SubOptic2019

TO THE BEACH AND BEYOND

RETHINKING GLOBAL NETWORKS

Moderator
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Infinera

Master-class 4: Updates to Transmission Technology

Name:	Ronald Freund	Masaaki Hirano	Tony Frisch
Company:	HHI	Sumitomo Electric	Xtera

Ronald started his career in 1996 as a co-founder of VPI Photonics and then moved to Fraunhofer Heinrich Hertz Institute, where he is currently leading the department Photonic Network and Systems with the focus on high-capacity submarine and core networks, high-speed access networks as well as satellite and quantum communication networks (www.hhi.fraunhofer.de/pn).

In 2017 he was appointed Professor for Photonic Communication Systems at the Technical University of Berlin. He holds a MBA from RWTH Aachen.

Name: Ronald Freund

Title: Head of Department

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Fraunhofer Heinrich Hertz Institute

Hirano joined Sumitomo Electric Industries, Ltd. in 1997 and has been engaged in R&D on various specialty optical fibres including low-loss fibre, dispersion-shifted fibre, high-nonlinearity fibre, etc.

He is now a group leader at optical fibre engineering and market development, responsible for submarine fibres.

Name: Masaaki Hirano

Title: Manger of Optical Fibre Engineering

Email: Masahirano@sei.co.jp

Tony started at BT's Research labs and then moved to Alcatel Australia, becoming involved in testing and commissioning submarine systems.

A move to Bell Labs gave him experience in terminal design and troubleshooting, after which he went to Alcatel France, eventually heading subsea Product Marketing.

He joined Xtera in 2004 and is now CTO.

Name: Tony Frisch
Title: CTO
Email: Tony.Frisch@xtera.com

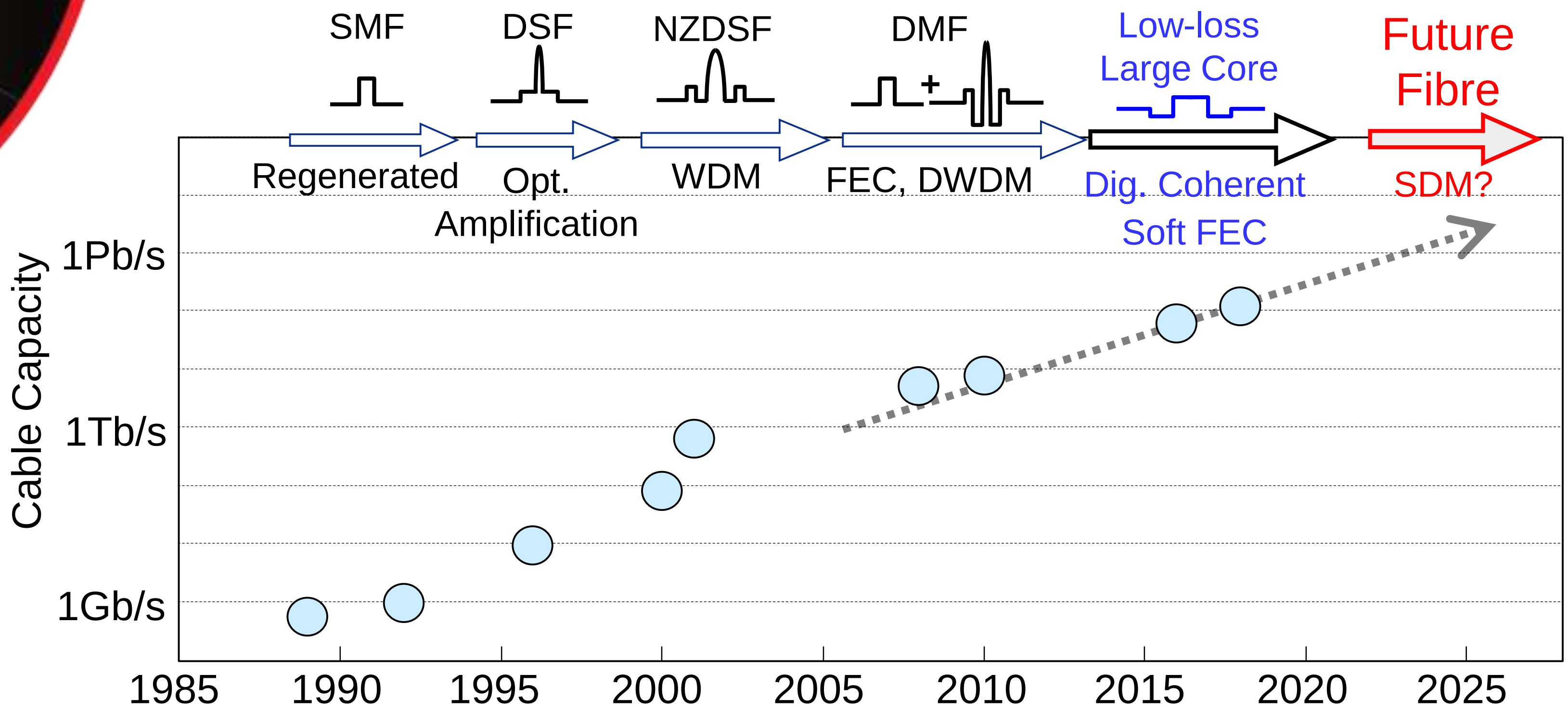
XTERA

Contents

1. Basics
   – Shannon and Nyquist Laws
   – Power, cost, complexity
   – Coherent transmission
2. Building Blocks
   – Constellations
   – Amplifiers
   – Fibre
   – FEC
3. Possible future technology
   – SDM

Long High-capacity Systems	Regional Systems
Unrepeatered Systems (UR)	Upgrade (Legacy) Systems

A brief history of transmission



Recent developments

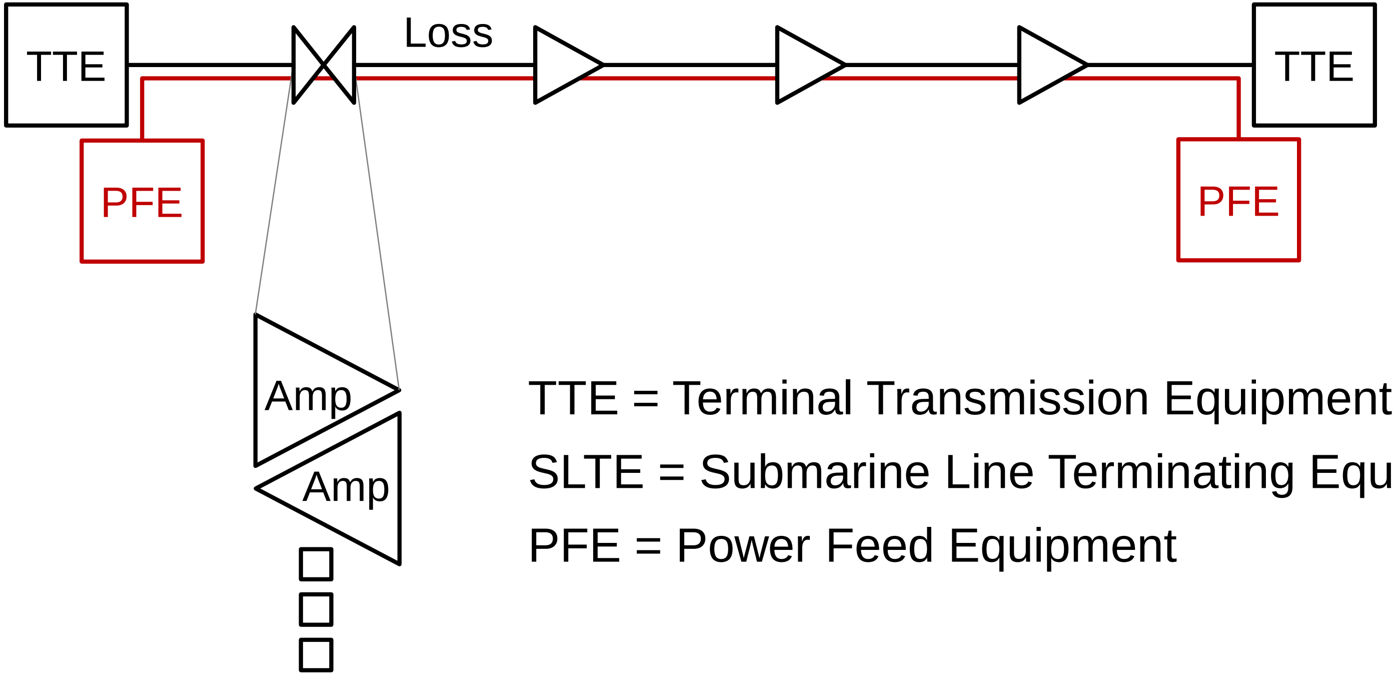
- No major change is subsea amplifier bandwidth
  Nearly all system are C-band-only: a few C+L
- Fibre attenuation dropped from 0.17 dB/km to 0.15 dB/km and Effective area increased to 150 $micron^2$ in the last decade

- **Significant improvements in DSP modules**
  DSP = Digital Signal Processing
- Interesting research on non-linear mitigation, multi-mode propagation …

Basics

TF

Typical subsea system



TTE = Terminal Transmission Equipment

SLTE = Submarine Line Terminating Equipment

PFE = Power Feed Equipment

Practical constraints

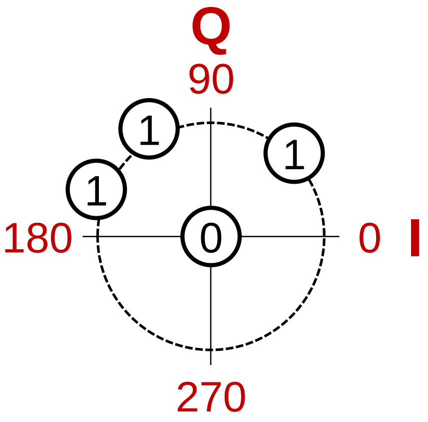
- Cost is important
  Quite a lot of fixed cost e.g. marine, environmental impact etc.

=> Maximise capacity to optimise cost per bit

- Repairing subsea plant is difficult, so reliability is important
  – favours simplicity
- Power has to be fed along cable to subsea amplifiers
  – lowest cable resistance currently 0.6 ohm/km
  – power is the ultimate practical limit to capacity

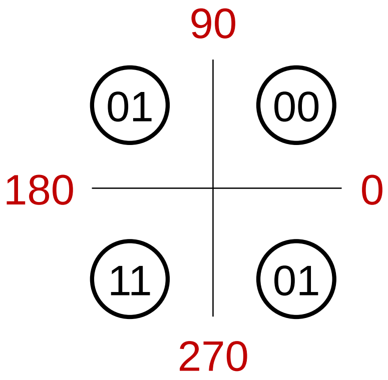
Coherent transmission

- On Off Keying (OOK)
  Phase not important



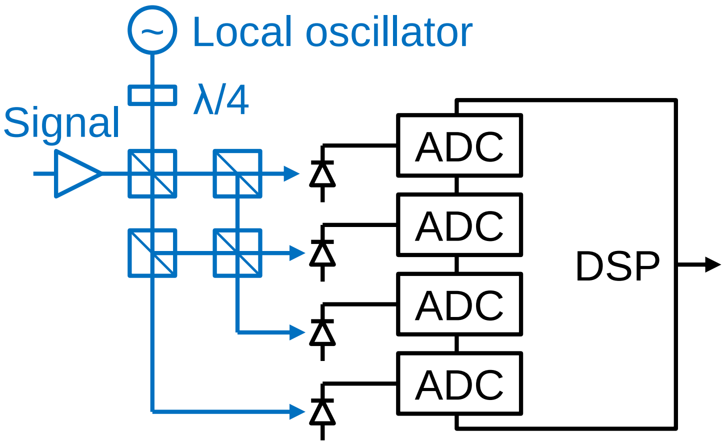
I = In-phase
Q = Quadrature

- Phase Shift Keying (PSK)
  Quadrature Amplitude Modulation (QAM)
- Phase and amplitude are modulated
- Points generally represent >1 bit



Coherent detection

- Add receive signal to Local oscillator
- Convert to electrical signal
- Analogue to Digital Conversion
- Estimate "carrier frequency"
- Separate polarisations
- Compensate for dispersion
- Compensate for non-linearity (optional)
- Decode constellation
- Decode FEC



Simplified – each detector is usually differential

Common constellations

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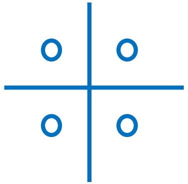
- Constellations with 4-16 points = 2-4 bits per symbol

2 polarisations
x 30 Giga symbols per second
x 2 bits per symbol
= 120 Giga bits per second

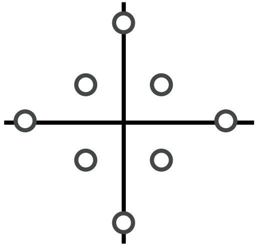
20% FEC overhead
100G per wavelength
37.5 GHz grid
2.7 bits/s/Hz

QPSK



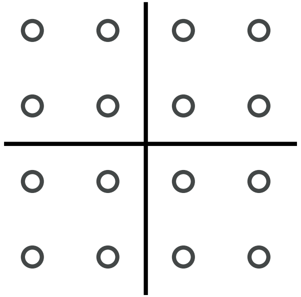
2 bits

8QAM



3 bits

16QAM

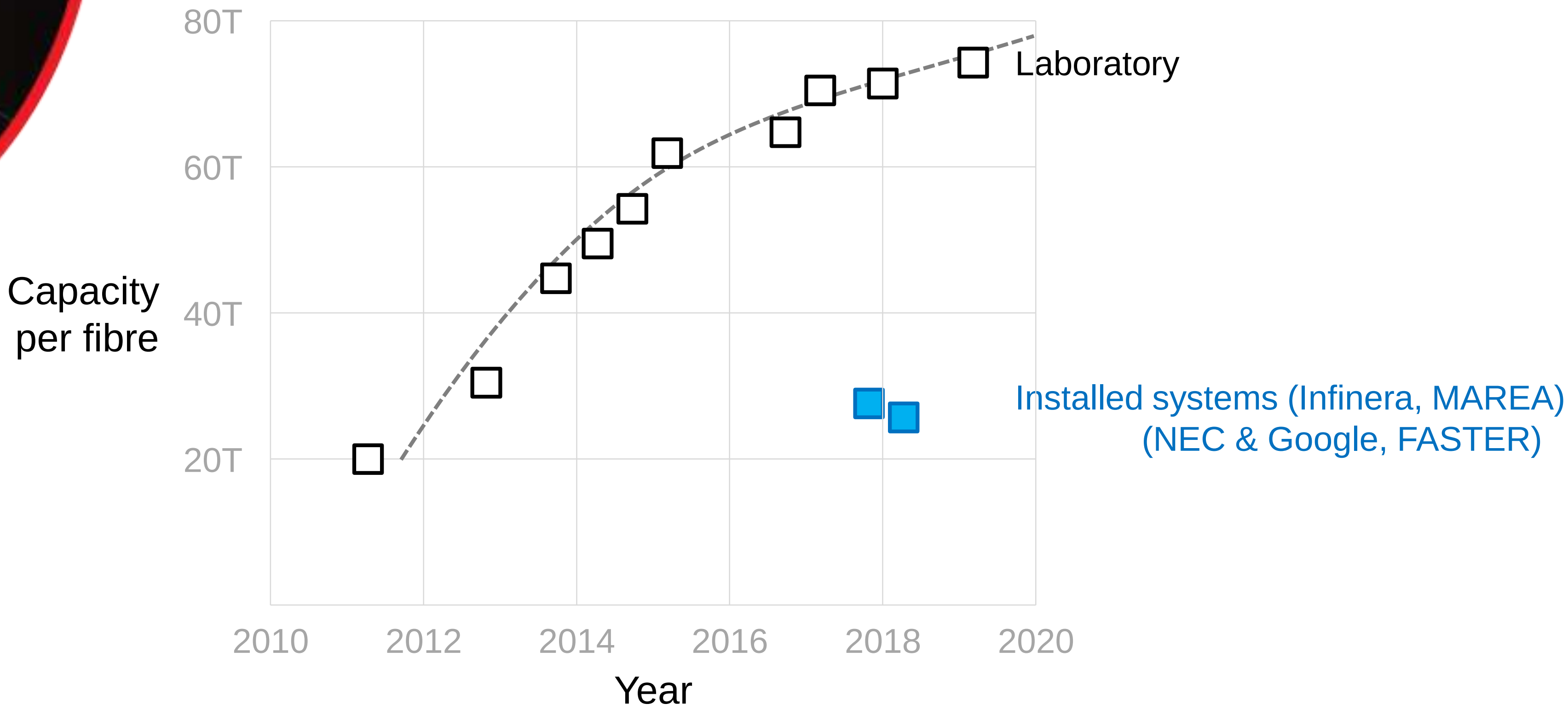


4 bits

Main trend / objective

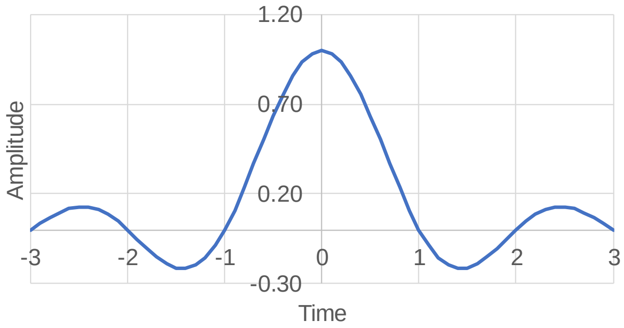
More capacity by increasing:	Publications
1. Number of constellation points	up to 256QAM = 8 bits/symbol
2. Symbol rate	up to 80 Gbaud
3. Number of wavelengths	up to 300

Demonstrations



Nyquist's law

- For a bandwidth of B (Hz) the maximum symbol rate is:
- B symbols per second
- Assumes a $\frac{\sin(\pi t)}{\pi t}$ pulse shape

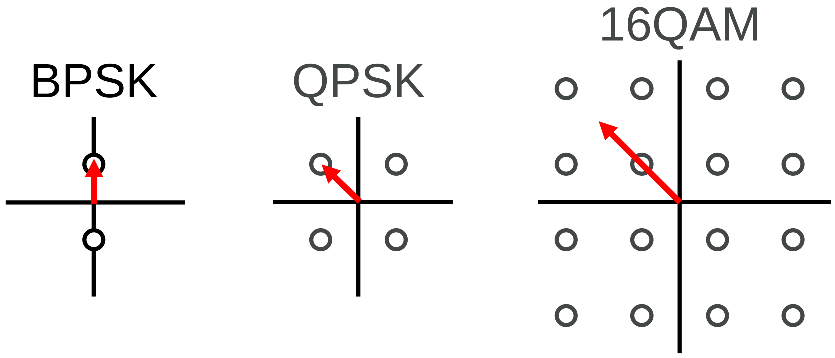


- Latest modules shape pulses using DACs to approximate this [DAC = Digital to Analogue Converter]

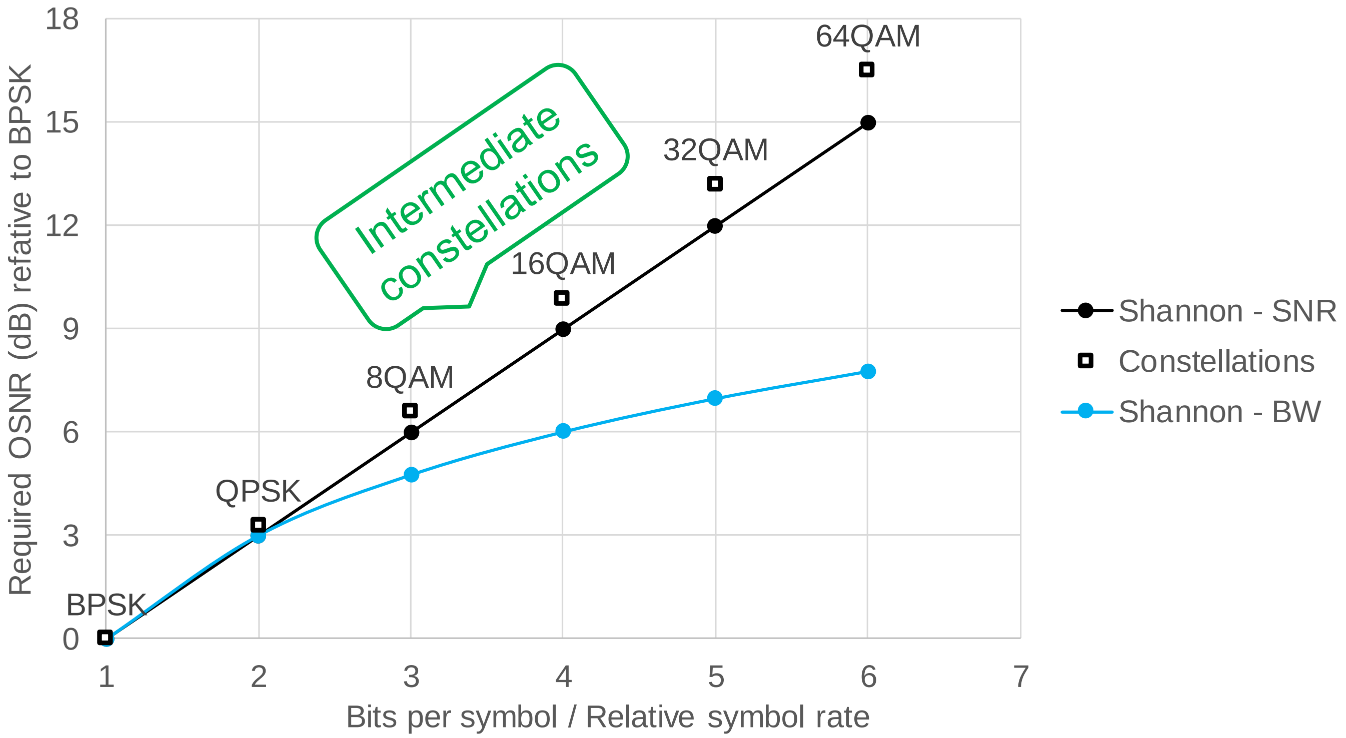
- Higher symbol rate = larger bandwidth = more noise

Shannon's law

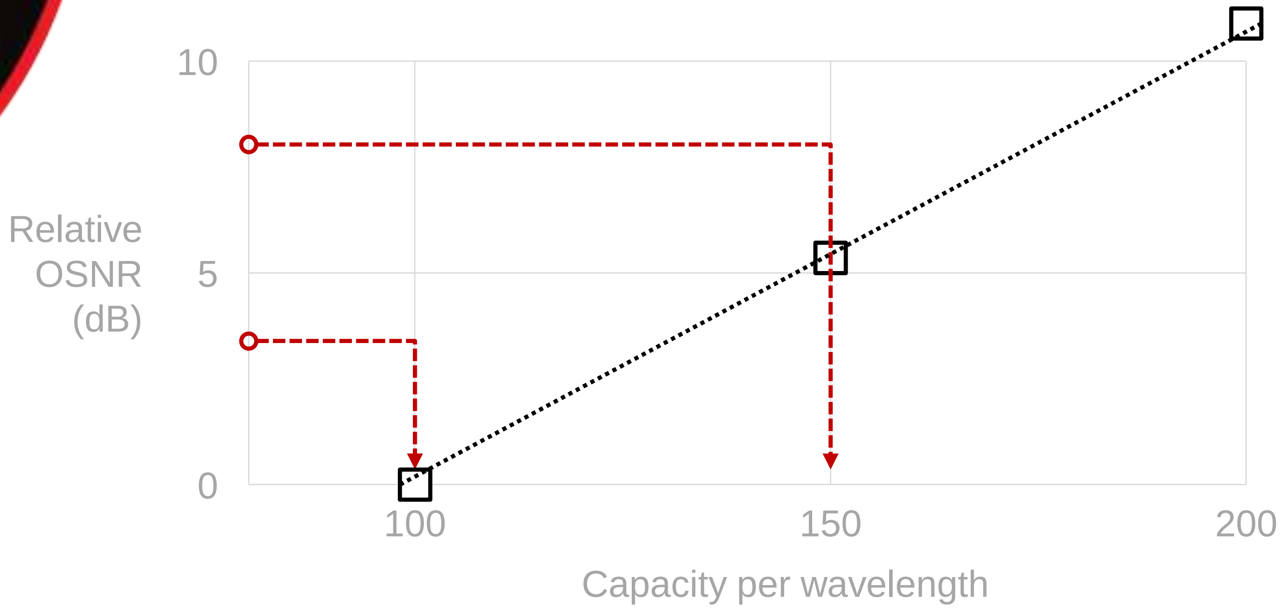
- Maximum information capacity is: $B \cdot \log_2(1 + SNR)$
- Approximately (optical): $2B \cdot \log_2\left(\frac{Popt}{Noise}\right)$
- Ideal; assumes a linear system
- Different constellations need different SNR



Shannon's law



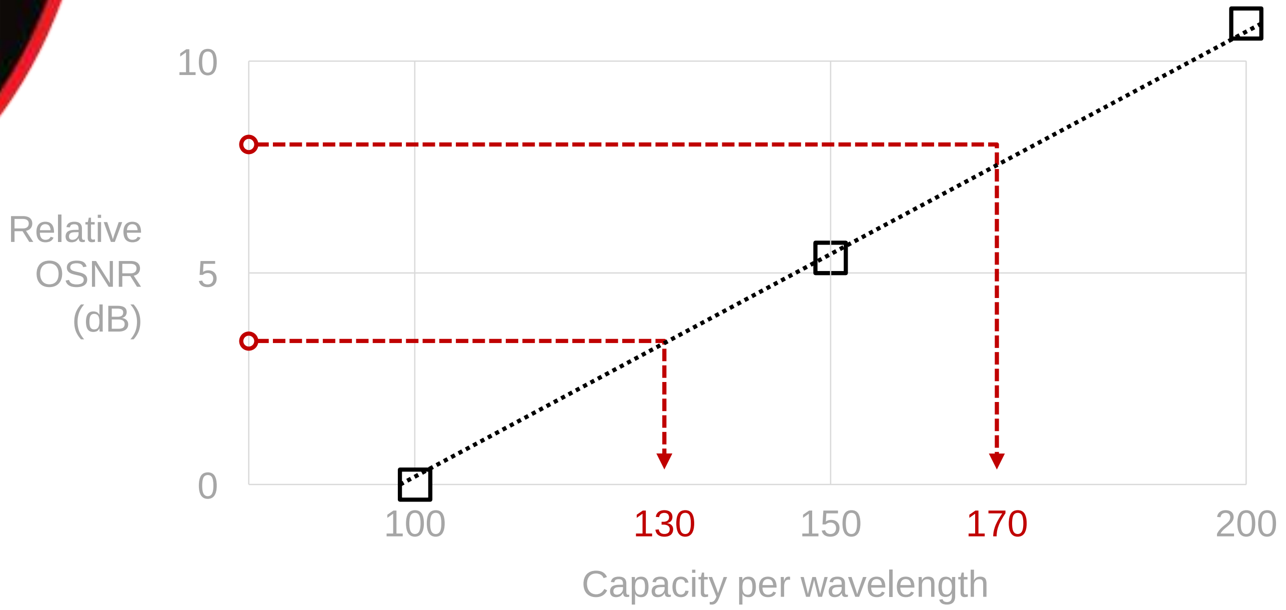
QPSK, 8QAM & 16QAM



Limits capacity unless SNR is just right

Intermediate modulation schemes

Ideal case

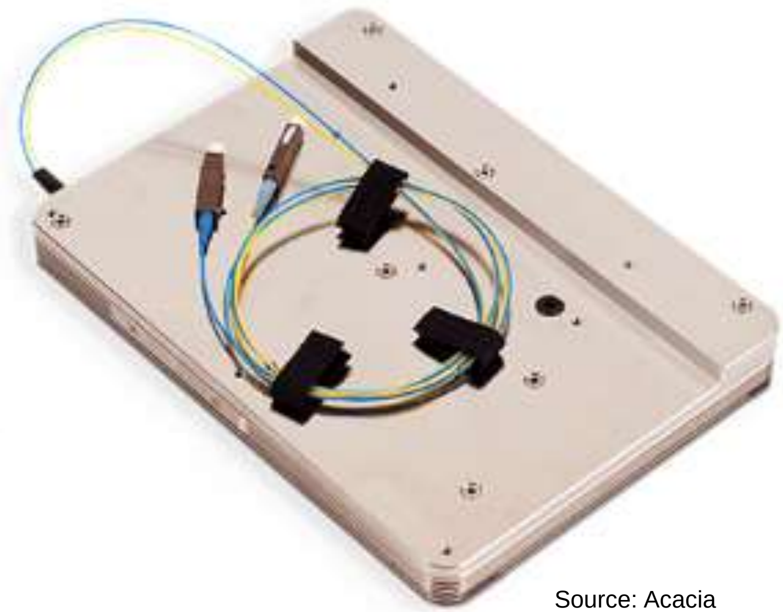


Maximises capacity for a given SNR

Available modules

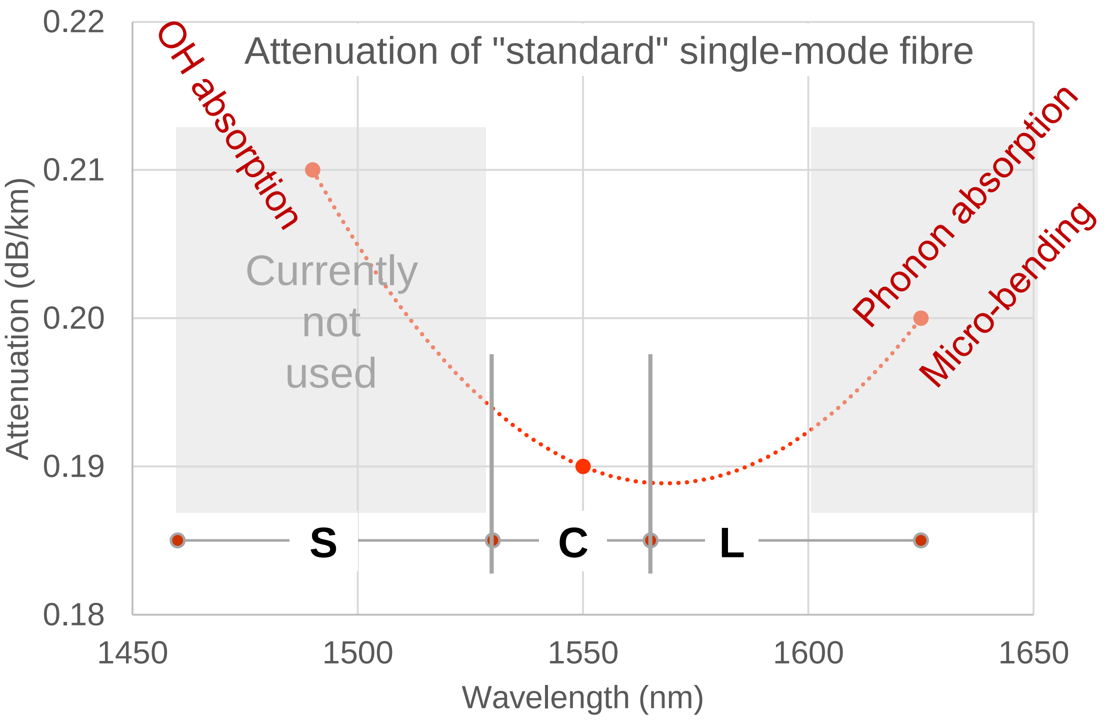
- 5 x 7 inch modules
- Offer up to 800G per wavelength – capacity set by line design
- Steps of 25G
- *Flexibility also on symbol rate, WL grid and FEC parameters*

- Most suppliers integrate 2 wavelengths in the same module Maybe more in the future



Source: Acacia Communications

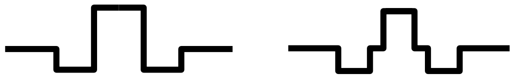
Fibre and optical bands



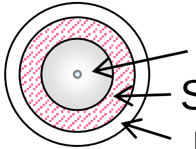
Fibre

- Low attenuation — 0.150-0.156 dB/km available
- See OP-18 for details of — 0.14 dB/km

- Negligible cabling loss
  – Index profile



  – Multi-layer coatings



- Low non-linearity
  – Large effective area — 130-150 micron^2
  – High chromatic dispersion — ~20 ps/km/nm

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Break

Break for questions

TF

Forward Error Correction (FEC)

- Initially Reed-Solomon, then Product codes, now Soft Decision
- Q limit (typically at BER = 1E-13)

  11 dB (RS hard decision)

  8 dB (Product hard decision)

  5 dB (Soft decision)

- 5 dB means correction of around 1 error per 25 bits (average)

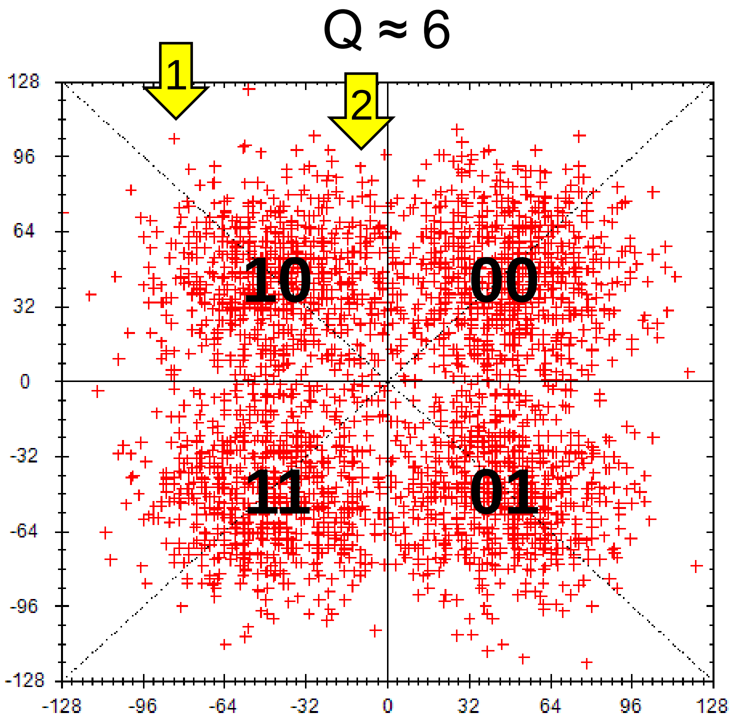
Principle of soft-decision FEC

<u>Hard-decision FEC</u>

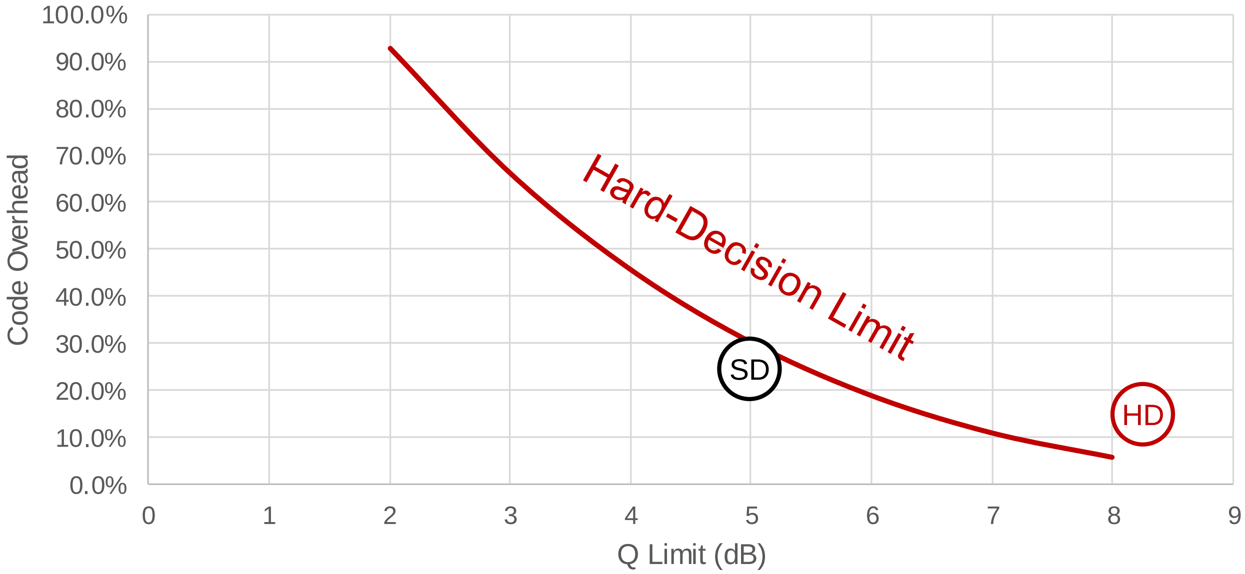
- Decide what symbol was detected
- Apply FEC decoding
- Fails if error probability is too high

<u>Soft-decision FEC</u>

- Uses the symbol value <u>before</u> decoding to determine if an error is likely



FEC limits

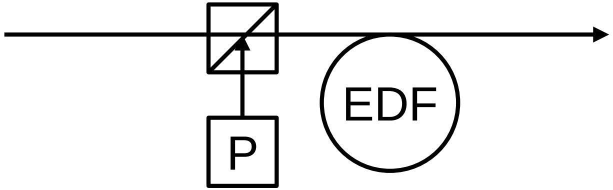


- Higher coding gain needs more overhead = more processing
- Overhead starts to reduce data capacity as Q limit decreases

Fibre-based amplifiers

- EDFA

- NF ~4.5 dB



+ Compact
+ Low consumption
– Bandwidth limited to C-band, ~40 nm

- Most common in subsea (and terrestrial) systems

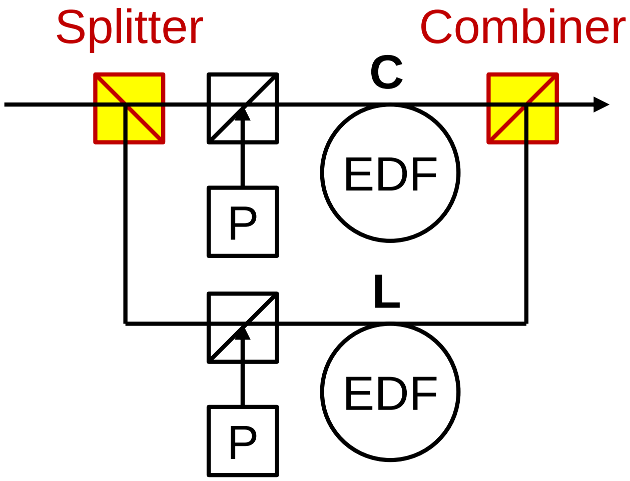
Fibre-based amplifiers

- C + L using couplers

- NF ~4.5 dB

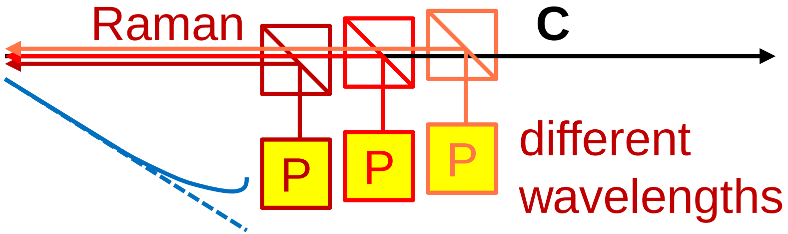
+ Essentially the same technology
+ Bandwidth ~70 nm
– Loss of splitter and coupler
– L amplifier generally more complex than shown

- *Only one supplier offering this*



Fibre-based amplifiers

- Distributed Raman
- Amplification occurs in the cable
- NF 0-3 dB



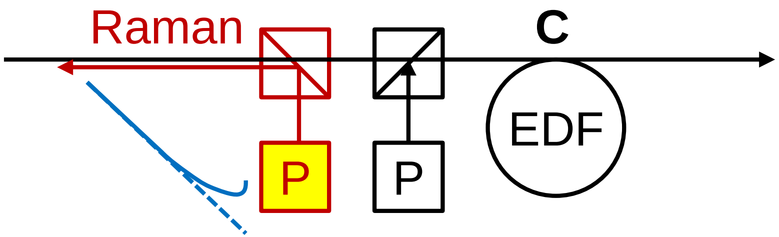
\+ Low noise
\+ Bandwidth up to 100 nm
– Needs several high power Raman pumps

- *Not used in subsea amplifiers, but good for unrepeatered systems*

Fibre-based amplifiers

- EDFA + Raman

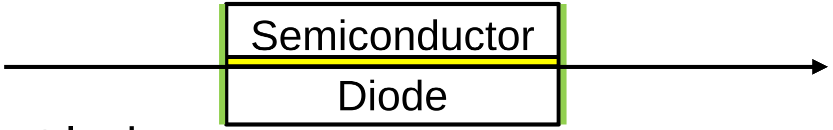
- NF ~2.5 dB



+ Low noise
+ Bandwidth ~70 nm
– Needs Raman pump as well EDFA Pump – similar powers

- *Only one supplier offering this*

Semiconductor Optical Amplifier



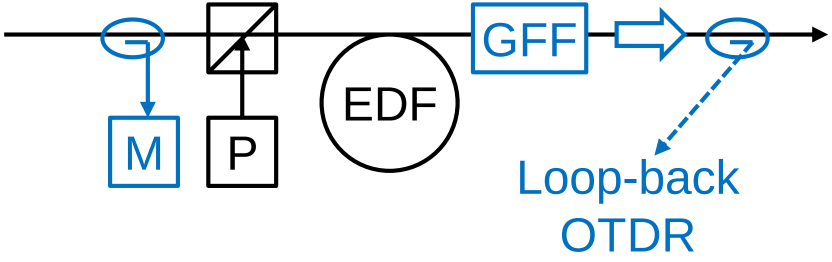
- SOA
- Anti-reflective coating to prevent lasing
- NF 6-10 dB

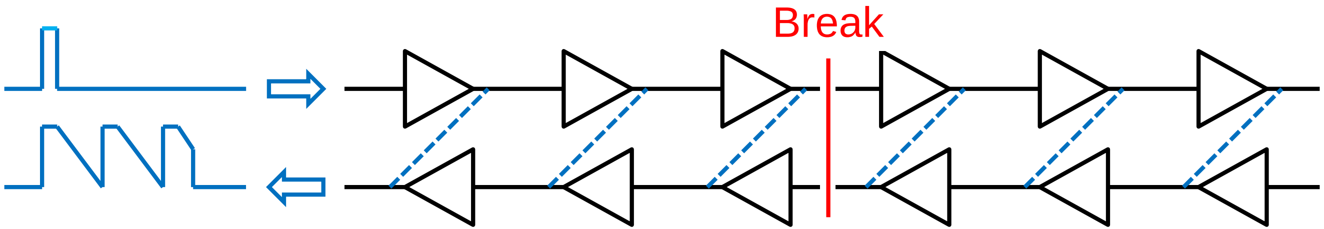
+ Compact
+ Low consumption
+ Large bandwidth >100 nm
– Noise performance not so good 6-10 dB

- *Used in non-telecoms applications e.g. fibre-gyroscopes*

Optical amplifier extras

- Optical Monitoring
- Gain Flattening Filter (GFF)
- Isolator for stability
- Loop-back / OTDR path
  Passive mechanism for fault location



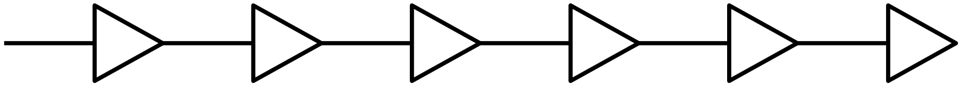


Amplifier noise

- ALL amplifiers generate noise
- Noise spectral density = G·hv·NF
  (for 2 polarisations)
  EDFA NF ~3 (4.5 dB)
  EDFA-DRA ~2 (3 dB)

G = Gain
h = Planck’s constant
v = Frequency
NF = Noise Figure

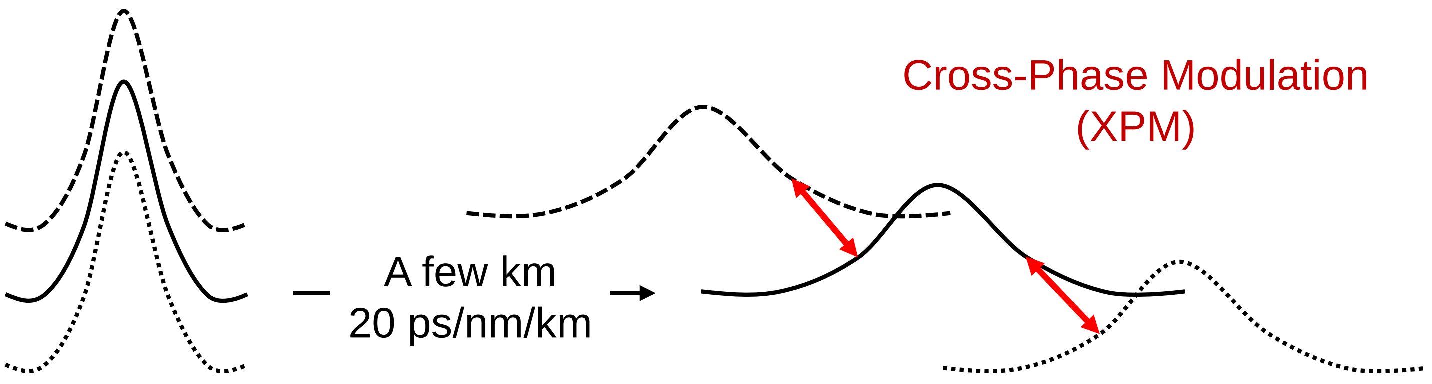
- After N amplifiers



- **Total noise ≈ N·G·hv·NF** (assumes all sections are the same)

Dispersion and non-linearity

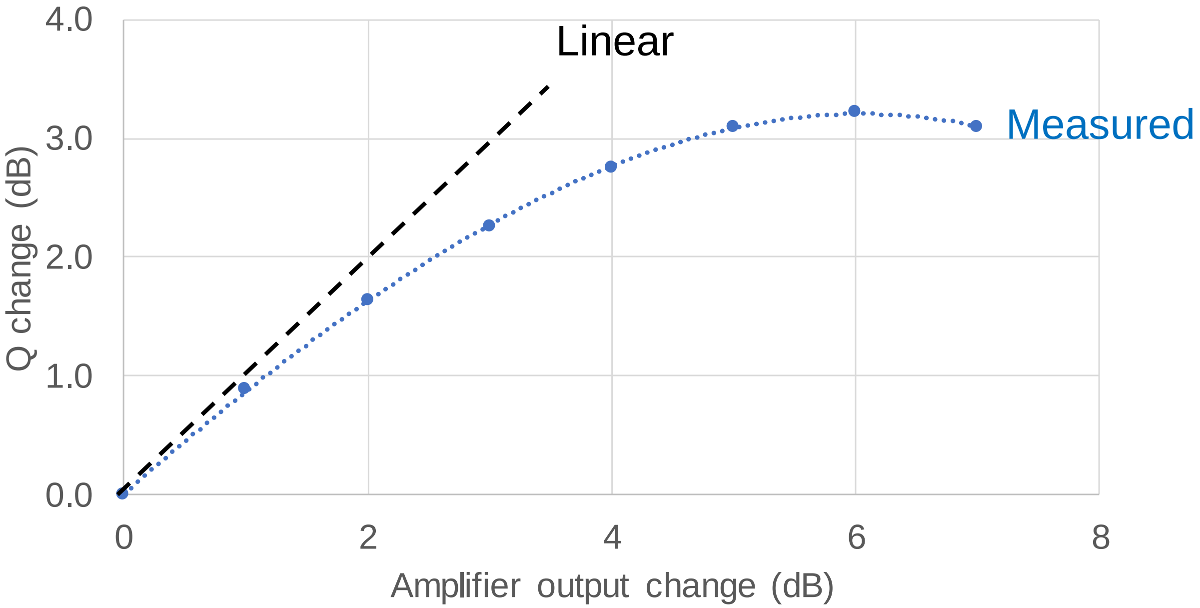
- Chromatic dispersion: different wavelengths travel at different speeds



- Reduces non-linear interaction between different wavelengths
- Most significant effect is Self-Phase Modulation (SPM)

Non-linear effects

Real example



- Benefits of increasing power are limited by non-linear effects

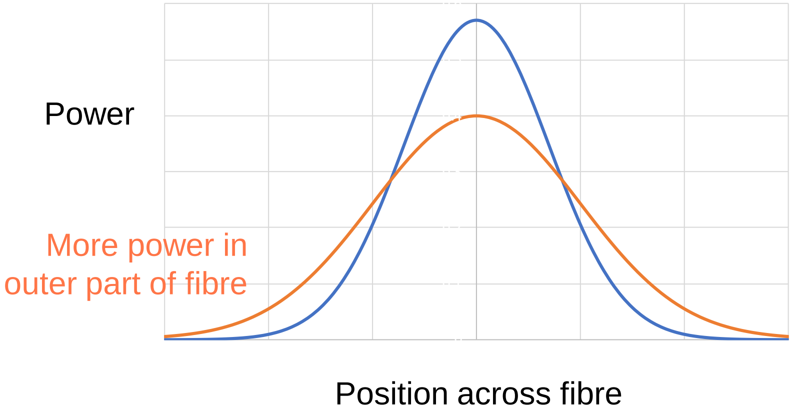
Reducing the effects of non-linearity

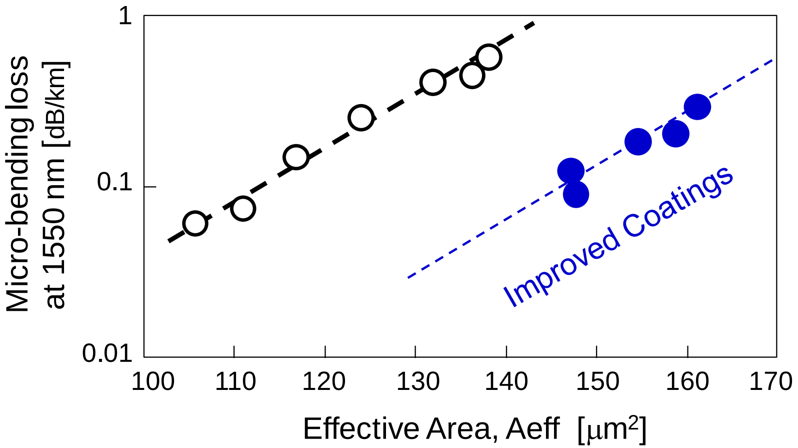
- Several solutions

1. Large core fibre
2. Modification of transmitted constellation
3. Non-linear compensation in receiver

1. Large-core fibre

- Increase mode field diameter: reduce power density

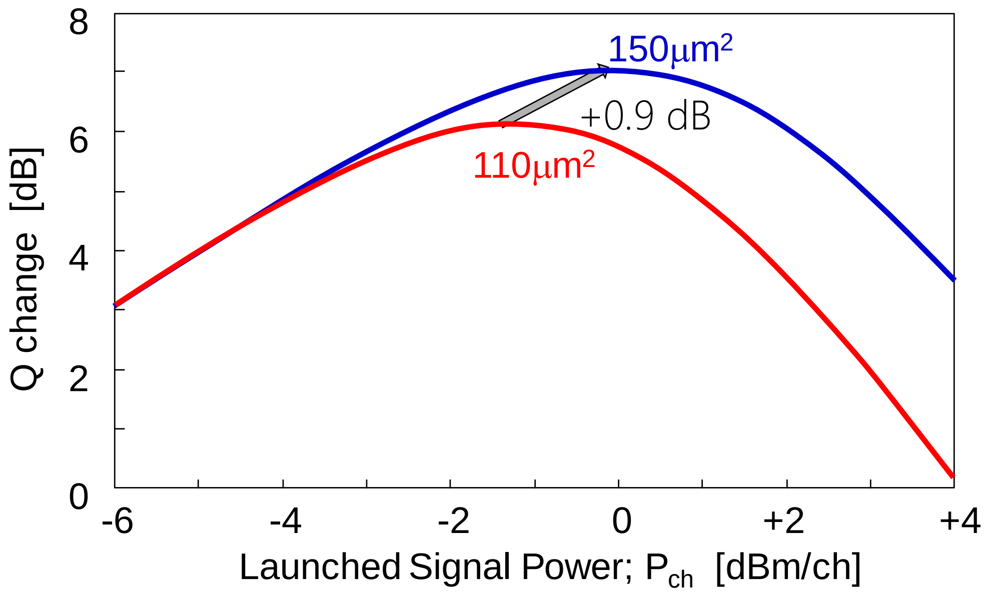




- Needs careful design to avoid increasing micro-bending sensitivity

Improvement due to large-core fibre

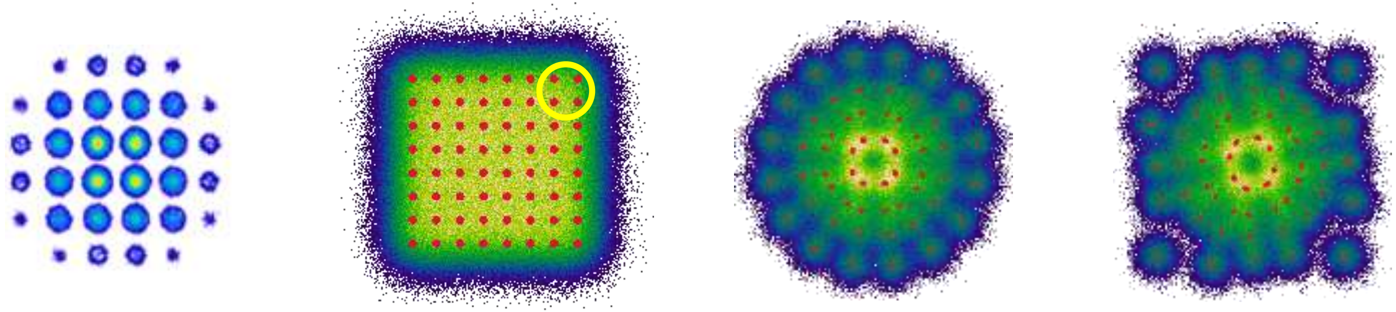
- Increases the level of power that can be used



2. Improved constellations

Constellation shaping

- Geometric (**GCS**): Modify the position of the points

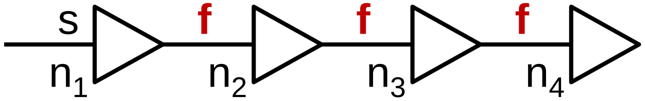


Probabilistic | Square | Geometric | Carrier recovery

- Probabilistic (**PCS**): Modify the relative probabilities of different points

- Need to consider both non-linear performance and carrier recovery

3. Non-linear compensation



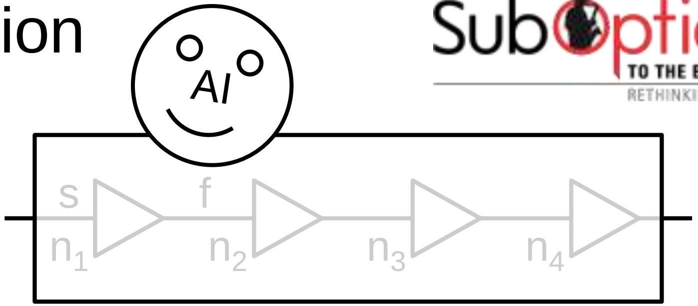
- Back propagation
- $s \rightarrow \mathbf{f}(s + n_1)$
- $s \rightarrow \mathbf{f}(\mathbf{f}(s + n_1) + n_2)$
  $\rightarrow \mathbf{f}(\mathbf{f}(\mathbf{f}(s + n_1) + n_2) + n_3)$
  $\rightarrow \mathbf{f}(\mathbf{f}(\mathbf{f}(\mathbf{f}(s + n_1) + n_2) + n_3) + n_4)$ ...

s is signal, n is noise

f is a non-linear transfer function

- Compensation requires applying $\mathbf{f}^{-1}$ multiple times to derive s
- This process known as "Backward propagation"
- Very complex, but some good alternatives being developed

3. Non-linear compensation



- Using neural network
- Nice demonstration by NEC and Google on the FASTER cable system

- Treats the transmission system as a "black box“
- Initial training allows the network to learn what output should be based on knowing what was transmitted
  Then apply this to unknown traffic
- Not as complex as digital back propagation

Comparison

1. Large core fibre	commonly used solution
2. Constellation shaping	slightly more complex DSP
3. Non-linear compensation	much more complex DSP 0.5-0.8 dB improvement today

- Can be used in combination

Break

Possible Future Technology

RF

Possible technologies

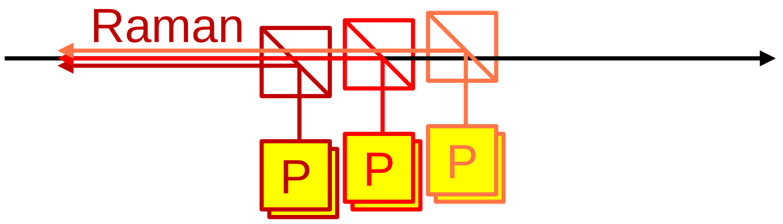
- Cable capacity proportional to:
  number of Fibre-pairs x cores x modes x Bandwidth x $\log_2(1 + SNR)$

- Improved amplifiers — Bandwidth
- Enhanced non-linear compensation — SNR
- Conjugate transmission / reflection — SNR

- SDM (Spatial Division Multiplexing) — Fibre pairs
  – Multi-core fibres — Fibre cores
  – Multi-mode fibres — Fibre modes

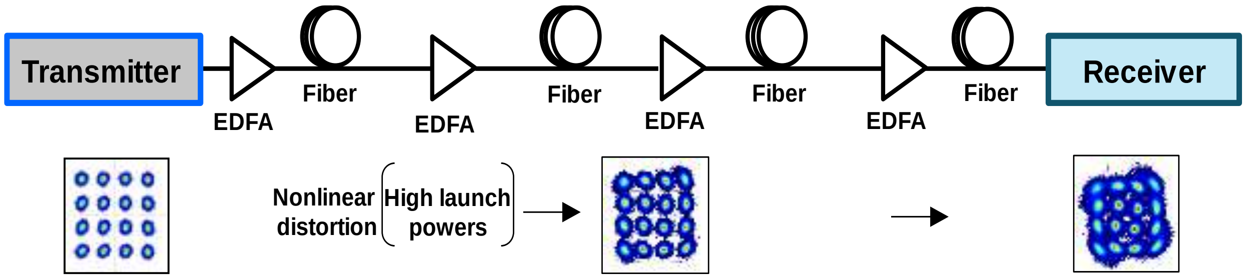
Even greater bandwidth amplifiers

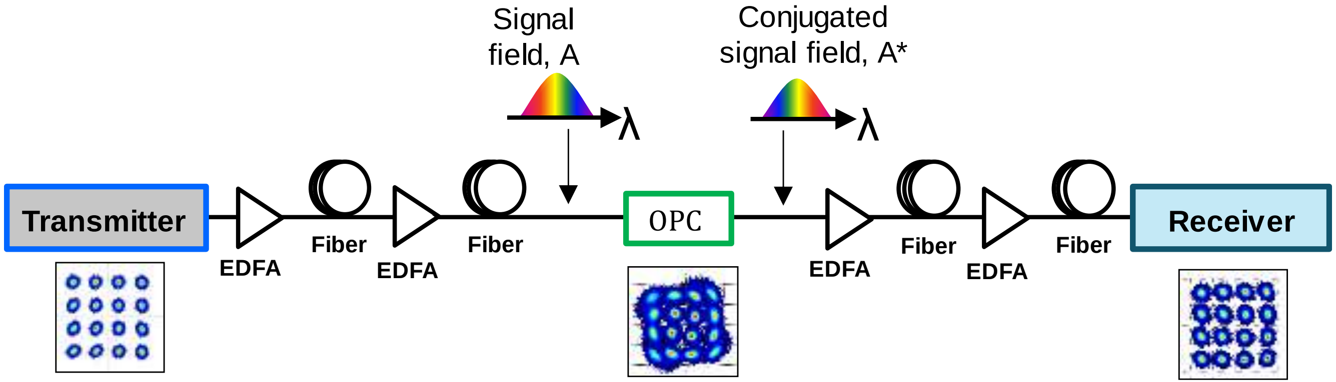
- Possible with Raman – greater than 100 nm demonstrated
- Good noise figure
- BUT
  – more pumps
  – more power
  – more complexity



- A good solution where power is not a limitation
  Example: Unrepeatered systems

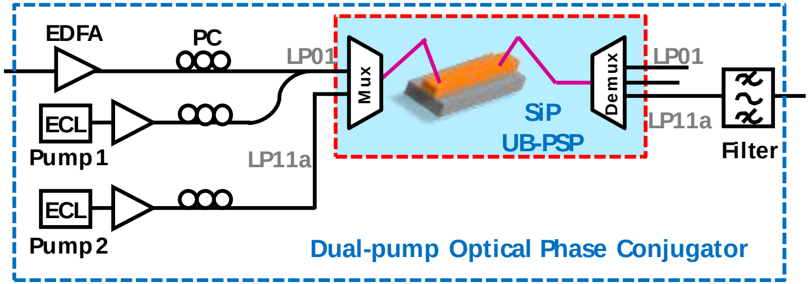
Optical Phase Conjugation (OPC)

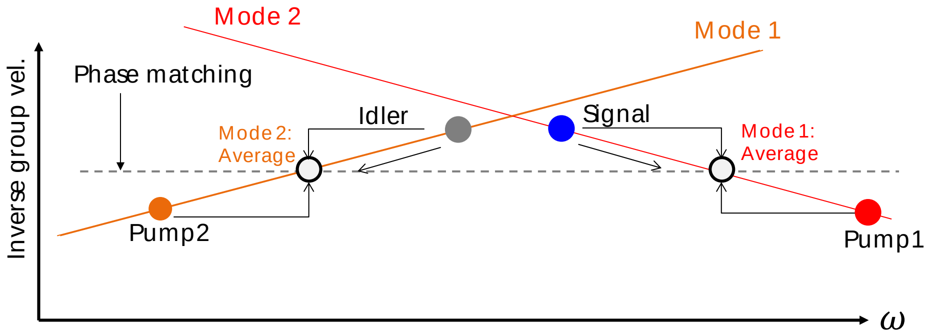


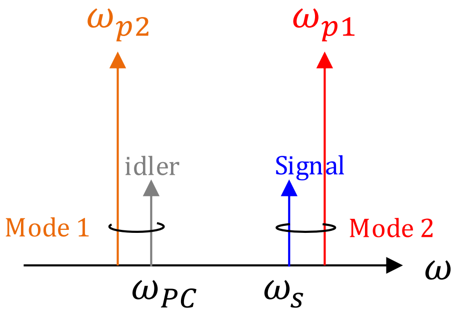


Not easy to find practical realisation

Phase conjugation using non-degenerate intermodal FWM





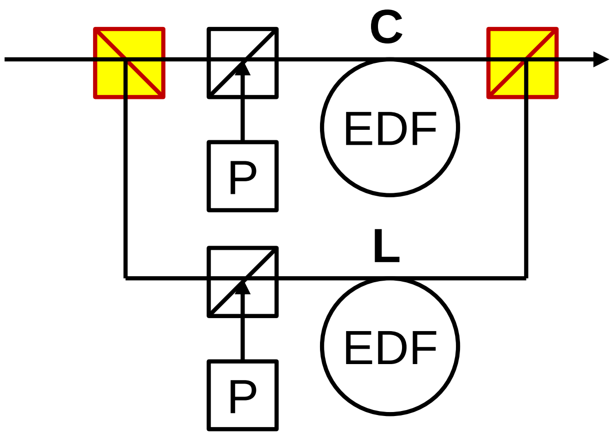


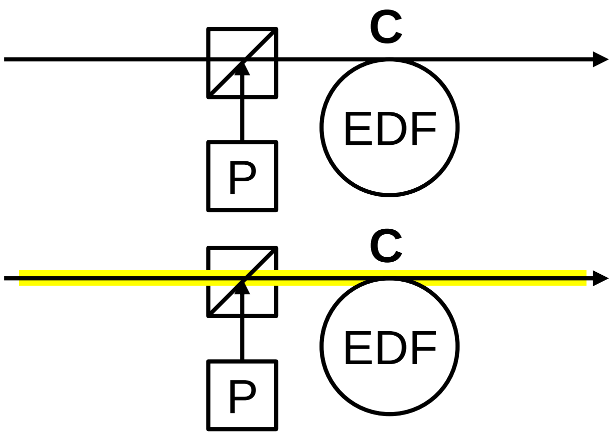
Energy conservation:

$\omega_{p1} + \omega_{p2} = \omega_s + \omega_{PC}$

Broadband operation can be achieved using dispersion-engineered waveguide

C + L or C + C?

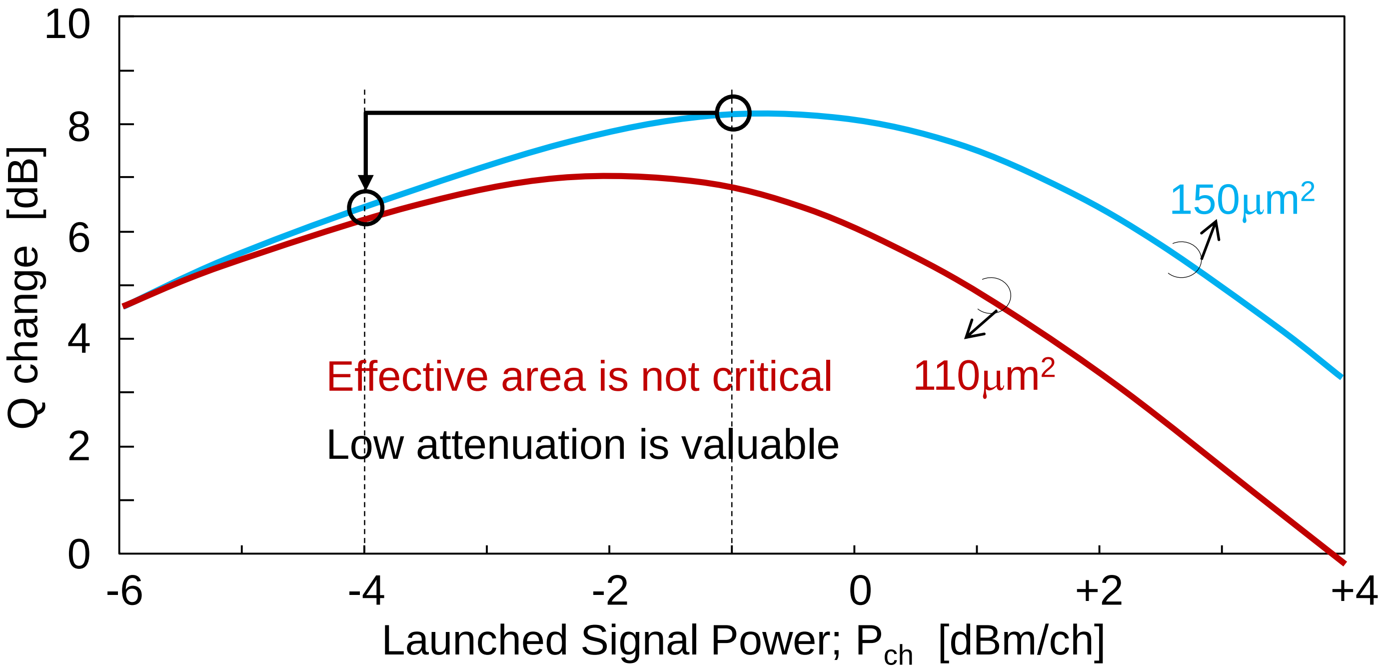




+ Saves fibre
– Adds couplers
– More complex L amplifier

+ Saves power
+ Simpler
– More fibre (or cores)

Also reduce power



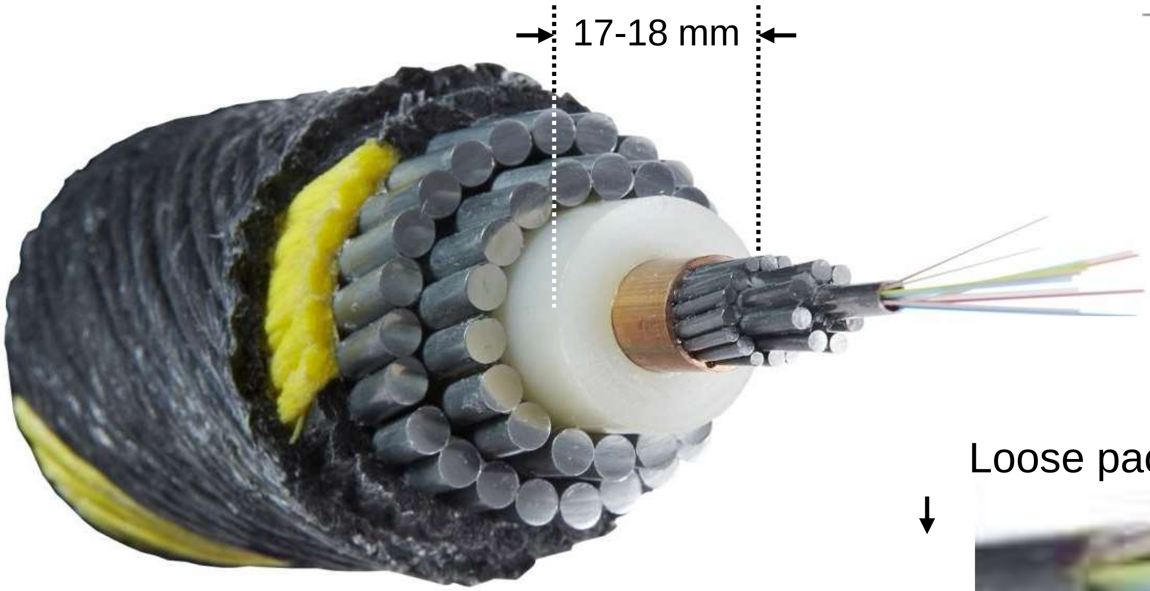
- Power reduction is significantly greater than Q change

Attenuation

- Affects consumption by changing the power needed from the amplifier

- Example: 100 km spacing
  0.01 dB/km reduction
  = 1.00 dB per section
  = 20-25% more amplifiers for the same total consumption

Typical cable



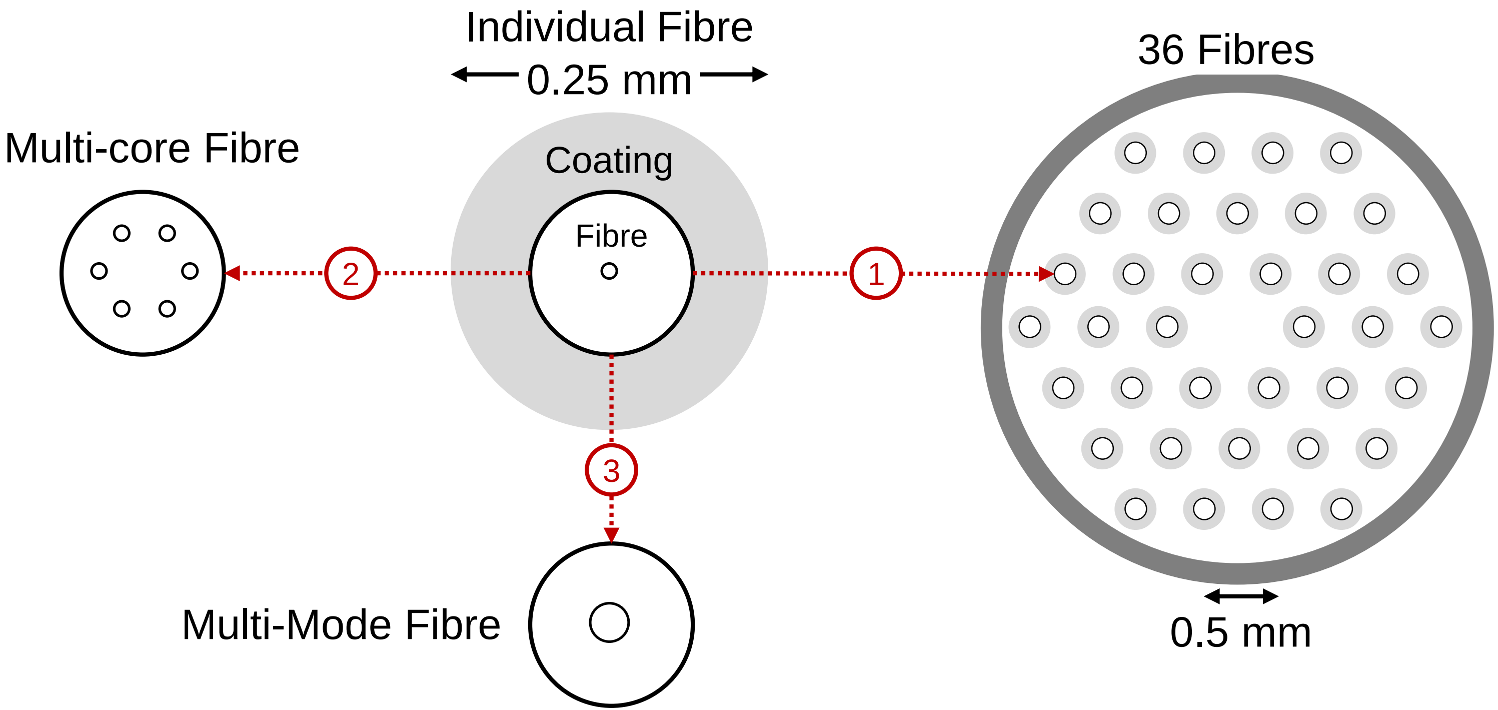
Source: Nexans

Loose packing

~3 mm

- Highly desirable to maintain cable size
  Cost, Handling, Length that can be loaded …

Possible SDM routes



Possible SDM fibres

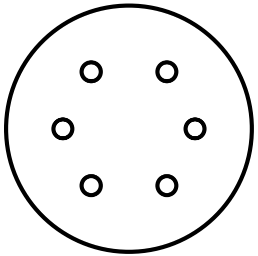
- OP-10 "Low-loss multi-core fibers for submarine transmission"

Single-core fibre	2 core fibre	4 core fibre	Multi-mode fibre

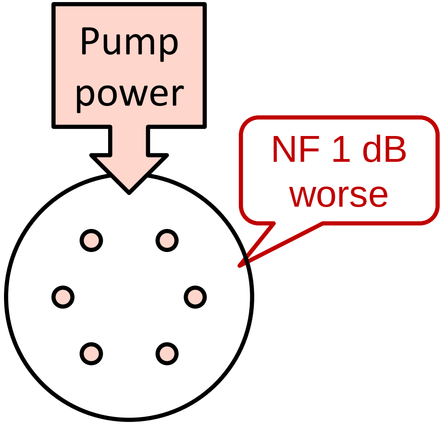
0.15 dB/km	0.16 dB/km	0.16 dB/km	0.23 dB/km
SiO_2	SiO_2	SiO_2	GeO_2+SiO_2
		Needs MIMO	Needs MIMO

Multi-core fibres

- More compact, so will fit in existing tubes
- Core interaction is an issue



- Will probably need individual amplifiers
  Cladding pumped amplifier doesn’t solve:
  Gain flattening
  Loop-back / OTDR coupling



Multi-mode fibres

- By changing the core, a fibre can propagate several modes
- Each could carry different data

- It is relatively easy to create multi-mode EDF amplifiers, which avoids problems coupling fibre to amplifier
- BUT

- What will the performance of multi-mode fibre be like?
  - Micro-bending?
  - Mode coupling?
- How are the modes coupled into the fibre and separated at the end?

TF

Sum-up

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Summary – to provoke questions!

	Don’t take too seriously
• New types of amplifier	Not soon
• Larger core fibre	No; SDM instead
• Better non-linear mitigation	No; SDM instead – upgrades?
• Improved FEC	Getting harder to improve?
• More flexible constellations	Better granularity
• Lower consumption DSP	Yes
• Spatial Division Multiplexing (SDM)	Yes
• Multi-core fibre	Some challenges
• Multi-mode fibre	Mode mixing?

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SubOptic2019

TO THE BEACH AND BEYOND

RETHINKING GLOBAL NETWORKS

Thanks for listening

We hope it was useful, interesting

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