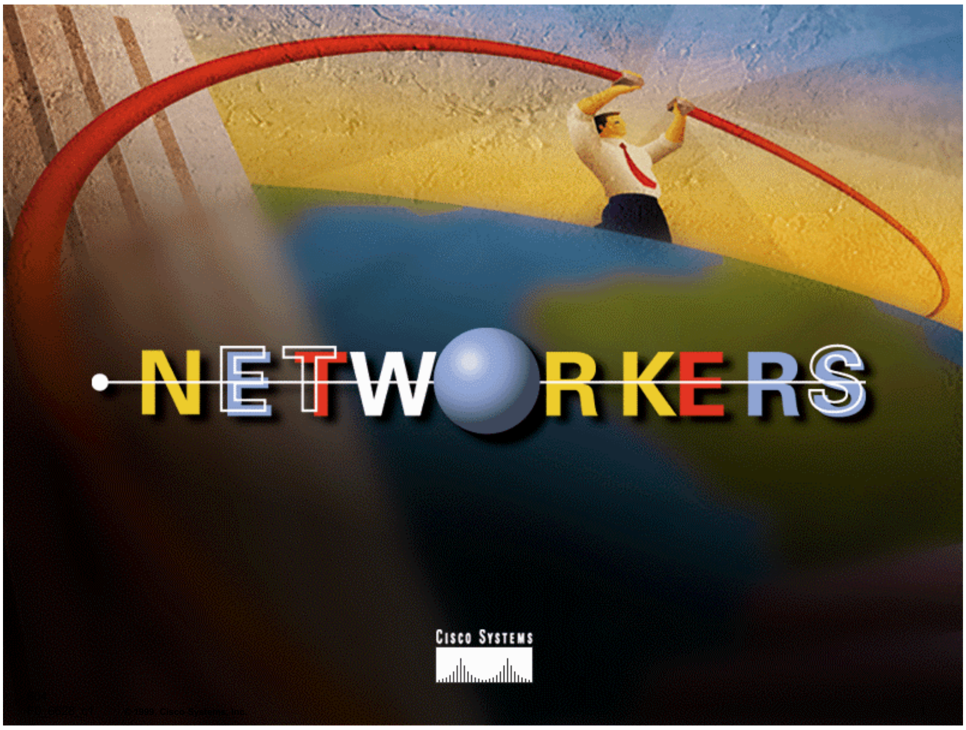
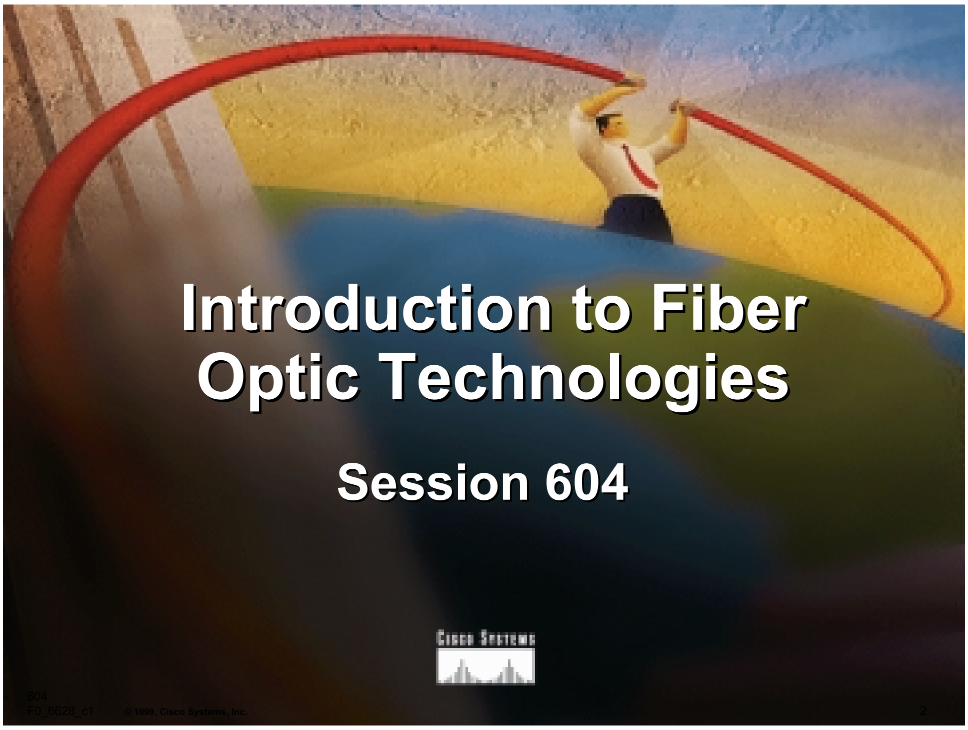

NETWORKERS
Cisco Systems


Introduction to Fiber Optic Technologies
Session 604
Cisco Systems
604
F0_6628_c1
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2

Agenda

- Introduction
- Fiber Optics Fundamentals
- Dense Wave Division Multiplexing
- Optical Internetworking

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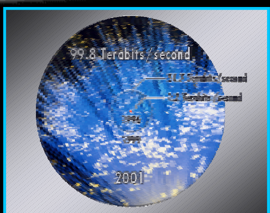
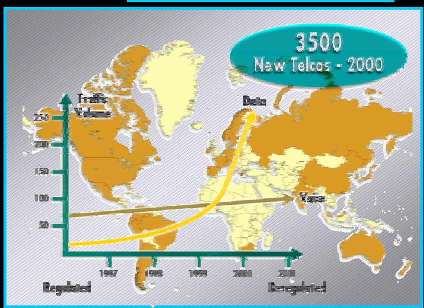
Evolution of the Internet Infrastructure

- Network Providers evolving away from TDM centric infrastructure
  to support emerging data services
- Bandwidth capacity is exploding
- Emergence of IP as the common foundation for all services



Source: Fortune, March 15, 1999



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IP Services Are Increasing Bandwidth Requirements

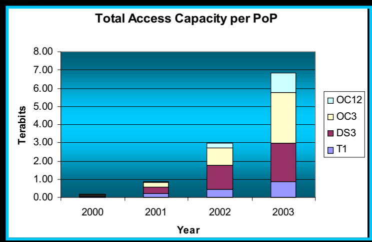
- Increase in number users

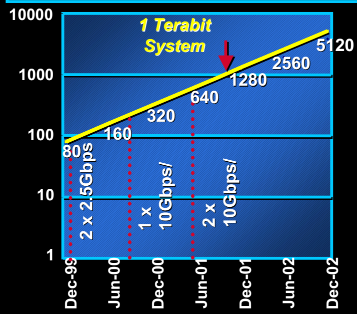
  Significant growth expected in number of access ports, particularly at high speeds—DS3, OC-3, OC-12 access ports

- Resulting backbone capacity

  Most inter-city links are 2 x 2.5 Gbps today with low average utilization

  Backbone bandwidth doubling every 6 to 9 months





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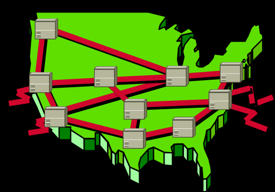
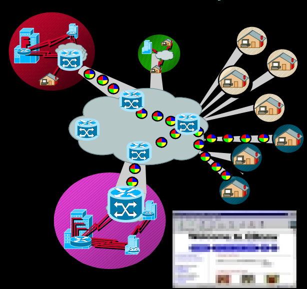
New World Service Foundations

- Two distinct areas where service providers want to invest to realize revenue growth and profitability

  New World Transport

  Optical Internetworking





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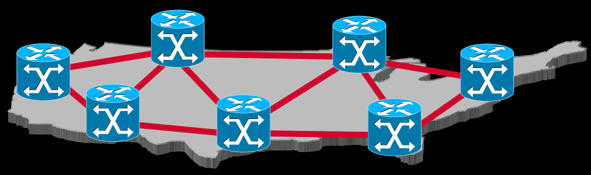
Core IP Solution

- Deliver optical IP transport
- Direct connection to DWDM and/or fiber
- Streamline layers, simplify management
- New functions: optical integration and management, fast restoration



Agenda

- Introduction
- Fiber Optics Fundamentals
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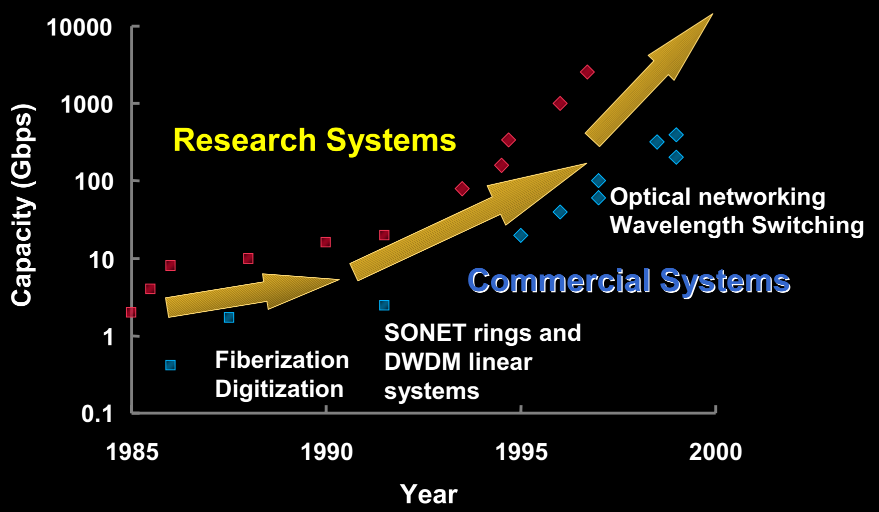
Glass Purity Breakthrough

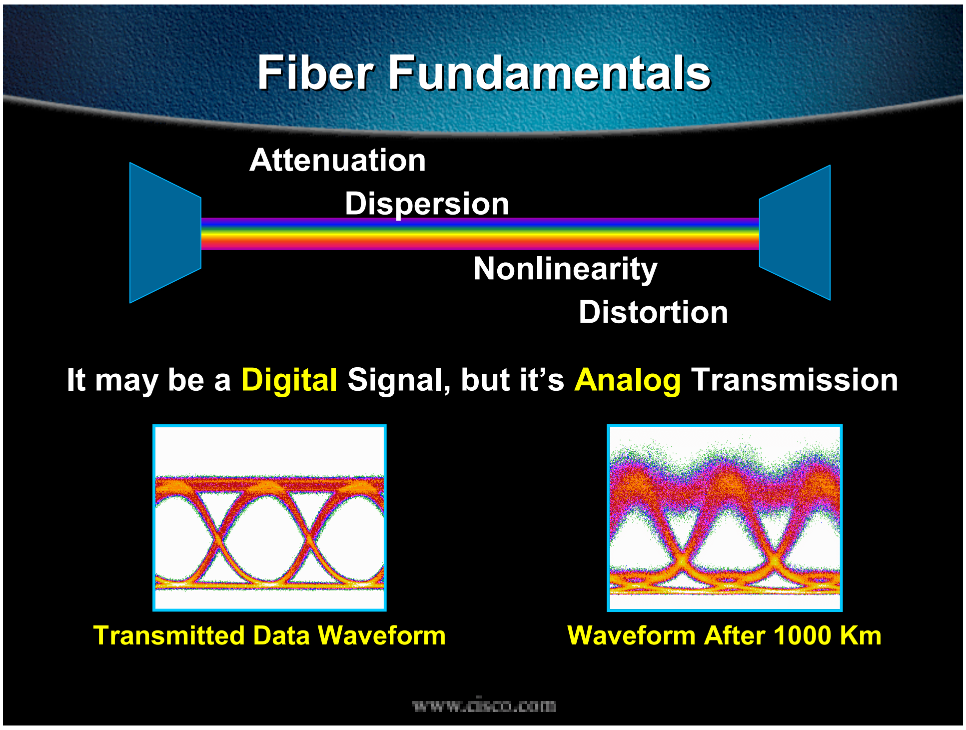
Fiber Optics Requires Very High Purity Glass

Window Glass	1 inch (~3 cm)
Optical Quality Glass	10 feet (~3 m)
Fiber Optics	9 miles (~14 km)

Propagation Distance Need to Reduce the Transmitted Light Power by 50% (3 Db)

Modern Lightwave Eras




Fiber Fundamentals
Attenuation
Dispersion
Nonlinearity
Distortion
It may be a Digital Signal, but it's Analog Transmission
Transmitted Data Waveform
Waveform After 1000 Km
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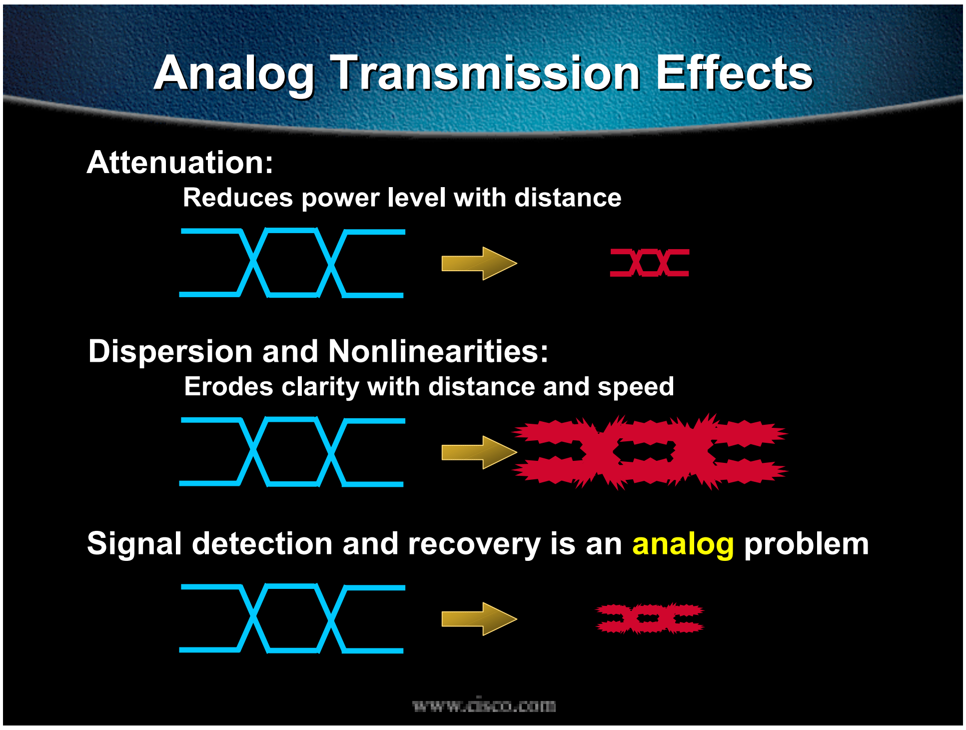
Analog Transmission Effects
Attenuation:
Reduces power level with distance
Dispersion and Nonlinearities:
Erodes clarity with distance and speed
Signal detection and recovery is an analog problem
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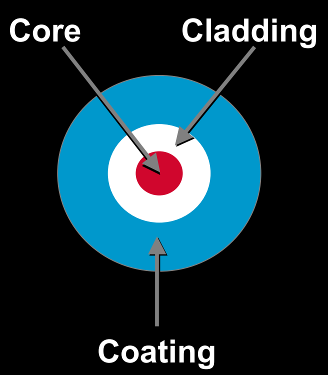
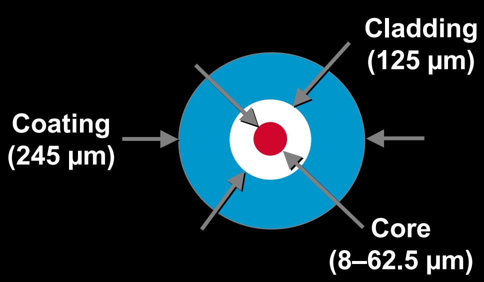
Fiber Geometry

- An optical fiber is made of three sections:
  - The core carries the light signals
  - The cladding keeps the light in the core
  - The coating protects the glass



Fiber Dimensions

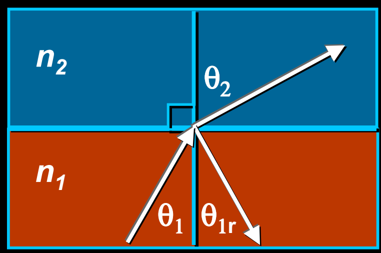
- Fiber dimensions are measured in µm
  - 1 µm = 0.000001 meters (10-6)
  - 1 human hair ~ 50 µm



- Refractive Index (n)
  - n = c/v
  - n ~ 1.46
  - n (core) > n (cladding)

Geometrical Optics

- Light can be described as:
  - Particles (classical optics)
  - Waves (electromagnetic theory)
- Light is reflected/refracted at an interface
  - θ_1 = Angle of incidence
  - θ_{1r} = Angle of reflection
  - θ_2 = Angle of refraction
- Above $\theta_{critical}=\text{Sin}^{-1}(n_2/n_1)$, all light is **totally internally reflected**

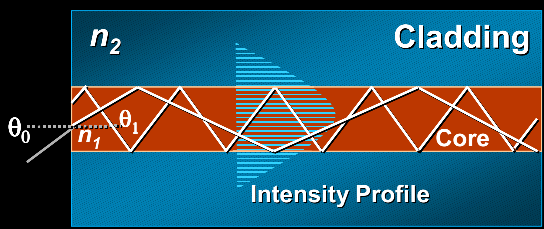


Snell's Law

$\theta_1 = \theta_{1r}$

$n_1 \text{Sin}\ \theta_1 = n_2 \text{Sin}\ \theta_2$

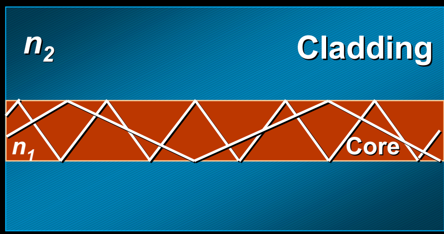
Propagation in Fiber

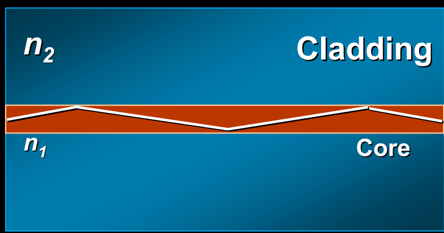


- Light propagates by total internal reflections at the core-cladding interface
- Total internal reflections are lossless
- Each allowed ray is a mode

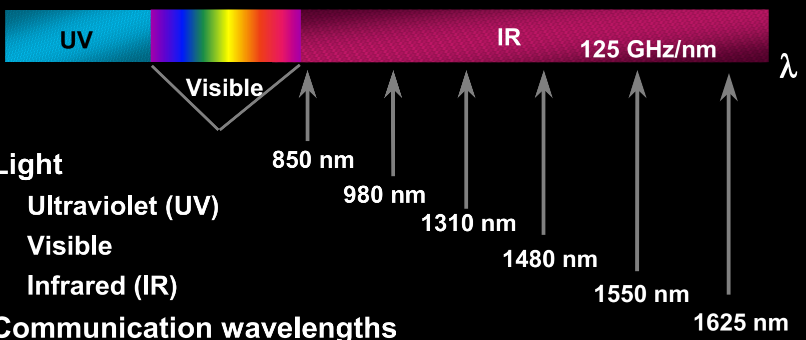
Different Types of Fiber

- **Multimode fiber**
  - Core diameter varies
    - 50 mm for step index
    - 62.5 mm for graded index
  - Primarily used for intra-office applications
  - Not less expensive than single mode
- **Single-mode fiber**
  - Core diameter is about 9 mm
  - Only one mode (ray) propagates
  - Bit rate-distance product >100 THz-km





Optical Spectrum



- **Light**
  - Ultraviolet (UV)
  - Visible
  - Infrared (IR)
- **Communication wavelengths**
  - 850, 1310, 1550 nm
  - Low-loss wavelengths
- **Specialty wavelengths**
  - 980, 1480, 1625 nm

$C = f \times \lambda$

Wavelength: λ (nanometers)

Frequency: f (terahertz)

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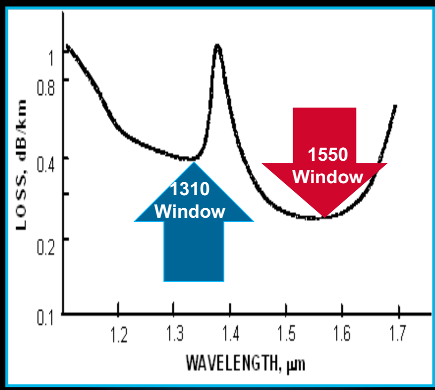
Optical Attenuation

- **Specified in loss per kilometer (dB/km)**
  - 0.40 dB/km at 1310 nm
  - 0.25 dB/km at 1550 nm
- **Loss due to absorption by impurities**
  - 1400 nm peak due to OH ions
- **EDFA optical amplifiers available in 1550 window**



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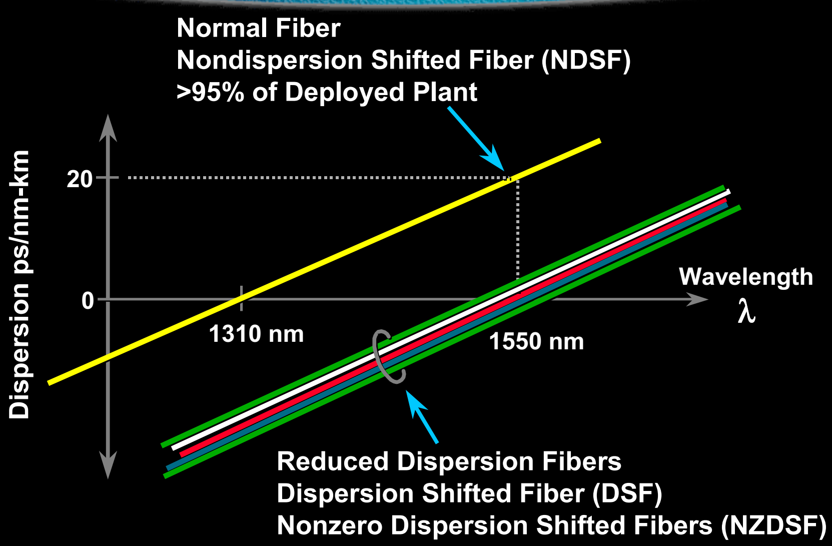
Fiber Dispersion Characteristics



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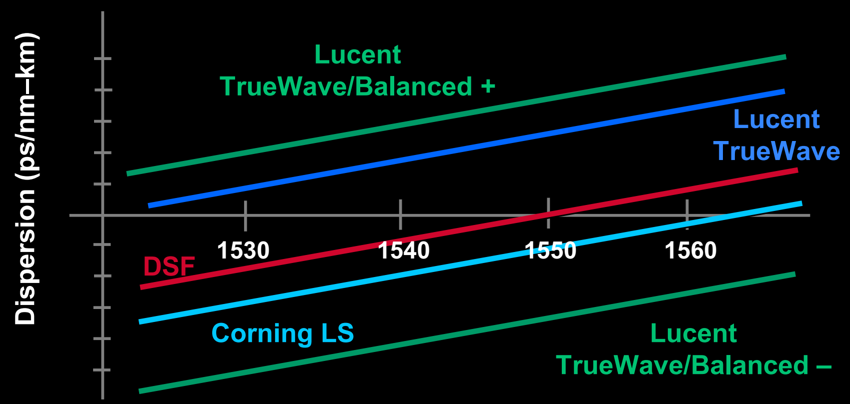
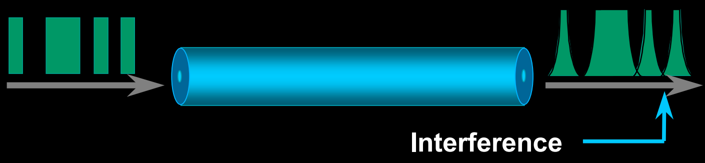
Dispersion Shifted Fibers



Types of Single-Mode Fiber

- **SMF-28 (standard, 1310 nm optimized, unshifted)**
  - Most widely deployed by far
  - Introduced in 1986
- **SMF/DS (dispersion shifted)**
  - For single channel operation at 1550 nm
- **SMF-LS (nonzero dispersion shifted)**
  - For WDM operation in the 1550 nm region
- **LEAF and TrueWave**
  - Latest generation fiber developed in mid 90s
  - For better performance with high-capacity DWDM systems

Fiber Dispersion



- Effects single channel and DWDM systems
- A pulse spreads as it travels down the fiber
  - Degradation scales as (bit-rate)^2
  - Depends on fiber type and laser used

Impact of Dispersion on Bit-Rate

Dispersion Scales as (bit-rate)^2

Dispersion Effects **Sixteen Times Greater** at OC-192

Types of Dispersion

- Chromatic Dispersion
  - Different wavelengths travel at different speeds
  - Causes spreading of the light pulse

- Polarization Mode Dispersion (PMD)
  - Single-mode fiber supports two polarization states
  - Fast and slow axes have different group velocities
  - Causes spreading of the light pulse

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Combating Chromatic Dispersion

- Dispersion generally not an issue below OC-192
- New fiber types (NZ-DSF) greatly reduce effects
  - Dispersion mapping with NZ-DSF +/- segments (submarine systems)
- Dispersion compensation techniques
  - Dispersion compensation fiber
  - Dispersion compensating optical filters
  - Available in some optical amplifiers

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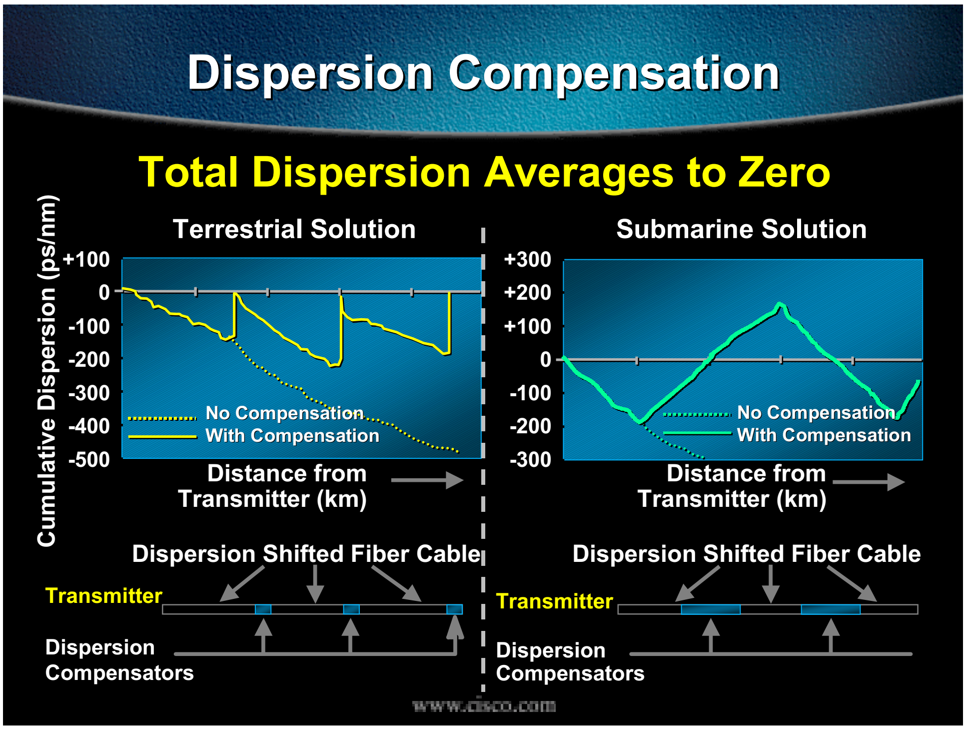
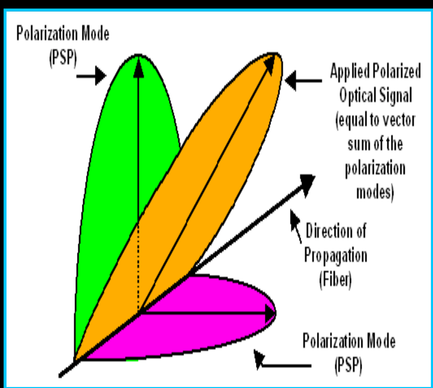


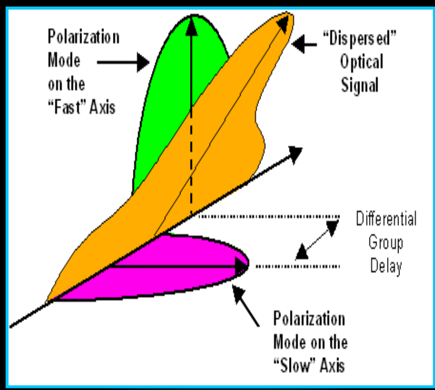
Polarization Mode Dispersion

- **Caused by ovality of core due to:**
  - **Manufacturing process**
  - **Internal stress (cabling)**
  - **External stress (trucks)**
- **Only discovered in the 90s**
- **Most older fiber not characterized for PMD**



Polarization Mode Dispersion

- "Fast" axis of propagation and a "slow" axis
- Travel down the fiber is desynchronized (out of phase)
- PMD presents a greater problem to system performance because it can vary with time

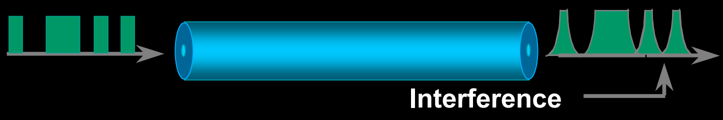


Fiber Nonlinearity

- Nonlinear effects are the ultimate limits to transmission performance
- Today's systems have longer interaction lengths
  - Attenuation can be amplified
  - Dispersion can be compensated
  - Nonlinearities just accumulate
- High-capacity systems require high optical power which causes nonlinear effects

Effects of Nonlinearity

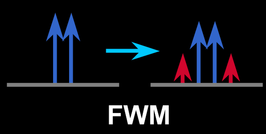
- A single channel's pulses interact as they travel

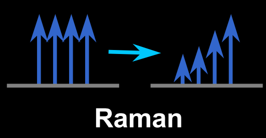


- Multiple channels interact as they travel

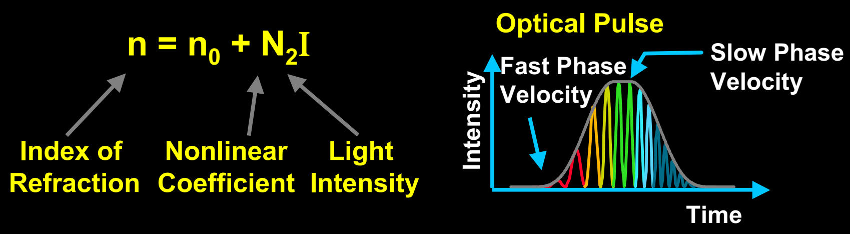
Types of Nonlinearities

- Nonlinear index
  - Four-wave mixing
  - Self-phase modulation
  - Cross-phase modulation
- Stimulated scattering
  - Raman
  - Brillouin



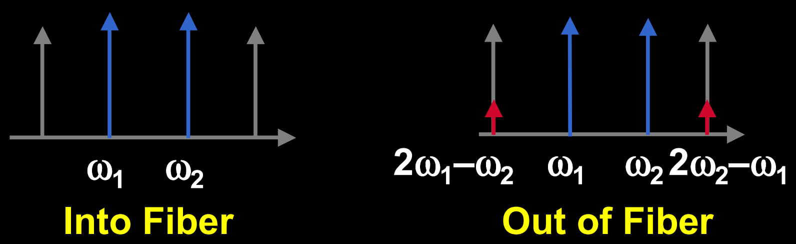


Optical Fiber's Nonlinear Index

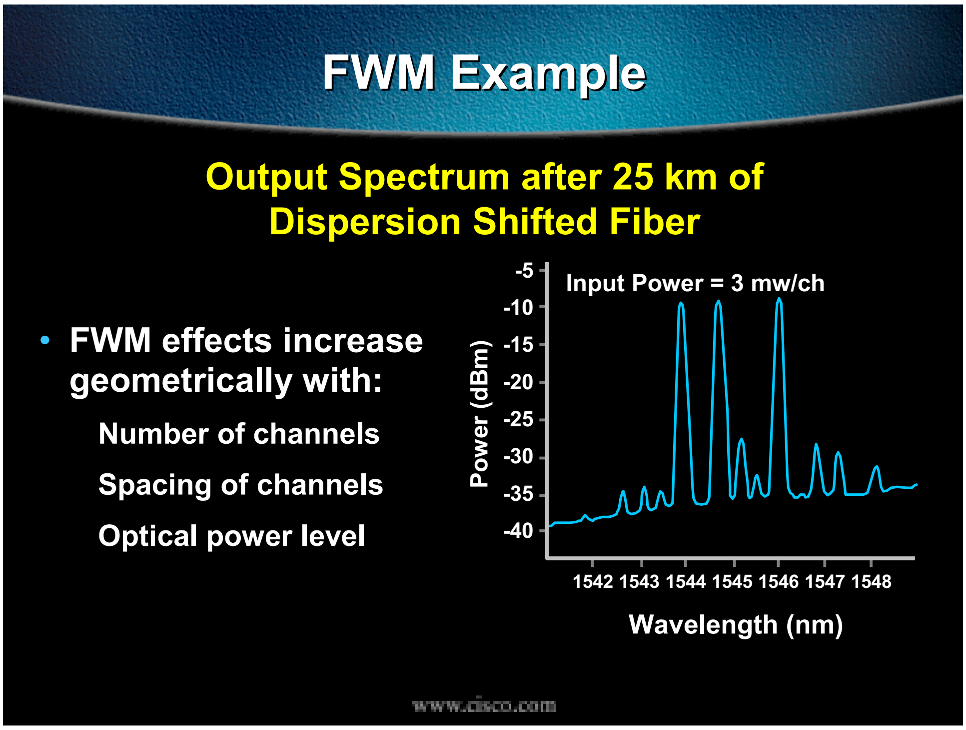


- Intensity of an optical pulse modulates the index of refraction
- Nonlinearity scales as (channel power)^2

Four-Wave Mixing



- Channels beat against each other to form intermodulation products
- Creates in-band crosstalk that can not be filtered (optically or electrically)


FWM Example
Output Spectrum after 25 km of Dispersion Shifted Fiber
• FWM effects increase geometrically with:
Number of channels
Spacing of channels
Optical power level
Input Power = 3 mw/ch
Power (dBm)
-5
-10
-15
-20
-25
-30
-35
-40
1542 1543 1544 1545 1546 1547 1548
Wavelength (nm)
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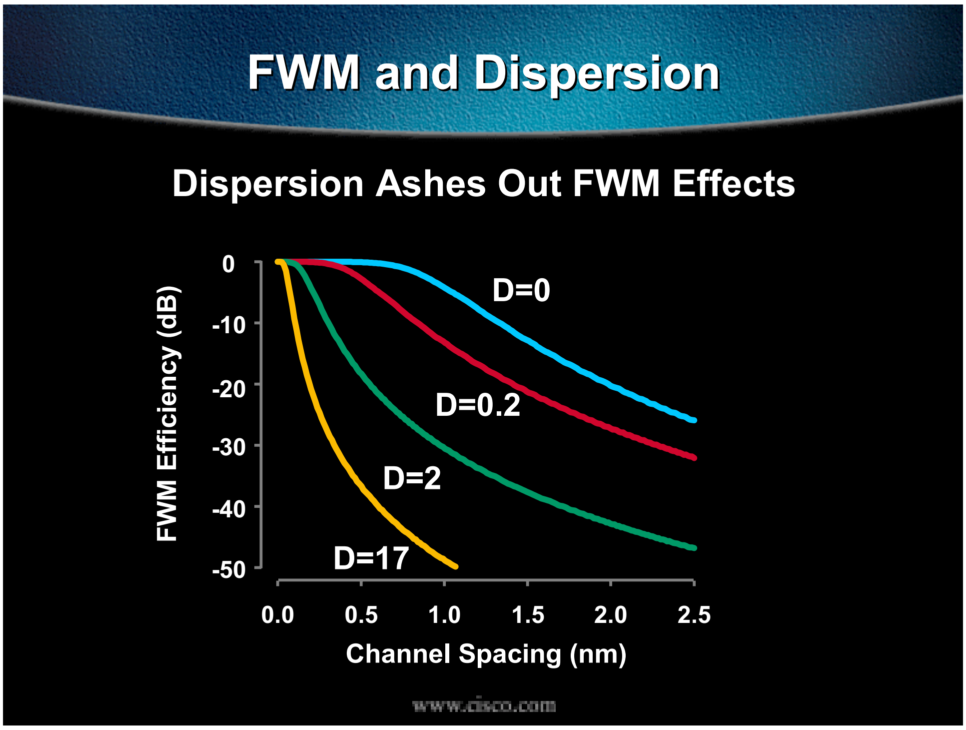
FWM and Dispersion
Dispersion Ashes Out FWM Effects
FWM Efficiency (dB)
0
-10
-20
-30
-40
-50
D=0
D=0.2
D=2
D=17
0.0
0.5
1.0
1.5
2.0
2.5
Channel Spacing (nm)
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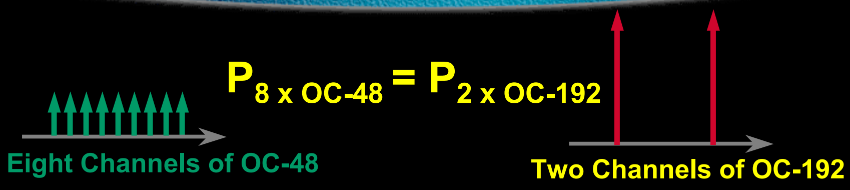
Physics of Higher Capacity



- High capacity requires high-optical powers—it's basic physics
  - DWDM power scales with channel count
  - TDM power scales with bitrate
- The same fundamental nonlinear limits apply to both
- The art is in the design trade-offs

Different Solutions for Different Fiber Types

SMF-28
- Good for TDM at 1310 nm
- Bad for TDM at 1550 nm
- OK for WDM at 1550 nm
- May have TDM limit due to PMD

DSF
- Good for TDM at 1550 nm
- Bad for WDM at 1550 nm

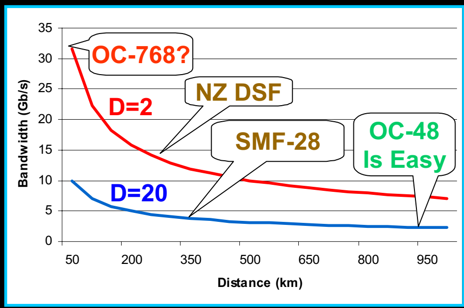
NZ-DSF
- Good for TDM and DWDM at 1550 nm

Next Gen
- Great for TDM and DWDM in L and C bands

The Difference Is in the Dispersion Characteristics

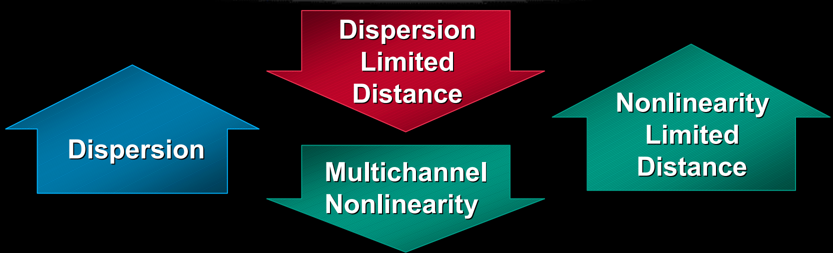
Dispersion Limits

Dispersion Limited Bandwidth vs. Distance Curves for 1550 nm



- Dispersion limits TDM bandwidth
- Chromatic dispersion can be managed, but generally is not
- PMD is an issue for OC-192 on older fiber

Dispersion Benefits



- Dispersion mitigates nonlinearities
- Enables larger number of DWDM channels at tighter spacing
- To balance TDM and WDM requirements
  - Maintain zero-average dispersion at end of link
  - Avoid local zero-dispersion points

Fiber Optics Summary

- Each single-mode optical fiber has over 25 THz of bandwidth
- 10 Tbps transmission systems are on the horizon

    Faster TDM **yes!**

    Wider DWDM **yes!**

    Better OAs and fiber **yes!**

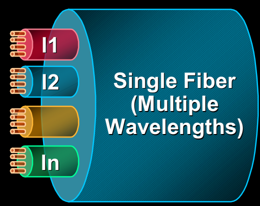
Agenda

- Introduction
- Fiber Optics Fundamentals
- **Dense Wave Division Multiplexing**
- Optical Internetworking

Fiber Networks

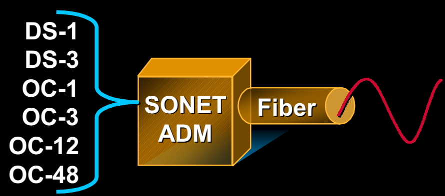
- Time division multiplexing
  - Single wavelength per fiber
  - Multiple channels per fiber
  - 4 OC-3/STM1 channels in OC-12/STM4
  - 4 OC-12/STM4 channels in OC-48/STM16
  - 16 OC-3/STM1 channels in OC-48/STM16

- Wave division multiplexing
  - Multiple wavelengths per fiber
  - 4, 16, 24, 40 channels per system
  - Multiple channels per fiber

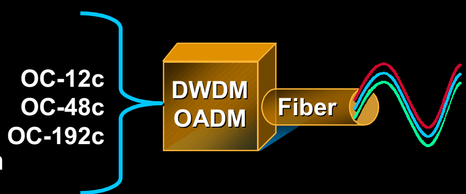


TDM and DWDM Comparison

- TDM (SONET/SDH)
  - Takes sync and async signals and multiplexes them to a single higher optical bit rate
  - E/O or O/E/O conversion



- (D)WDM
  - Takes multiple optical signals and multiplexes onto a single fiber
  - No signal format conversion



Why DWDM? The Technical Argument

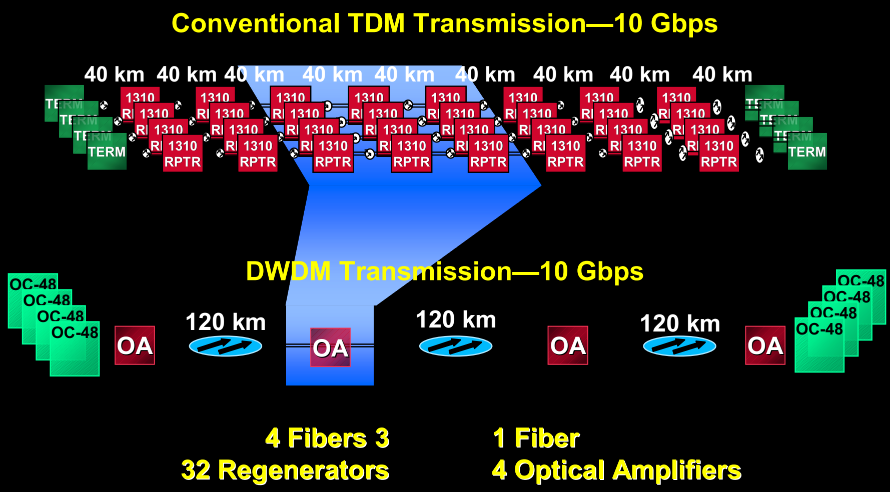
- **DWDM provides enormous amounts of scaleable transmission capacity**

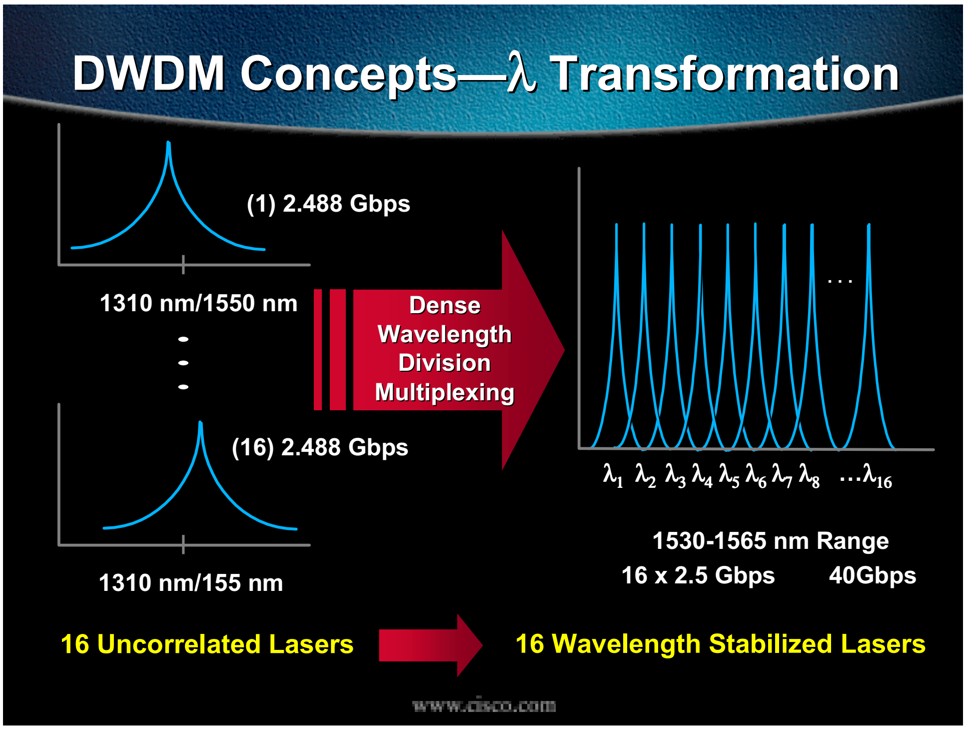
  Unconstrained by speed of available electronics

  Subject to relaxed dispersion and nonlinearity tolerances

  Capable of graceful capacity growth

Why DWDM—The Business Case




DWDM Concepts—λ Transformation
(1) 2.488 Gbps
1310 nm/1550 nm
Dense Wavelength Division Multiplexing
(16) 2.488 Gbps
1310 nm/155 nm
λ1 λ2 λ3 λ4 λ5 λ6 λ7 λ8 …λ16
1530-1565 nm Range
16 x 2.5 Gbps 40Gbps
16 Uncorrelated Lasers
16 Wavelength Stabilized Lasers
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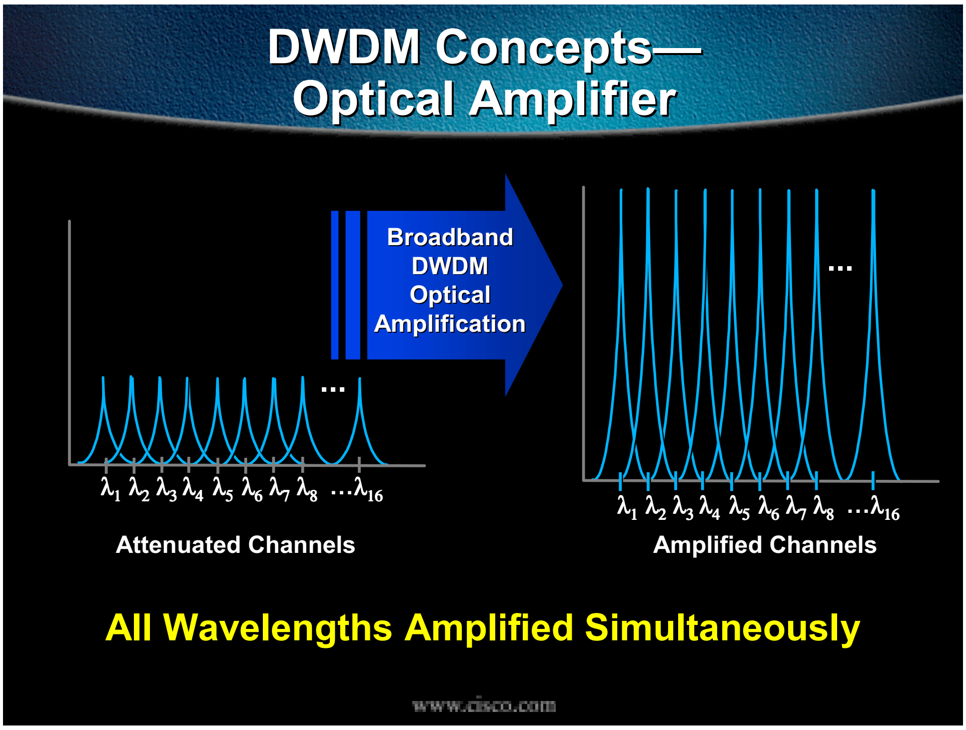
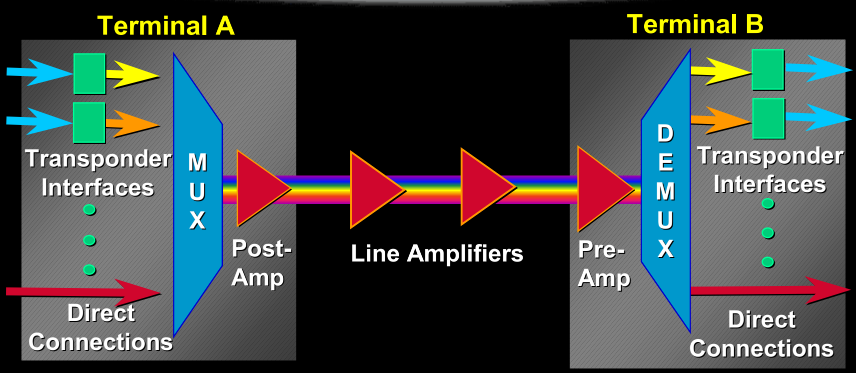

DWDM Concepts—
Optical Amplifier
Broadband DWDM Optical Amplification
λ1 λ2 λ3 λ4 λ5 λ6 λ7 λ8 …λ16
Attenuated Channels
λ1 λ2 λ3 λ4 λ5 λ6 λ7 λ8 …λ16
Amplified Channels
All Wavelengths Amplified Simultaneously
www.cisco.com

DWDM History

- Early WDM (late 80s)
  - Two widely separated wavelengths (1310, 1550nm)
- “Second generation” WDM (early 90s)
  - Two to eight channels in 1550 nm window
  - 400+ GHz spacing
- DWDM systems (mid 90s)
  - 16 to 40 channels in 1550 nm window
  - 100 to 200 GHz spacing
- Next generation DWDM systems (late 90s)
  - 64 to 160 channels in 1550 nm window
  - 50 and 25 GHz spacing

Anatomy of a DWDM System



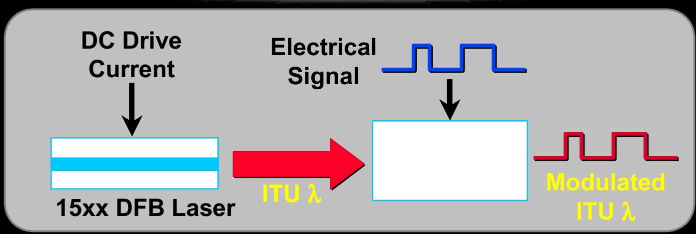
Basic building blocks
- Optical amplifiers
- Optical multiplexers
- Stable optical sources

Typical configurations
- 7 x 20 dB
- 5 x 25 dB
- 3 x 33 dB

DWDM Enabling Technologies

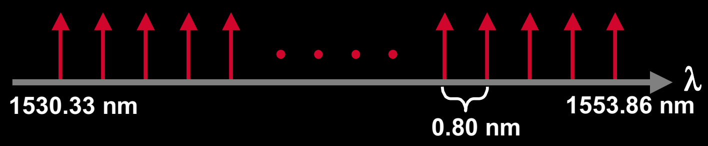
- Stable and narrow line-width lasers
  - Low-chirp and high-extinction ratio
- High-selectivity wave-length filters
  - Low-insertion loss and crosstalk
- High-power optical amplifiers
  - Low noise
  - Wide, flat passband

DWDM Laser Sources



- Direct modulation of laser diode
  - Nonlinearity leads to chirping
  - Complicates dispersion management
- Use of an external modulator (preferred)
  - Separates λ generation and signal modulation
  - Low chirp or negative chirp possible

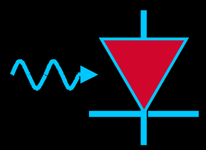
ITU Wavelength Grid



- ITU-T λ grid is based on 191.7 THz ± 100 GHz
- Its purpose is to standardize **lasers** not DWDM systems
- There is no standard for DWDM systems

  Number and spacing of λs are design variables

DWDM Receiver Requirements



$$SNR_{elec} = \frac{(Signal)^2}{(N_{sig\text{-}ase})^2 + (N_{ase\text{-}ase})^2 + (N_{thermal})^2 + (N_{shot})^2}$$

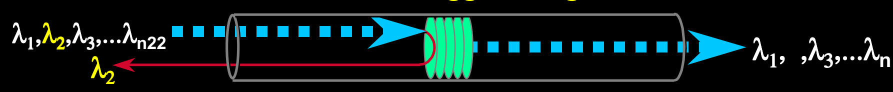
- Optical detectors obey the square law
- In systems with OAs, SNR is determined by

  Signal • ASE beat noise for "ones"

  ASE • ASE beat or thermal noise for "zeros"
- DWDM receivers use dynamic thresholds

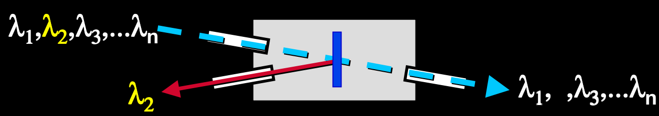
Optical Filter Technology

Fiber Bragg Grating



Low cost, based on standard. Singlemode fiber
Ultranarrow, but hard to control filter shape

Dielectric Filter



Well established technology, up to 200 layers
100 GHz limit today, but good filter shape

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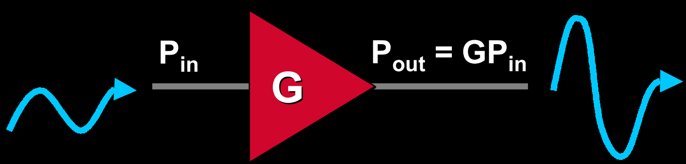
Optical Amplifier



- 4 THz of optical bandwidth near 1550 nm
- Nearly ideal noise performance
- Low signal distortion, low cross talk
- High-output saturation power
- Simple and efficient

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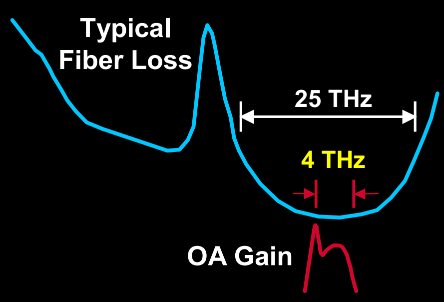
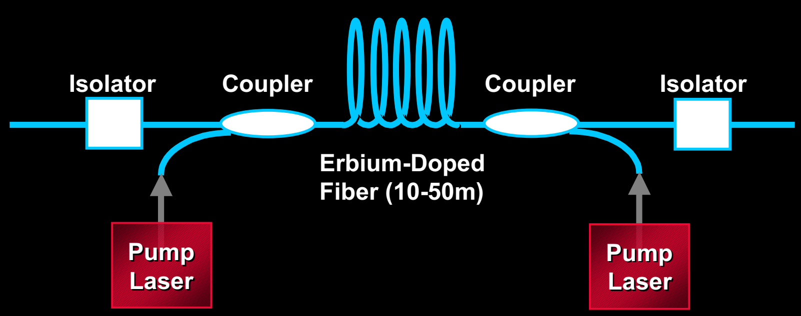
OA Gain and Fiber Loss



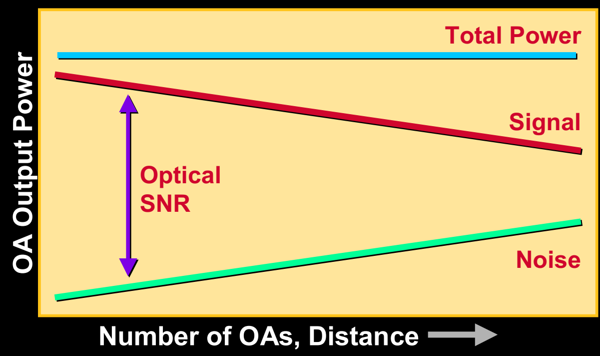
- OA gain is centered in 1550 window
- OA bandwidth is less than fiber bandwidth

Erbium-Doped Fiber Amplifier



- Simple device consisting of four parts
- Pump laser is only active part
- Signal path is entirely passive

The Limit of Optical Amplification



- OAs can be cascaded over long distances
- Limit imposed by noise accumulation and finite gain

DWDM Interface Evolution

- Early WDM systems used ITU transmitters, but had no internal receivers
  - WDM vendor’s Tx, SONET vendor’s Rx
  - No visibility into signal
- Most DWDM systems use transponders
  - Allows performance monitoring
  - Provides 3R regeneration function
- Emerging option for direct optical interface
  - Potential cost savings
  - Potential technical risk

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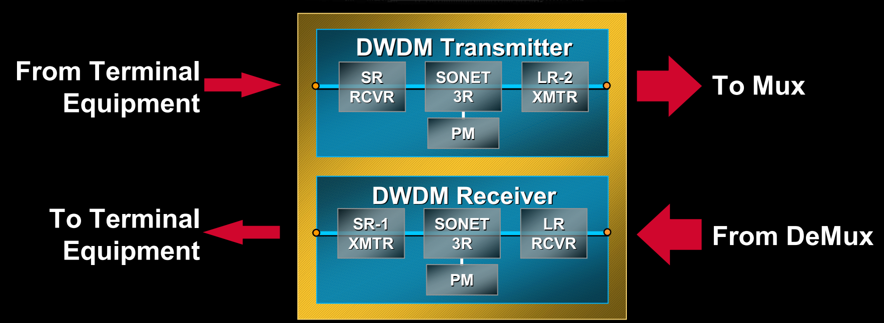
Direct Optical Interfaces to DWDM

- Transponder becomes a passive interface
- ITU laser in router/switch drives long-haul link

Pros	Cons
Low Cost	No clear point of demarcation
Transparency	Stocking of spares
	Stringent technical requests
	Potential interactions

- Might make sense in metro, but not long-haul networks

DWDM Transponder Interfaces



- One transponder required per wavelength
- Full 3R functionality (re-amp, re-shape, re-time)
- Terminal side is 1310 SR, line side is 15xx LR
- Limited SONET/SDH performance monitoring

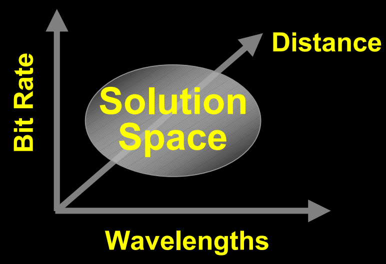
Performance Monitoring

- SONET/SDH performance monitoring performed on a per wavelength basis through transponder
- Computation of B1 and monitor J0 at each channel input and output
  - B1 = section bit error rate
  - J0 = section path trace
- No modification of SONET/SDH overhead
  - Data transparency is preserved

Element Management System

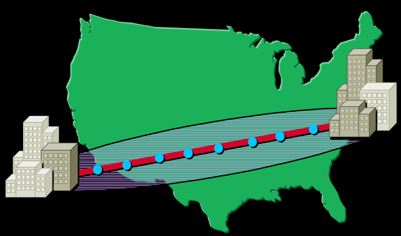
- EMS is available on most DWDM systems
- EMS used to correlate alarms
  - Fault isolation/PM information
  - Configuration mismatches
  - Communicate with NMS
- Optical Supervisory Channel (OSC) extends EMS capability to remote OAs
  - Dedicated out-of-band wavelength used

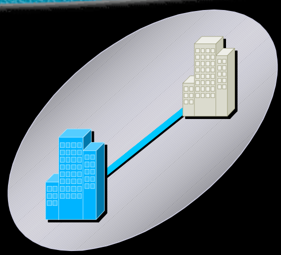
Designing for Capacity



- Goal is to maximize transmission capacity and system reach
  - Figure of merit is Gbps • Km
  - Long-haul systems push the envelope
  - Metro systems are considerably simpler

Metro DWDM





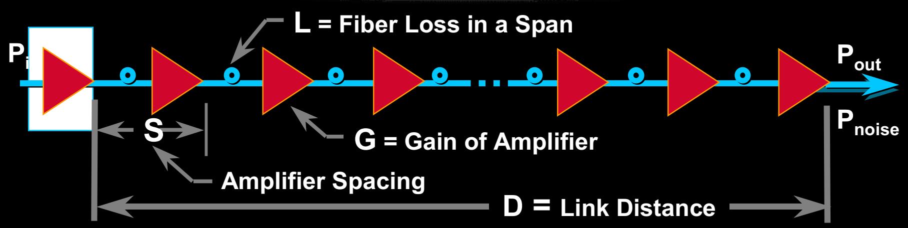
- Metro DWDM is fundamentally different than long-haul DWDM
- Metro DWDM is driven by demand for fast service provisioning, not fiber exhaust
- Metro DWDM is designed for > 100 Km and uses no OAs

Bit Rates and Wavelengths

- SNR: For fixed OAs, WDM and TDM same
- Dispersion is less of an issue at lower speed
- Fiber nonlinearities generally favor more lower speeds
- Economics and manageability favor higher speeds

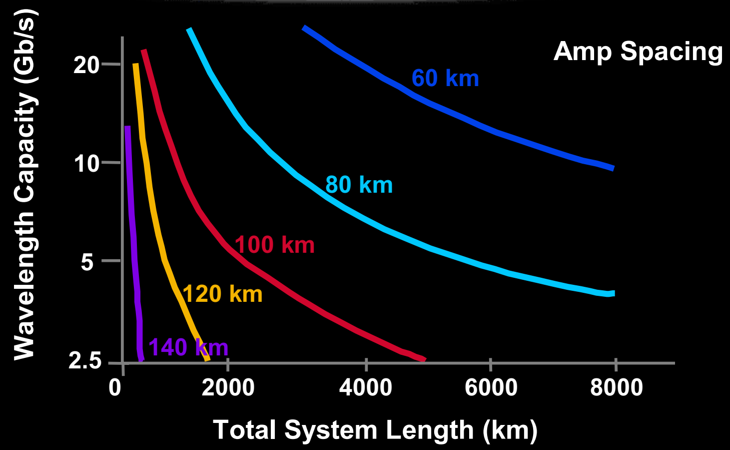
Common Design Approach Is to Use Highest Possible Bit Rate, then Maximize Wavelengths

Designing for Distance



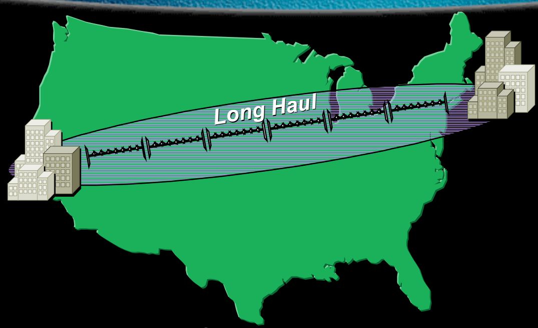
- Link distance (D) is limited by the minimum acceptable electrical SNR at the receiver
  - Dispersion, Jitter, or optical SNR can be limit
- Amplifier spacing (S) is set by span loss (L)
  - Closer spacing maximizes link distance (D)
  - Economics dictates maximum hut spacing

Link Distance Vs. OA Spacing



- System cost and and link distance both depend strongly on OA spacing

DWDM Multiple Spans



- OA noise and fiber dispersion limit total distance before regeneration
  - Optical-Electrical-Optical conversion
  - Full 3R functionality: Reamplify, Reshape, Retime
- Longer spans can be supported using back to back systems

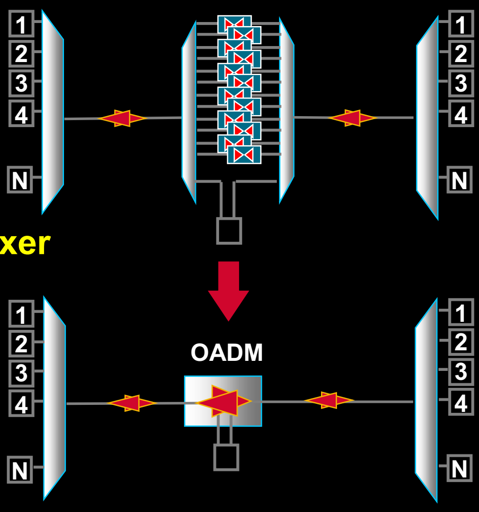
Optical Add/Drop Multiplexers

Back-to-back DWDM

- Express channels must be regenerated
- Two complete DWDM terminals needed

Optical add/drop multiplexer

- Provides drop-and-continue functionality
- Express channels only amplified, not regenerated
- Reduces size, power, and cost



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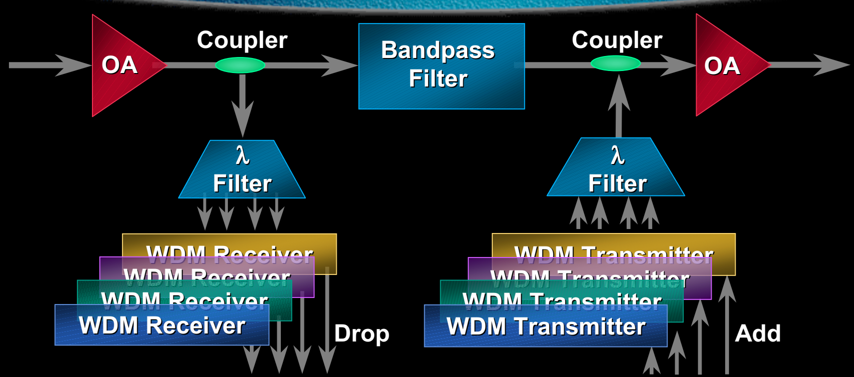
OADM Operation



- OADMs are really extensions to OAs
- OADMs provide drop and continue functionality
- Currently only static configurations available

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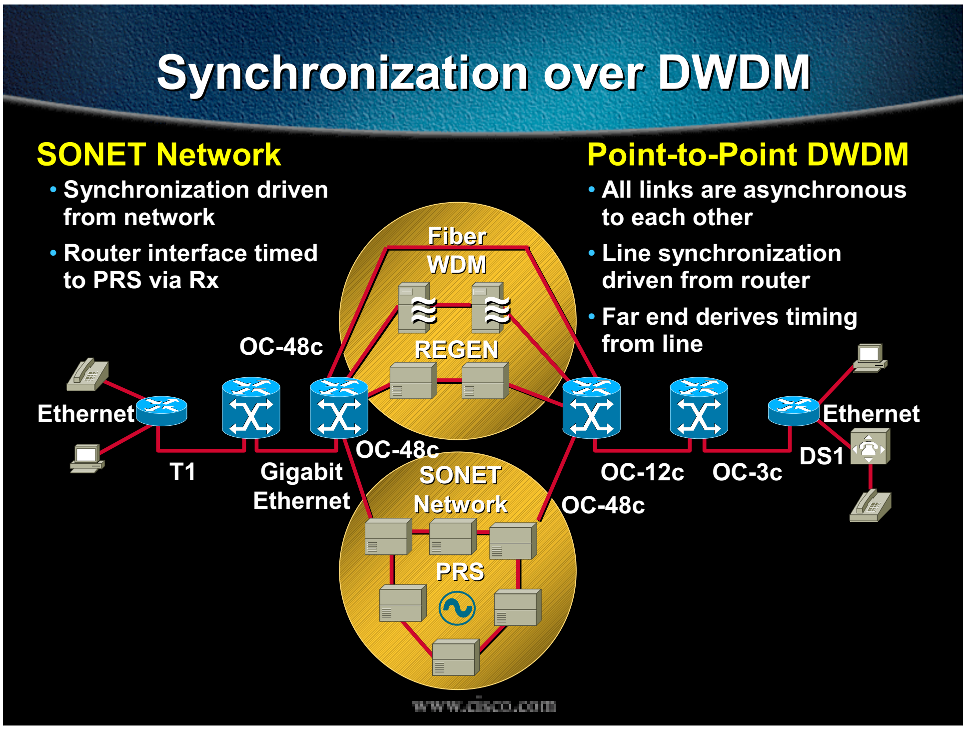
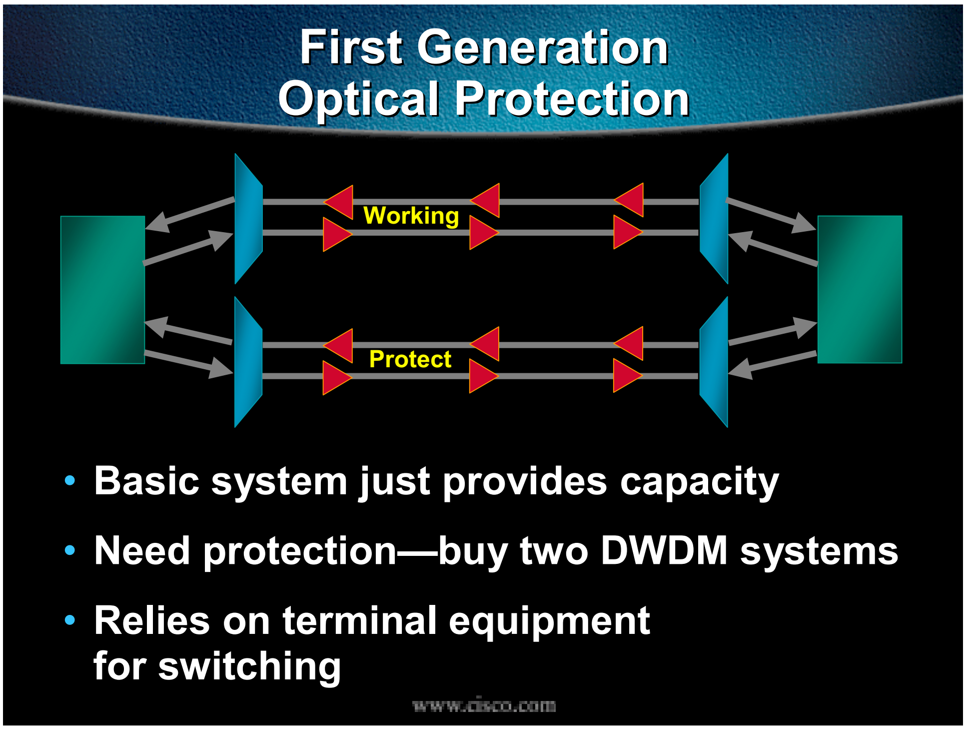

Synchronization over DWDM
SONET Network
• Synchronization driven from network
• Router interface timed to PRS via Rx
Point-to-Point DWDM
• All links are asynchronous to each other
• Line synchronization driven from router
• Far end derives timing from line
Fiber WDM
REGEN
OC-48c
Ethernet
T1
Gigabit Ethernet
OC-48c
SONET Network
PRS
OC-12c
OC-3c
OC-48c
DS1
Ethernet
www.cisco.com


First Generation Optical Protection
Working
Protect
• Basic system just provides capacity
• Need protection—buy two DWDM systems
• Relies on terminal equipment for switching
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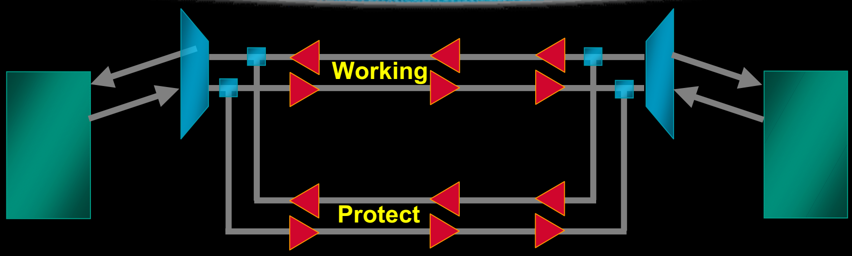
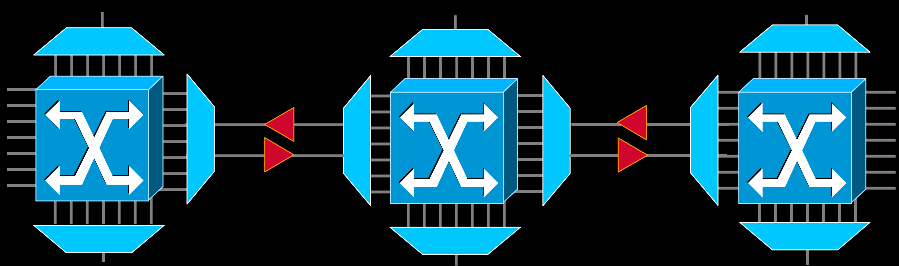
Second Generation Optical Protection



- Protection migrates to DWDM equipment
  - Only one DWDM with protection modules needed
  - Switching decision controlled by transponders
  - Technologies include optical switching and OA gating

Next Generation Optical Protection



- Protection controlled by large cross-connects on tributary side of DWDM
- Protection migrates from fiber to λ level
- Line, ring, and mesh restoration options

DWDM Benefits

- DWDM provides hundreds of Gbps of scalable transmission capacity today
  - Provides capacity beyond TDM's capability
  - Supports incremental, modular growth
  - Transport foundation for next generation networks

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But That's Not Why it Sells

- It's the economics, not the technology, that service providers buy into
- Long-haul DWDM market is driven by the high cost of new fiber
  - Fiber exhaust of the mid 90s
  - Today's new builds are fiber rich
- DWDM is being commoditized

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Metro DWDM

- Metro DWDM is an emerging market for next generation DWDM equipment
- The value proposition is very different from the long haul
  - Rapid-service provisioning
  - Protocol/bitrate transparency
  - Data-centric protected transport
- Metro DWDM is not yet widely deployed

Pirelli WaveMux Platform

- Scalable DWDM platform
- Flexible deployment options
- Economical platform

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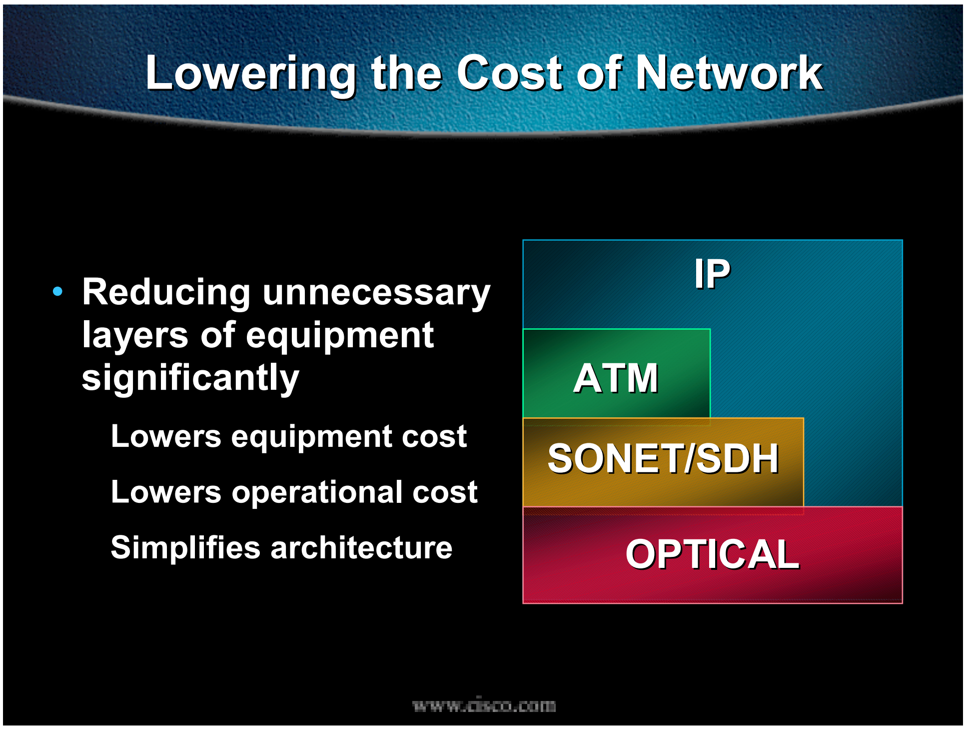
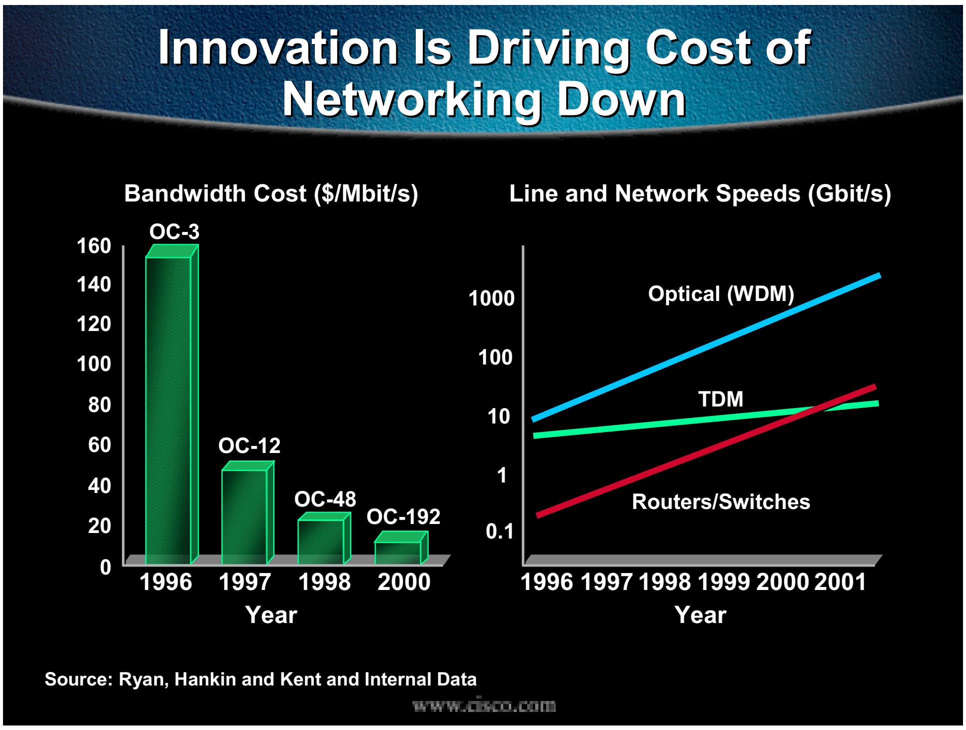
Optical Networks

- Enter the optical cross connect
- DWDM moves beyond simply transport
  - Wavelength provisioning
  - Mesh-based restoration
- Intelligence in the optical layer
  - Light-weight routing protocols

Agenda

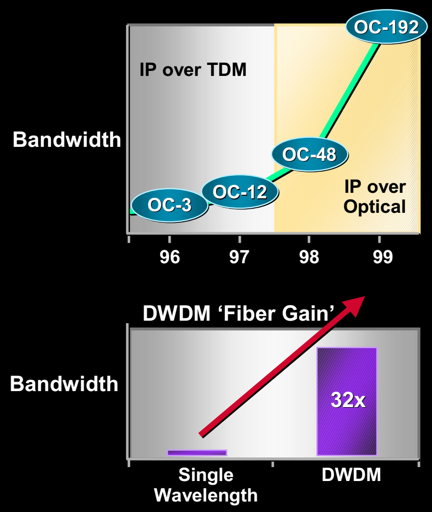
- Introduction
- Fiber Optics Fundamentals
- Dense Wave Division Multiplexing
- Optical Internetworking


Lowering the Cost of Network
• Reducing unnecessary layers of equipment significantly
Lowers equipment cost
Lowers operational cost
Simplifies architecture
IP
ATM
SONET/SDH
OPTICAL
www.cisco.com


Innovation Is Driving Cost of Networking Down
Bandwidth Cost ($/Mbit/s)
160
140
120
100
80
60
40
20
0
OC-3
OC-12
OC-48
OC-192
1996 1997 1998 2000
Year
Line and Network Speeds (Gbit/s)
1000
100
10
1
0.1
Optical (WDM)
TDM
Routers/Switches
1996 1997 1998 1999 2000 2001
Year
Source: Ryan, Hankin and Kent and Internal Data
www.cisco.com

Optical Internetworking
IP + Optics

- **Optical internetworking is the integration of internetworking and optical technologies**



Delivering the Optical Internet

- **Optical Transport Network**
  - DWDM
  - Optical Cross Connect
  - Data Aware ADM/DCSs

+

- **Optical Internetworking Solutions**
  - Packet over SONET/SDH (POS)
  - Dynamic Packet Transport
  - IP over DWDM

Benefits of Optical Internetworking

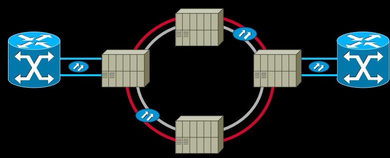
- **Increased capacity** to switch huge volumes of packet-based information
- **Lowers cost** by eliminating unnecessary layers of equipment
- **Maintain and enhance reliability** to handle most demanding requirements
- **Improved flexibility** to support yet unimagined IP-based applications and services

Cisco 12000 GSR IP Backbone Leadership

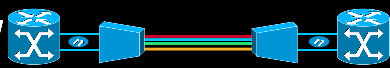
- WW Internet proven deployment
- Carrier-class architecture
- Premier IP-routing software
- Leading interface breadth
- Technology innovation

Examples of Optical IP Backbones Being Deployed Today

- Connect to tributary interfaces on SONET/SDH muxes (OC-3c/STM1 to OC-48c/STM16)

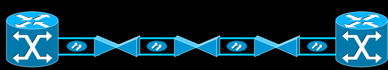


- Connect to transponder-based DWDM system (typically OC-12c/ STM4 or OC-48c/STM16)

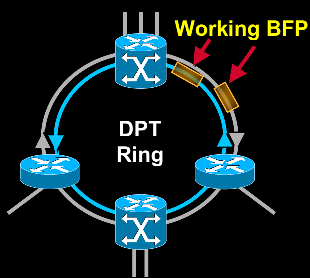


Examples of Optical IP Backbones Being Deployed Today

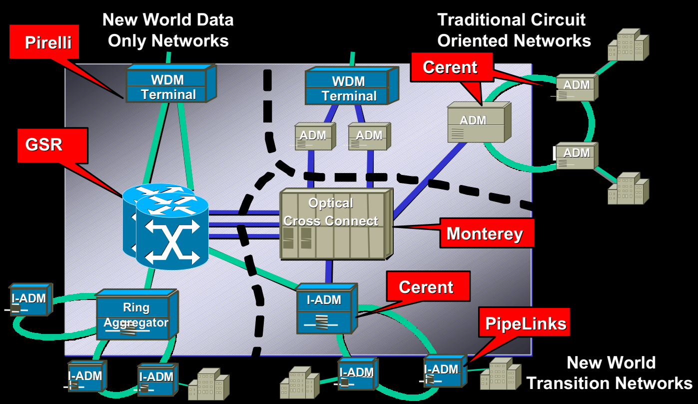
- Interconnect GSR directly over dark fiber with regenerators to extend the distance of LR interfaces (typically OC-48c/ STM16)



- IP-based packet ring using Dynamic Packet Transport (DPT) available at OC-12c/STM4 today



Architecting the New IP Central Office



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