Next Generation Optical Transport for IP Network Evolution

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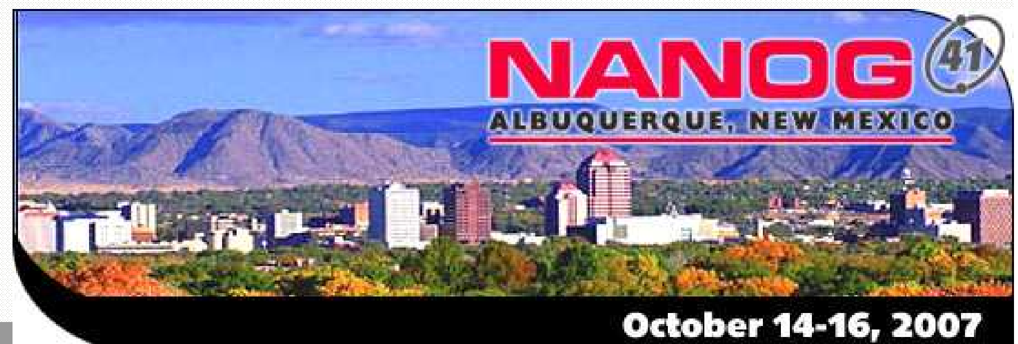
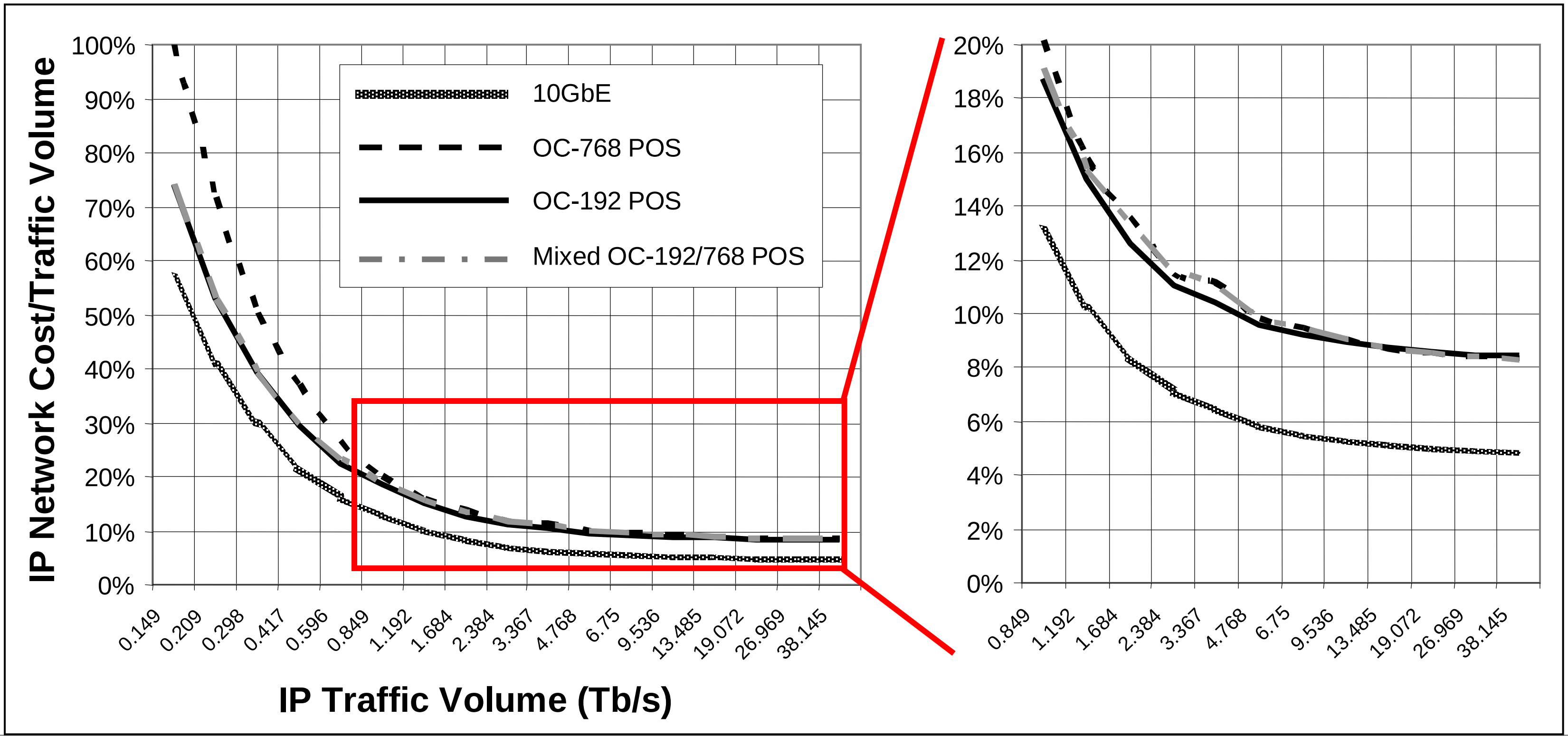


Agenda

- Optical transport requirements for future IP networks
  - Ethernet services
  - Super-λ services
  - 10 GbE, 100 GbE and TbE
  - Reconfigurable IP Router Bypass
- Modulation approaches for higher capacity
- Photonic integration

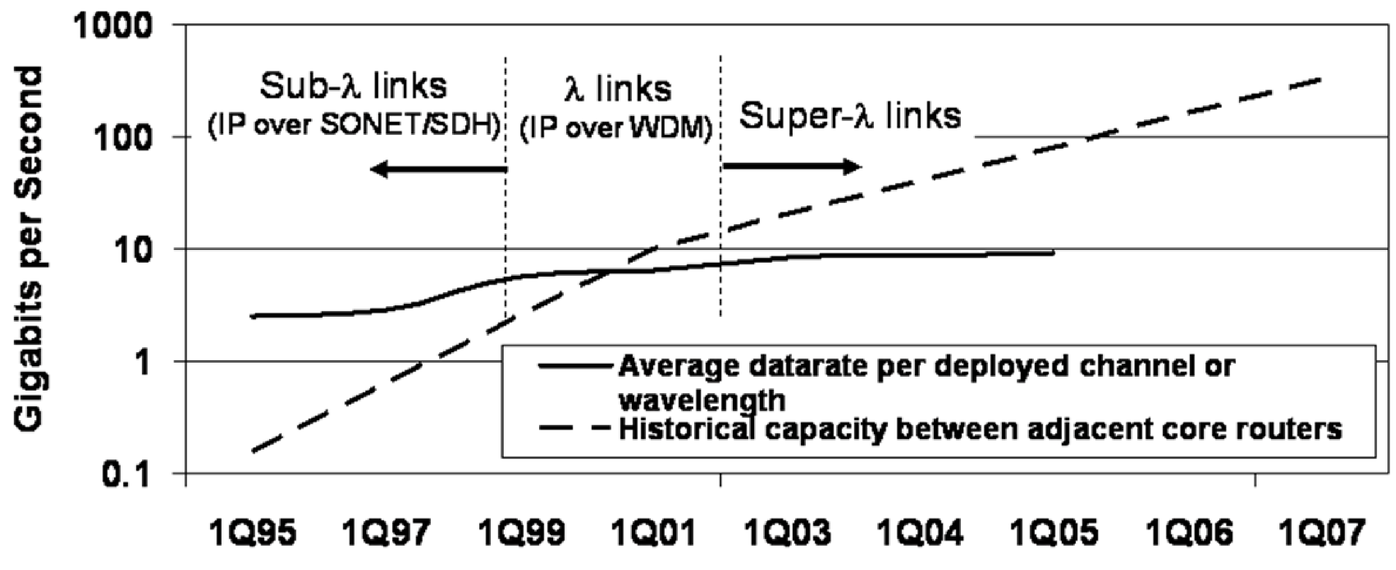
10 GbE More Economic Than 10G and 40G POS

- Economics (First-in and ongoing CapEx and OpEx) is foremost concern
  - *It's the economics, stupid!*
- Study of CONUS IP and transport network costs shows 10 GbE most cost effective IP link technology
- Future optical transport network should be Ethernet-based



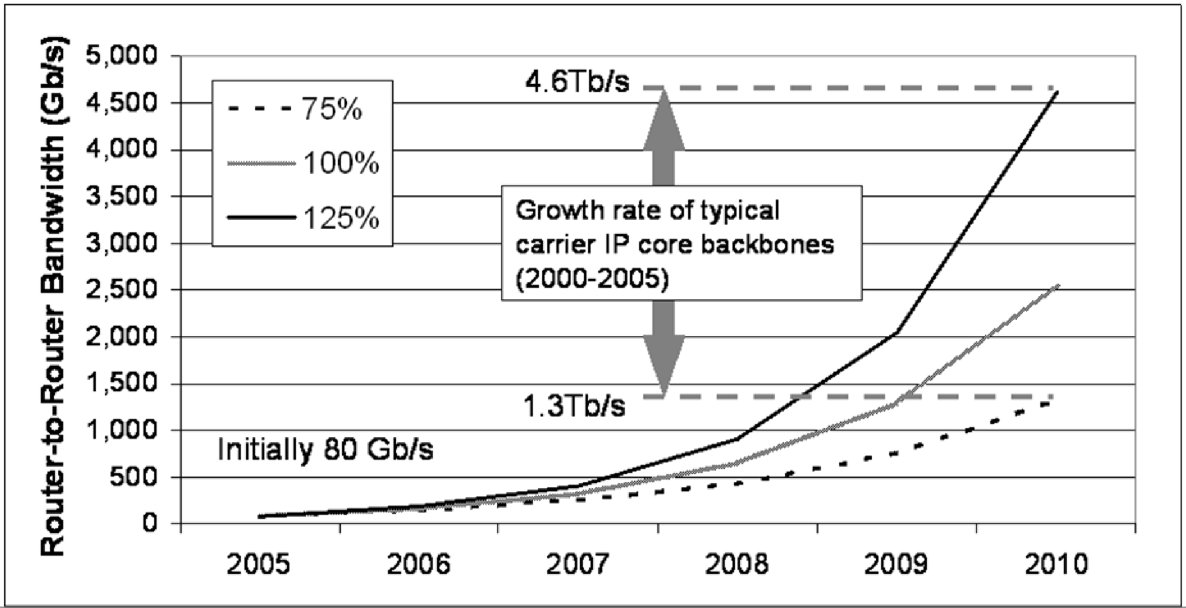
IP Now Requires Super-λ (Multi-wavelength) Links

- IP links once used sub-λ SONET/SDH circuits
- Capacity growth of IP links has out-paced capacity growth of a single λ
- By late 1990s IP links required full 2.5G and then 10G λs
- IP now requires super-λ links (composite links, LAGs, etc.)



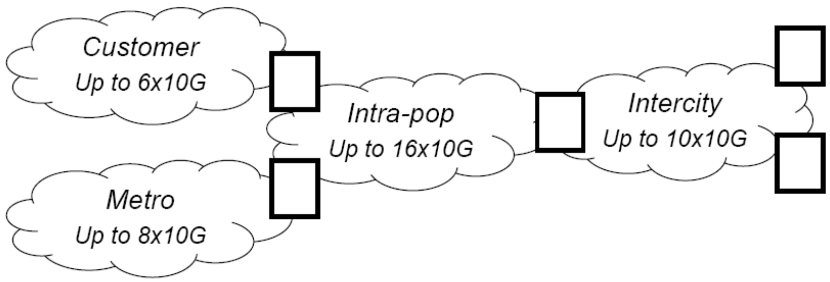
The Future Belongs to Tb/s Links!

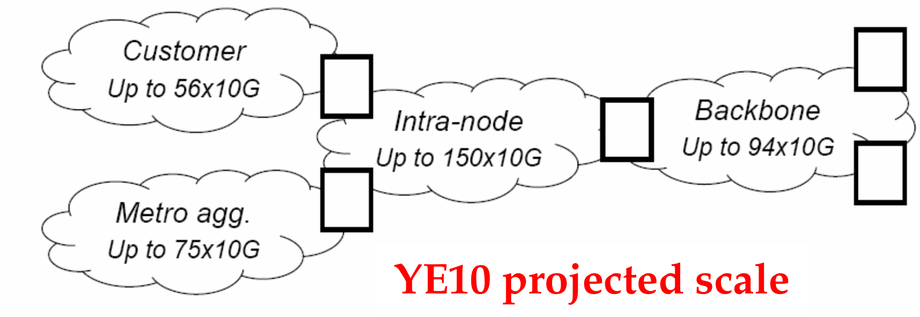
- Carriers deployed Nx10 Gb/s links several years ago
  - N has now surpassed hardware limits of 8-32 in some networks
- Some carriers now deploying Nx40 Gb/s router links
  - Is this like putting out a 5-alarm fire with a garden hose?
- Current IP growth rates, if sustained, will require IP link capacity to scale beyond 1 Tb/s by 2010



Carrier/Network Operator Input to IEEE

Current 10GE Scaling Requirements





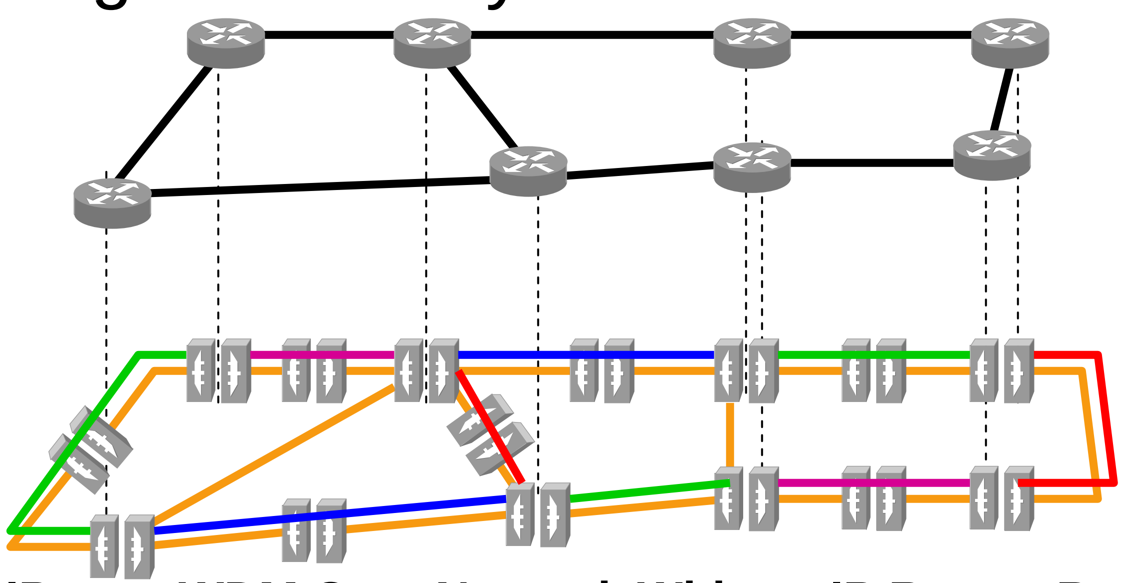
- Figures are maximum 10GE capacity between individual elements

Source: Level3, OFC 2007 100GbE Workshop

- Other views on timing of 100GbE:
  - *"100GigE Needed for Broadband Customer Aggregation urgently in the core by 2009 and across the board by 2011",* Jason Weil, Cox Communications, IEEE HSSG April, '07
  - *"2009 timing: Will be a very uncomfortable wait"*, Donn Lee, Google, IEEE HSSG March '07
  - *"Bundles of 8 means that we will need 100 Gbps ye 2008 / beginning 2009"*, Ad Bresser, KPN IEEE HSSG May '07
  - *"Work needs to begin on whatever follows 100G as soon as possible",* Ted Seely, Sprint Nextel, IEEE HSSG March '07

IP Network Economics Study: No IP Router Bypass Links

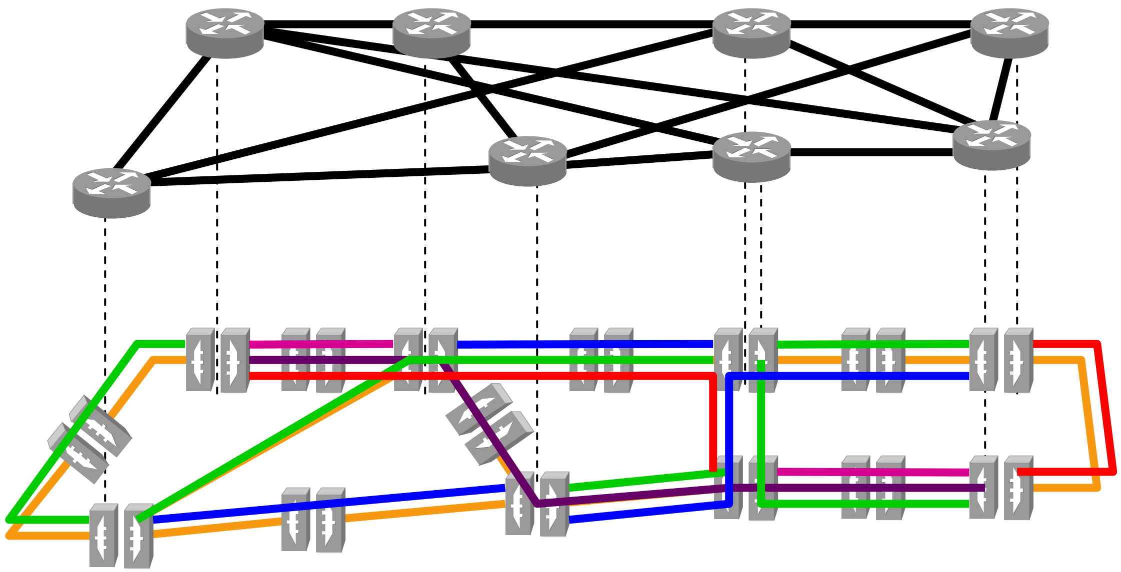
- IP links connected between adjacent routers
- IP core links carried over WDM network
- No IP router bypass links
  - End-to-end IP demands switched hop-by-hop
- Increasing inefficiency & cost as traffic volume scales



IP over WDM Core Network Without IP Router Bypass Links

IP Network Economics Study: With IP Router Bypass Links

- Reduce end-to-end IP demands transiting through multiple router hops
- Increase number of direct router-to-router core links
- IP router bypass in WDM layer
- Minimize use of high-cost router ports and capacity



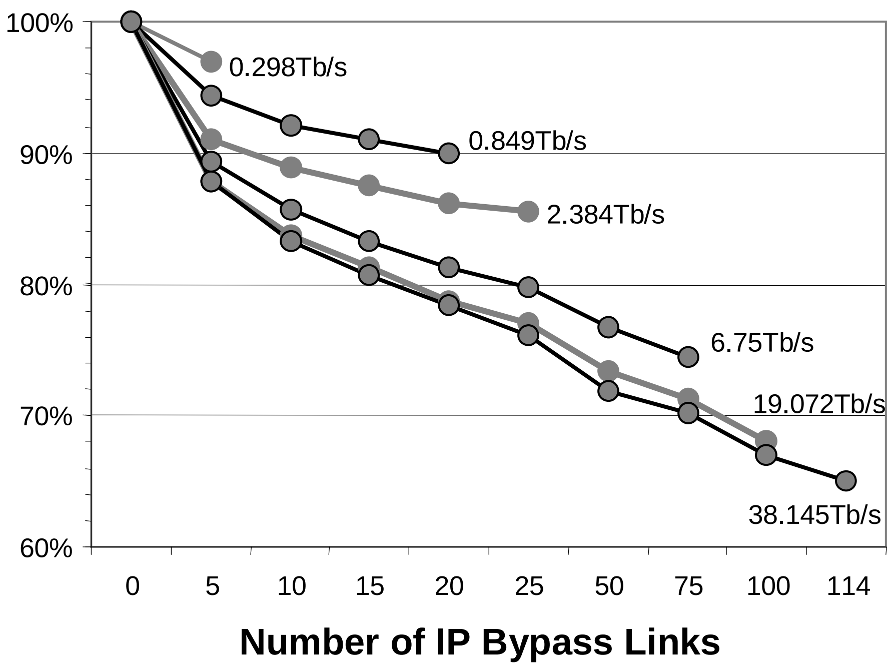
IP over WDM Core Network with IP Router Bypass

IP Router Bypass Yields Dramatic Cost Savings: 10 GbE

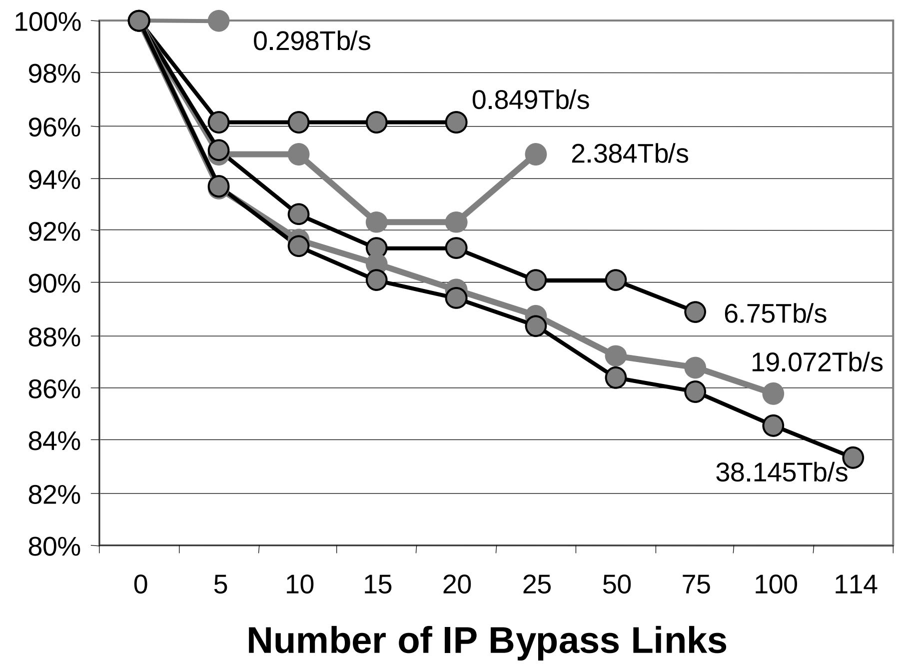
- Network cost savings rises with network scale
- Network cost rises after last point shown
- Sparse mesh least costly

18-node IP core network modeled
18x17=306 possible bypass links

Relative IP Network Costs (10 GbE Ports)



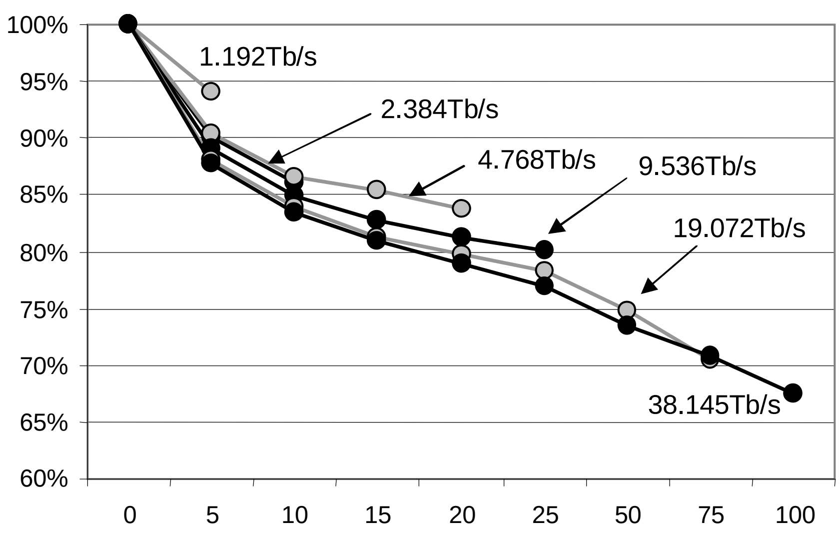
Relative WDM Network Costs (10 GbE Ports)



IP Router Bypass Yields Dramatic Cost Savings: 40G POS

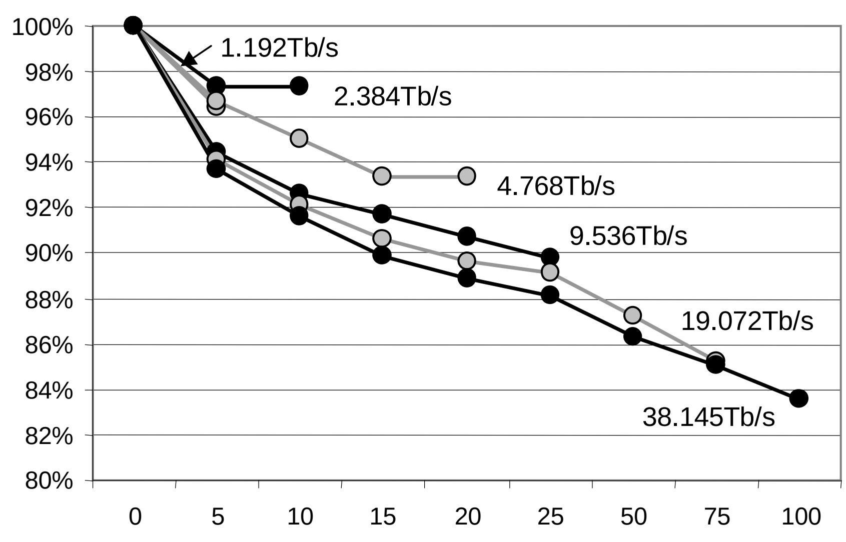
- 40G POS more costly than 10 GbE (see above)
- 40G defers benefits of IP router bypass
  - 4x demand required for each bypass link
- Optical transport network must be rapidly reconfigurable to maximize IP router bypass benefits
  - Adjust for route changes, changing traffic sources, etc.

Relative IP Network Costs (40G POS Ports)



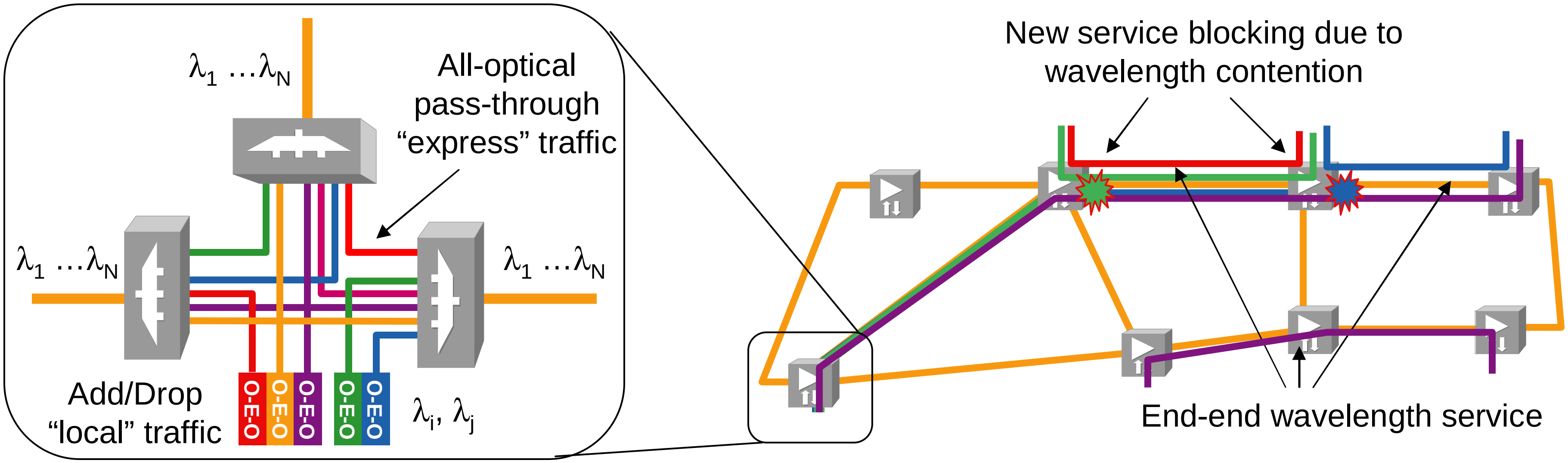
Number of IP Router Bypass Links

Relative WDM Network Costs (40G POS Ports)



Number of IP Router Bypass Links

All-Optical ROADMs



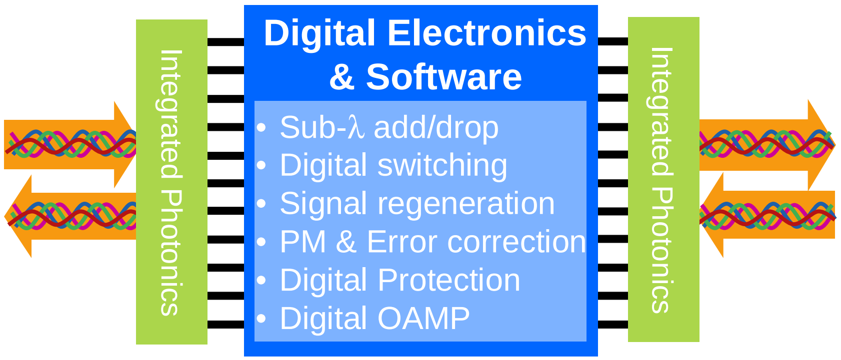
- All-optical wavelength switching using filters, ROADM, WSS, etc.
- OEO only for local add/drop
- No sub-wavelength add/drop
- No wavelength interchange
- No digital PM or OAMP

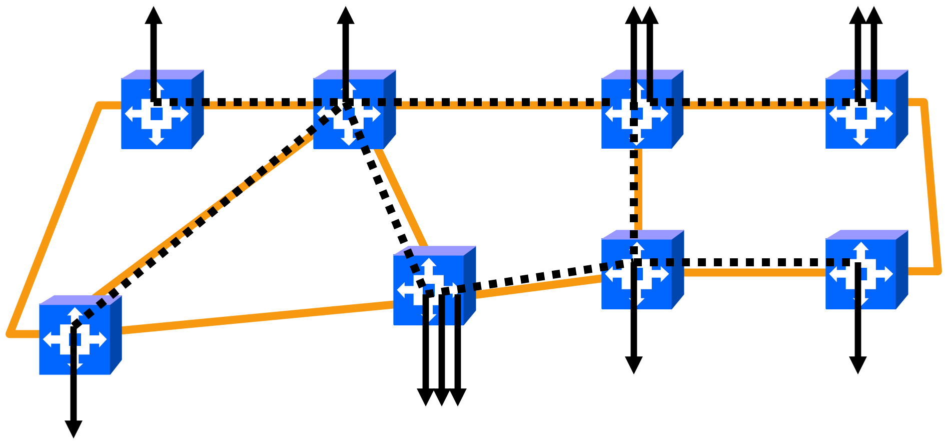
- Wavelength contention and blocking
  - Up to 30-40% incremental OEO for I-conversion = hidden CapEx premium
- Service limited by wavelength path
  - Optical reach
  - Number of (R)OADM nodes passed
  - Fiber characteristics

Economic gain limited by all-optical ROADMs implementation

Digital ROADM

Full Reconfigurability at Every Node



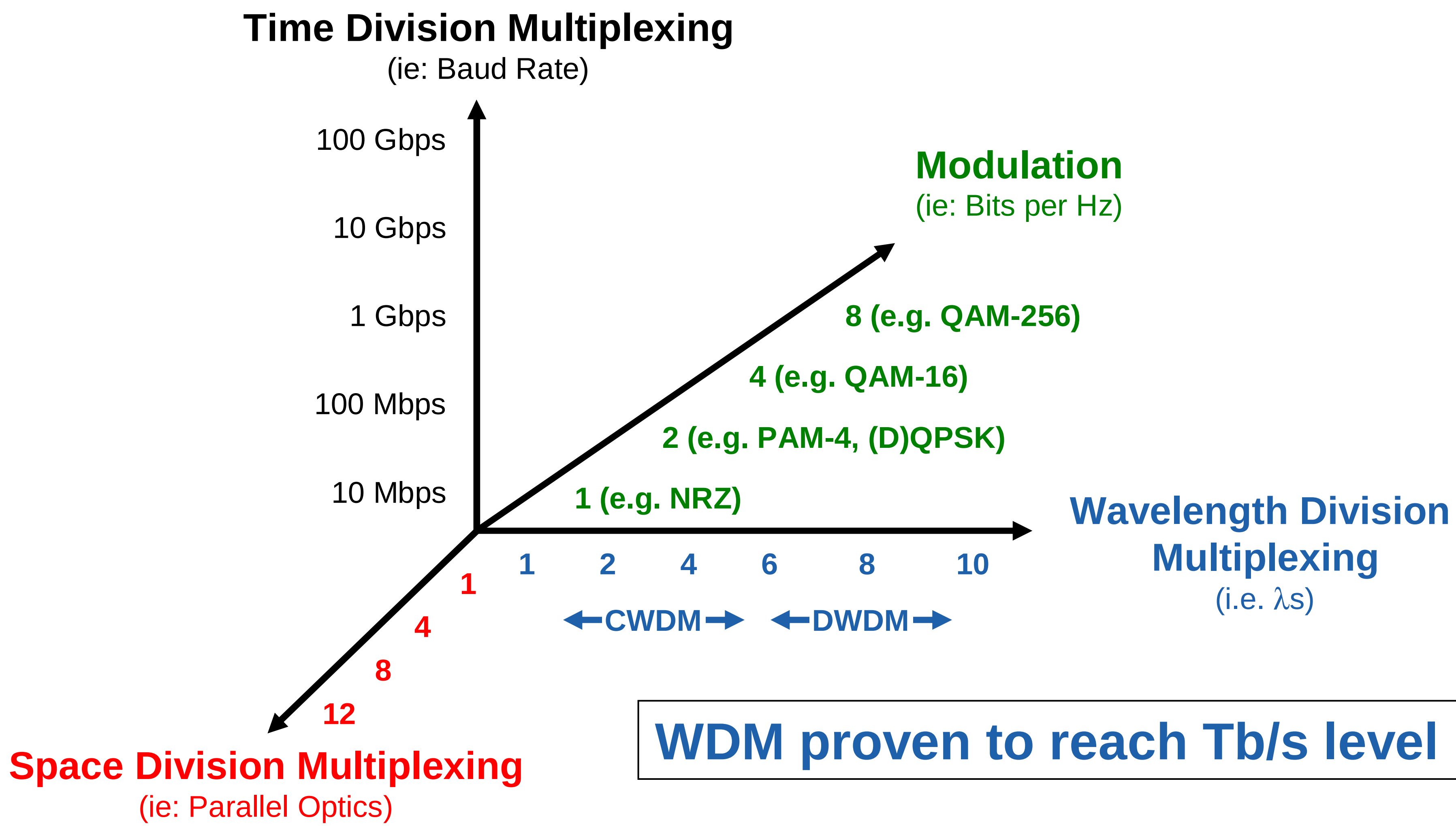


- Use (analog) photonics for what it does best: WDM transmission
- Use (digital) electronics for everything else
- Digital add/drop, switching, grooming, PM and protection…
- …at every node

- Unconstrained digital add/drop
- Any service at any node
- End-end service delivery independent of physical path
- Robust digital PM and protection
- Digital OAMP & management

Truly unconstrained reconfigurable optical networking

How Will Capacity Be Scaled In The Future?



WDM proven to reach Tb/s level

It’s Really a Question of Economics

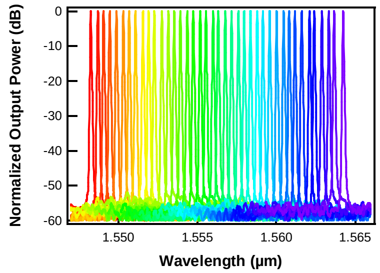
- 40G per λ TDM: Service Provider experience thus far
  - 4x bandwidth increase, but » 4x cost increase
  - Not 2.5x as historically experienced and now expected/wanted
  - cost(1x 40 Gb/s) » cost(4x 10 Gb/s)
- 100G per λ Modulation: Data released so far
  - Complicated, power-hungry electronics (21W per 40G!)
  - Will require significant integration to yield acceptable costs
  - Will it cost < 10x 10 GbE?
  - Equipment vendor(s) predicting 100 GbE may cost ~2.5x 40G POS
    - cost(2.5x 40 Gb/s) » cost(10x 10 Gb/s)
- 10x 10G per λ DWDM: Equipment deployed today
  - Integrated via PICs and shipping since 2004
  - Prediction: cost(10x 10 Gb/s λs) will likely remain « cost(1x 100 Gb/s λs) for a long time

Multi-Tb/s Line Capacity and Tb/s Line Cards Will Require Massive Integration

- 10 – 100x advancements in integration required to meet density, power, reliability and cost requirements
  - E.g. 100G line cards will not set the hurdle; better be thinking 1T!

Enabling Technologies

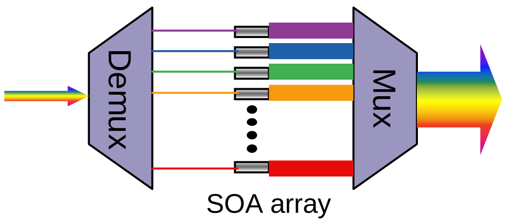
Higher Line Rates
(PIC Capabilities)



1.6Tb/s PICS (40ch x 40G)

1.6 Tb/s

Beyond C-band
(Enabled by PIC SOA)



PIC based SOA amplification

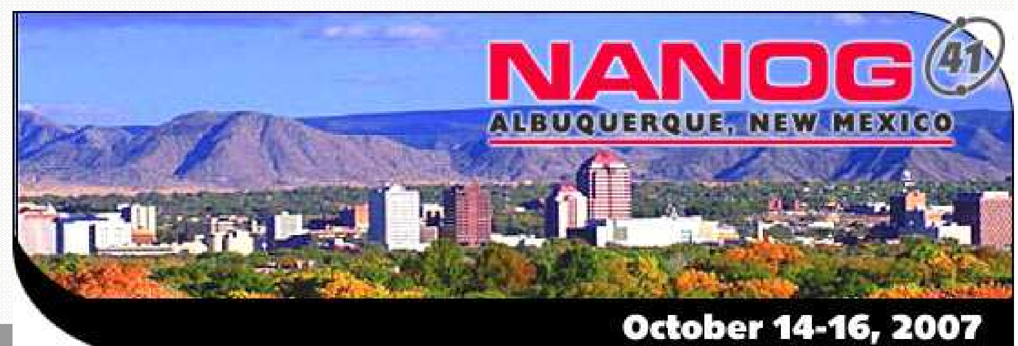
10's Tb/s

Example Capacities

Summary

- Ethernet will rule the day economically
- Super-λ implementations have become and will remain the norm
- Optical transport network must be flexible to enable greatest economic savings from IP router bypass
- Multi-Tb/s line systems and Tb/s line cards required
- Massive integration of optical, OEO and electronic components required

Thanks!



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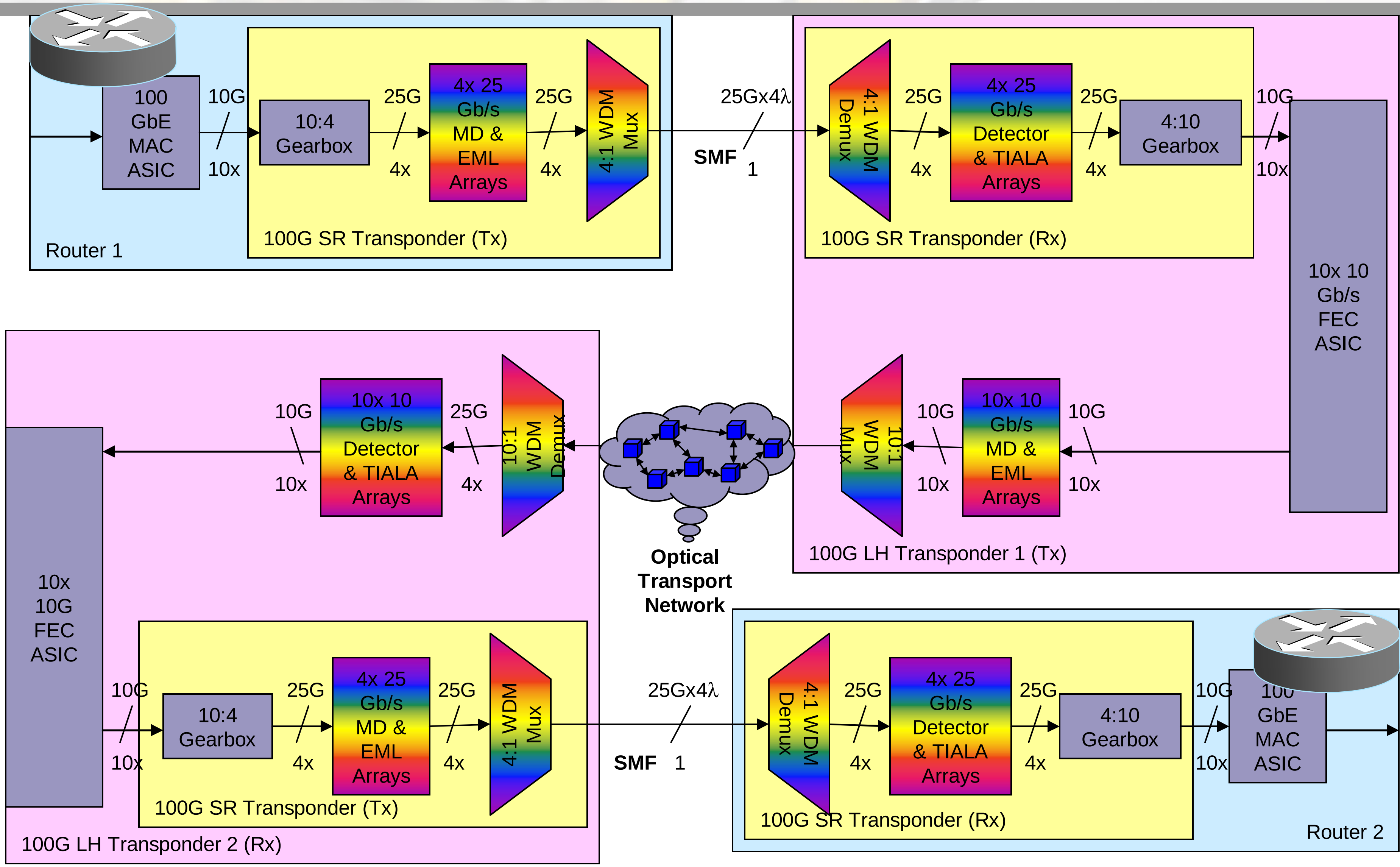
100 GbE Over DWDM Transport –
10x 10Gb/s Example (1 of Several Possibilities)



IP over WDM Analysis

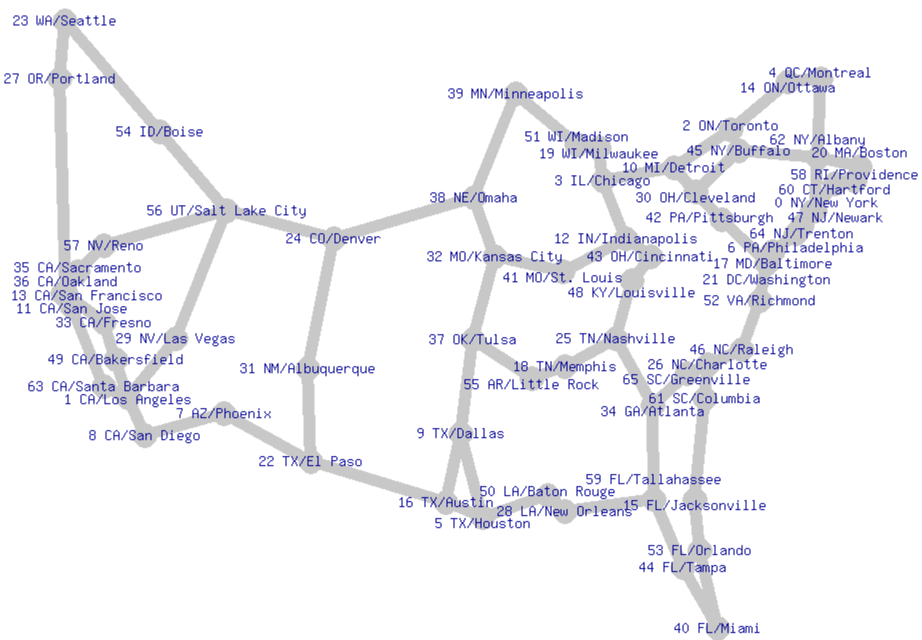
- Develop base-line representative model of core IP & optical networks
  - Ensure realistic and accurate modeling
  - Realistic set of equipment options considered: router ports, WDM layer, etc.
  - Realistic assumptions on market pricing: router ports, transponders, ROADMs, etc.
  - Realistic optical layer design: regeneration, wavelength blocking etc.
- Investigate impact of network architecture changes to IP layer:
  - IP designs that reduce router interface count can greatly reduce overall network cost.
  - IP design has impact on architecture and cost of WDM layer
  - Degree of router bypass on core links
  - IP core link (trunk) and router scaling
  - IP port evolution: 10G vs. 40G and 100G
- Investigate various optical transport options
  - Legacy & next-gen WDM technology options
  - Impact of WDM layer functions: optical bypass, restoration, reconfiguration, etc.
  - Impact of IP design on transport layer (ie: fewer IP trunk interfaces versus longer optical spans)

IP Network Cost Study Methodology

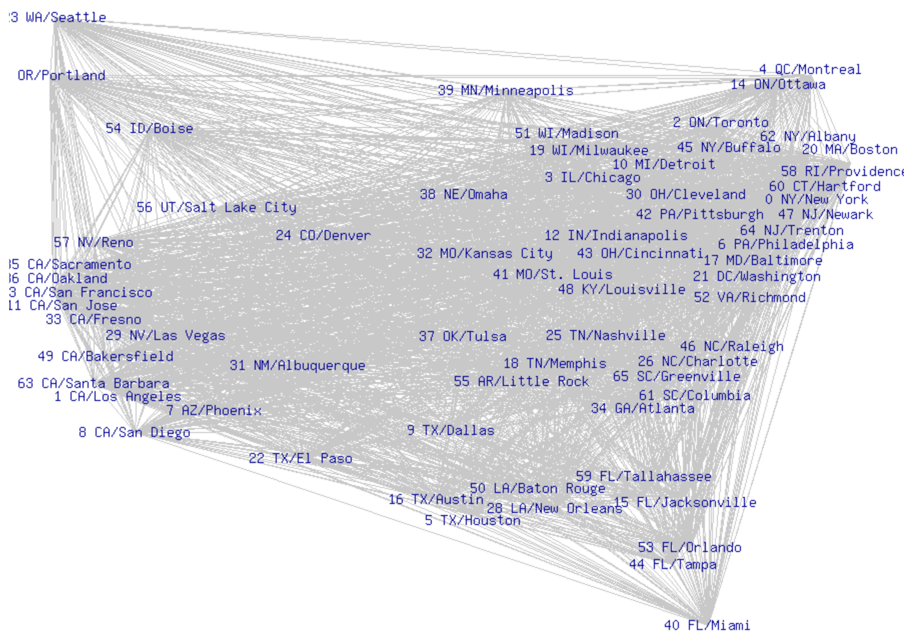
- Develop IP traffic model: generic A-Z city-city demand set
- Generate IP demands: collector and core
- Pick IP core nodes
- Generate IP core links
- Determine router-to-router link capacity
- Generate cost comparisons
- Sensitivity analysis
  - Sensitivity on IP traffic volume: 1x to 256x initial traffic
  - Sensitivity to degree of IP router bypass

Fiber Topology and A-Z Demands

Network Fiber Topology

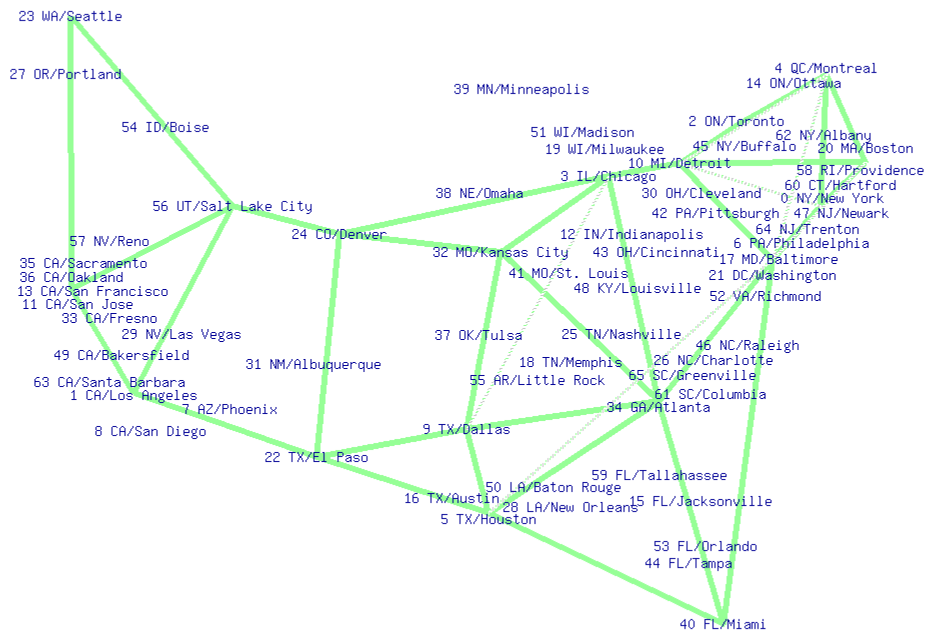


IP Network A-Z Demands

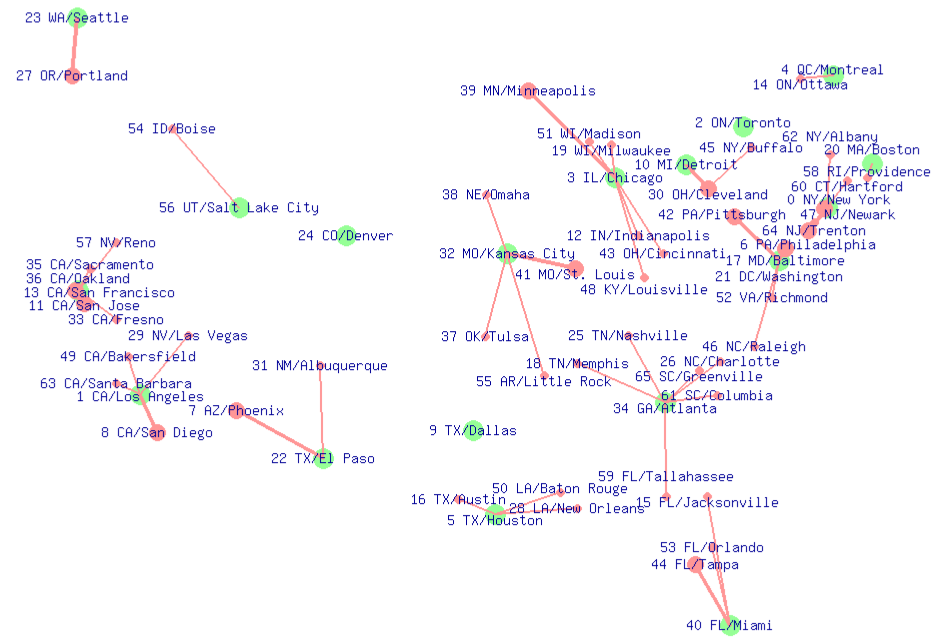


Core and Regional Links

IP Core Links

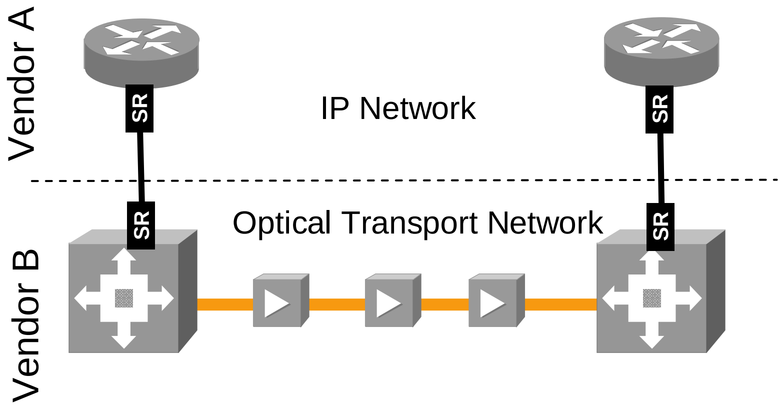


IP Regional Links

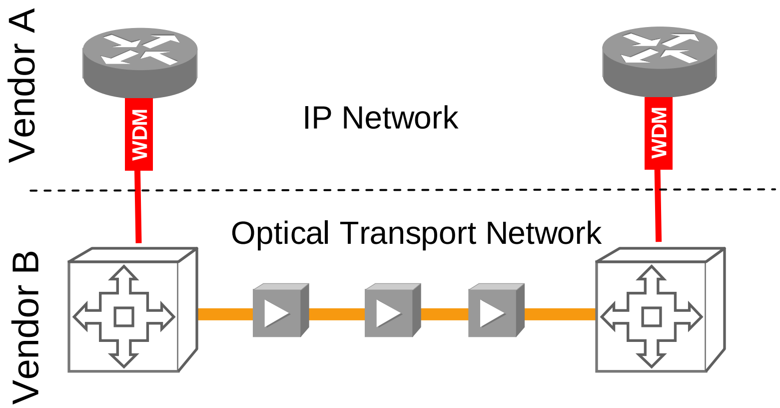


“Alien” Wavelengths

Practical Considerations & Operational Implications



Native Wavelengths



“Alien” Wavelengths

- Interconnect IP routers to WDM transport via short-reach optics
  - Clear demarcation between client signal and transport layer
  - Full end-end optimization, control & management of end-end service
  - “Best-in breed” IP and transport systems
- Integrated ITU-grid WDM optics on router input directly to WDM line system
  - No end-end control/management plane
  - Design optical link budgets to worse-case
  - Loss of end-end turn-up automation
  - Complex or no inter-network protection
  - Loss of PM and fault sectionalization capabilities
  - Complex service activation
  - Minimal CapEx savings – if any – from transponder reduction offset by design tradeoffs and operational complexity