OECC 2009 Plenary Session

Optical Communications: Innovations (and Their Needs) Abound

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When a person's reputation precedes him/her…

$(\text{Respect})^2$

Thank You!!!!

… to Prof. Alex Wei for your gracious and kind invitation.

… to all my wonderful colleagues in Hong Kong.

… and for the generous support of Cisco, DARPA, HP, Intel, NSF, Packard Foundation.

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Blazing Saddles: Lilly

"A wed wose. How owdinawy."

BORING?

- CIENA in 1996: 8X2.5 Gbit/s over 500 km with 100-GHz spacing. *BORING*.
- Is it boring enabling "Moore's Law"?
- It's boring in the "middle", when advances seem easy and more advanced "systems" haven't appeared.

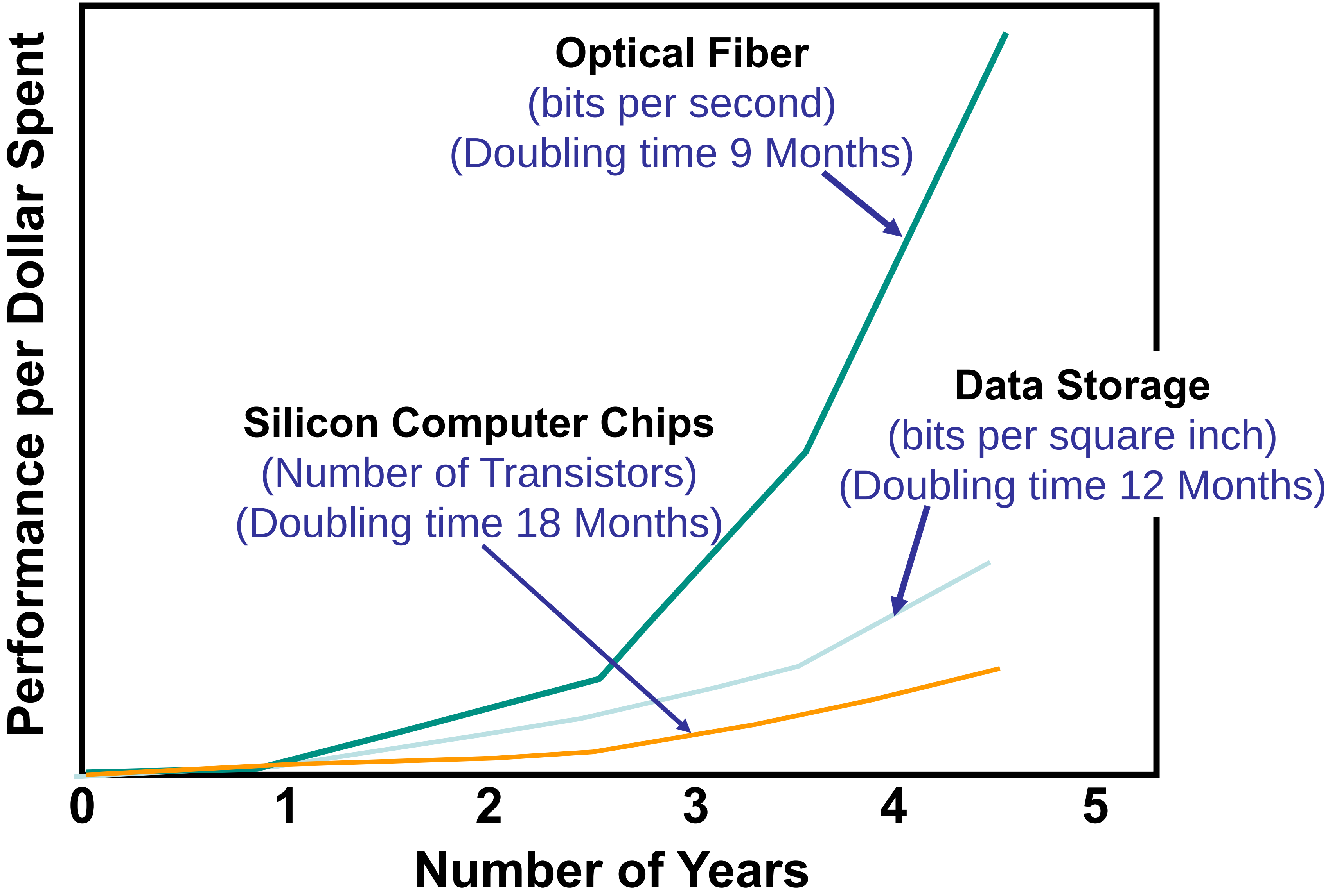
IMDD, MLSE, coherent, OFDM, ODC/EDC.

- Can be even more exciting, since completely new markets can open up. ☺

Outline

1. Overarching Perspective
2. Heterogeneity & Grooming
3. Optical Performance Monitoring
4. Optical Signal Processing

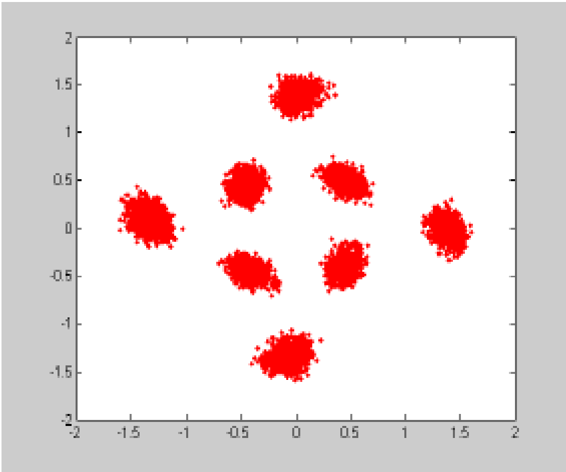
Optical Networks are Critical for Future Growth

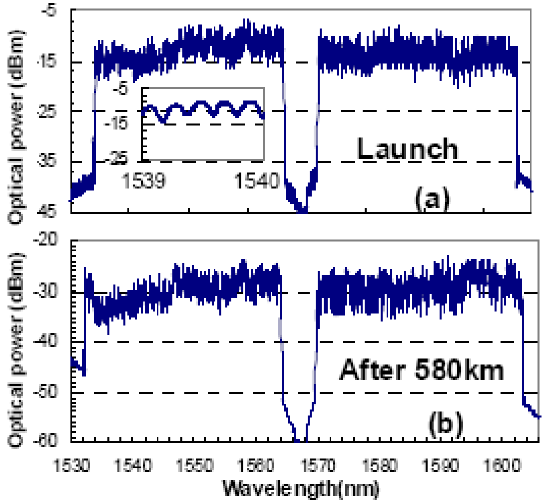


Scientific American, January 2001

Latest Results on High Capacity/S.E. Transmission

32Tb/s PDM-RZ-8QAM over 580km Ultra-low-loss Fiber

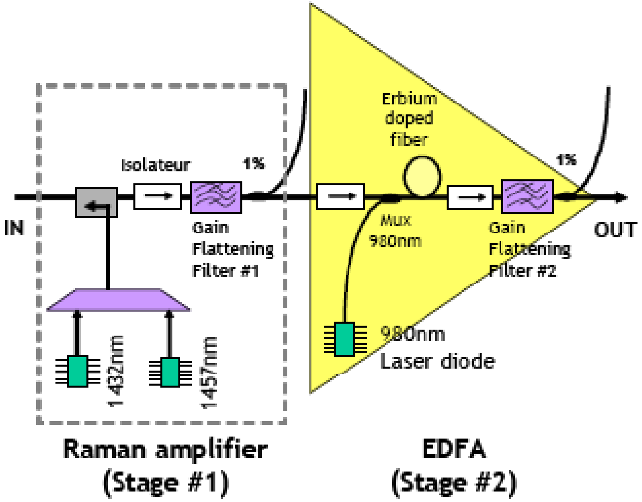


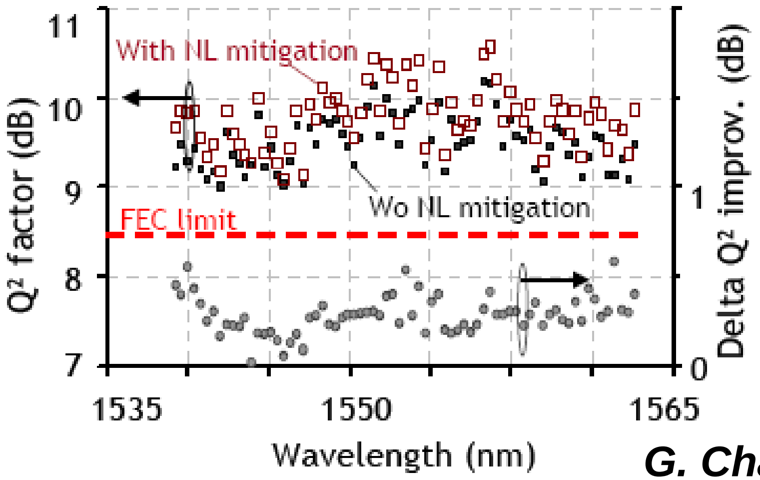


- PDM-RZ-8QAM
- Digital coherent detection
- EDFA-only Amplification
- 25GHz-spaced
- 320x114Gb/s
- length / loss ratio 82.8km / 14.6dB

X. Zhou, OFC 2009 PDP

72x100Gb/s over 7040km Large Effective Area Fiber





- 100Gb/s channels
- 88x80km distance
- Raman-Erbium amplification
- coherent receiver

G. Charlet, OFC 2009 PDP

Spectral Efficiency

Improving Spectral Efficiency

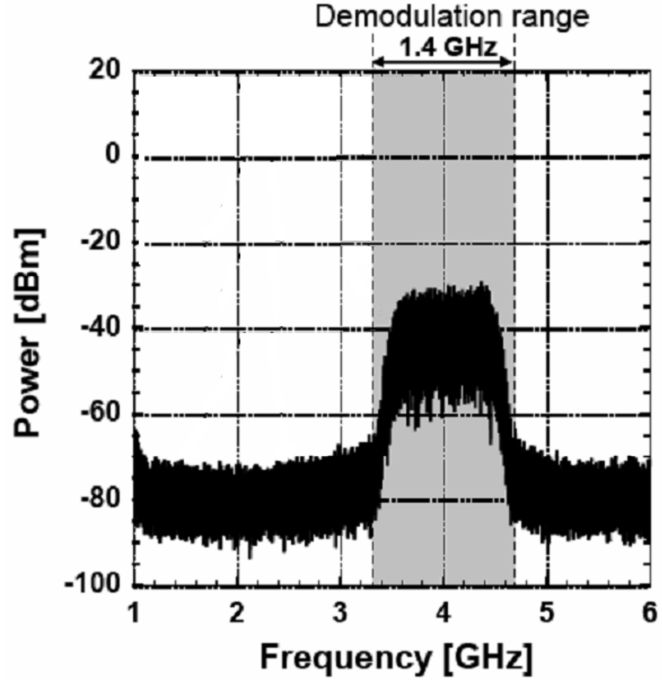
- ❑ Challenge: to explore multilevel optical modulation formats
- ❑ Pack more bits per symbol: DQPSK, APSK, OFDM, QAM
- ❑ Powerful tool: orthogonal modulation

Several Examples

Modulation	Spectral Efficiency	Reference
10×112 Gbit/s PolMux 16-QAM	6.2 bit/s/Hz	A. H. Gnauck PDPB8 2009
8×65.1 Gbit/s coherent PolMux-OFDM	7 bit/s/Hz	H. Takahashi PDPB7 OFC2009
PolMux 1Gsymbol/s 128 QAM 14 Gbit/s	10 bit/s/Hz	H. Goto JThA45 OFC2008

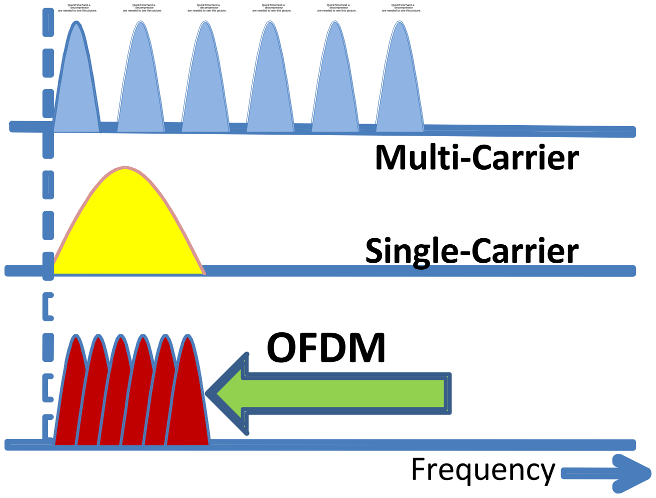
To date, largest spectral efficiency

10 bit/s/Hz Spectral Efficiency



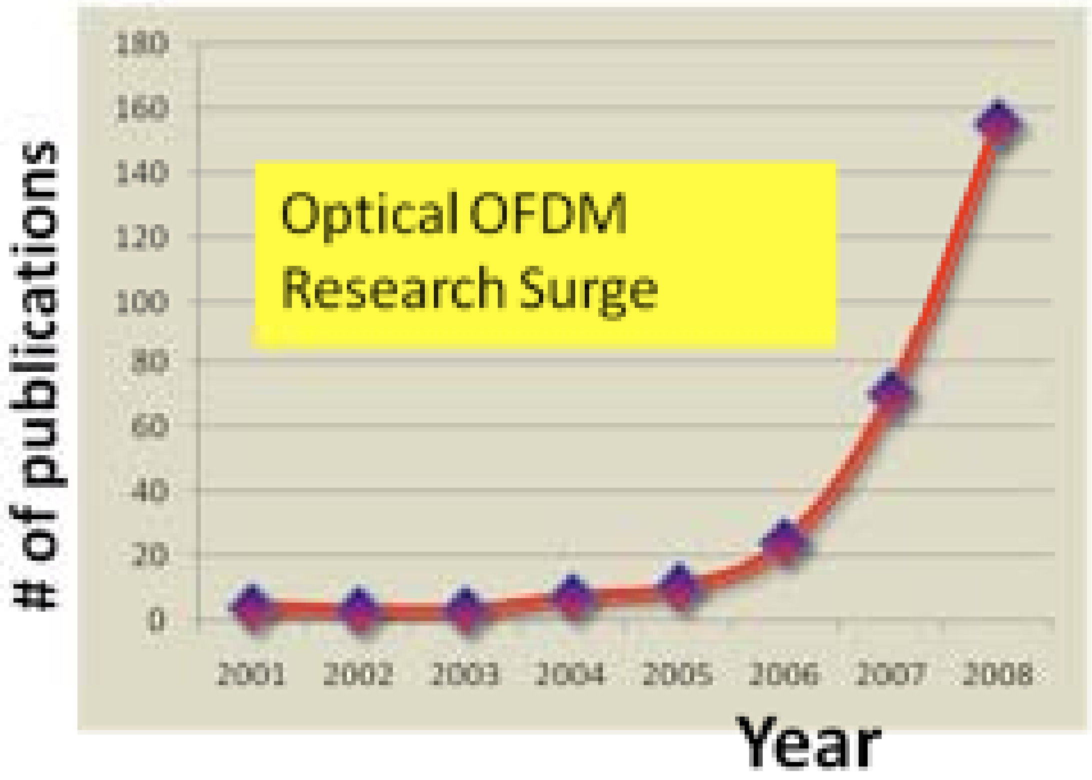
Pol-Mux 1 Gsymbol/s, 128 QAM (14Gbit/s) (BW: 1.4 GHz)

OFDM : “I come not to …”



Access to phase, ampl. and freq.

Mitigation of linear impairments



➢ OFDM pushes complexity into the electric domain: # of computations needed for OFDM at transmitter is more than Coherent-Single-Carrier.
➢ Compared to conventional multi-carrier, OFDM saves ~ half the optical bandwidth.

Bendable Optical Fiber

TIME

THE BEST INVENTIONS OF THE YEAR

IEEE

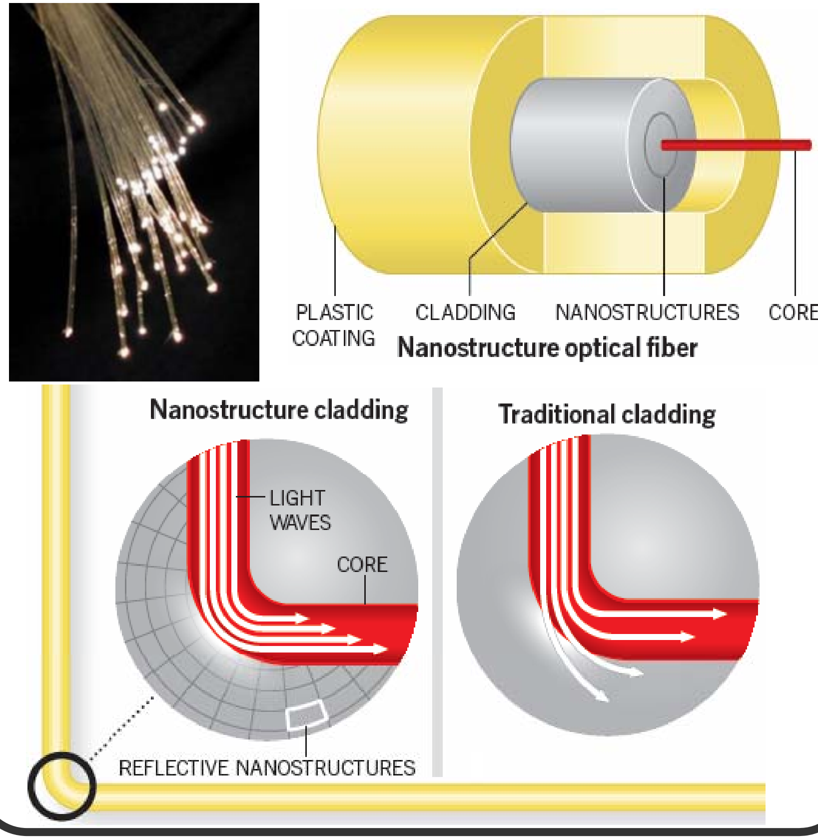
Corporate

Innovation

Recognition

2009

Corning ClearCurve Fiber



- Corning NanoStructures Technology
- Best macrobending performance
- Compatible with current optical fibers
- **Attenuation: 0.19-0.21 dB/km (1550nm)**
- **Macrobend Loss: <0.10 dB (Radius: 5 mm)**

Corning Incorporated

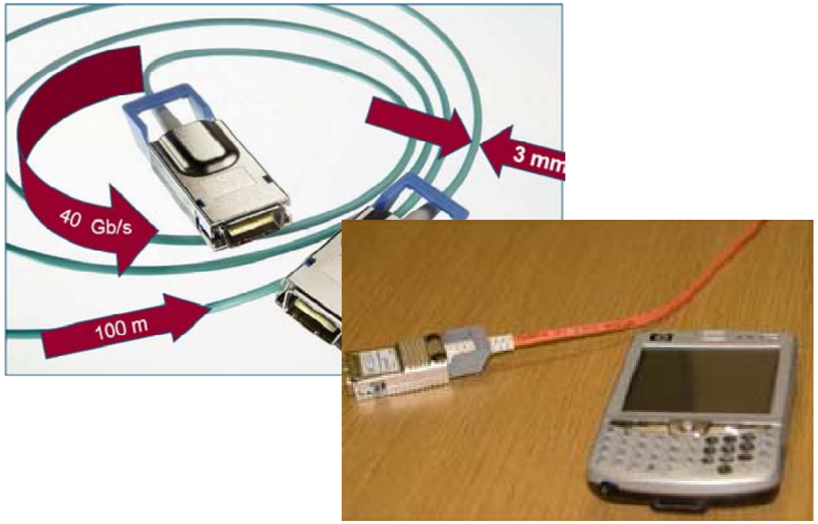
Active Optical Cable

USC Optical Communications Laboratory

Classical Copper Cable

- ❑ Max Speed: 10 Gbit/s
- ❑ Max Length: 10 m
- ❑ Bending Radius: 10 cm
- ❑ Thickness: ~5 cm (Compaq alpha-server)
- ❑ Cost: 18 $/Gbps/m (HP Superdome)

Active Optical Cable



- ❑ Max Speed: 20 Gbit/s
- ❑ Max Length: 200 m
- ❑ Bending Radius: 25 mm
- ❑ Thickness: 3 mm
- ❑ Cost: 0.2 $/Gbps/m

G. Astfalk , T. Morris : Applied Physics A '09

M. Boermans, Tyco Electronics, 2009

“Brittle Network”

Bran Ferren

Chief Creative Officer

Applied Minds, Inc., USA

OFC - Plenary Speaker ‘06

Predicted “bursting” of bubble in ‘97

- **Optical systems are brittle**
- **Optical systems are difficult to use**
- **Need “plug-and-play” robustness**

Michael Jackson's Death Strains the Internet

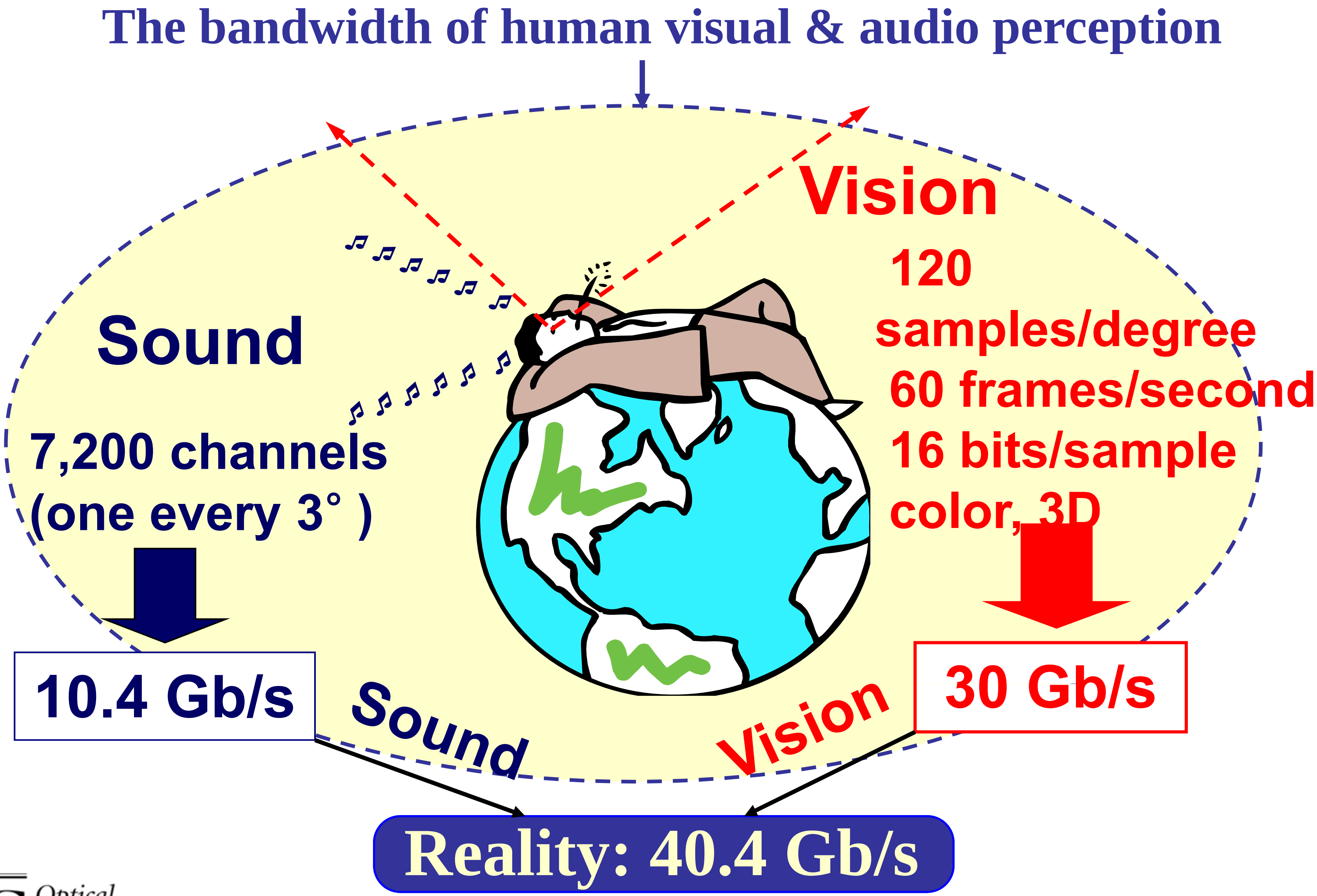
LONDON (CNN) -- How many people does it take to break the Internet? Just one -- Michael Jackson. The story took a slice of the Internet.

"Between ~2:40 p.m. PDT and 3:15 p.m. PDT today, some ***Google News*** users experienced difficulty accessing search results," Google told CNET. Also, users complained that Google News was down.

As sites fell, users raced to other sites: ***TMZ*** had several outages; users then switched to ***Perez Hilton***, which also struggled. ***CNN*** reported a 5X rise in traffic in ~1 hour. ***Twitter*** crashed as users saw multiple "fail whales". Twitter had had to temporarily disable its search results.

CNET reported that by 3:15 p.m. PT, ***Wikipedia*** seemed to be "temporarily overloaded." The ***Los Angeles Times*** suffered outages. ***AOL's*** instant messenger was hit, "AIM was down for ~40 minutes."

The Bandwidth of Tomorrow's "Immersive" Reality



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Tom Holman, *USC, Multimedia Center, 2001*

Bob Metcalfe: OFC 2008 Plenary Talk

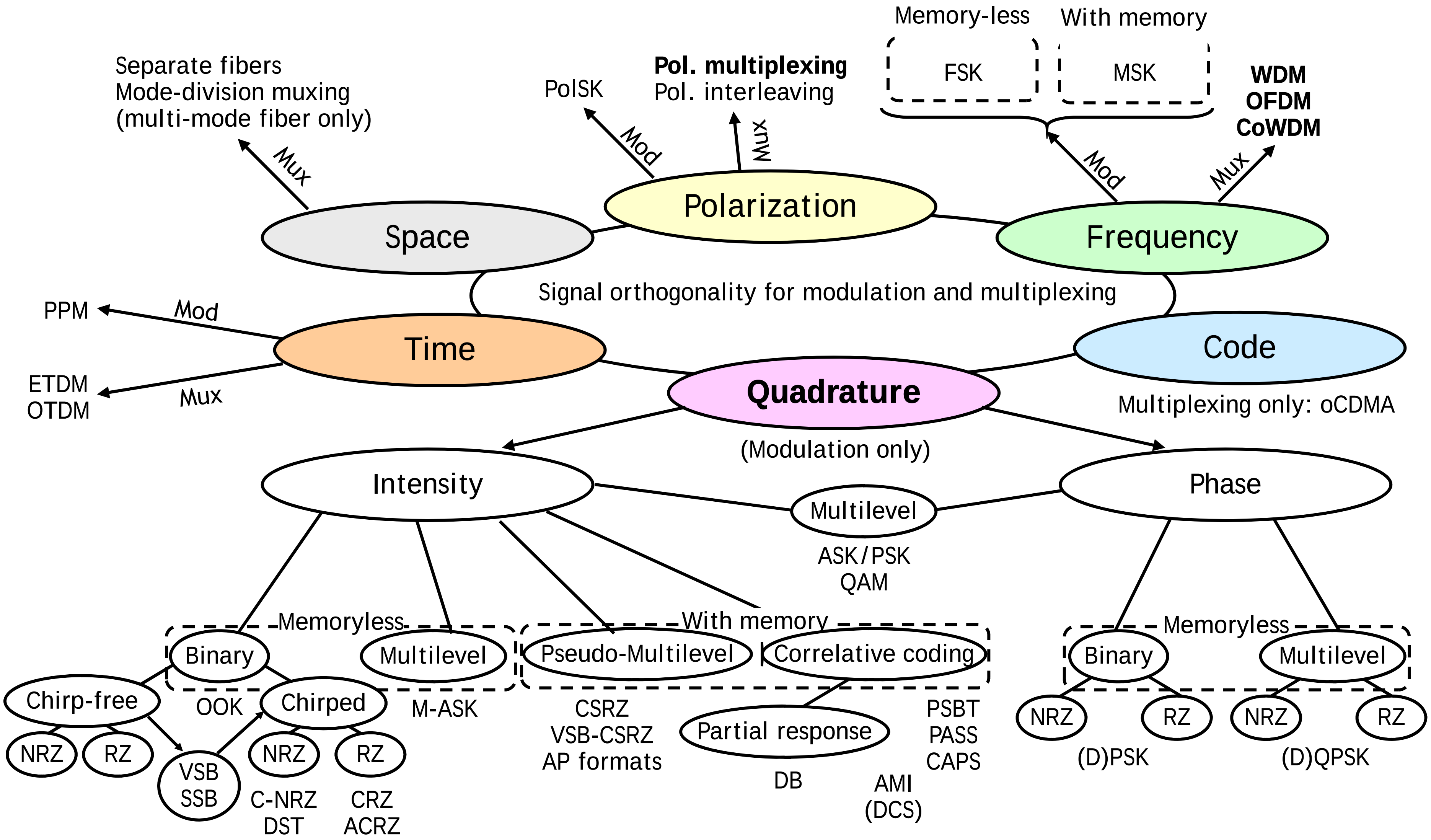
- <u>**40 Gb/s**</u>**: Shipping today in 50G ITU grid thanks to hard work**

- <u>**100 Gb/s**</u>**: Spectral efficiency will enable same happy outcome (same hut spacing, existing fiber, WDM grid, …),** <u>***IEEE standards by 2010***</u>

- <u>**1 Tb/s**</u>**: Will not fit in current infrastructure. Break current constraints:**

  - **Advanced modulation formats**
  - <u>***Break out of 50G spacing***</u>
  - **Break out of C/L bands**
  - **New fiber types**
  - **New lasers**

Optical Signal Spaces for Modulation / Multiplexing



Winzer and Essiambre, OFT VB, ch. 2, 2008

“Indiana Jones and the Last Crusade”

HJ: “We will face 3 devices of lethal cunning …”

HJ,J: “How do we stop them?”

HJ: “I don’t know?”

Replace Function, Not Device

Electronic Device
Photonic Device

→ Function

Integrated Photonics

Replace

Nick Tabellion, CTO, Fujitsu Softek: "The commonly used number is: For every $1 to purchase storage, you spend $9 to have someone manage it."

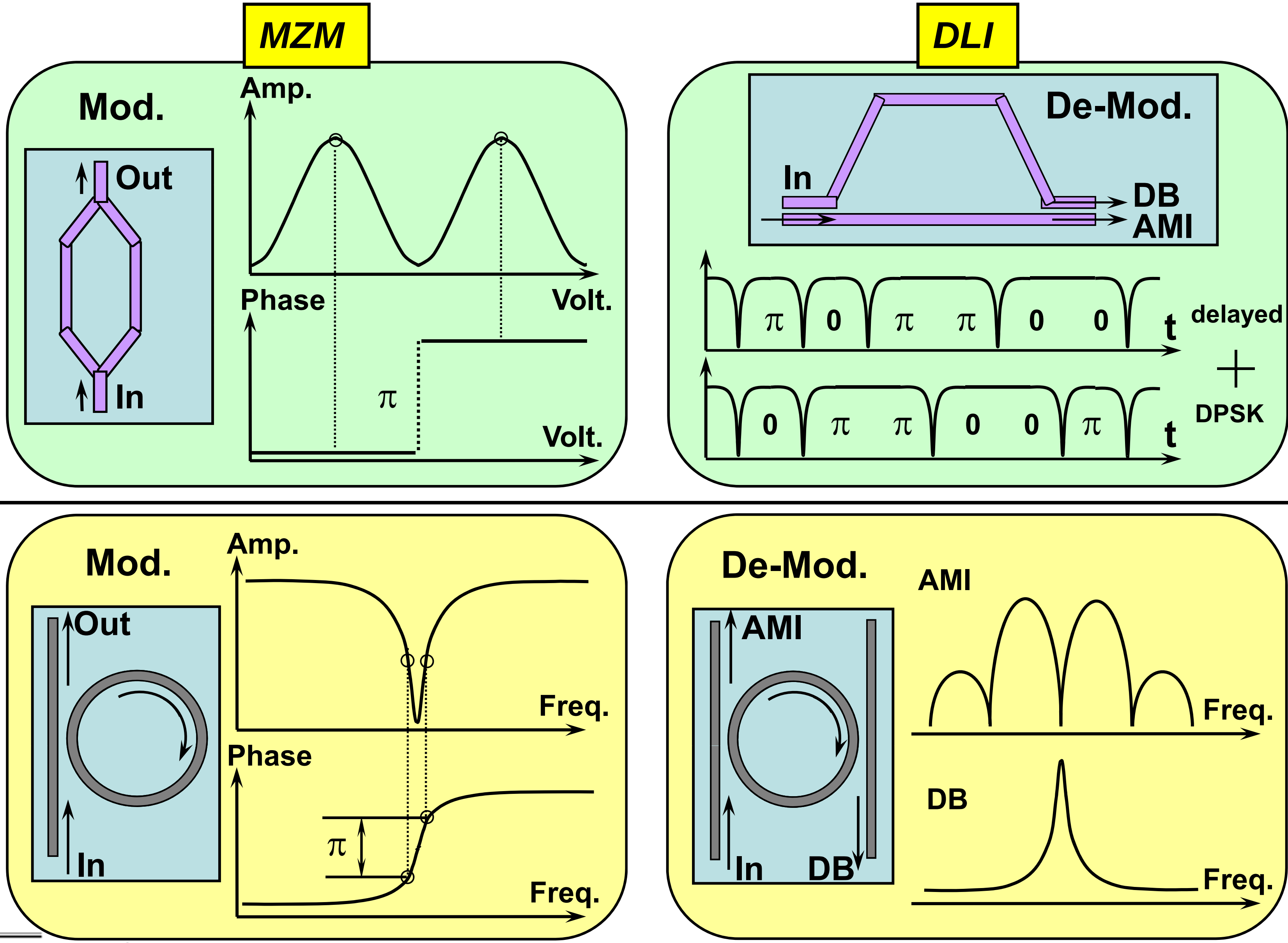
Cost: Equipment < Operation < Management

Integrated Photonics

Integrated Photonics

Enable monitoring and automated management

Microring-Based DPSK Principle



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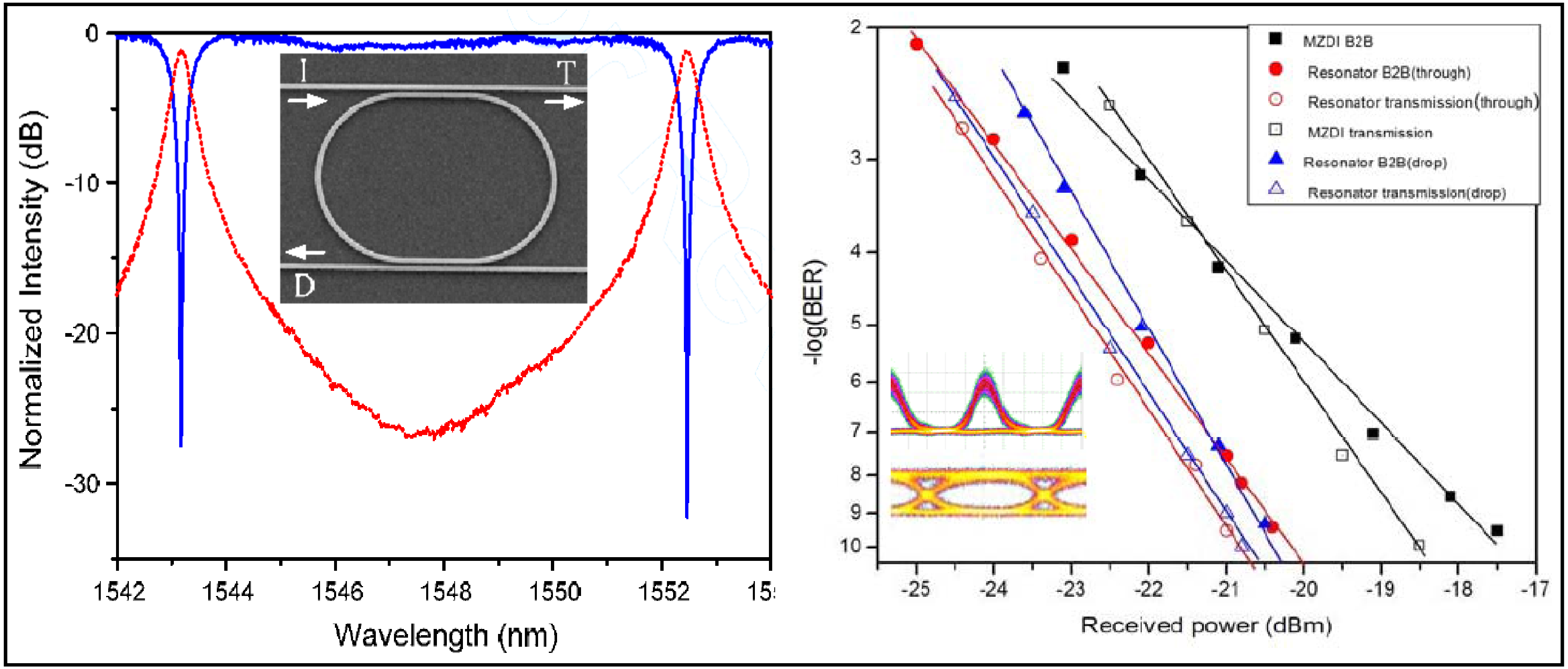
L. Zhang, et al., Opt. Express, p.11564, 2007

Experimental Demonstration



Silicon photonics enables:

- **Ultra compact structure.**
- **Low power consumption.**
- **Achievable bit rates of up to 40Gb/s.**
- **Cost-effective fabrication.**
- **Tolerant to phase shift and demodulator frequency offset.**

Silicon microring filters show <0.7 dB power penalty than standard MZM+DLI. Here the DLI itself has 3-dB penalty due to imperfection.

L. Xu, et al., Photonic Switching 2008, post-deadline

Data Centers

- What the heck is a “data center”?

- Do data centers represent a new set of research challenges?

  - *Fat pipes and short (?) distance.*
  - *Latency is crucial.*
  - *Multiple-order nodes, multicasting.*
  - *Data aggregation and granularity.*

- Go forth and explore….

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RF to Optical Transition

RF/Electronic History

Coherent Transmission

Multi-level Modulation

Transatlantic Transmission

FEC Introduced by Shannon

Equalization

Variable Bit Rate Systems

Dynamic Bandwidth Allocation

S/W-Defined Radio

Time

?

Optical History

Coherent Optical Systems

Multi-level Modulation

First Transatlantic Line

FEC for Transatlantic

Optical Equalization

Coherent Systems Revisited?

Variable Bit Rates Systems?

Dynamic Bandwidth Allocation?

"S/W-H/W Defined" Reconfigurable Optical Systems?

Device Capabilities Drive System Applications

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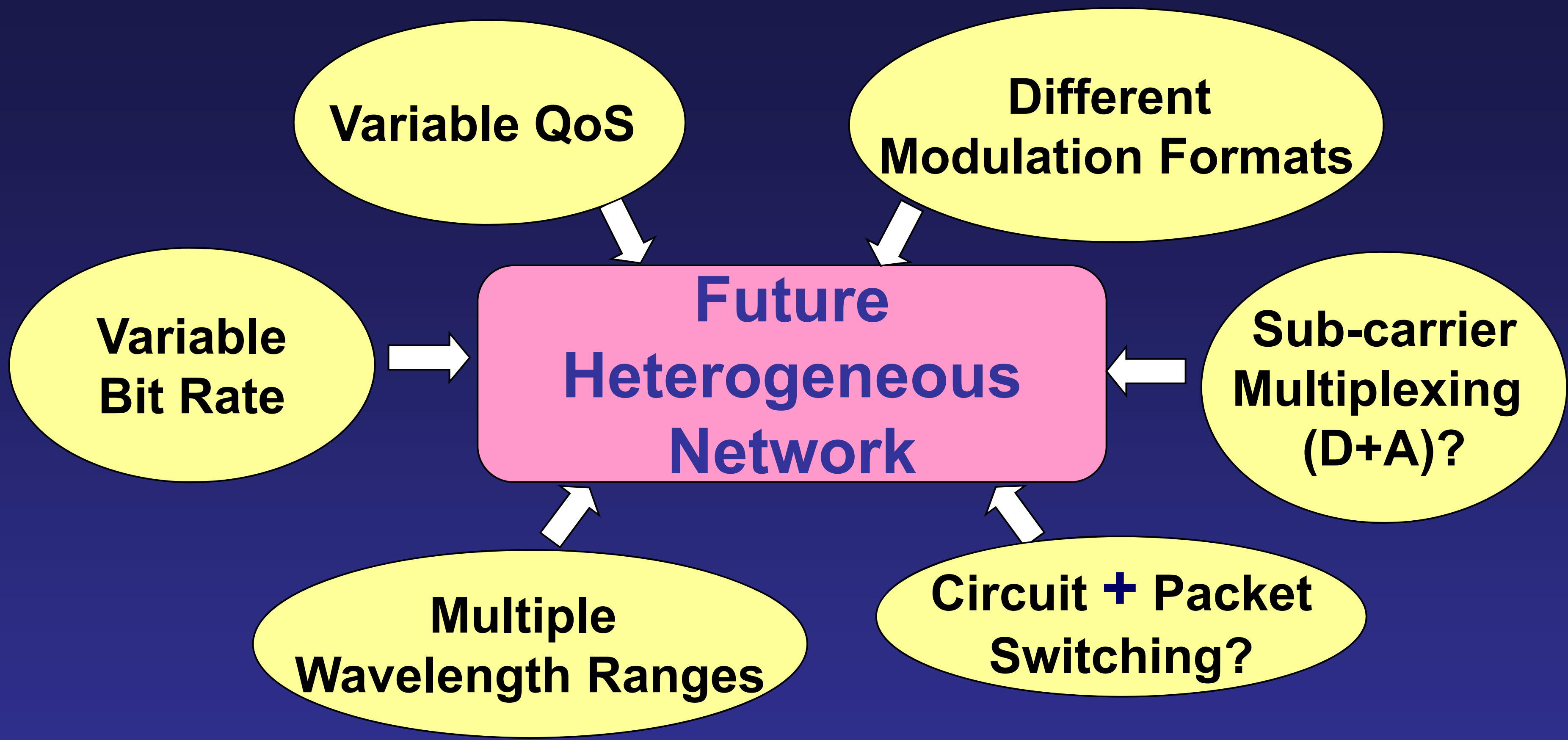
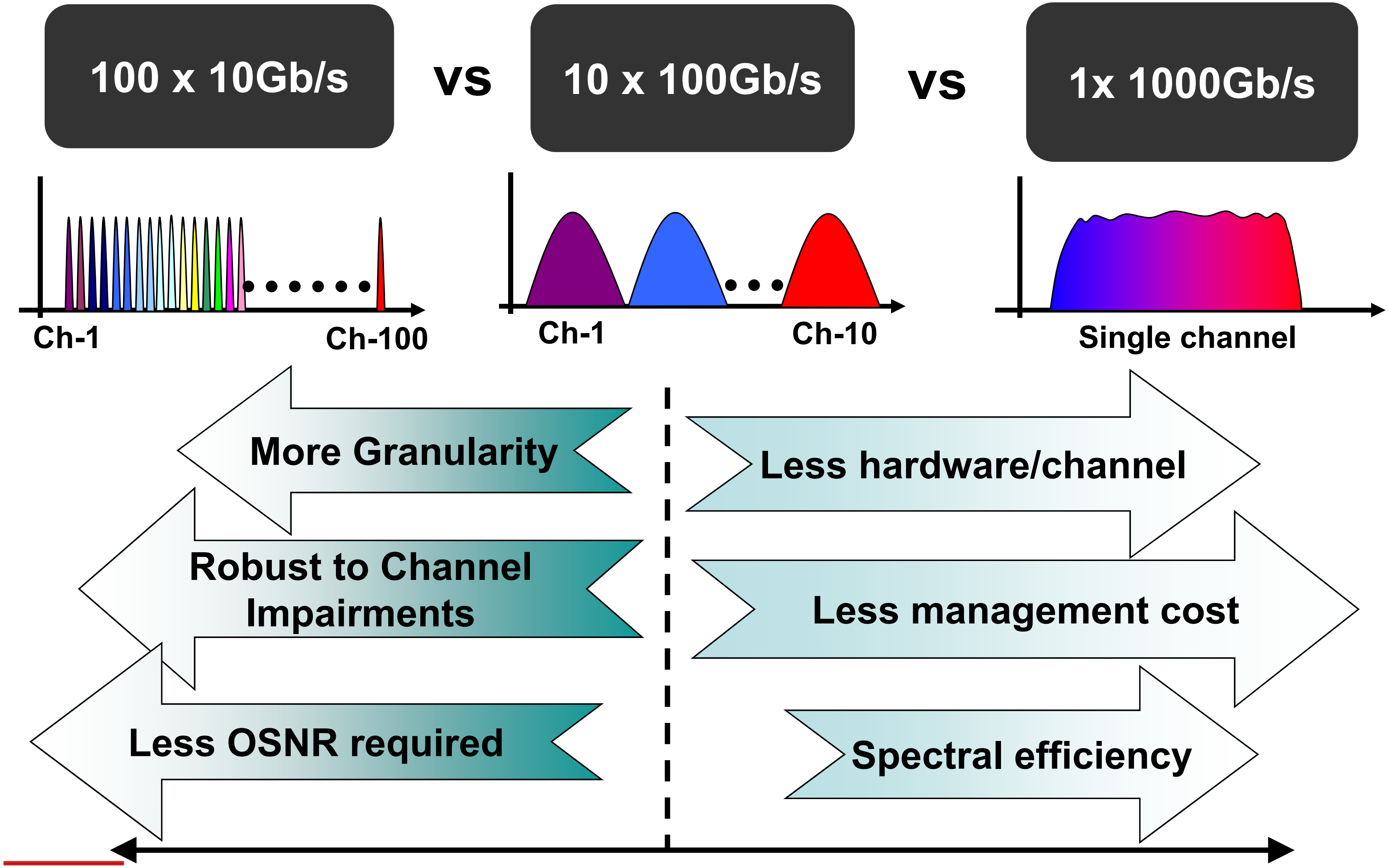
Heterogeneous Systems: *One Network Fits All*



- Hardware should be reconfigurable and transparent
- An intelligent network could use the ***optimal*** method from the application/user viewpoint.

Economics: Early market entry of new services (CATV??)

Data Granularity: Which Costs LESS to Deploy?



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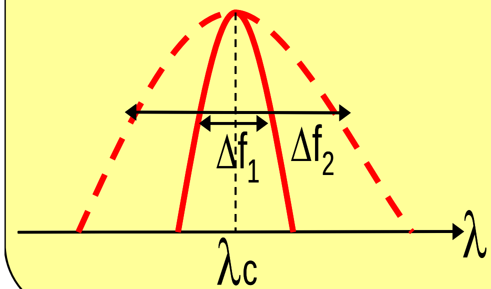
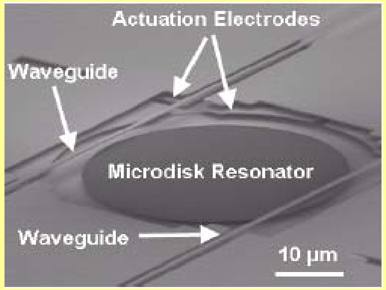
Grooming: Dynamic BW Allocation

Tunable BW filter

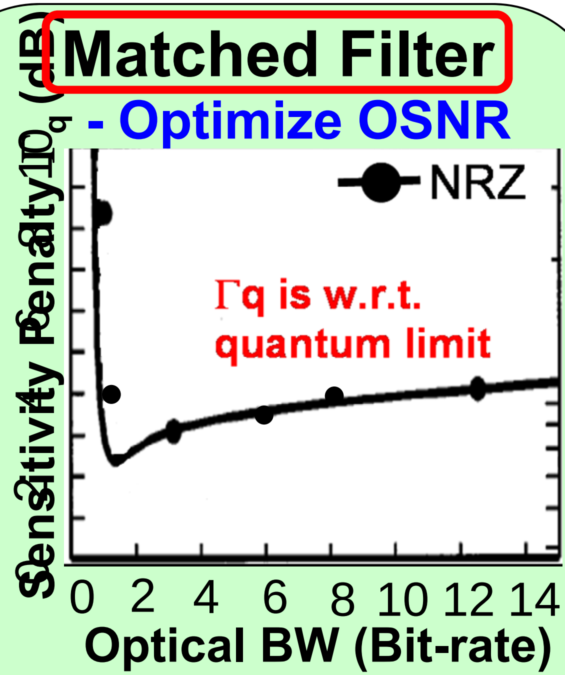




Yao, et *al*., OFC, 2006

Matched Filter

- Optimize OSNR

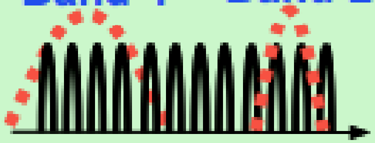


Pfennigbauer, et *al*., PTL, 2002

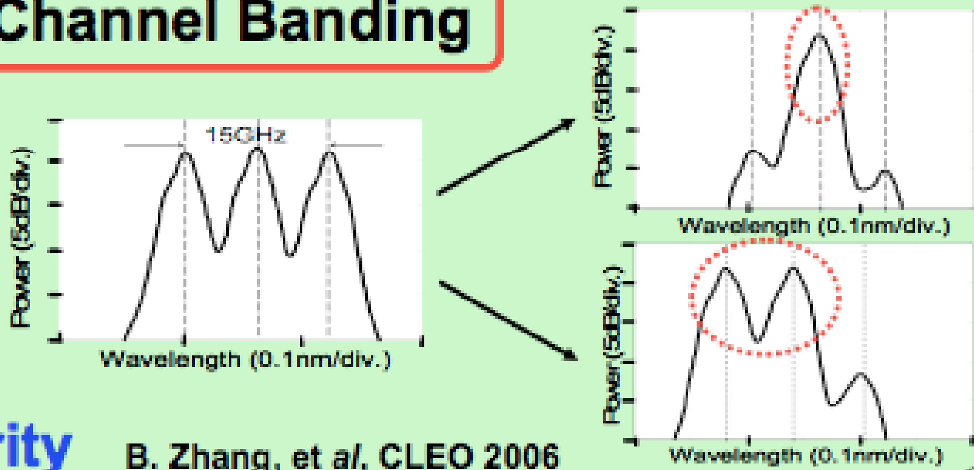
Variable Bit-Rate Channel

- Efficient allocation

Reconfigurable Channel Banding



- Common routing
- Common processing
- Reconfigurable granularity



B. Zhang, et *al*, CLEO 2006

Grooming in Optical Domain

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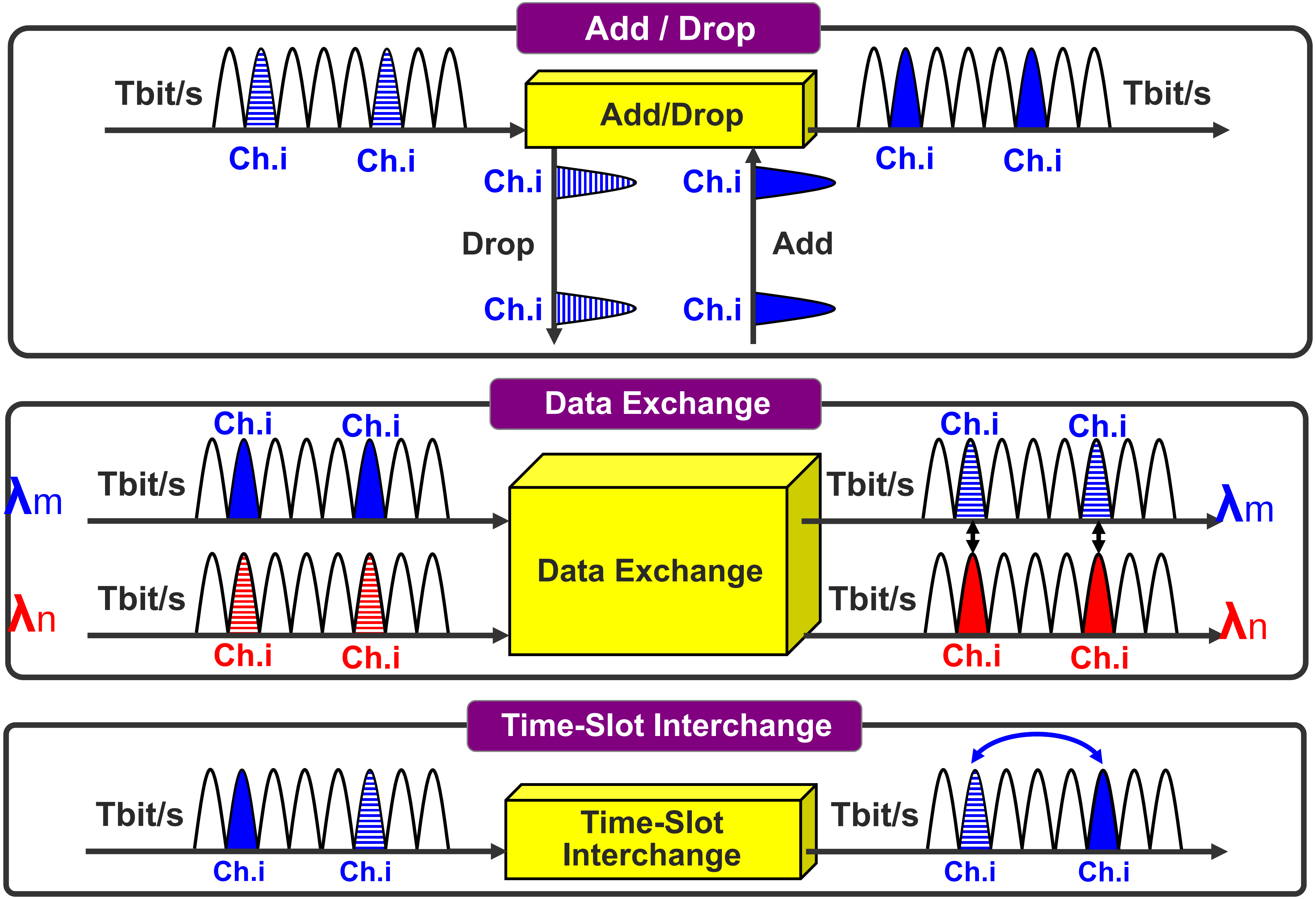

Data Grooming: Wavelength Exchange

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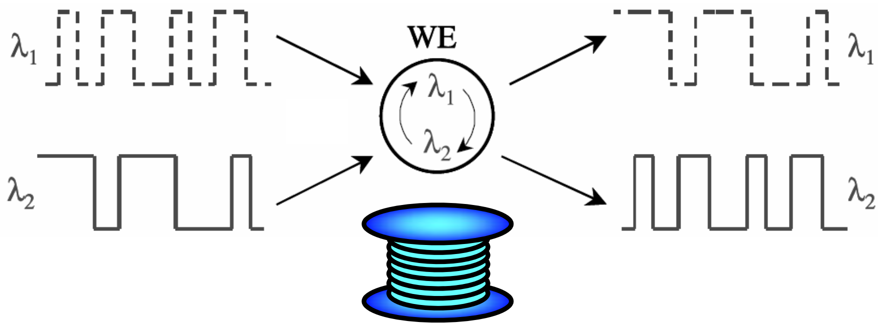
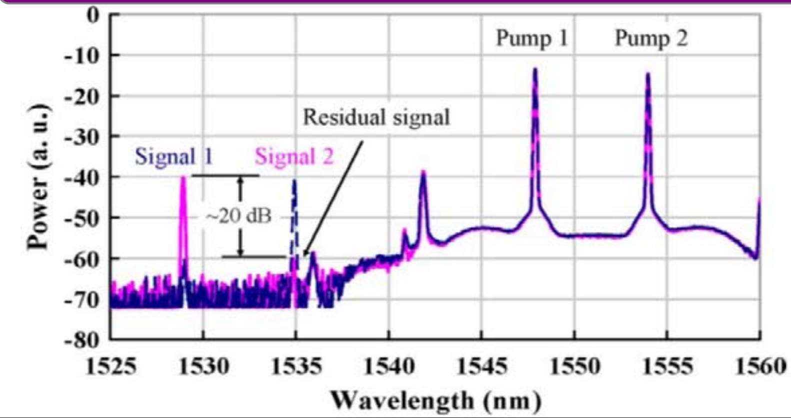
Concept

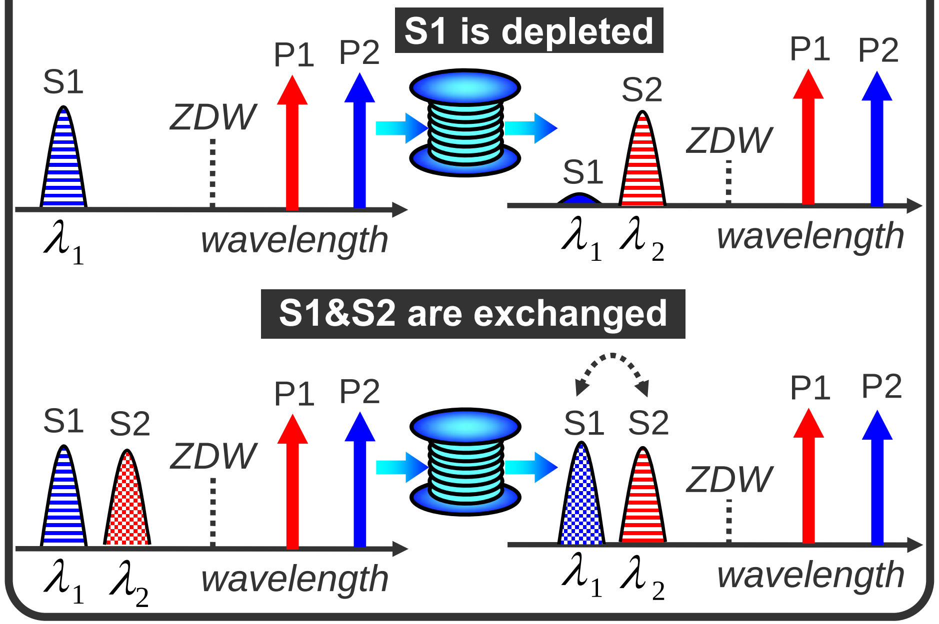


HNLF: highly nonlinear fiber

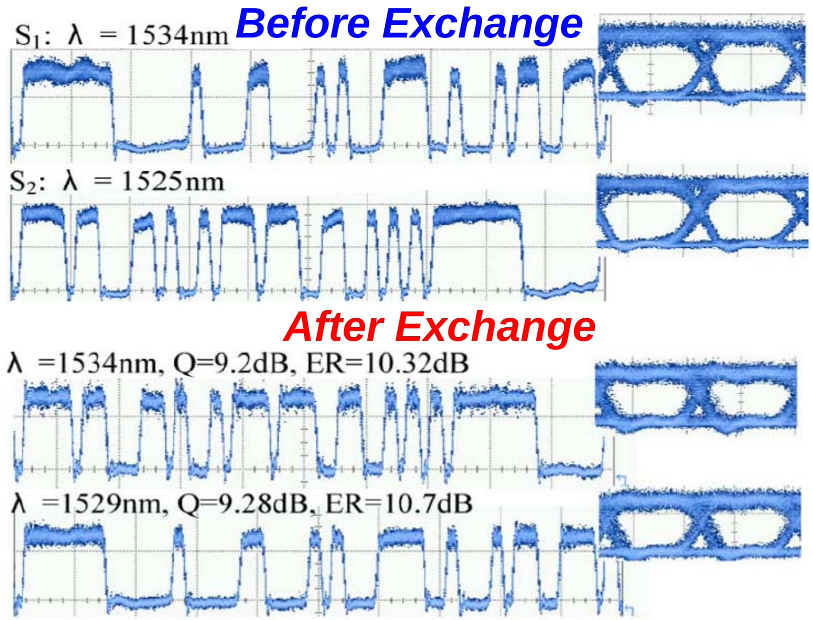
10-Gbit/s Exchange (Spectrum)



Principle: Parametric Depletion



10-Gbit/s Exchange (Waveform)



Fung, Cheung, Wong, PTL 2007

Multi-Rate, Multi-Format Receiver Design

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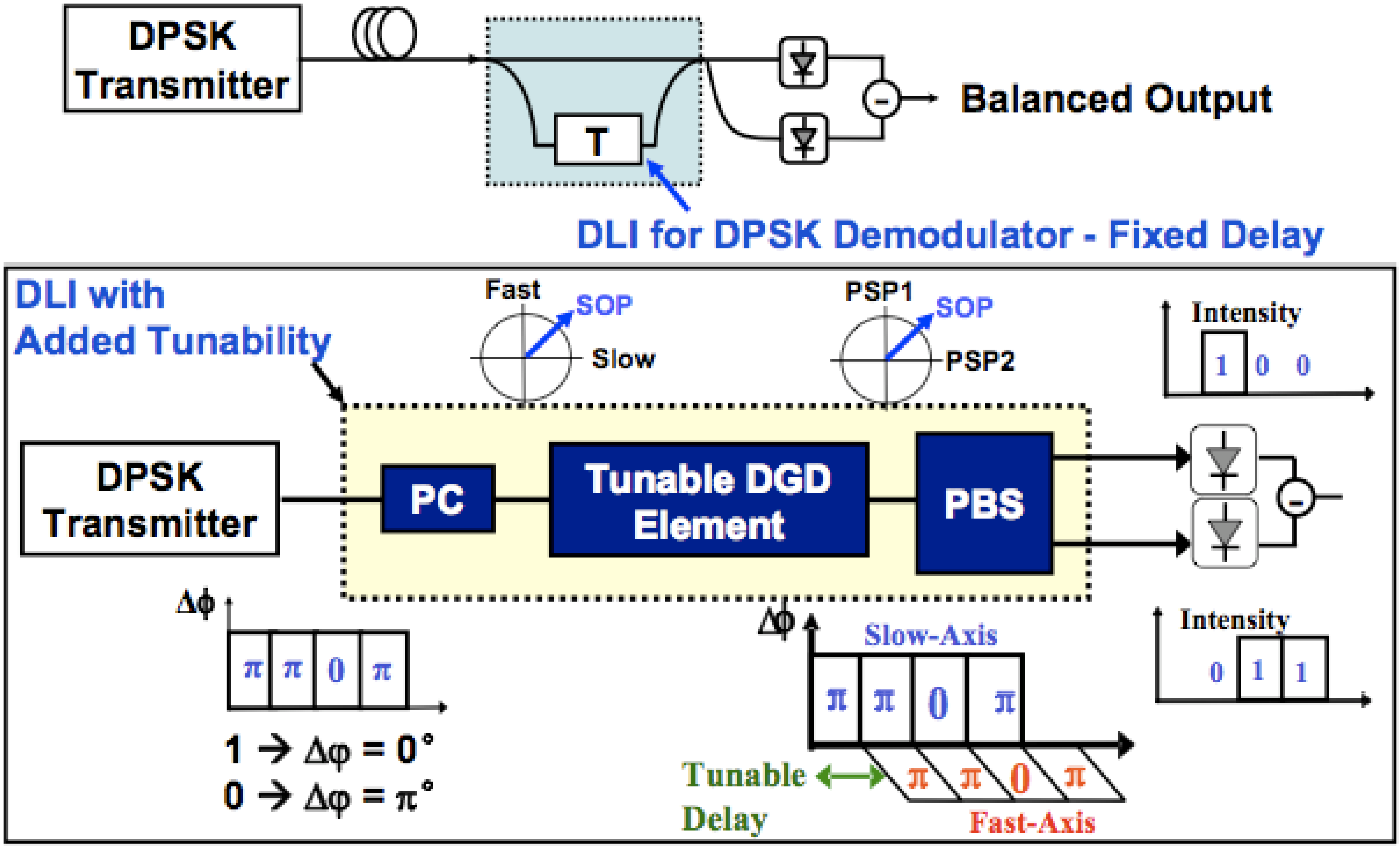
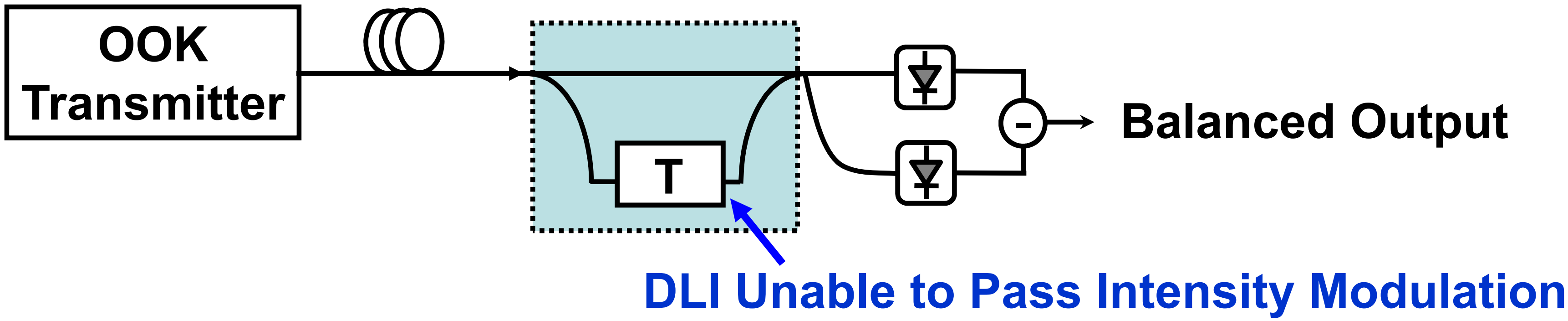
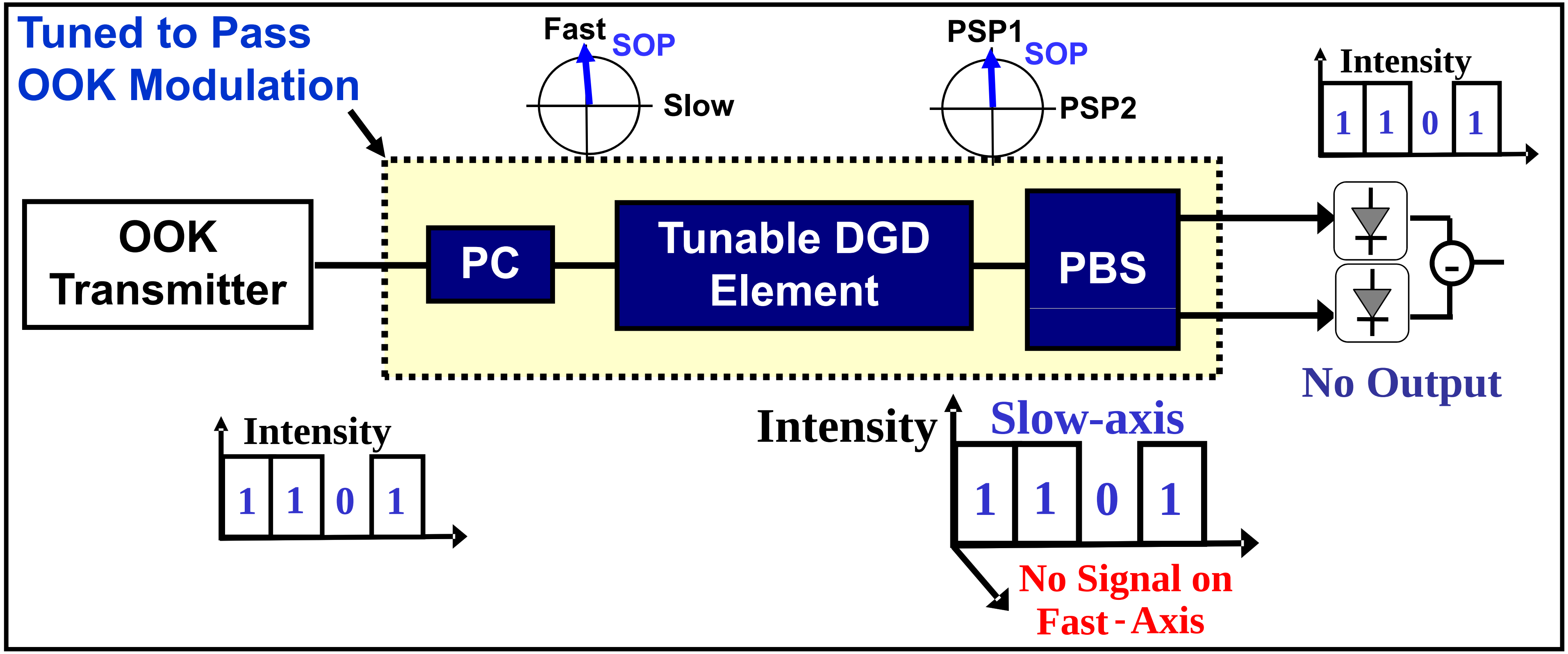


L. C. Christen et. al., Optics Express, 2008

Multi-Rate, Multi-Format Receiver Design

USC Viterbi School of Engineering





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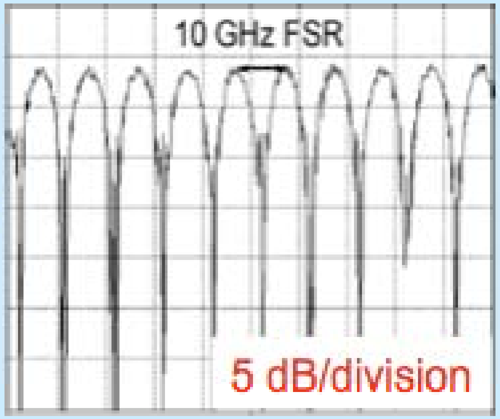
L. C. Christen et. al., Optics Express, 2008

cisco

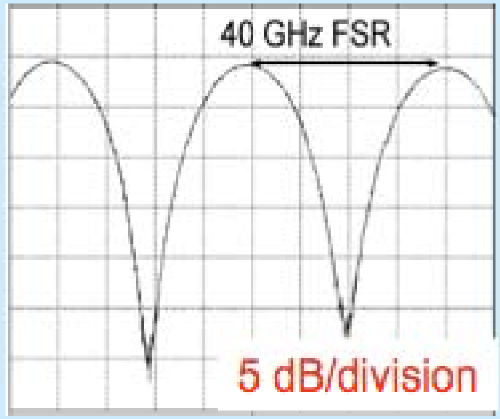
Multi-Rate, Multi-Format Receiver Design

- Transmission responses of the interferometer tuned to receive different bit rates

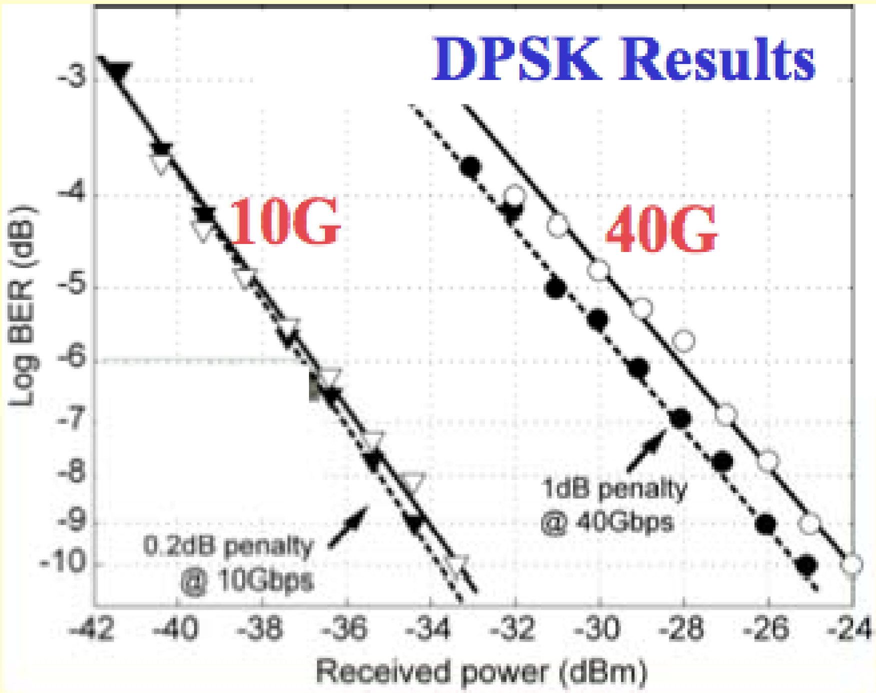
(Desired FSR → Bit Rate)

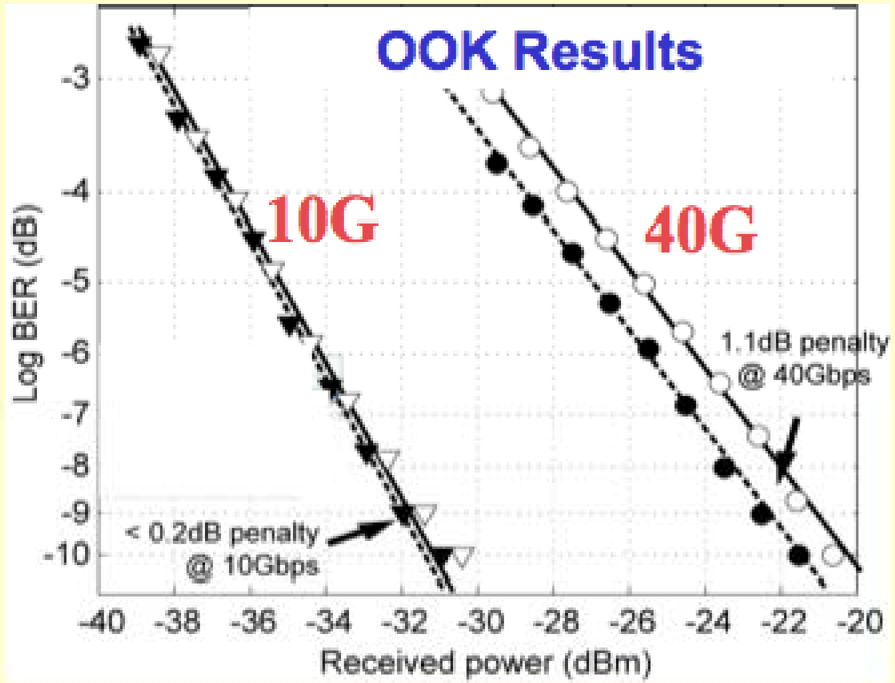


10GHz FSR for 100ps DGD



40GHz FSR for 25ps DGD





L. C. Christen et. al., Optics Express, 2008

D.2. DQPSK Multiplexing and Multicasting

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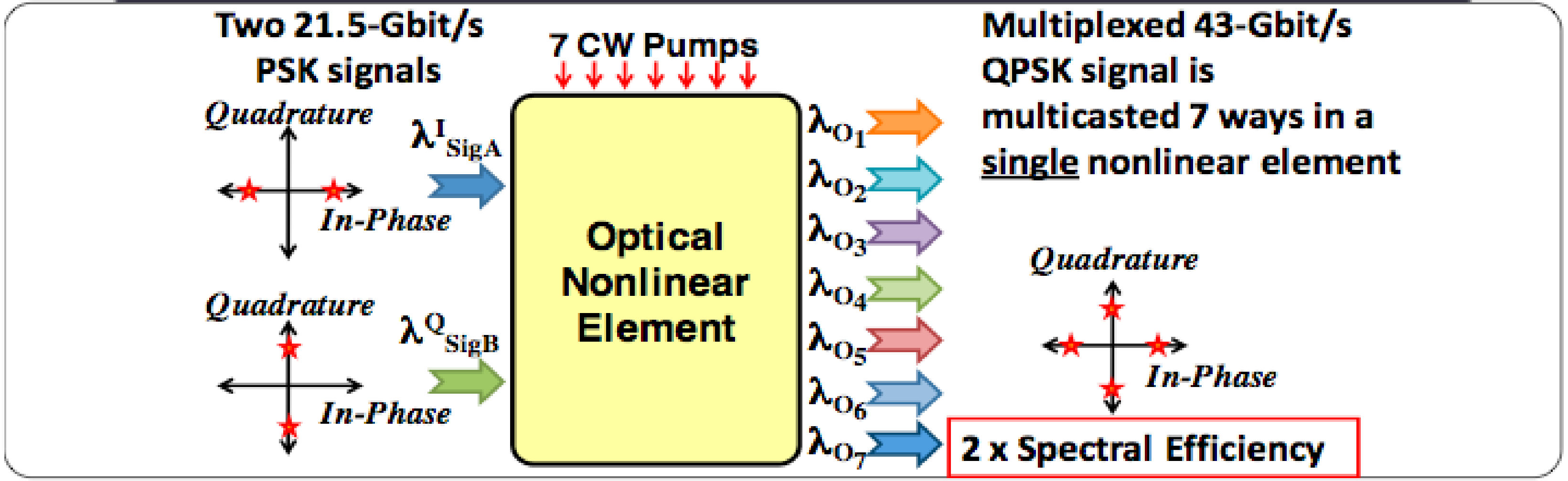
Simultaneous Multiplexing/Multicasting

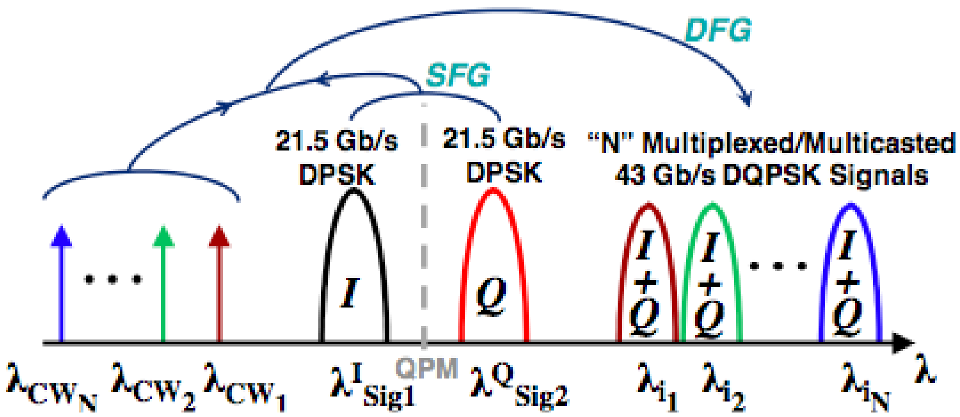


$E_{i,N} \sim E_{Sig1} \times E_{Sig2} \times E^{*}_{CW,N}$

$\phi_{i,N} \sim \phi_{Sig1} + \phi_{Sig2} - \phi_{CW,N}$

Phase of the output idler is a linear combination of the phase of the two pumps and the dummy CW lasers.

SFG: Sum Frequency Generation
DFG: Difference Frequency Generation



O. Yilmaz, et. al, OFC 2009, OThM4

QuickTime?and a
decompressor
are needed to see this picture.

Outline

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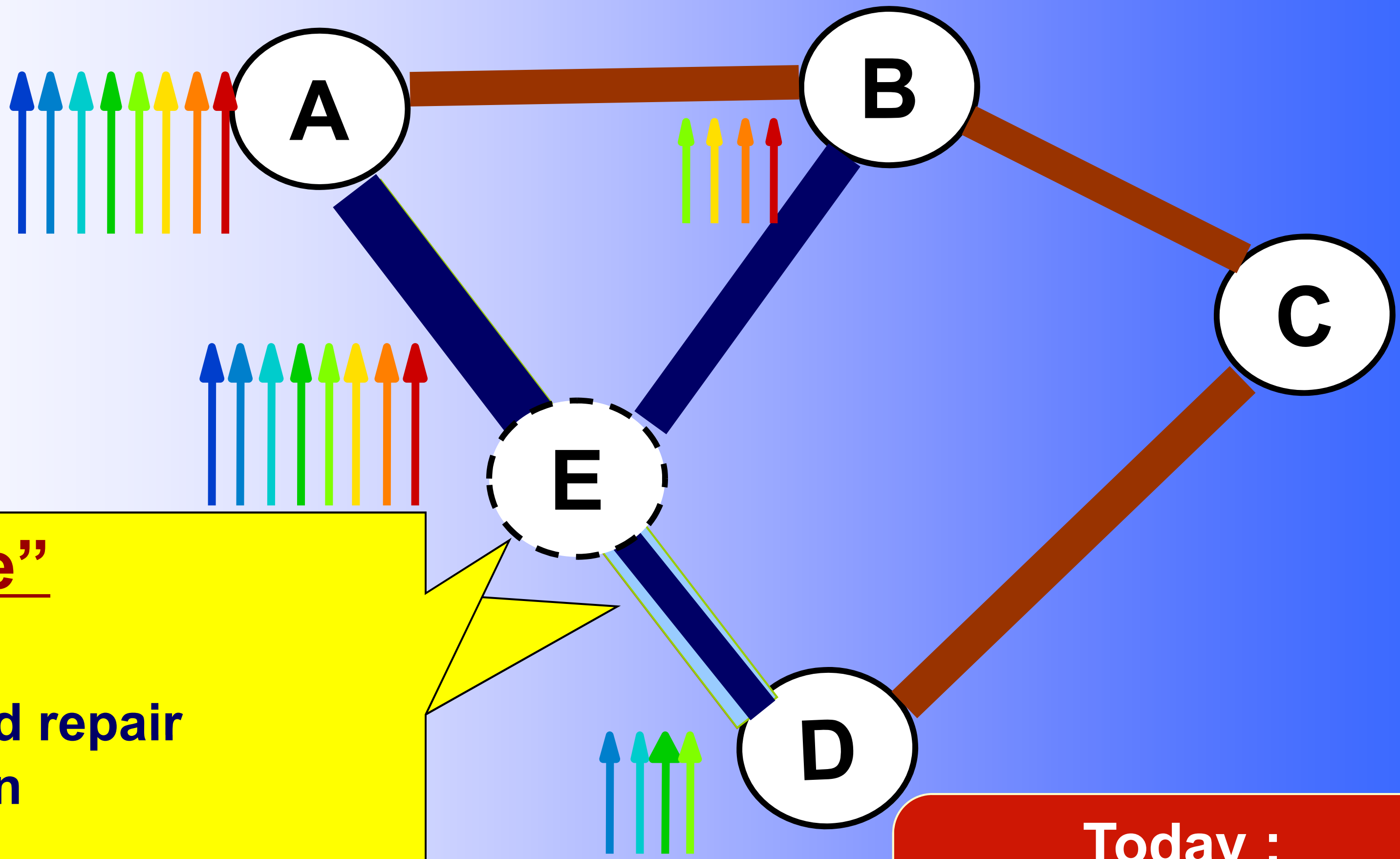
Think “wireless laptop LAN” …

Self-Managed Networks



"Adaptive" Resources

- Diagnose and repair
- BW allocation
- Gain/Loss
- Dispersion Compensation
- λ-Routing
- Look-up tables

Today :
Measure, Make, Tweak, Pray.

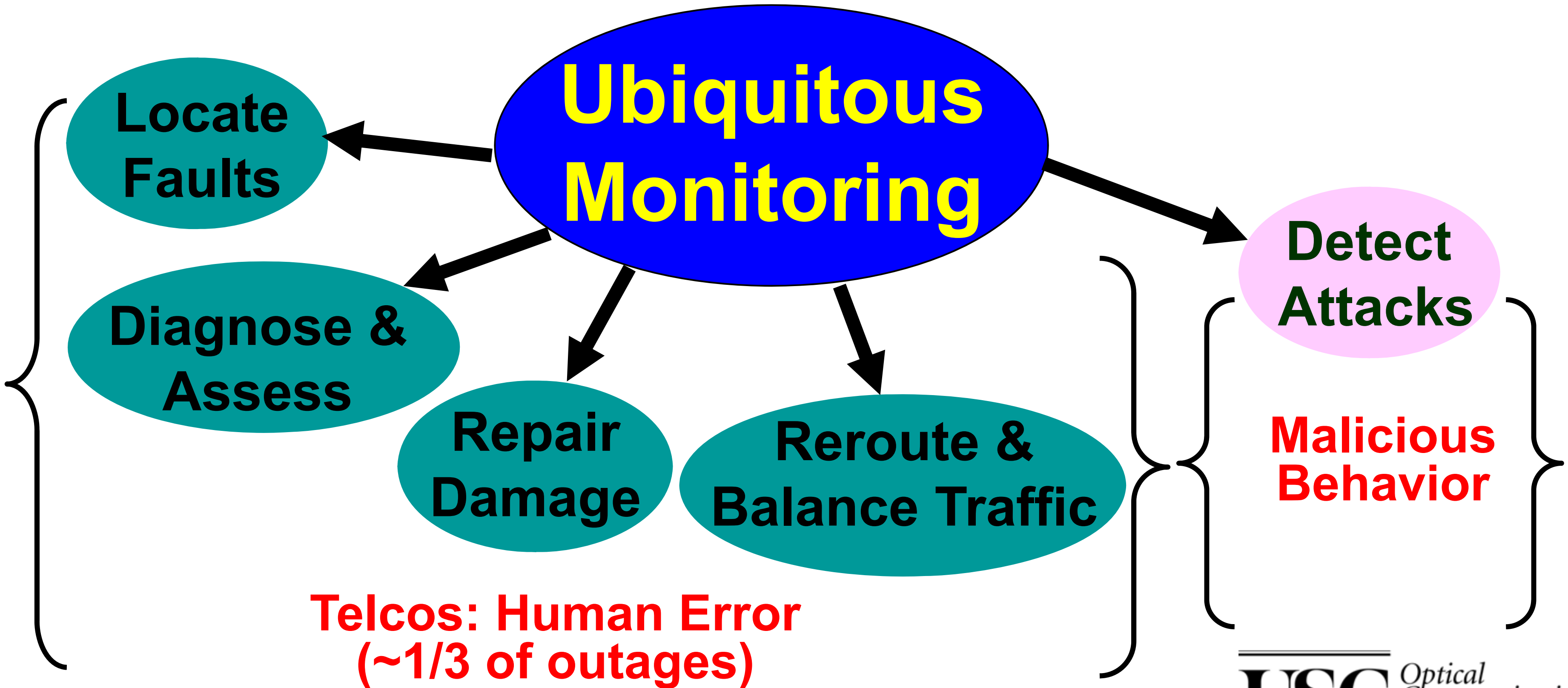
Automation + Intelligence + Monitoring

Keep the person out of the loop

Monitoring the State of the Network

Window of operability is shrinking → Monitoring is required

- Monitor non-catastrophic data degradation
- Isolate specific impairments
- Ubiquitous deployment
- Graceful routing based on physical state of network?



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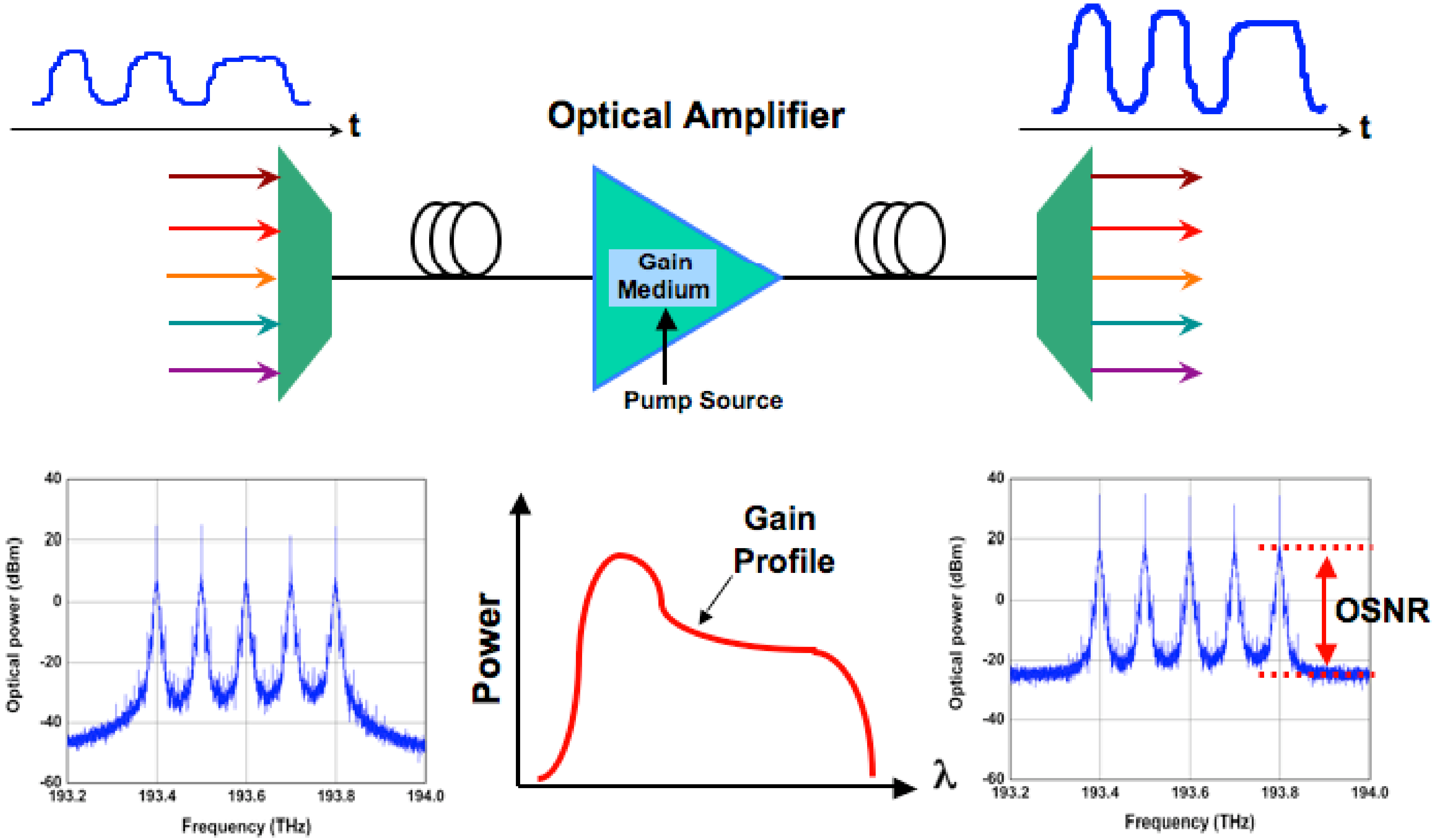
Monitoring for an Efficient Network

Robert Shapiro, former Undersecretary of Commerce:
"*Accommodating the fast-rising demands on bandwidth will require a significant acceleration in industry investments – totaling $300 billion to $1 trillion for the US".*

- ✓**Operate closer to the "red line".**
- ✓**Less need to over-build.**
- ✓**Decrease mean-time-to-failure.**
- ✓**Decrease mean-time-to-repair.**
- ✓**Decrease human error.**

Optical Signal-to-Noise Ratio



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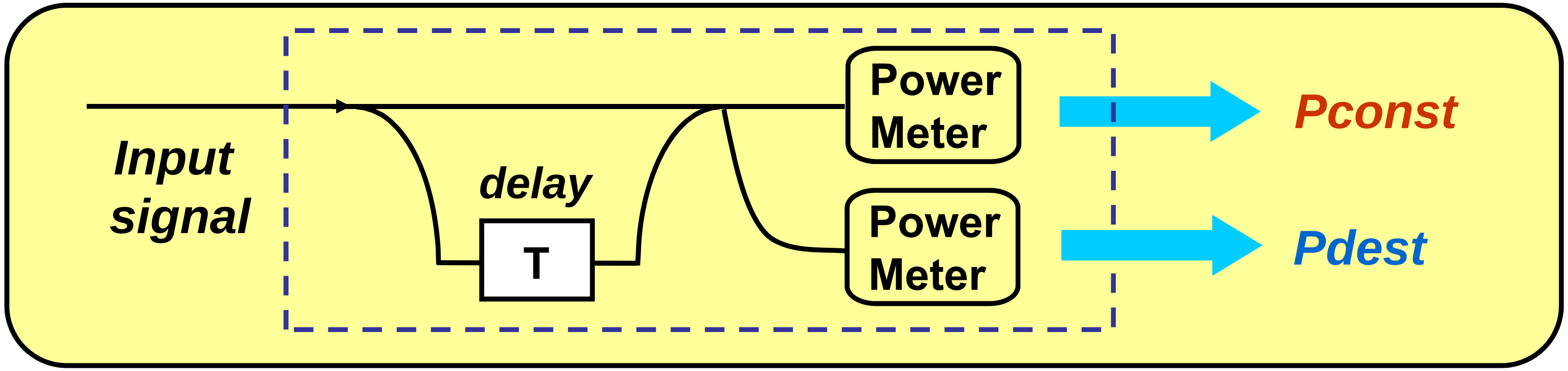
OSNR Monitoring for Multiple Modulation Formats



Signal has coherent interference, noise doesn't

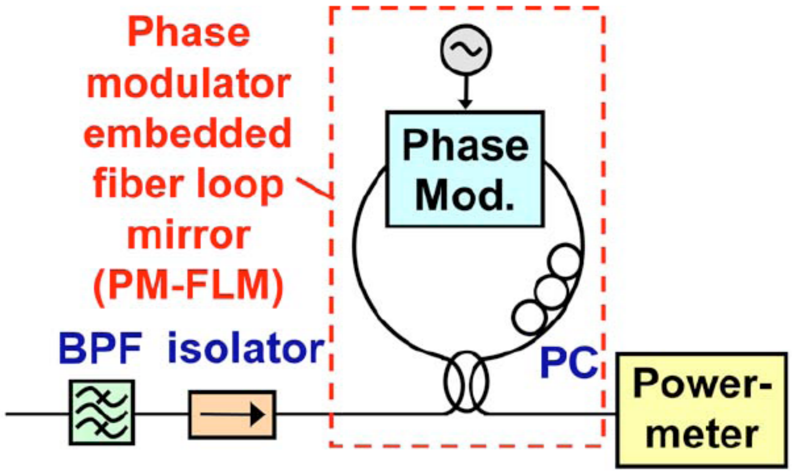
$$Ratio = \frac{(\frac{3}{4}P_{signal} + \frac{1}{2}P_{noise})}{(\frac{1}{4}P_{signal} + \frac{1}{2}P_{noise})}$$

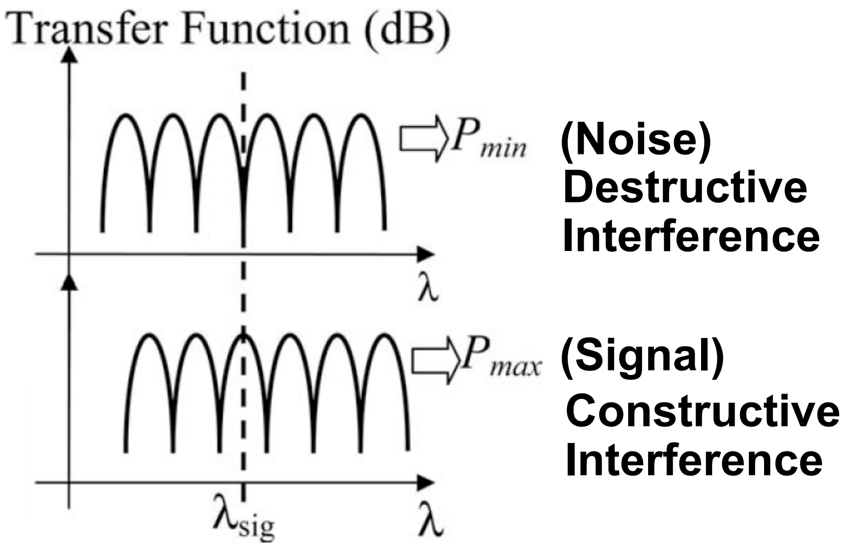
- **Using partial bit delay-line Interferometer (DLI)**
- **OSNR is proportional to the Ratio (=*Pconst* / *Pdest*)**
- **Applicable to OOK, DPSK data**

Y. Lize, et. al., PTL' 07 and JLT' 08

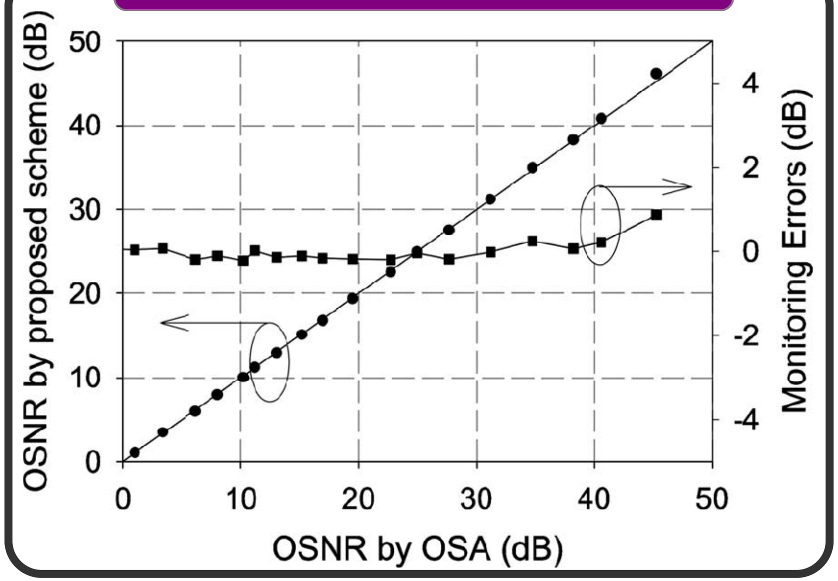
OSNR Monitoring

In-Band OSNR Monitoring





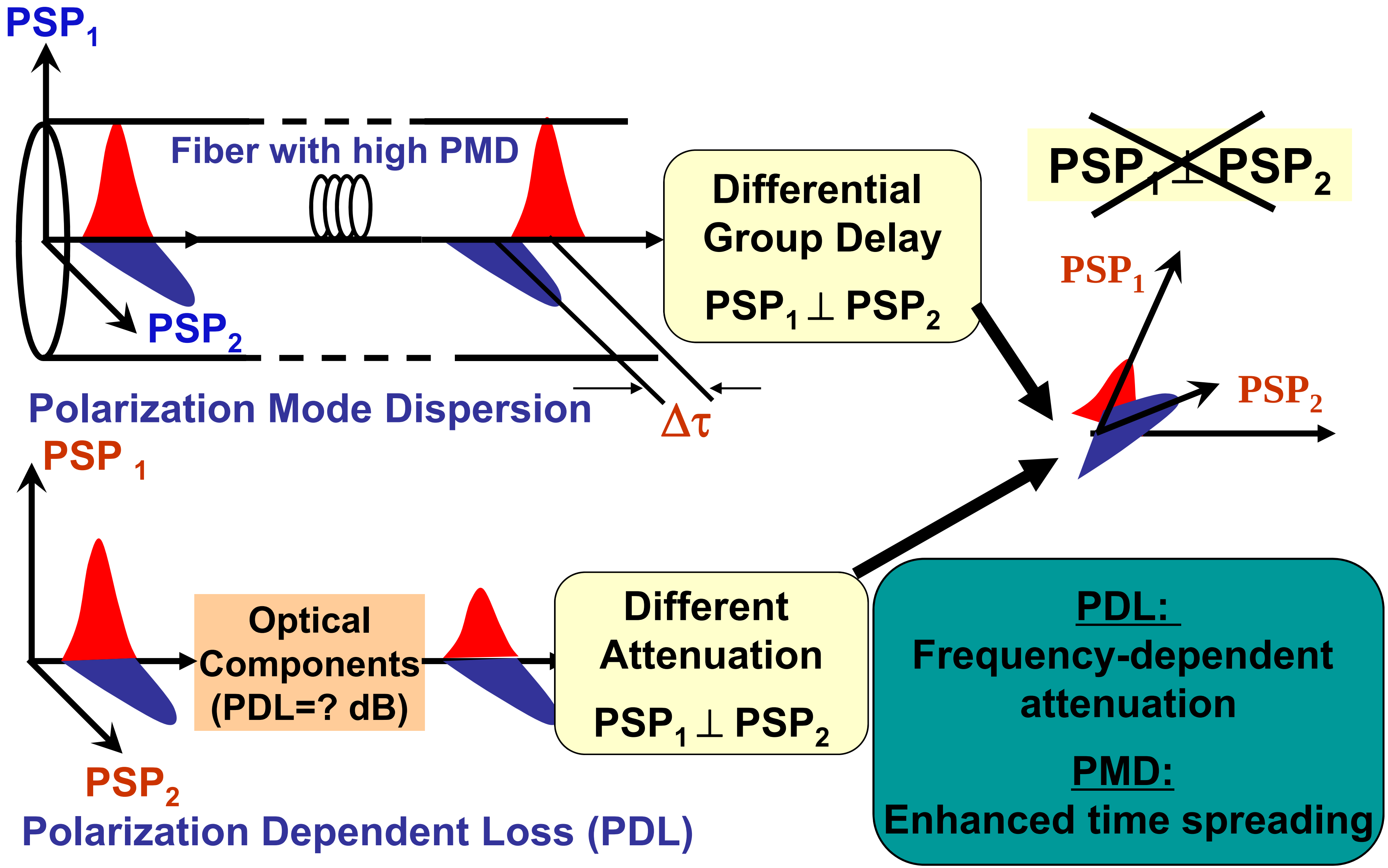
Monitoring Results



- ❑ Noise: incoherent
- ❑ Phase Modulator: introduces intrinsic birefringence inside the loop
- ❑ Altering the voltage of phase modulator shifts the transfer function
- ❑ Constructive interference: signal is extracted
- ❑ Destructive interference: noise level is extracted

Y. C. Ku, C. K. Chan, L. K. Chen, Opt. Lett. 2007

Combined Effects of PMD and PDL



B. Huttner, et al., JSTQE, 2000

L.-S. Yan, et al., PTL, 2003

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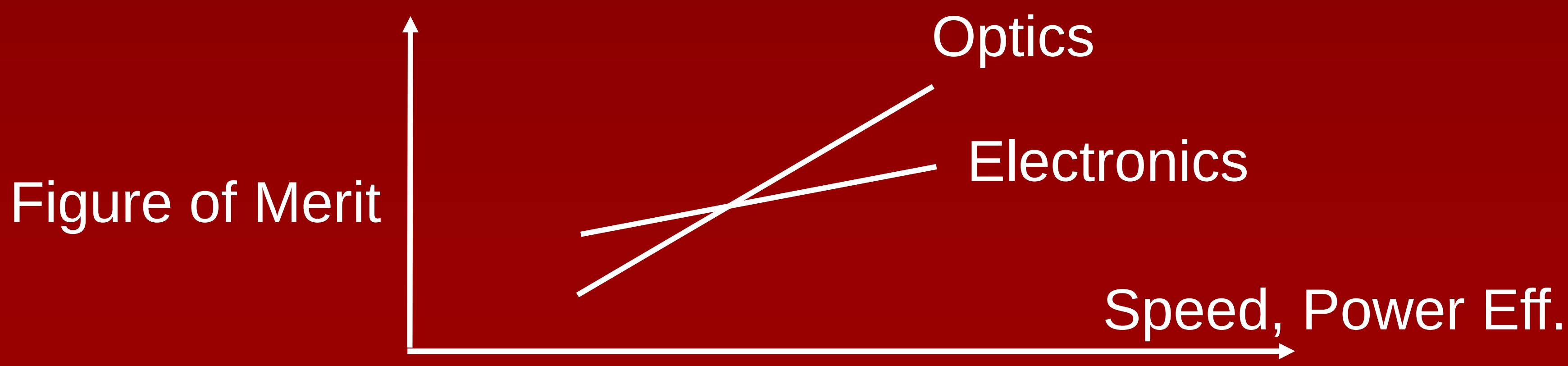
2. Heterogeneity & Grooming
3. Optical Performance Monitoring
4. Optical Signal Processing

Where, O' where, is the cross-over point?

- The assumption is that optics should be better than electronics for speed & power efficiency.
- Depends on the "function" (simple & fast).
- Is now the time for on-chip interconnections and signal processing applications?

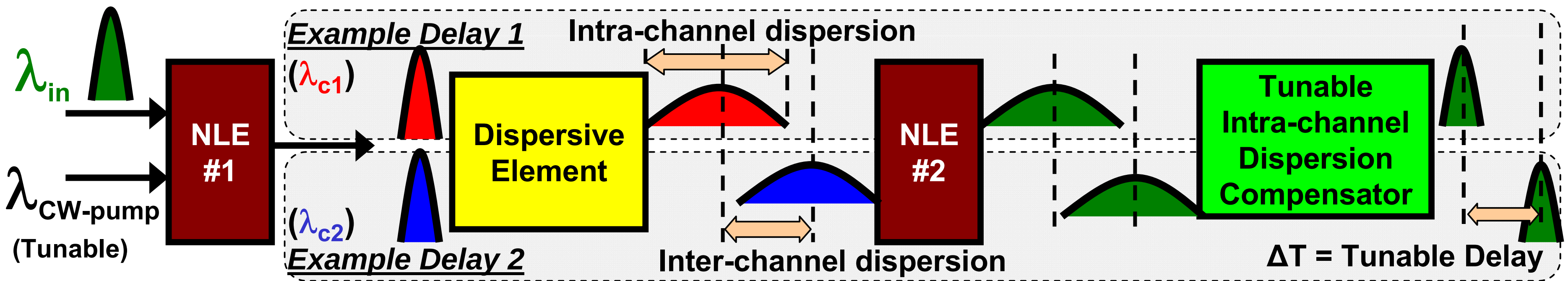


Please tell me, where's your pain?

(even muxing at 100G in electronics)

Continuously & Widely Tunable Delays

Use wideband, low-noise optical nonlinearities to achieve dramatic increases in continuously tunable delays for very high bit rate signals.



λ-conversion via first nonlinear element (NLE) (pump determines λ_c)

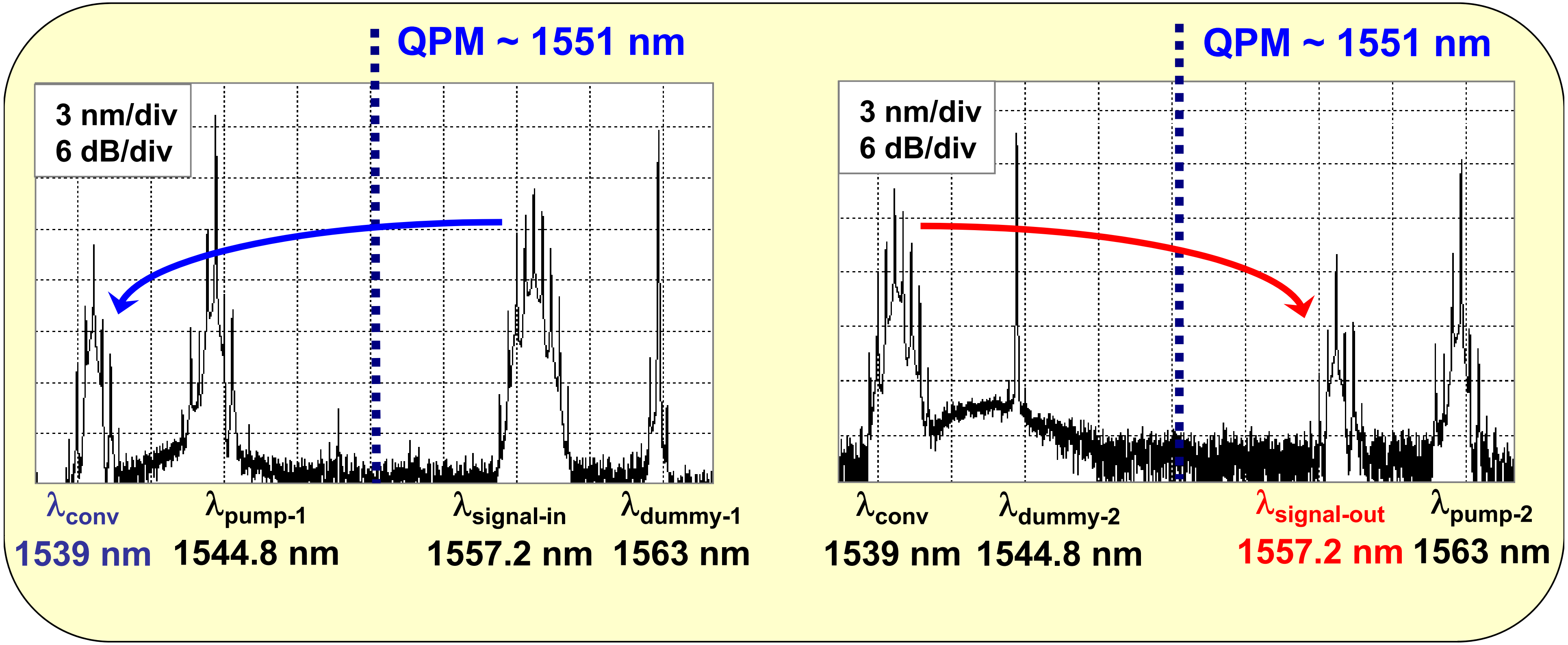
Desired delay is selected through tuning of $\lambda_{CW\text{-}pump}$

λ-conversion back to λ_{in} via second nonlinear element (NLE)

Time delay depends on relative inter-channel dispersion

PPLN: Conversion Spectra

λ-Conversion Stage 1 → Dispersion → λ-Conversion Stage 2



- Approximately -12 dB conversion efficiency in both stages
- Converted signals in both stages above ASE noise floor

(L. Christen, et. al., Optics Letters 2008)

All-Optical Signal Processing : Tunable Delays

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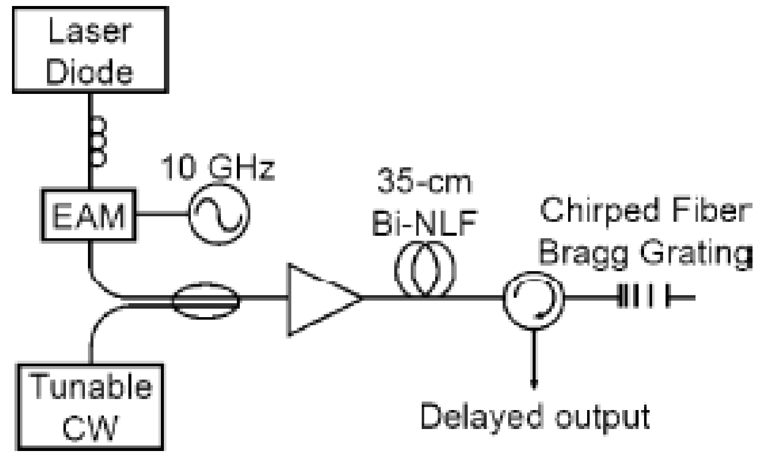
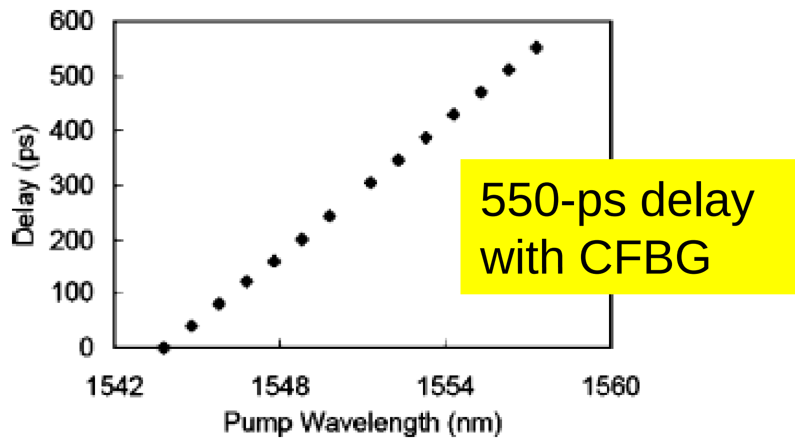
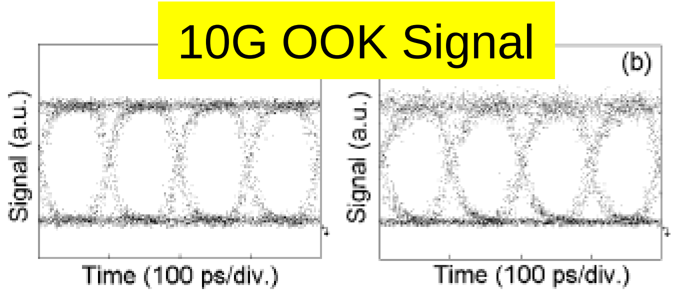
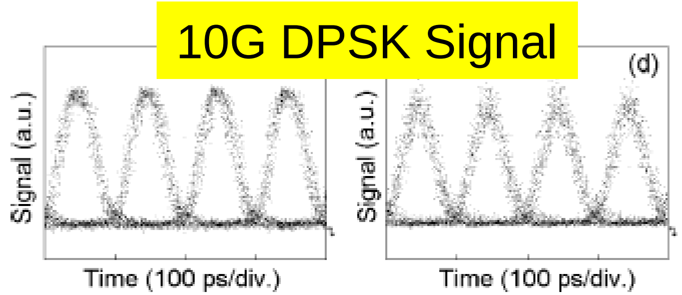


Delay vs Pump λ





Input Eye Delayed Eye



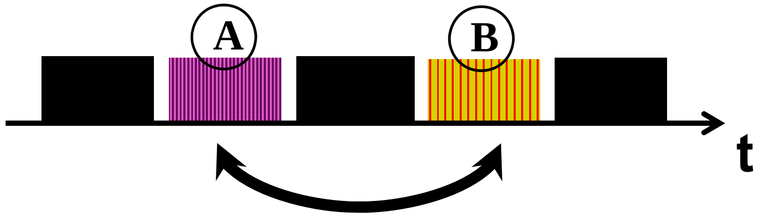
Input Eye Delayed Eye

- ❑ Bismuth oxide HNLF and chirped fiber Bragg gratings result in **small footprint**.
- ❑ By using four wave mixing in Bi-HNLF, **modulation-format transparency** is achieved in the all-optical delay module.
- ❑ < 3.5 dB power penalty demonstrated for both OOK and DPSK signals

Fok, Shu, OFC '09

Optical Time-Slot Interchange

- **Manipulation of time domain data (bit/packet swapping) can mitigate output port contention and may improve network efficiency.**
- **20 packets, 500 bits/packet, 40-Gbit/s = 25 ns**



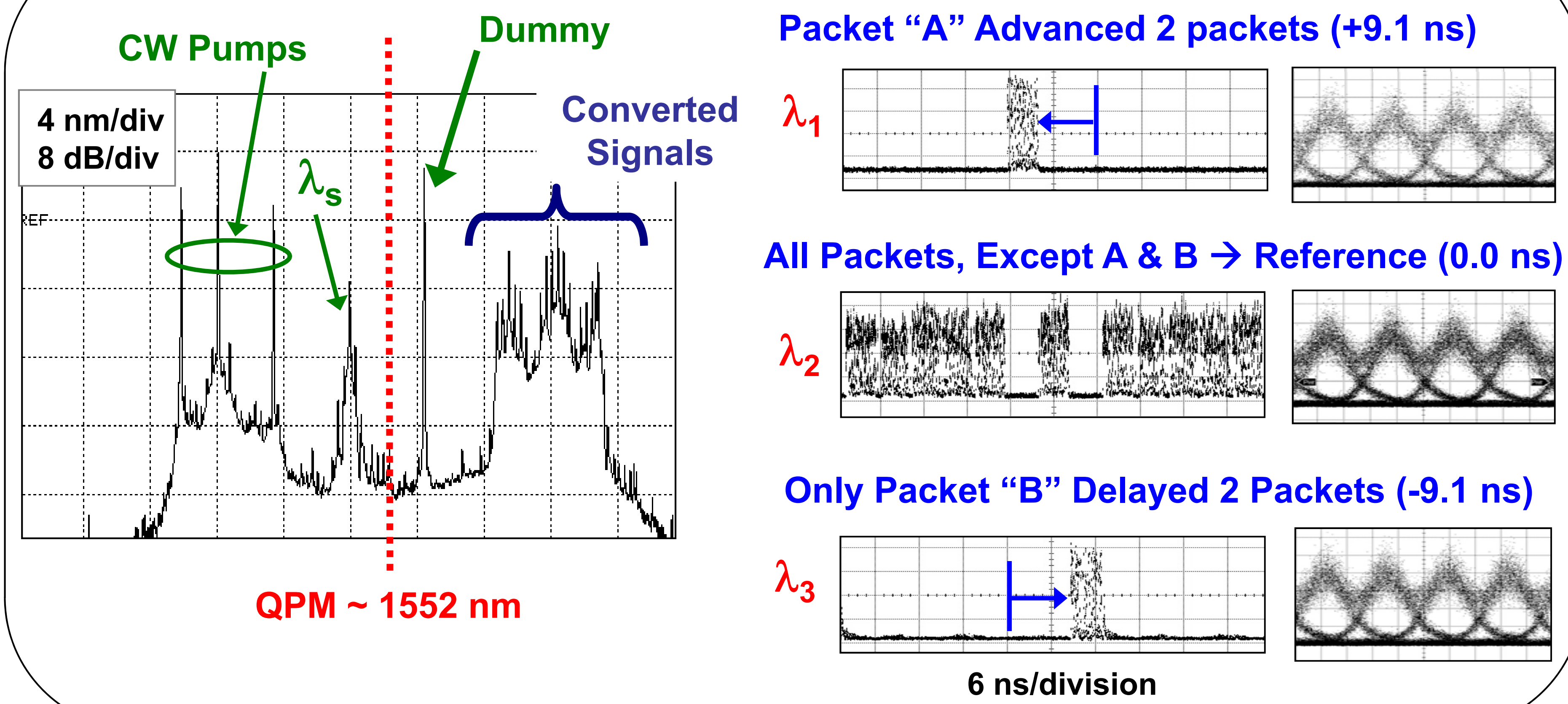
Interchanger swaps packets A & B

> **Desirable Features for Interchanger:**
> - **Multi-rate and -format handling capability**
> - **Ability to handle variable packet size**
> - **Input/output wavelength independent**
> - **Non-discrete set of delay values**

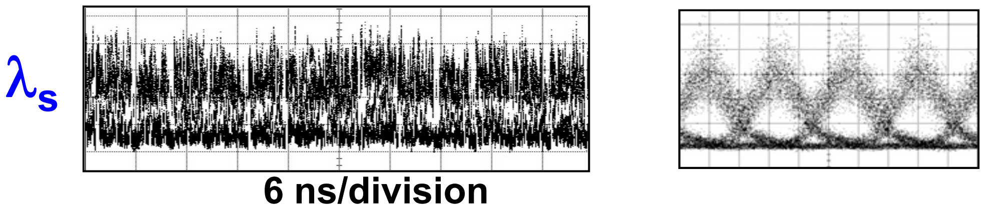
Experimental Results at 40-Gb/s

(O. Yilmaz, et al, Optics Letters, 2008)

Wavelength Conversion via SFG/DFG in PPLN



Output Multiplexed Signal After Dispersion Compensation



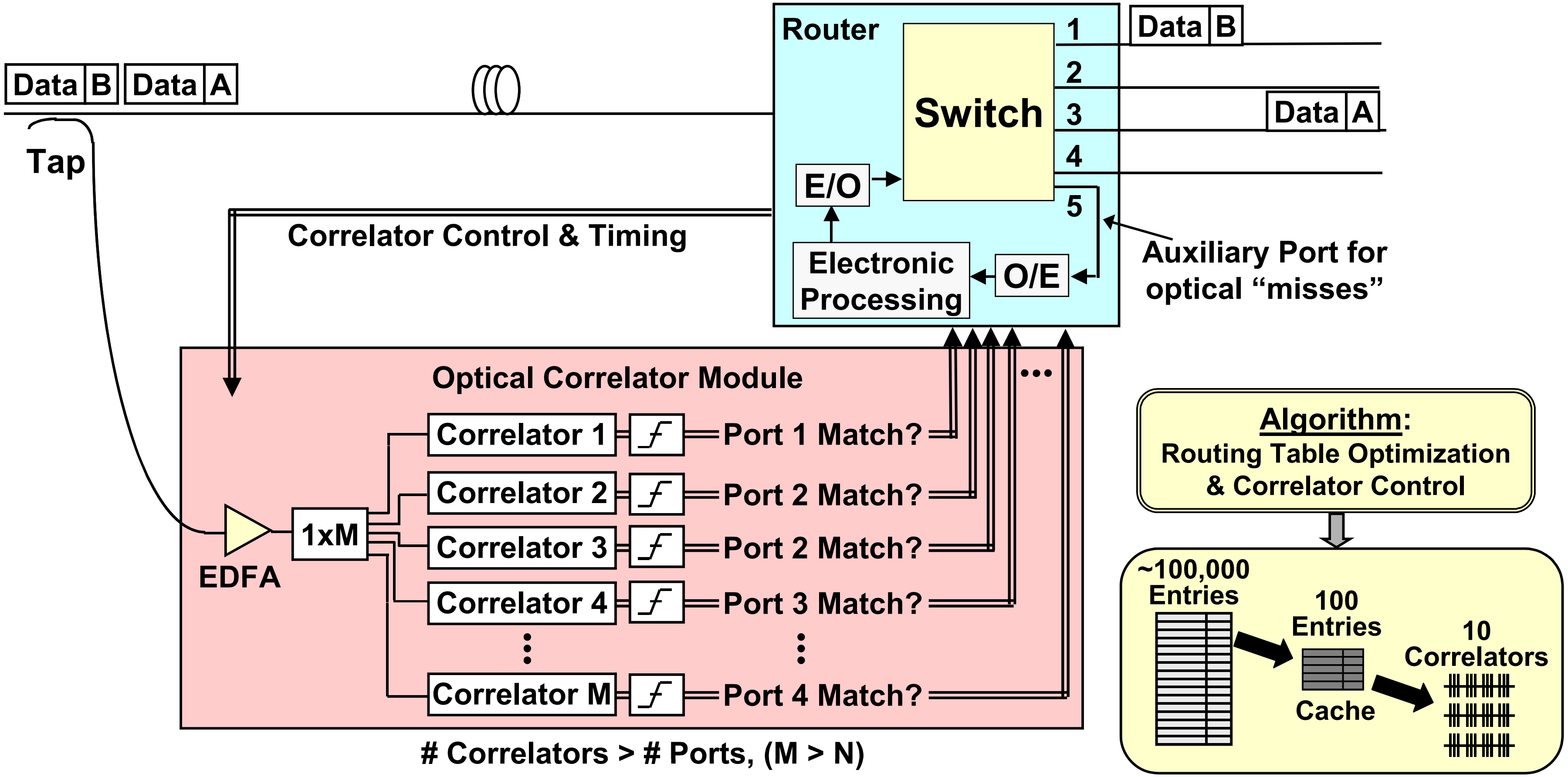
(A and B packets swapped)

QuickTime?and a
decompressor
are needed to see this picture.

QuickTime?and a
decompressor
are needed to see this picture.

QuickTime?and a
decompressor
are needed to see this picture.

Correlators for Boosting Internet Routing Capabilities



Implement a subset of the routing table creating an "optical bypass" to route the most common packet headers optically

If you can’t measure it, you can’t experiment and make progress.

<u>Whither 100-Gbit/s?</u>

Use nonlinearities to …

Photrix, Picosolve, etc.

QuickTime?and a
decompressor
are needed to see this picture.

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The Power of Photonics: Greener & Healthier

Bosons & Waves: $A\cos(\omega t+\phi)$

- **High energy can be directed with very low loss.**
  - ✓*Ex.: lighting, manufacturing, displays, solar energy, fusion, transmission, medical treatment, fabrication, defense, low power consumption.*
- **Many different wave properties (i.e., degrees-of-freedom) can be manipulated.**
  - ✓*Encode amplitude, frequency, phase, polarization, direction.*
  - ✓*Ex.: communications, sensing, information processing, computing, data storage, security.*
- **Coherent waves have unparalleled accuracy, speed & dynamic range.**
  - ✓*Ex.: medical diagnostics, clocks, imaging, spectroscopy, instrumentation, reconfigurable/flexible systems, fundamental physical processes, ultrafast/ultrastable probing.*

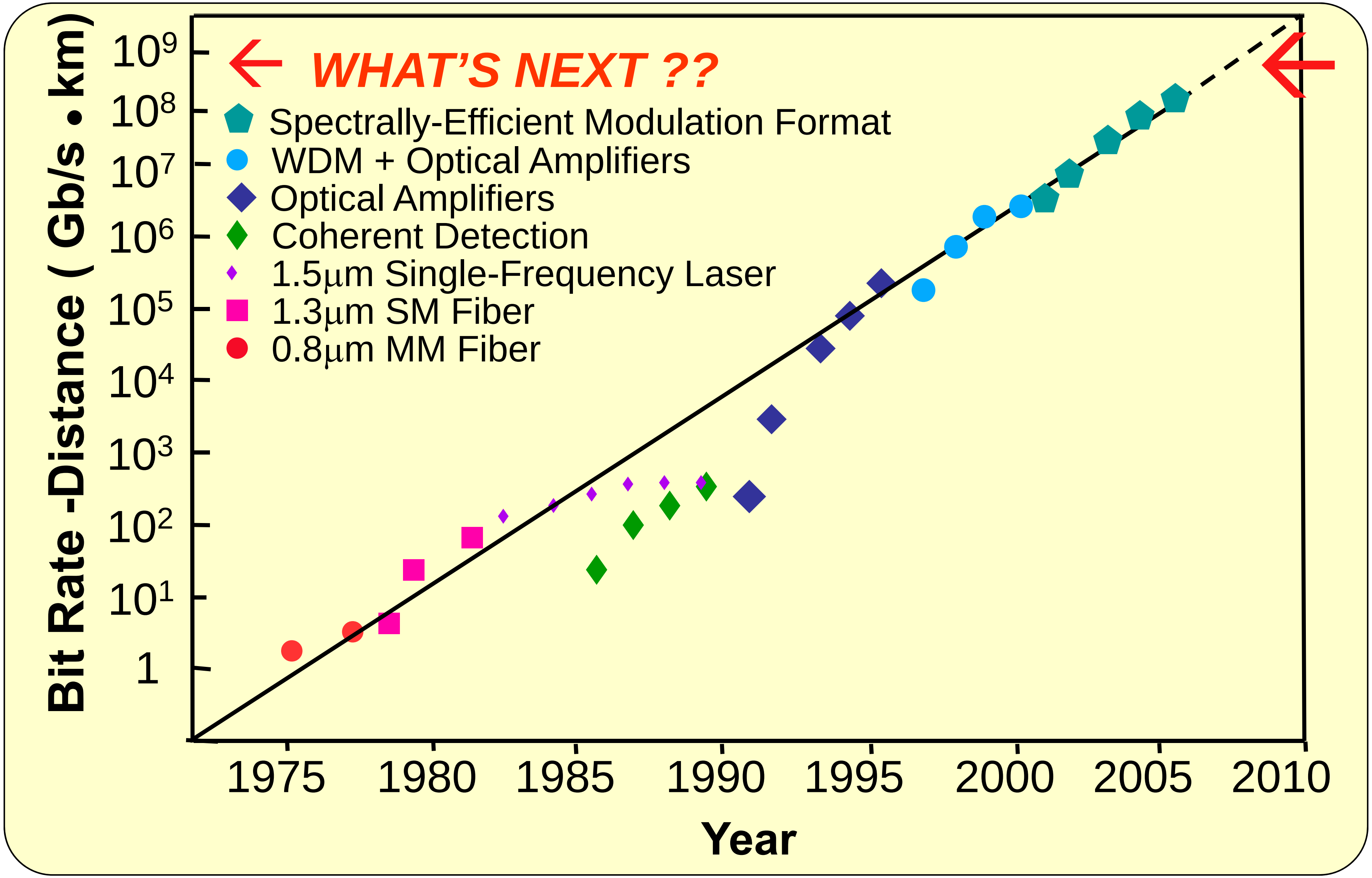
Compelling Issues Necessitating a Study

- **Orders-of-magnitude growth in technical performance.**
  - ✓*Ex.: Clocks, communications, medical diagnostics, storage, energy density.*
  - ✓*Optics has enjoyed Moore's Law-like growth but also has fundamental limits that must be attacked.*
- **Optics has cemented itself as a transformative, enabling technology affecting many aspects of society.**
  - ✓*Ex.: Social penetration of the Internet.*
  - ✓*Optics is critically important in healthy economic times and, potentially, even more important in a difficult economy (I.e., telepresence, telecommuting, etc.).- Nortel, Metro Networks.*
  - ✓*Yet optics is viewed as an exotic, non-robust technology.*

Summary

- ✓ Photonics might dramatically change the cost, robustness, functionality and performance of communication systems.
- ✓ A force-multiplier is to enable a “function” rather than simply replace a device 1-for-1.
- ✓ There are a rich set of research problems that must be pursued to herald this vision.

Bit-Rate Distance Product



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Source: Tingye Li and Herwig Kogelnik