Photonics Enabling the Zettabyte Network Evolution

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cisco

Future Household Bandwidth Requirements

Household Bandwidth Needs in 2010 (U.S.)

Cisco estimation: ~ TB/month = HDTV + SDTV + PVR + VoIP + HSD

Twenty future homes would generate more traffic than the entire 1995 Internet backbone.
Emerging Zettabyte IP Networks

Figure 1. Cisco Forecasts 44 Exabytes per Month of IP Traffic in 2012.

Operationally enhanced evolution is very important in network innovation...

"Don't bother me with new ideas; I've got a battle to fight!"
Outline

- Traffic Evolution
- WDM Evolution
  - ROADM and WXC Networking
  - 40 and 100 Gb/s Transmission
- Network Architecture Evolution
  - Packet & WDM Transport Convergence r&D
  - Flexible/Adaptive Transport R&D
- Summary

Acknowledgements

- Many colleagues at cisco, especially in the Emerging Markets, Core Routing, Optical, and URP, and particularly Dr. Ori Gerstel

- interactions (around the world) with service providers, network equipment, and academia, particularly A. Willner (USC), and B. Yoo (UC-Davis).
1st Gen. OFC = Transmission

\[ \text{Bit Rate} \times \text{Distance (Gb/s \cdot km)} = \text{WHAT'S NEXT ??} \]

- WDM + Optical Amplifiers
- Optical Amplifiers
- Coherent Detection
- 1.5\(\mu\)m Single-Frequency Laser
- 1.3\(\mu\)m SM Fiber
- 0.8\(\mu\)m MM Fiber

* T. Li and Herwig Kogelnik

Multi-service Network Architecture

IP/MPLS

ATM / Ethernet

SDH/OTN

DWDM
2nd Gen OFC: Multi-service WDM OADM Transport

- Flexible transport (RPR/SONET/λ)
- Automation (ROADM, software)
- Pluggable optics

Increase Revenues (New Services)

Flexible & Scalable Multiservice WDM Transport

Challenge: Common low-cost transmission engineering for different applications
- Add/drop percentage and location flexibility
- Multiple service rates and interface types
- Channel number variation (fiber cuts/traffic changes)
- Long-term aging effects
- Minimize regeneration

Solution: Advanced System Design
- Automatic power control
- Advanced EDFA (variable-gain, and transient suppression) gain tilt control, ASE suppression
- Low-loss OADM, DCF (>250 FoM),...
- Forward error correction
- Metro-optimized transponders

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**AutoPowerControl for Multi-service WDM Transport**

**Goal #1: Maximize OSNR**
- Minimize EDFA ASE, gain tilt, power variation (max channel min ONSR),

**Goal #2: Operational Simplicity**
*Installation, Operation, Maintenance*

**Solution: Monitor & Control power, coordinating around ring**
*Installation: pre-provisioning/optimization, Operation: const Gain sub-ms transients (local)*
*Maintenance: Pout account aging (OSC/EMS) Intelligence: like the ASE correction (“true channel power”) allows 10G-FEC spec 7x20dB!

*24dB OSNR at 10Gb/s in 15-node 120dB channels*

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**Fault Localization in An Optical Network**

- Optical networks were harder to troubleshoot due to their analog nature
- Historically:
  - No signaling to correlate alarms
  - Not enough visibility into the signal
  - Can’t look into the bits at middle nodes

- Solved by MSTP:
  - Implements fault localization
  - Integrated photodiodes everywhere for max visibility

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3rd Gen: Reconfigurable Open WDM Transport

- Transparent Open Transmission (EFEC, adv. mod.)
- Operationally Friendly (G.709 OAM&P, tunability, monitoring)
- Network planning flexibility (ROADM, Planning tools)

New DWDM Operational Paradigm

Traditional DWDM
- Fixed Filters
- Fixed Transmit Lasers
- Manual or Semi-automatic VOAs
- Manually Configured Amplifier Gain
- Manual Configuration of DWDM Parameters

Next-Gen DWDM
- Reconfigurable Filters
- Tunable Lasers
- Automatic VOAs
- Automatically Configured Amplifier Gain
- Design Tool Provisions DWDM Parameters
Optical Innovation

- Flexible/Reconfigurable OADM,
- Optical Module integration;
- Tunable lasers
- Enhanced FEC,
- Electronic (post-Detection) Equalization,
- Advanced Modulation,
- Advanced amplification,
- Dispersion compensation,
- Performance monitoring,
- 40/100G upgrade

Improve network deployment cost (CapEx), density, and flexibility (OpEx).

Optical Tx/Rx Module Designs

- XFP
- XPAK
- 200 Pin MSA
- 300 Pin Small Form Factor MSA
- 300 Pin MSA

Increasing Data Density Clustering:

- 0.04
- 0.13
- 0.20
- 0.26
- 1.46

NEC(4.4 dB)
NEC(4.2 dB)
Uncoded
RS(255,239)
RS(255,239)
Optics energy and density Innovation

- J. Eng, Finisar, 2009 OIDA AF

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WDM Transmission Evolution to 40 and 100 G

Growth Trends in IP Traffic and DWDM System Throughput

- Higher rate initially deployed in highly congested links
  - lower TCO vs higher $/bit/s/km/channel
- Higher rate channels (= less wavelengths) preferred (less HW & managements)
- Higher rate preferable over IP link bundling
- Mainstream deployments require operational parity (OSNR, PMD), TCO advantage

Advanced Modulation for 40/100 Gb/s WDM evolution

- DIGSK: 2
- Duobinary: <
- NRZ-OOK, NRZ-DPSK
- CSKZ
- Δf (NRZ)

Source: P. Winzer, OECC '05
40G WDM Adoption – in progress...

<table>
<thead>
<tr>
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<td>10</td>
<td>2.5</td>
<td>10</td>
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<td>40</td>
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<td>100</td>
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<td>OSNR</td>
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<td>17</td>
<td>5</td>
<td>6</td>
<td>13</td>
<td>7-8</td>
<td>6</td>
<td>&lt; 10</td>
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<tr>
<td>CD</td>
<td>2000</td>
<td>400</td>
<td>5400</td>
<td>1200</td>
<td>150</td>
<td>700</td>
<td>1000</td>
<td>&gt; 400</td>
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<td>Density</td>
<td>2</td>
<td>4</td>
<td>0.2 (sfp)</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1-2</td>
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<tr>
<td>Cost</td>
<td>6</td>
<td>20</td>
<td>~1</td>
<td>4-5</td>
<td>&gt; 25</td>
<td>TBD</td>
<td>&lt; 10</td>
<td>TBD</td>
</tr>
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</table>

100G WDM Adoption

- **support the existing infrastructure:**
  - Reach 1,000 - 1,500km ( < 10 dB OSNR at 0.5 nm RBW)
  - Avoid changes of line equipment, especially current EDFA spacing, and in-line DCF (ideally CD & PMD tolerance comparable to current 10G)
  - > 10 cascaded ROADMs @ 50GHz spacing (LH)
  - > 20 cascaded ROADMs @ 100GHz spacing (Metro)
- **Power & footprint same as current 40G (< 40W)**
- **Cost** effective to maintain the TCO level

PMD tolerance increasingly important (given the lack of an effective PMDC):
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SP Economics

SP Consumer Access Margin per Gigabyte
CAGR 2006 -> 2017: Revenue -15.7%, Costs -14.8%

Source: IBSG Analysis, Cisco Visual Networking Study
Background for the Next-Gen IP Network Revolution

SALES ARE DROPPING LIKE A ROCK.

OUR PLAN IS TO INVENT SOME SORT OF MPLS NETWORK THAT EVERYONE WANTS TO BUY.

THE VISIONARY LEADERSHIP WORK IS DONE. HOW LONG WILL YOUR PART TAKE?

Networks Transition from Service Specific

Challenges:
- Capex
- Opex
- Service Velocity
Changing Application & Traffic

**Consumer**
- **2004**
  - 24,500 TB/month
- **2008**
  - 654,000 TB/month
  - **93% CAGR**
  - Consumer Broadband (TB/month)
  - Consumer VoIP (TB/month)
  - Consumer IPTV / VoD
  - Consumer FTTH (TB/month)
  - Rise of Video / IPTV

**Business**
- **2004**
  - 172,000 TB/month
- **2008**
  - 1,190,000 TB/month
  - **47% CAGR**
  - Business DSL
  - IP VPN
  - Private Line (IP Portion)
  - ATM / FR (IP Portion)
  - Ethernet
  - Proliferation of Business Broadband

Source: Cisco Estimates, Ovum, Bernstein, Public Company Data

IP/MPLS-over-Optical Next-Generation Networks
Wireline & Wireless, Residential & Business, convergence

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Statistical Multiplexing Gain – a simple example

One 4 site GE Customer
Six PtP FrGE Customers
One SAN Customer: 2GE & 2 FC

Required VC4:

<table>
<thead>
<tr>
<th>VCAT Only</th>
<th>CET</th>
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<tbody>
<tr>
<td>91</td>
<td>30</td>
</tr>
<tr>
<td>84</td>
<td>30</td>
</tr>
<tr>
<td>49</td>
<td>26</td>
</tr>
<tr>
<td>245</td>
<td>94</td>
</tr>
</tbody>
</table>

Total VC4: 40% full

- Scaling the IP POP has been a challenge; interconnect technologies innovation
- Value: Convergence of core, peering, and edge functions = CapEX/OpEx savings

Router Evolution

- Late 1980s
- Early 1992s
- Mid 1995s
- 1998-99
- 2000-02
- 2003-future

Core Routing Systems

1.2 Tbps to 92 Tbps
Router evolution and the role of optics

- Early 90’s: routers over FDDI
- Mid 90’s: routers over ATM networks
- Later 90’s: routers over SONET → external optical i/f
- Early 00’s: routers over DWDM → direct mapping over optical network – no extra grooming
- Mid 00’s: multi chassis routers → internal optical i/f between chassis
- Late 00’s: IPoDWDM → DWDM directly in routers
- Early 10’s: advanced modulation in routers, interaction with optical switched networks
- Beyond: bigger role for optical processing inside routers?

How good is Today’s Architecture for IP evolution?

- High OPEX unjustified
- CAPEX and power higher – spread over multiple technologies
-Sensitive to accurate forecast per service type
Benefits of IPoDWDM solution

- Lower CapEx
  - Elimination of OEOs
- Lower OpEx
  - Space, power, management
- Enhanced resiliency
  - Fewer active components
- Investment protection
  - 40G and beyond, interoperability over existing 10G systems

IP+DWDM Value Proposition

Layered
- ROADM
- Core
- Peering
- Edge
- Access

IP NGN over WDM

Capex/Opex reduction, Increased Service Flexibility

IPoWDM Savings

(IEOC 2006 W5 – L. Paraschis)
IP-over-DWDM Advanced Protection feature

Reference: OFC2008 - O. Gerstel et al. NWD4

Experimental Results for MPLS FRR

Reference: OFC2008 - O. Gerstel et al. NWD4

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Proactive FRR</th>
<th>Fault</th>
<th>Packet loss (in ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Min</td>
</tr>
<tr>
<td>1</td>
<td>Y</td>
<td>Optical-switch</td>
<td>3.10</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
<td>Fiber-pull</td>
<td>3.17</td>
</tr>
<tr>
<td>3</td>
<td>Y</td>
<td>Noise-injection</td>
<td>0.009</td>
</tr>
<tr>
<td>4</td>
<td>N</td>
<td>Optical-switch</td>
<td>4.51</td>
</tr>
<tr>
<td>5</td>
<td>N</td>
<td>Fiber-pull</td>
<td>3.12</td>
</tr>
<tr>
<td>6</td>
<td>N</td>
<td>Noise-injection</td>
<td>2233</td>
</tr>
</tbody>
</table>
Open WDM evolution – Alien-Wavelength transmission
(Reference: D. Ventorini et. al. Embratel Brazil OFC 2008 NME3)

- **Definition:**
  Tx/Rx vendor ≠ DWDM net vendor

- **Motivation:**
  Avoid costly OEO conversions
  Flexible scaling
  Independent Tx/Rx innovation

- **Management of DWDM network includes Tx/Rx**

- **Challenge:**
  Missing demarcation between the layers → need good impairment monitoring (OSNR, CD, PMD, …)

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Open WDM evolution to 40G Alien-Wavelength transmission
(Reference: T. Kozar et. al. 2009 Netia Poland)

- **40G core upgrade**

- **40G DPSK IPoDWDM (cisco)**
  500-700 km links

  Over existing 10 Gb/s WDM system (Siemens)
Next-Gen WDM Transport Goals

- **More Flexibility:** Cost-effective scalable (plug-and-play) transmission and non-blocking switching

- **Manageability:** Seamless operations and trouble shooting (w/out requiring a Ph.D. degree)
  
  Advanced monitoring of optical impairments for each channel modulation format

- **DWDM aware control plane, and intelligent management**
  
  Routing based also on WDM (impairment) aware path-computation

- **Long-term: Adaptive:** collaboration among optical and routing for cost-optimized bandwidth use
  
  Future potential for flexible spectrum extraction – not just a fixed grid

Flexible WDM Transport

- Flexible Add/Drop
- Directionless (fully Meshed)
- Colourless
- Seamless Provisioning
- Routing (regeneration)
- Alien Wavelength
- Monitoring
- Intelligent Control Plane, and Management
So far the optical layer was assumed to be static…

- Can the optical layer become dynamic?
- What value does this bring to the IP layer?
- What constraints does the solution have?

Why is the optical layer still not dynamic?

1. Optical switches did not provide switched add/drop until recently, or were too complicated and expensive
2. Network management systems and operations practices not geared towards dynamic optical networking
   - Trouble shooting when paths are unknown
   - Manage resources instead of micro-managing the network
3. Hard to calculate optical feasibility in control plane
   - Significant optical data exchange
   - Standard bodies reluctant to burden signaling protocols with this data
   - Method for assessing feasibility considered a proprietary "secret sauce"
Why is the optical layer still not dynamic?

4. DWDM networks have not been built for fast reaction
   • Due to optical layer power mgmt
   • Worse for 40G/100G due to need to adjust Tx/Rx

5. Regenerators in dynamic networks add additional complexity/cost
   • Need to be pre-deployed to support future traffic
   • Hard design problem if traffic is unknown
     [Raza et al, “Predeployment of resources …”, JLT 2004]

6. Lack of clear “killer app”
   • Biz case for Bandwidth on Demand (BoD) in DWDM layer hard: must reuse the same bandwidth for enough different users

(7) Concerns about optical protection

- L0 Protection does not cover all failure modes
- Dedicated L0 protection wastes bandwidth
- Shared L0 protection relies on unproven and slow control plane
- L0 protection does not deal well w multiple failures
- Having both L0+L3 protections may create race conditions & oscillations
Signs of Changes – towards Dynamic Optical Networking

1. Add/drop optical switches → being productized
2. Operations → still not supporting dynamic networking
3. Control plane → move towards “impairment aware GMPLS”
4. DWDM networks → will remain slow reacting
5. Regenerator pre-deployment → best fix is to remove them by extending the reach
6. Some promising applications are being proposed
   Biz case for Bandwidth on Demand → still non-existent
7. Optical protection → limited use for now

More Control Plane Examples

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharing knowledge about degrading links</td>
<td>More robust protection</td>
</tr>
<tr>
<td>Sharing of risk group information from the optical layer</td>
<td>More robust protection</td>
</tr>
<tr>
<td>Alarm correlation between the two layers</td>
<td>Reduce operational cost</td>
</tr>
<tr>
<td>Sharing metrics related to the cost of a lightpaths</td>
<td>Reduce capital cost</td>
</tr>
<tr>
<td>Reconfiguration of the optical layer to alleviate congestion on router links</td>
<td>Reduce capital cost</td>
</tr>
<tr>
<td>Combined restoration between layers</td>
<td>Reduce capital cost</td>
</tr>
</tbody>
</table>
### Router Driven Lightpaths

#### Concept

- Router measures utilization for each link
- If utilization is high – request another lightpath from L0
- If utilization drops – release unused lightpath

### Router Driven Lightpaths

#### Constraints

- Must stick to original IP topology
- Otherwise – may destabilize IP routing
- And create congestion elsewhere
Router Driven Lightpaths
How does this reduce the cost?

Today
- Need to over-provision to ensure capacity exists when IP needs it.
  Need to do it everywhere since location of surge is unknown

Automated IPoDWDM
- Extra interface per node can be deployed when a link becomes congested. No need to over-provision per link

Discussion
- Real life traffic surge evidence:
  - “When we analyze the surge magnitude distribution, we find that the addition of one extra, temporary link between affected router pairs will support up to 97% of all surges...

- Concerns:
  - Is it worth pre-deploying 100G Tx/Rx w/o using them?
  - Is WL granularity too coarse?
  - How much churn in the optical layer?
Adaptive WDM transmission vision

- Does the network need 100G for every pair of core routers?
  Not necessarily...
  Is there a way to cost-optimize component, regen, scaling?
  … and still maintain Optical Network simplicity and flexibility…

Shifting away from a Rigid Optical Layer

- Towards an adaptive network:
  1. Adaptive bit rate per channel
  2. Flexible usage of the Spectrum
  3. Sliceable Tx/Rx

- Can this be done?
- Is it worth it?
Is adaptive Bit-Rate & Spectrum Transmission Possible?
Reference: Paraschis, Gerstel, 2009 LEOS TuD-2.2 invited presentation

Non-adaptive

10G  2000 Km
100G 500 Km
100G  2000 Km

Adaptive

30G  2000 Km
100G  2000 Km using more spectrum

50GHz Grid

100GHz Grid

Flex Spectrum

50GHz 200GHz Future 25GHz

Research in adaptive Bit-Rate & Spectrum Transmission

Willner et. al. “PSK/ASK Variable Bit Rate” ECOC 2006


Fig. 1. (a) Experimental setup: Measured spectral intensity (circles) and phase (triangles) for a (i) 2010 10Gb/s OOK signal and (ii) 01010101 DPSK signal. Target values (×). Measured temporal intensity (dotted) and phase (solid) for the (c) OOK signal and (d) DPSK signal. Target values (shaded).

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Summary

- Network traffic, predominantly IP, is growing > 40-50% CAGR, approaching by 2012 the Zettabyte per year
  ➔ Need for cost-effective in scale and operations

- WDM has offered the most scalable transmission and has evolved to an reconfigurable Multi-service Open Transport layer

- WDM transport is scaling 40 Gb/s and will need cost-effective 100G over existing infrastructure asap

- Convergence of IP & WDM offers significant Network benefits, and future Router & WDM integration potential for more sophisticated collaboration towards an adaptive cost-optimized WDM transport
  where expensive resources like 40G and 100G could be conserved using advanced monitoring, optical switching, and intelligent network control plane.

Thank you

For questions/comments, please contact:
Loukas Paraschis loukas@cisco.com
Other Vendors also Believe this is the Future

Ethernet (IP) Over Optics (WDM) Technology Enables Cost-Efficient Terabit Connection

- Optical transport (and access) will jointly evolve with class of e2e services
- Carrier Ethernet transport will over time substitute Sonet/SDH-based TDM services with improved service features & significant opex savings
- Cross-layer optimization will continue to improve overall cost efficiencies
- IP-over-WDM technologies, along with packetized optical networks, will serve the new Internet connectivity infrastructure for both fixed & mobile communities

How different optical switching technologies relate to each other

<table>
<thead>
<tr>
<th>Technology</th>
<th>Switching speed</th>
<th>How</th>
<th>Hard</th>
<th>Easy</th>
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<tbody>
<tr>
<td>OPS (Packet)</td>
<td>1e-7 seconds (*)</td>
<td></td>
<td></td>
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<tr>
<td>OBS (Burst)</td>
<td>1e-5 seconds (**)</td>
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<td>OFS (Flow)</td>
<td>1e-3 seconds</td>
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<tr>
<td>Agile IPoDWDM</td>
<td>Seconds-minutes (***)</td>
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<tr>
<td>Today’s DWDM</td>
<td>Days-Months (***))</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

(*) Assuming 1KB packets
(**(Assuming o(100) packets per burst
(***Assuming steady state switching (not protection)
Current Limitations of Optical Packet Switching

- The important challenge in router scalability:
  - Reduce cost of transferring a bit through a node
  - Reduce power consumption
- OPS technical challenges:
  - Buffering – or else blocking
  - Cost per optical gate
- Alternative practical evolution in the IP & Optical synergies:
  - IP-over-DWDM is already reducing cost, power, improve reliability, maintain scalability, and…
  - can allow for increased network intelligence…

Differences between optical and electronic technologies

- Abundance of bandwidth
- No cost-effective optical random access memory
- SiCMOS ~ $10^9$/gate – optical ~ $10^4$-$10^5$/gate, 12 orders
- Min switching energy of optical logic gate ~ $h\nu$, >> $kT$
- Electronic time slot interchangers cheaper (~ 6-7 orders) than dual in the optical WDM domain: wavelength converters.
- Optical wavelength switches are more efficient switching in bulk
- Optics inherently a better broadcast medium
  - Lasers are more expensive than electronic signal sources.
- Electronic network architectures are designed for efficient use of electronics – fine grain switching
- Optical network should use architecture created to exploit optical properties of light – coarse granularity switching