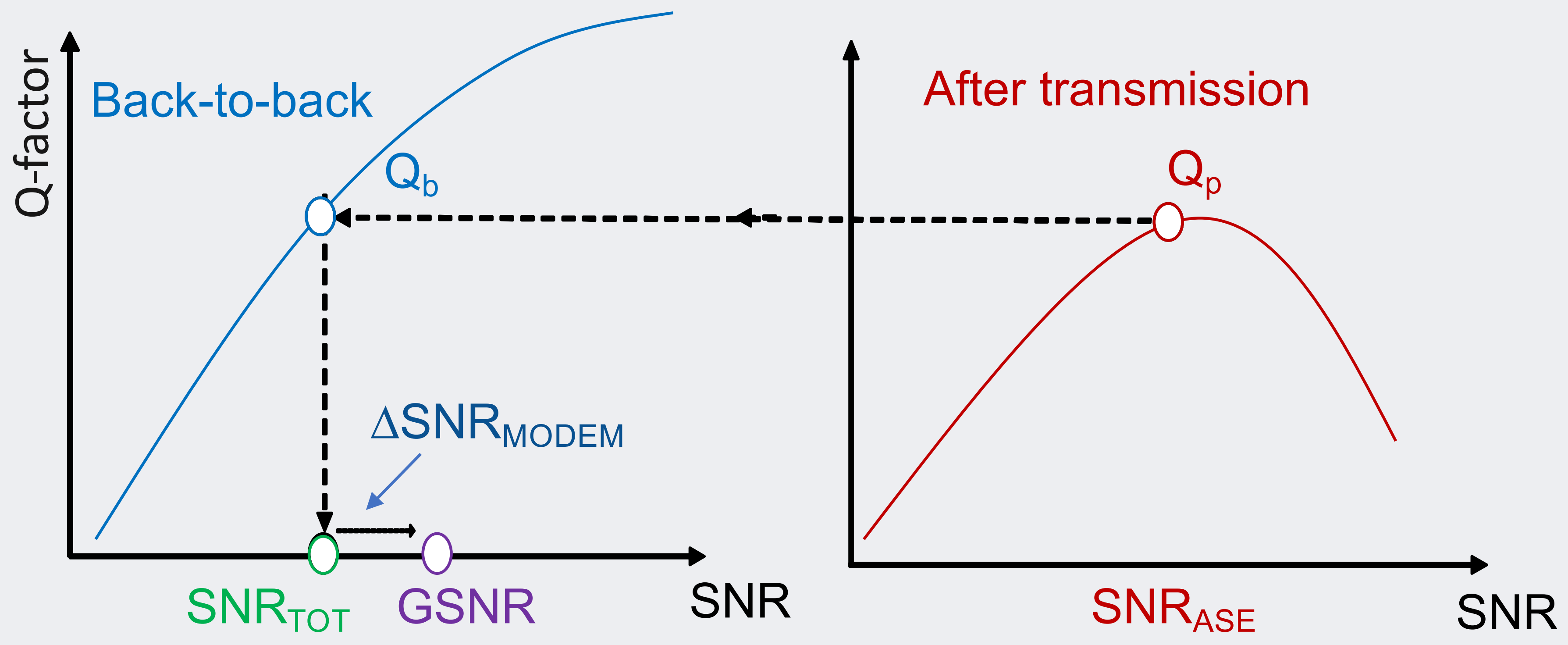
GSNR is derived via a Q measurement from a (typically QPSK) modem, which incorporates both linear and nonlinear noise, as well as noise introduced by the modem during propagation



$$\frac{1}{SNR_{TOT}} = \frac{1}{SNR_{ASE}} + \frac{1}{SNR_{NLI}} + \frac{1}{SNR_{MODEM}}$$

Modem Implementation

- Total System SNR
  - $\frac{1}{SNR_{TOT}} = \frac{1}{GSNR} + \frac{1}{SNR_{MODEM}}$

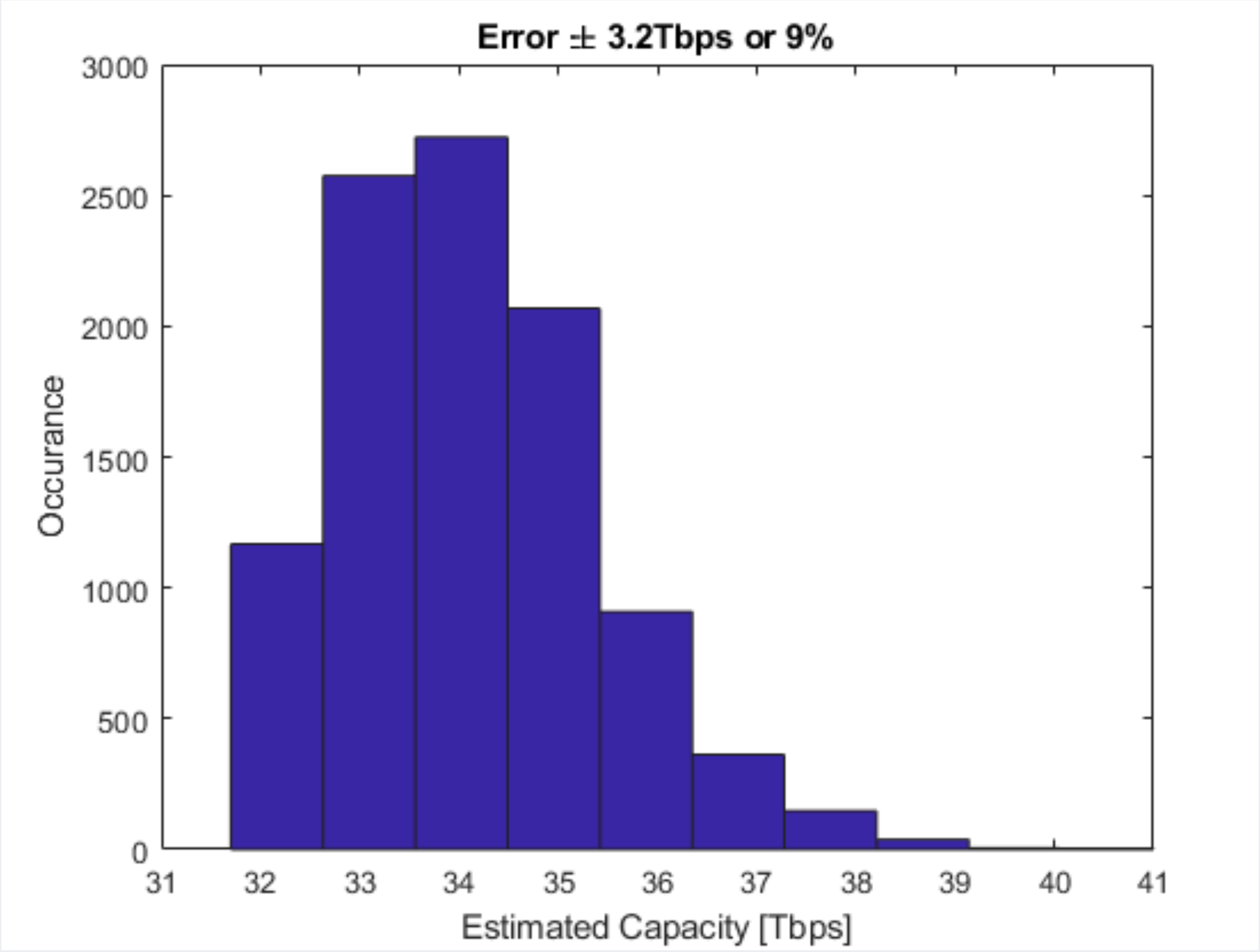


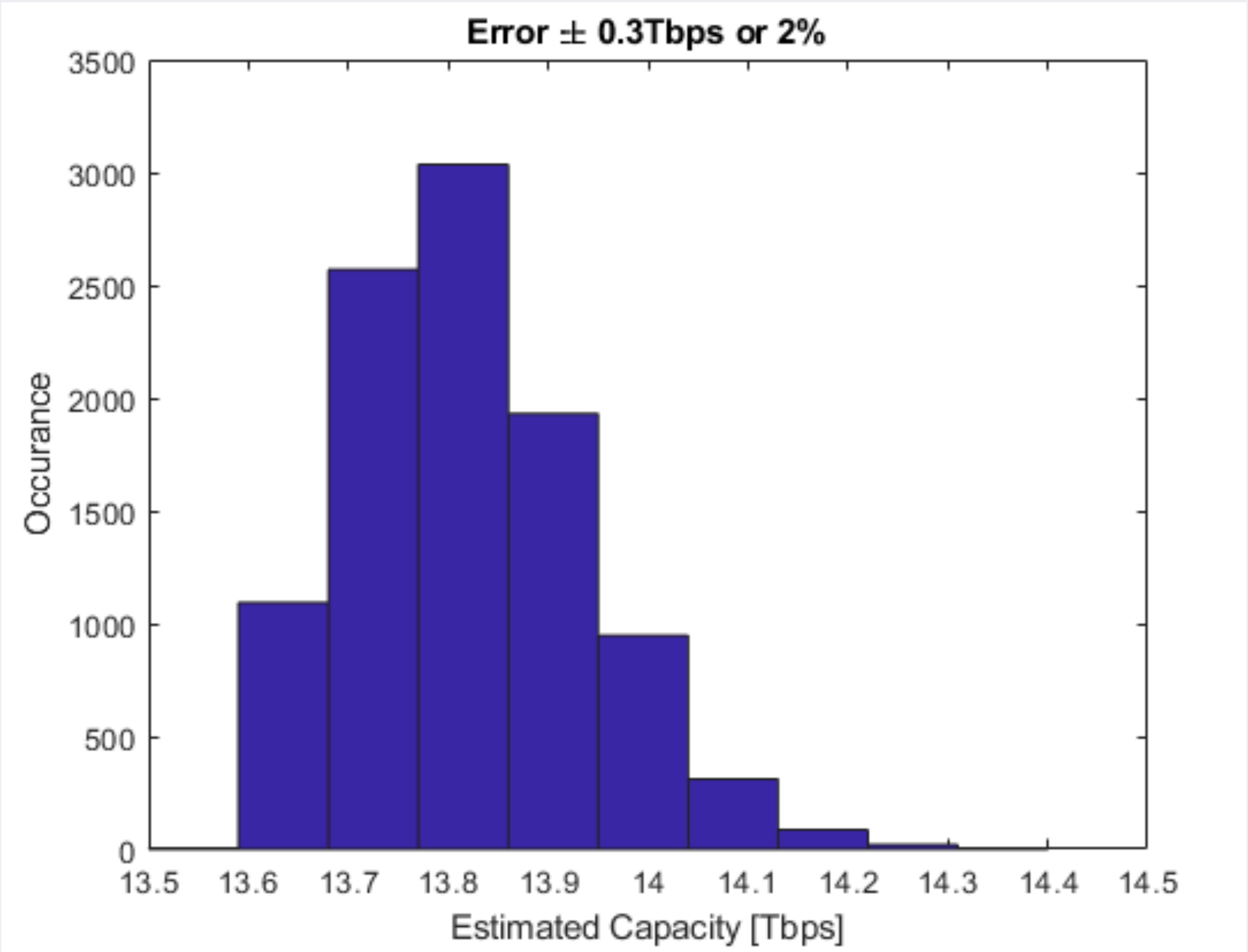
- Modem Implementation
  - $\frac{1}{SNR_{MODEM}} = \frac{1}{SNR_m} + \sum_{i=0}^{4} \frac{1}{SNR_i}$
  - SNR_i : PDL, CDC, Laser linewidth, and Wavelength tolerance
  - Typically between 23-35 dB (SNR) each
    - *Monte-Carlo of $\sum_{i=0}^{4} 1/SNR_i$

*See Monte Carlo simulation of impact of variable modem implementation penalties on GSNR in SubOptic Open Cables Working Group paper

Impact of Errors

- High OSNR and High TOP
  - $\mathrm{SNR}_{\mathrm{ASE}} = 18\text{ dB and }\mathrm{SNR}_{\mathrm{NLI}} = 20\text{ dB}$
  - Capacity estimation error between similar modems ~ 9%
- Low OSNR, SDM Design
  - $\mathrm{SNR}_{\mathrm{ASE}} = 8\text{ dB and }\mathrm{SNR}_{\mathrm{NLI}} = 15\text{ dB}$
  - Capacity estimation error between similar modems ~ 2%
  - System dominated by linear noise so “typical” modem implementations impact are negligible



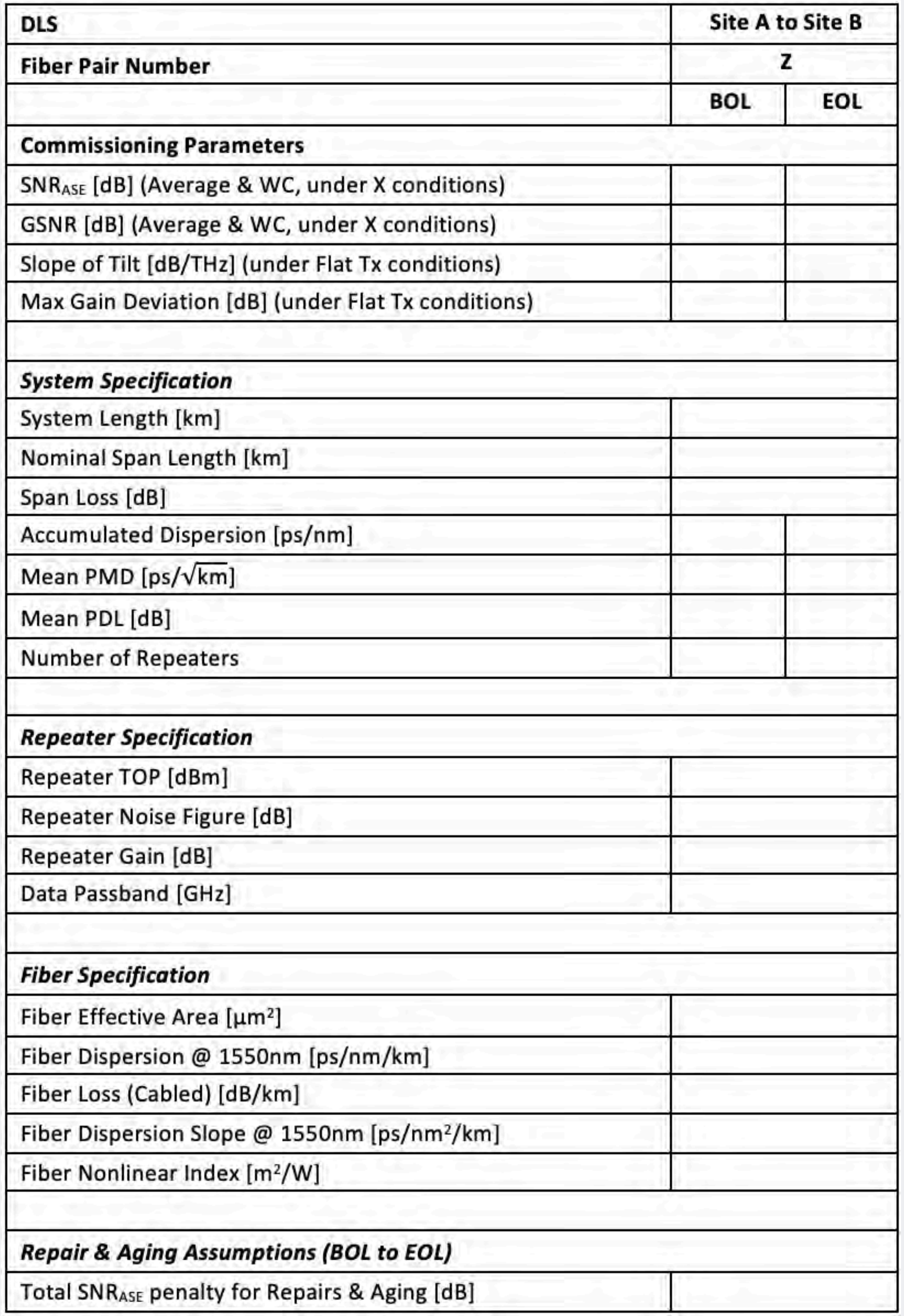


*See Monte Carlo simulation of impact of variable modem implementation penalties on GSNR in SubOptic Open Cables Working Group paper

Commissioning & Acceptance

Key Parameter Table

- A key parameter table is used during the design phase of a subsea cable to specify the most important contributors to the system performance, along with the commissioning parameters
- Information about the line design, the type of fiber used, and and specifications of the repeaters are essential
- Usually commissioning parameters are specified as "average" with a set of boundary conditions, as it's very difficult to know the exact frequency dependencies that will exist until the cable is built!



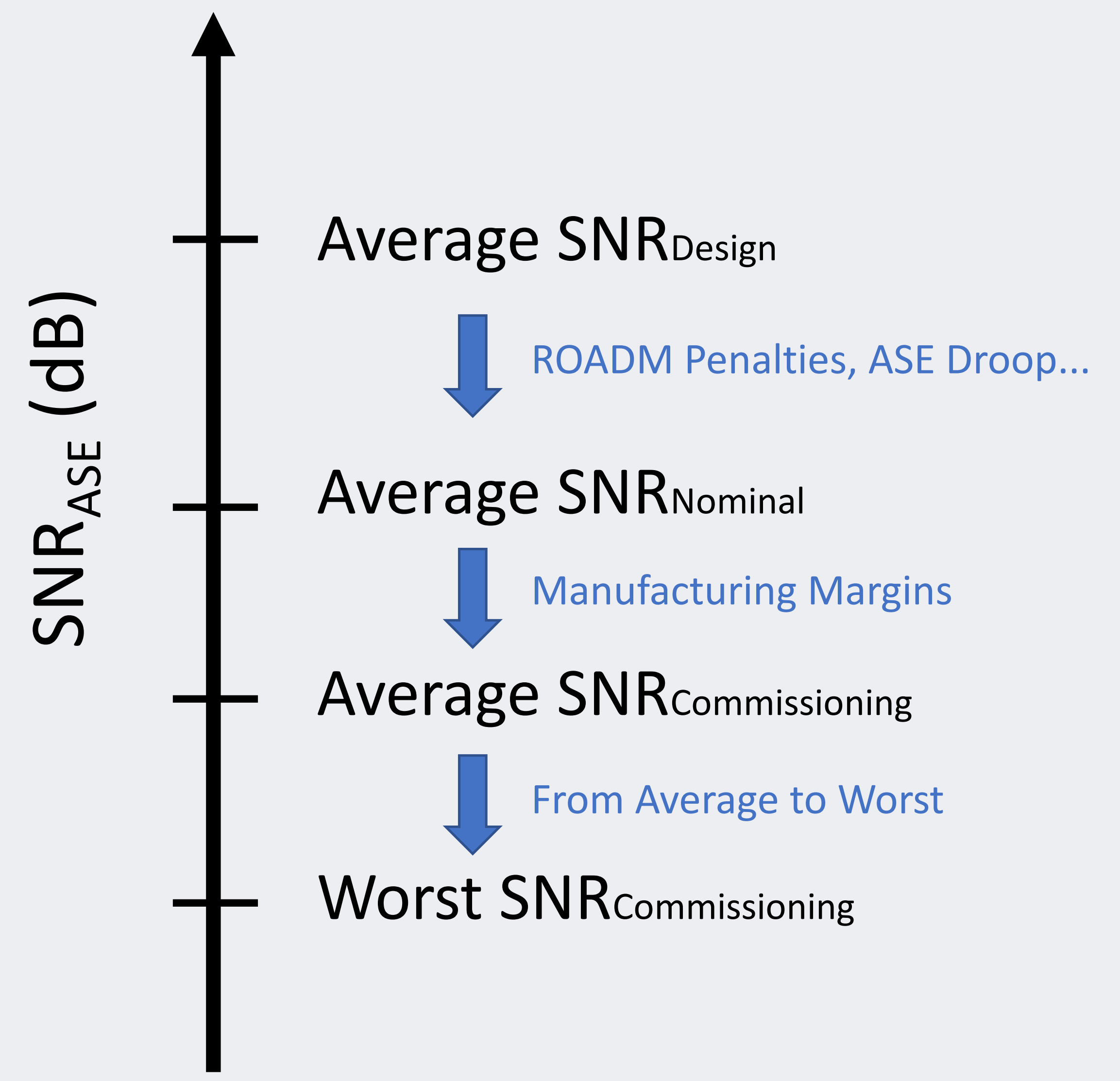
DLS	**Site A to Site B**	
Fiber Pair Number	**Z**	
	BOL	**EOL**
Commissioning Parameters		
SNR_{ASE} [dB] (Average & WC, under X conditions)		
GSNR [dB] (Average & WC, under X conditions)		
Slope of Tilt [dB/THz] (under Flat Tx conditions)		
Max Gain Deviation [dB] (under Flat Tx conditions)		
System Specification		
System Length [km]		
Nominal Span Length [km]		
Span Loss [dB]		
Accumulated Dispersion [ps/nm]		
Mean PMD [ps/√km]		
Mean PDL [dB]		
Number of Repeaters		
Repeater Specification		
Repeater TOP [dBm]		
Repeater Noise Figure [dB]		
Repeater Gain [dB]		
Data Passband [GHz]		
Fiber Specification		
Fiber Effective Area [μm^2]		
Fiber Dispersion @ 1550nm [ps/nm/km]		
Fiber Loss (Cabled) [dB/km]		
Fiber Dispersion Slope @ 1550nm [$ps/nm^2/km$]		
Fiber Nonlinear Index [m^2/W]		
Repair & Aging Assumptions (BOL to EOL)		
Total SNR_{ASE} penalty for Repairs & Aging [dB]		

*KPT as proposed in SubOptic Open Cables Working Group paper

Commissioning Parameters

A typical set of Commissioning Parameters may include:

1. Commissioning OSNR (average & worst case under X conditions)
2. Commissioning GSNR (average & worst case, under X conditions)
3. Slope of Tilt [dB/THz] & Gain Deviation [dB]



SNR_{ASE} (dB)

Average $\text{SNR}_{\text{Design}}$

ROADM Penalties, ASE Droop...

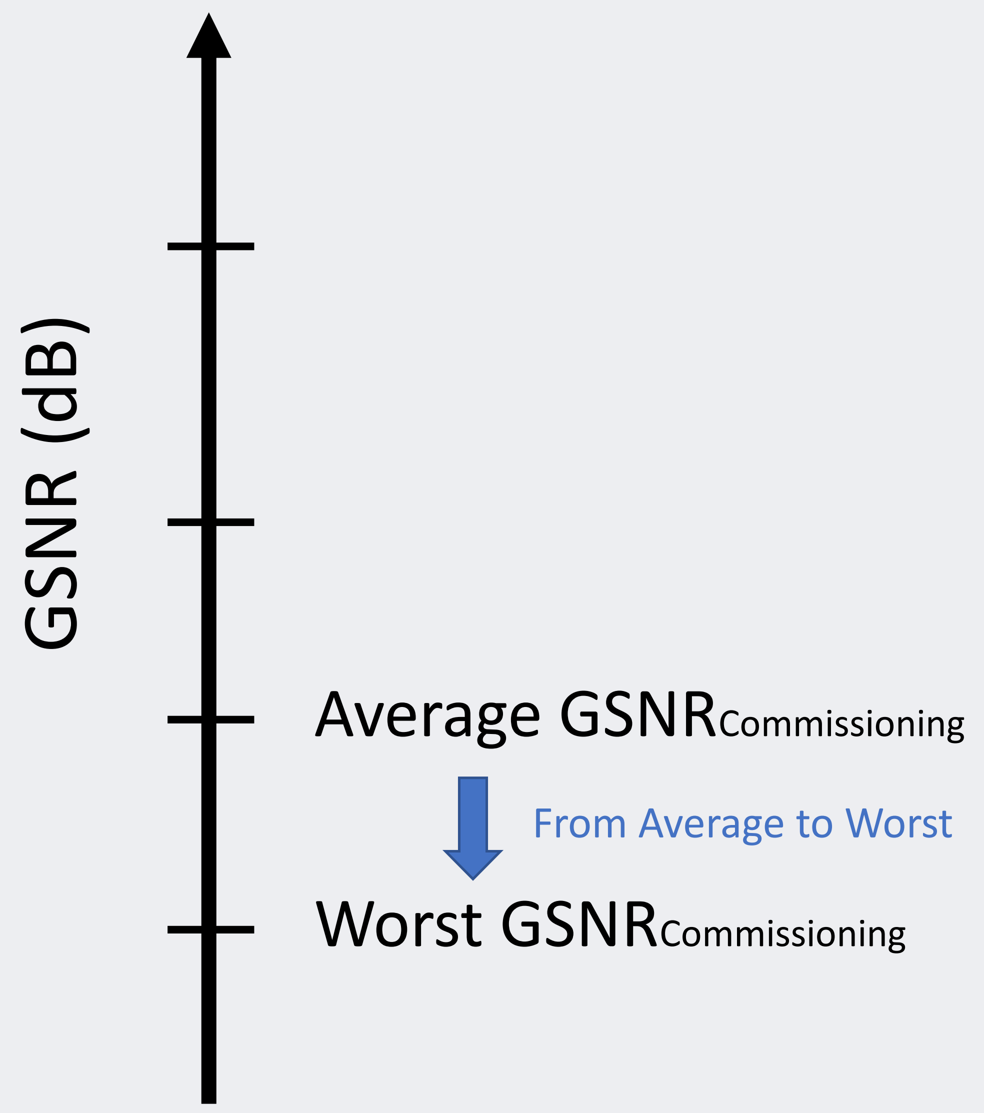
Average $\text{SNR}_{\text{Nominal}}$

Manufacturing Margins

Average $\text{SNR}_{\text{Commissioning}}$

From Average to Worst

Worst $\text{SNR}_{\text{Commissioning}}$

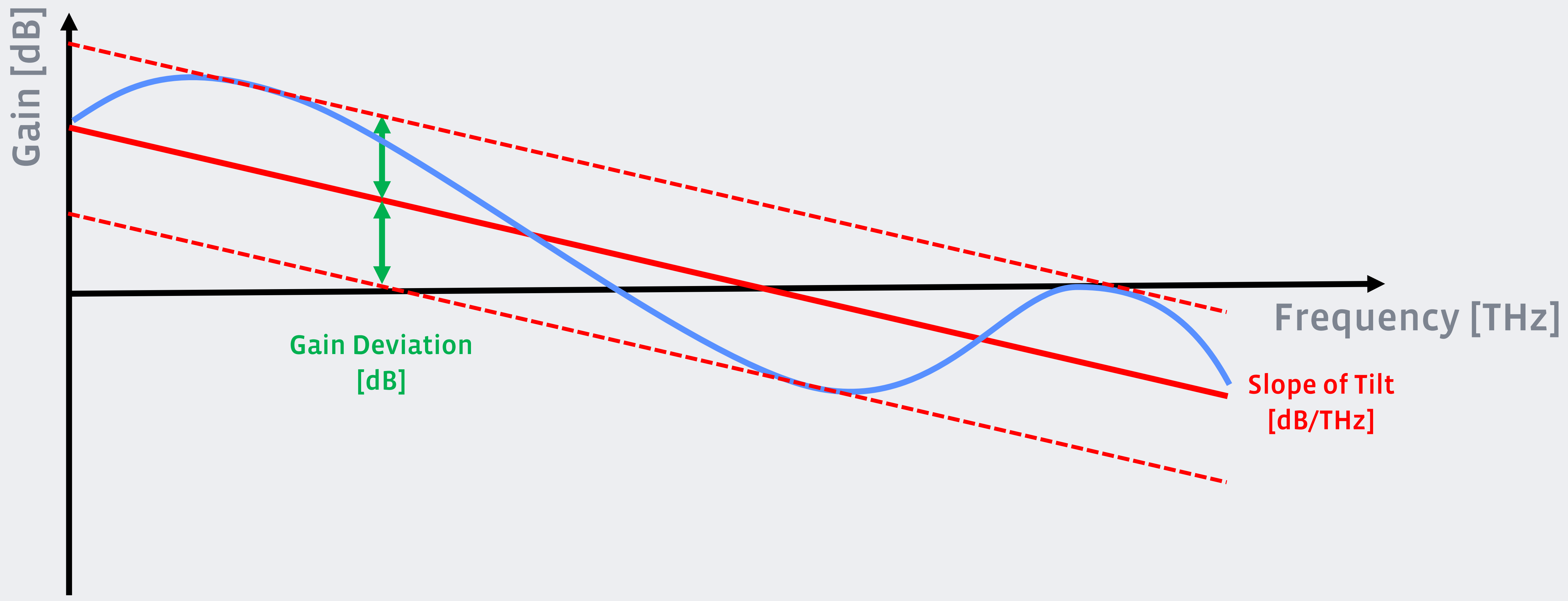


GSNR (dB)

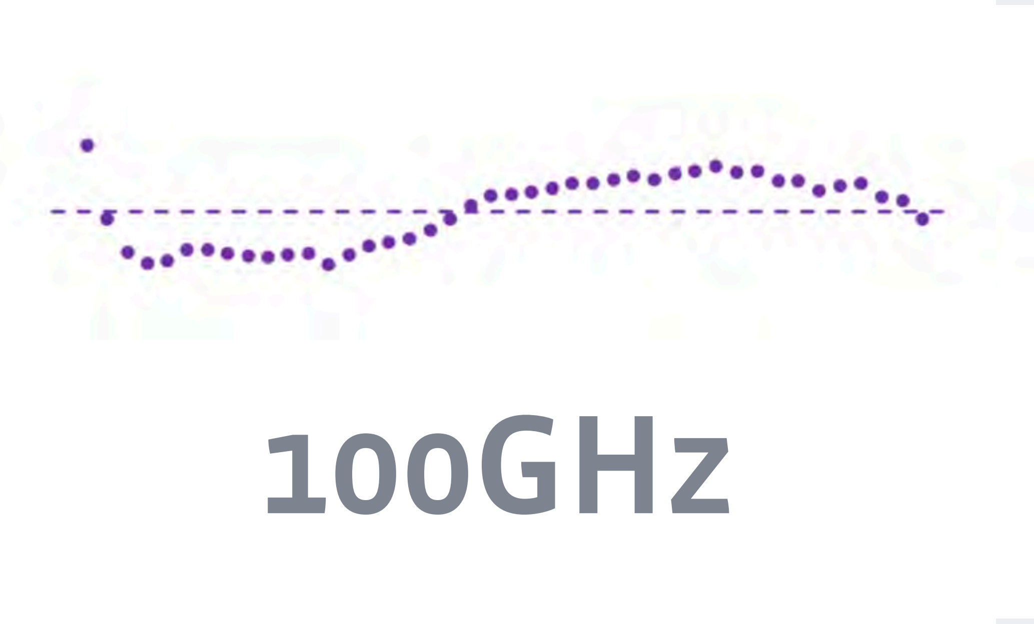
Average $\text{GSNR}_{\text{Commissioning}}$

From Average to Worst

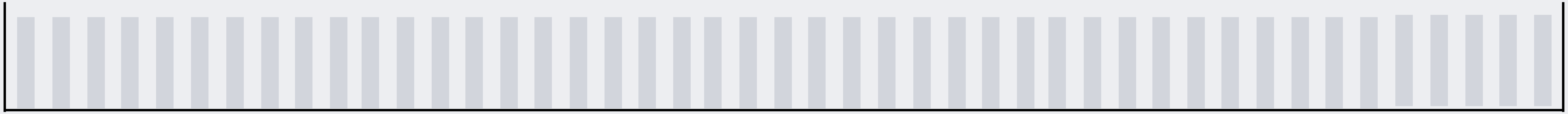
Worst $\text{GSNR}_{\text{Commissioning}}$

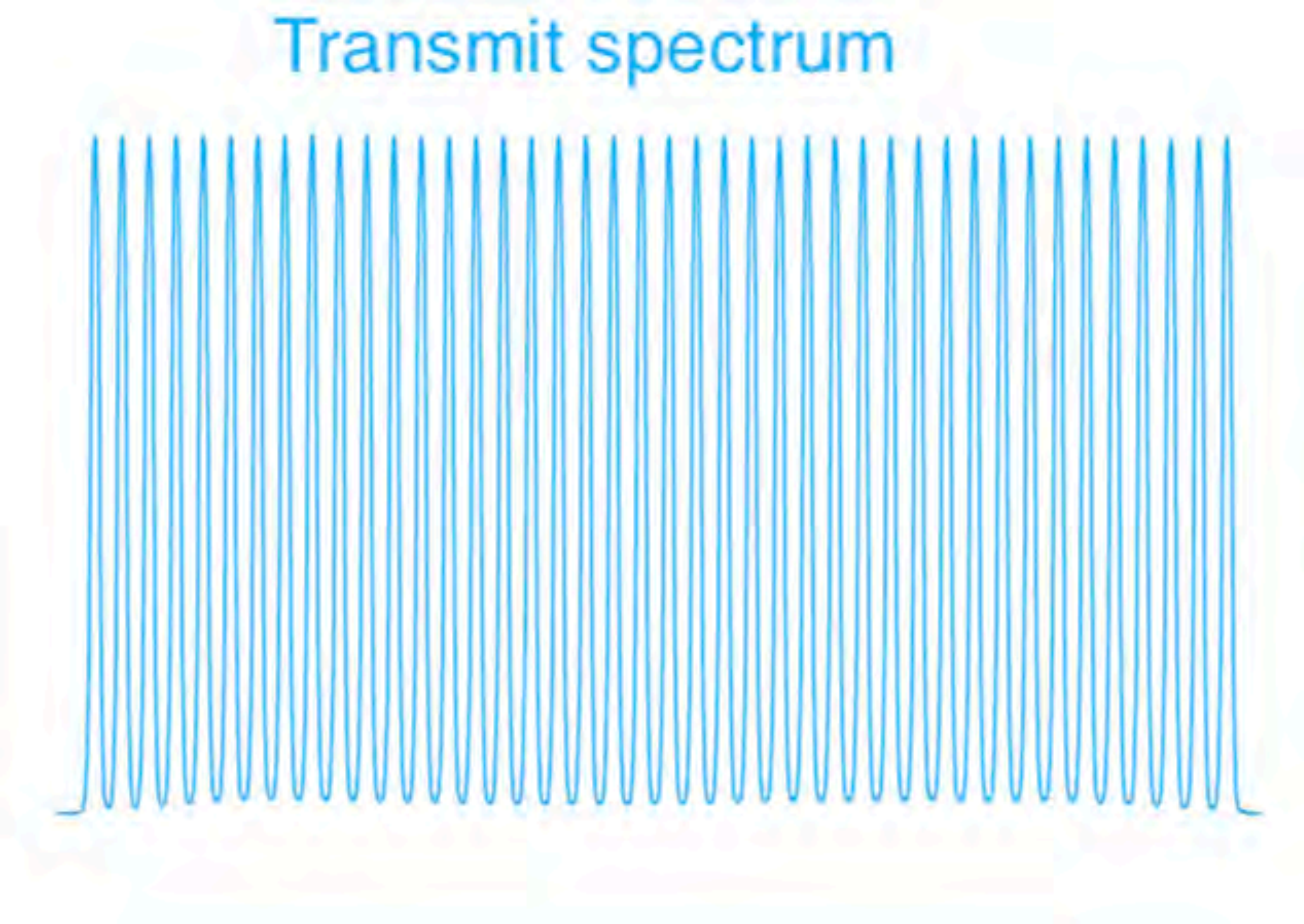


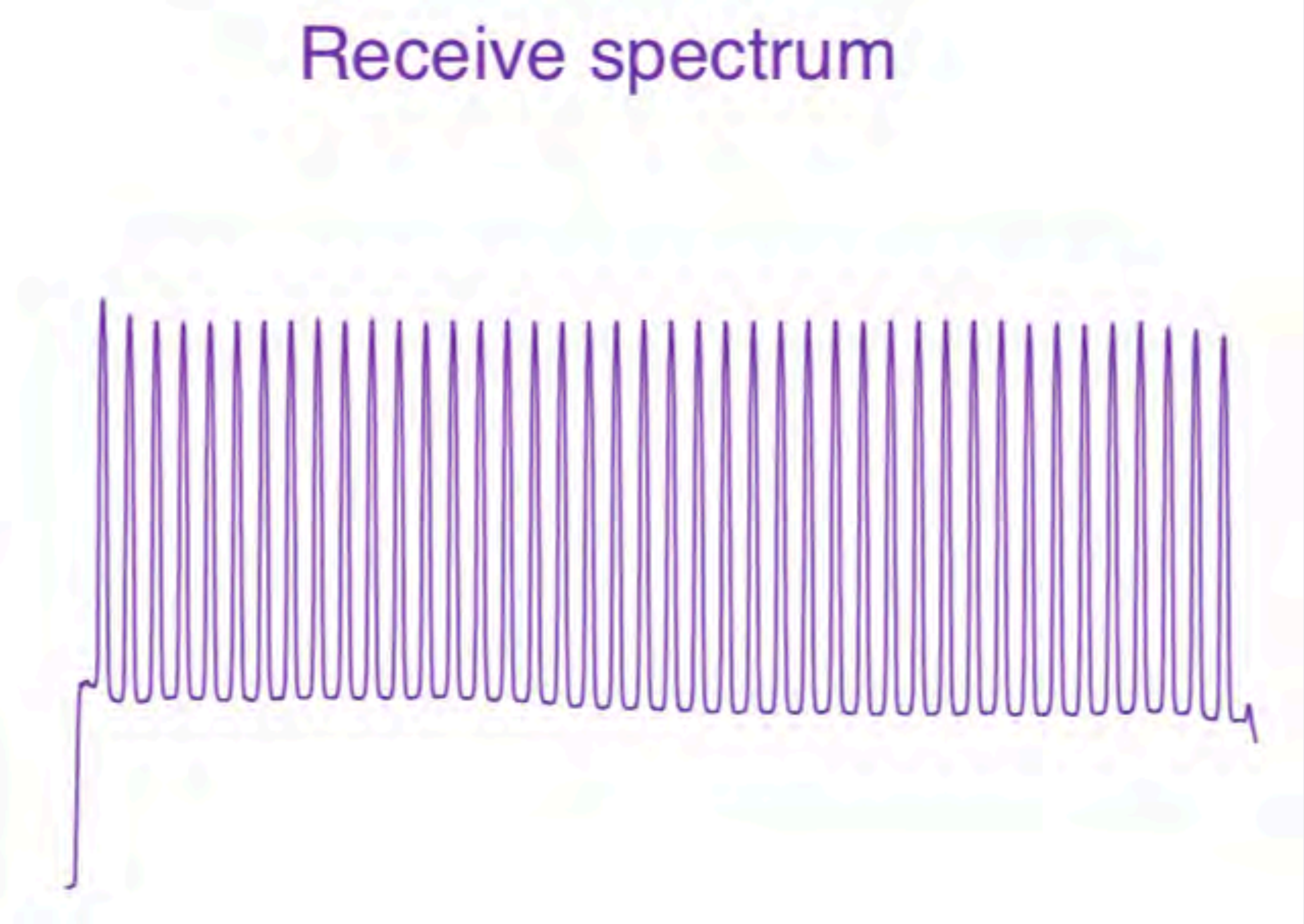
Measuring OSNR – ASE Comb Method



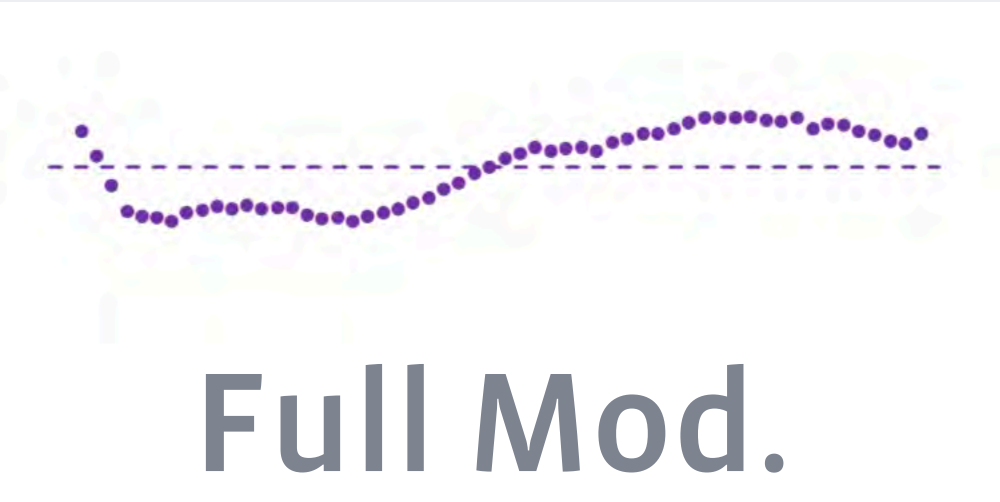
ASE Comb, 100GHz



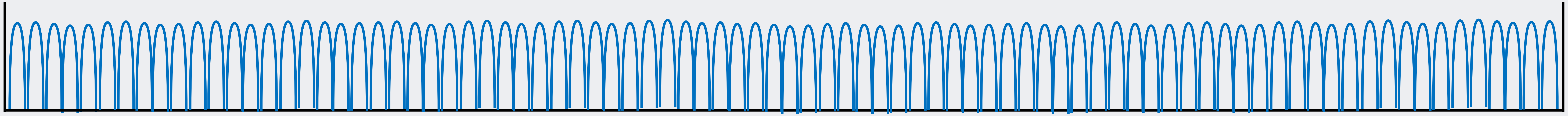




Measuring OSNR – Channel Plucking



Full spectrum of (mostly bulk) modulated channels

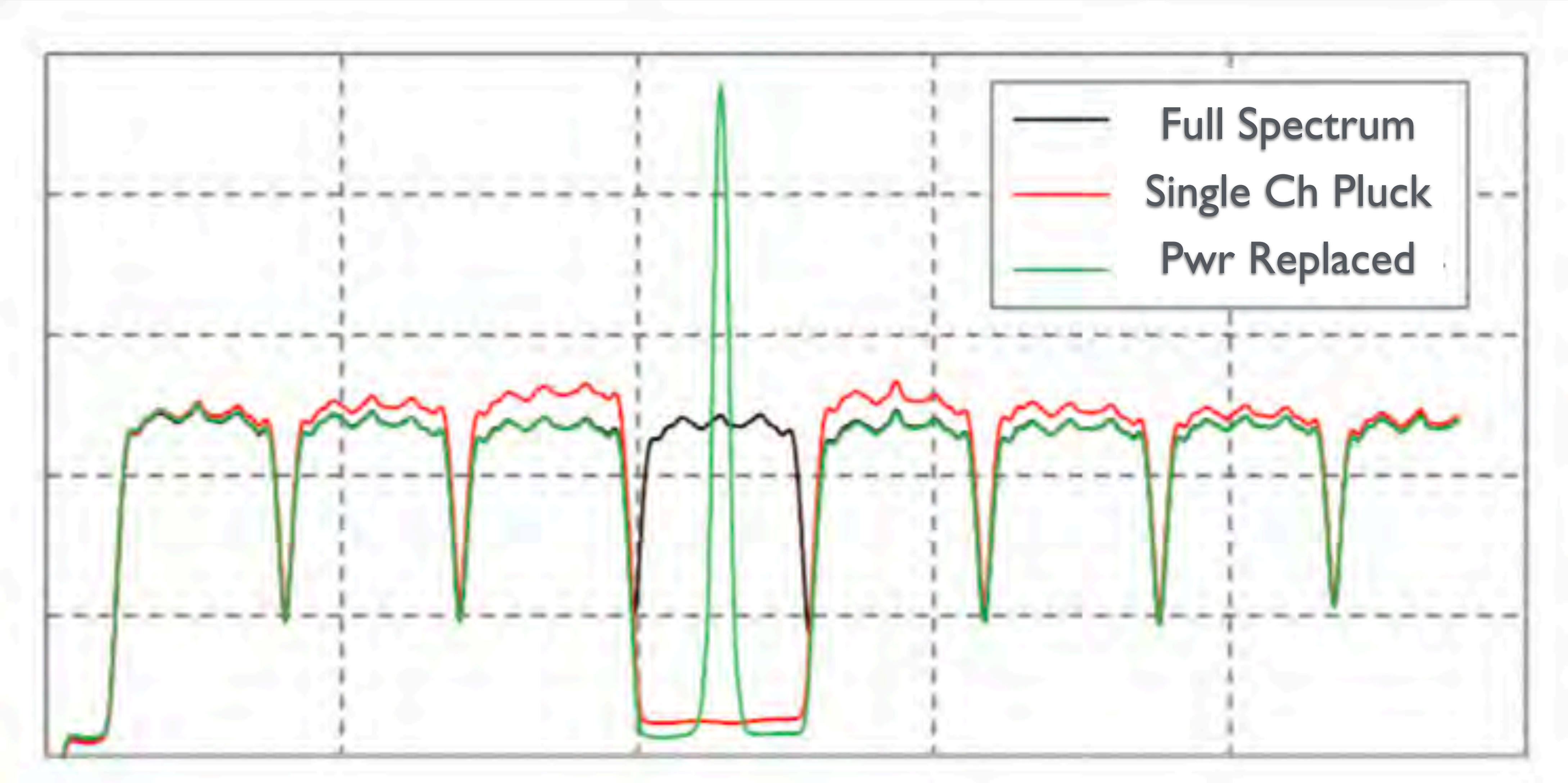


*Slope of tilt & gain deviation profile are also calculated from these Tx / Rx power profiles

Measuring OSNR – Channel Plucking

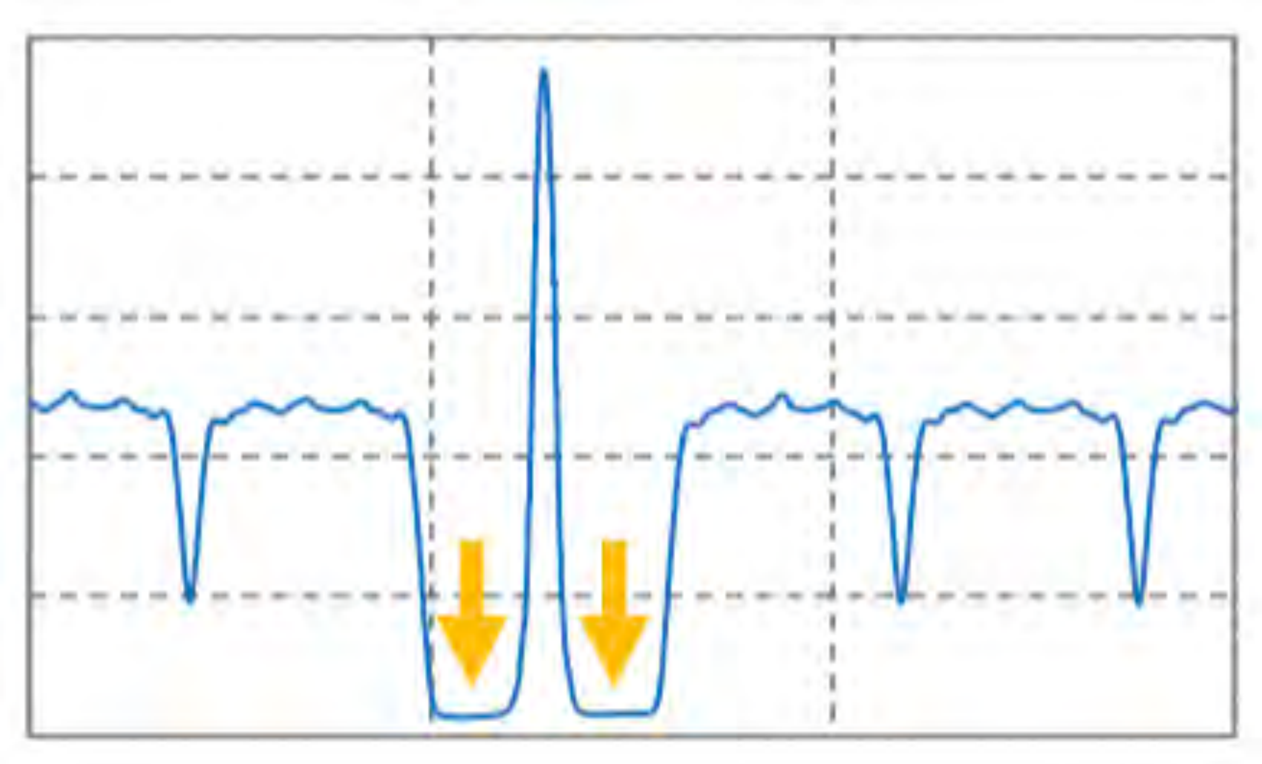
However, channel plucking can cause small localized gain distortions from SHB, and must be considered for an accurate measurement

Impact of Channel Plucking:

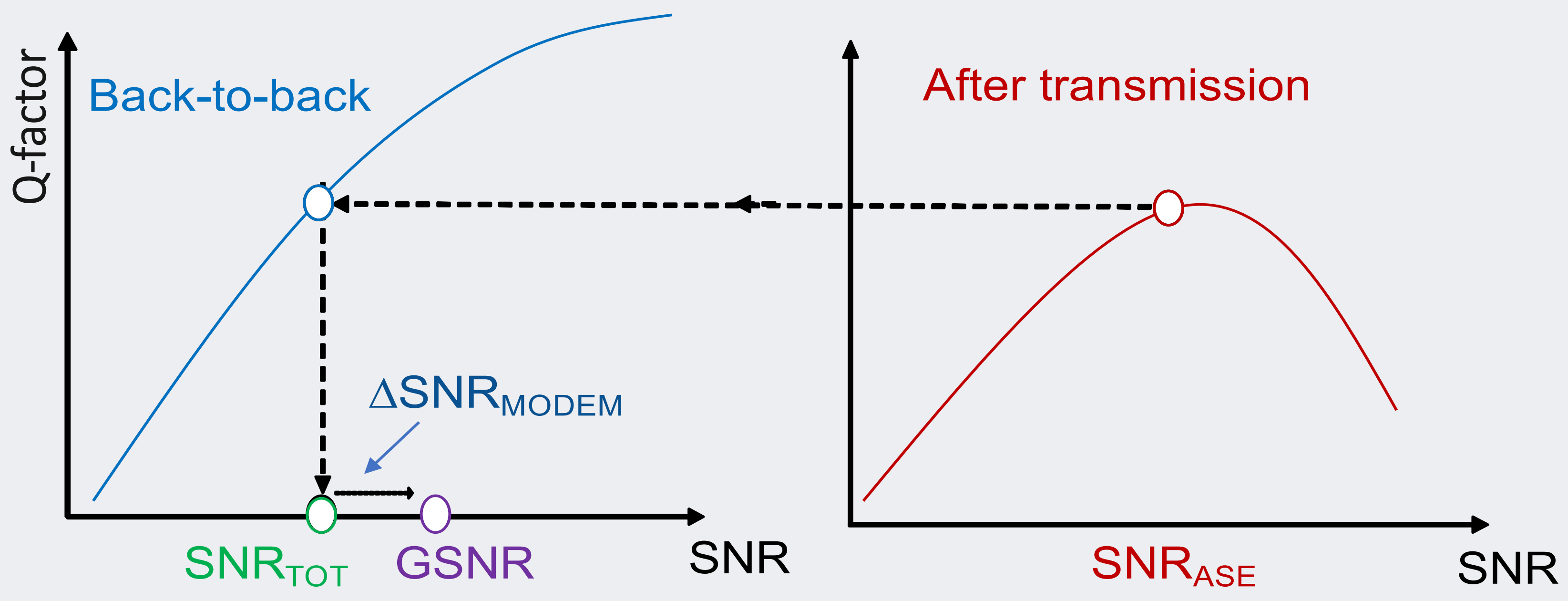


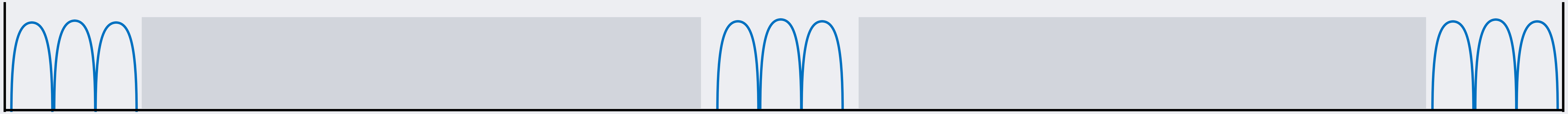
Signal Pwr Measurement

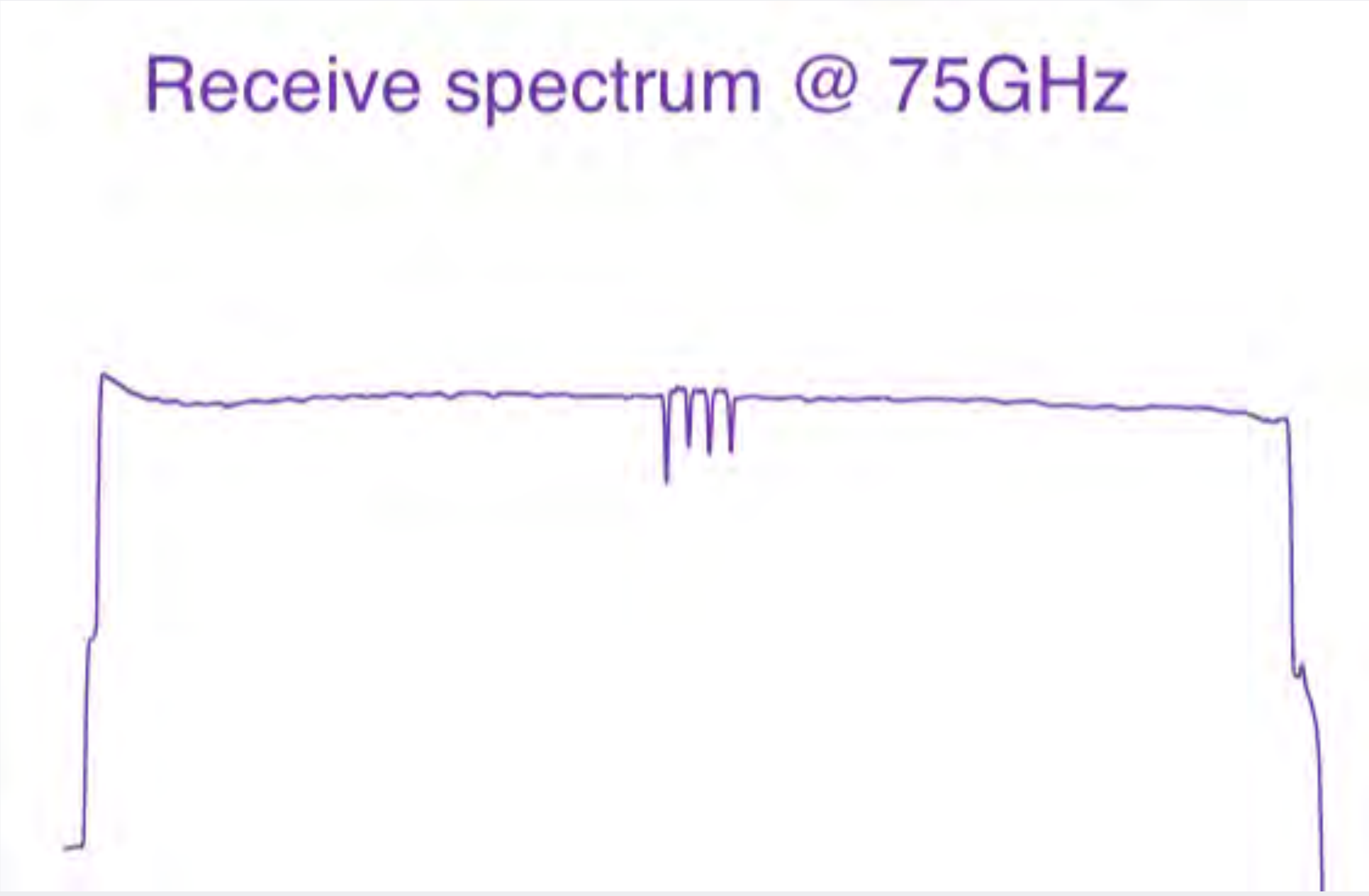
Noise Pwr Measurement



Measuring GOSNR

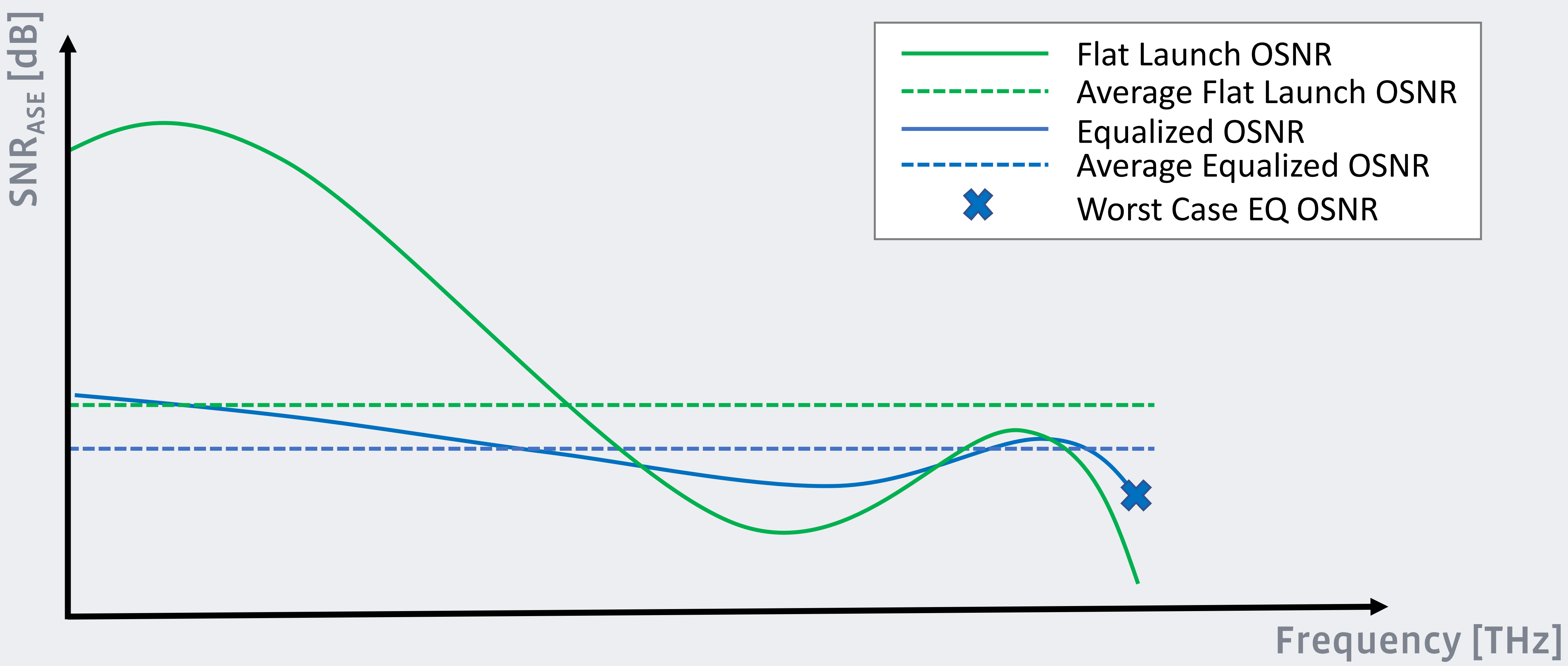


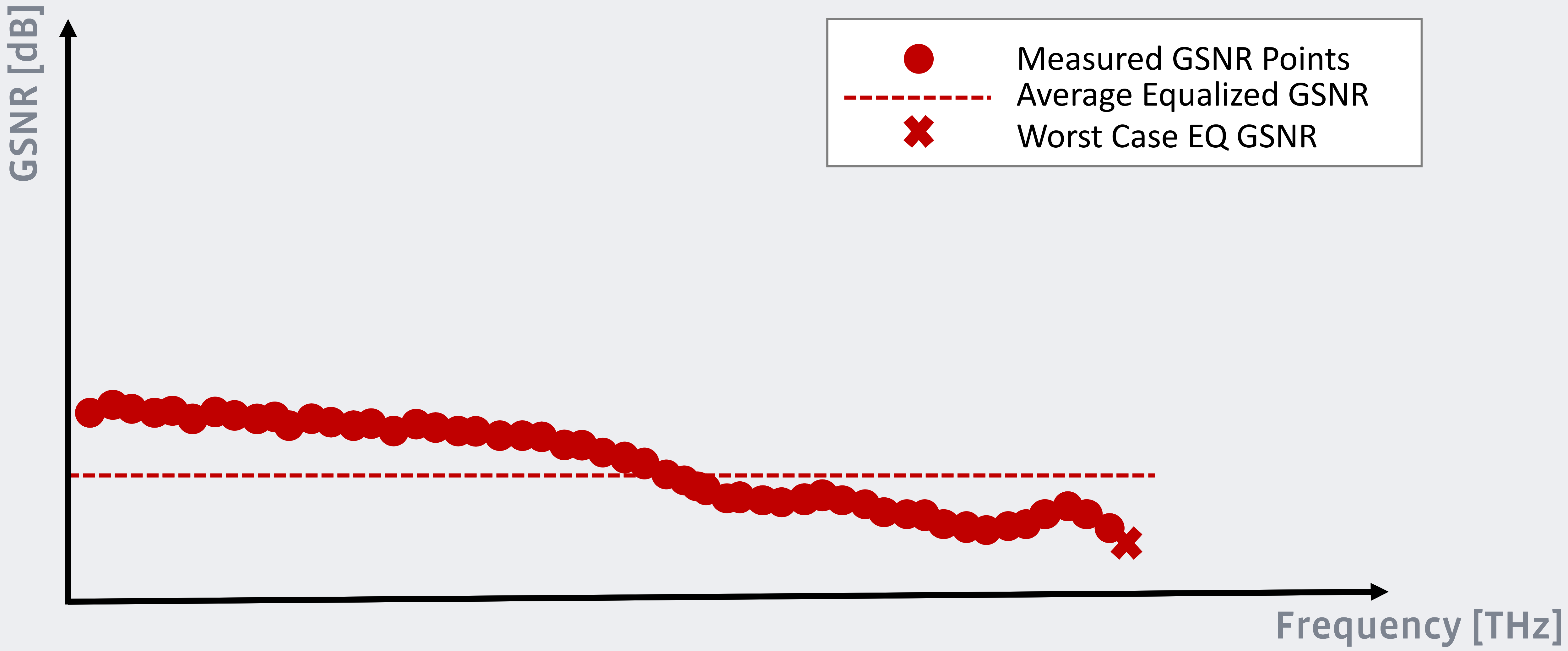




Commissioning Data Collected

- At System Commissioning, the true system performance, and all of its inherent frequency and pre-emphasis based dependencies can be characterized in detail.
- The collected data are highly valuable for detailed modeling of capacity for 3rd party SLTE
- The averages of this data can be used to compare against the Commissioning Parameters previously defined.



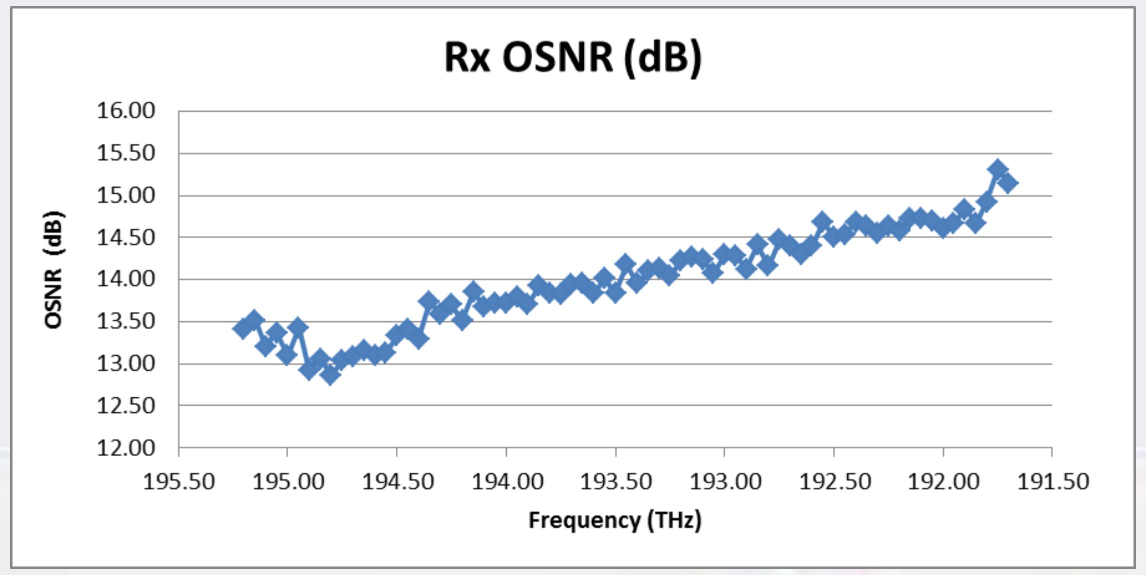


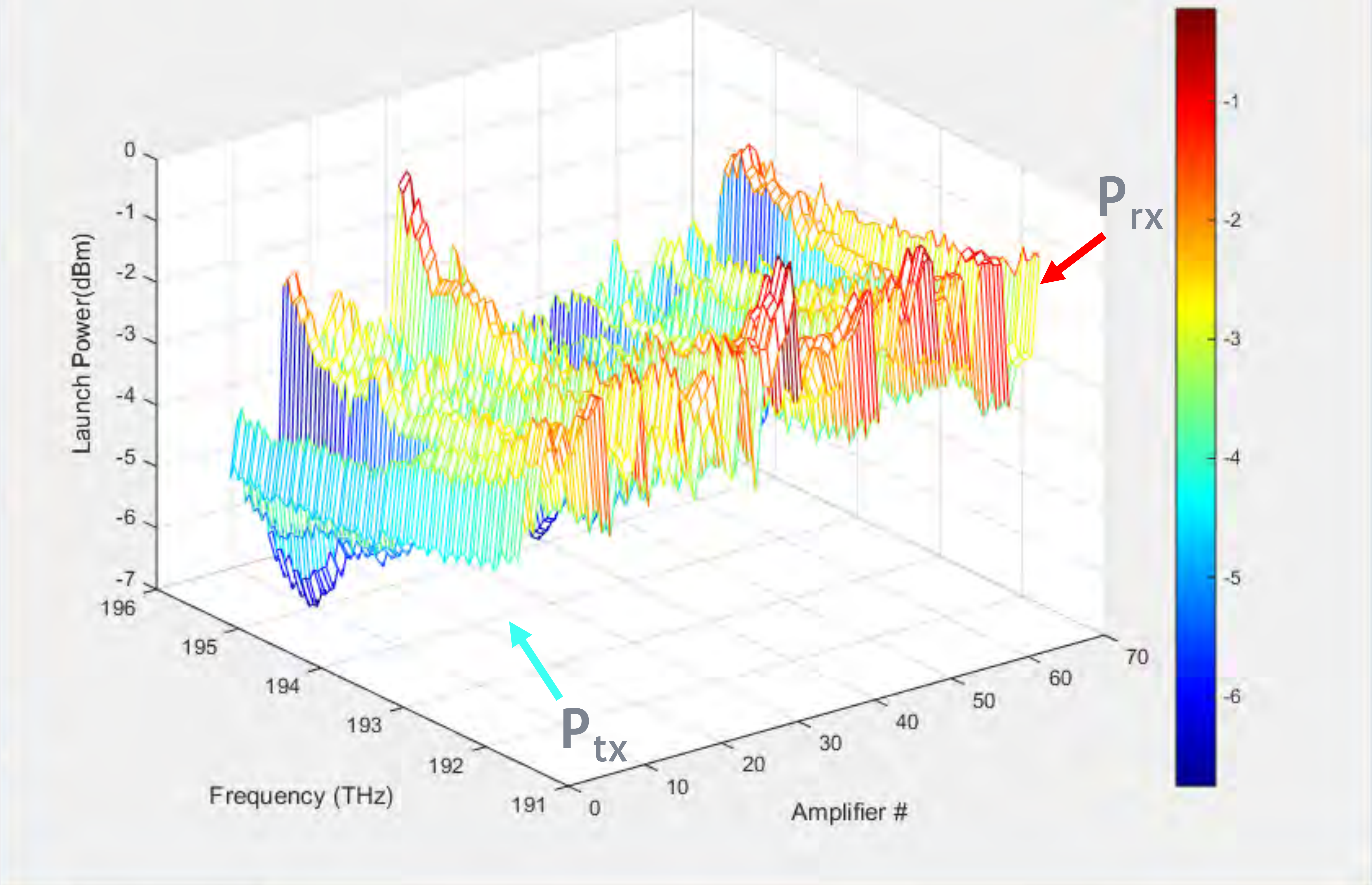
GSNR Testing can be time consuming, but as procedures become automated more data points can be collected!

What’s really going on in there?

- What we can see at the Tx and Rx of the Subsea “black box” is only an indication of what’s really going on through the 100’s of subsea spans

- OSNR and GOSNR profiles at the Rx give good **indications** of the hidden linear and nonlinear characteristics of the cable, and thus the capacity we can achieve

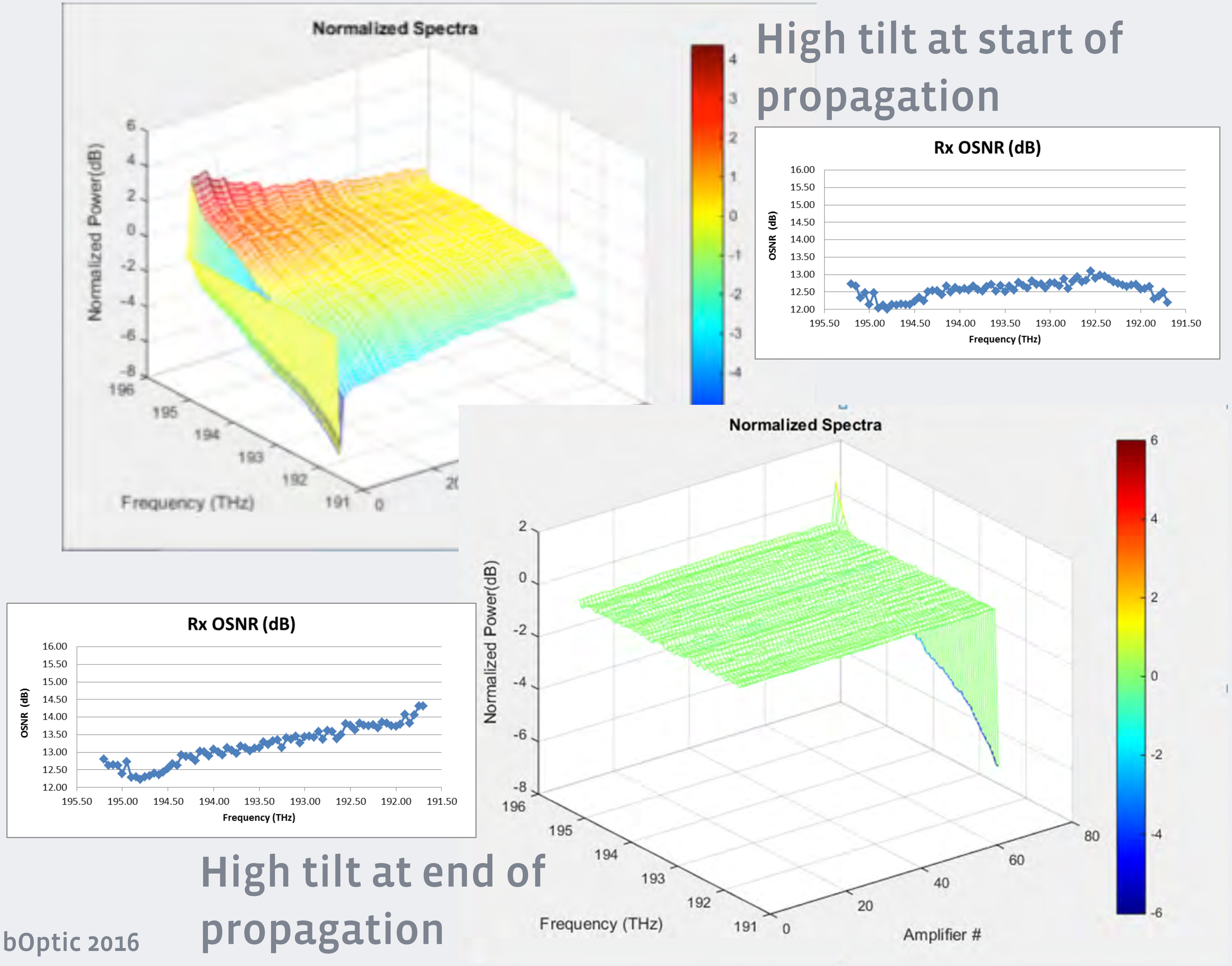




L.Berg et al., Wet Plant Tilt Correction, SubOptic 2016

What can we measure that’s useful?

- SNR profile of linear (OSNR) and nonlinear (GOSNR) noise better reflect the quality of the cable
- Tilt and gain excursions through propagation impact the linear SNR and the nonlinear SNR
- OSNR and GOSNR tilt and excursions, via a flat launch profile, give very good indications of the true conditions



High tilt at start of propagation

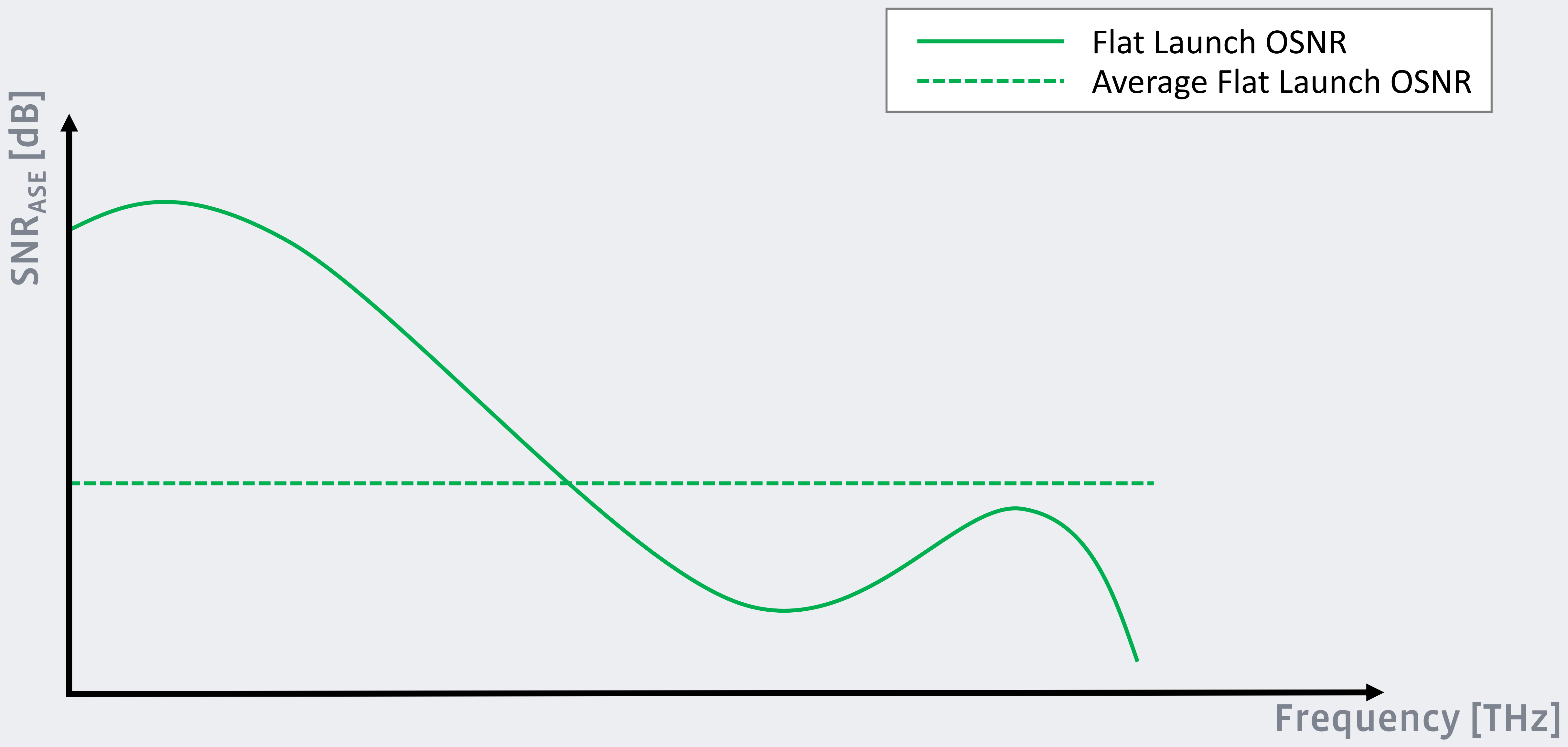
High tilt at end of propagation

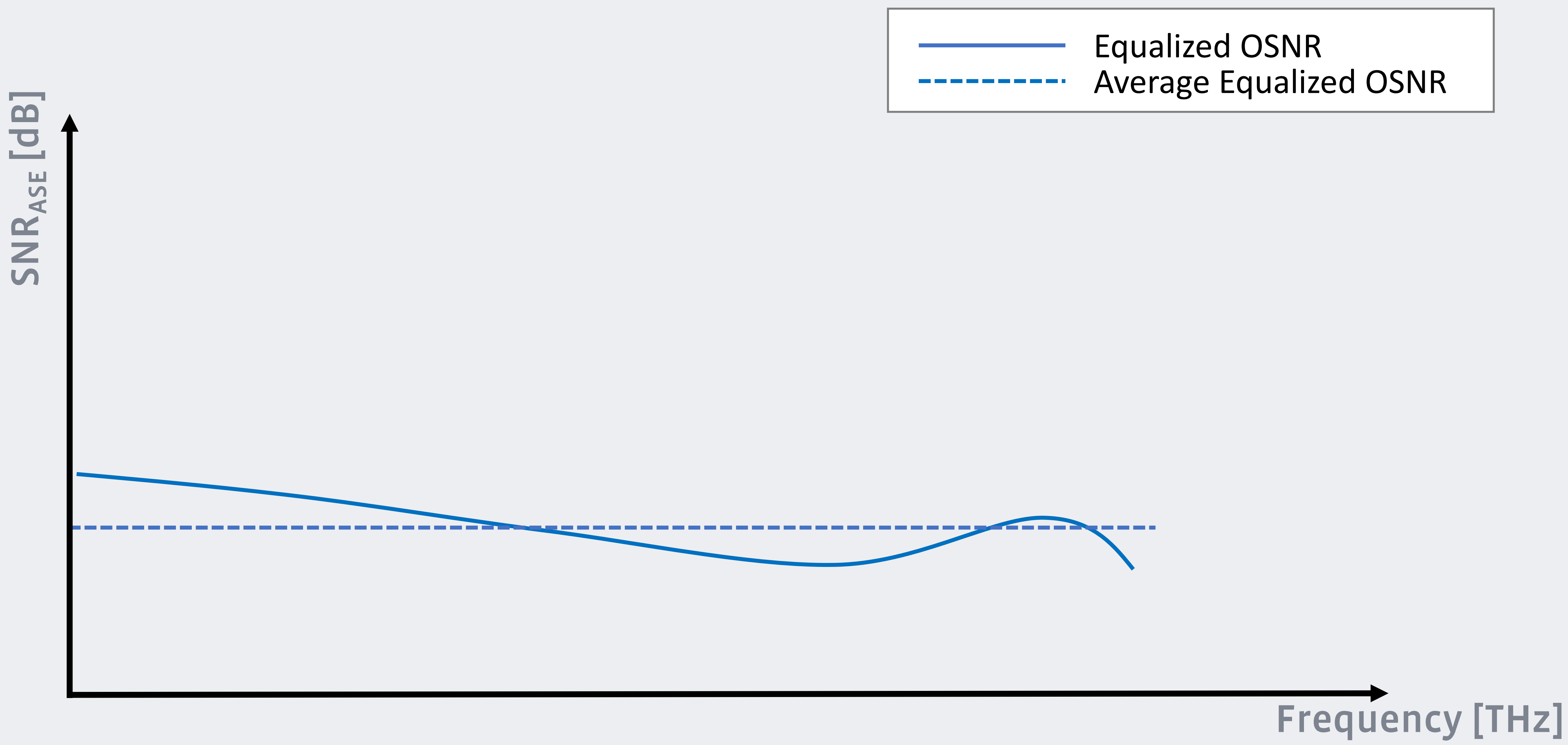
L.Berg et al., Wet Plant Tilt Correction, SubOptic 2016

Maximizing Subsea Capacity

Performance will always be variable across the spectrum of a given FP in a manner that **cannot be precisely known until system commissioning**, and will undoubtedly **change over time** due to repairs and aging

- Intersection with supported SLTE data rates changes with every SLTE generation, and every vendor (i.e. not all value from small SNR advantages can be extracted at all times)





So what's the best equalization strategy? Flat launch or Equalized? And what kind of Equalization?

Maximizing Subsea Capacity

Performance will always be variable across the spectrum of a given FP in a manner that **cannot be precisely known until system commissioning**, and will undoubtedly **change over time** due to repairs and aging

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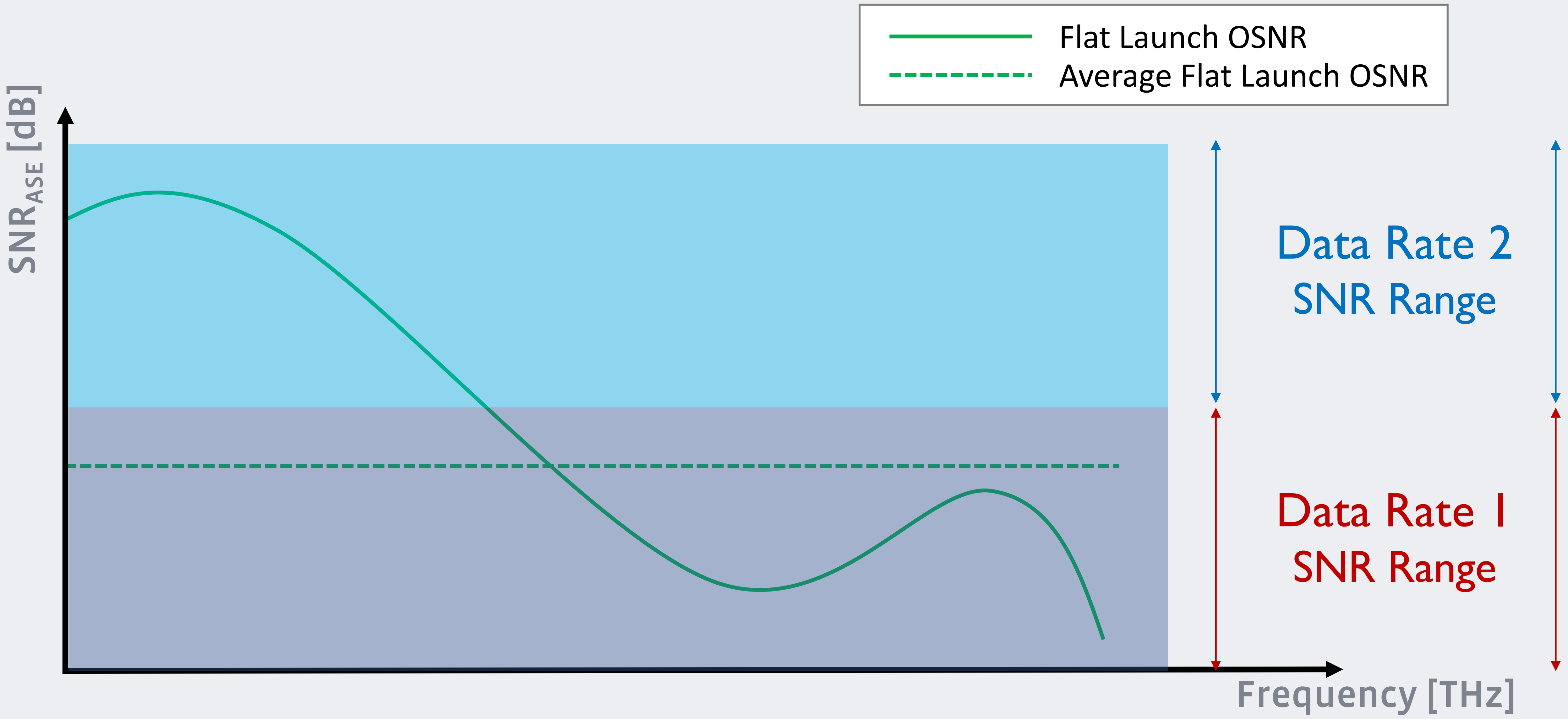

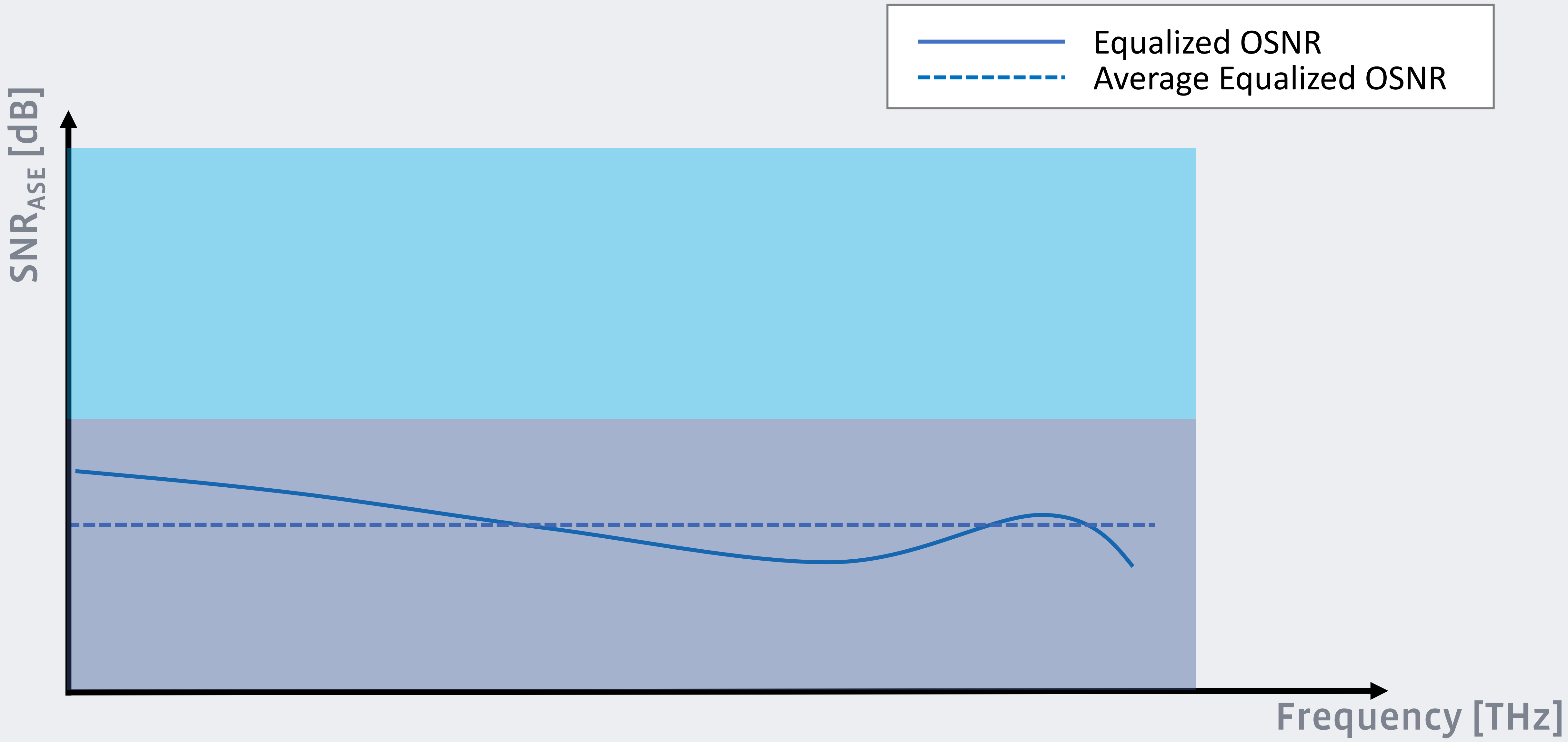

Maximizing Subsea Capacity

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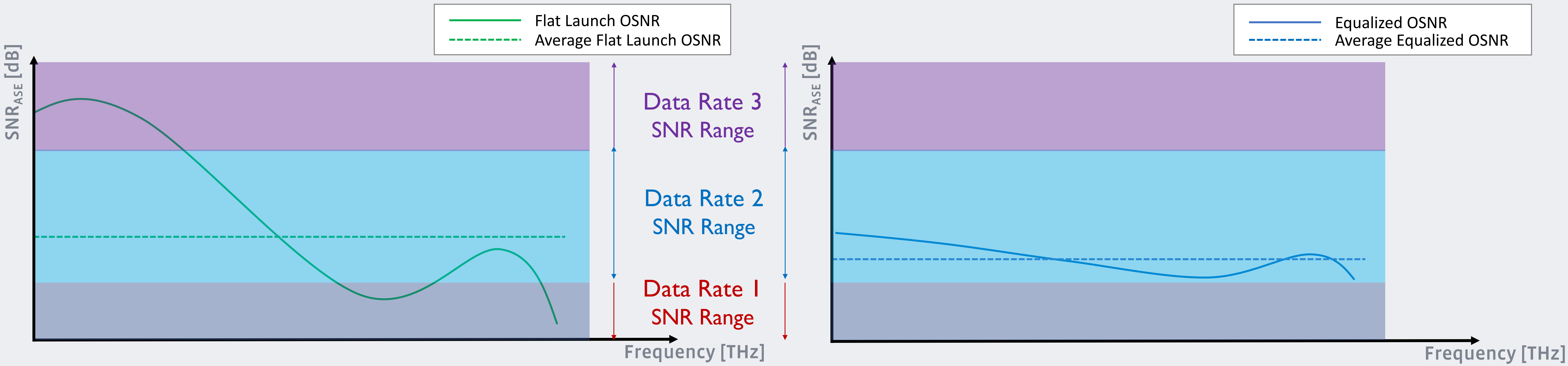


C&A on a Real Subsea Network

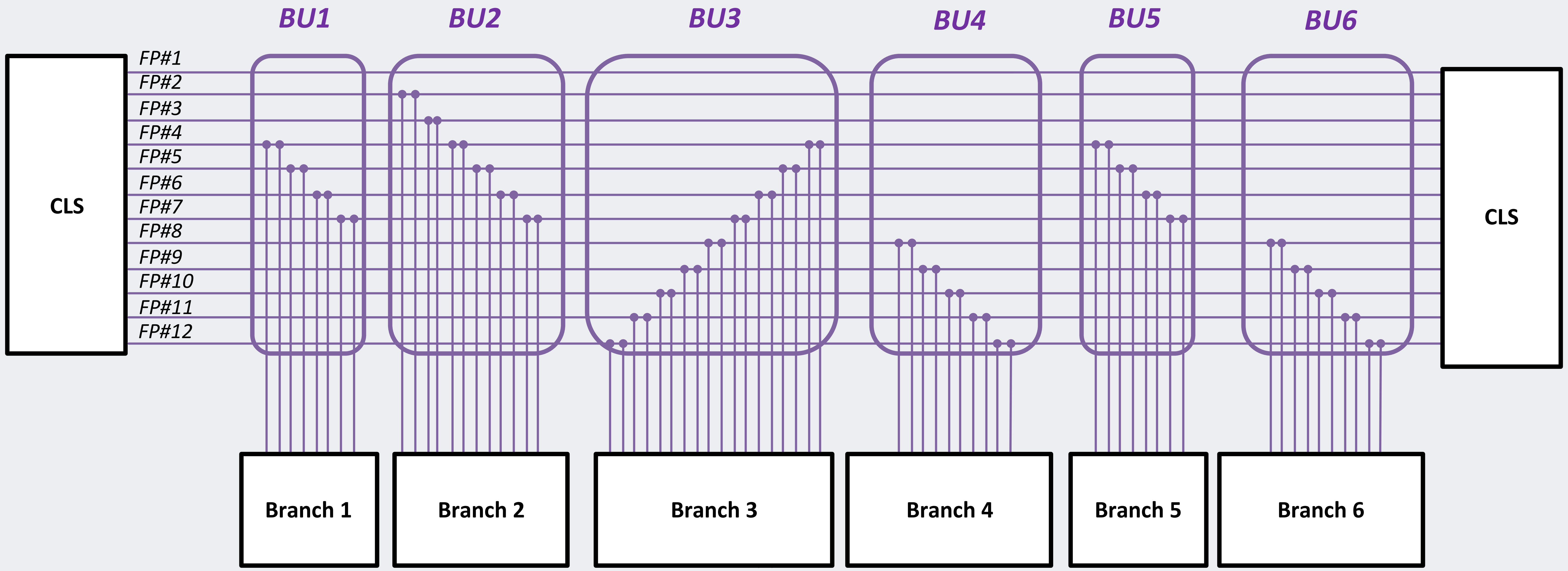
Our typical set of Commissioning Parameters:

1. Commissioning OSNR (average & worst case under Flat & EQ conditions)
   - Across 12 FPs, may take a day or two (with automation)
2. Commissioning GSNR (average & worst case, under Flat & EQ conditions)
   - Across 12 FPs, may take 1 week (with very good automation)
3. Slope of Tilt [dB/THz] & Gain Deviation [dB]
   - Comes for free with Test 1. 😉

C&A on a Really Complex Subsea Network

Our typical set of Commissioning Parameters (needs to be reduced to keep C&A reasonable):

1. Commissioning OSNR (average & worst case under Flat & EQ conditions)
   - Always test this everywhere. Equalized testing only on trunk FPs.
2. Commissioning GSNR (average & worst case, under Flat & EQ conditions)
   - Tested on trunk path only, all 12 FPs.
3. Slope of Tilt [dB/THz] & Gain Deviation [dB]
   - Still free with Test 1. 😉



Future Evolution

Where Do We Go From Here?

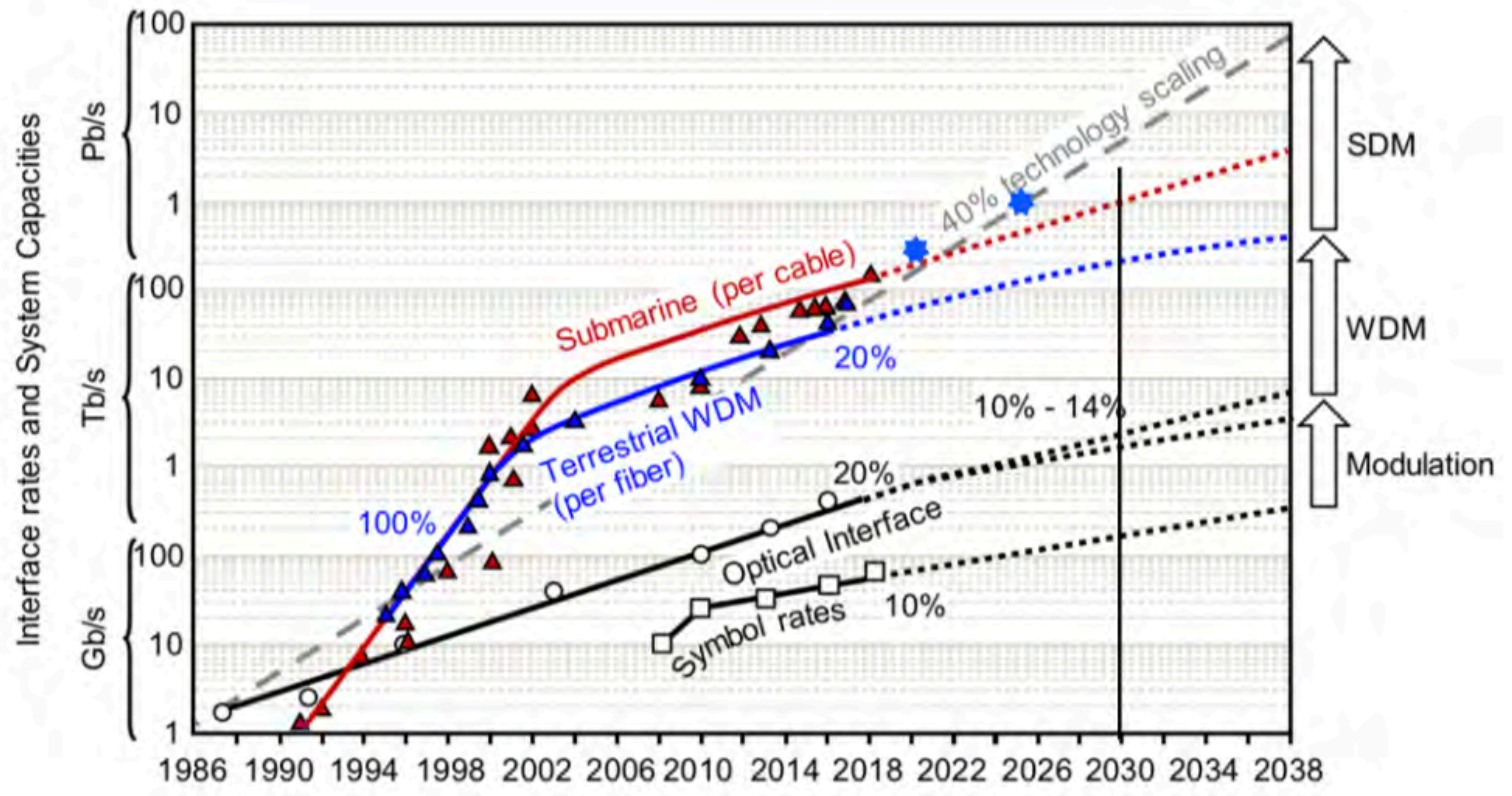
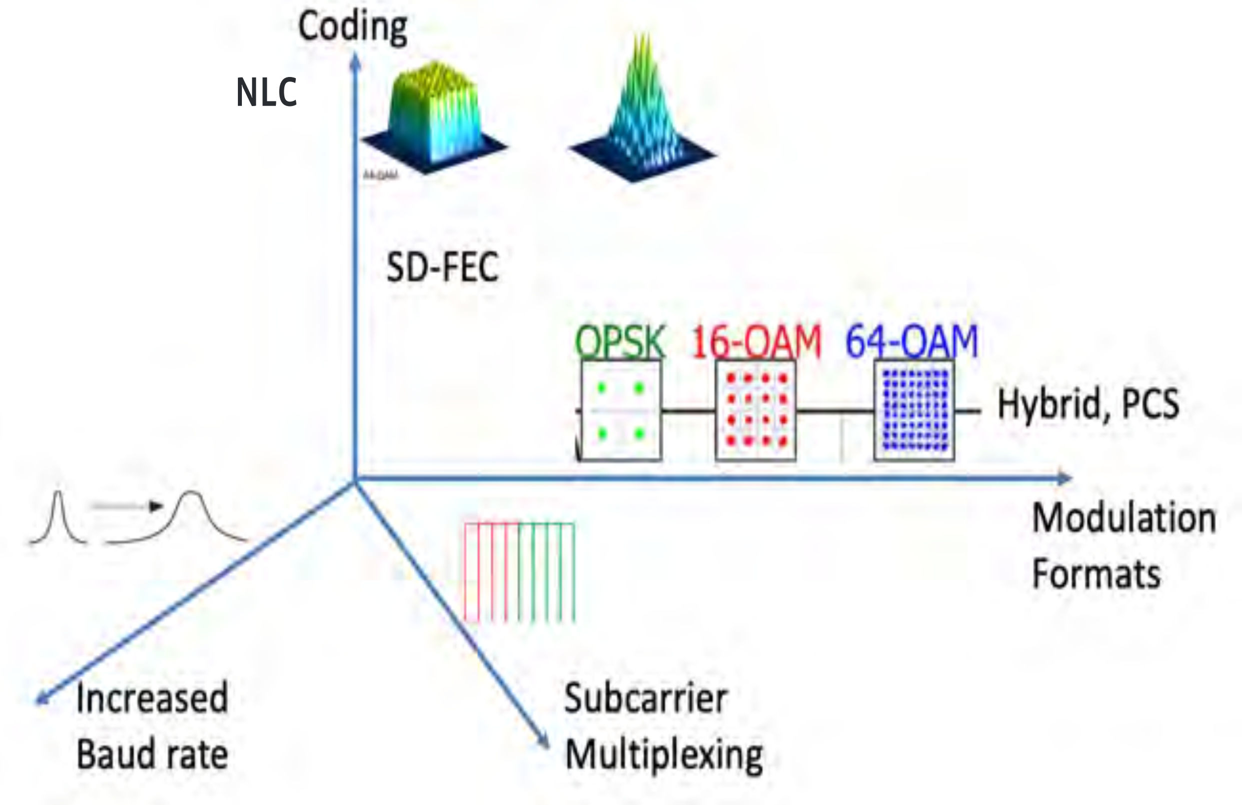


Figure 1: Evolution of commercial optical transmission systems over the past 30 years and extrapolations for the coming 20 years (after [1]).

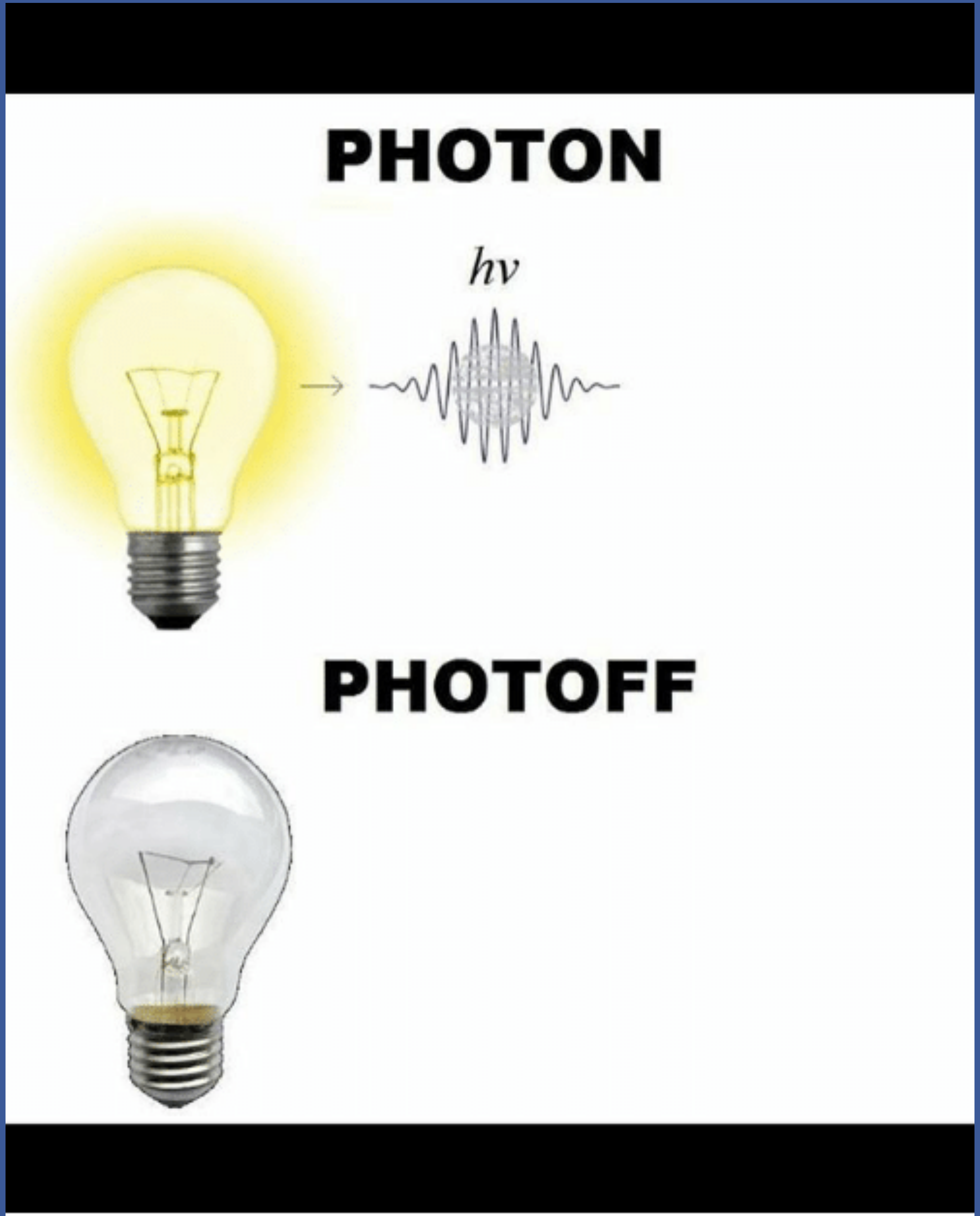
After P.Winzer et al

Shannon Capacity:

$C = 2*B*\log_2(1+SNR)$

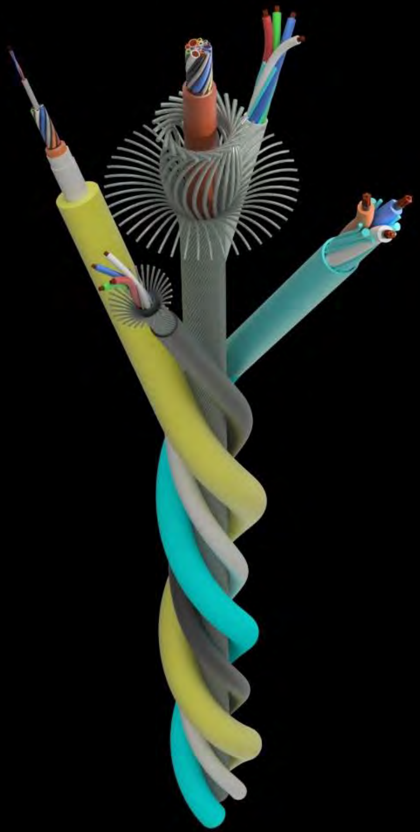


Where Do WE Go From Here?



#badsciencejokes

SUBSEA HYBRID ENERGY CABLES

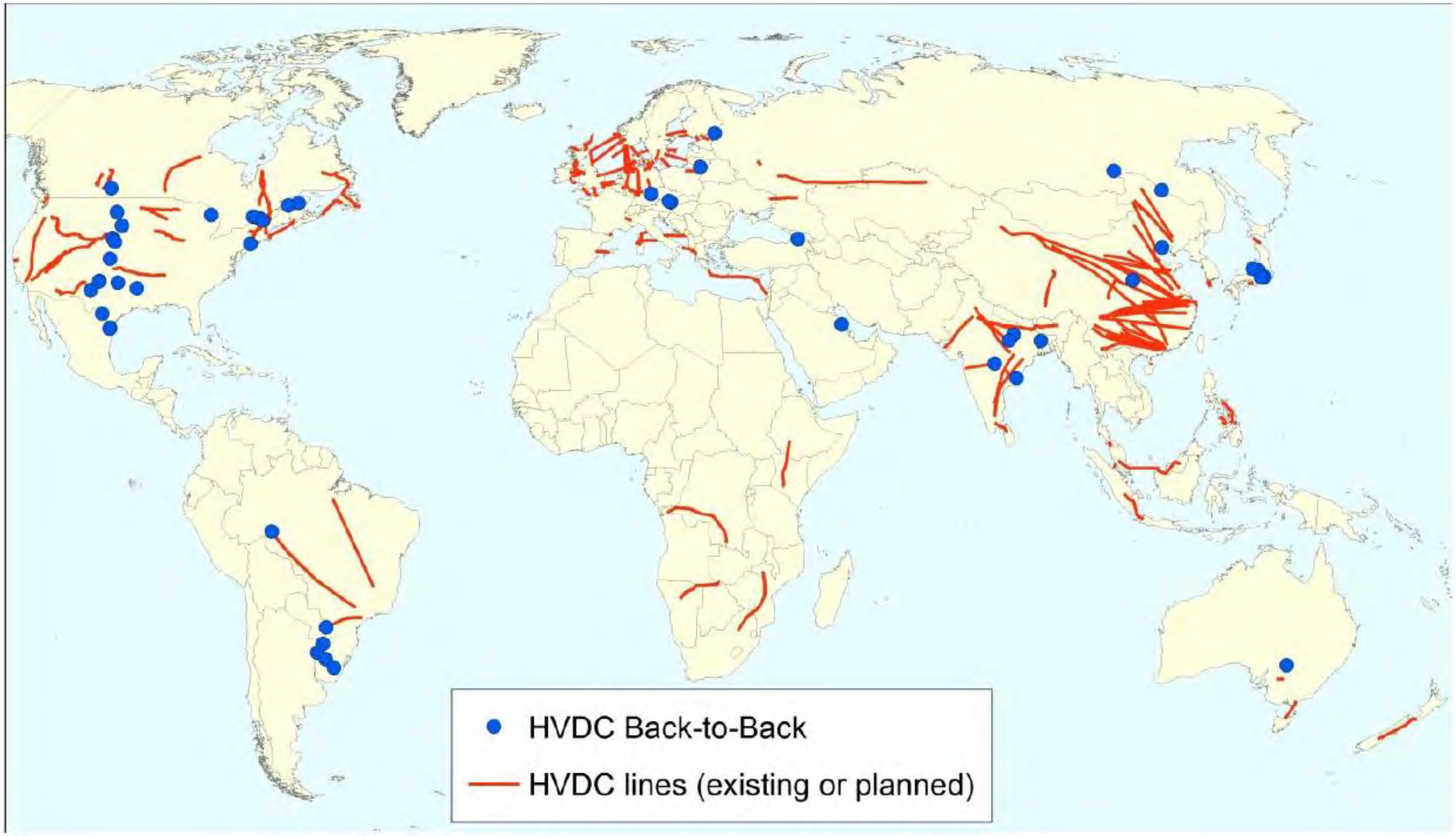


Nexans
BRINGS ENERGY TO LIFE

Content

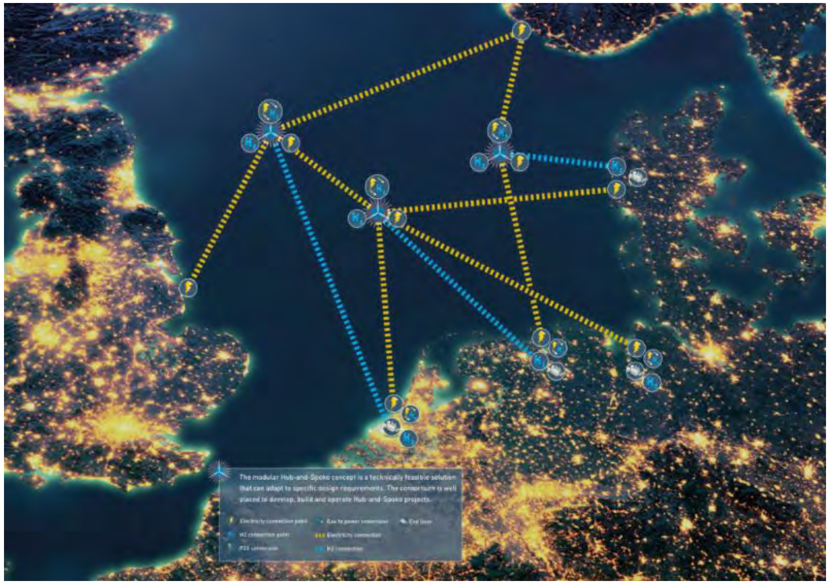
- In perspective
- Application & design
- The role of fibre optics

Towards a global power super grid?



Source: Ardelean, M., Minnebo, P., A China-EU electricity transmission link. (2017)

«Baby» super grids to harvest intermittent renewable energy sources

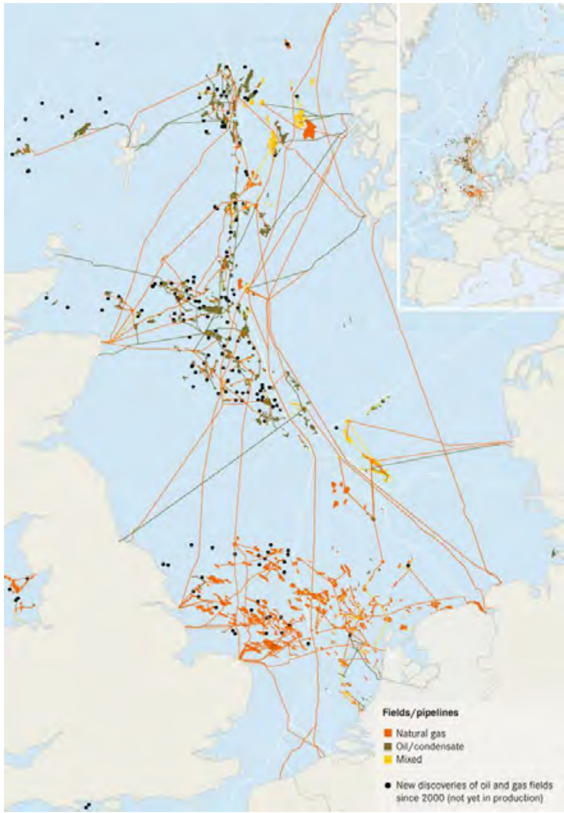


The modular Hub-and-Spoke concept is a technically feasible solution that can adapt to specific design requirements. The consortium is well placed to develop, build and operate Hub-and-Spoke projects.

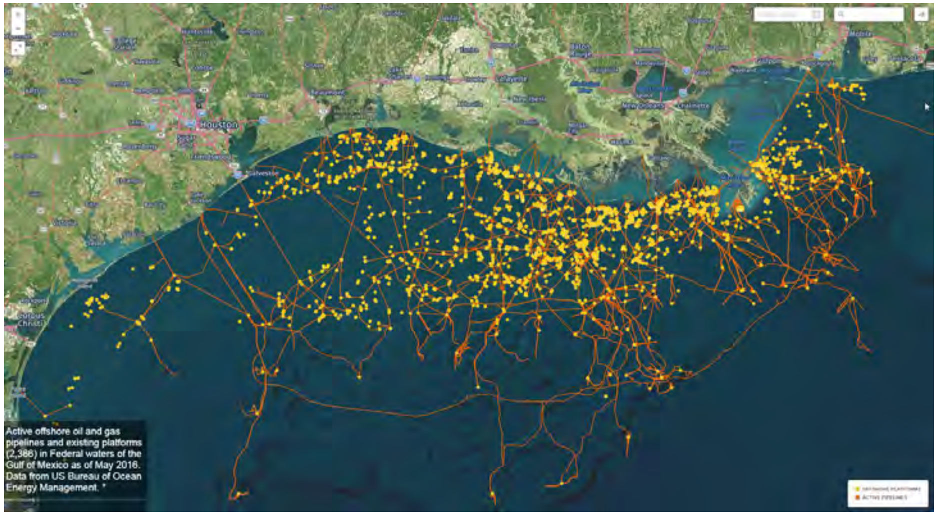
Source: https://northseawindpowerhub.eu

Offshore oil & gas in decline?

The North Sea



The Gulf of Mexico



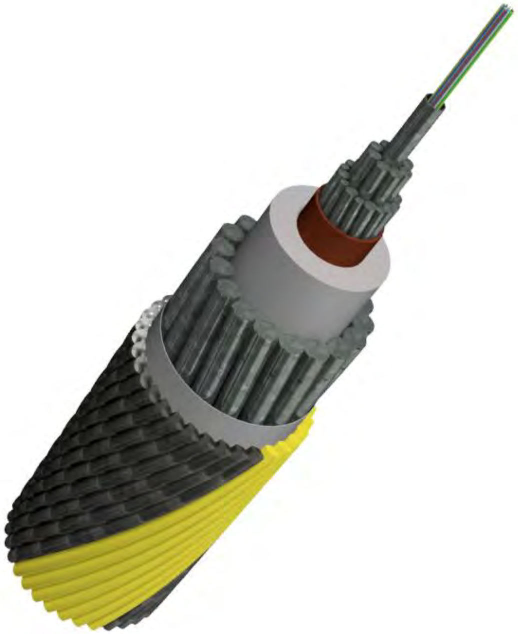
Active offshore oil and gas pipelines and existing platforms (2,386) in Federal waters of the Gulf of Mexico as of May 2016. Data from US Bureau of Ocean Energy Management. "

The busy life of an oil & gas field

Source: AkerSolutions

applications & designs

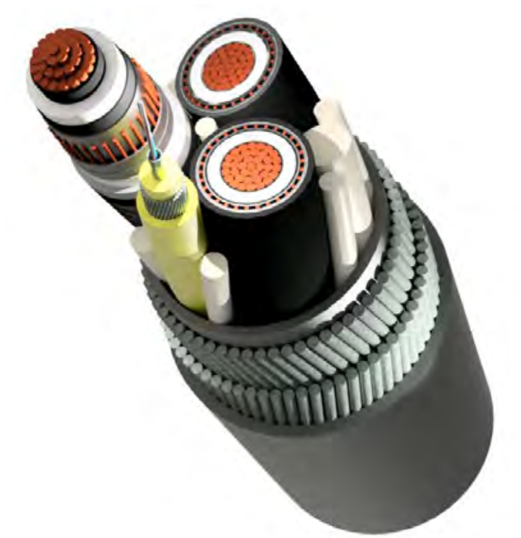
The ingenious design of subsea fibre optic cables



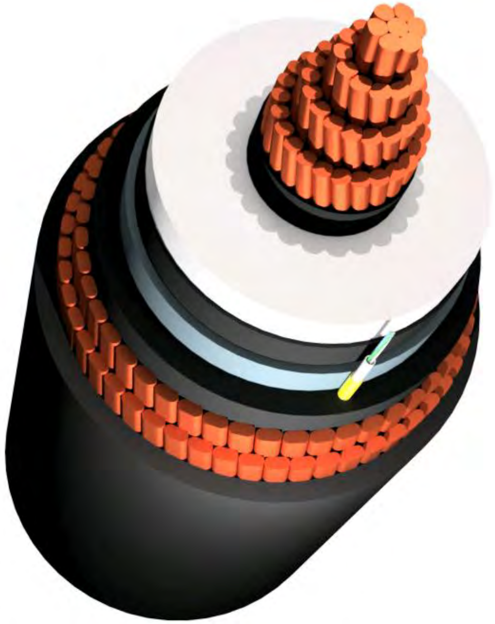
ROC-2

URC-1

Power cables w/ integrated fibre optics



HVAC



HVDC

The tallest building in Norway – for extrusion of power core insulation (!)

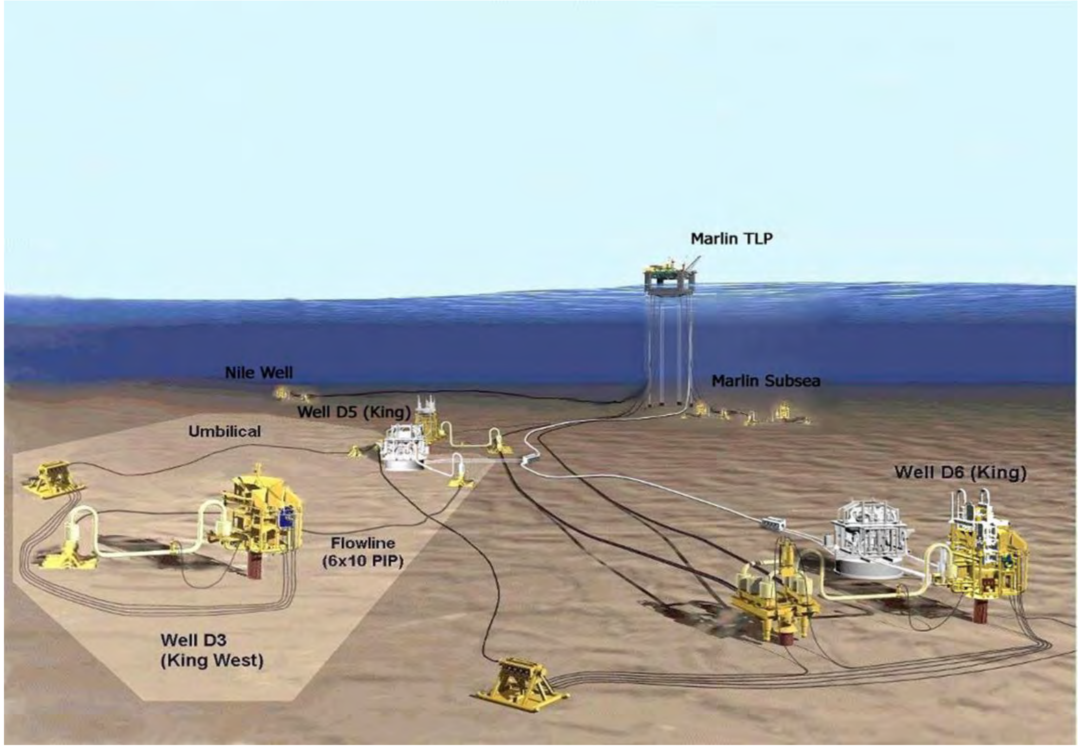
Specialized subsea cables w/ integrated fibre optics

ROV lifting umbilical

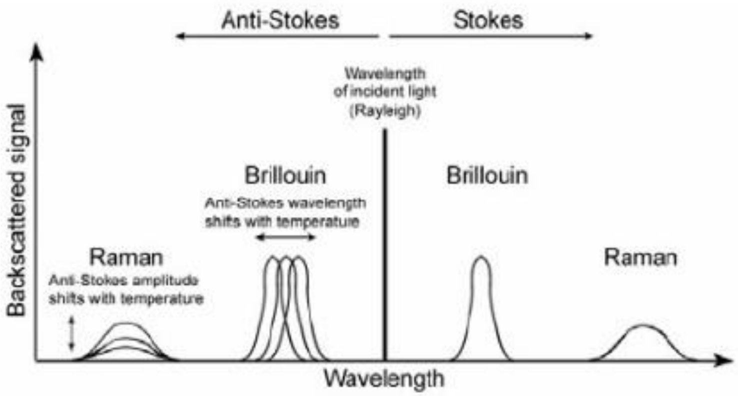
ROV launch and recovery system

Specialized subsea cables w/ integrated fibre optics

Control umbilical

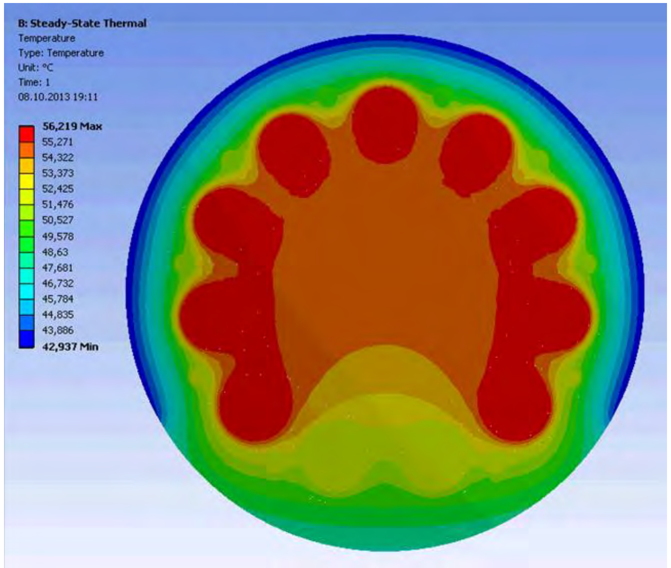


the role of fibre optics



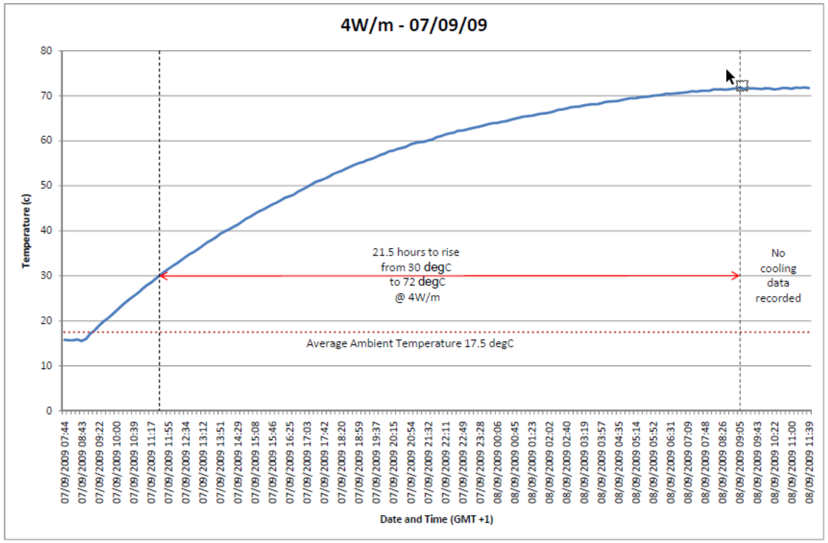
«The heat source»

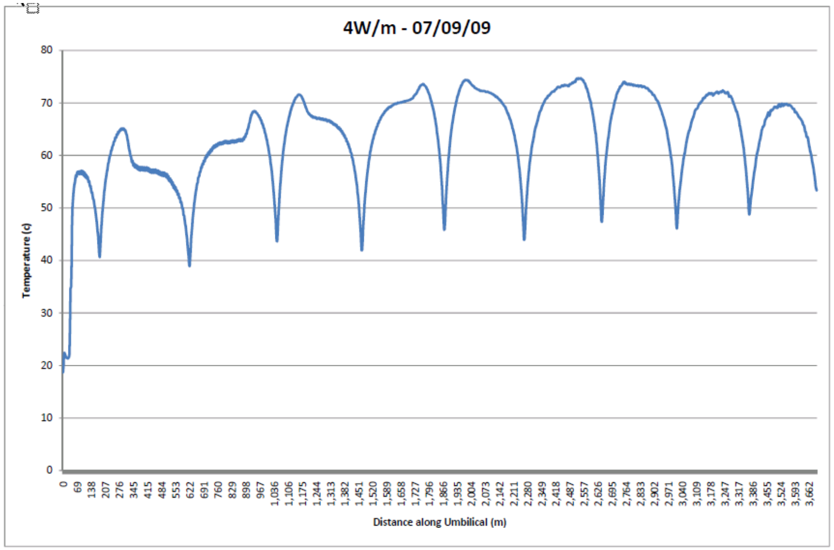
Resistance to electrical current induce heat



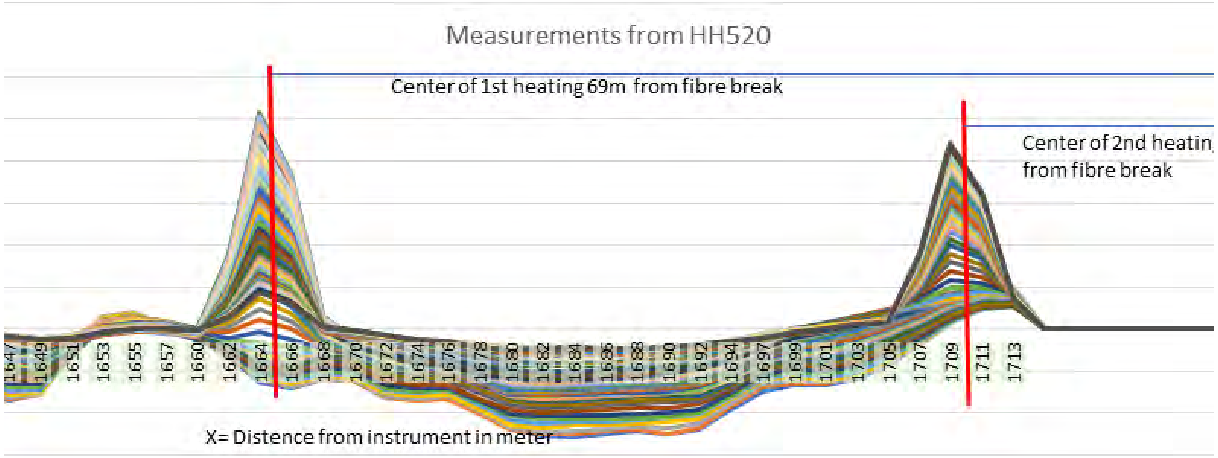
Temperature rise dependent on material thermal conductivity and surface heat dissipation.

Temperature sensing – System learning & optimisation

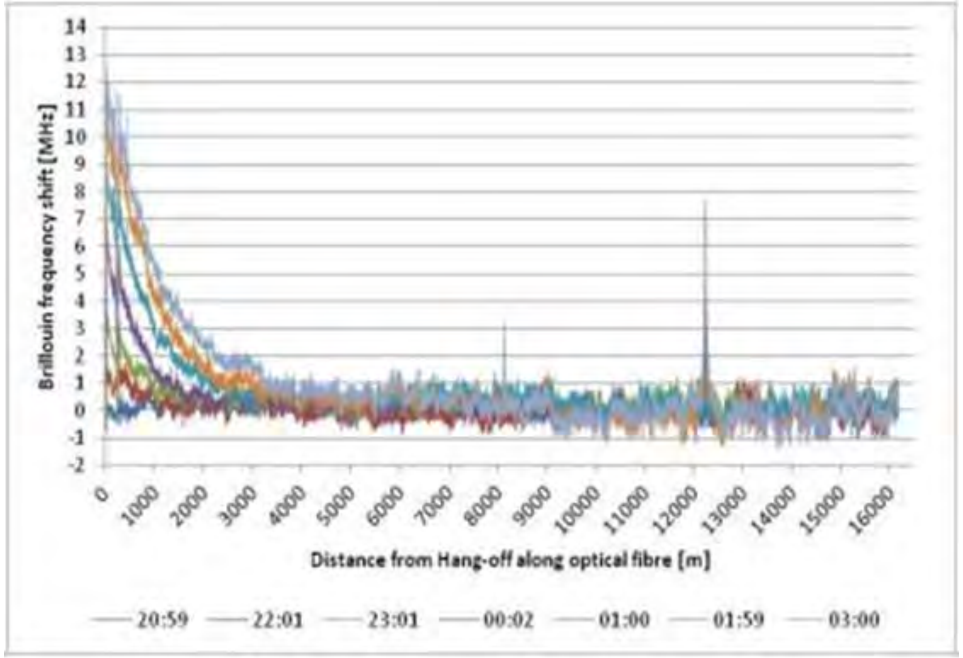




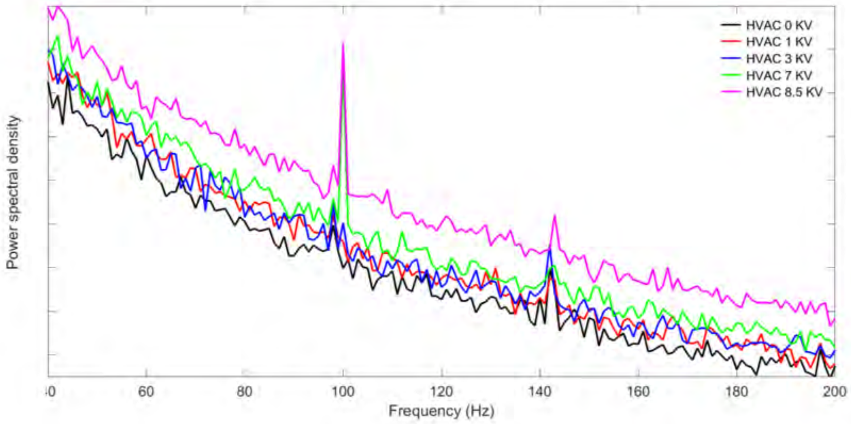
Temperature sensing - Accurate localisation of faults by external heat source

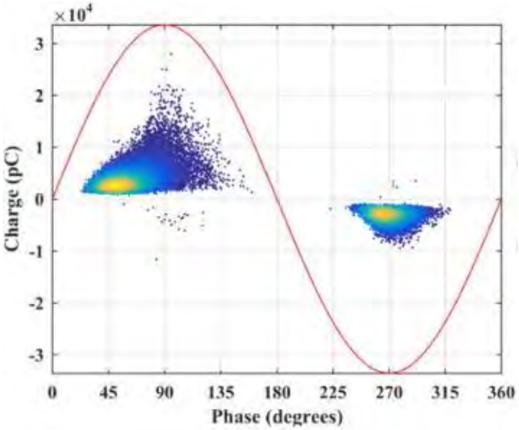


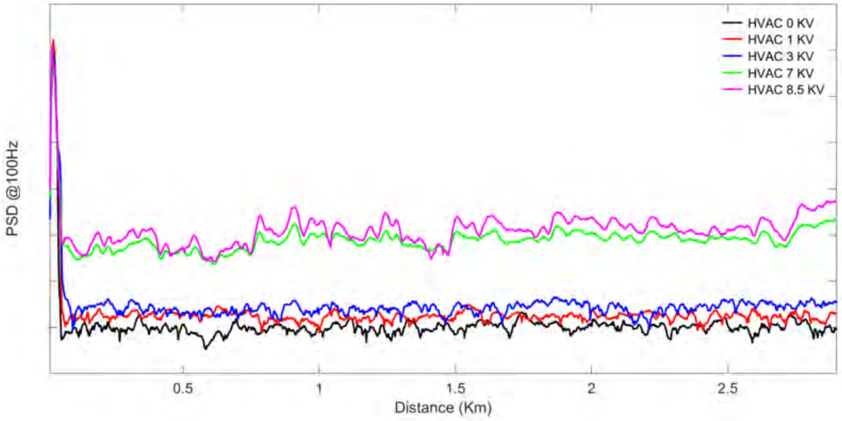
Temperature sensing – tube leakage detection

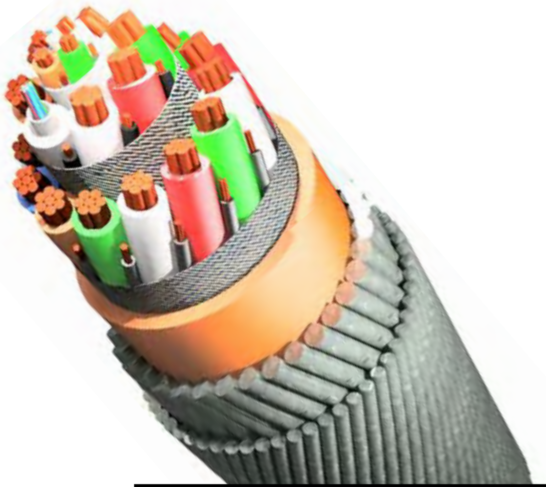


Accoustic sensing - partial discharge detection

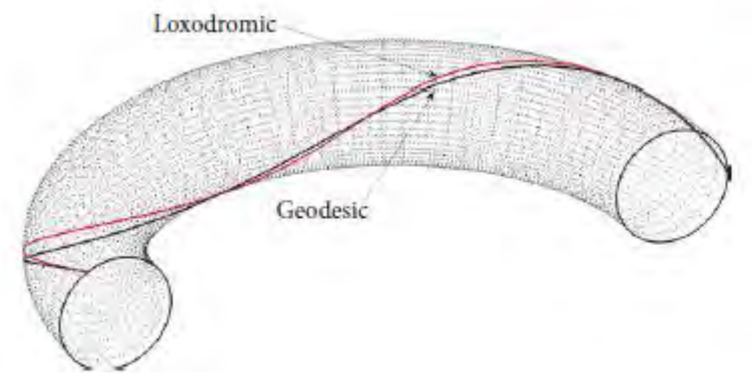


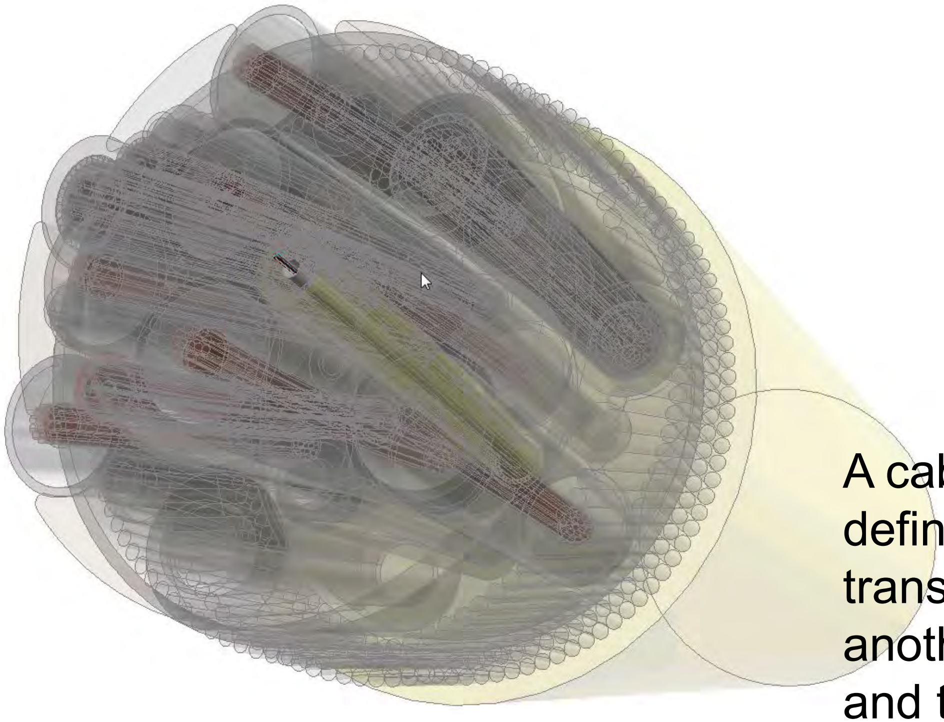






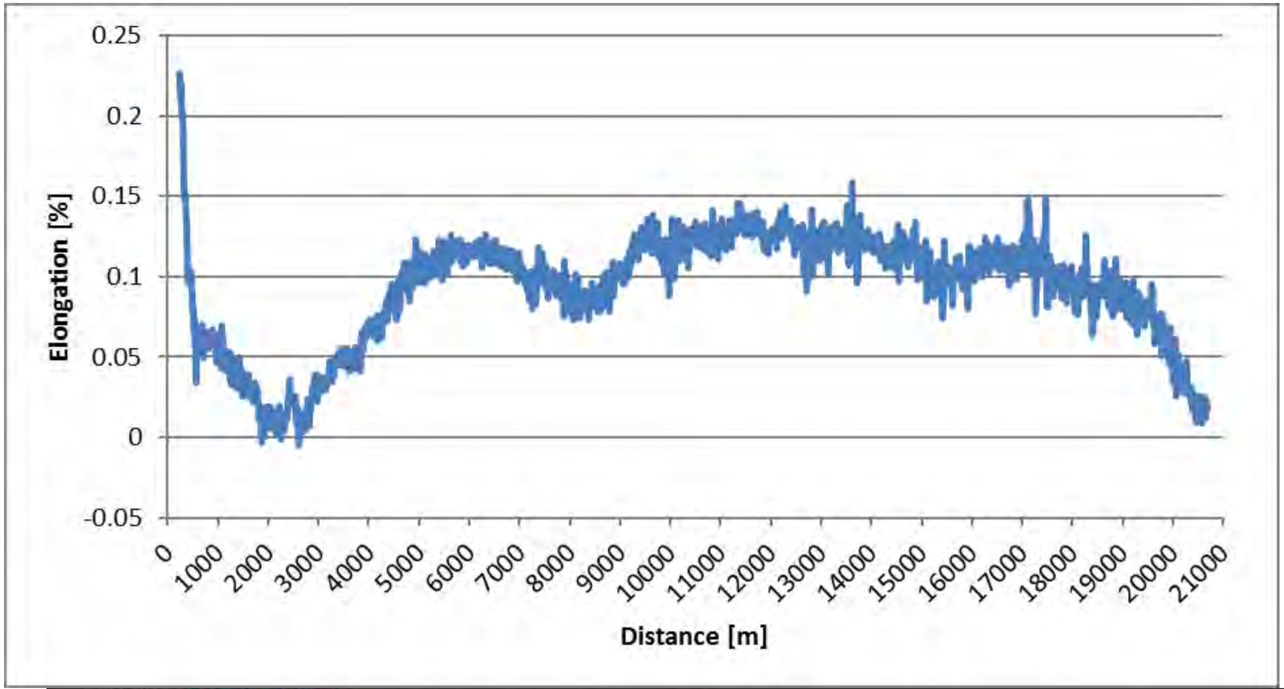
«The mechanical machine»





A cable is a machine, by dictionary definition: "An assembly of parts...that transmit forces, motion, and energy one to another in some predetermined manner and to some desired end."

Strain measurement of control umbilical



Approximate elevation profile of seabed

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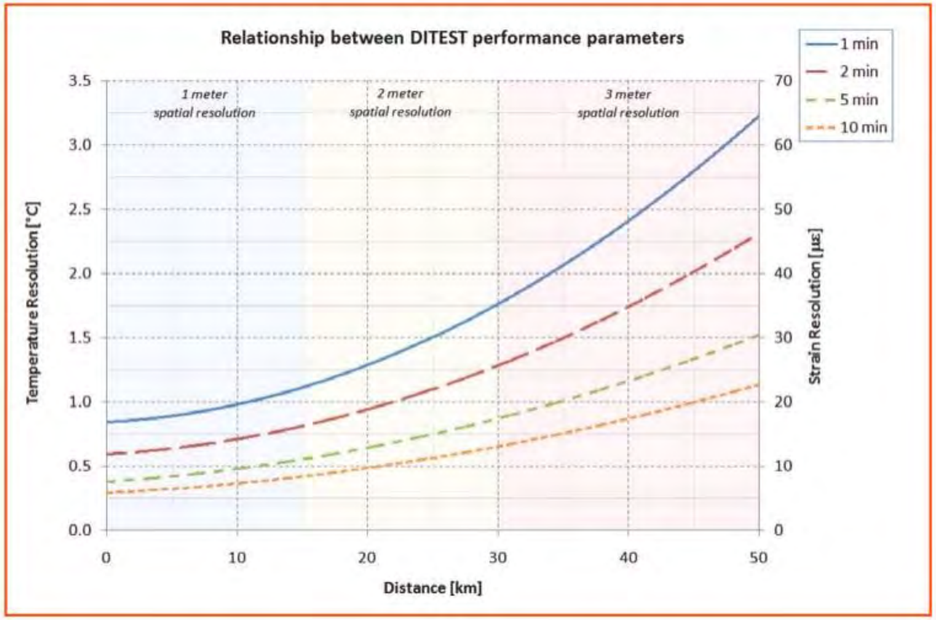
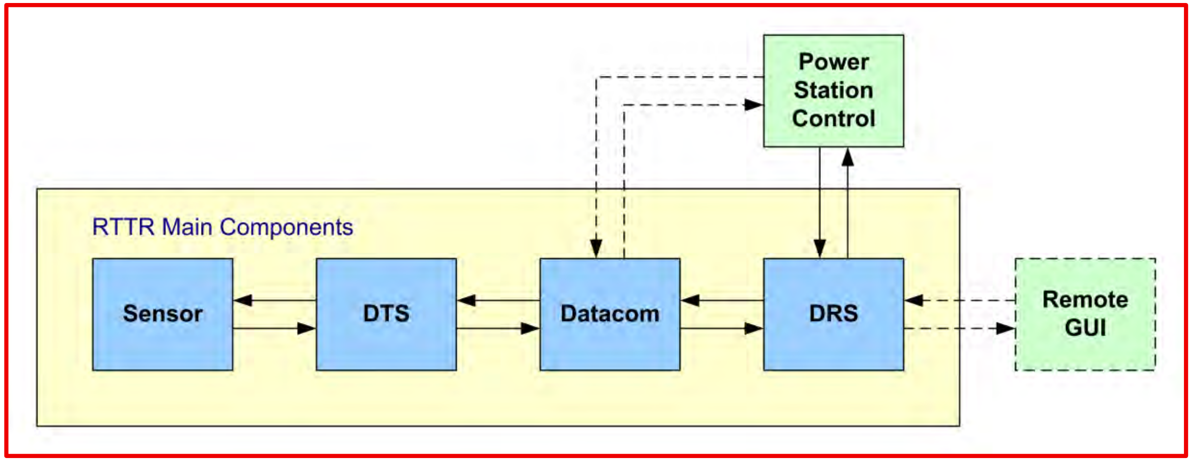
Limitations & trade off's

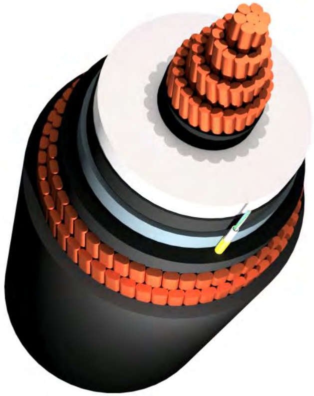


Source: Omnisens

Towards self driven power links and grids in the future?

Real Time Temperature Rating





"All of old. Nothing else ever.
Ever tried. Ever failed.
No matter. Try again.
Fail again. Fail better."

Nexans
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Nexans
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International Cable Protection Committee

ICPC has the vision of being the premier international submarine cable authority through providing leadership, knowledge and guidance on issues related to submarine cable security and reliability.

- ✓ ICPC has more than 175 MEMBERSin over 60 COUNTRIES
- ✓ ICPC represents 97% of the world’s subsea telecom cables
- ✓ ICPC represents most cable ships that lay and repair submarine cables and a great number of leading international HVDC power cable operators/owners and manufacturers

International Cable Protection Committee

ICPC core functions :

- ✓ Publications
- ✓ Recommendations
- ✓ Newsletters
- ✓ Annual Plenary
- ✓ Cable Films
- ✓ Notifications of cable laying and recovery
- ✓ Out reach to other seabed users
- ✓ Research

ICPC working groups:

- ✓ Affiliations
- ✓ Biodiversity Beyond National Jurisdiction (BBNJ)
- ✓ Business Plan
- ✓ Cable Security
- ✓ Media & Public Relations
- ✓ Recommendations

International Cable Protection Committee

Cable protection initiatives

- ✓ International Hydrographic Organisation (IHO)—Charting
- ✓ Environmental Research
- ✓ Submarine Cable Repair Report
  Ocean Planning
- ✓ IMO-Strengthen COLREGS to provide for improved safety for ships during cable operations

Cable repair initiatives and permits

- ✓ Council for Security Cooperation in the Asia Pacific (CSCAP)
- ✓ Indonesia Cabotage
- ✓ International Maritime Organization: Convention on the International Regulations for Preventing Collisions at Sea (IMO–COLREGs)

ICPC publications

International Cable Protection Committee
1958 • 2018

Compilation of an extensive, dedicated source of international cable legislation, legal articles and cases, and a topic index of reported cases and rulings involving submarine cables. The only such collection worldwide.

Compilation of a very large source of environmental information and data related to the installation maintenance and protection of submarine cables.

Unique data available nowhere else. The global comparison of cable repair times produced annually showing average repairs per year, average time to begin repair, and repair cause breakdown.

A peer reviewed book, jointly compiled by the United Nations Environment Programme (UNEP) and the ICPC titled :

Submarine Cables and the Oceans: Connecting the World.

The book has contributions from ICPC members, cable industry associates, ICPC's Marine Environmental Advisor (MEA) and International Cable Law Advisor (ICLA). From the ICPC website alone, the publication has been Downloaded over 72,000 times.