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Converging IP and Optical Networks

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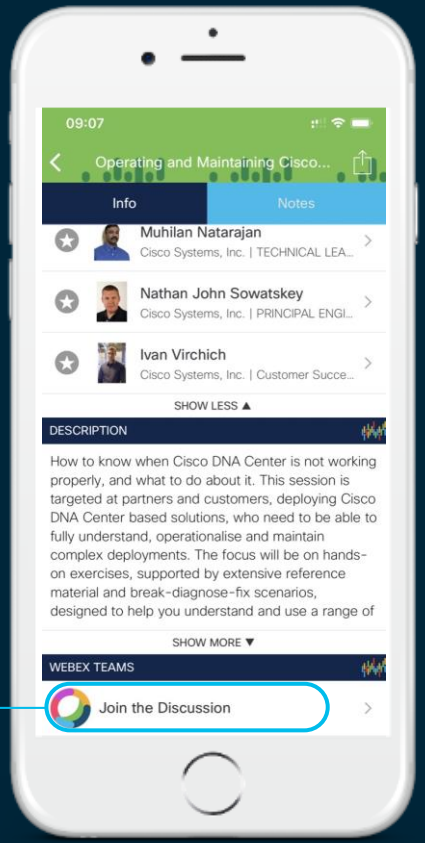


Agenda

- IP and Optical transport networks: key macro trends and drivers
- Evolution of pluggable optics technology
- Hop-by-Hop architectures in core networks
- Hop-by-Hop Architectures in aggregation networks
- Network Level CapEx and OpEx: EMEA Case Studies
- Conclusion

Key macro trends and drivers

Service Provider Objectives

- Reduce Total Cost of Network Ownership
- Decrease Time to Market for existing and new Services
- Reduce Operational Complexity
- Simplify the Network

Reduce Network Complexity
Drive down Overall TCO

How to improve the economics of networking?

Incremental Improvements

Build faster networks (Moore's Law)

Higher interface speeds

Higher chassis capacities

Lower cost per unit

Improve network utilization

Better traffic engineering

Telemetry + Analytics

Maximize use of assets

Disruptive Changes

Transform Network Operations

Consistent operations

Automation + Orchestration

Services agility, speed

Re-architect end-to-end network

Simplify, collapse layers

Minimize functional overlaps

Remove complexity

Traditional Network Building Blocks

IP

VPN Services
L3VPN, L2VPN

Internet Services
High Speed Internet
Dedicated Internet Access

Peering Services
Transit
Content

TDM

Private Line Services
GE, 10GE, OTU2 (10G)

High SLAs
Guaranteed BW
>99.9% Availability

Traffic Grooming
Filling OTU4 interfaces

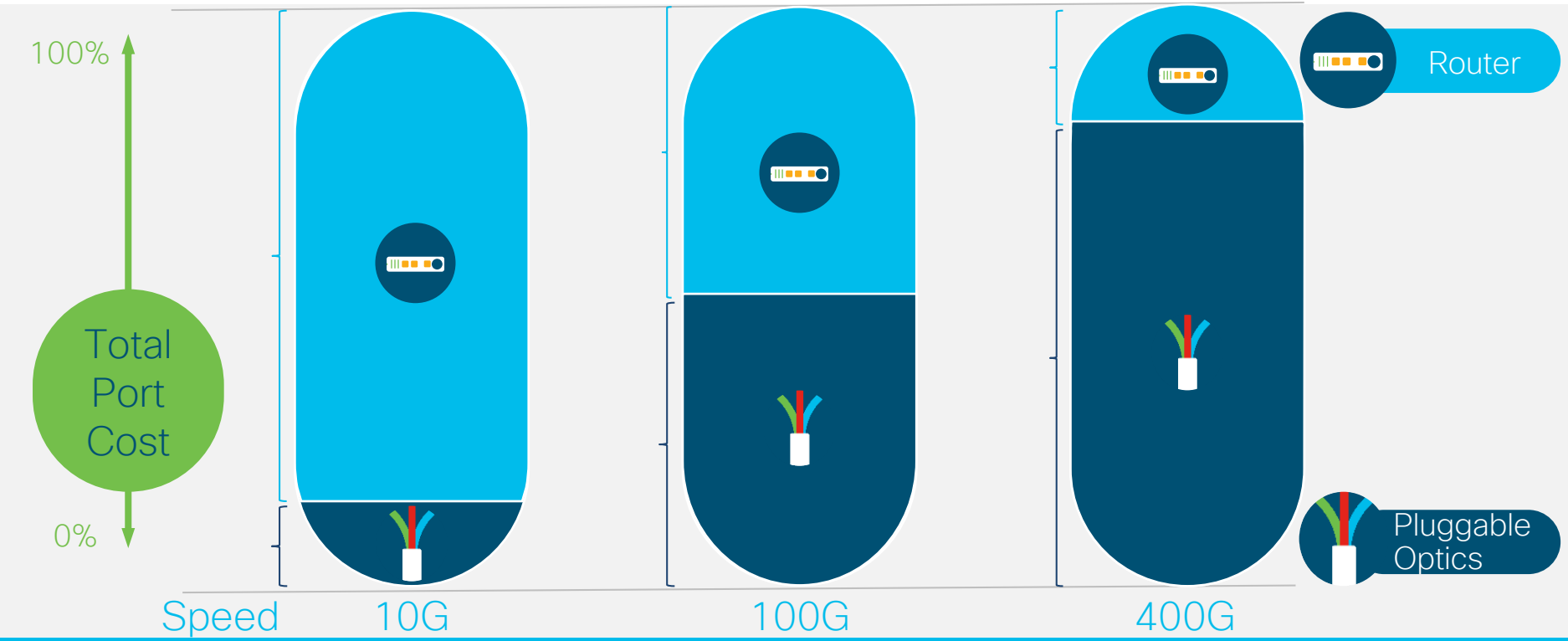
DWDM

Wavelength Services
OTU4 (100G)

Optical Performance
1.000's of kms

Fiber + Wavelength Capacity
Super channels
200 Gbps – 600 Gbps

Percentage of spend on optics will continue to increase as speeds increase



WHY? Router host port costs are decreasing FASTER than optics technologies.
Optics complexity increases with speed.

Disrupting the network architecture

Converge Services

Build a converged packet network for L1, L2 and L3 services

Use Router as the only switching element

Remove Layers

Eliminate OTN switching while keeping private line services

Private Line Emulation

Better Integration

Eliminate Transponders while maintaining port density

Use 400G ZR/ZR+ pluggable optics

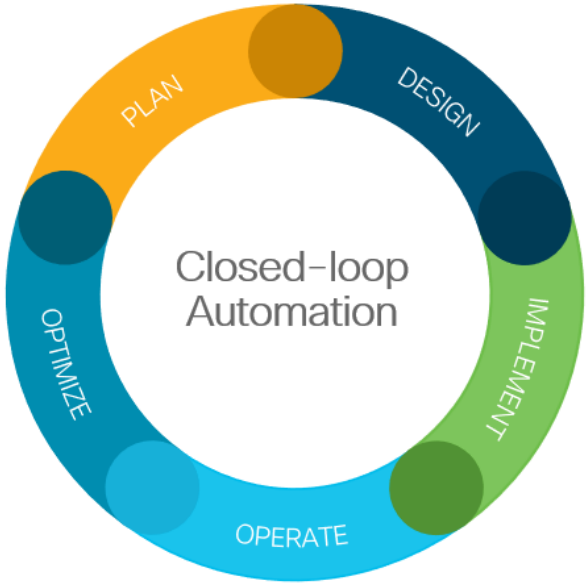
Simplify Layers

Eliminate ROADMs

Run all channels hop-by-hop between routers

Converged SDN Transport architecture operational goals

- Unified design and planning
- Unified Management
  - Option of separate management for siloed organizations
- End to and automation (IP and Optical)
  - Model driven configuration and telemetry
  - ZTP
  - Capacity augmentation
- End-to-end network optimization engine



How will this be different from IPoDWDM and Multilayer?

Converged Services over Packet
L3, L2 and L1 services – including OTN Private Line and Wavelength services

Mass-scale Routing Platforms
- Multi Tbps NPUs and line cards
- Less space/power per bit
- Cost-effective for all services

Common Hardware
- No dedicated hardware
- Zero port density trade-offs
- No hidden hardware costs

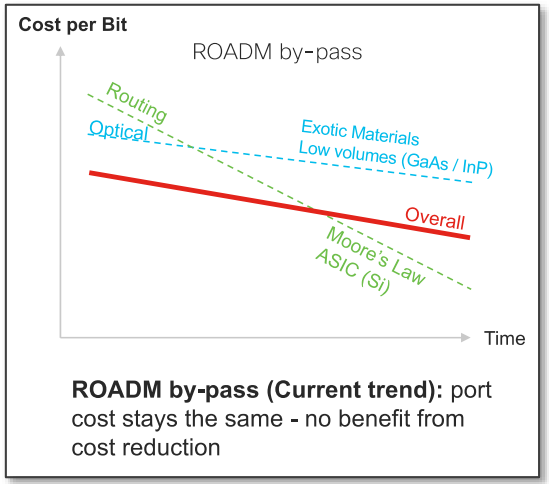
Standardized Optics
- Multi-vendor ecosystem
- Gains of scale
- QSFP-DD form factor
  - large industry
  - Re-usable

Simplified Management
- SR control plane
- Data model-driven, programmable
- Flexible management models (Silo or converged orgs)

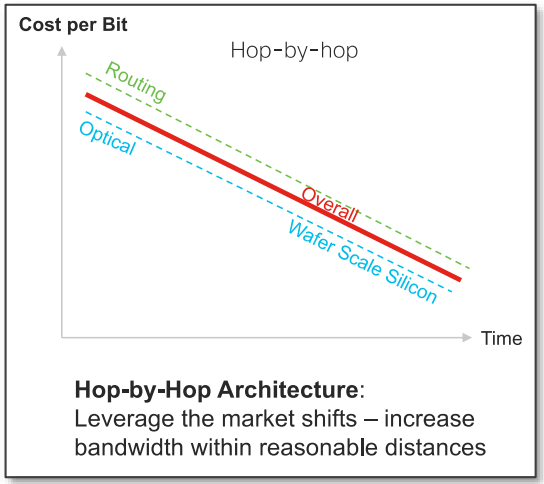
ROADM by-pass vs. Hop-by-hop

Game Changers

- **IPoDWDM**: QSFP56-DD provides, eventually, the same density as grey optics
- **400G DWDM (ZR/ZR+) Pluggable Technology**: expected to have a very low COGS squeeze a 400G Transponder into a 17/18W QSFP pluggable
- **Wavelength Utilization**: minimize optical distance, maximize throughput into the fibre and the utilization of the optical infra
  - **Multi-vendor**: no ROADM means no by-pass. Network can be segmented in P2P simple DWDM links, possibly multi-vendor if not based on white-boxes (i.e. OpenROADM, TIP initiatives);
  - **Simplified Design, Operation and Maintenance**: reduce complex analog DWDM mesh networks to simple P2P links



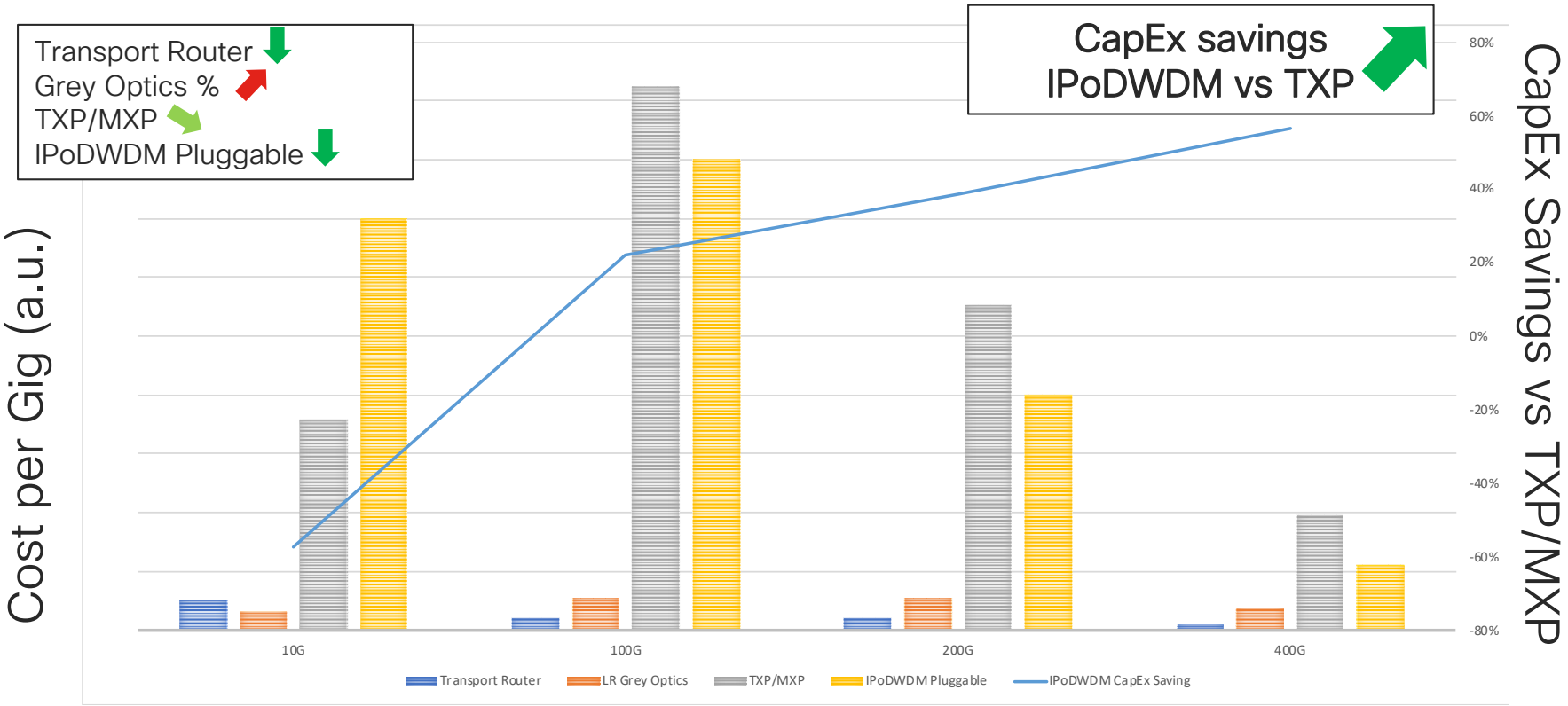
ROADM by-pass (Current trend): port cost stays the same - no benefit from cost reduction



Hop-by-Hop Architecture: Leverage the market shifts – increase bandwidth within reasonable distances

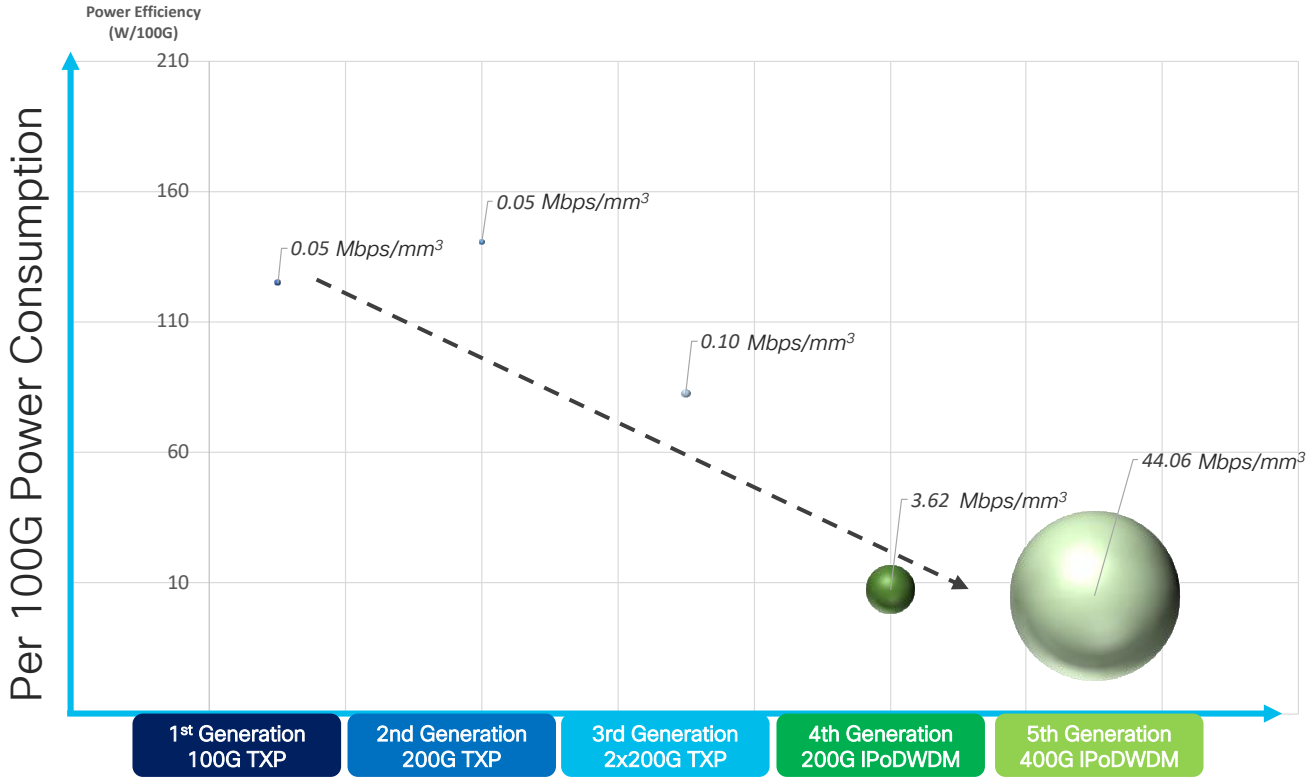
Evolution of pluggable optics technology

CapEx Evolution with IPoDWDM



Going Green with IPoDWDM

Power Efficiency (W/100G) vs. Transmission Efficiency (Mbps/mm3)



Bubble Chart Legend

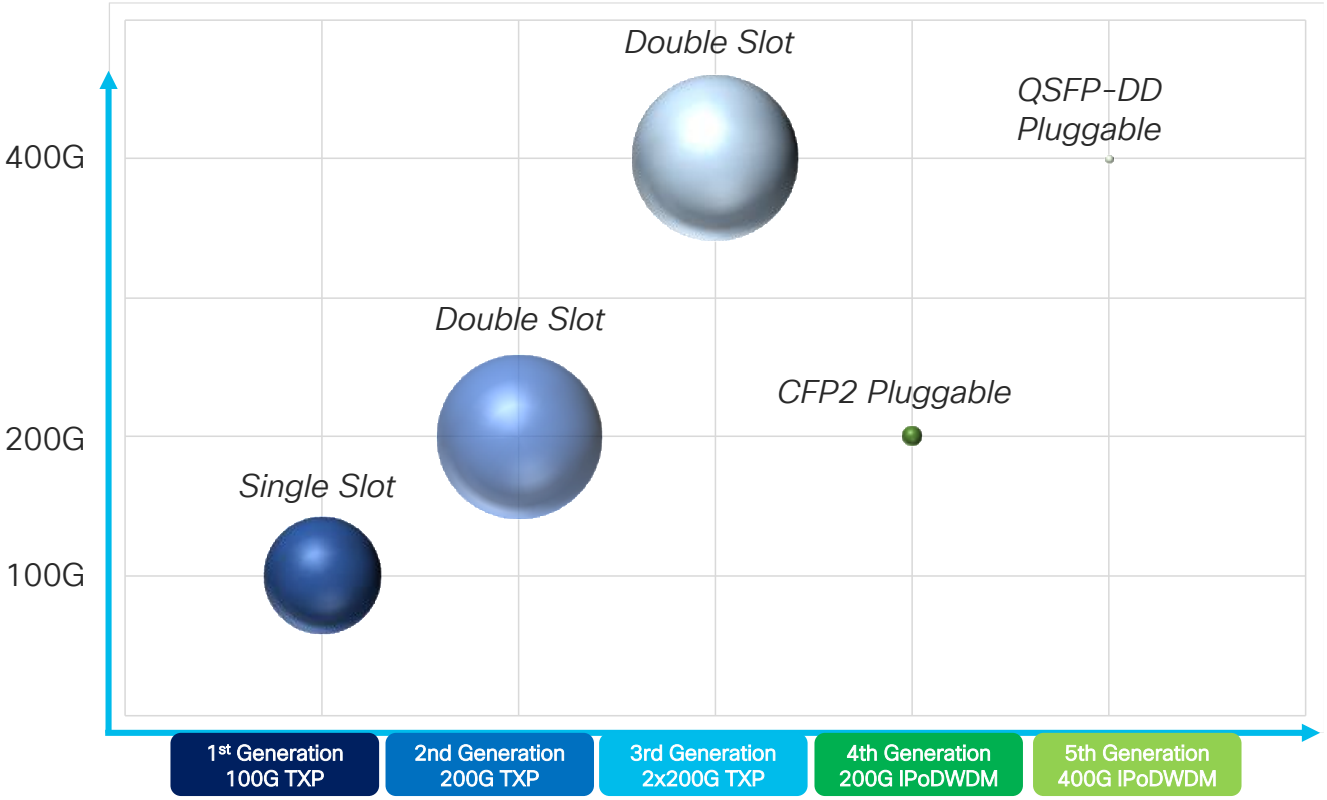
Less Mbps per mm3

Increasing Transmission Efficiency

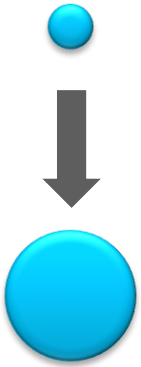
More Mbps per mm3

Going Green with IPoDWDM

Throughput vs. Volume (mm^3)



Bubble Chart Legend

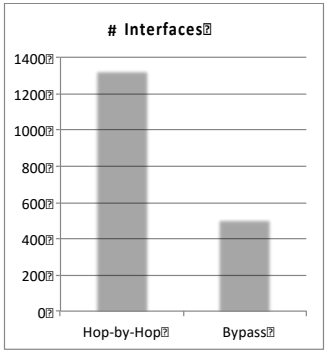


Increasing Volume

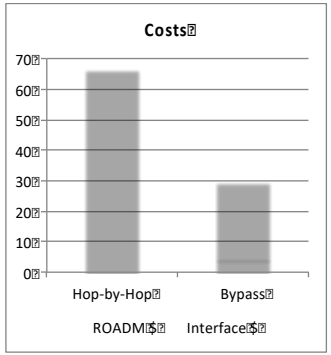
Architectural Evolution

From ROADM to Hop-by-Hop Networks

Today

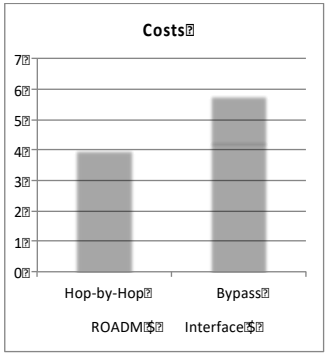


Hop-by-hop will always consume **more interfaces** and router capacity



Today: Interfaces dominated network cost

Tomorrow



Future: low-cost commoditized interfaces and NPUs scale challenge the need for ROADMs

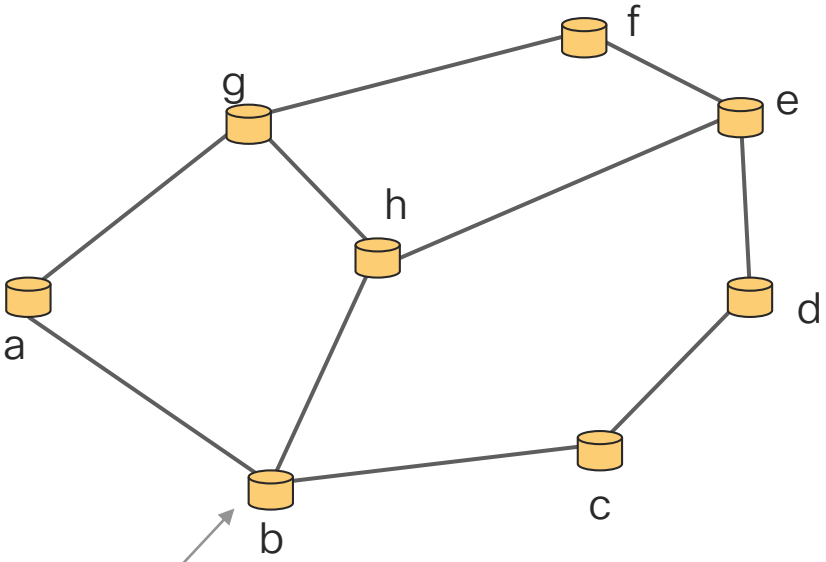
Hop-by-Hop architectures in core networks

Section Goals

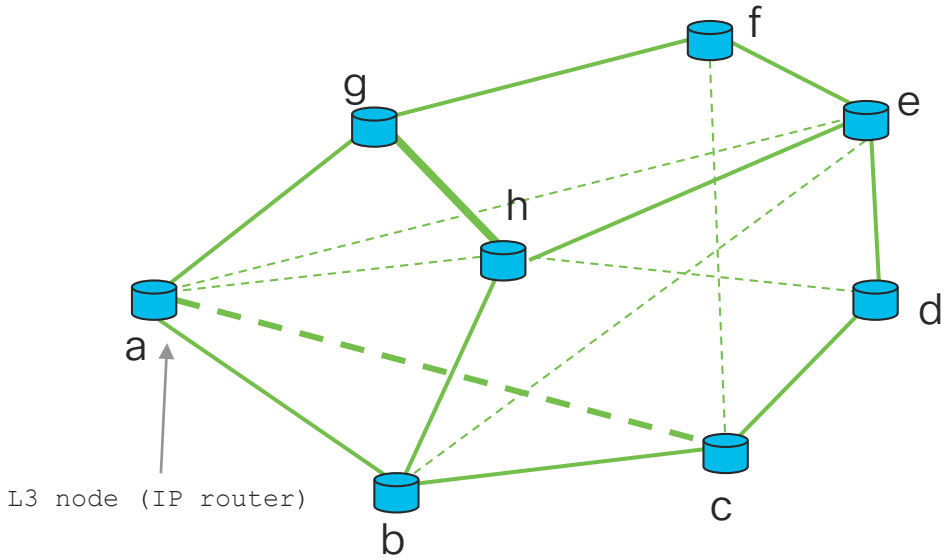
- The goal of this section is to compare classic IP+Optical architectures to new, alternative architectures in core networks
- Baseline architecture (PMO):
  - Grey interfaces on IP routers
  - Transponders/Muxponders with grey client interfaces
  - ROADM based optical infrastructure
- Converged SDN Transport – IPoDWDM (FMO # 1):
  - DWDM pluggable interfaces on routers (no transponder/Muxponders required)
  - ROADM based optical infrastructure
- Converged SDN Transport – IPoDWDM (FMO # 2):
  - DWDM pluggable interfaces on routers (no transponder/Muxponders required)
  - Simple P2P DWDM infrastructure (FMO # 2a)
  - Simple P2P DWDM infrastructure with limited bypass (FMO # 2b)

Router bypass with ROADMs

L0 (fibre) Topology

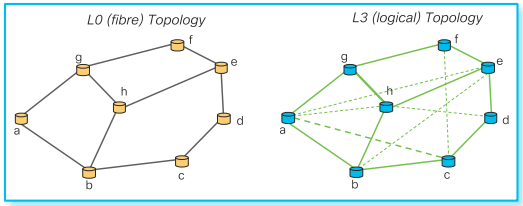


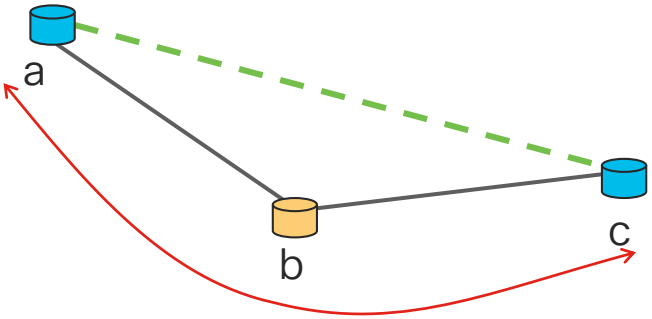
L3 (logical) Topology



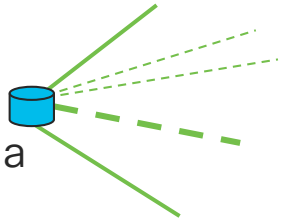
L3 demand requires router bypass @ intermediate locations

Router bypass with ROADMs
Additional Details





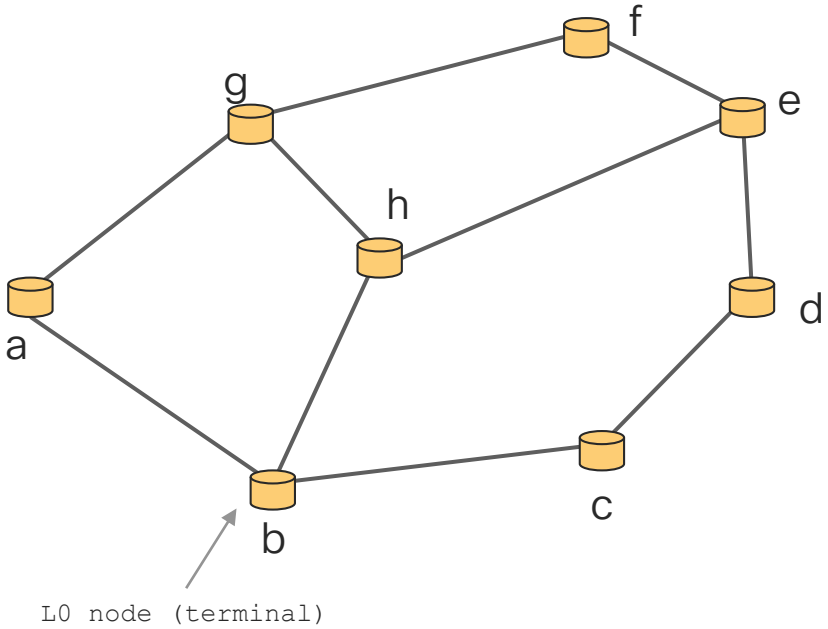
ROADM used to route waves
E2E Connection routed on physical fibre
Require optical bypass (ROADM) at intermediate nodes



Sub-optimal wavelength utilization
Traffic is split onto dedicated E2E waves (based on destination)

Hop-by-Hop no ROADMs

L0 (fibre) Topology



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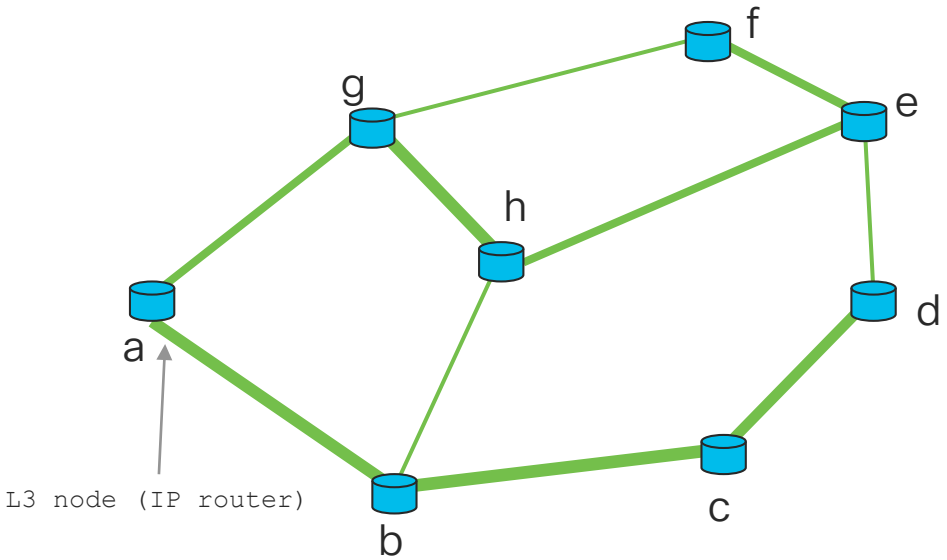
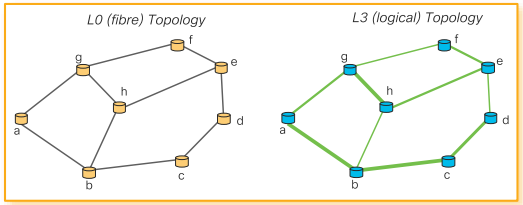
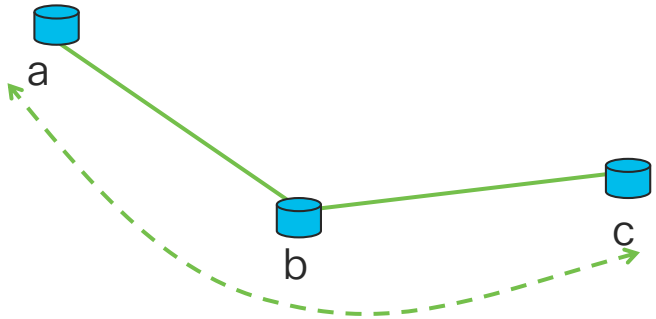


L3 topology is the same as L0 topology

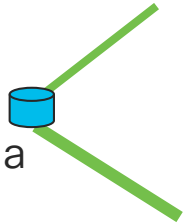
Increasing Transmission Bitrate

Hop-by-Hop no ROADMs
Additional Details





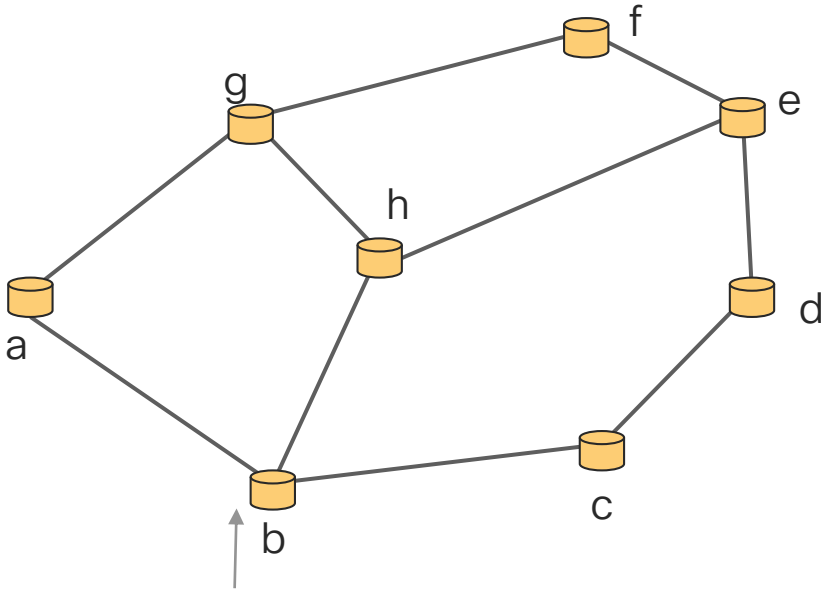
L3 Routers used to route demands
Traffic is sent to the next router and digitally bypassed



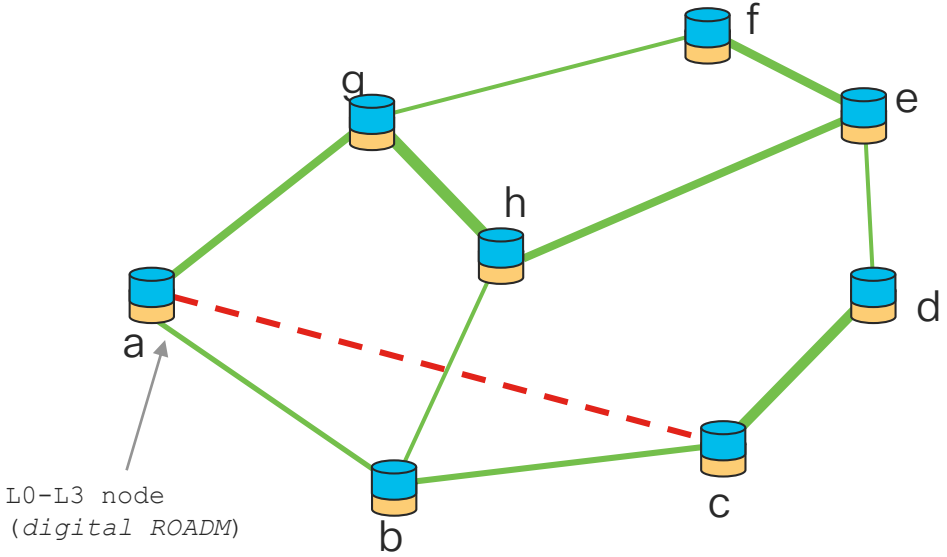
Optimal wavelength utilization
Traffic is groomed on fewer interfaces increasing wavelength utilization

Hop-by-Hop with *tactical* by-pass

L0 (fibre) Topology



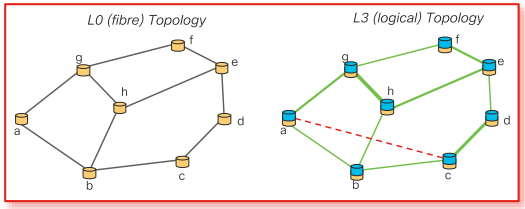
L3 (logical) Topology

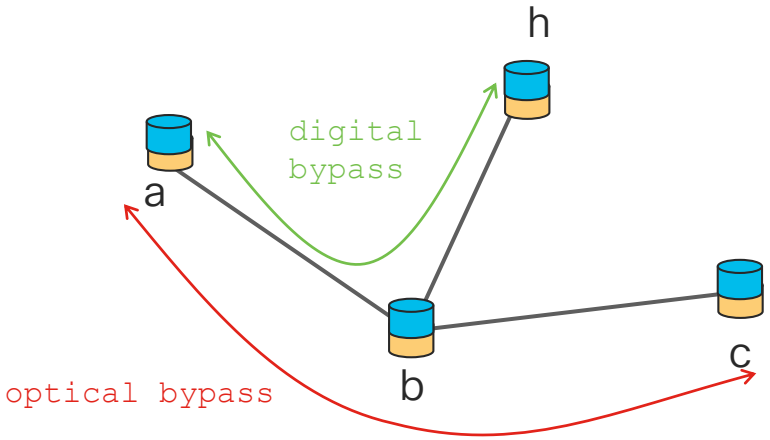


Increasing Transmission Bitrate

Similar to pure Hop-by-Hop
Provide some L0 by-pass capability

Hop-by-Hop with *tactical* by-pass
Additional Details





Multi-Degree Digital ROADM (*e.g. Node b*)

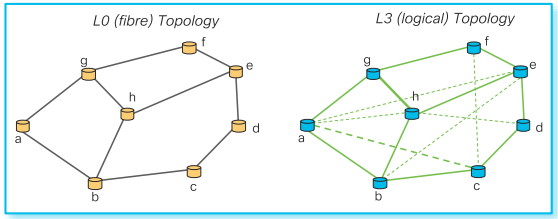
Simplified hop-by-hop L0 still provides some partial bypass capability:

- a⇔c L3 demand: can be **optical bypassed** in b (L0 forward)
- a⇔h L3 demand: it is **digitally bypassed** in b (L3 forward)

L0 Node sides tactically coupled based on traffic matrix and flows growth

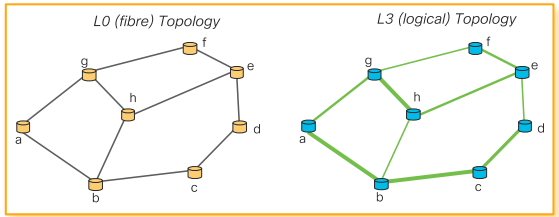
Two Ways To Implement Networks:
Router bypass vs. Hop-by-Hop

Router bypass with ROADMs



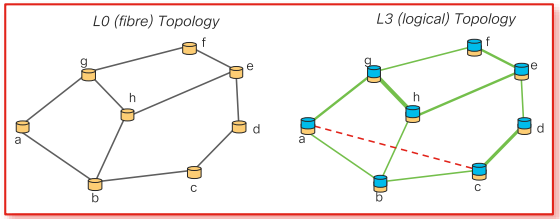
- Waves to distant switches, offloading intermediate switches
- ROADM used to route waves
- Up to 60% less interfaces
- Long Optical Paths – Lower bit-rate

Hop-by-Hop no ROADMs



- Waves only between adjacent switches
- Switches forward traffic to destination
- Interface-intensive
- Fabric-intensive
- Short Optical Paths – Higher bit-rate

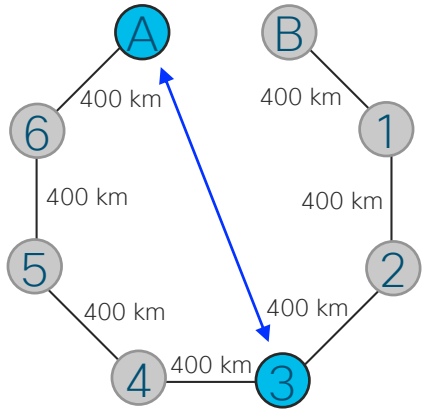
HbH with *tactical* bypass



- Waves MOSTLY between adjacent switches
- Hybrid photonic & digital forwarding
- Interface-intensive
- Fabric-intensive
- Short Optical Paths – Higher bit-rate

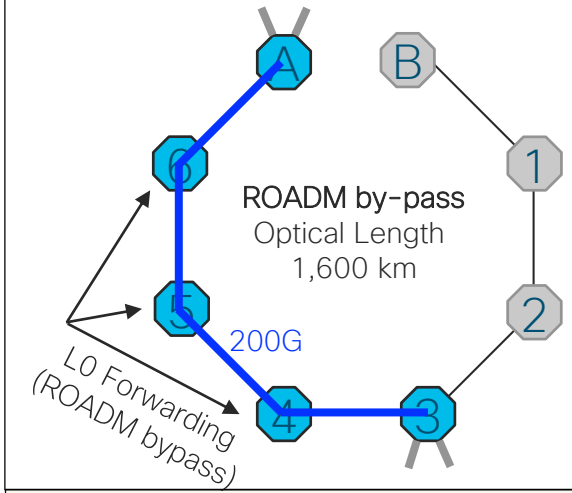
Optical Length and Wavelength Utilization

Example Network



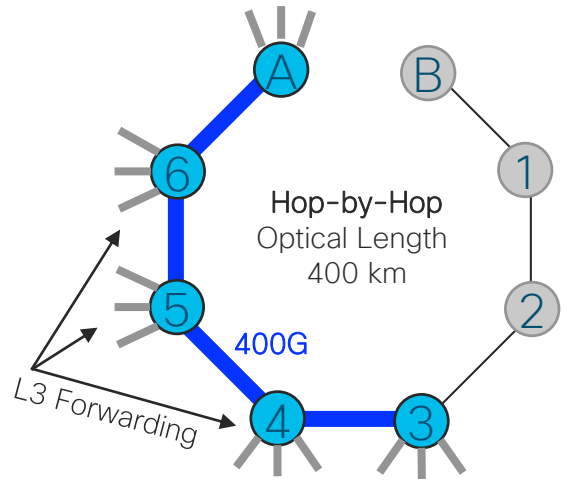
- 400 km optical length between hops
- Example Link/Connectivity between Hop A and 3
- 1600km total optical length

L0 - ROADM bypass



- ROADM bypass requires longer optical links *(expensive custom DSPs)*
- Longer links supports lower bit-rates
  - reduced fibre utilization (i.e. 200G)
- P2P Connectivity
- No traffic offloading/aggregation in transit hops

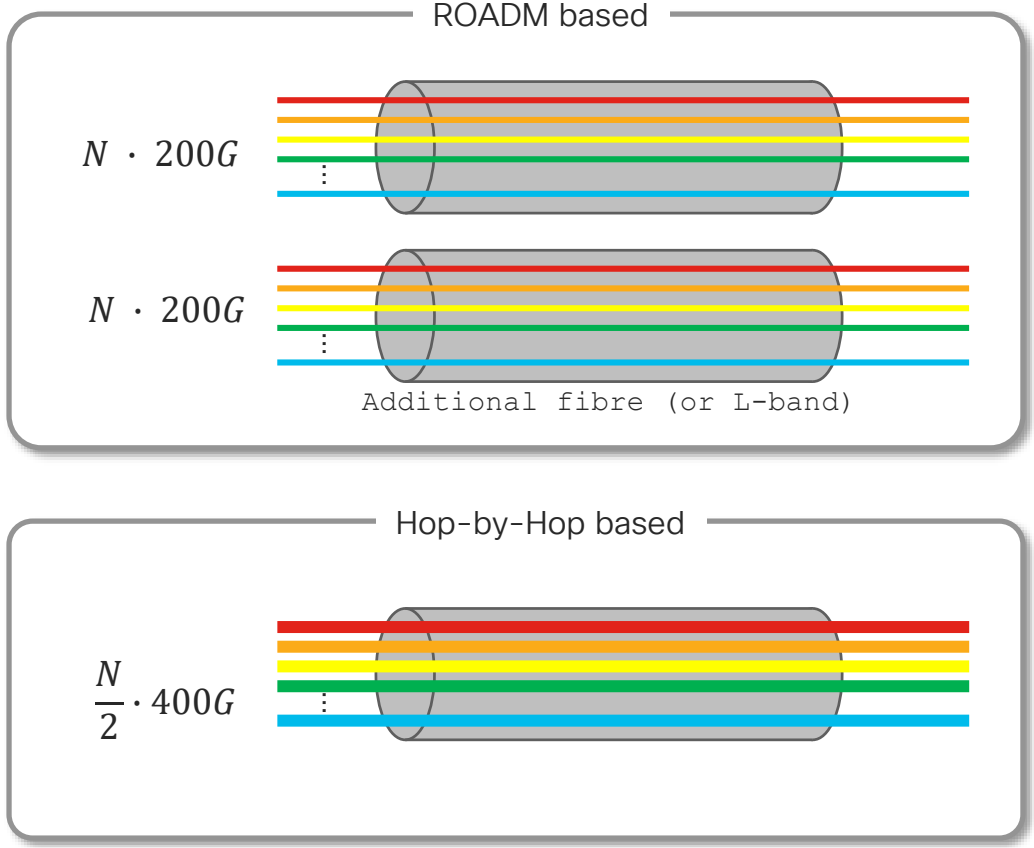
L3 - Hop-by-Hop



- Hop-by-Hop uses short optical links, but more L3 I/Fs *(economically cost efficient)*
- Shorter links support higher bit-rates
  - optimized fibre utilization (i.e. 400G)
- Any-2-Any connectivity
- Traffic offloading/aggregation capabilities in transit Hops

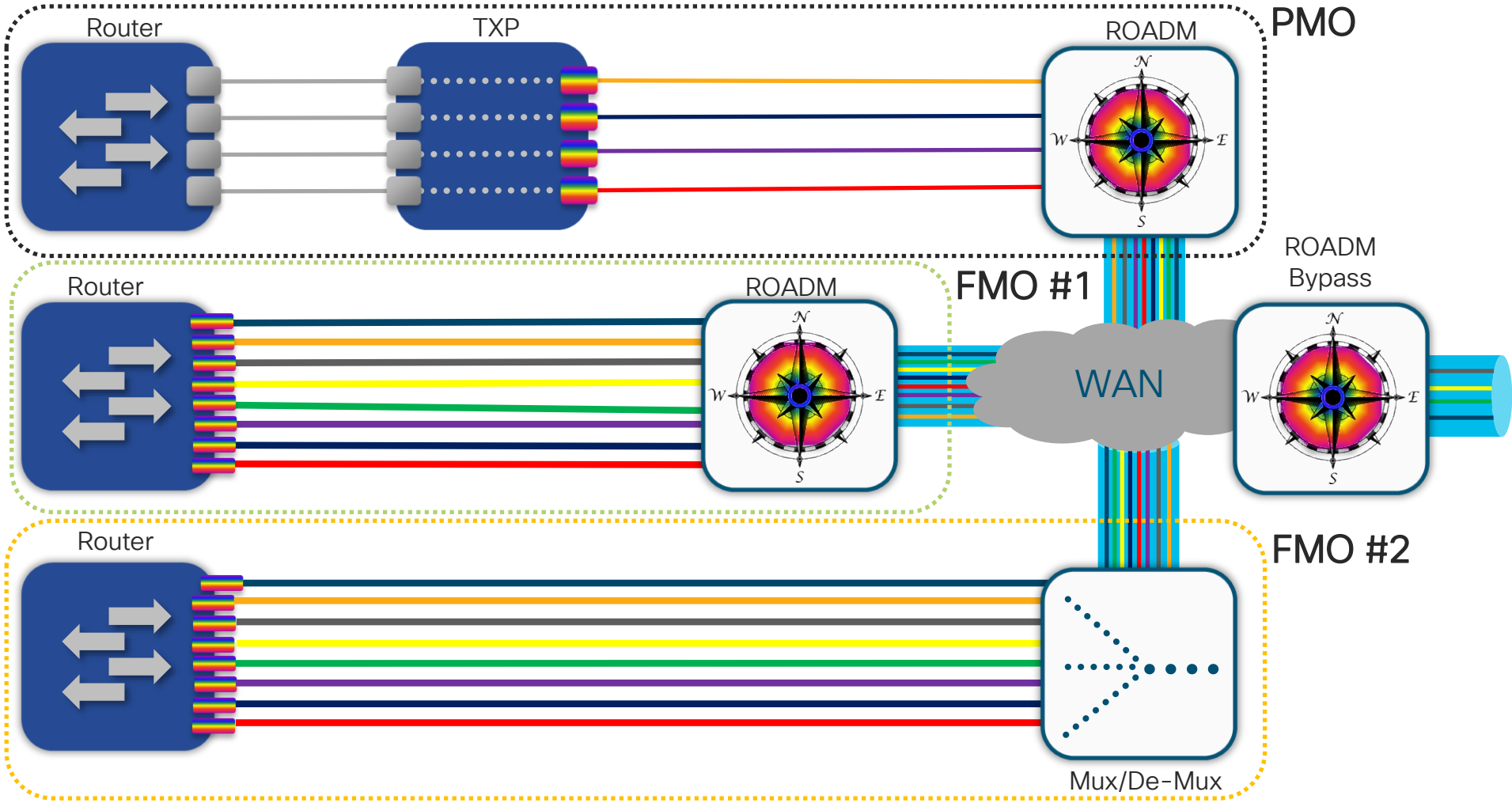
Maximizing Fibre Capacity

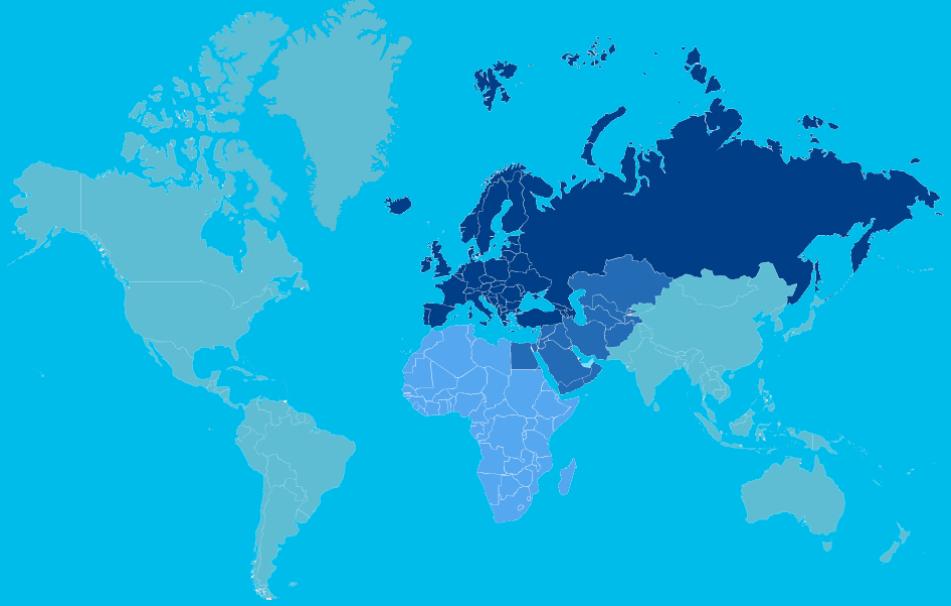
- Hop-by-Hop allows maximizing optical infrastructure utilization (fibre and amplifiers)
- Long E2E links require scaling bit-rate down to match the OSNR at the receiver
- Hop-by-Hop guarantees shorter E2E links and potentially higher bit-rates
- This push out in time the need for deploying a second fibre (or an L-band system on the same fibre)



Modelling Exercise

- 3 scenarios are compared
- Scenarios compared in terms of price (CapEx)



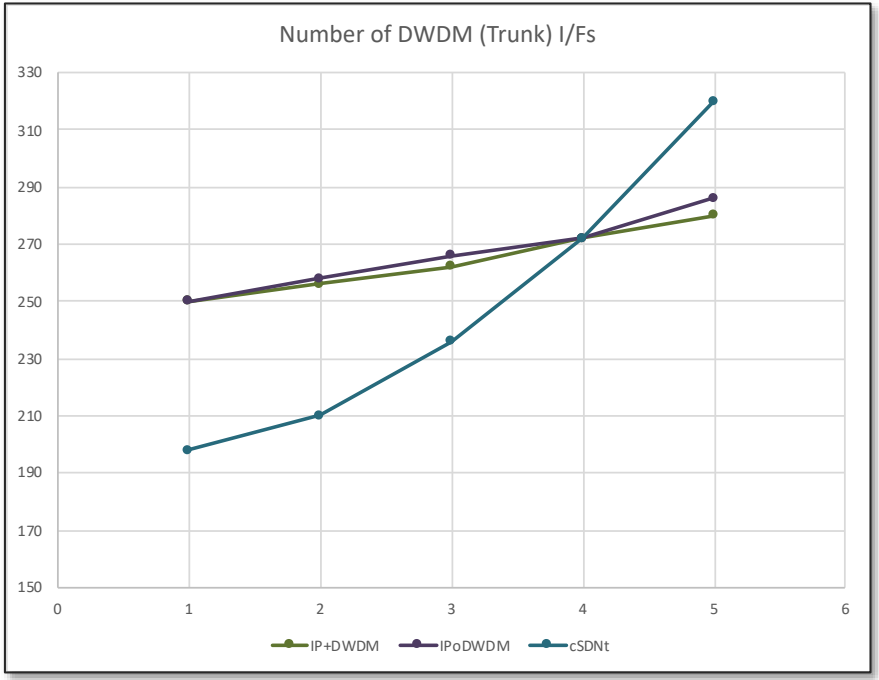


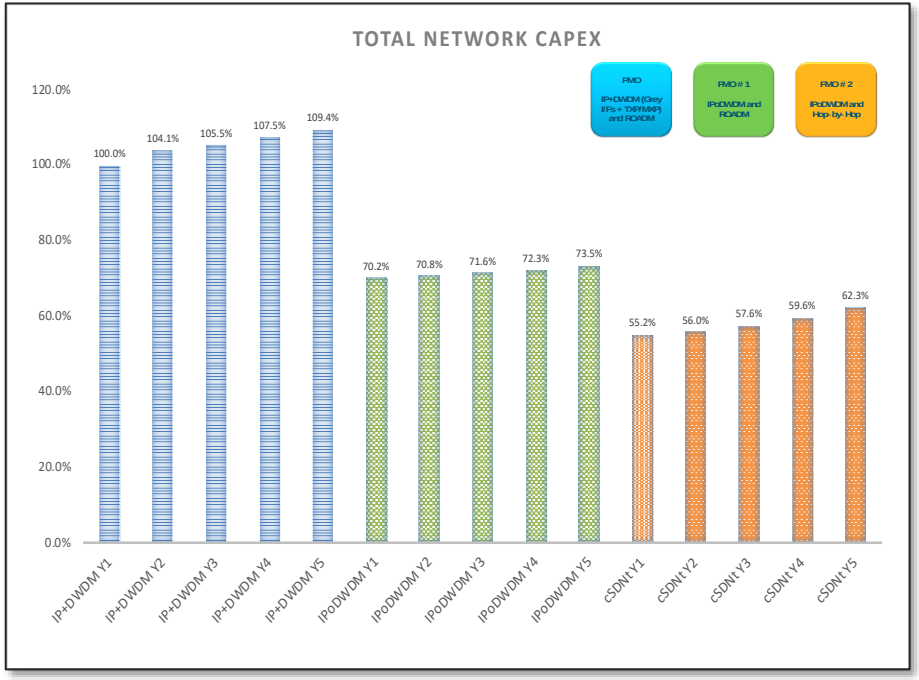
TCO Analysis – EMEAR

Network CapEx

TCO Results – Case # 1

- *Hop-by-Hop*, as expected, utilizes more interfaces as traffic grows
- *IPoDWDM & IPoEoF* total network CapEx are lower thanks to:
  - Removal of transponders and transport shelves
  - QSFP56-DD pricing
  - Simplified DWDM infrastructure (IPoEoF)

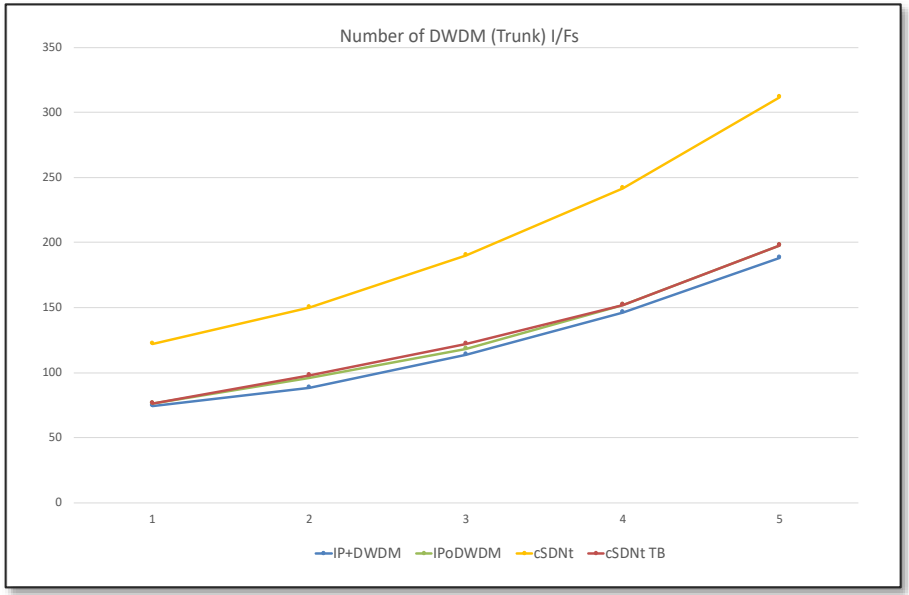


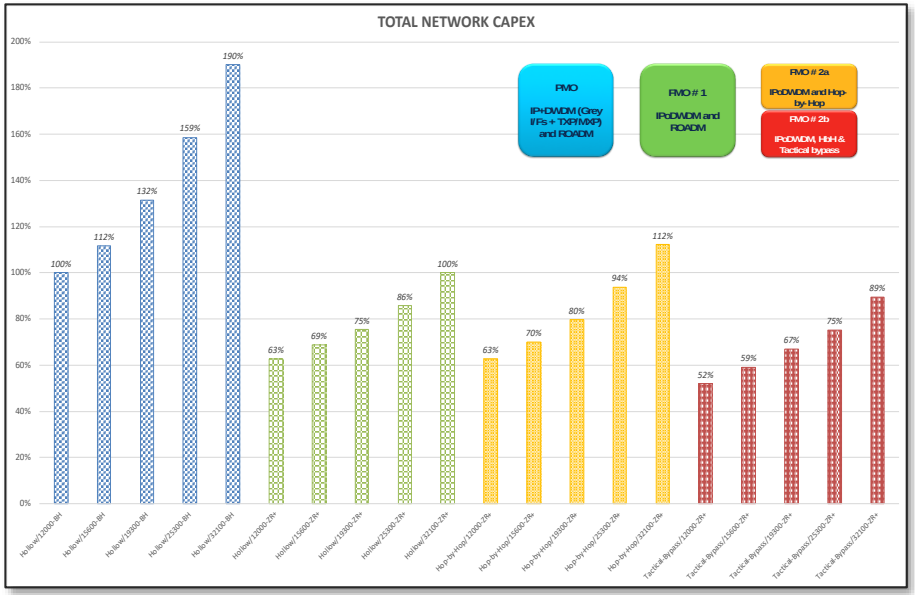


Network CapEx

TCO Results – Case # 2

- *Hop-by-Hop*, as expected, utilizes more interfaces as traffic grows
- *IPoDWDM & IPoEoF* total network CapEx are lower thanks to:
  - Removal of transponders and transport shelves
  - QSFP56-DD pricing
  - Simplified DWDM infrastructure (IPoEoF)



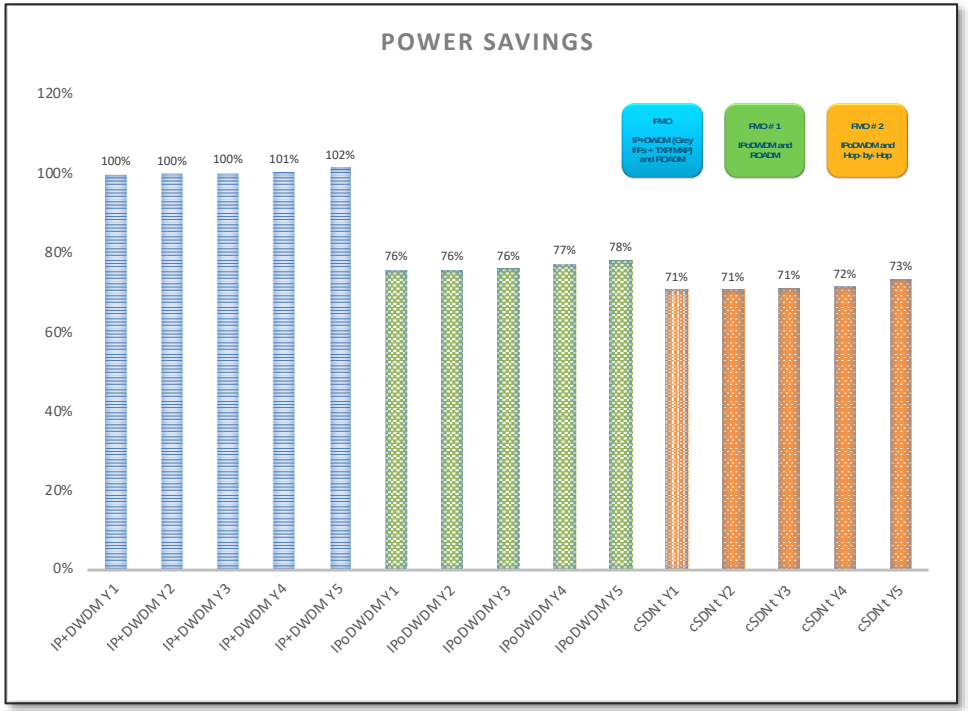


OpEx: Network Total Power Consumption

- Classic *IP+DWDM* is the most power hungry
- *IPoDWDM & Converged SDN Transport* total network Power Consumption is lower thanks to:
  - Removal of transponders and transport shelves
  - QSFP56-DD Low Power Consumption (5W/100G)

Additional OpEx saving opportunities:

- *Services (OpEx) Savings:* IPoDWDM and IPoEoF architectures reduces the number of parts in the network, simplifying procurement and sparing
- Operational Savings (provisioning of new services, etc.)



Additional OpEx Savings: MTBF

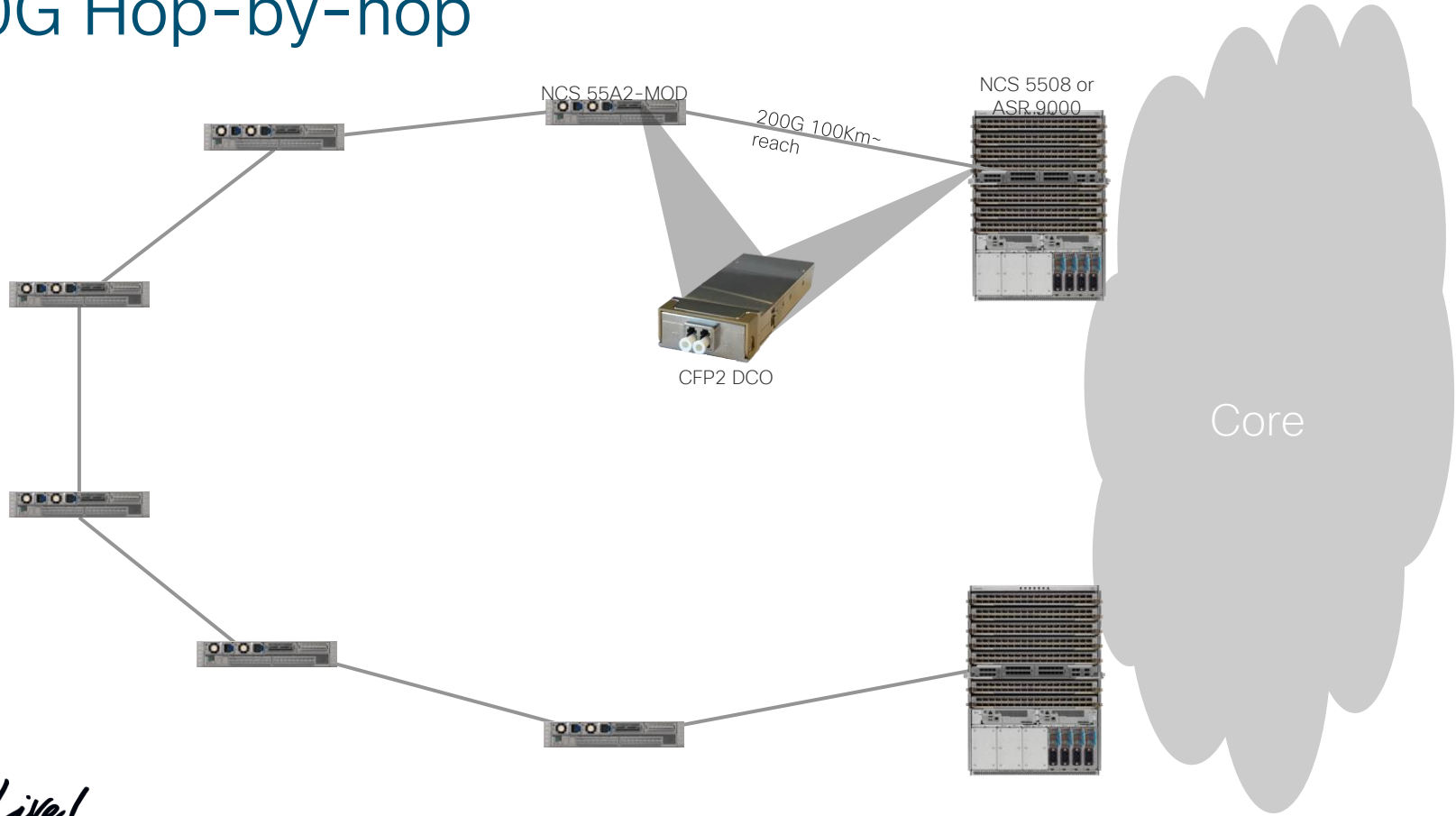
- We can use MTBF, AFR (Annual Fail Rate) and calculate the average number of units failing every year
- We can then value ($) the yearly investment to replace the failed units (spare parts)
- BOM simplifications, provided by IPoDWDM and Converged SDN Transport, give the possibility to reduce the amount OpEx related to spare part management
- Example:
  - Transponder parts completely removed
  - Universal LC on routers simplify and standardize nodes composition

Hop-by-Hop Architectures in aggregation networks

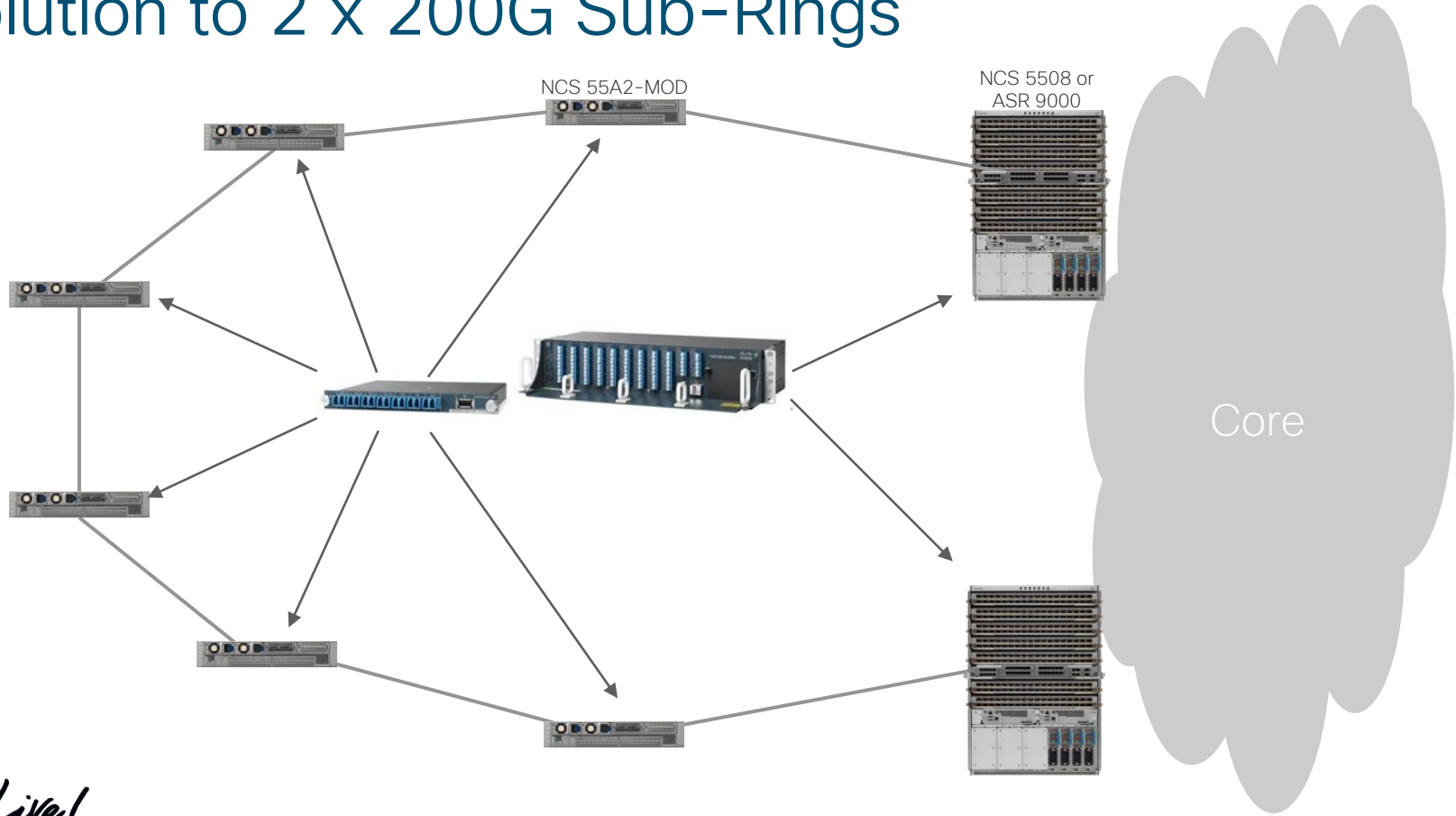
Section Goals

- The goal of this section is to compare classic IP+Optical architecture to new, alternative architectures in **aggregation** networks
- We will compare a Hub & Spoke architecture (with wavelengths dedicated to each aggregation node) to a hop-by-hop architecture
- We can build a parametric model so to identify the area of CapEx savings in terms of:
- Node Count (i.e. number of nodes in the network)
- Average traffic per node
- This can be done for 100/200G wavelengths (available today) and 400G wavelengths

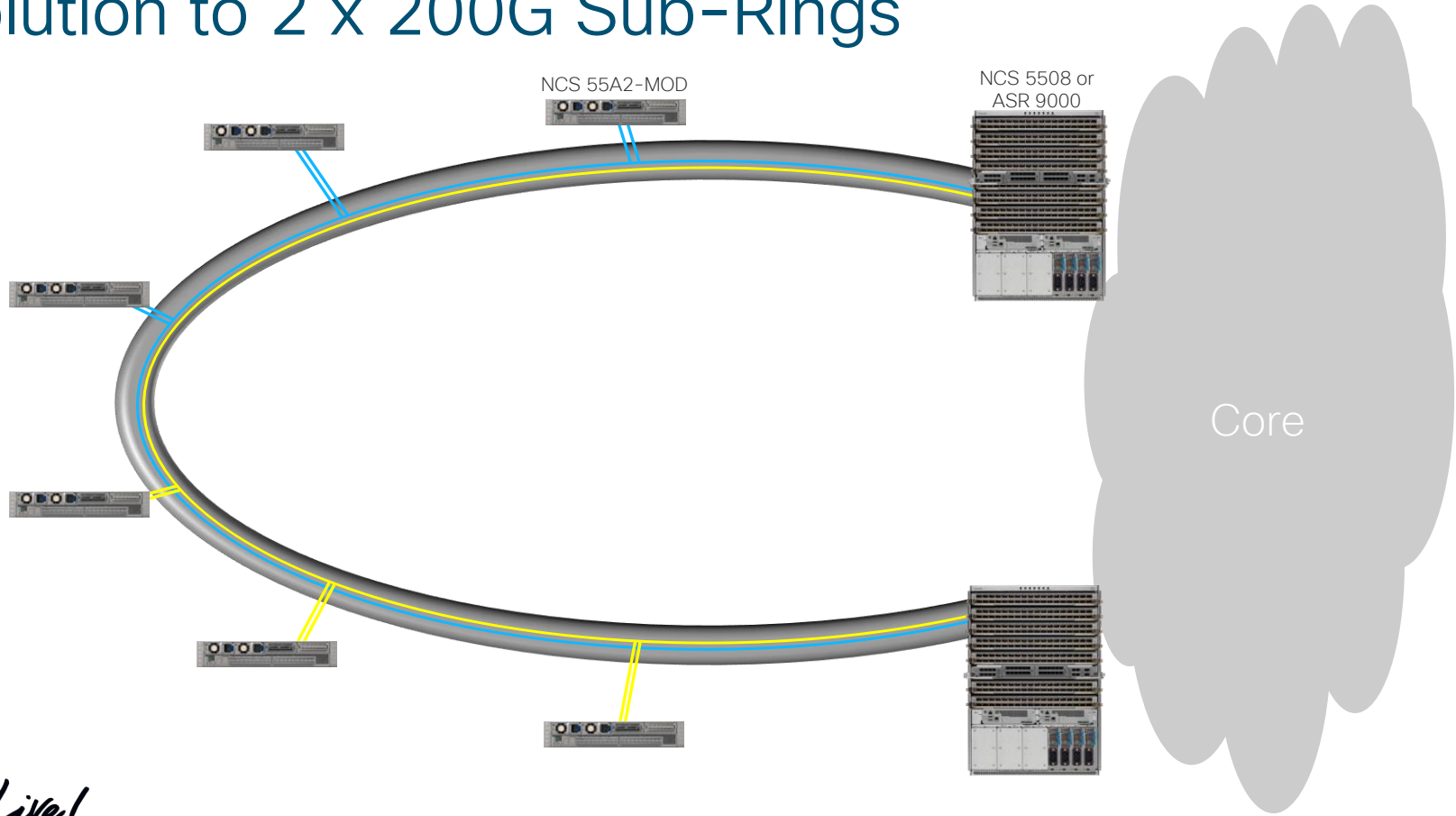
5G-ready IPoDWDM Unified Aggregation 200G Hop-by-hop



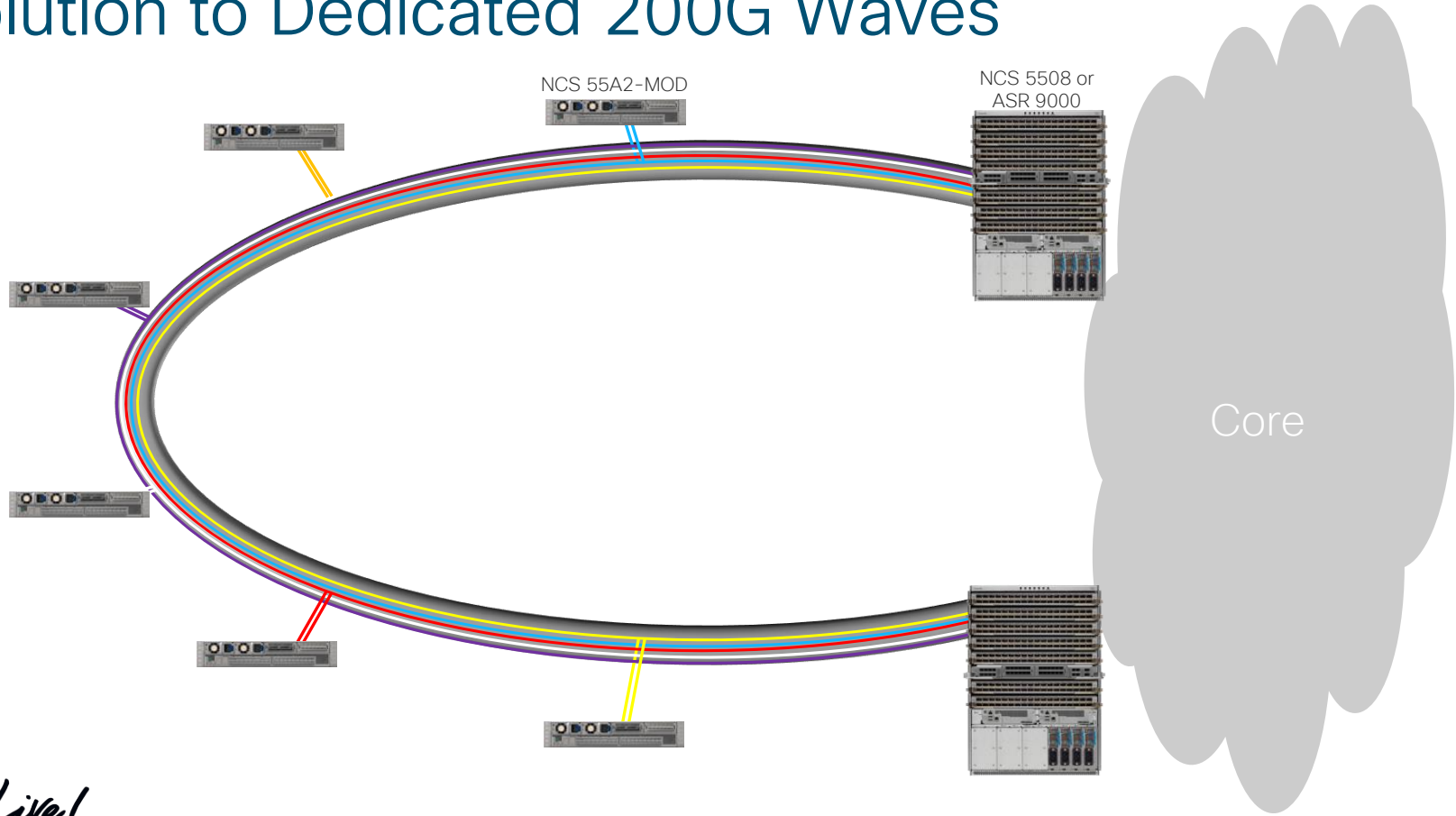
5G-ready IPoDWDM Unified Aggregation Evolution to 2 x 200G Sub-Rings



5G-ready IPoDWDM Unified Aggregation Evolution to 2 x 200G Sub-Rings

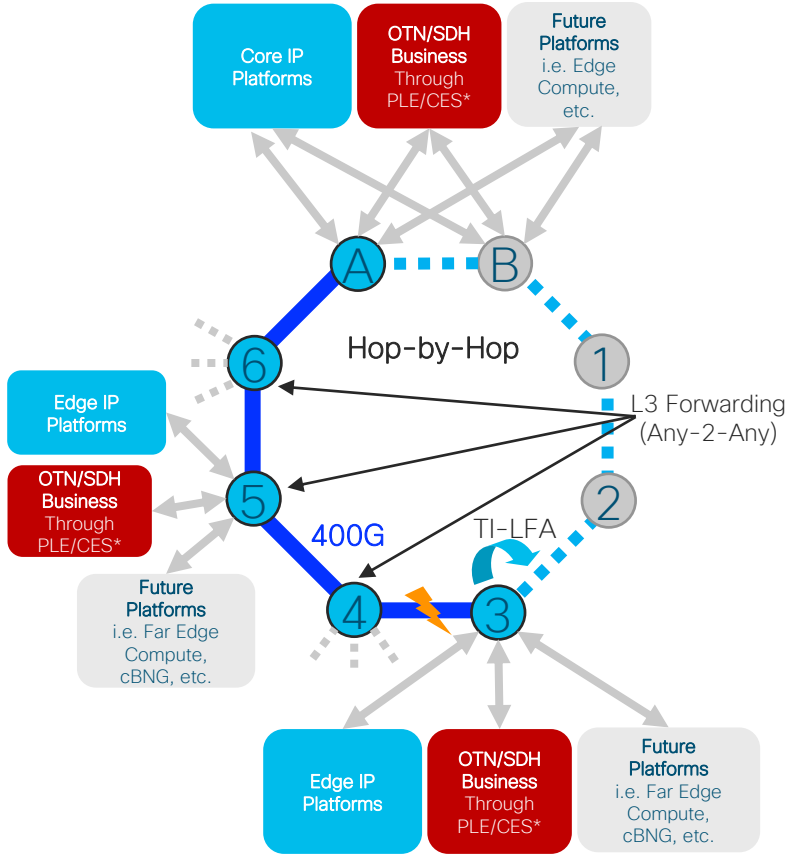


5G-ready IPoDWDM Unified Aggregation Evolution to Dedicated 200G Waves



Hop-by-Hop Architecture - further benefits

- Hop-by-Hop architecture enables ***Any-2-Any*** connectivity per design between Core Sites A/B and all the other nodes
- This allows for
  - ***Aggregating*** traffic from ***any*** site onto the optical link and/or ***offloading*** traffic directly into ***any*** other site
  - Any-to-Any or ***P2P connectivity*** with ***Private Line / Circuit Emulation*** for OTN/SDH business service (dedicated or integrated)
  - ***Easy & flexible integration and placement*** of new Platforms, like Far Edge compute, cloud native BNG, etc.
  - ***Optimizing*** Optical Link / Fiber usage
  - ***Built-in Fast-Convergence***/Protection mechanisms (IP-FRR/TI-LFA)
- Layer Consolidation
  - Simplified optical layer -> mainly MUX/DMX + Amplifiers
  - SR as Single control plane vs. IP/MPLS + GMPLS + WSON/SSON
- Network Slicing through Segment Routing
  - Low Latency path, Disjoint Path, Highest BW path, etc.



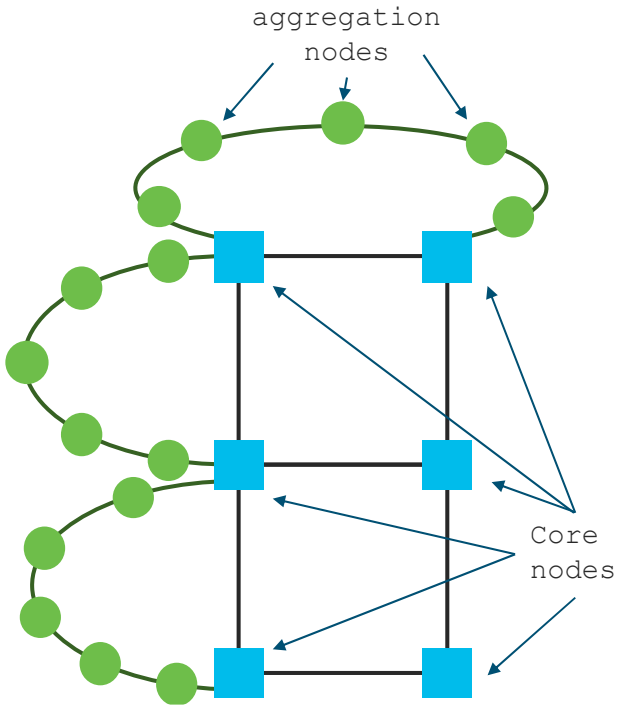
* Intra & inter horseshoe

Aggregation Network Example

- Aggregate the Aggregation nodes into the IP Core
- External Transponders and grey I/F on Routers or Integrated pluggable I/Fs

Network Parameters

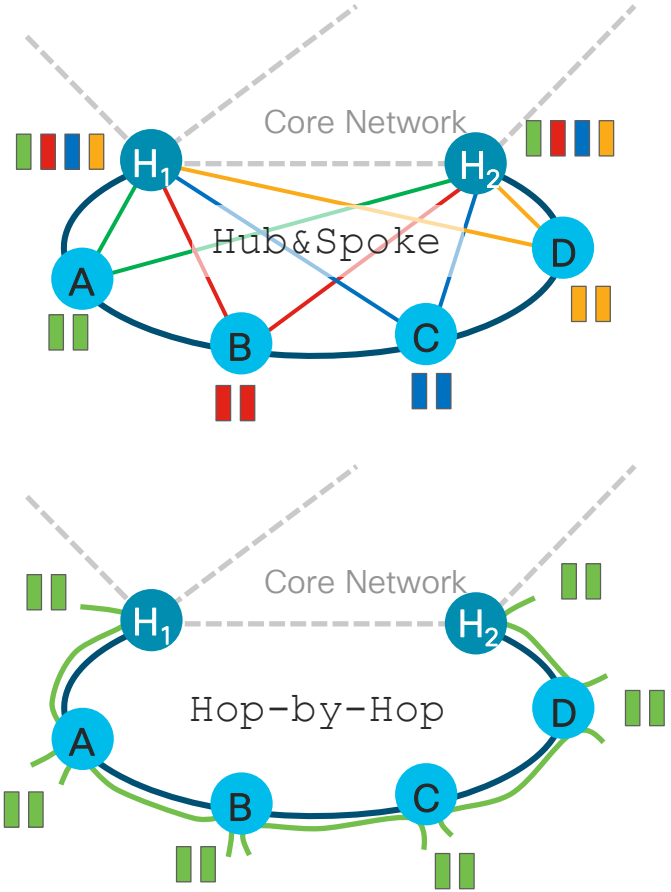
- Average # of nodes per aggregation ring: 3 – 5
- Number of aggregation rings: hundreds
- Average hop distance



Hop-by-Hop vs. (R)OADM bypass

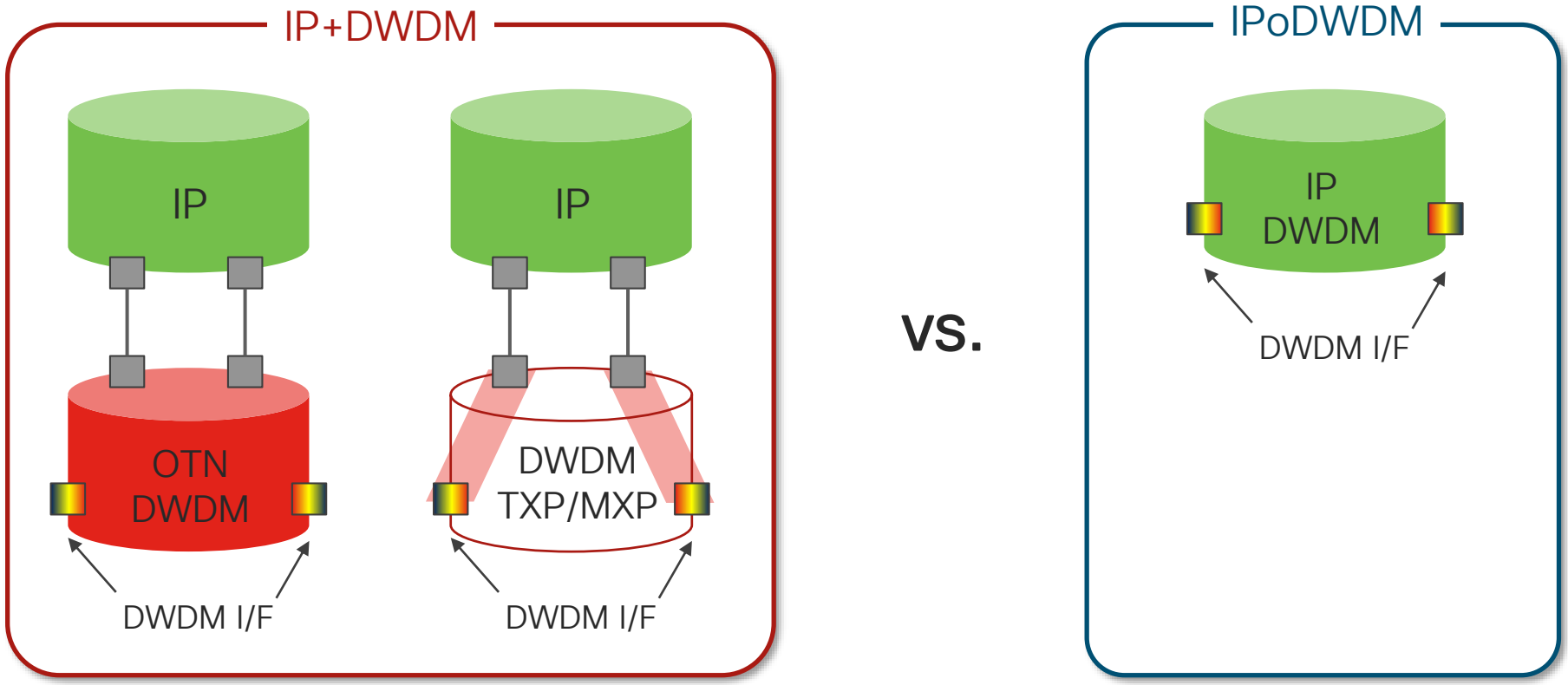
GOAL

- Compare a ROADM bypass model (e.g. Hub&Spoke) aggregation strategy vs. a Hop-by-Hop strategy
- Run the comparison using 2 different traffic type: *full-mesh* and *dual-homing*
- Compare network cost changing:
  - Number of nodes in the network
  - Node (Traffic) Capacity



IP+DWDM vs. IPoDWDM

Architecture Details



Hop-by-Hop vs. OADM by-pass: I/Fs ONLY

Counting the number of interfaces

200G IPoDWDM Trunks

Trunk Capacity (Gbps)	200	IPoEoF vs Hub&Spoke (OADM by-pass) Relative Number of Interfaces									
		N - Total # of Nodes									
		3	4	5	6	7	8	9	10	11	12
C - Node Local Traffic (Gbps)	10	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
	20	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
	30	-2	-2	-2	-2	-2	-2	14	16	18	20
	40	-2	-2	-2	-2	-2	12	14	16	18	20
	50	-2	-2	-2	-2	10	12	14	16	38	42
	60	-2	-2	-2	8	10	12	30	34	38	42
	70	-2	-2	6	8	10	26	30	34	58	64
	80	-2	-2	6	8	10	26	30	52	58	64
	90	-2	-2	6	8	22	26	46	52	78	86
	100	-2	-2	6	8	22	26	46	52	78	86
	120	-2	4	6	18	22	40	62	70	98	108
	140	-2	4	14	18	34	54	62	88	118	130
	160	-2	4	14	28	34	54	78	106	138	152
	180	-2	4	14	28	46	68	94	124	158	174
	200	-2	4	14	28	46	68	94	124	158	196
	220	-4	2	12	26	44	66	92	122	156	194
	240	-4	2	12	26	44	80	108	140	176	216
	260	-4	2	12	36	56	80	124	158	196	238
	280	-4	2	20	36	56	94	124	176	216	260
	300	-4	2	20	36	68	94	140	176	236	282
	320	-4	8	20	46	68	108	156	194	256	304
	340	-4	8	28	46	80	122	156	212	276	326
	360	-4	8	28	56	80	122	172	230	296	348
	380	-4	8	28	56	92	136	188	248	316	370
	400	-4	8	28	56	92	136	188	248	316	392
	450	-6	6	26	54	102	148	202	264	354	434
	500	-6	6	34	64	114	162	234	300	394	478
	550	-6	12	42	74	126	190	266	336	434	544
	600	-6	12	42	84	138	204	282	372	474	588
	650	-8	10	40	82	148	216	296	388	512	630
	700	-8	10	48	92	160	230	328	424	552	674
	750	-8	16	56	102	172	258	360	460	592	740
	800	-8	16	56	112	184	272	376	496	632	784

400G IPoDWDM Trunks

Trunk Capacity (Gbps)	400	IPoEoF vs Hub&Spoke (OADM by-pass) Relative Number of Interfaces									
		N - Total # of Nodes									
		3	4	5	6	7	8	9	10	11	12
C - Node Local Traffic (Gbps)	10	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
	20	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
	30	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
	40	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
	50	-2	-2	-2	-2	-2	-2	-2	-2	18	20
	60	-2	-2	-2	-2	-2	-2	14	16	18	20
	70	-2	-2	-2	-2	-2	12	14	16	18	20
	80	-2	-2	-2	-2	-2	12	14	16	18	20
	90	-2	-2	-2	-2	10	12	14	16	38	42
	100	-2	-2	-2	-2	10	12	14	16	38	42
	120	-2	-2	-2	8	10	12	30	34	38	42
	140	-2	-2	6	8	10	26	30	34	58	64
	160	-2	-2	6	8	10	26	30	52	58	64
	180	-2	-2	6	8	22	26	46	52	78	86
	200	-2	-2	6	8	22	26	46	52	78	86
	220	-2	4	6	18	22	40	46	70	78	108
	240	-2	4	6	18	22	40	62	70	98	108
	260	-2	4	6	18	34	40	62	88	98	130
	280	-2	4	14	18	34	54	62	88	118	130
	300	-2	4	14	18	34	54	78	88	118	152
	320	-2	4	14	28	34	54	78	106	138	152
	340	-2	4	14	28	46	68	78	106	138	174
	360	-2	4	14	28	46	68	94	124	158	174
	380	-2	4	14	28	46	68	94	124	158	196
	400	-2	4	14	28	46	68	94	124	158	196
	450	-4	2	12	26	44	66	92	122	176	216
	500	-4	2	12	26	56	80	108	140	196	238
	550	-4	2	20	36	56	94	124	158	216	260
	600	-4	2	20	36	68	94	140	176	236	282
	650	-4	8	20	46	80	108	156	194	256	326
	700	-4	8	28	46	80	122	172	212	276	348
	750	-4	8	28	56	92	136	188	230	296	370
	800	-4	8	28	56	92	136	188	248	316	392

Sweet Spot: N=4 – 7, equivalent to 2 – 5 agg. nodes

Hop-by-Hop vs. OADM by-pass: I/Fs ONLY

Relative $$$

200G IPoDWDM Trunks

Trunk Capacity (Gbps)	200	IPoEoF vs Hub&Spoke (OADM by-pass) Relative Number of Interfaces									
		N - Total # of Nodes									
		3	4	5	6	7	8	9	10	11	12
C - Node Local Traffic (Gbps)	10	-23%	-35%	-53%	-65%	-95%	-107%	-125%	-137%	-167%	-179%
	20	-23%	-35%	-53%	-65%	-95%	-107%	-125%	-137%	-167%	-179%
	30	-23%	-35%	-53%	-65%	-95%	-107%	-73%	-78%	-102%	-107%
	40	-23%	-35%	-53%	-65%	-95%	-61%	-73%	-78%	-102%	-107%
	50	-23%	-35%	-53%	-65%	-56%	-61%	-73%	-78%	-36%	-35%
	60	-23%	-35%	-53%	-33%	-56%	-61%	-20%	-19%	-36%	-35%
	70	-23%	-35%	-27%	-33%	-56%	-16%	-20%	-19%	29%	37%
	80	-23%	-35%	-27%	-33%	-56%	-16%	-20%	40%	29%	37%
	90	-23%	-35%	-27%	-33%	-17%	-16%	32%	40%	95%	109%
	100	-23%	-35%	-27%	-33%	-17%	-16%	32%	40%	95%	109%
	120	-24%	-17%	-29%	-2%	-19%	27%	81%	94%	155%	176%
	140	-24%	-17%	-2%	-2%	20%	73%	81%	153%	221%	248%
	160	-24%	-17%	-2%	31%	20%	73%	133%	212%	286%	320%
	180	-24%	-17%	-2%	31%	59%	119%	185%	271%	352%	392%
	200	-24%	-17%	-2%	31%	59%	119%	185%	271%	352%	464%
	220	-11%	-4%	4%	38%	72%	132%	192%	278%	365%	477%
	240	-11%	-4%	4%	38%	72%	177%	245%	337%	430%	549%
	260	-11%	-4%	4%	70%	111%	177%	297%	396%	496%	621%
	280	-11%	-4%	30%	70%	111%	223%	297%	455%	561%	693%
	300	-11%	-4%	30%	70%	151%	223%	349%	455%	626%	765%
	320	-12%	15%	29%	101%	148%	266%	398%	509%	687%	831%
	340	-12%	15%	55%	101%	187%	312%	398%	568%	753%	903%
	360	-12%	15%	55%	134%	187%	312%	450%	627%	818%	975%
	380	-12%	15%	55%	134%	227%	358%	503%	686%	884%	1047%
	400	-12%	15%	55%	134%	227%	358%	503%	686%	884%	1119%
	450	-11%	3%	38%	117%	243%	369%	514%	704%	968%	1205%
	500	-11%	3%	64%	149%	282%	414%	619%	822%	1099%	1349%
	550	-12%	22%	89%	180%	319%	503%	720%	936%	1225%	1560%
	600	-12%	22%	89%	213%	358%	549%	773%	1054%	1356%	1704%
	650	1%	35%	107%	220%	410%	607%	844%	1120%	1500%	1861%
	700	1%	35%	134%	252%	449%	653%	949%	1237%	1631%	2005%
	750	0%	53%	158%	283%	486%	742%	1050%	1351%	1757%	2215%
	800	0%	53%	158%	316%	525%	788%	1102%	1469%	1888%	2359%

400G IPoDWDM Trunks

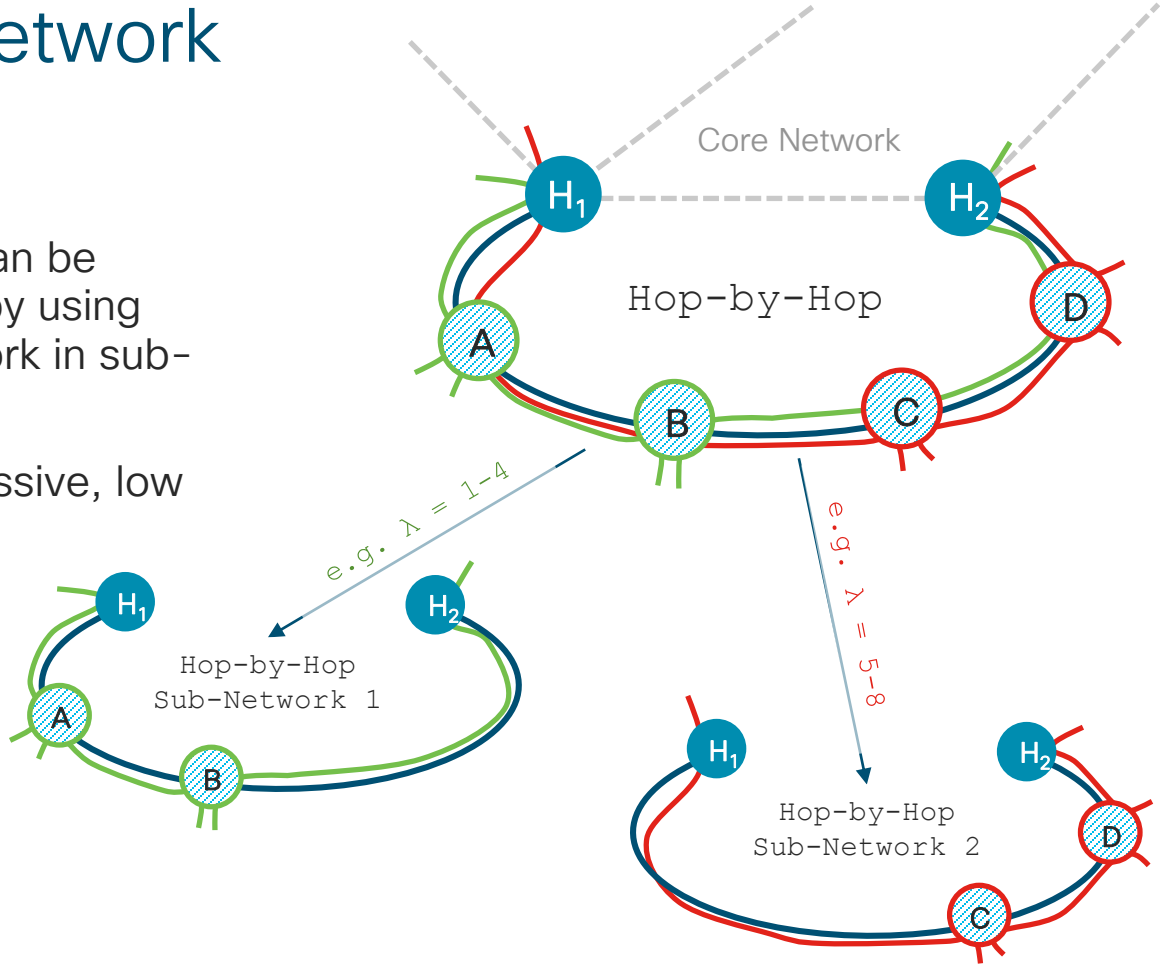
Trunk Capacity (Gbps)	400	IPoEoF vs Hub&Spoke (OADM by-pass) Relative Number of Interfaces									
		N - Total # of Nodes									
		3	4	5	6	7	8	9	10	11	12
C - Node Local Traffic (Gbps)	10	-24%	-37%	-55%	-68%	-98%	-111%	-129%	-141%	-172%	-184%
	20	-24%	-37%	-55%	-68%	-98%	-111%	-129%	-141%	-172%	-184%
	30	-24%	-37%	-55%	-68%	-98%	-111%	-80%	-87%	-111%	-118%
	40	-24%	-37%	-55%	-68%	-98%	-68%	-80%	-87%	-111%	-118%
	50	-24%	-37%	-55%	-68%	-62%	-68%	-80%	-87%	-50%	-51%
	60	-24%	-37%	-55%	-37%	-62%	-68%	-32%	-32%	-50%	-51%
	70	-24%	-37%	-31%	-37%	-62%	-26%	-32%	-32%	10%	16%
	80	-24%	-37%	-31%	-37%	-62%	-26%	-32%	22%	10%	16%
	90	-24%	-37%	-31%	-37%	-25%	-26%	17%	22%	71%	83%
	100	-24%	-37%	-31%	-37%	-25%	-26%	17%	22%	71%	83%
	120	-25%	-20%	-32%	-9%	-28%	14%	6%	73%	127%	144%
	140	-25%	-20%	-8%	-9%	9%	56%	62%	128%	188%	211%
	160	-25%	-20%	-8%	21%	9%	56%	110%	182%	248%	278%
	180	-25%	-20%	-8%	21%	45%	99%	159%	237%	309%	345%
	200	-25%	-20%	-8%	21%	45%	99%	159%	237%	309%	411%
	220	-13%	-8%	-3%	26%	55%	108%	162%	240%	317%	419%
	240	-13%	-8%	-3%	26%	55%	151%	210%	294%	378%	486%
	260	-13%	-8%	-3%	56%	91%	151%	259%	349%	439%	553%
	280	-13%	-8%	21%	56%	91%	193%	259%	403%	499%	620%
	300	-13%	-8%	21%	56%	128%	193%	308%	403%	560%	686%
	320	-14%	9%	19%	84%	125%	233%	353%	454%	616%	748%
	340	-14%	9%	44%	84%	162%	275%	353%	509%	677%	815%
	360	-14%	9%	44%	115%	162%	275%	401%	563%	738%	881%
	380	-14%	9%	44%	115%	198%	318%	450%	618%	798%	948%
	400	-14%	9%	44%	115%	198%	318%	450%	618%	798%	1015%
	450	-14%	-4%	25%	95%	209%	322%	454%	628%	869%	1085%
	500	-14%	-4%	49%	126%	245%	365%	551%	737%	990%	1218%
	550	-14%	13%	72%	154%	279%	447%	644%	842%	1107%	1414%
	600	-14%	13%	72%	184%	316%	489%	693%	951%	1228%	1547%
	650	-3%	25%	89%	189%	362%	541%	757%	1009%	1358%	1689%
	700	-3%	25%	113%	219%	398%	584%	854%	1118%	1479%	1822%
	750	-3%	42%	136%	247%	432%	665%	947%	1223%	1596%	2017%
	800	-3%	42%	136%	278%	469%	708%	996%	1332%	1717%	2151%

Sweet Spot: N=4 – 7, equivalent to 2 – 5 agg. nodes

Partitioning the Network

Using DWDM

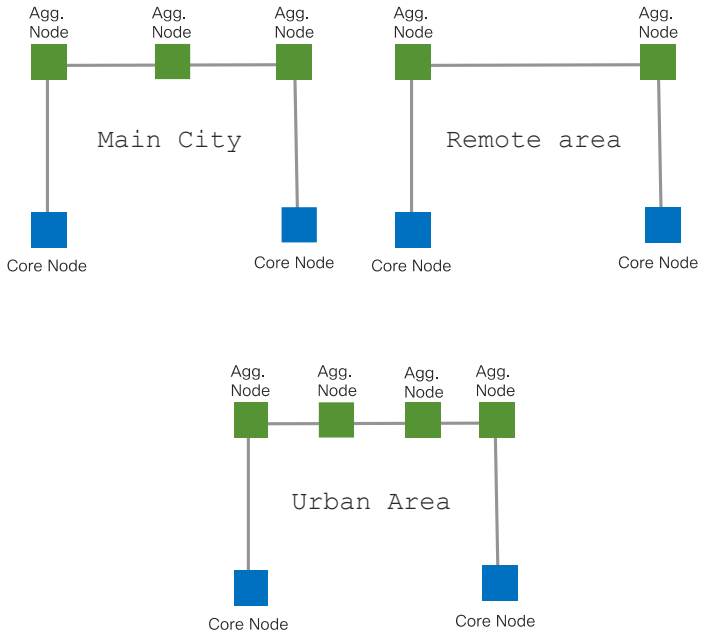
- High node count networks can be reduced to low node count by using DWDM to partition the network in sub-networks
- Easily implemented using passive, low loss optical filters



Optical Infrastructure (L0)

IPoEoF vs. OADM by-pass

	Hop-by-Hop		OADM Based		Hop-by-Hop Savings
Agg. Net. Type	Composition	Net (a.u.)	Composition	Net (a.u.)	
Main City	2x Passive Terminal 3x Passive OADMs	100.00	2x Terminal 1/2 Full + 1/2 Half OADM 2x Half OADM	722.49	86%
Medium Size City	2x Passive Terminal 4x Passive OADMs	111.55	2x Terminal 4x Half OADM	820.50	86%
Small City	2x Passive Terminal 2x Passive OADM	88.45	2x Terminal 2x Half OADM	553.76	84%
Urban Area	2x Passive Terminal 4x Passive OADMs	111.55	2x Terminal 1/2 Full + 1/2 Half OADM 3x Half OADM	855.86	87%
Rural Area	1x Terminal 1x Passive Terminal 1/2 Full + 1/2 Passive OADM 2x Passive OADM 1x OLA	427.64	2x Terminal 1/2 Full + 1/2 Half OADM 2x Half OADM 1x OLA	843.02	49%
Remote Area	2x Terminal 2x 1/2 Full + 2x 1/2 Passive OADM 4x OLA	984.79	2x Terminal 2x 1/2 Full + 2x 1/2 Half OADM 4x OLA	1106.61	11%

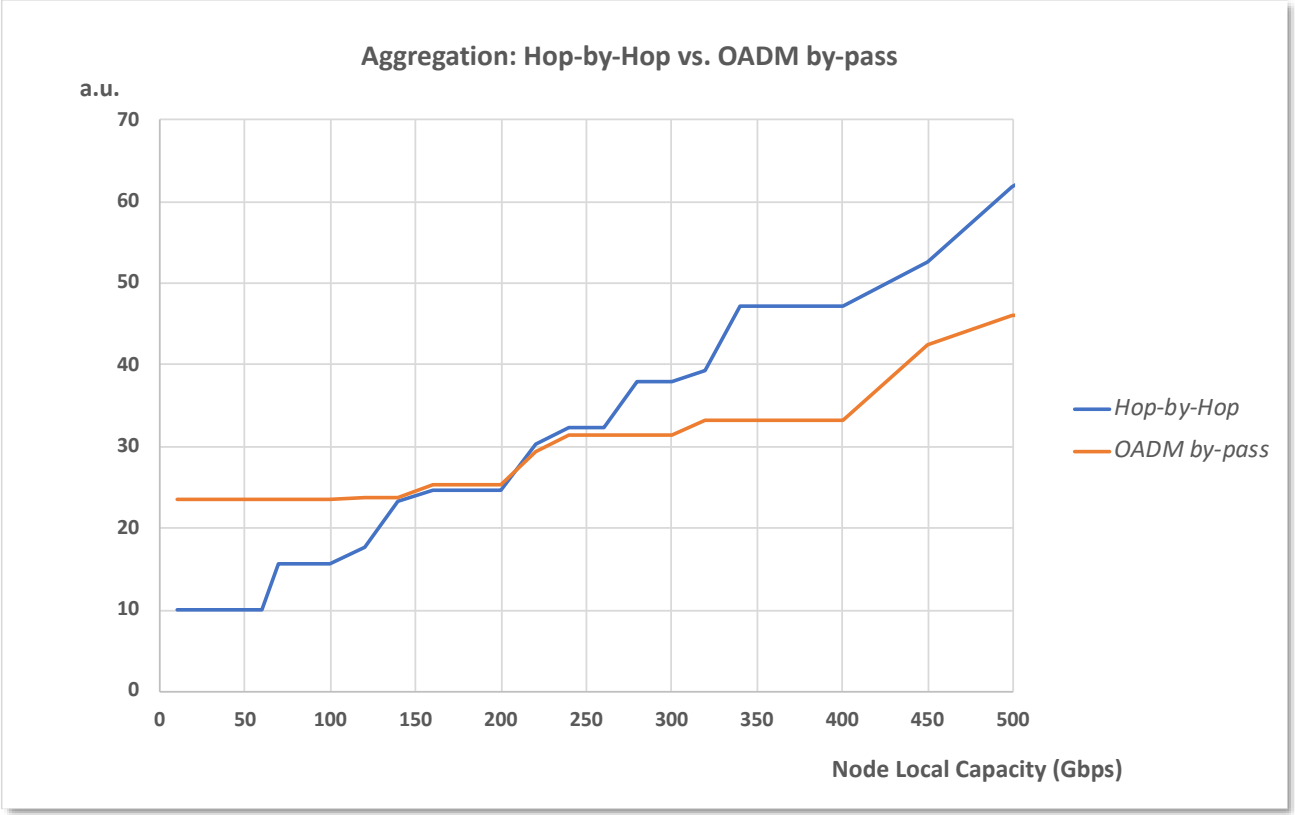


- Hop-by-Hop provide savings in optical infrastructure, requiring no Amplifiers in 4 networks out of 6 and reducend number of amplifiers in rural networks

Aggregation: Hop-by-Hop vs. OADM by-pass

CFP2-DCO 200G

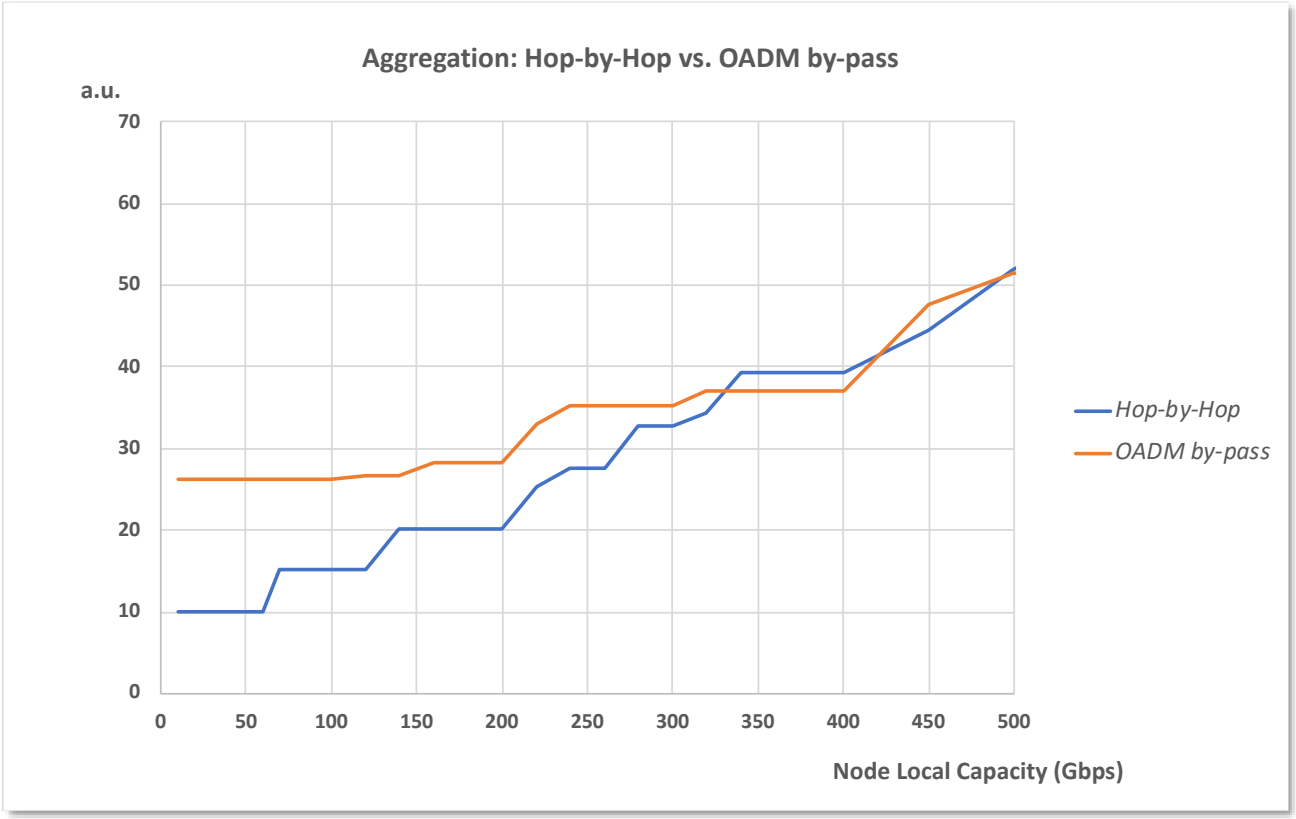
- Hop-by-Hop is cheaper up to 150Gbps – 200 Gbps node's local capacity
- This means a total ring capacity around 450 Gbps – 600 Gbps



Aggregation: Hop-by-Hop vs. OADM by-pass

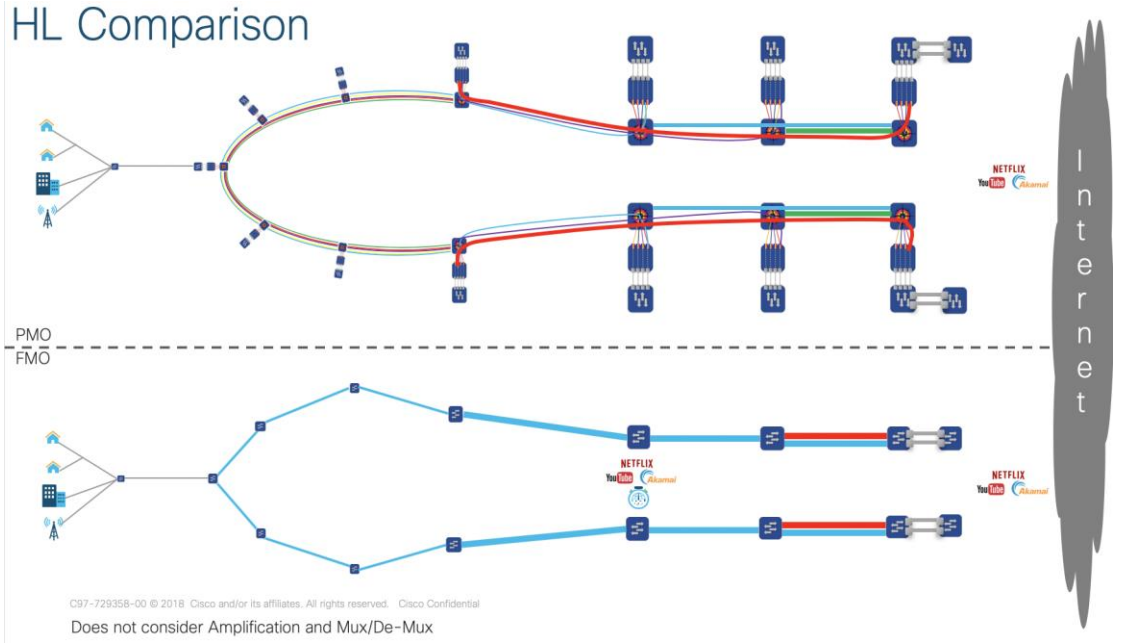
QSFP-DD 400G

- QSFP-DD (400G) can scale up node capacity beyond 300 Gbps
- This means a total ring capacity around 1 Tbps



Impact of Hop-by-Hop architectures on overall latency

- Low latency is increasingly a key performance indicator and differentiator for 5G services
- Additional Routed hops increase latency (typically between 4 and 10 µsec)
- Light-propagation latency in fibre is ~5 µs/km
- Hop-by-hop designs reduce the requirement for optical amplifiers
- Additional Routed hops can degrade phase accuracy
- Router hardware has an accurate class support (B or C), there is more than enough budget to increase the hops towards a Grand Master clock
- Clocking accuracy is highly sensitive to any asymmetries in networks
  - ROADM and Optical infrastructures often induces unpredictability and inconsistent symmetries



Summary

- When 100G+ Coherent required in (Pre-)Aggregation, today's IPoDWDM solution makes business and scale sense
- QSFPDD ZR+ has the *potential* to drive an architectural shift to p2p designs across Core networks
  - business case built on what is a challenging development
  - requiring significant market/standardization consensus
  - Applicability use-case dependent / requirement for additional modelling
- This has been a comparison of opposites, whilst a hybrid approach might best serve certain designs and traffic flows

Additional Benefits

- Reduce Network overall CapEx: benefits from price reduction driven by 400G ZR/ZR+ technology
- Opportunity to simplify the network
  - Flexible (orchestrated) L3, where all the services are provisioned
  - Simple & Static L0 (DWDM)
- Truly multivendor
  - ZR/ZR+ standardized – easy to interop
  - L0 segmentation into P2P systems: easy to have them from different vendors
- Simplified DWDM design, installation, operation, maintenance and upgrade; this can translate into an OpEx reduction opportunity

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