Spatial Division Multiplexing
A New (Subsea) Cable Paradigm

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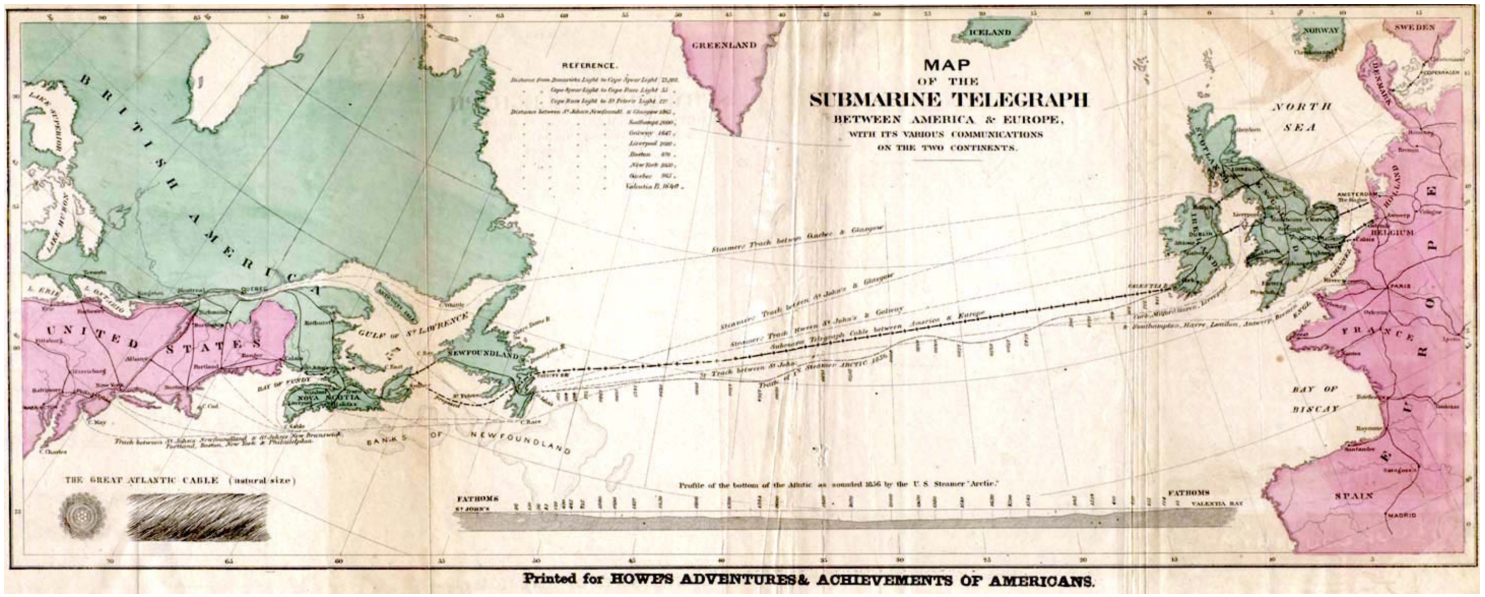
INFINITE WAVES

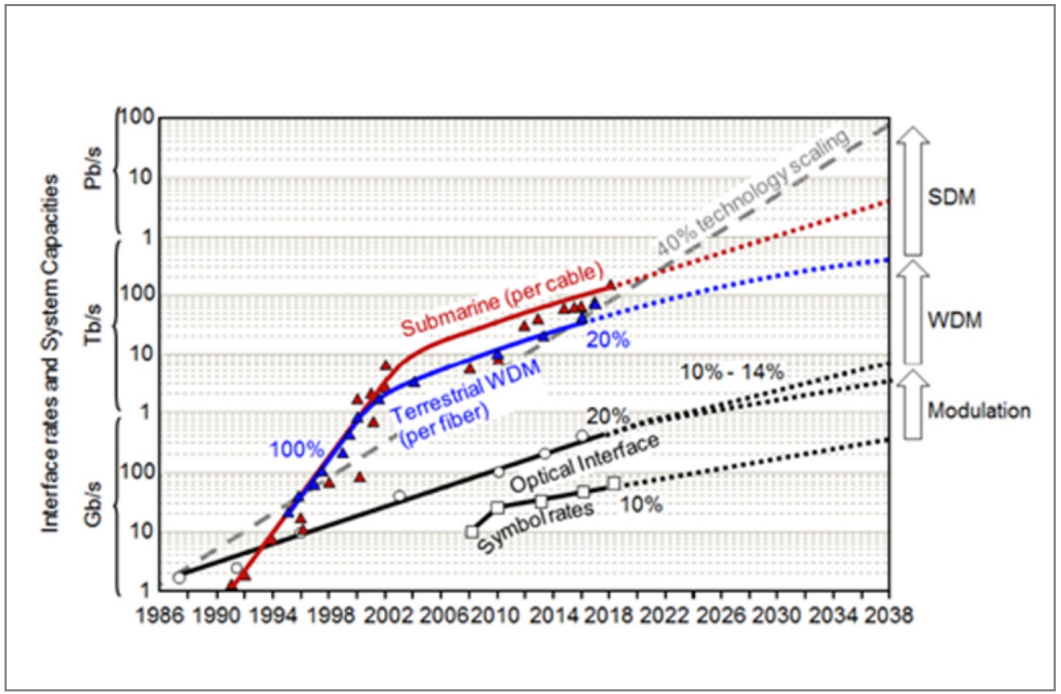
History



- Subsea cables have been in operation since 1866.
- Fibre optic subsea cables began carrying traffic in 1956 (TAT-1).
- Subsea cables are carrying 1.5Pbps annually, as of 2024 (~99% of all trans-continental traffic.

Evolution

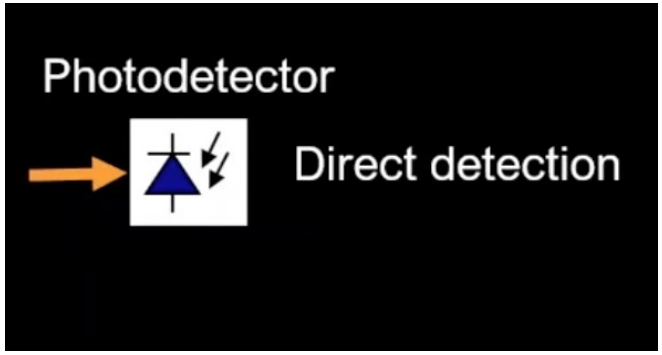
Evolution Snapshot



- Initial transmission technologies were based on analog modulation.
- The next phase was Wavelength Division Multiplexing (WDM).
- The future is Space Division Multiplexing (SDM).

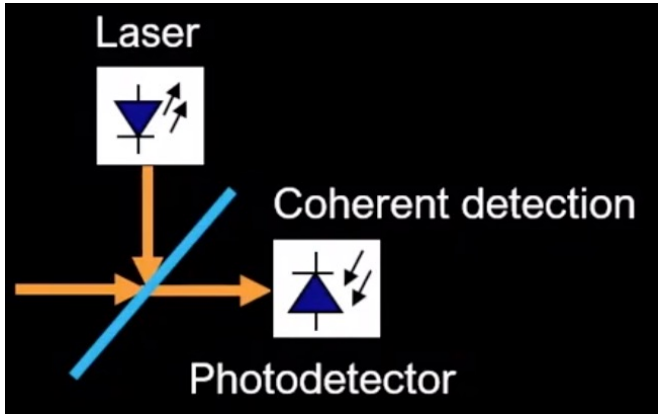
Optical Technology

Direct Detection



- Direct Detection was the predominant technology, until 2010.
- Uses only amplitude (intensity of light) to transmit data.
- 1 for bright light. 0 for dim light.
- Maximum capacity is 10G.
- Prone to linear impairments, primarily chromatic dispersion.

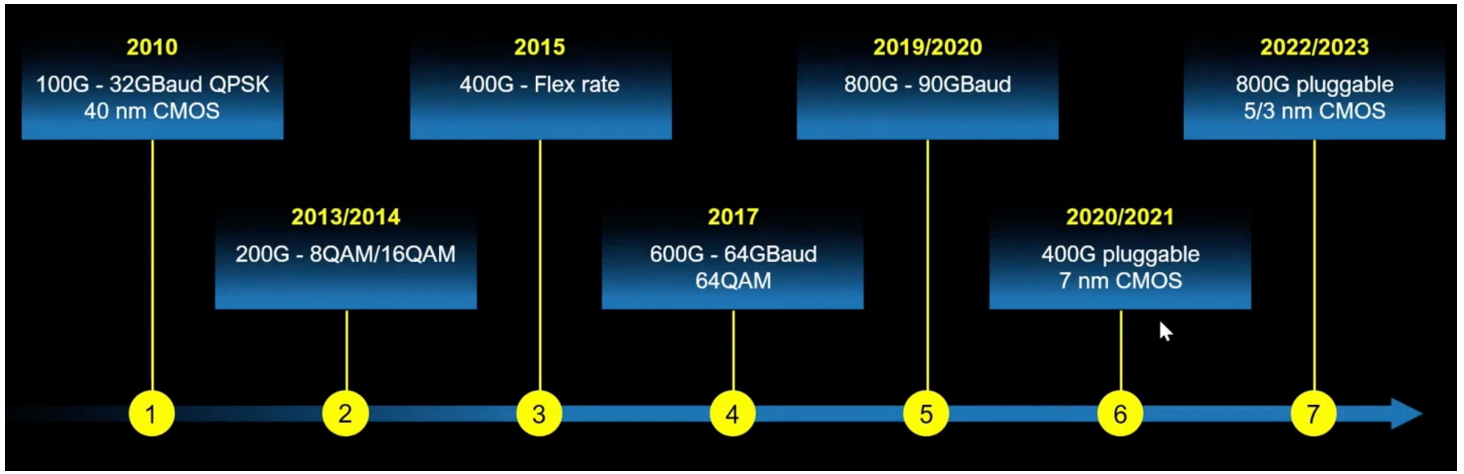
Coherent Detection

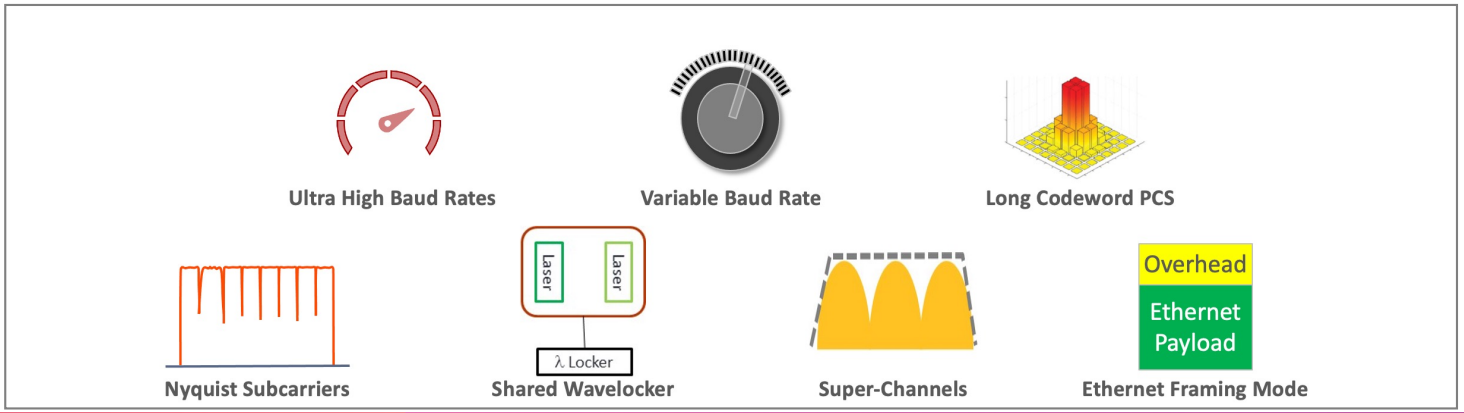


- Coherent Detection came on the scene in 2008, commercialized 2012.
- Uses amplitude, phase and polarization to transmit data.
- Allows for up to 1.6T per wavelength (as of 2024).
- Permits great distances at lowest power consumption possible.
- Inherently compensates for linear impairments via the DSP.

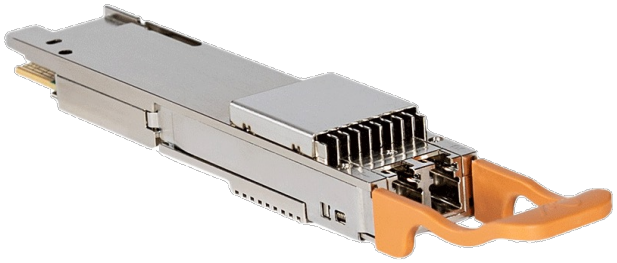
Coherent Evolution

Coherent Detection Development Milestones & Roadmap



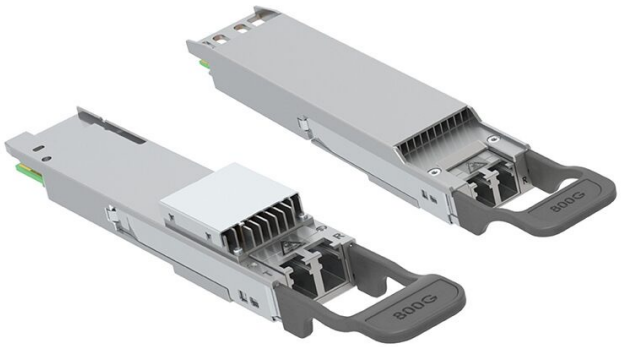


Coherent Evolution - Pluggables



- 400G-ZR/ZR+ QSFP-DD and OSFP form factors.
- 100G – 400G application modes (QPSK, 8QAM and 16QAM).
- 0dB low power, +1dB high power version & >+1dB higher-power version.
- C-band tunable.
- Encryption support (AES256).
- CMIS 5.0 support.
- PCS support (>+1dB version).
- MSA/OpenROADM/OpenZR/OIF compliant.
- <24W.

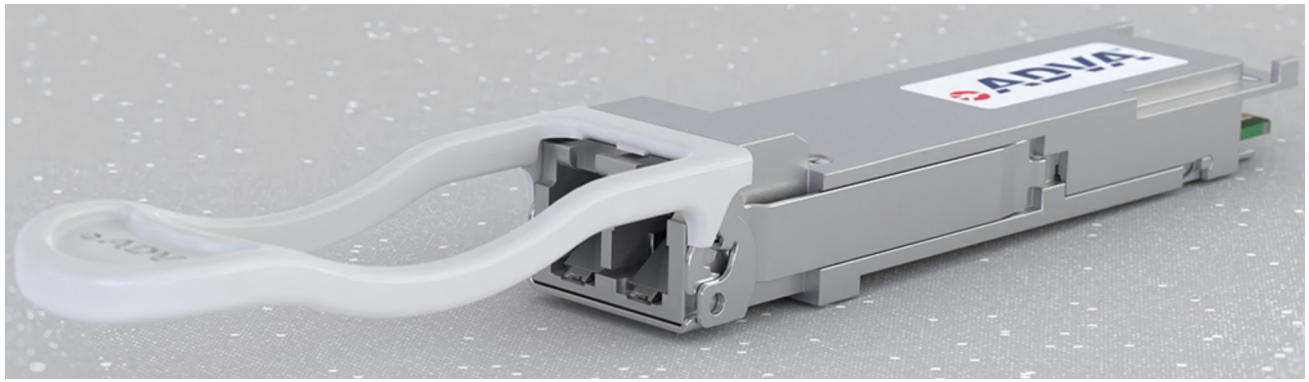
Coherent Evolution - Pluggables



- 800G-ZR/ZR+ QSFP-DD and OSFP form factors.
- 100G – 800G application modes (QPSK, 8QAM, 16QAM and 64QAM).
- >+1dB power.
- C-band tunable.
- CMIS 5.2 support.
- PCS support (ZR+ version).
- MSA/OpenROADM/OpenZR/OIF compliant.
- <30W.

Coherent Evolution - Pluggables

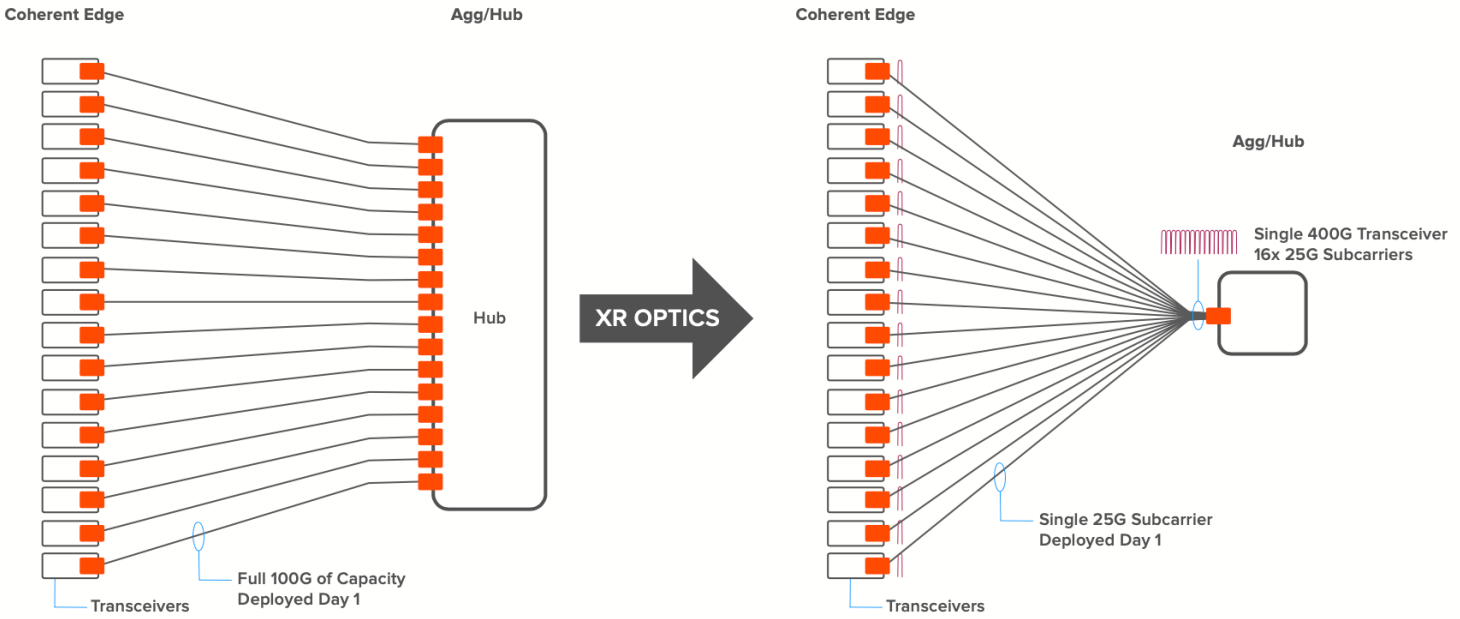
100G Coherent ZR Optics



- 100G coherent ZR+ pluggable.
- Developed by Adva, Coherent and Acacia.
- 120km unamplified, 900km amplified.
- C-band tunable.
- QSFP28 interface.
- <5W.
- MSA/OpenROADM/OpenZR/OIF compliant.

Coherent Evolution - Pluggables

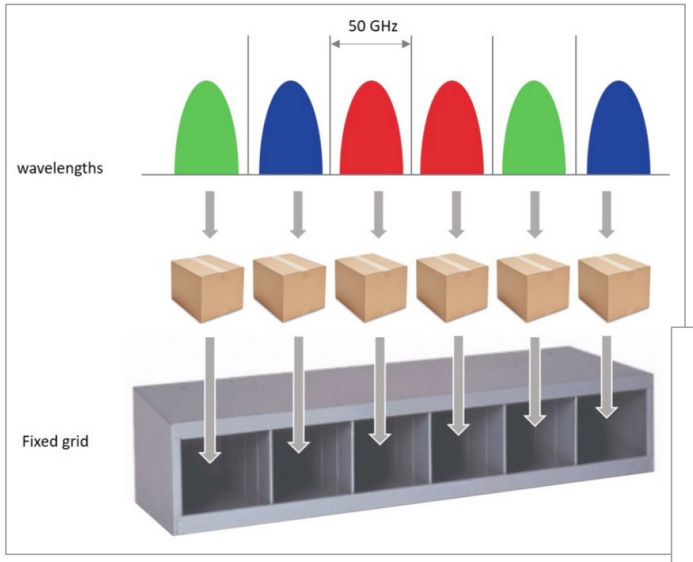
XR Optics



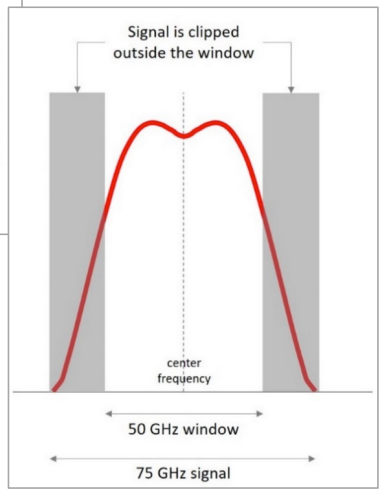
- XR pluggables, largely being developed by Infinera.
- Standardized in the OpenXR Forum.
- Specification for p2p and p2mp optical wavelengths.
- Supports BiDi use-cases (200G capacity).

Fixed Grid DWDM Systems

Fixed DWDM Grid



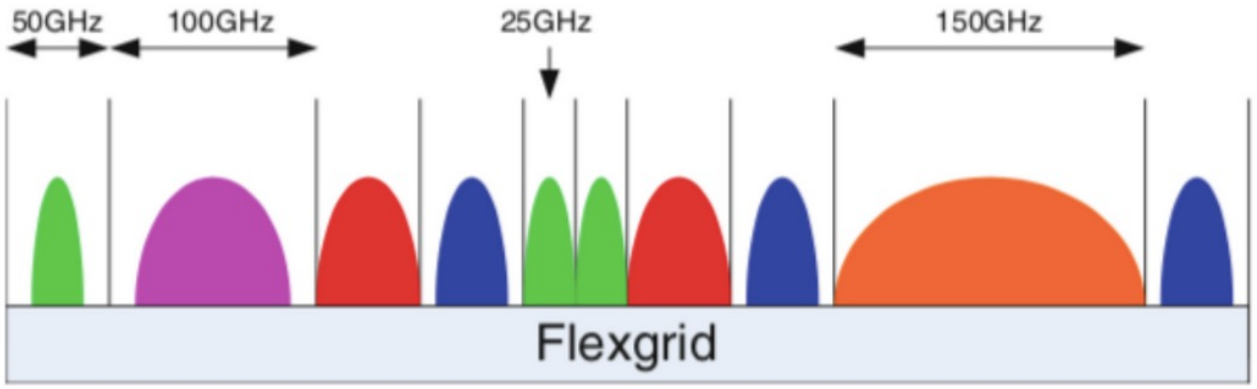
- Most DWDM systems today use a fixed-grid layout.
- Ideal when transponders use the same baud rate per wave.
- Today, transponders can run at various baud rates.
- Increasing baud rate increases bandwidth capacity per wave.
- But higher baud rates require wider grid frequencies.



- The edges of the 75GHz signal are clipped in the 50GHz channel.
- Leads to poor signal and/or transmission errors.

Flexible Grid DWDM Systems

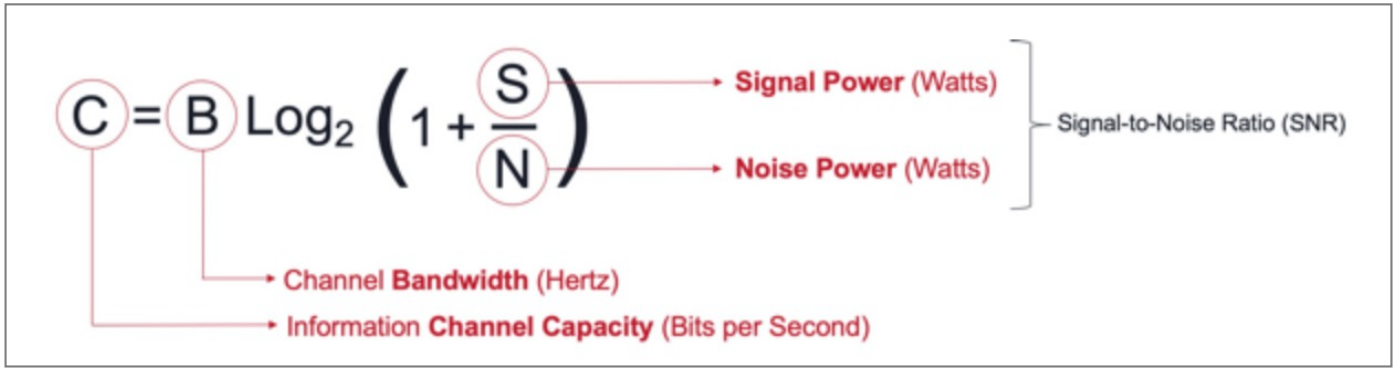
Flexible DWDM Grid



- Flex(ible) grids are the solution to the fixed grid limitations.
- Provides a continuous 4.8THz – 6.1THz block of spectrum (C-Band).
- Operators can choose to assign spectral width per wavelength, as needed.
- It is granular, up to 12.5GHz per channel.
- Eliminates stranded capacity as in the case of fixed grid systems.
- More capacity can be carried across the entire system.
- Different services can be delivered without suffering spectral inefficiency.

Shannon's Limit

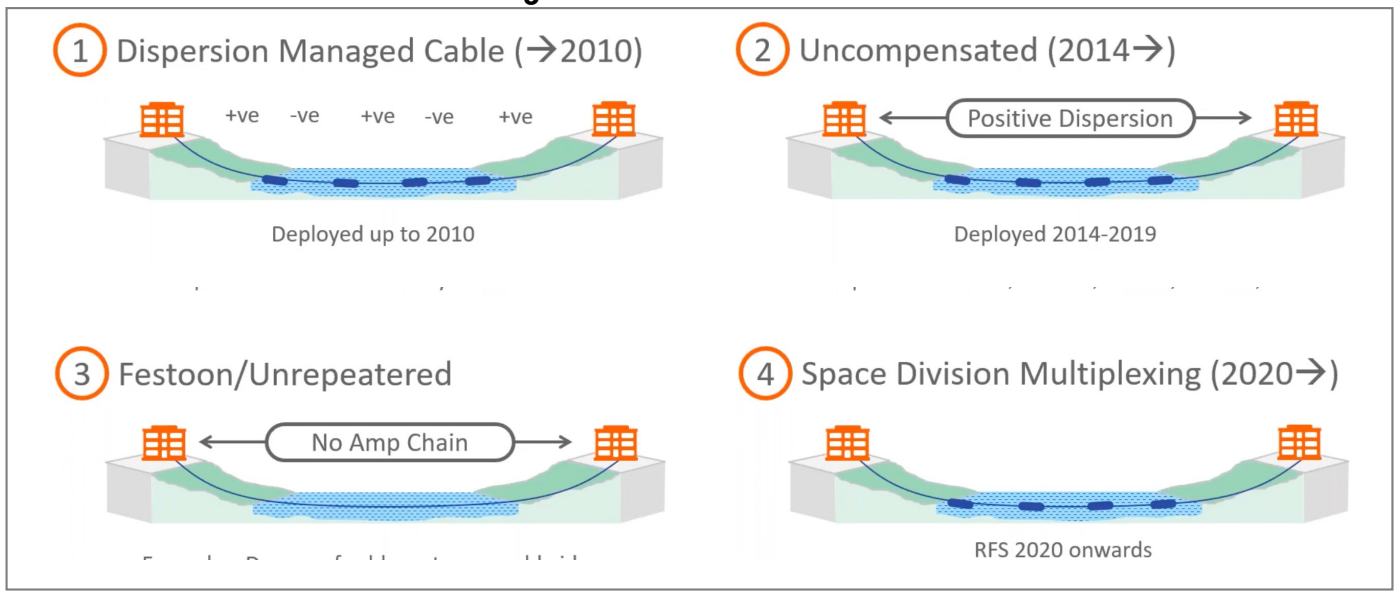
Shannon's Limit Equation



- Once a submarine cable is laid, "B" is fixed based on the number of fibre pairs.
- Current subsea amplifiers are only 4.55THz wide.
- The only thing to improve is the SNR, so that we can increase "C".
- In the last 13 years, we have done this with coherent optical technology.
- But we are nearing Shannon's limit with subsea, primarily due to power constraints.
- Time to go back to basics and build "hardware", so as to grow capacity.

Subsea Cable Technology Evolution

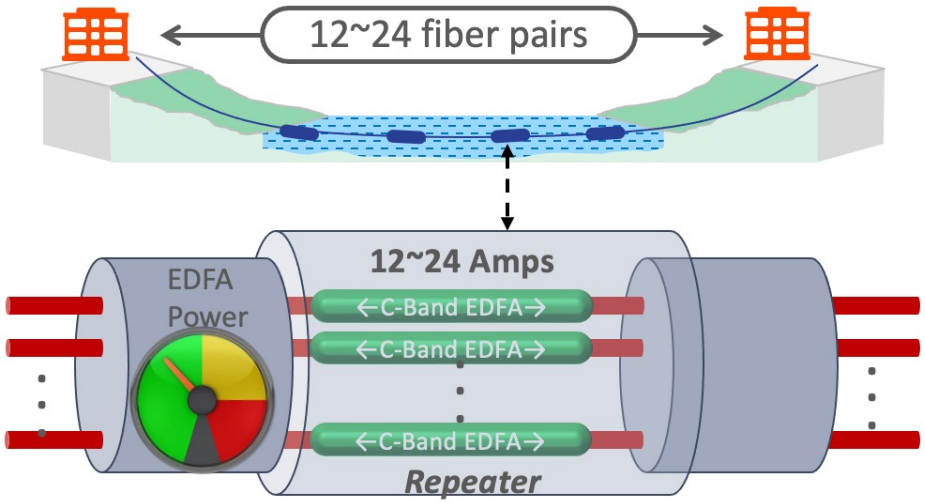
Evolution of Submarine Cable Design



- Uncompensated (high-dispersion) fibres are the most preferred.
- LEAF (Large Effective Area Fibre) fibres are used for subsea application = lower PMD = more power.
- New long-haul subsea cables will mostly be SDM-based.
- Especially if content providers are involved in the build.

SDM: Side-Stepping Shannon's Limit

SDM Submarine Cables



- We can be as clever as we have been, but at some point, we need to build things.
- SDM looks at adding more fibre pairs, as opposed to improving SNR.
- Rather than increase fibre pair capacity, we increase overall cable capacity.

What Is SDM

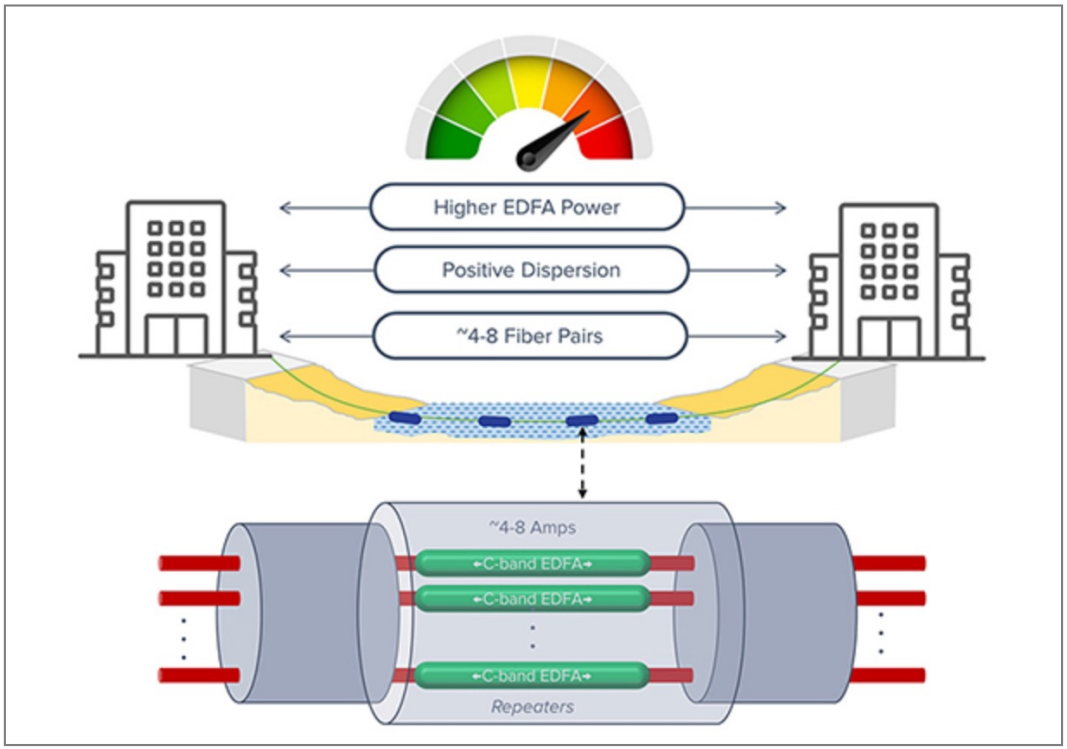
Latest approach to maximizing the capacity of a subsea cable

SDM techniques (examples)	Consequences of SDM
Optimize repeater power and space • Longer amplifier spacing • Lower amplifier power • Pump sharing	• Lower launch power • Better OSNR • Lower non-linear penalties • Operation in linear regime

Lower fibre pair capacity but **more fibre pairs** delivering higher **total cable** capacity

Uncompensated Cables: How We Reach Maximum Capacity

Uncompensated Cable Design



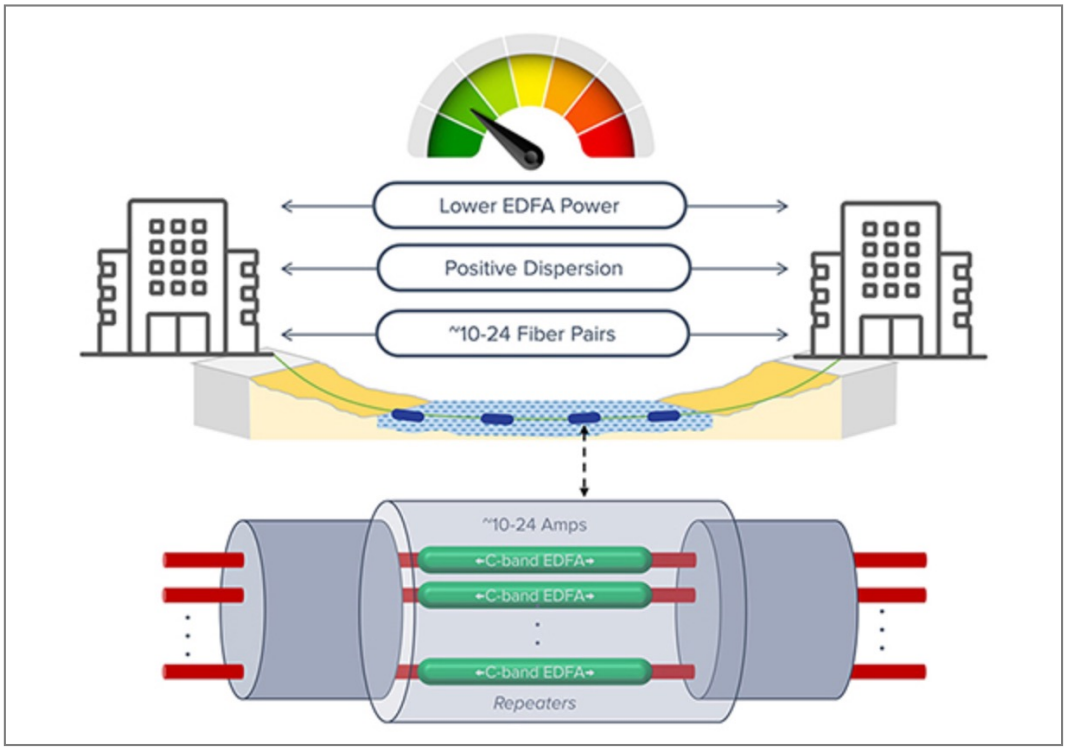
- Uncompensated fibre technology.
- First appeared in 2015.
- 2, 4, 6 or 8 fibre pairs in the cable.

- Maximize spectral efficiency per fibre pair.
- Maximize spectral capacity per fibre pair.
- (not the overall cable).

- High amplifier power.
- 100G – 800G channels, today.
- Anywhere from 4T – 24T per fibre pair.
- 32T – 192T per cable system.

SDM Cable: How We Reach Maximum Capacity

SDM Cable Design



- SDM fibre architecture.
- First appeared in 2020.
- 10, 12, 16, 18, 20 or 24 fibre pairs in the cable.

- Sacrifice spectral efficiency per fibre pair.
- Sacrifice spectral capacity per fibre pair.
- Compensate by increasing fibre pairs in the cable.

- Low amplifier power.
- 100G – 800G channels, today.
- Anywhere from 4T – 24T per fibre pair.
- 40T – 576T per cable system.
- Lots more margin for future capacity.

Generational Evolution of Trans-Atlantic Subsea Cable

Cable Design & Capacity Growth – Direct Detection vs. Coherent Technology

	Dispersion Managed **Apollo**	*Uncompensated* **MAREA**	*SDM* **Dunant**	*SDM* **Anjana**
RFS Date:	2003	2018	2021	Q4'24
Fibre Pairs:	4	8	12	24
FP Capacity:	10Tb/s	26.2Tb/p	25.2Tb/s	21Tb/s
Cable Capacity	**40Tb/s**	**210Tb/s**	**312Tb/s**	**504Tb/s**

SDM Benefits

- SDM = lower capacity per fibre pair, BUT more capacity per cable.
- Lower wavelength power = better OSNR at receiver.
- Lower power requirements compared to previous cable technologies.
- Lower power = plenty of margin to adapt to new transponder technology.

SDM Cables Built & Planned

SDM Cable Build Projects

SDM Cable System	Fibre Pairs	RFS
Dunant	12	2021
H2HE	16	2021
Amitié	16	2022
Equiano	12	2022
APRICOT	16	2024
JUNO	20	2024
2Africa	16	2024
Bifrost	12	2024
MEDUSA	24	2024
Hawaiki Nui	12	2025
Caribbean Express	18	2025
SMW-6	10	2025
CSN-1	12 – 17	2025

- For each of these, you are looking at 15T – 20T per fibre pair.
- Total system capacity in excess of 400T - 500T.

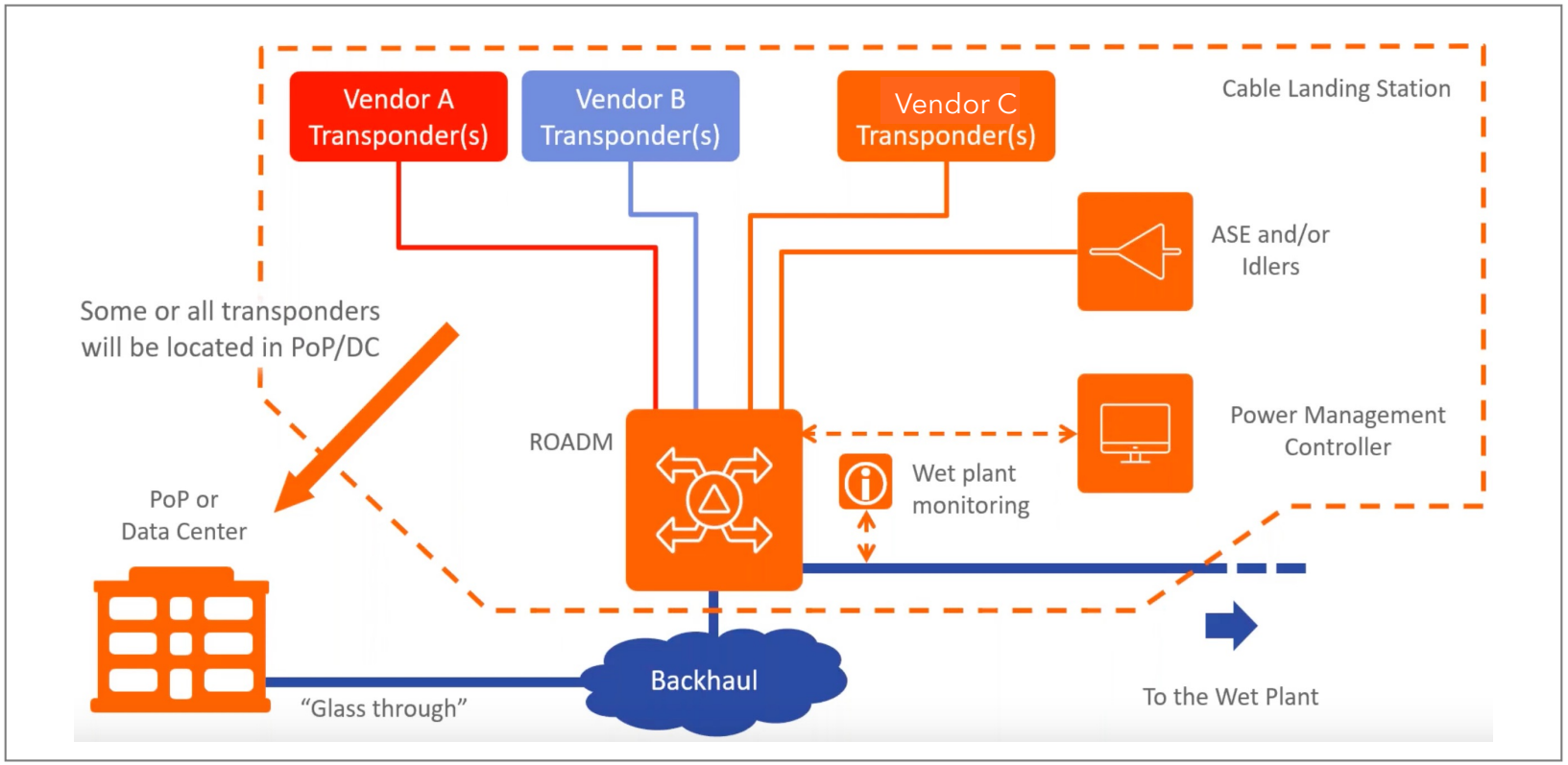
SDM Challenges

It's not all roses…

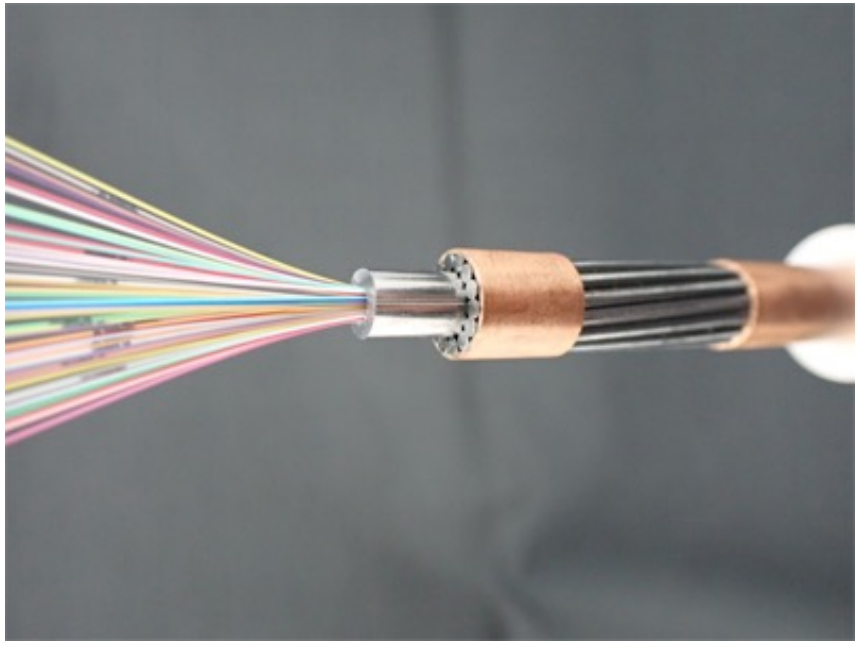
- Latest SDM cables are promoted as being "open".
- When is a cable RFS?
- How do you manage spectrum?
- Who operates the cable system?
- How do you perform testing quickly?
- How do you provision quickly?
- Who do you call when things go wrong?

SDM Challenges

It is rather logistical…



SDM & Optical Future



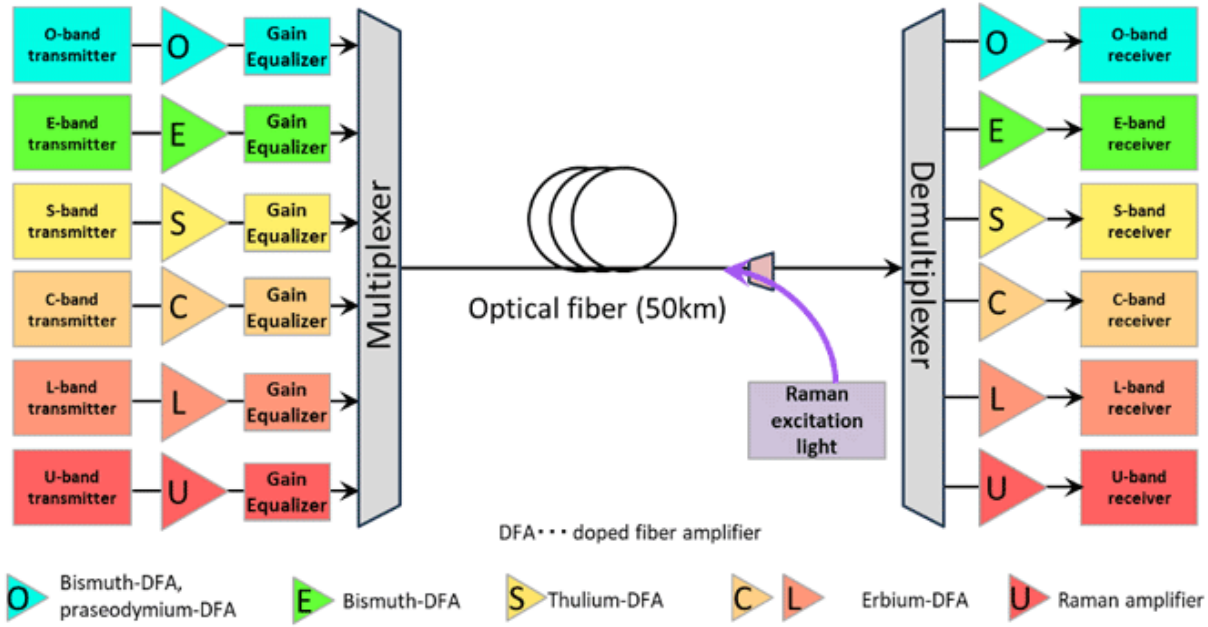
- 32 – 40 FP's per cable is currently underway.
- Limitations for the # of FP's is the amplifiers.
- Novel fibre technologies.
- C+L to increase spectrum (9.6THz – 12.2THz).

SDM & Optical Future

NICT (Japan)

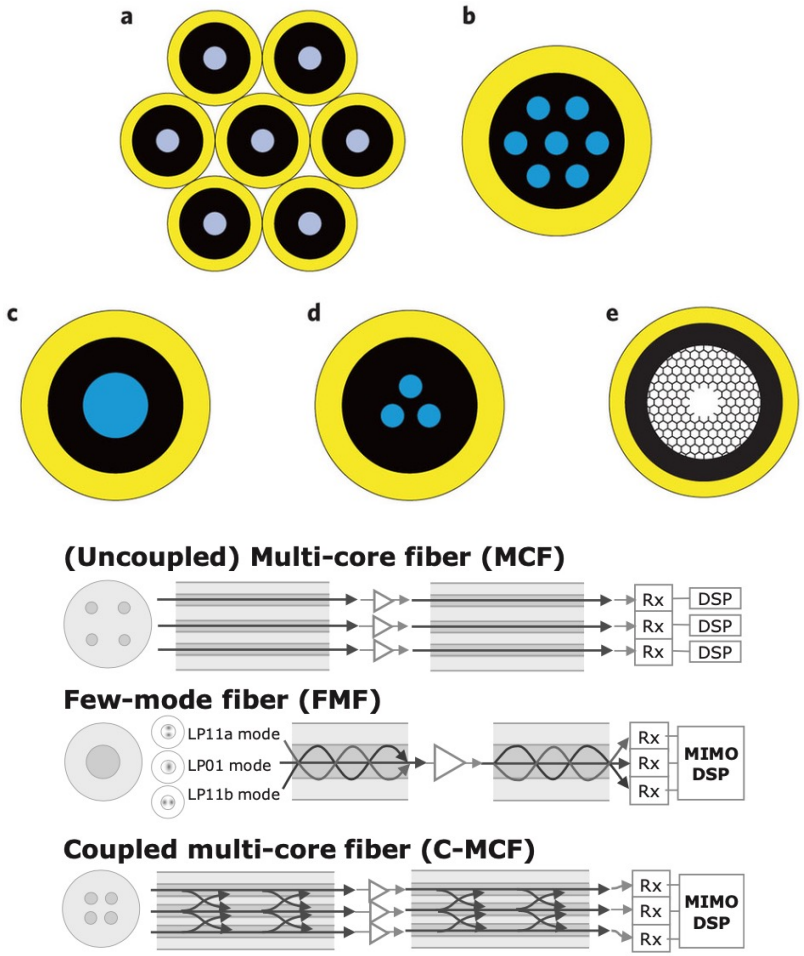
National Institute of Information & Communications Technology

Experiment to increase fibre optic capacity using novel technologies.



- Achieved 402T of raw bandwidth.
- 378T of payload capacity.
- 37.6THz of optical spectrum, in all bands.
- 1,505 individual wavelengths.
- 16, 64, and 256 DP-QAM.
- 50km distance.
- Doped & Raman amplification.

SDM & Optical Future



Novel Fibres

- a) Standard SMF.
- b) MCF (uncoupled).
- c) FMF.
- d) C-MCF.
- e) HCF.

- Ultimately, we can't run away from physics.
- At some point, we need to lay more fibre.
- For 2024, an option for fibre-rich markets.
- New subsea builds will focus on a), for now.

Q & A

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2024