SUBCOM

# SDM Power-Efficient Ultra High-Capacity Submarine Long Haul Transmission Systems

(Tutorial)

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# Abstract

**Submarine long-haul systems have a unique set of challenges to address the capacity demand. The tutorial will examine the need for power efficiency, SDM solutions for capacity and greater economy, and ways to move forward.**

# Power Efficiency Metric

- Power efficiency for given system length can be defined as:

$$PE = \frac{Capacity}{Power}$$

- Power total electrical power provided to all repeaters

**Tutorial will focus on optical side of power efficiency problem**

# Power Efficiency Impacts Cost Efficiency

- Why do we worry about power efficiency?
- Cost efficiency characterized as “cost-per-bit” or “cost-per-unit-capacity”:

$$C_c = \frac{Cost}{Capacity}$$

- Cost efficiency expressed through power efficiency

$$C_c = \frac{Cost}{PE \cdot Power} \sim \left.\frac{\boldsymbol{Cost}}{\boldsymbol{PE}}\right|_{\boldsymbol{fixed\ cost}}$$

- Examples: more power efficient system requires less power conductor
  - More power efficient system provides more capacity for the same cost

*Footnote: the most power efficient case is not always the most cost efficient*

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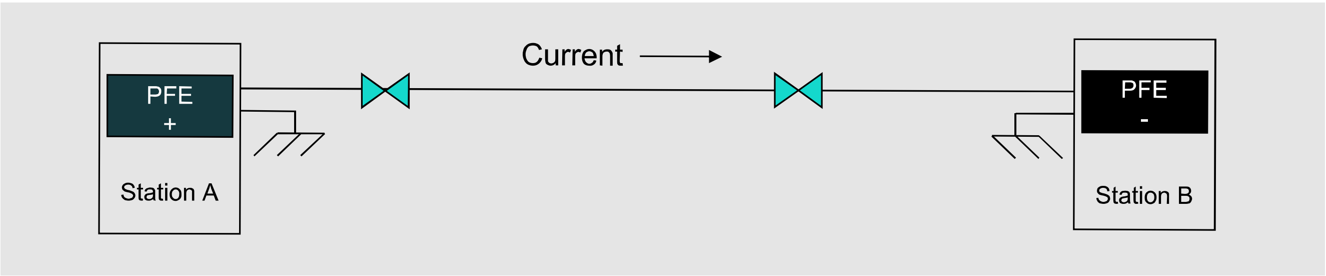
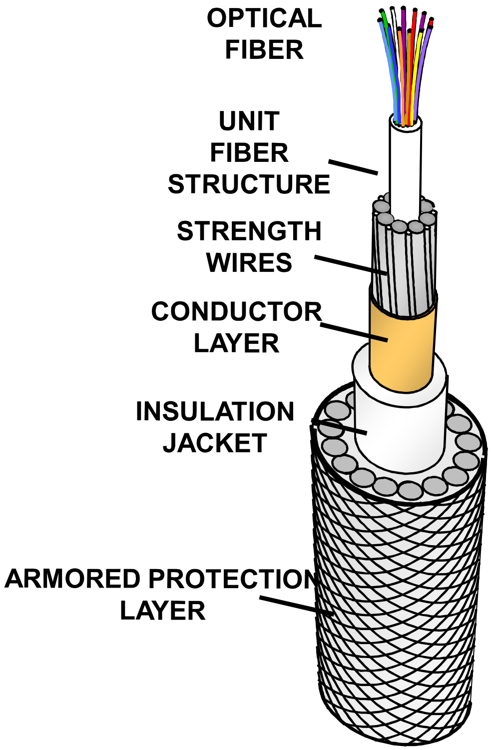
**Focus on what can be done optically for power efficiency**

*Footnote: the most power efficient case is not always the most cost efficient*

# Undersea Systems and Power Efficiency

# Undersea Cable Specifics




- Full C-Band or C+L EDFA based repeaters
- Distances up to 15,000 km
- Amplifier spacing 70-110 km
- Power feed from the shores: up to 15 kV
  - *Maximum voltage and cable resistivity set limit on the amount of available power to the repeaters*


Ref: Frishch T. and Desbruslais S., "Electrical power, a potential limit to cable capacity," Proc. SubOptic 2013, paper TUIC-04, Paris, France, 2013

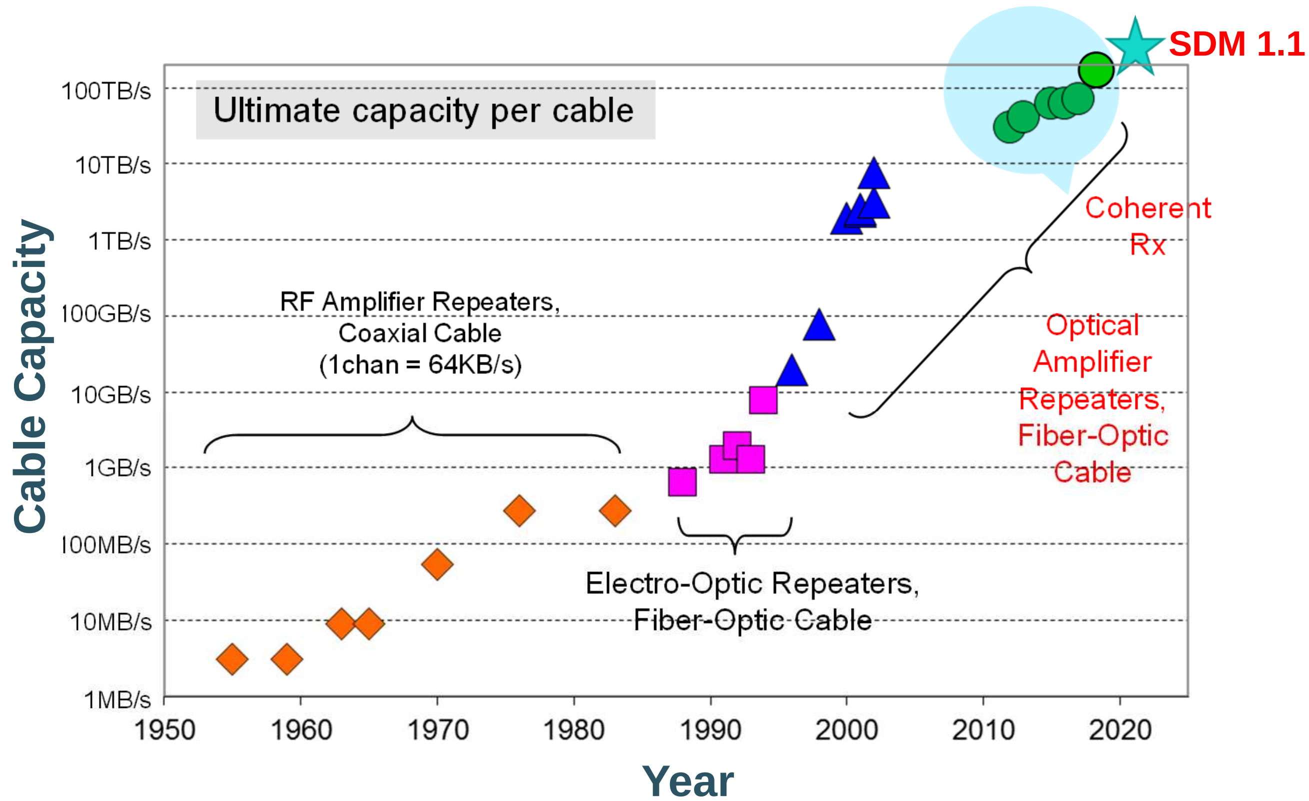
# Power Related Important Parameters

- Signal to noise ratio
  - Number of amplifiers
  - Amplifier output power, NF, gain
  - Amplifier bandwidth
  - Fiber loss and effective area
- Optical amplifier power efficiency: laser pump power to signal power
- Electrical to optical pump power conversion
- Power delivery through the cable
  - Cable resistance and maximum voltage
  - Power feed circuitry for optimal power delivery

Ref: Frishch T. and Desbruslais S., "Electrical power, a potential limit to cable capacity," Proc. SubOptic 2013, paper TUIC-04, Paris, France, 2013

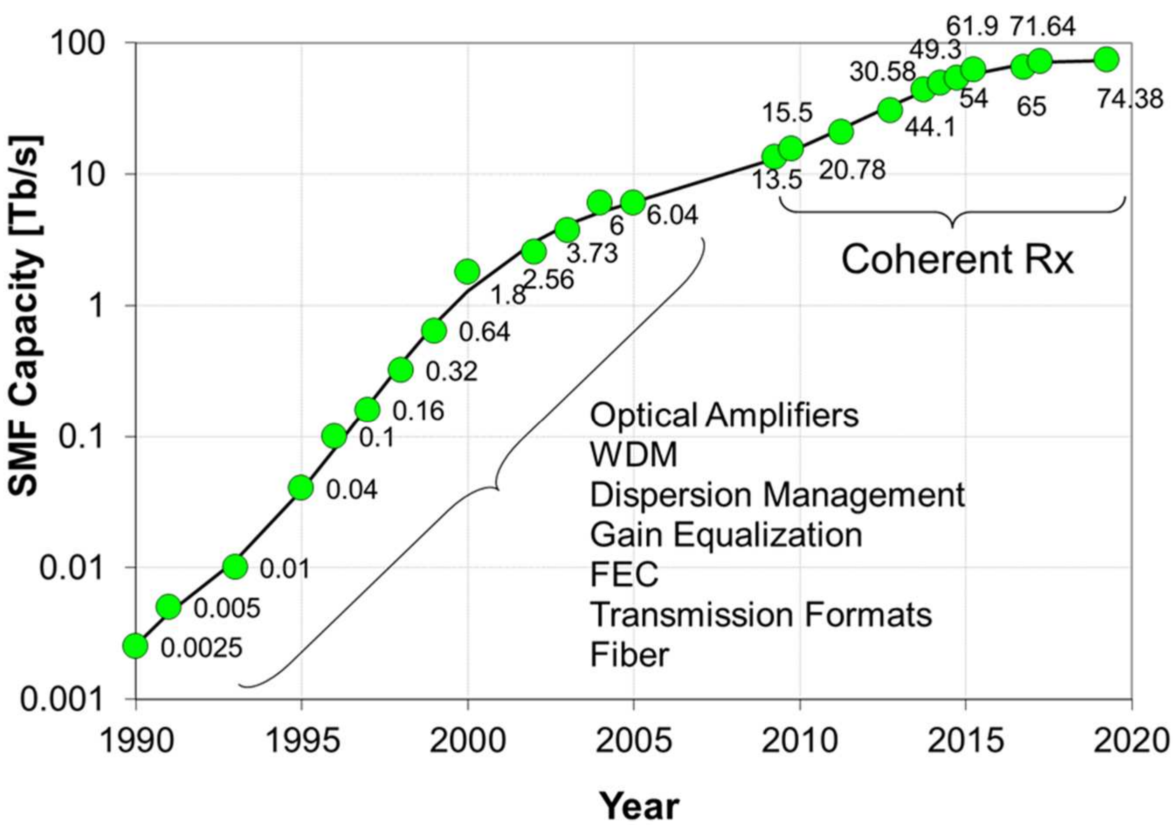
# Cable and Fiber Capacity

# Undersea Cable Capacity Evolution




- 5 orders of magnitude in cable capacity in single mode fiber transmission
- Even more orders of magnitude in cost per bit improvement
- Cable structure is largely unchanged
  - Power efficiency also had exponential growth

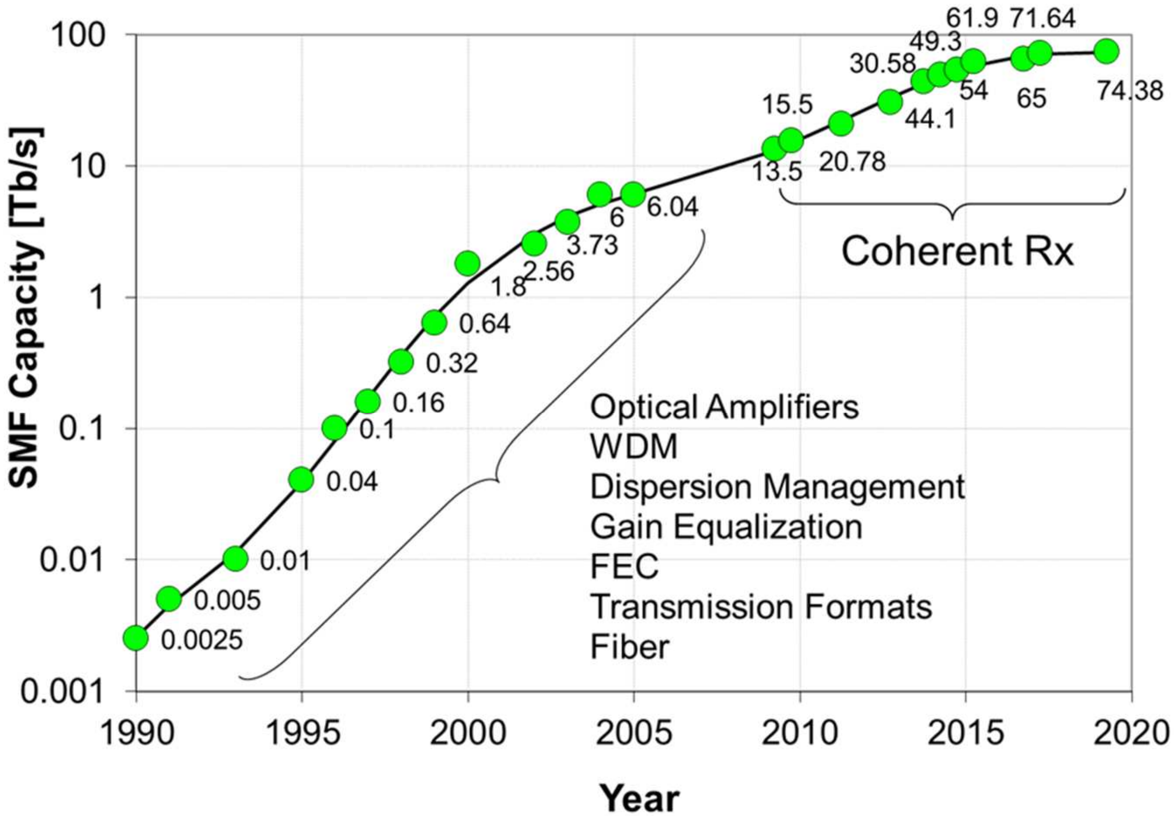
# Single Mode Fiber Long-Haul Record Capacity




## Fiber capacity increase:

- ~15dB is due to amplification bandwidth
- ~*2 dB due to amplifier NF*
- *~10 dB to fiber: loss, effective area*
- *~20 dB: FEC, coherent RX, spectral shaping, modulation*

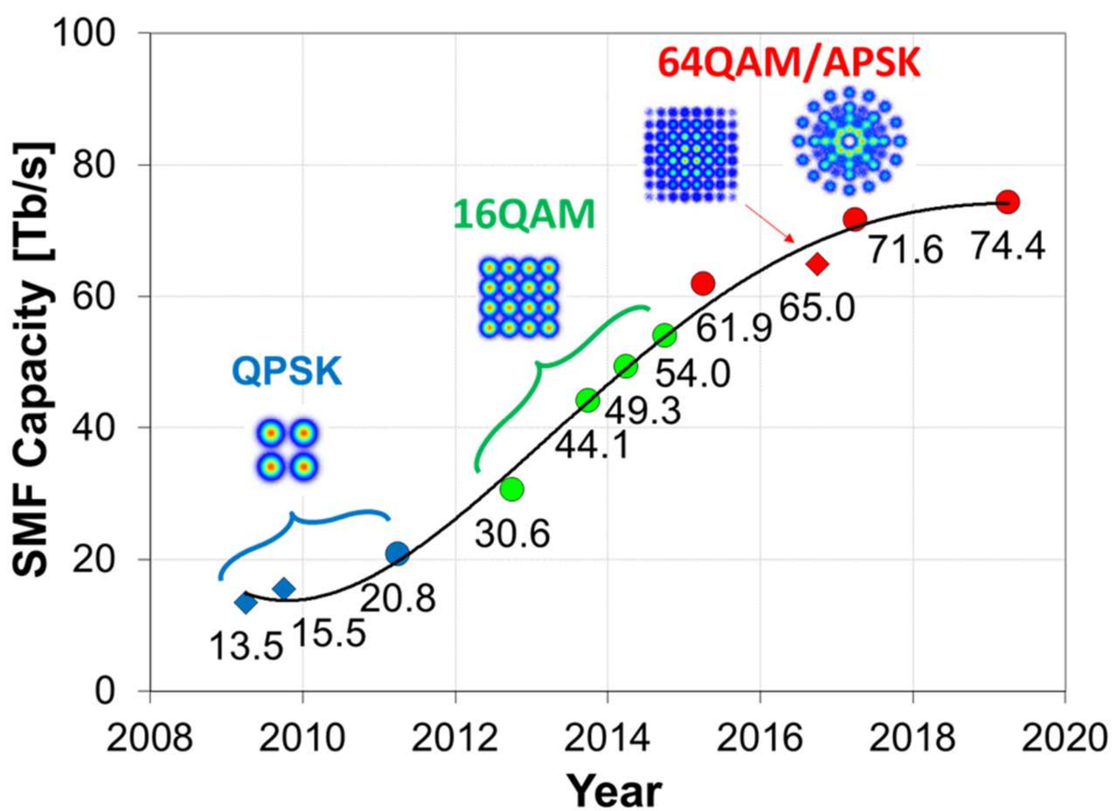
# Single Mode Fiber Long-Haul Record Capacity




PHILOSOPHY:

**Maximizing transmission performance in a fiber**

# Single Mode Fiber Capacity with Coherent Rx



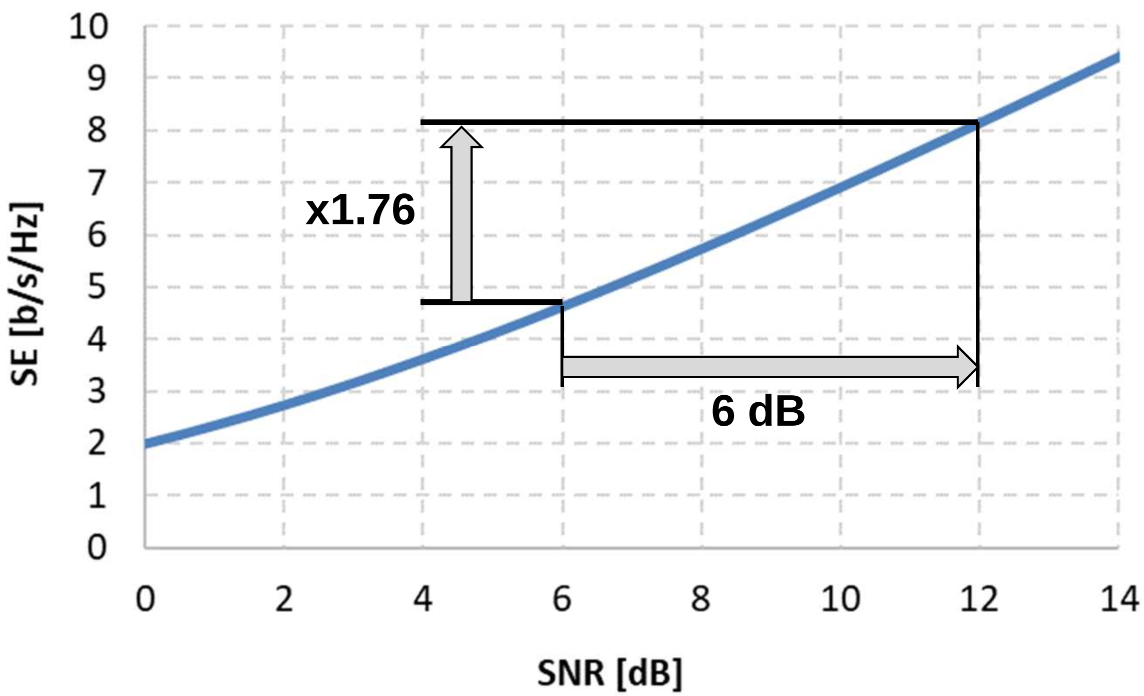

- Higher spectral efficiency
- Higher SNR
- Larger effective area lower loss fiber
- Nonlinearity mitigation and compensation
- Mirrored by the trends in actual system design
    - Higher SNR targets are decreasing PE

# Techniques Used in SMF Results

- Advanced Modulation Schemes with Variable Spectral Efficiency
  - High OSNR Sensitivity
  - Maximizing fiber capacity through maximizing SE
- Nonlinear mitigation
  - Large effective area 150 $\mu m^2$ low loss fiber
- Nonlinear compensation
  - **Up to 1.5 dB**
  - **Transmission path design to take advantage of NLC-optimal launch power at every wavelength**
    - 22.5 dBm in C+L bands
- *Maximizing SE is contrary to maximizing power efficiency*

Ref: Cai, J.-X., Batshon, H., Mazurczyk, M., et al.: “70.46 Tb/s Over 7,600 km and 71.65 Tb/s Over 6,970 km Transmission in C+L Band Using Coded Modulation with Hybrid Constellation Shaping and Nonlinearity Compensation”, J. of Lightwave Tech., 2018, 36, (1), pp 114-121.

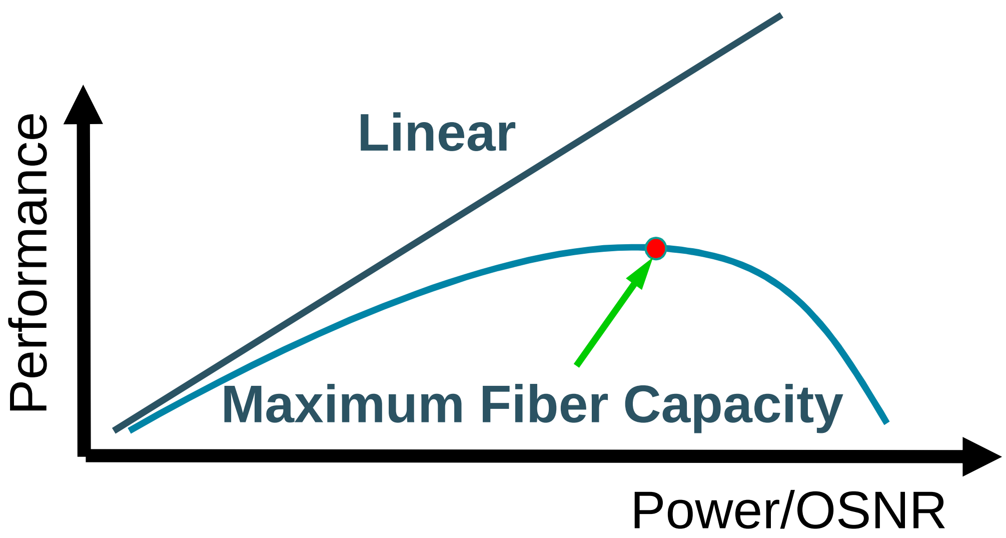
# Shannon Limit




$$SE = 2\log_2(1 + SNR)$$

- 1.76 increase in SE requires 4x more SNR
- Large effective area fibers and nonlinear compensation are needed to operate at large SNR

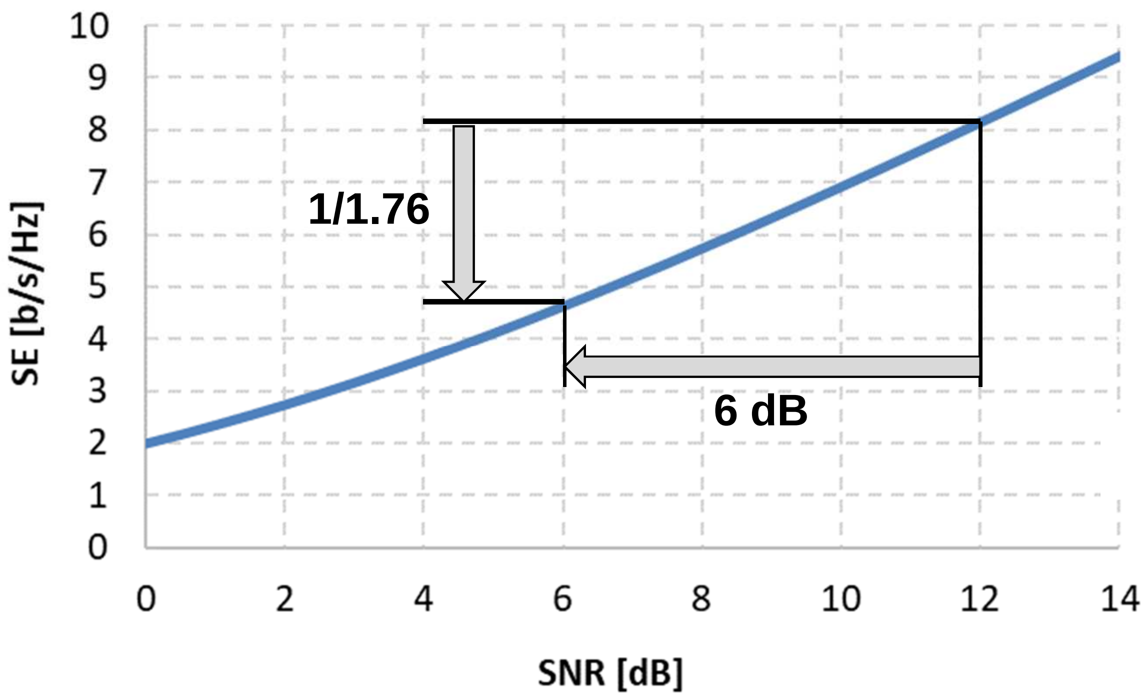
# System Design Philosophy Until Now



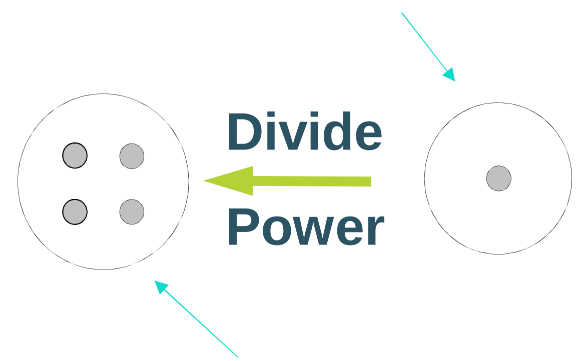

- Maximize Fiber Capacity
- Operate at Peak Performance
- Nonlinearity mitigation and compensation
  - Fiber choice
  - DSP
  - Future proofing

# Shannon Limit, SDM, and Power Efficiency

# Shannon Limit and SDM




$$SE = 2\log_2(1 + SNR)$$

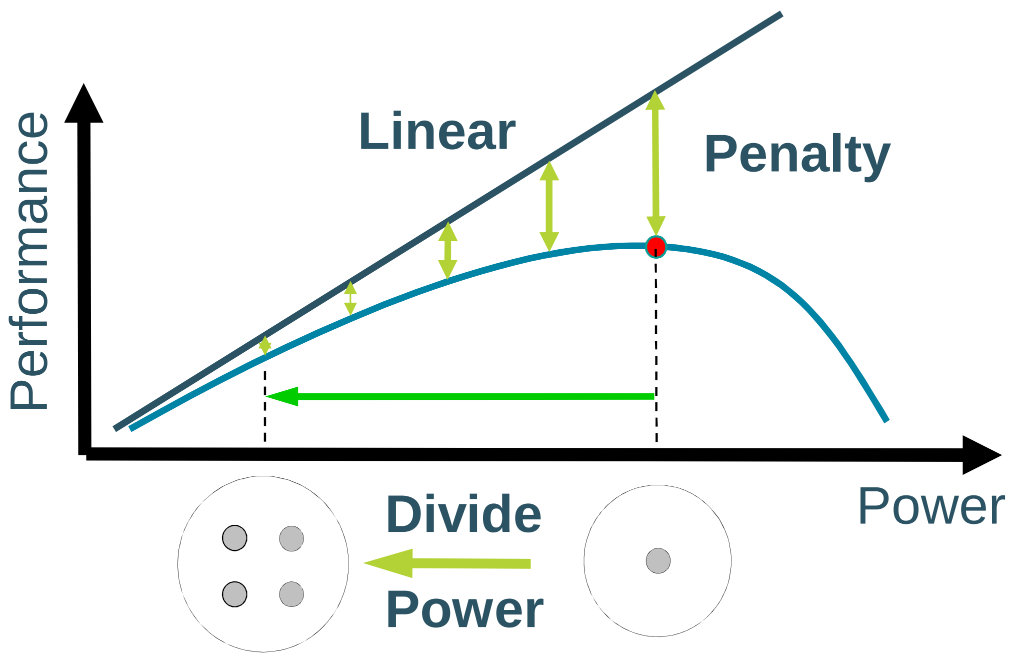



$$SE = 2 * M * \log_2(1 + SNR/M)$$

- Increase in capacity by ~2.3
- Degree of freedom in system design

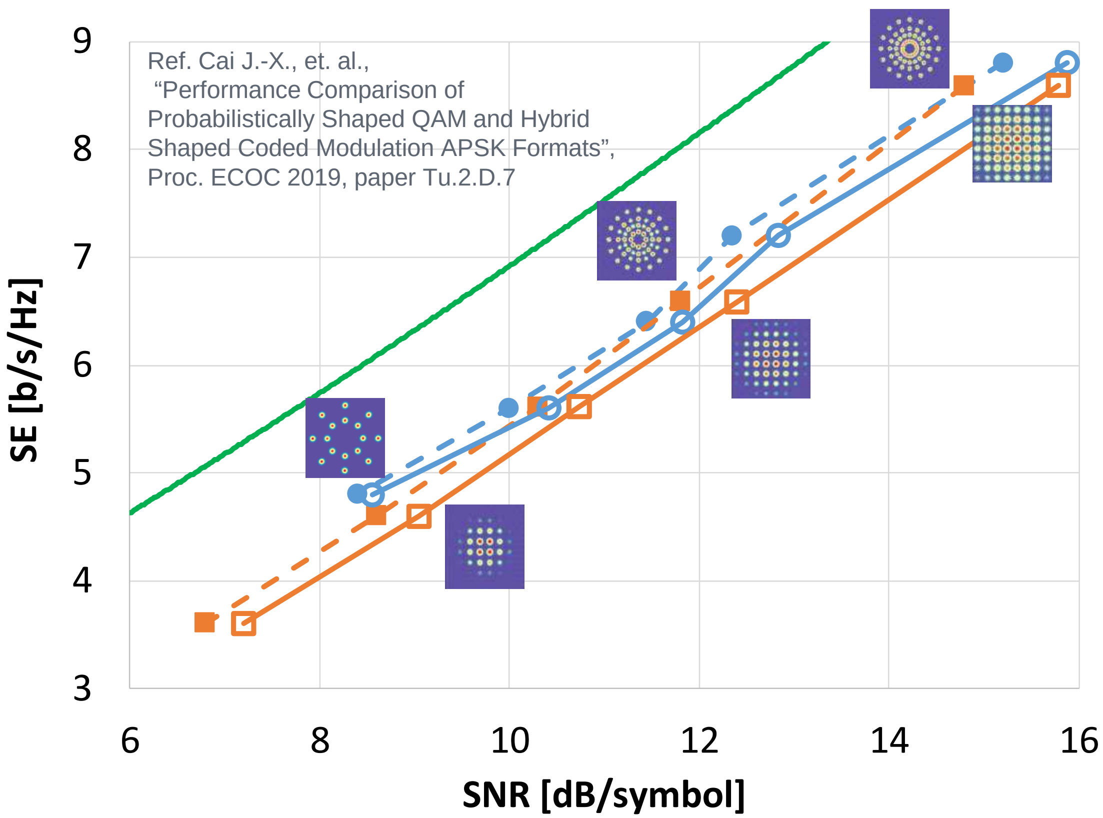

Ref. R.-J. Essiambre and R. W. Tkach," *Capacity Trends and Limits of Optical Communication Networks*", Proc. of the IEEE, Vol. 100, pp 1035-1055, (2012)
Ref: A. Pilipetskii, *" High Capacity Submarine Transmission Systems",* Tutorial W3G.5, OFC 2015

# Reducing Nonlinear Power Penalty with SDM




- ~33% of optical power at peak performance is creating nonlinear noise
- SDM reduces nonlinear penalty
- Larger choice of fiber types

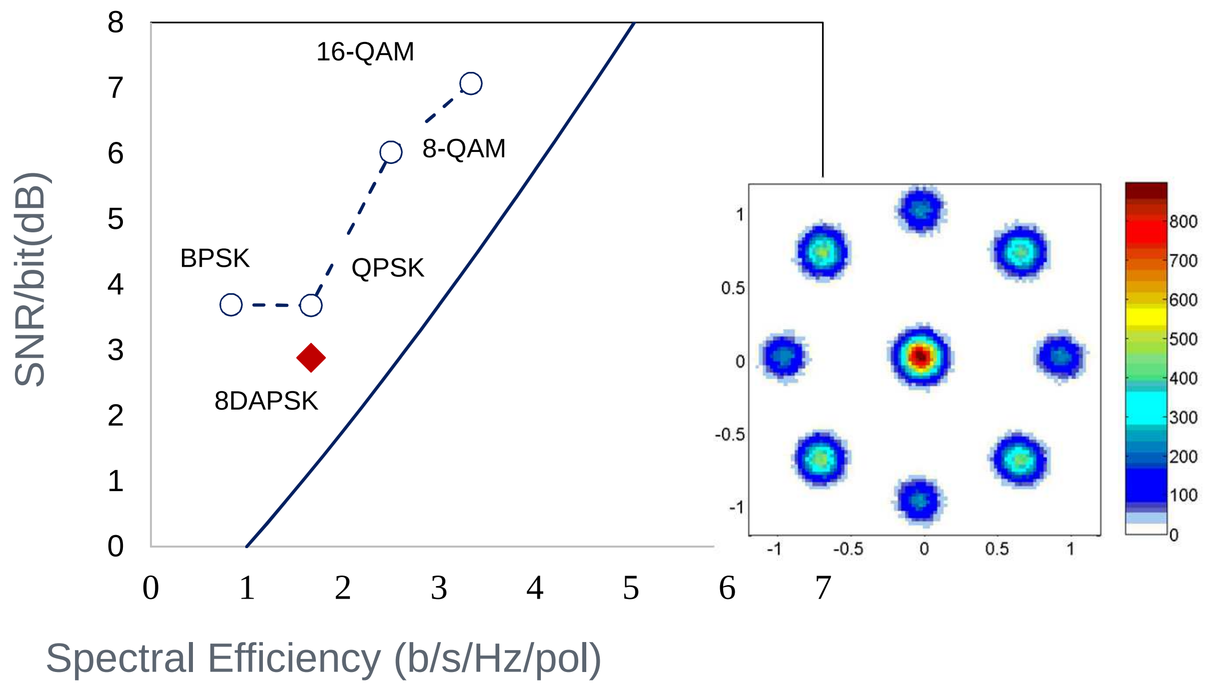
# Shannon Limit and Modulation Formats




- Multiples ways to approach Shannon limit
  – Choice of spectral efficiency is available
- Known modulation schemes (with FEC) are about 2 dB away from Shannon limit
  – ~15 % capacity increase is still possible
  – Direct relation to power efficiency
- Potential SNR gain due to fiber loss reduction ~ 1 dB
  – Capacity increase~5-7%
  – Lower loss fibers lead to power efficiency

# Power Efficient Modulation Formats

$$PE \propto \frac{1}{SNR\ per\ bit}$$



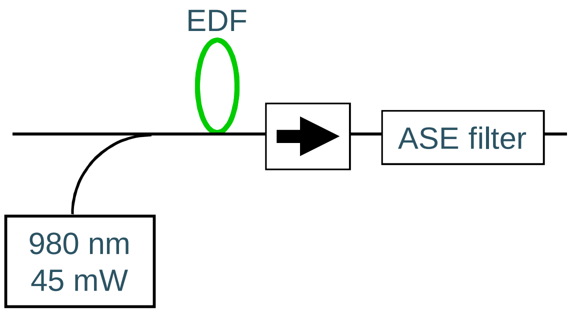

Ref. H. Zhang, et.al., “Power-Efficient 100 Gb/s Transmission over Transoceanic Distance Using 8-Dimensional Coded Modulation”, ECOC 2015, Paper Th.2.2.1.

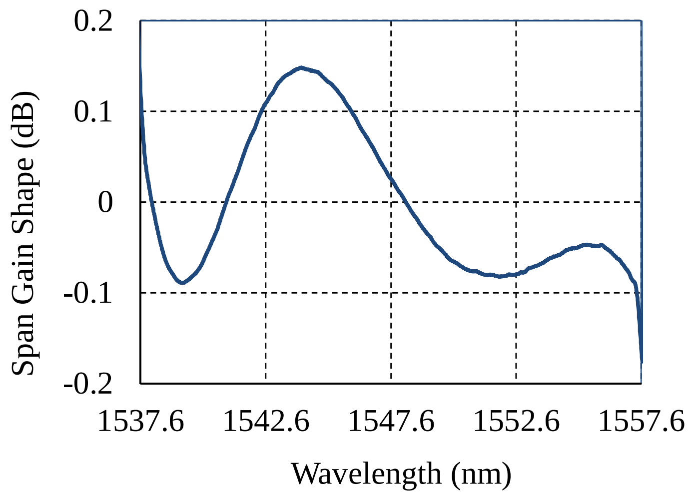
# What Can Be Done Optically to Improve PE?

- Space Division Multiplexing
- Modulation formats
- Low loss fibers and components
- Amplifier bandwidth and spacing
  - Transmission experiments
  - Amplifier comparison

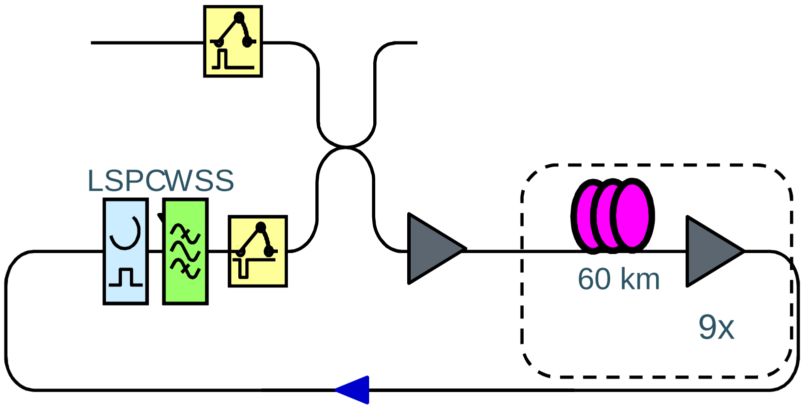
# Transmission Experiments, Amplifier Comparison in Experiments

# Power Efficient SMF Transmission Experiment



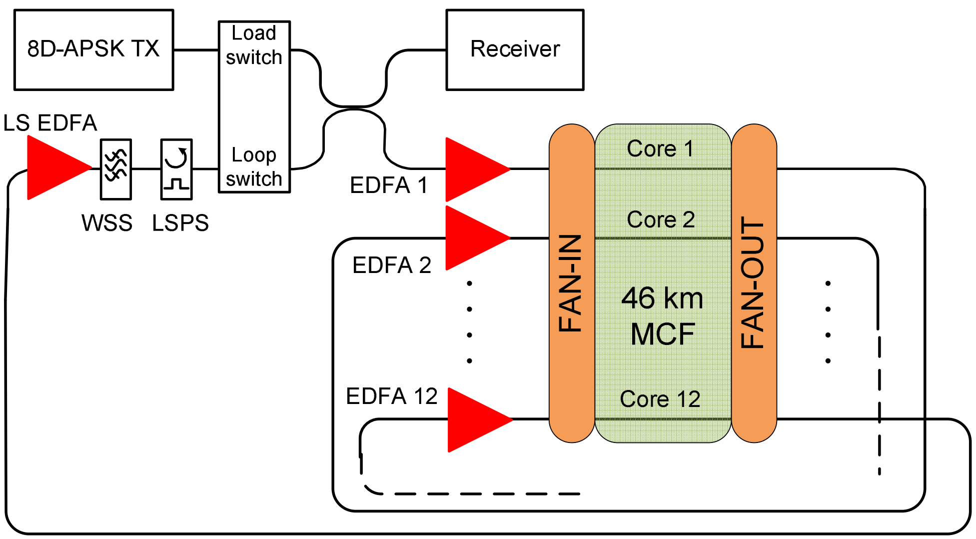




- Narrow BW single-stage EDFAs
  - *No gain equalization in EDFA (no extra loss)*
- 45 mW pump power per EDFA
- Near optimal repeater spacing
- 8.12 Tb/s capacity over 9,750 km
- *~5x more power efficient than record capacity experiments*




Ref. H. Zhang, et.al., “Power-Efficient 100 Gb/s Transmission over Transoceanic Distance Using 8-Dimensional Coded Modulation”, ECOC 2015, Paper Th.2.2.1.

# Power Efficient MCF Transmission Experiment

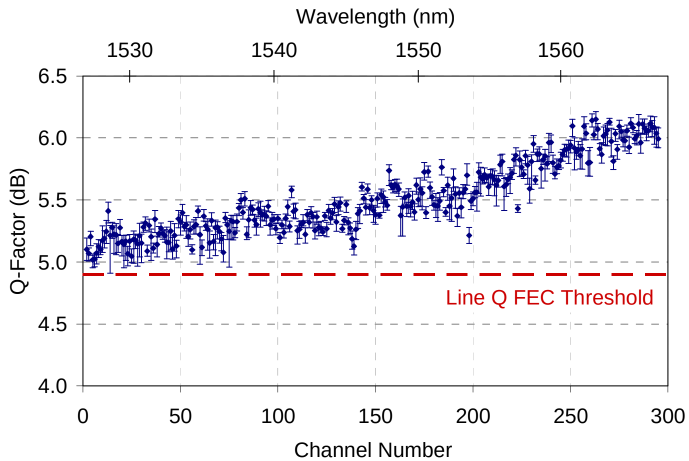


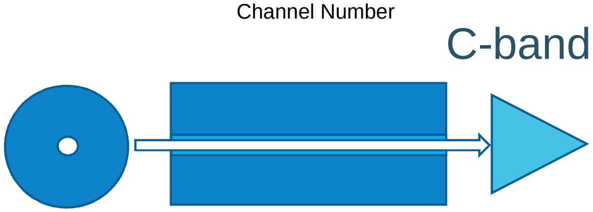

- 46km 12 core MCF spans
- 14,350km transmission
- 82X106.8 Gb/s per core
- 105.1 Tb/s capacity
- **Total Pump Power = 800mW**

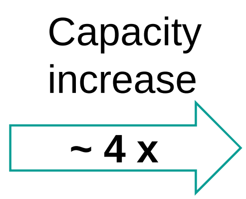
Ref: A. Turukhin, et. al., "105.1 Tb/s Power-Efficient Transmission over 14,350 km using a 12-Core Fiber", Proc. OFC 2016, paper Th4C.1

# Power Efficiency Boost in SDM Experiment

**C-band 30.58 Tb/s Capacity over 6,630 km**

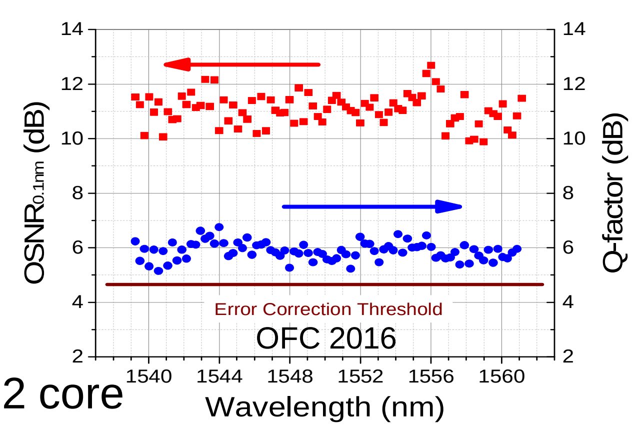


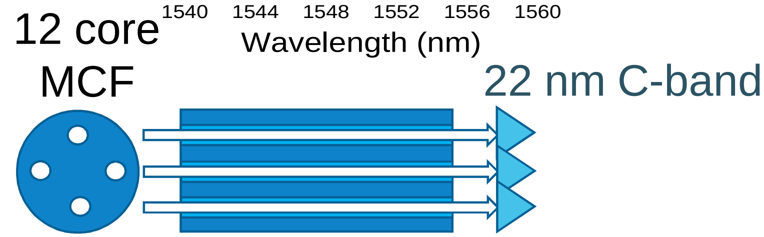




**SDM C-band 105.1 Tb/s Capacity over 14,350 km**

**12 core MCF**



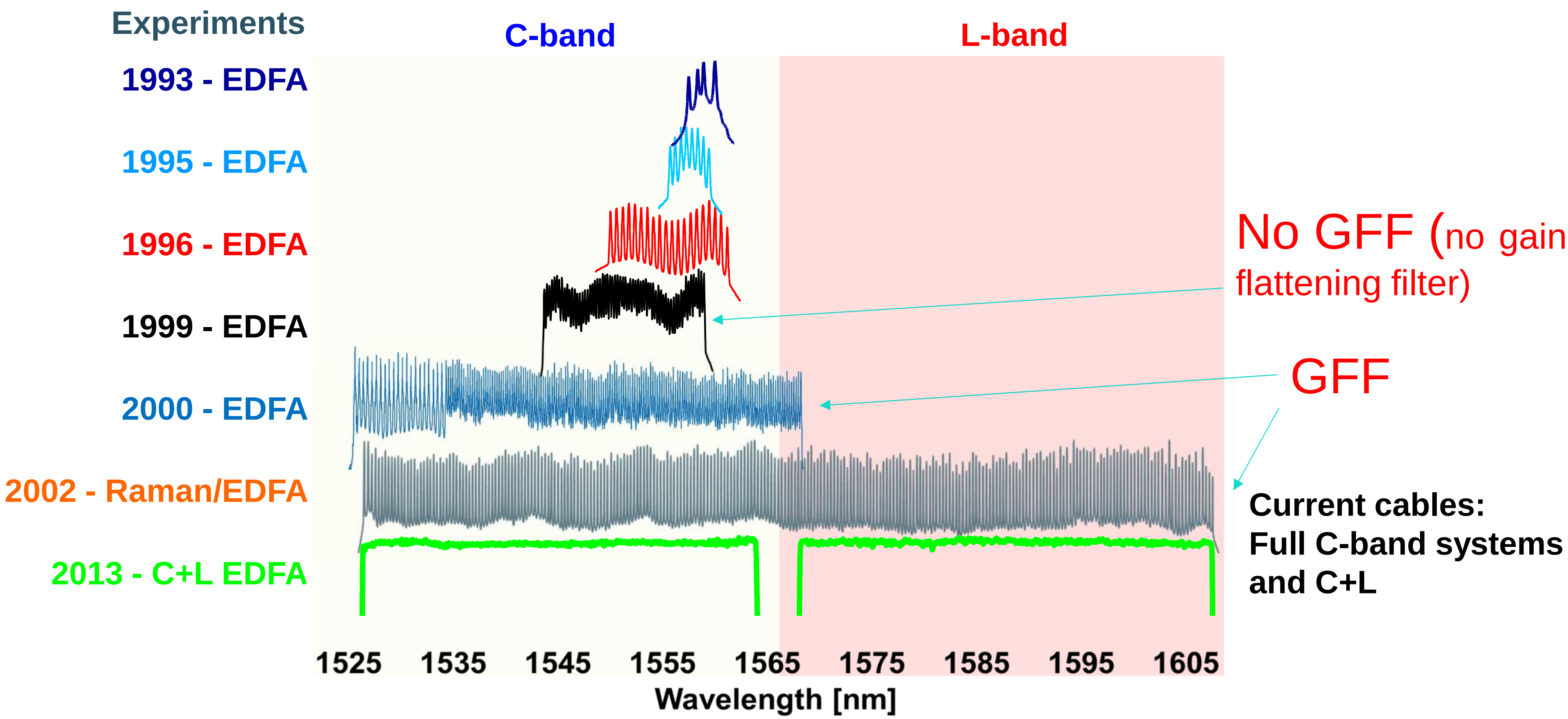




Ref: M. Mazurczyk et. al., Proc. ECOC 2012, Paper Th.3.C.2

Ref: A. Turukhin, et. al., Proc. OFC 2016, paper Th4C.1

- >4 x capacity improvement from single core to multiple cores with similar optical pump power consumption

# Amplifier Architecture and Bandwidth



# How to Compare PE in Different Experiments?

- Spectral efficiency (SE) and SNR only weakly depend on system length at optimal power efficiency
- Scale the results to the same reference length $L_{ref}$ while keeping SE or SNR and capacity the same:
- $PE \quad = \frac{Capacity}{Power_{at\,L}} \cdot \left(\frac{L}{L_{ref}}\right)^2$
- $Power_{at\,L}$ is the total optical pump power of all amplifiers in the system of length $L$
- The square scaling is due to
- Total power is proportional to the number of repeaters or system length
- Noise power grows nearly linear with system length, i.e for the similar SNR signal power should grow with distance too
- PE scaling with span length, span and other component losses:
- $PE \quad = \frac{Capacity}{Power_{at\,L}} \cdot \left(\frac{L}{L_{ref}}\right)^2 \cdot \frac{Loss_{span}}{Length_{span}} \cdot \frac{Length_{Span}^{ref}}{Loss_{span}^{ref}}$

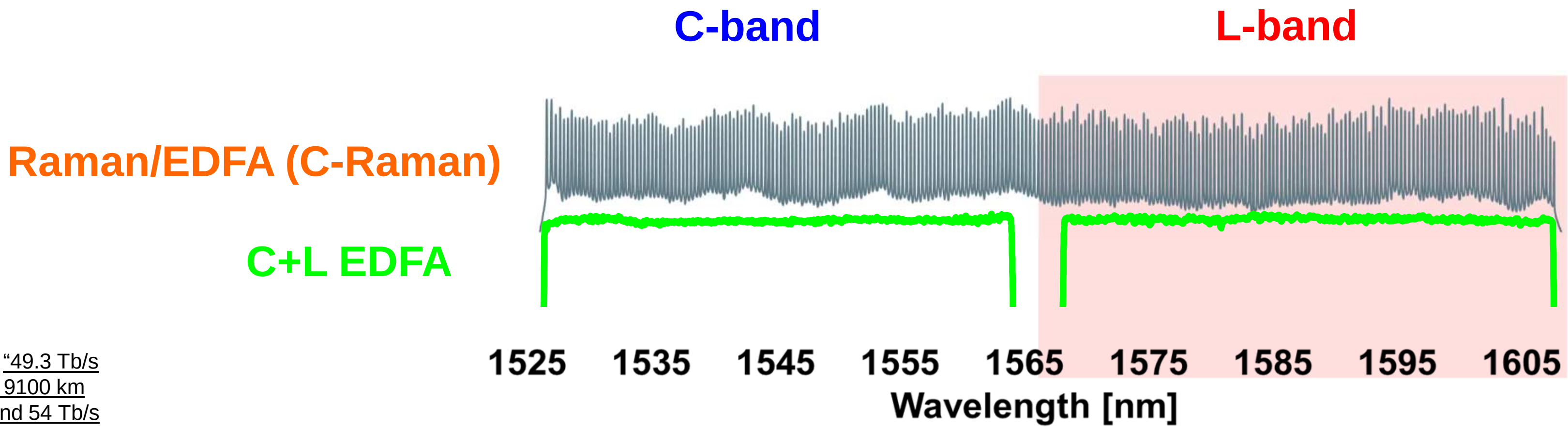
*All units are linear*

# Example of testbed results scaled to 10,000km

| Amplifier, transmission distance, SE | | Scaled PE for<br>• System Length<br>• Span loss and length | Reference |
|---|---|---|---|
| SMF 20-nm C-band, no GFF, 9750km, SE=3.2 | | 100 | ECOC 2015, Paper Th.2.2.1 |
| MCF: 22-nm C-band, no GFF, 14350km SE=3.2 | | 98 | OFC 2016, paper Th4C.1 |
| C+L: 20-nm C-band 30 nm L-band, no GFF, 14000 km SE=2.2 | | 71 | ECOC 2018, paper Mo4G.4 |
| Micro-assembly amplifier: 40 nm C-band, GFF, MCF, 12500km, SE=2.2 | | 84 | OFC 2019, paper M2I.4 |

- PE impacted by bandwidth, amplifier design and amplifier components, SE,
- Full C-Band affected by GFF and higher micro-assembly losses
- Span loss budget is important

# Comparison of PE of C+L vs. C-Raman amplifiers

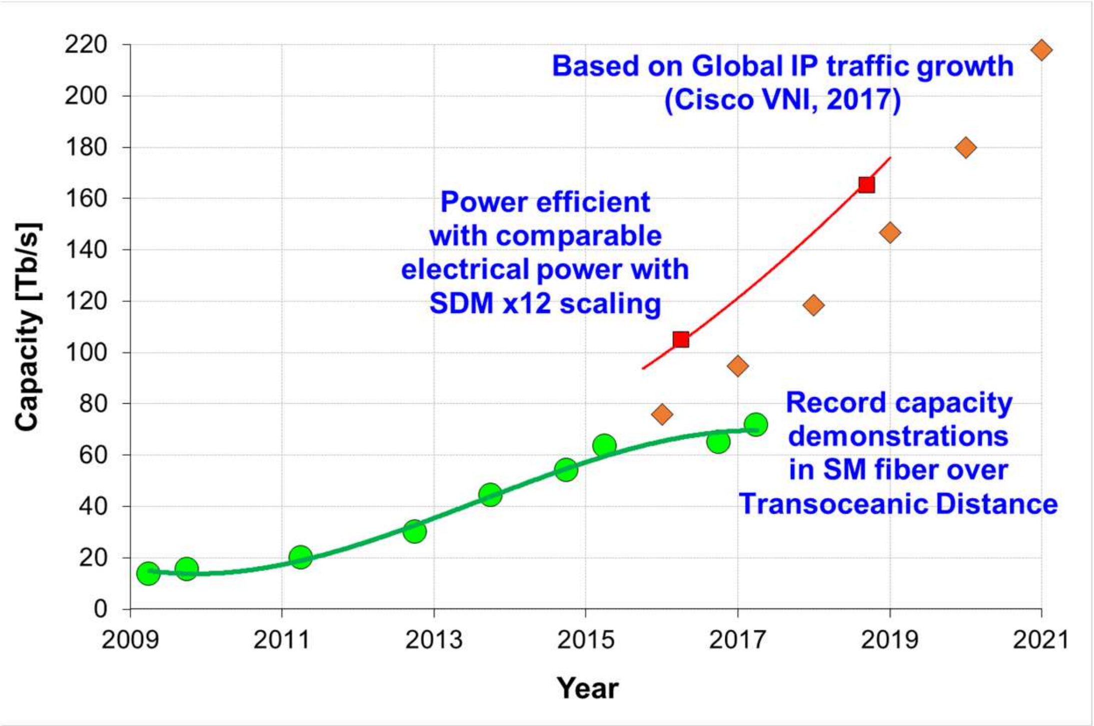



Ref: Cai J-X. et al.; "49.3 Tb/s Transmission Over 9100 km Using C+L EDFA and 54 Tb/s Transmission Over 9150 km Using Hybrid-Raman EDFA", Lightwave Technology, Journal of , (2015), Vol.: 33, P 2724 .

| Amp. Type | Noise Figure [dB] | Optimum Path Ave. Power [dBm] | $GSNR_{NL}$ [dB] | Capacity [Tb/s] | Electrical Power/span [W] |
|---|---|---|---|---|---|
| C+L | 4.9 | -6.4 | 16 | 49.3 | 3.1 |
| C-R | 1.7 | -7.9 | 17.8 | 54 | 5.5 |
| Δ | 3.2 | -1.5 | 1.8 | 9.5% | 2x* |

- Schemes compared at peak performance: SDM will favor EDF even more
- Raman/EDFA scheme required ~2x power to achieve extra 10% capacity

# SDM Extends Capacity Growth




- Power efficient SDM with *SMF* extends exponential capacity growth
- For how long? Is it economical?

# SDM Cable Capacity Publications


1. A. Pilipetskii, *" High Capacity Submarine Transmission Systems",* Tutorial W3G.5, OFC 2015
2. A. Turukhin, et. al., *"105.1 Tb/s Power-Efficient Transmission over 14,350 km using a 12-Core Fiber",* paper Th4C.1, OFC 2016.
3. E. Mateo, et. al., *"Capacity Limits of Submarine Cables"*, paper TH1A.1, SubOptic 2016.
4. A. Pilipetskii, et. al., *"Optical Designs For Greater Power Efficiency",* paper TH1A.5, SubOptic 2016.
5. O. D. Domingues, et. al., "Achievable Rates of Space-Division Multiplexed Submarine Links Subject to Nonlinearities and Power Feed Constraints", *JLT*, vol. 35, pp. 4004, 2017.
6. J. D. Downie, "Maximum cable capacity in submarine systems with power feed constrains and implications for
7. SDM requirements", Proc. ECOC 2017, paper Tu 1.E.4
8. J. D. Downie, " Maximum Capacities in Submarine Cables With Fixed Power Constrains for C-band, C+L band and
9. Multi-core fibers", JLT, vol. 36, p 4025, 2018
10. O. V. Sinkin, et. al, "SDM for Power-Efficient Undersea Transmission", *JLT*, vol. 36, p. 361, 2018.
11. P. Pecci, et. al., "Pump Farming As Enabling Factor To Increase Subsea Cable Capacity", paper OP14-4, SubOptic 2019

# SDM 1.1: Dunant Cable System

*https://www.wired.com/story/google-cramming-more-data-new-atlantic-cable/

- “Dunant undersea cable connects the U.S.A. and France, it will transmit 250 Terabits of data per second”*

- “Dunant will be the first cable in the water to use space-division multiplexing (SDM) technology”*

- New generation of high capacity SDM 1.1 cables: 200-400 Tb/s per cable capacity

# Noise Accumulation in EDFA Chains and Optimal Power Efficiency

# EDFA Chains and Noise Accumulation

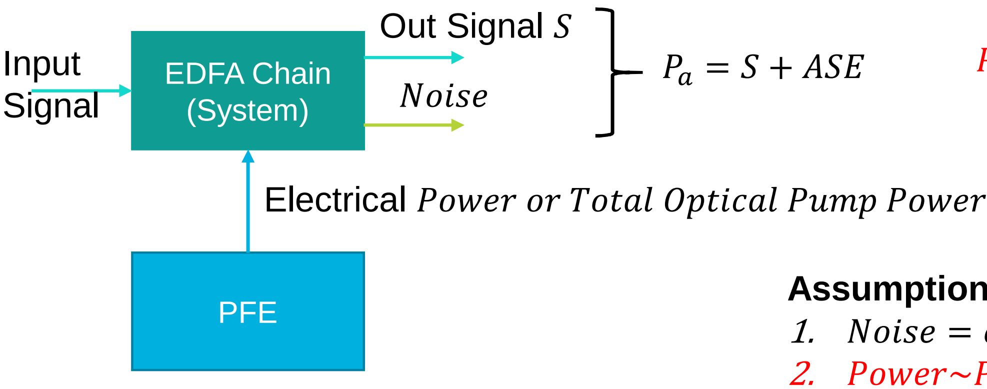
## EDFAs operate in saturation (gain compression)

- Total EDFA power including signal and ASE noise is ~ constant
- Effect of “signal droop” is important in low amplifier output power regimes
  - Important consideration for SDM, when optical power divided between optical paths

## Questions to address:

- At what SE and SNR optimal EDFA pump power efficiency is achieved?
- Formalism to take into account signal droop for SNR calculation after chains of EDFAS

# Black Box Model of EDFA Chain




$$PE = \frac{Capacity}{Power} = \frac{2B\,log_2(1+SNR)}{Power} = \frac{2B\log_2\left(\frac{P_a}{Noise}\right)}{Power}$$

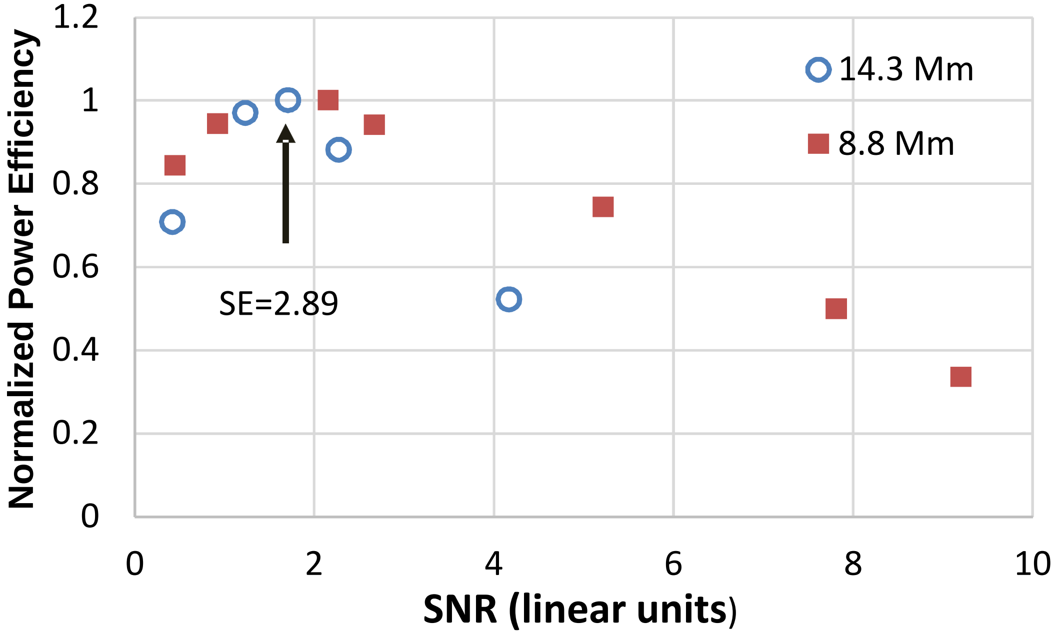
**Assumptions**: (treat system as an amplifier with unit gain)

1. $Noise = const$ for any $SNR$ since the gain is the same
2. $Power \sim P_a \qquad (Power = \alpha \cdot P_a)$

- The smallest amount of assumptions (expecting Occam's razor to work)
- $PE \sim \left.\frac{\log_2\left(\frac{P_a}{Noise}\right)}{\alpha P_a}\right|_{P_a = Noise\cdot(SNR+1)} \sim \frac{\log_2(SNR+1)}{(SNR+1)}$
- This expression has optimum at SNR = 2.4dB or SE=2.89 b/s/Hz if operating at Shannon limit
- This optimum does not depend on anything! (no system length, no span length dependence)
- Reasonable agreement with experiment

Ref: O. Sinkin et. al., *"Maximum Optical Power Efficiency in SDM-Based Optical Communication Systems"*, IEEE Phot. Tech. Lett., Vol.29, pp 1075-1077, (2017).

# Experimental Study of Optimal Power Efficiency

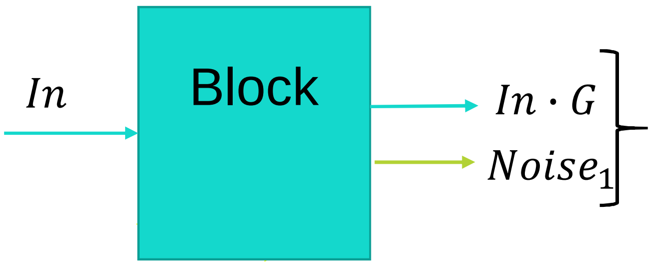



- Tested at two different system length 8.8 and 14.3 Mm
- The results are near "Black Box" model
- Optical pump power to EDFA was used in place of electrical $Power$

Ref: O. Sinkin et. al., *"Maximum Optical Power Efficiency in SDM-Based Optical Communication Systems",* IEEE Phot. Tech. Lett., Vol.29, pp 1075-1077, (2017).

# Signal Droop Model

System as concatenation of identical blocks-amplifiers plus span with amplifier output power$P_a$




$P_a = In \cdot G + Noise_1 = const$ for all blocks $\Longrightarrow$ $G \equiv \dfrac{P_a - Noise_1}{In}$

- Blocks are identical, $In \equiv P_a$ and
- $G = \frac{P_a - Noise_1}{P_a} = 1 - \frac{Noise_1}{P_a}$

- Signal at the link output with $N$ blocks: $S = G^N S_{in} = G^N P_a$
- Noise at the link output: $Noise = P_a - S = (1 - G^N)P_a$

$\Longrightarrow$ $SNR = \dfrac{G^N}{(1 - G^N)}$

- Signal droop model is a good and convenient calculator for system SNR with given *Pa, NF, gain*


Ref: J-C. Antona, et. al., "Transmission Systems with Constant Output Power Amplifiers at Low SNR Values: a Generalized Droop Model",Proc. OFC 2019, paper M1J.6.
Ref: J. D. Downie, et. al., "Extension of SNR droop model for constant output power Amplifier systems," Proc. ECOC 2019, paper W.1.D.6.

# Signal Droop vs Black Box: PE Predictions

$$PE = \frac{Capacity}{Power} = \frac{2B\,log_2(1+SNR)}{Power} = \frac{2B\log_2\left(\frac{P_a}{Noise}\right)}{Power}$$

$P_a$ - total block output power

$Noise_1$ - Noise of a single block

$n$ - # of amplifiers in link

**Black box model**

$N = const$

$$PE \sim \frac{log_2(SNR+1)}{(SNR+1)}$$

Maximum at

$SNR$ = 2.4 dB

$SE$ = 2.9 b/s/HZ

**Close to experiment**

$$Power = \alpha P_a$$

Assumption of EDFA output power linearly proportional to pump power

**Noise Droop Model:** $N = (1 - G^n)P_a$

$$PE \sim \frac{-\log_2\left(1 - \left(1 - \frac{Noise_1}{P_a}\right)^n\right)}{P_a}$$

For large *n* maximum at

$SNR$ = 0 dB

$SE$ = 2 b/s/HZ

**Not so close to the experiment**

- Reason: $Power = \alpha P_a$ is not good approximation at low $P_a$ , but it can be fixed by ignoring ASE Noise dependence on $P_a$

# Optimal PE and Signal Droop Model

- Signal droop model properly calculates SNR at the end of the chain
- How to make it work for PE problem?

$$PE \sim \frac{-\log_2(1 - G^n)}{Power}$$

Definition of power?

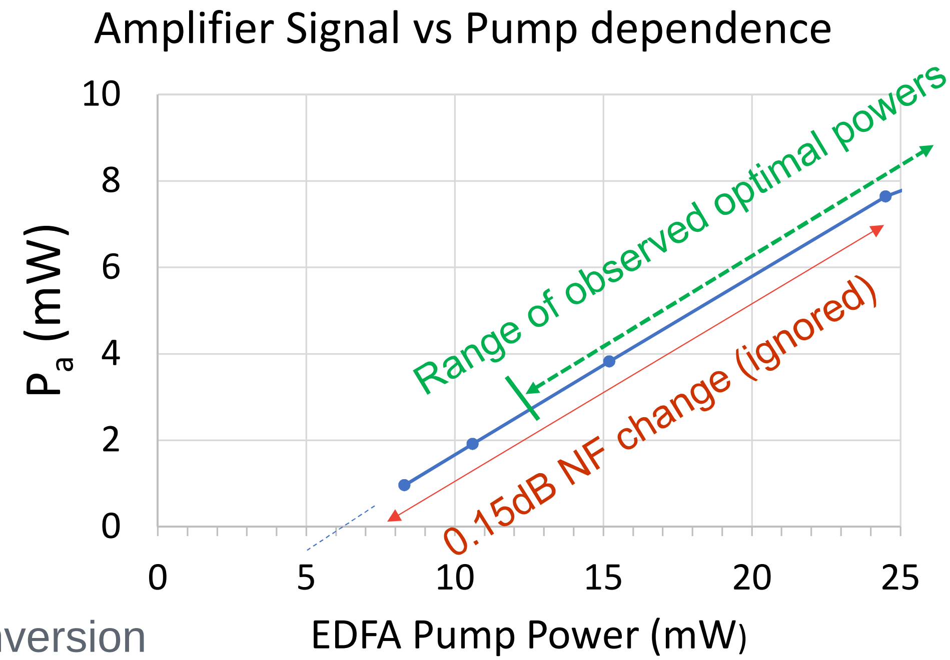
- Assumption of electrical or optical pump powe $Power = \alpha P_a$ **is not accurate for small amplifier powers**

1. **Optical Pump Power** to EDFA case: $Power$ is optical pump power to EDFA, approximated as $\sim P_a + \Delta_1$
2. **SDM** case: $Power$ is optical pump power to EDFA split between SDM paths, $\sim( P_a+\Delta_1)/ Loss_{split}$
3. **Electrical Pump Power** case: $Power$ is electrical pump laser power, approximated as $\sim P_a + \Delta_2$

# Amplifier Model: Simulation Example

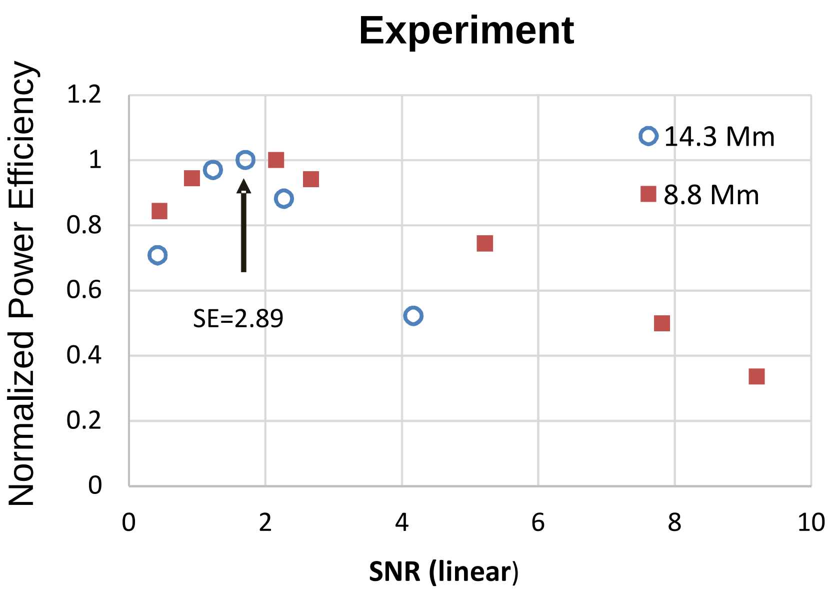
| | | |
|---|---|---|
| NF | 3.7 to 4.3 | dB |
| ASE, single amplifier | 0.039 | mW |
| In Loss | 0.3 | dB |
| Out Excess Loss | 1 | dB |
| Gain | 14 | dB |

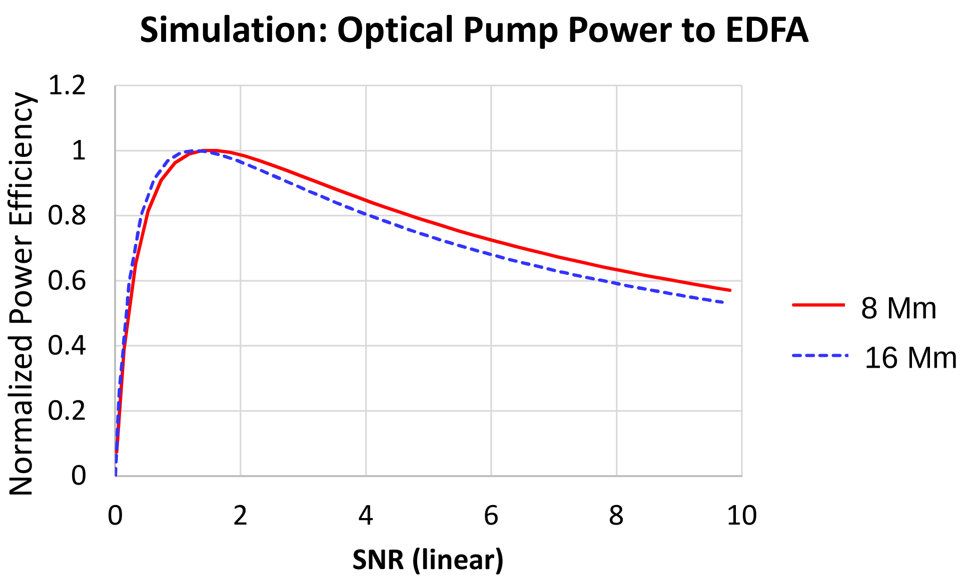
- With 1dB extra output loss for monitoring
  - ~ 80km span with 0.16dB/km fiber




- $\Delta_1 = 6\text{mW} \cdot c$ ; $c = 5.9$dB: EDFA pump to signal conversion
- Assumption $\Delta_2 = 3 \cdot \Delta_1$ ; for ~20mA threshold current of pump
- For SDM case, pump power 800mW and 0.15dB loss per splitter + splice

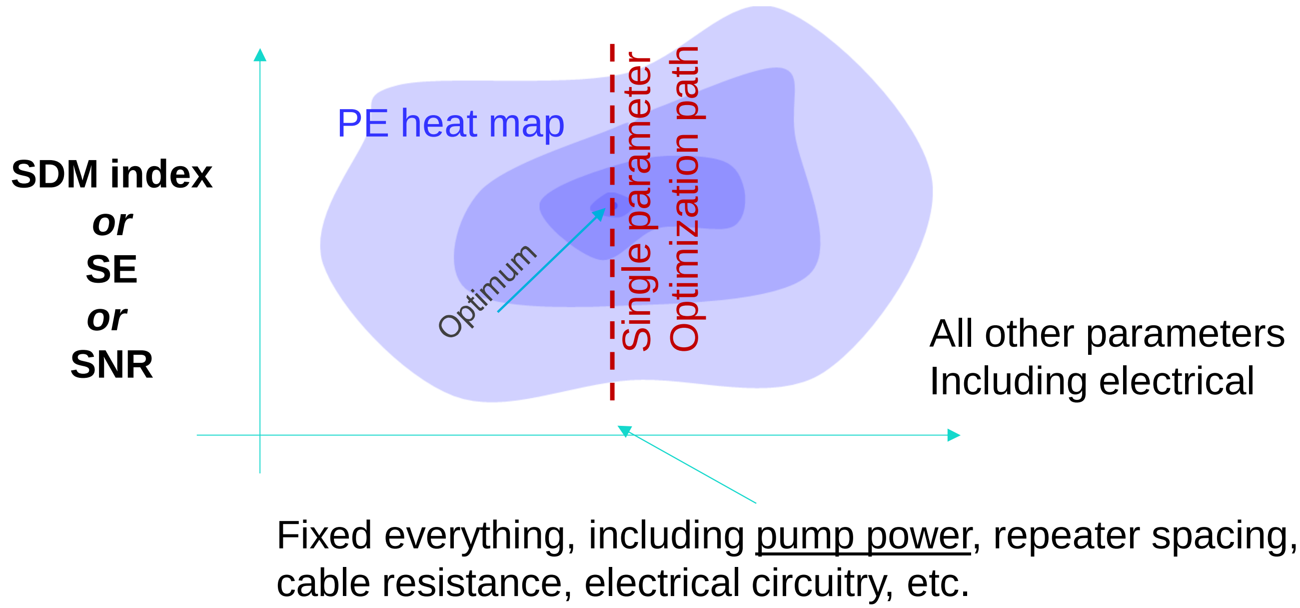
# Optimal PE Point: Experiment vs. Simulation

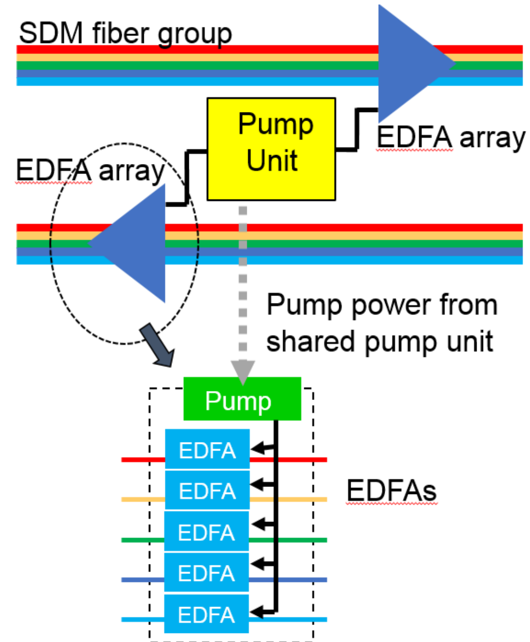



- Experimental PE was done  vs. optical pump power into EDFA
- The location of optimums in the simulations are close to the experiment

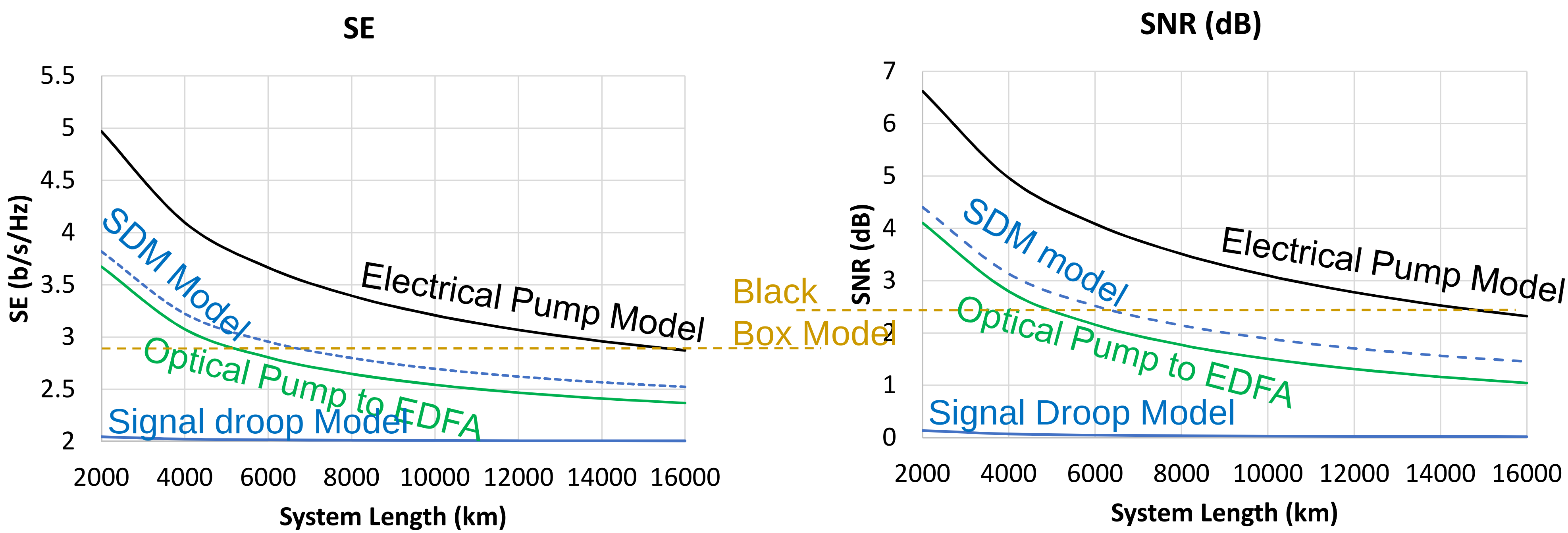
# SDM Case: Important Case for PE Optimization




- **<u>Only SDM index</u>** is adjusted through network of pump splitters
- Loss of splitters can be estimated as (Splitter + Splice losses)$\cdot \log_2(SDM_{\text{index}})$
- Changing SDM index allows to optimize PE keeping electrical parameters constant

# Optimal Power Efficiency: Comparison of Models



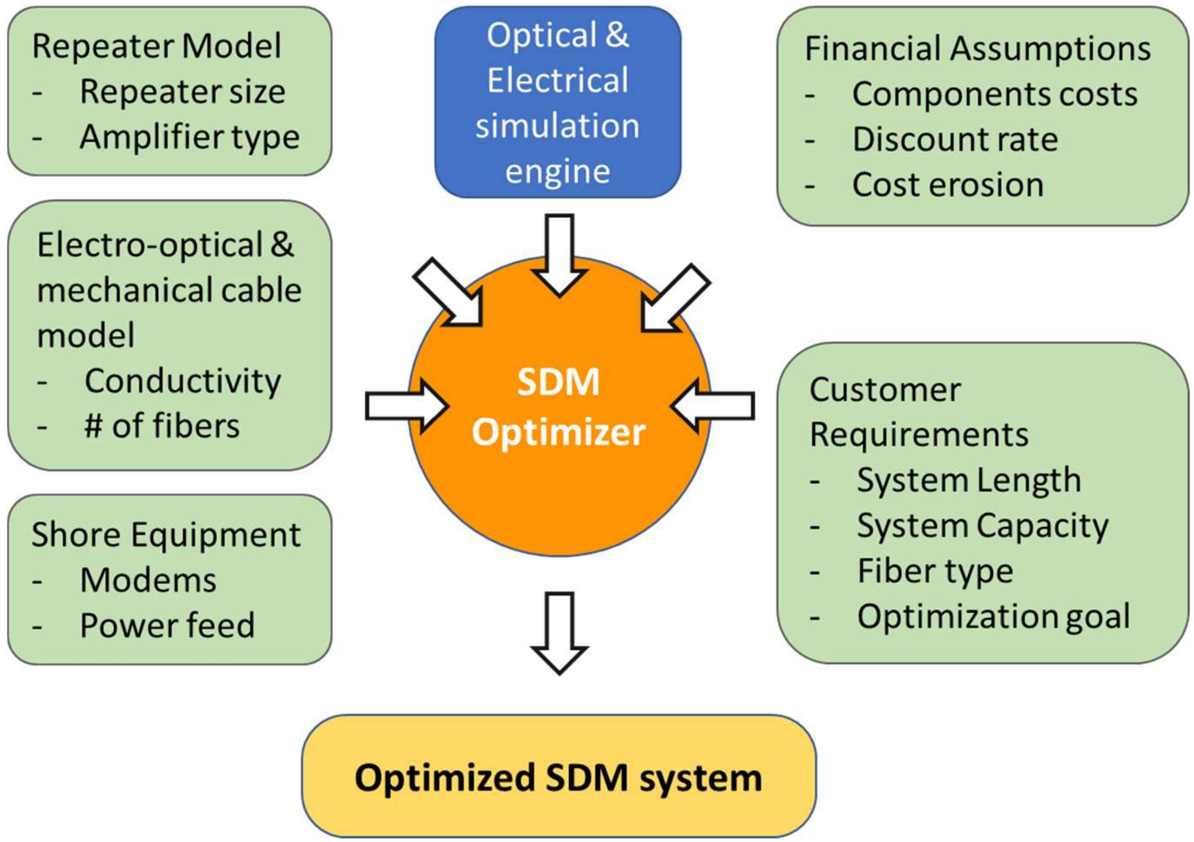

- Black Box is close to SDM, and Optical Pump to EDFA models at Trans-Atlantic distances
- Electrical Model loses a lot of power to current threshold
  - Run pump lasers at design power and split through network of SDM couplers

# Techno-Economic Models: Can SMF Based SDM System be Economical?

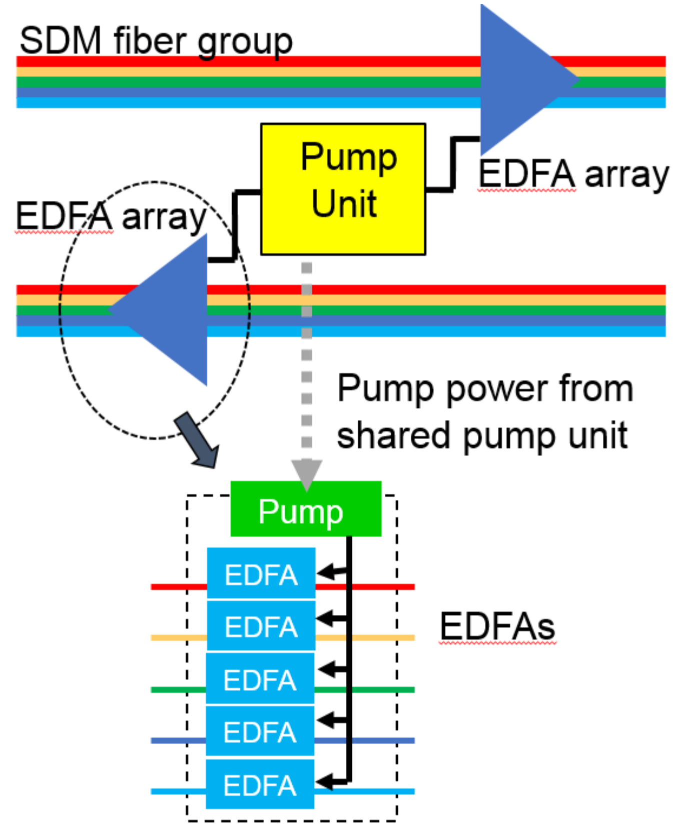
# Techno-Economic Models in the Recent Literature

- R. Dar, et. al., “Submarine Cable Cost Reduction Through Massive SDM” , paper Tu.1.E.5, ECOC 2017
- R. Dar, et, al., “ Cost Optimized Submarine Cables Using Massive Spatial Parallelism”,” JLT, vol. 36, p3855, 2018
- M. Bolshtyansky, et. al, "Cost-optimized Single Mode SDM Submarine Systems," paper OP18-1, SubOptic 2019
- M. Bolshtyansky et. al., “Single Mode Fiber SDM Submarine Systems”, to be published in JLT
-
- J. Downie, et. al., “On the Potential Application Space of Multicore Fibres in Submarine Cables”, paper M.1.D.4, ECOC 2019

# Economic Optimization of an SDM 1.1 Cable –SMF Technology

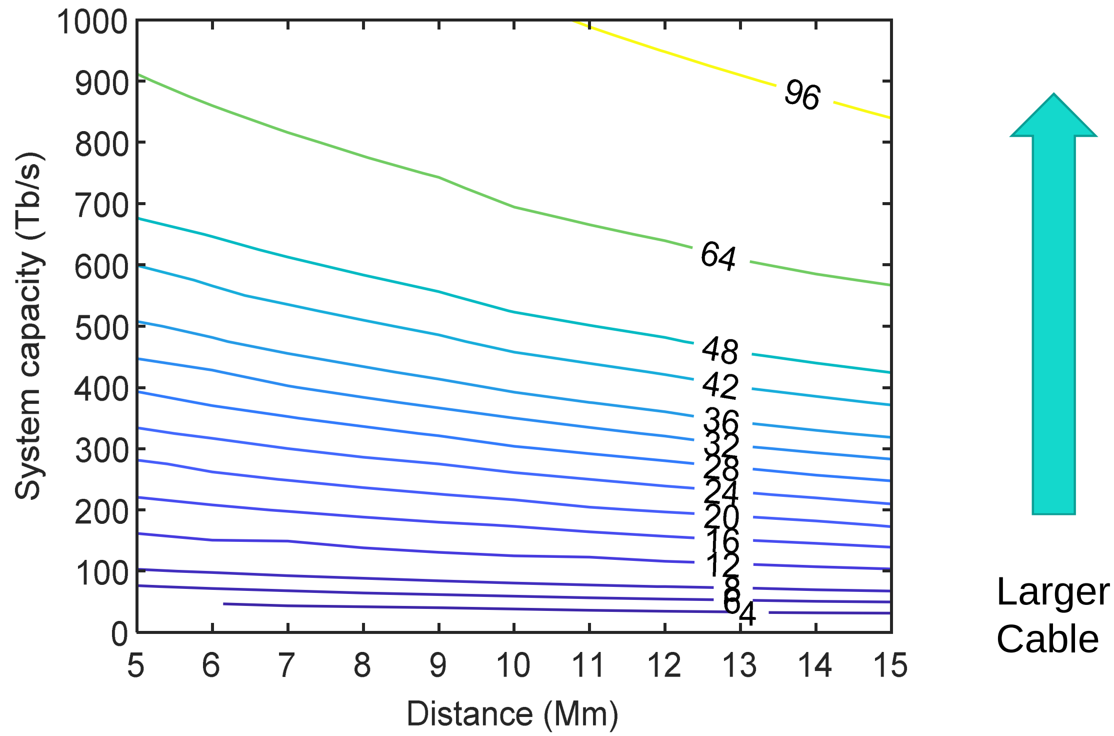



**Assumed topology**



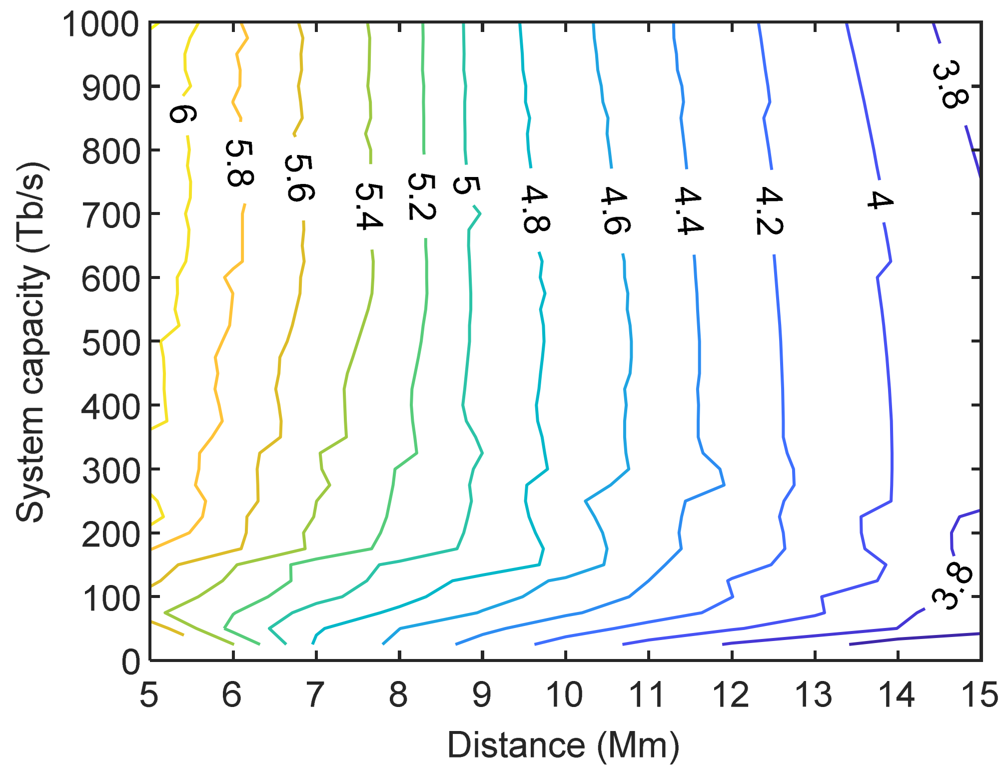
# Number of SMF Fibers for up to Pb/s Cable Capacities

- Every point on distance capacity plot is cost optimized
- Example for 80 $mm^2$ fiber
- Full C-band
- Cable size should grow to accommodate more fibers
  - Larger cable has larger conductor



# SE in Cost Optimized Solutions

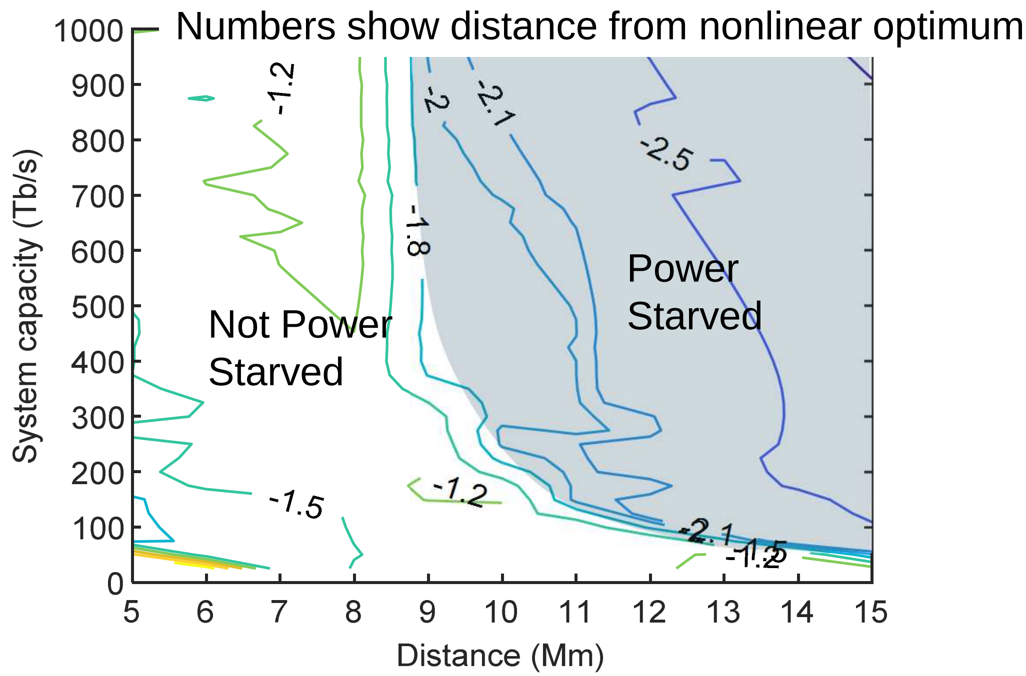
- Every point on distance capacity plot is cost optimized
- SE is mostly the function of distance, but not capacity
  - Results from assumption of larger cables for larger capacity
  - SE is Above PE optimum
    - Operation 3 dB away from Shannon limit
    - Operation at 6 dB away from Shannon limit results in ~2.5 bit/s/Hz minimal SE



# How Linear Systems Should Be?

## Level of Nonlinearity:

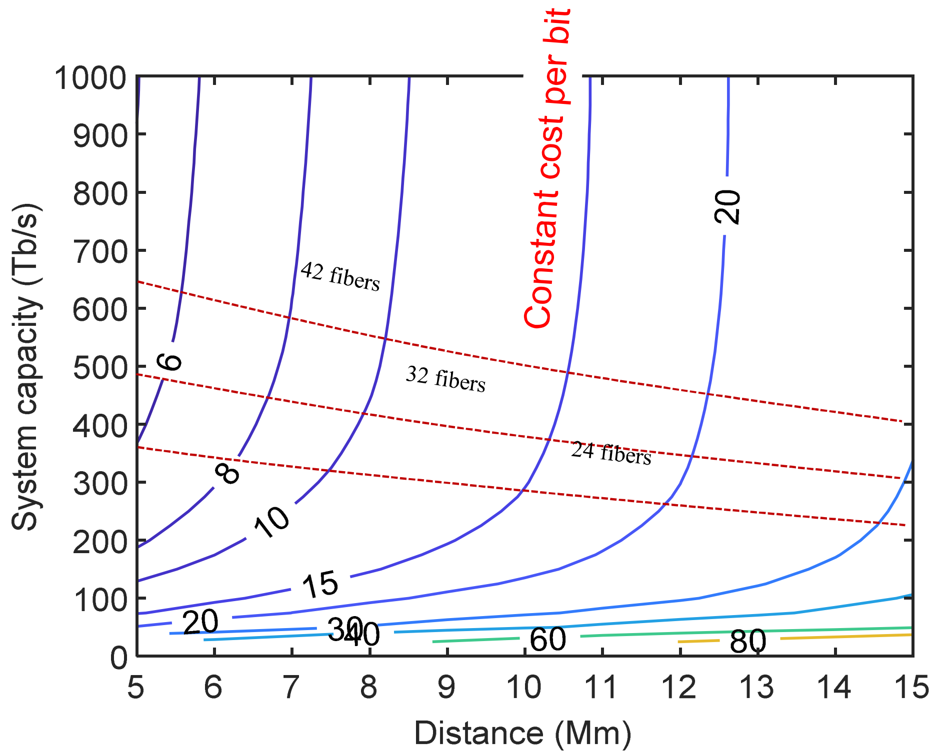
- Systems are not fully linear for large parameter space
  - Not power starved area
  - Cost Optimum ~ -1 dB from nonlinear peak
- Systems are close to linear in power starved area



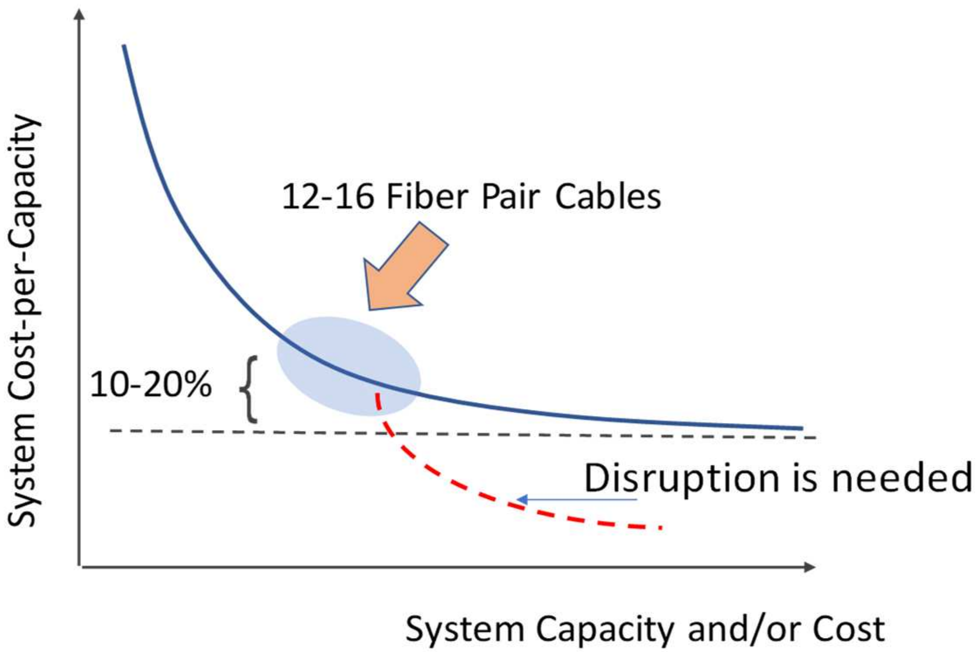
# “Cost Per Bit Crunch”

## “Cost per bit crunch” problem:

- Increasing amount of fibers per cable gives diminishing cost per bit returns



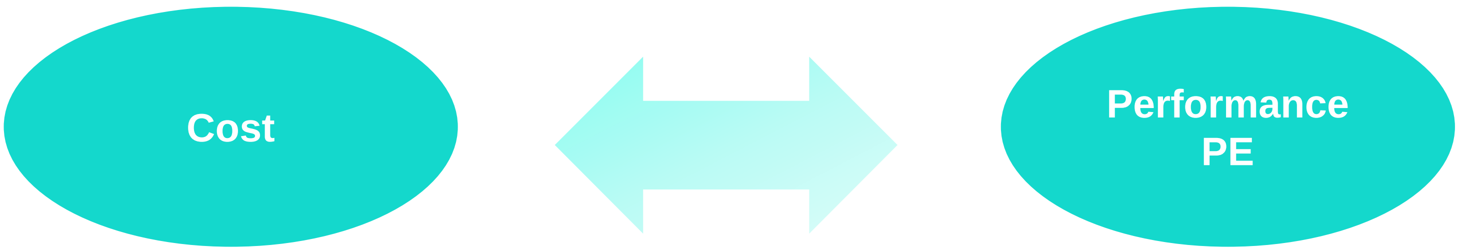
# “Cost Per Bit Crunch”




- Cost-per-Capacity improves with system capacity
- Improvement saturates for large capacity
- Technology disruption is needed to break the trend

# What is Next?

- Higher levels of integration to save space and cost?
  - Transmission in MCF, MMF? Amplifier micro-assemblies? SOA?
- Power efficiency together with costs will be part of the equation





1. R. Ryf., et. al., "Coupled-Core Transmission over 7-Core Fiber" , Proc. OFC 2019, paper Th4B.
2. K. Shibahara, "DMD-Unmanaged Long-Haul SDM Transmission Over 2500-km 12-core × 3-mode MC-FMF and 6300-km 3-mode FMF Employing Intermodal Interference Cancelling Technique", Proc. OFC 2018, paper Th4C.6.
3. A. Turukhin, et. al, " Demonstration of Potential 130.8 Tb/s Capacity in Power-Efficient SDM Transmission over 12,700 km Using Hybrid Micro-Assembly Based Amplifier Platform", Proc. OFC 2019, paper M2I.4
4. J. Renaudier, et. al.,.: '107 Tb/s Transmission of 103-nm Bandwidth over 3x100 km SSMF using Ultra-Wideband Hybrid Raman/SOA Repeaters'. Proc. OFC 2019, paper Tu3F.2

# Conclusions

- Power efficiency is important for the current and next generation undersea systems
- Optical factors affecting power efficiency: loss, amplifier design and bandwidth, signal droop, modulation scheme and spectral efficiency
- SDM allows to manage power efficiency and capacity
- Techno-economic models lead to practical optimized power efficient SDM solutions

# Thank You