Flexible Architectures for Next-Generation Optical Networks

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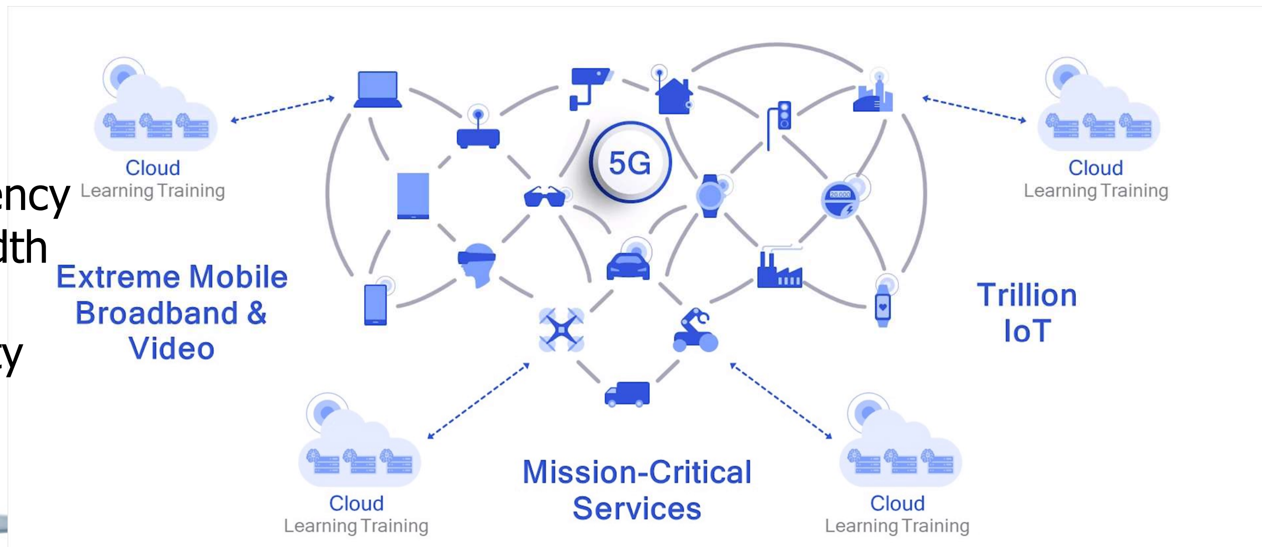
Outline

- Introduction
- Contribution I: High-precision time synchronization techniques for optical datacenter networks and a zero-overhead microsecond-accuracy solution
- Contribution II: Dynamic routing, spectrum, and modulation format assignment in co-existing fixed/flex-grid optical networks
- Contribution II: Cost-efficient C+L Bands Upgrade Strategies to Sustain Long-term Traffic Growth.
- Conclusion and future research ideas

Flexible Network Architectures

A flexible network solution enables customization of network operations according to the changing network demand

- ✓ Ultra low-latency
- ✓ High bandwidth availability
- ✓ Ultra reliability



Source: https://www.techspot.com/article/1582-state-of-5g-wireless/

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- Contribution II: Dynamic routing, spectrum, and modulation format assignment in co-existing fixed/flex-grid optical networks
- Conclusion and future research ideas

Agenda

✓Introduction to the problem

✓Proposed solution

- *PTP time synchronization in an optical datacenter network with zero-overhead transmission and microsecond-accuracy*

✓Results

✓Summary and future work

Time Synchronization

Coordinating independent clocks running on different machines with a standard time

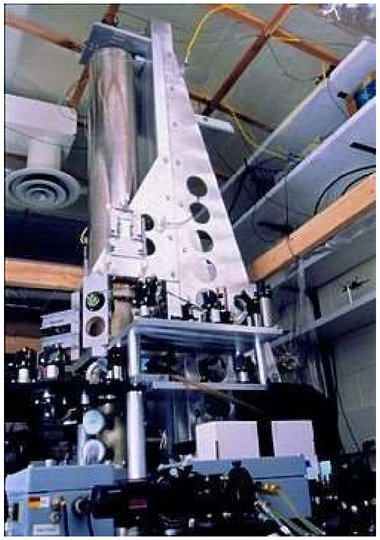
Atomic Clocks

- Use resonance frequencies of atoms

Global Navigation Satellite Systems:

- Periodically synchronize to atomic clocks

Oscillator Type	Accuracy	Cost
Quartz crystal	10^{-5} to 10^{-4}	Inexpensive
Rubidium	10^{-9}	\$800 USD
Cesium	10^{-13} to 10^{-12}	\$50000 USD



Atomic Clock, Boulder, CO, USA

Source: https://en.wikipedia.org/wiki/NIST-F1

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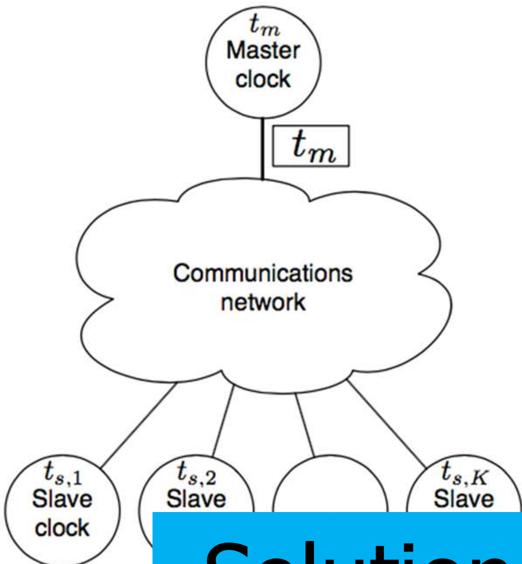
M. L´evesque and D. Tipper, " A Survey of Clock Synchronization Over Packet-Switched Networks," *IEEE Communications Surveys & Tutorials,* vol. 18, no. 4, pp. 2926-2947, Nov. 2016.

Time Synchronization: Distributed Systems

Multiple clocks in a distributed system needs to maintain same global time!



$$t_{s,k} = t_m + \theta$$

$t_{s,k}$: time at slave clock k

t_m: time at master node

θ: offset due to environmental effect

$$t_{s,k} = t_m + \theta + d$$

d: average delay between master and slave nodes

Solution is to find this offset and delay

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Time Synchronization Protocols: NTP

Network Time Protocol

(NTP)

- Hierarchical master-slave topology
- Millisecond-accuracy
- Slave clocks redistribute time information
- Update Interval (10 min)

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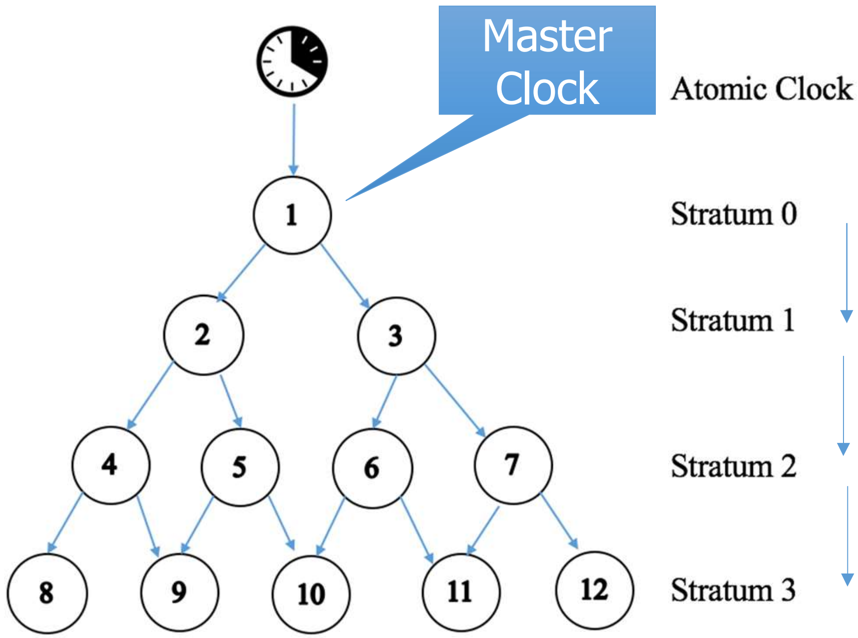
Time Synchronization Protocols: NTP



Stratum denotes distance from the master clock

Delay, d_1

Delay, $d_2 = d_1 + d_2$

Delay, $d_3 = d_1 + d_2 + d_3$

- Queueing delay
- Processing delay
- Routing path
- Cable length

NTP master clock

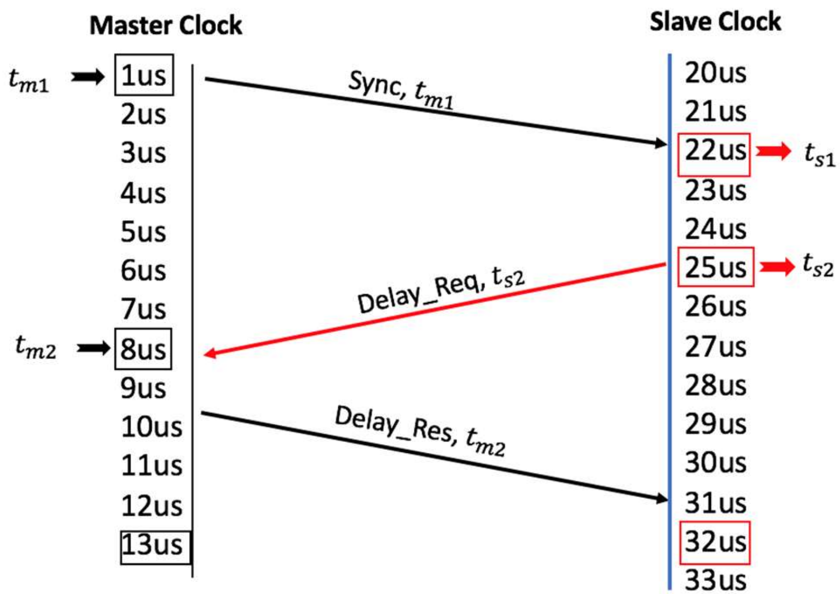
Source: https://www.worldtimesolutions.com/products/ntp_server.html

Time Synchronization Protocols: PTP

Precision Time Protocol

- Hierarchical master-slave topology
- Microsecond/nanosecond-accuracy
- Slave clocks **does not** redistribute time information
- Update interval (1 sec)

Time Synchronization Protocols: PTP



$$Avg\ path\ delay = \frac{(t_{s1} - t_{m1}) + (t_{m2} - t_{s2})}{2}$$
$$= \frac{(22-1)+(8-25)}{2} = 2\ us$$

$$Time\ offset = t_{s1} - t_{m1} - Avg\ path\ delay$$
$$= 22 - 1 - 2 = 19\ us$$

$$Slave\ clock\ time = 32\ - 19 = 13\ us$$

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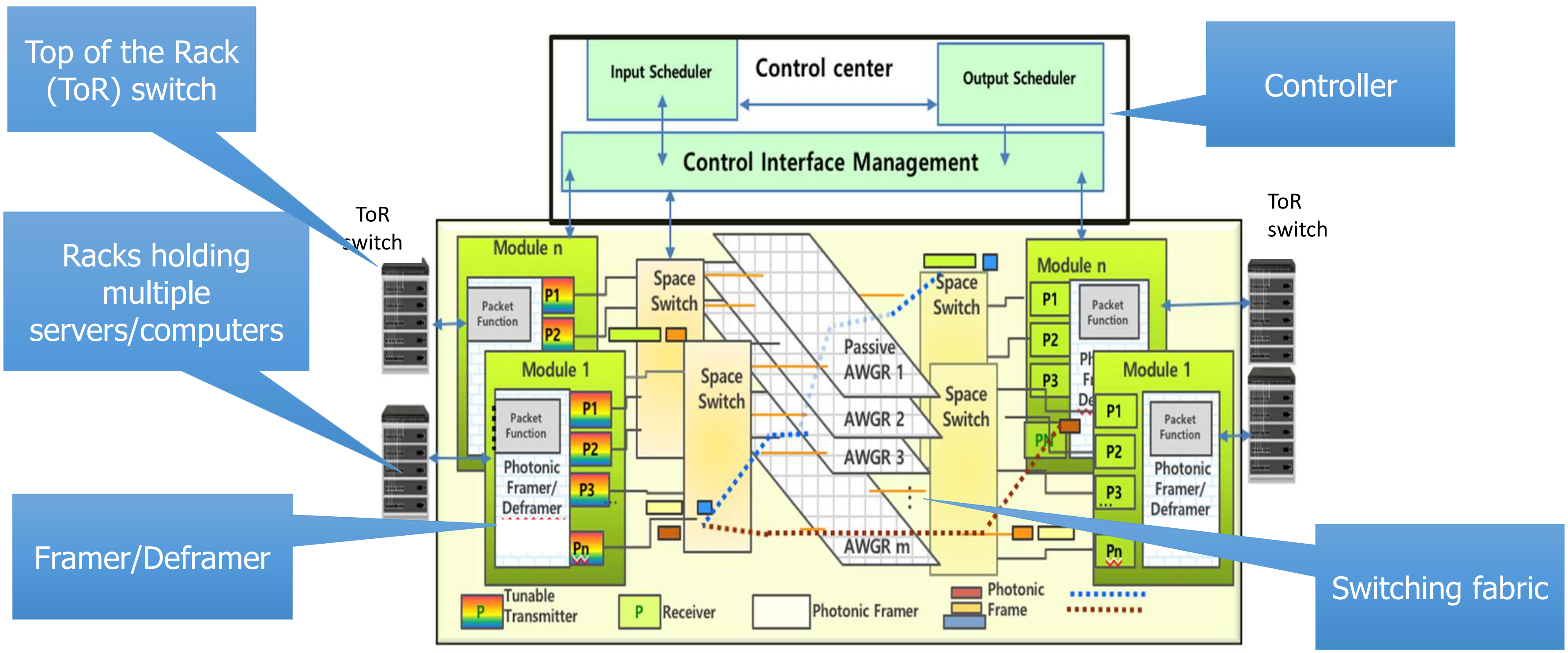
Packet Switched Optical Datacenter Network (PSON)



Source: Electronics and Telecommunications Research Institute, Korea

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Problem Statement

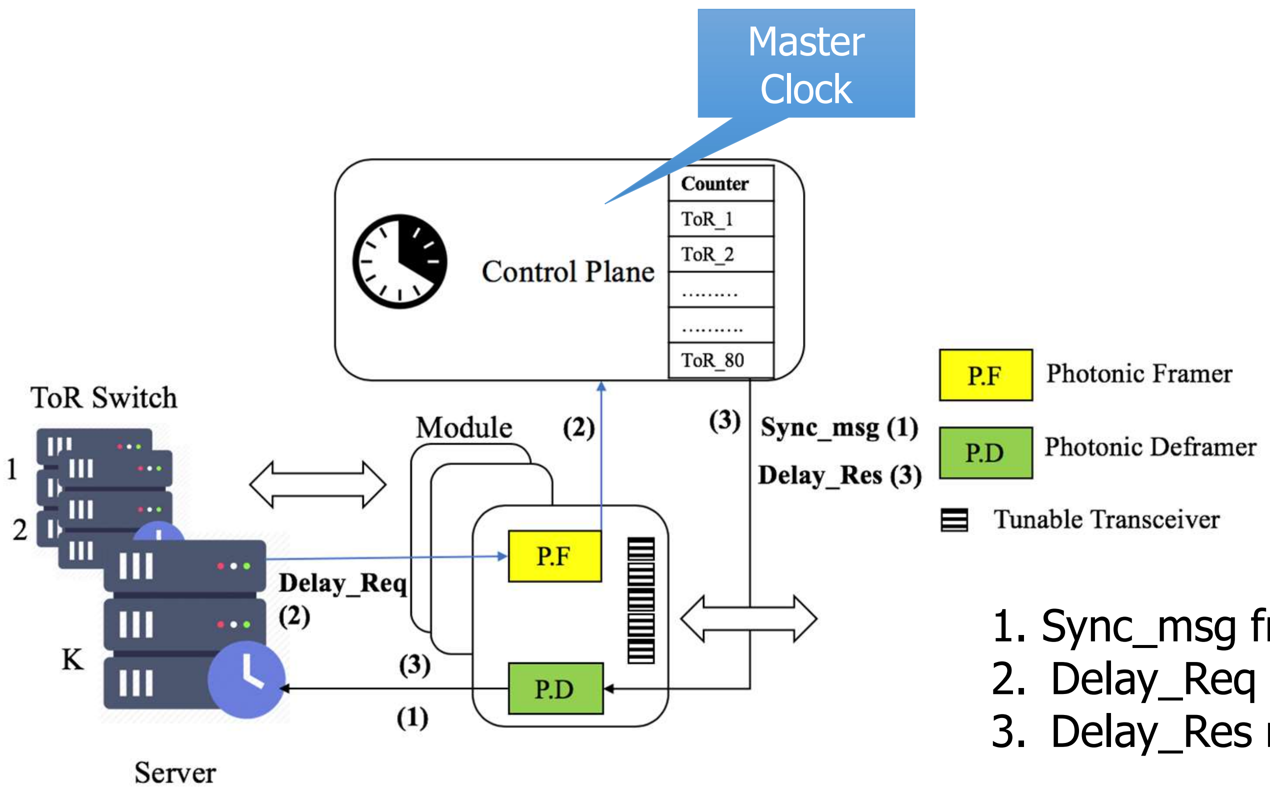
- Given:
  - PSON datacenter Architecture
  - Three traffic distributions: Lognormal, Pareto, Uniform
  - PTP enabled ToR switches
  - Controller with atomic/GPS clock information
- Objective:
  - *Synchronize ToR switches in a PSON with microsecond accuracy.*

Proposed Algorithm

Algorithm 1 PTP Time Synchronization Through In-Band Transmission

```
 1: Input: packet size, traffic load, link bandwidth of datacenter, number of ToR switches,
    resynchronization-interval time;
 2: Output: Time error;
 3: Initialize counter times for all ToR switches (limit time at resynchronization-interval time);
 4: Create a list of candidate ToR switches which have counter time equal to resynchronization-
    interval time (that means this ToR switch needs to be synchronized);
 5: if ToR switch ϵ candidate list then
 6:     wait_sync_time ← wait time for data packets in deframer to send ‘sync’ message to
 7:     candidate ToR switches with packets generated from a specific traffic distribution;
 8:     wait_delay_req_time ← wait time for data packets in framer to send ‘delay request’
 9:     message to controller with packets generated from the same traffic distribution;
10:     counter time of that ToR ← zero;
11:     Time error ← wait_sync_time + wait_delay_req_time;
12:     Candidate list ← candidate list  synced TOR;
13: else
14:     counter time of that ToR ← counter time++;
15: end if
16: Repeat from Step 4;
```

Proposed Method



PTP master clock

Source:
https://www.cisco.com/c/en/us/support/switches/nexus-3064-switch/model.html

1. Sync_msg from controller to ToR switch
2. Delay_Req msg from ToR switch to controller
3. Delay_Res msg from controller to ToR switch

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Simulation setup

- Number of ToR Switch: 80
- Number of Framer/deframer: 80
- Maximum length of PTP message: ~300 bits
- Data packet length: 200 to 1400 bytes
- Re-synchronization interval: 1 second

Performance Evaluation Metric

$$Time - error = Sync\_msg_{wait} + Delay\_req_{wait} + Delay\_res_{wait}$$

$$Sync\_msg_{wait} = wait\ time\ for\ data\ packets\ in\ deframer\ to\ send\ '\mathbf{Sync}'message\ to\ ToR\ switches$$

$$Delay\_req_{wait} = for\ data\ packets\ in\ framer\ to\ send\ '\mathbf{Delay\ request}',\ message\ to\ controller$$

$$Delay\_res_{wait} = for\ data\ packets\ in\ deframer\ to\ send\ '\mathbf{Delay\ response}',\ message\ to\ ToR\ switches$$

- Traffic load
- Packet-length
- Traffic distribution

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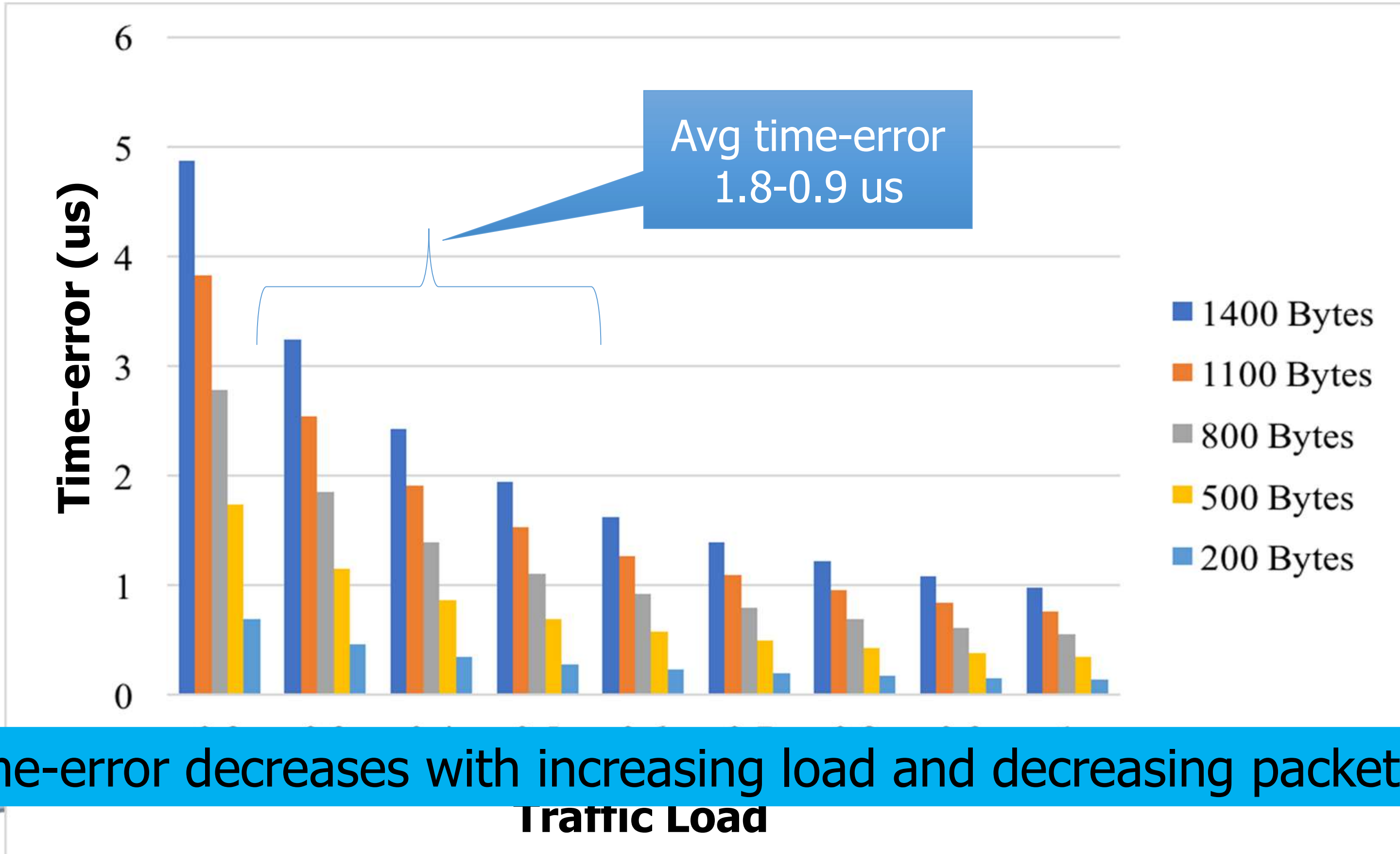
Results: Time-error vs. Load (Lognormal)



Time-error decreases with increasing load and decreasing packet-length

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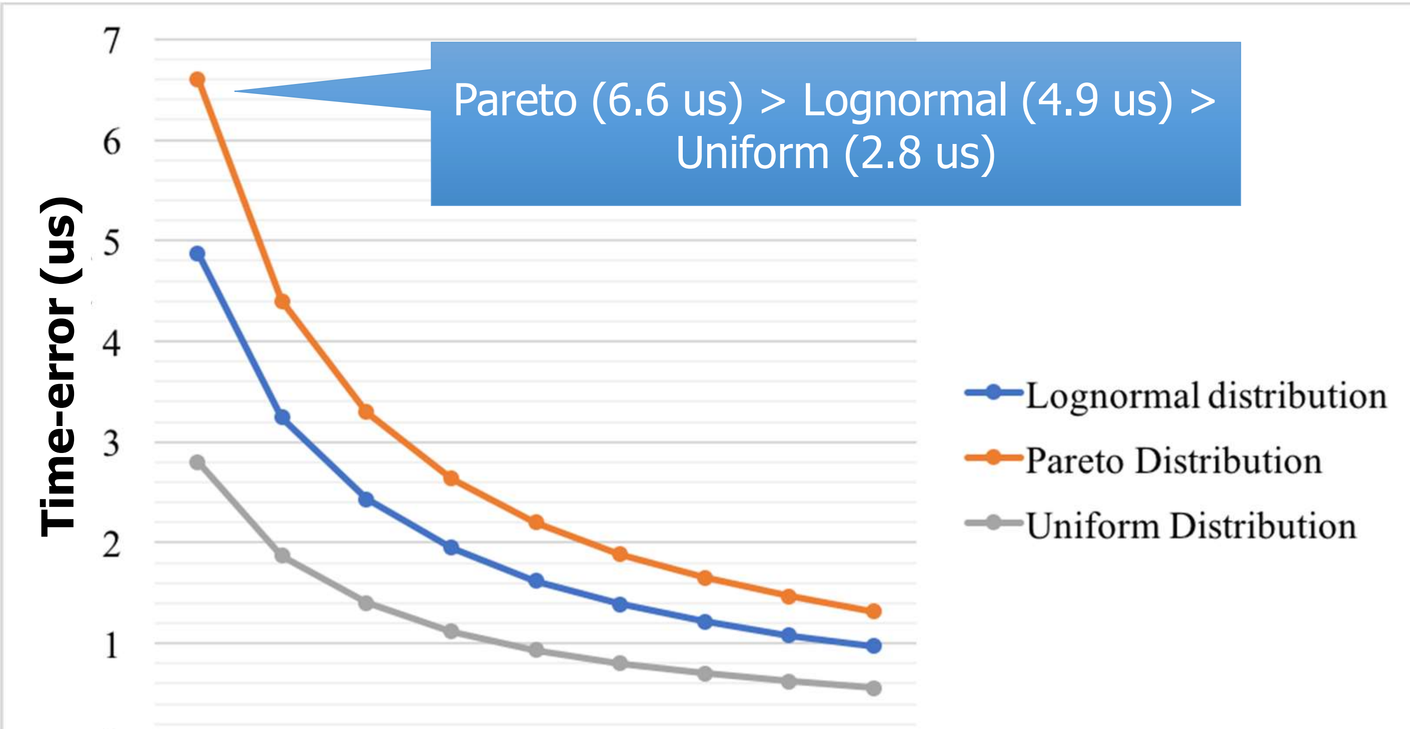
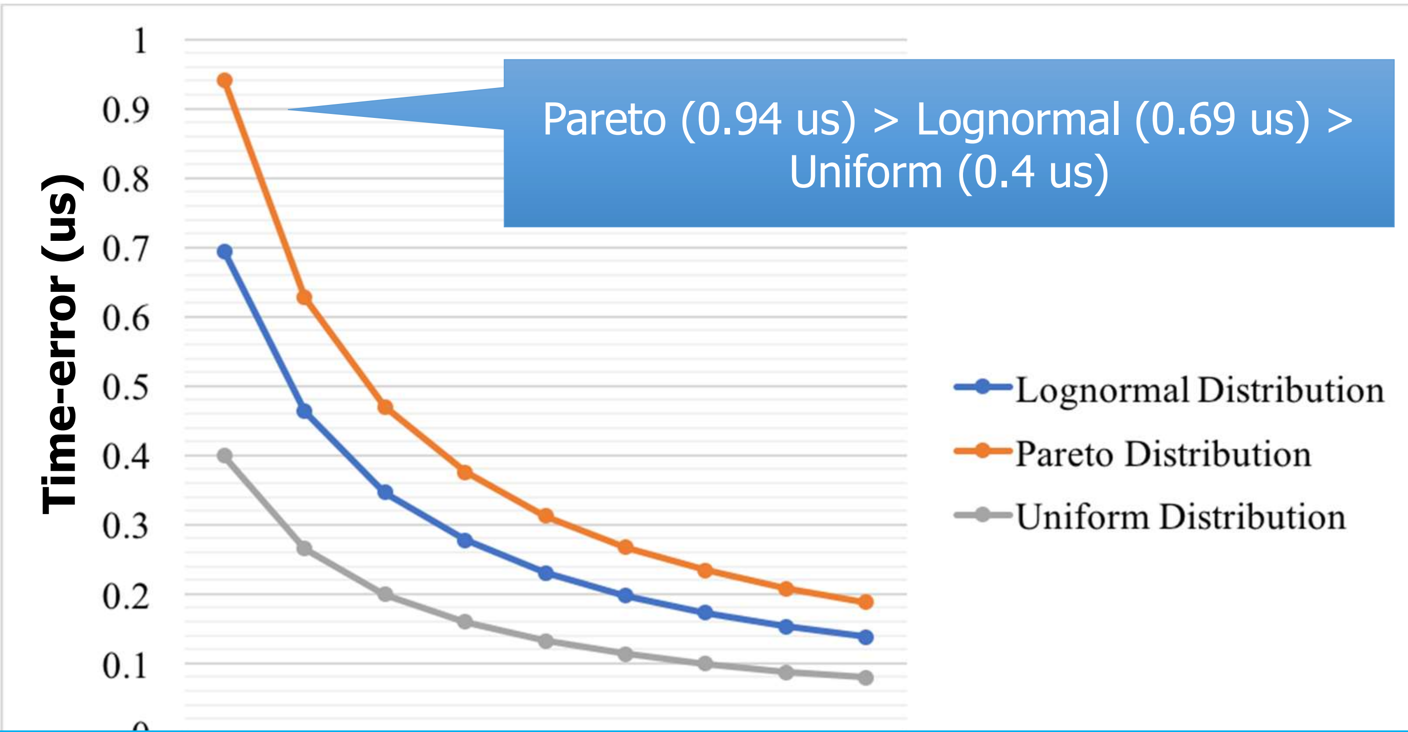
Results: Time-error vs. Load (1400 bytes)



Time-error is the highest for packet length of 1400 bytes. Pareto distribution obtains highest time-error among others

Results: Time-error vs. Load (200 bytes)



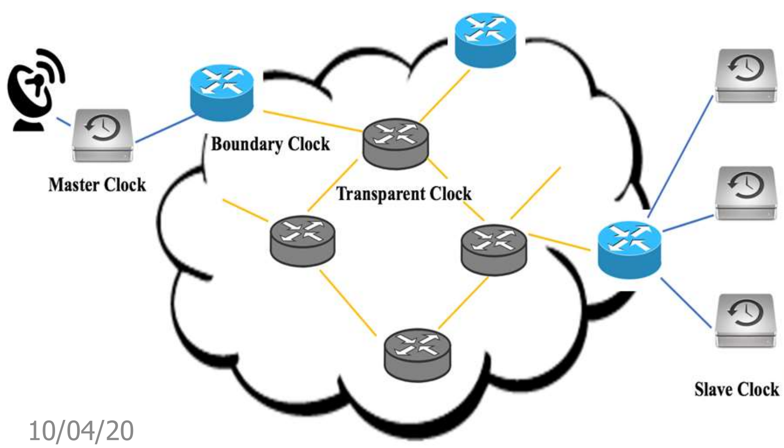
Time-error is the lowest for packet length of 200 bytes. Pareto distribution obtains highest time-error among others

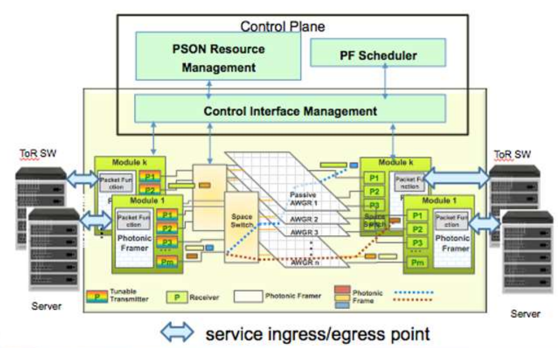
Summary and Future Research Ideas

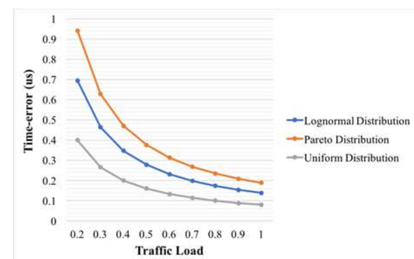
- Tested performance of PTP for a PSON datacenter architecture with zero-overhead and microsecond-accuracy.
- If the data packets are short and load is high PTP can achieve sub-microsecond accuracy

Future work:

- Implementing boundary clocks with multiple sub-networks
- Implementing an traffic adaptive resynchronization-time transmission







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Publications

- T. Ahmed, S. Rahman, M. Tornatore, K. Kim, B. Mukherjee, "A survey on high-precision time synchronization techniques for optical datacenter networks and a zero-overhead microsecond-accuracy solution," *Photonic Network Communications,* vol. 36, no. 1, pp. 56-67, Aug. 2018.

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- Conclusion and future research ideas

Agenda

- ✓Introduction to the problem
- ✓Proposed solution
  - *Spectrum efficient dynamic routing, spectrum, and modulation format assignment in a co-existing fixed/flex-grid network*
- ✓Results
- ✓Summary and future work

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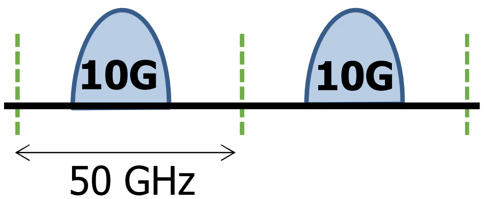
Fixed-Grid Optical Link

Single Line Rate (SLR)



Fixed Grid

Years 1990s, 2000s

Courtesy: Prof. Biswanath Mukherjee and Sabidur Rahman, Networks lab, UC Davis

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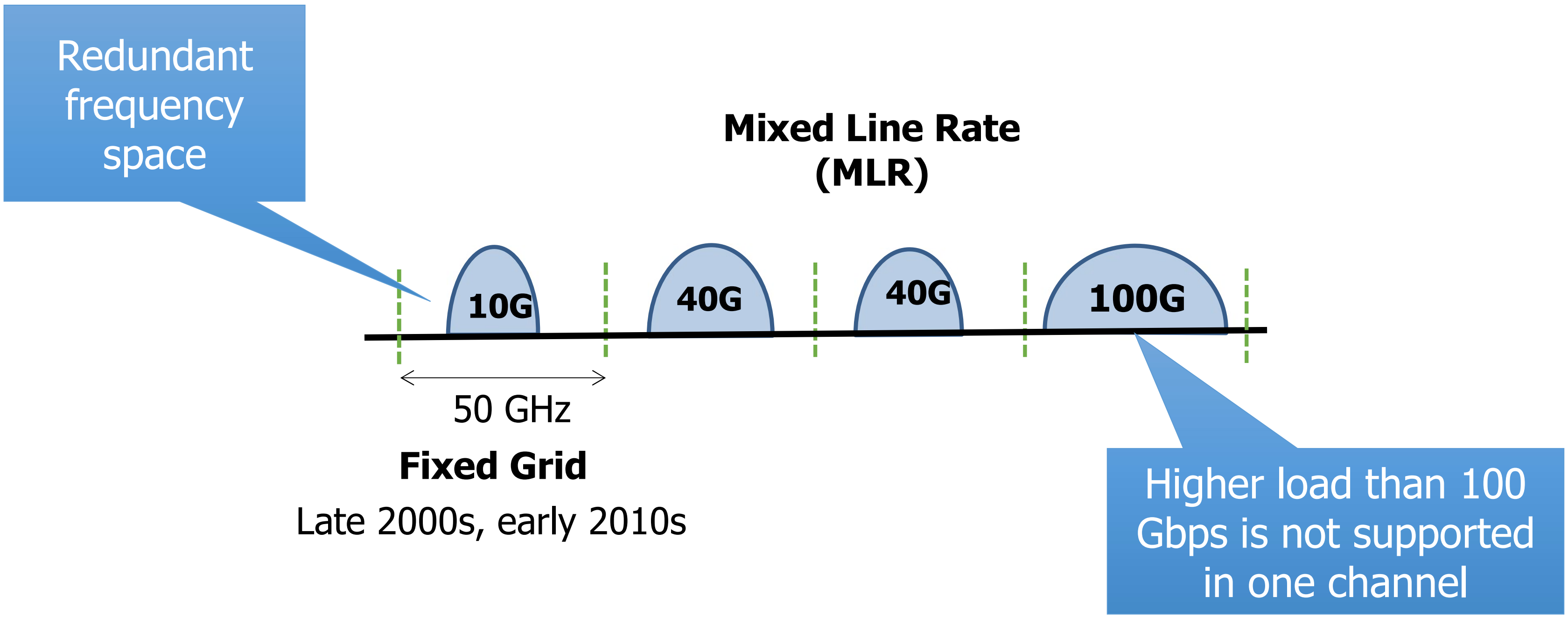
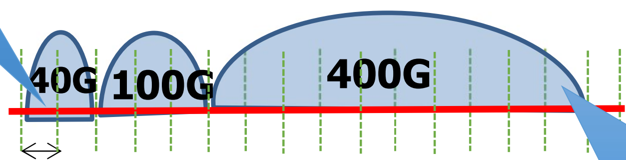
Fixed-Grid Optical Link



Courtesy: Prof. Biswanath Mukherjee and Sabidur Rahman, Networks lab, UC Davis

Flex-Grid Optical Link

Supports granular frequency



Flexible Grid

Supports higher load using super-channel

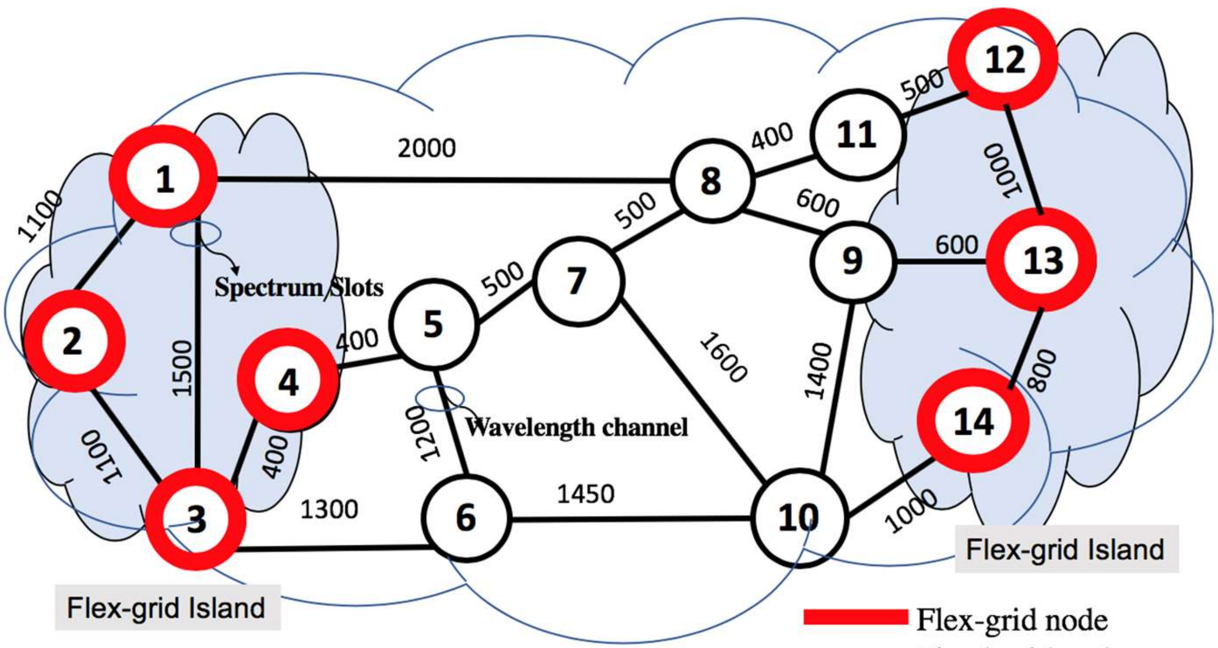
Improvement in spectrum usage

Bit-rate (Gbps)	Fixed (GHz)	Flex (GHz)
40	50	25
100	50	37.5
400	200	125

Starting 2011, ongoing research...

Courtesy: Prof. Biswanath Mukherjee and Sabidur Rahman, Networks lab, UC Davis

Migration from Fixed to Flex Grid: "Mixed-grid" Case



Migration decision depends on:

- Network load
- Population/DC placement
- Upgrade costs

Interoperability Challenge!

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Spectrum and Modulation Format Assignment: Mixed-grid

Spectrum occupation for various bit-rates.

Traffic Demand (Gb/s)	Fixed-Grid		Flex-Grid	
	Bandwidth (GHz)	#Wavelengths	Bandwidth Gap (GHz)	# Slots
40	50	1	25	2
100	50	1	37.5	3
200	100	2	75	6
400	200	4	150	12

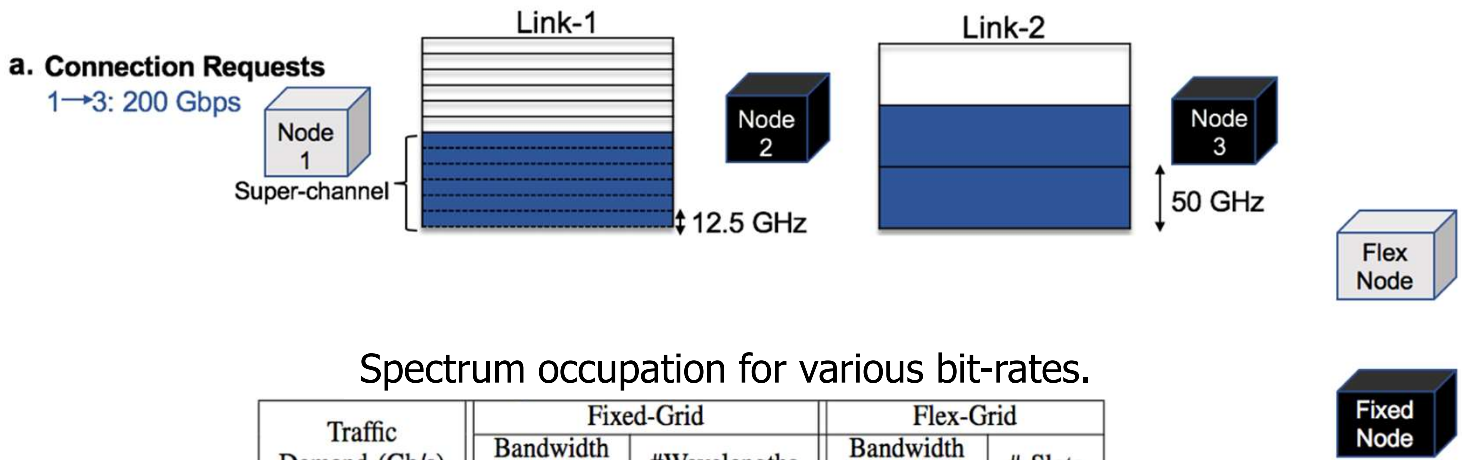
Distance and spectrum occupation in flex-grid.

Traffic Demand (Gb/s)	Modulation Format	Operating Bandwidth (GHz)	Distance (km)	#Slots
40	BPSK	50	6000	4
	QPSK	25	3000	2
	8QAM	12.5	1000	1
100	BPSK	75	4500	6
	QPSK	50	3500	4
	QPSK	37.5	3000	3
	8QAM	25	2500	2
	16QAM	18.75	1500	2
200	BPSK	100	2500	8
	QPSK	75	1500	6
	8QAM	62.5	1000	5
	16QAM	43.75	700	4
	32QAM	37.5	500	3

BPSK < QPSK < 8QAM < 16QAM < 32QAM
BPSK : Binary phase shift keying
QPSK : Quadrature phase shift keying
QAM: Quadrature amplitude modulation

Spectrum and Modulation Format Assignment: Mixed-grid

With QPSK



Spectrum occupation for various bit-rates.

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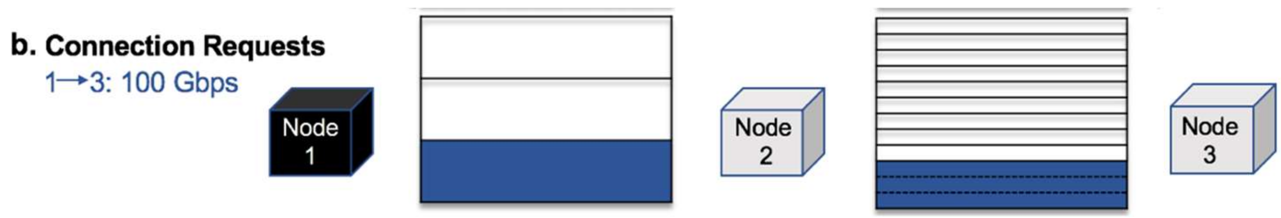

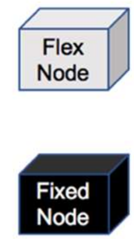

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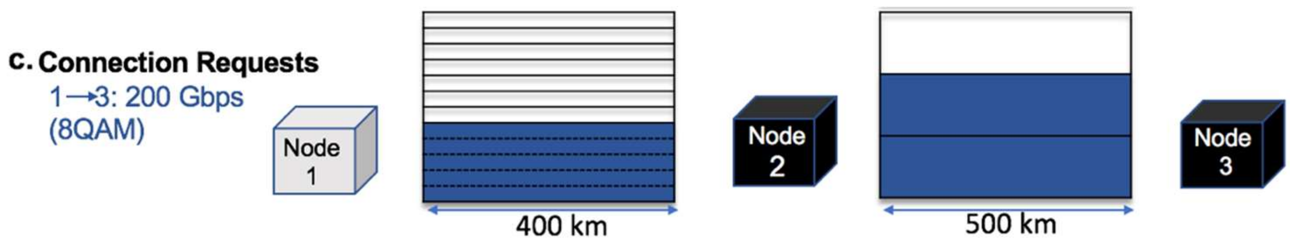
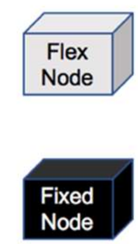




With Distance adaptive modulation format

Distance and spectrum occupation in flex-grid.

Traffic Demand (Gb/s)	Modulation Format	Operating Bandwidth (GHz)	Distance (km)	#Slots
40	BPSK	50	6000	4
	QPSK	25	3000	2
	8QAM	12.5	1000	1
100	BPSK	75	4500	6
	QPSK	50	3500	4
	QPSK	37.5	3000	3
	8QAM	25	2500	2
	16QAM	18.75	1500	2
200	BPSK	100	2500	8
	QPSK	75	1500	6
	8QAM	62.5	1000	5
	16QAM	43.75	700	4
	32QAM	37.5	500	3

Problem Statement

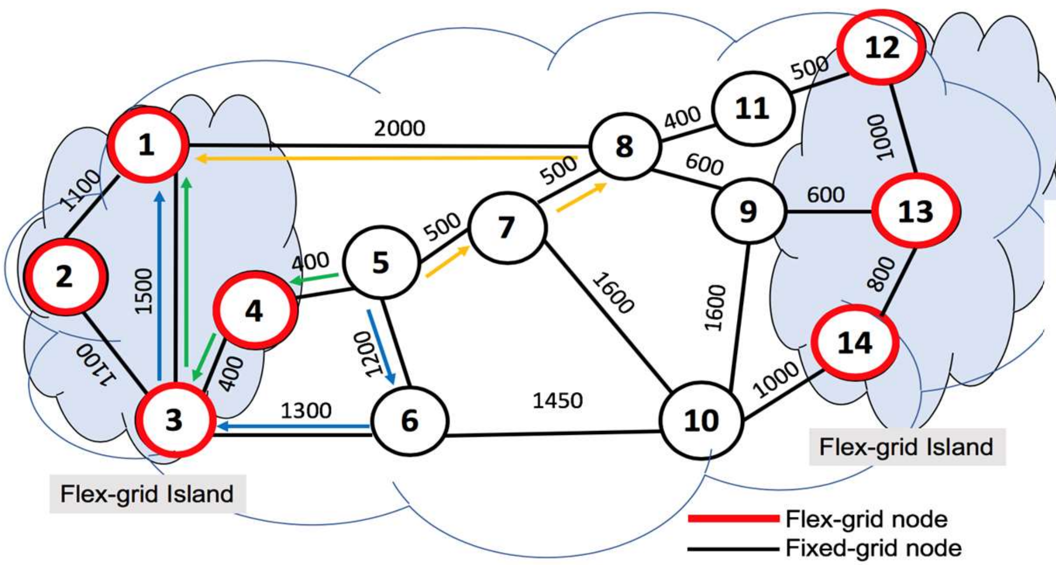
- Given:
  - Topology
  - Arrival rate of traffic flows
  - Set of traffic profiles
  - Set of fixed/flex-grid node locations with limited spectrum resources and constraints
- Objective:
  - *In a mixed-grid scenario provision optimal routes, spectrum, and modulation format with minimum bandwidth blocking*

Proposed Algorithm

Algorithm 1 Spectrum Efficient Dynamic Route and Spectrum Allocation (SEDRA)

Input: $N(V, E), p_{s,d}, \alpha_{s,d}$;
Output: Route, Spectrum, and Modulation Format;
for each connection request $(\alpha_{s,d})$ **do**
    $P_{s,d} \leftarrow$ find set of k-shortest paths $\alpha_{s,d}$;
        ▷ list of candidate paths with available spectrum
    for each $p_{s,d}$ **in** $P_{s,d}$ **do**
        if $(spectrum\_avail(p_{s,d}, \alpha_{s,d}) == True)$ **then**
            $\kappa_{s,d} \leftarrow \kappa_{s,d} \cup p_{s,d}$;
        end if
    end for
    for each $p_{s,d}$ **in** $\kappa_{s,d}$ **do**
        $m \leftarrow modulation\_format(p_{s,d}, \alpha_{s,d})$;
        $\gamma_T^p \leftarrow calculate\_spectrum(p_{s,d}, \alpha_{s,d}, m)$;
            ▷ find path requiring least spectrum for $\alpha_{s,d}$
        if γ_T^p is lowest **then**
            $\gamma_{min}^p \leftarrow \gamma_T^p$;
            $p_{s,d}^{best} \leftarrow p_{s,d}$;
            $m^{best} \leftarrow m$;
        end if
    end for
    Allocate lightpath on $p_{s,d}^{best}$ using modulation format m^{best} to achieve minimum spectrum allocation of γ_{min}^p;
end for

Spectrum Efficient Dynamic Route and spectrum Allocation (SEDRA)



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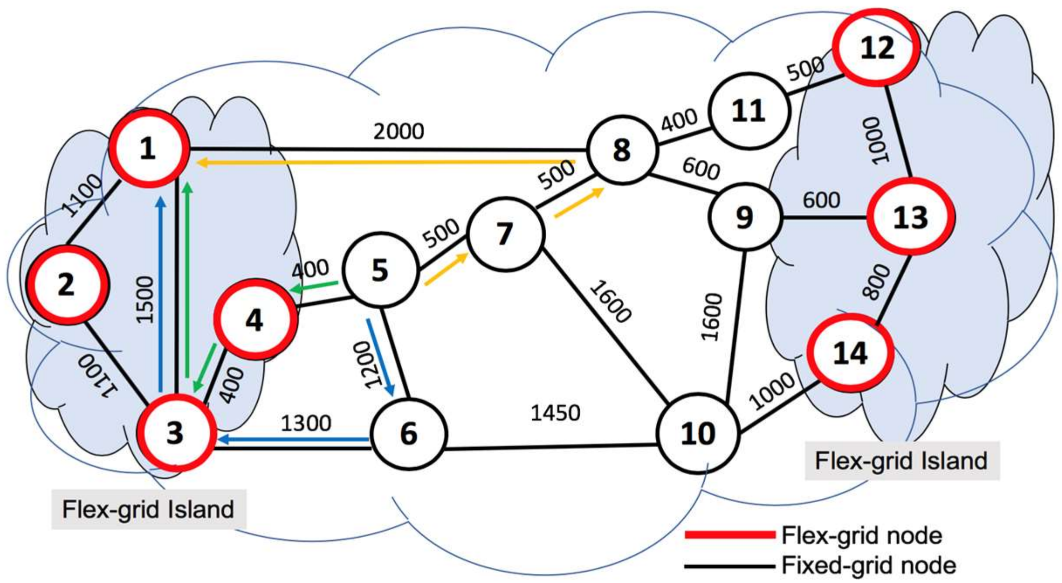
	Bandwidth (GHz)	#Wavelengths	Bandwidth Gap (GHz)	# Slots
40	50	1	25	2
100	50	1	37.5	3
200	100	2	75	6
400	200	4	150	12

- ✓Path 1, 5-7-8-1 (3 fixed-grid & 1 flex-grid nodes): (50*3) GHz = 150 GHz
- ✓Path 2, 5-4-3-1 (1 fixed-grid & 3 flex-grid nodes): (50 + 37.5*2) GHz = 125 GHz
- ✓Path 3, 5-6-3-1 (2 fixed-grid & 2 flex-grid nodes): (50*2 + 37.5) GHz = 137.5 GHz

SEDRA with Distance-Adaptive Modulation Assignment (SEDRA-DA)



Distance and spectrum occupation in flex-grid.

Traffic Demand (Gb/s)	Modulation Format	Operating Bandwidth (GHz)	Distance (km)	#Slots
100	BPSK	75	4500	6
	QPSK	50	3500	4
	QPSK	37.5	3000	3
	8QAM	25	2500	2
	16QAM	18.75	1500	2

- ✓ Non-distance adaptive approach, 5-4-3-1 (1 fixed-grid & 3 flex-grid nodes, QPSK, 3000 kms): (50 + 37.5*2) GHz = 125 GHz
- ✓ Distance adaptive (DA) approach, 5-4-3-1 (1 fixed-grid & 3 flex-grid nodes, 8QAM, 2500 kms): (50 + 25*2) GHz = 100 GHz

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Baseline Strategies

Routing:

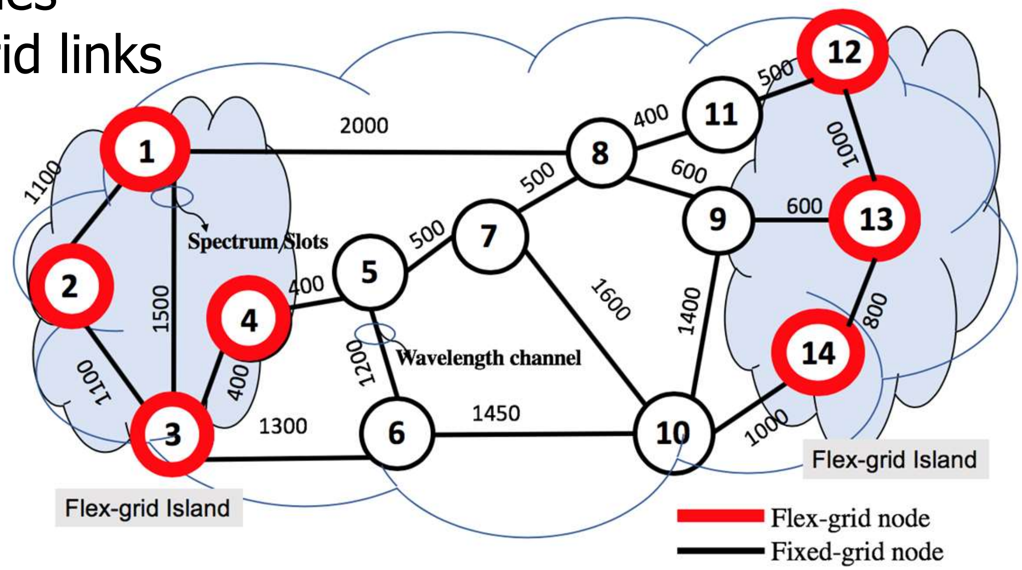
- Shortest Path First (SPF)
- Most Slots First (MSF)
- Largest Slot-over-Hops First (LSoHF)

Spectrum allocation:

- First Fit (FF)
- Random Fit (RF)
- Reusable Spectrum Allocation First (RSAF)

Simulation Setup

- 14 node NSFnet topology
- 7 flex-grid nodes and 7 fixed grid nodes
- 100 Wavelength channels for fixed-grid links
- 400 frequency slots for flex-grid links
- Poisson inter-arrival
- Exponential holding time



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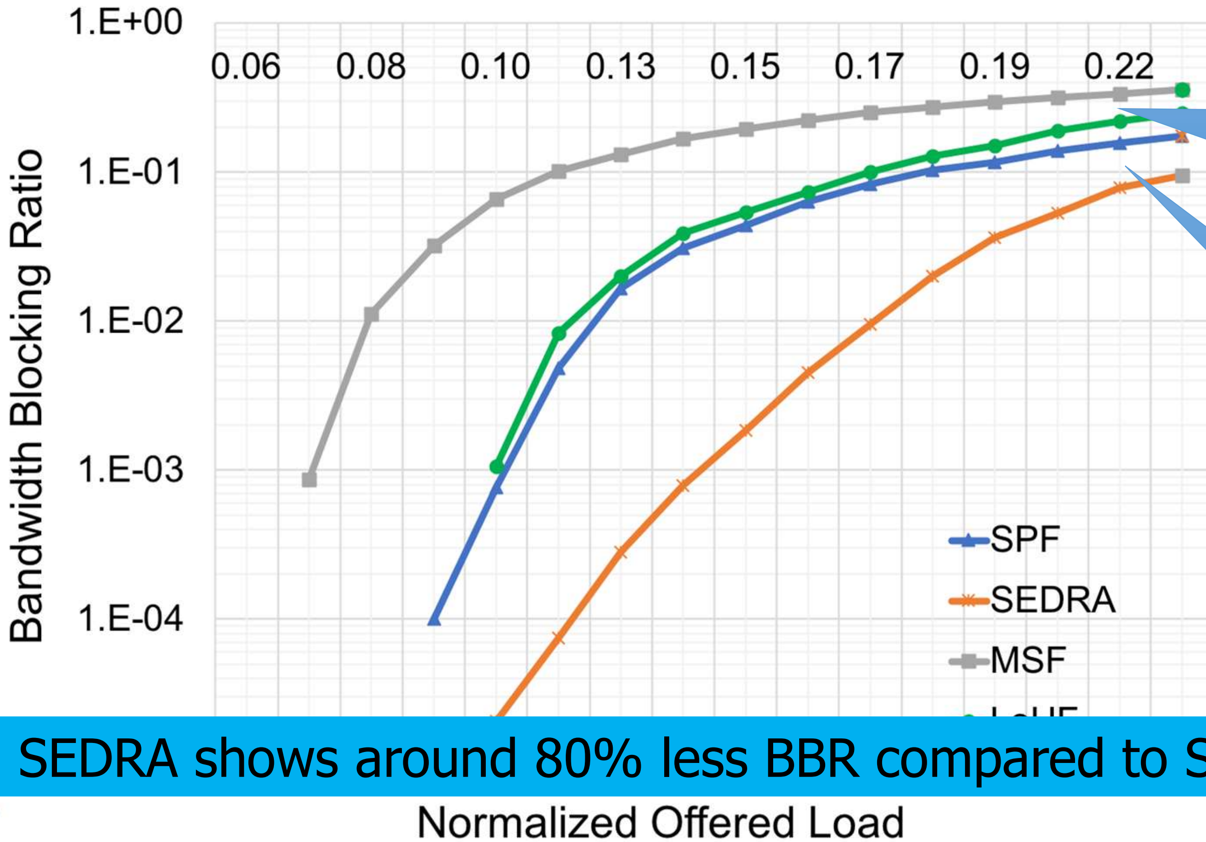
Performance Evaluation Metrics

$$Bandwidth\ blocking\ ratio = \frac{Rejected\ bandwidth}{Total\ requested\ bandwidth}$$

$$Spectral\ utilization\ ratio = \frac{Average\ spectrum\ occupied}{Network\ Capacity}$$

Results: BBR vs. Offered Load

- Shortest Path First (SPF)
- Most Slots First (MSF)
- Largest Slot-over-Hops First (LSoHF)
- Spectrum Efficient Dynamic Route and spectrum Allocation (SEDRA)



BBR at 22% load
MSF 0.35
LoHF 0.24

BBR at 22% load
SPF 0.17
SEDRA 0.09

SEDRA shows around 80% less BBR compared to SPF

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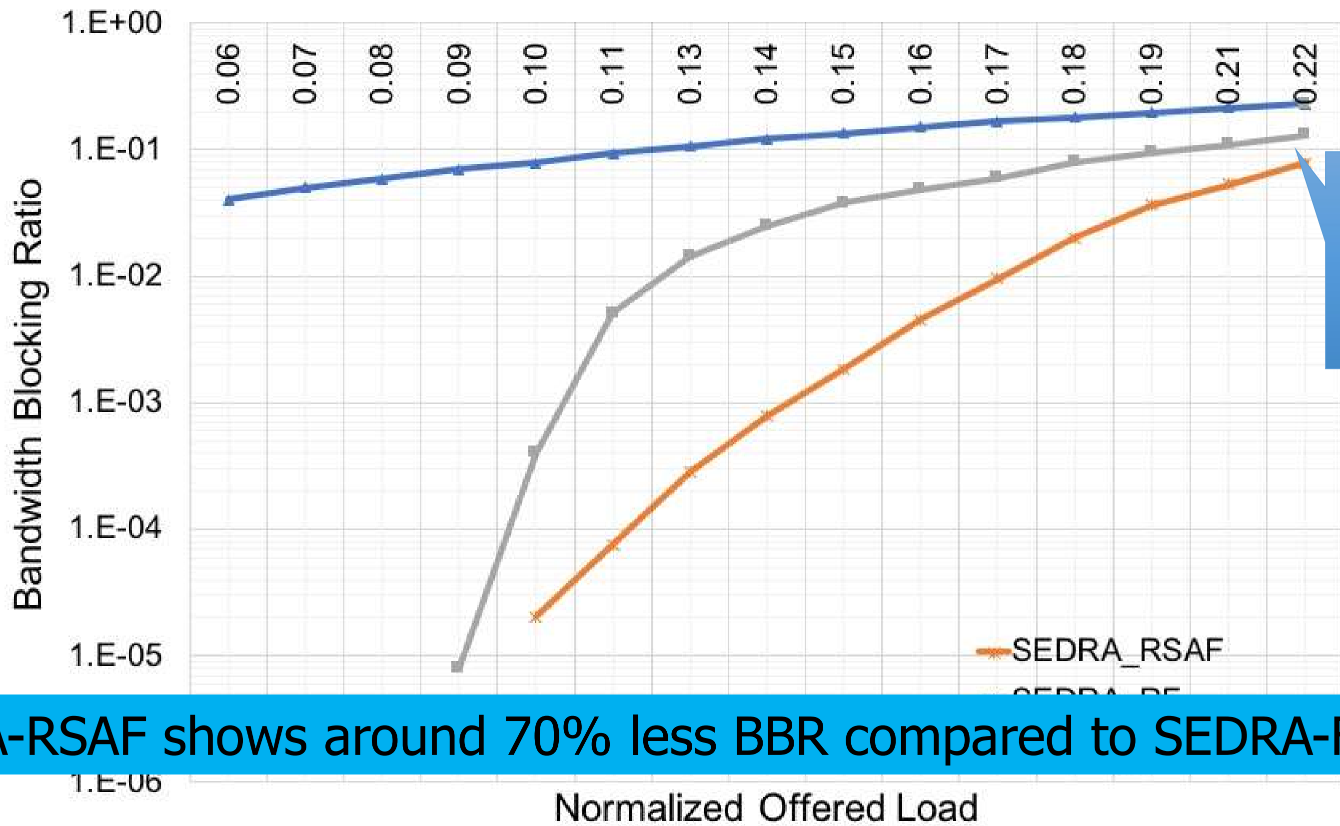
Results: BBR vs. Offered Load

- First Fit (FF)
- Random Fit (RF)
- Reusable Spectrum Allocation First (RSAF)



BBR at 22% load FF 0.16 RSAF 0.09

SEDRA-RSAF shows around 70% less BBR compared to SEDRA-FF

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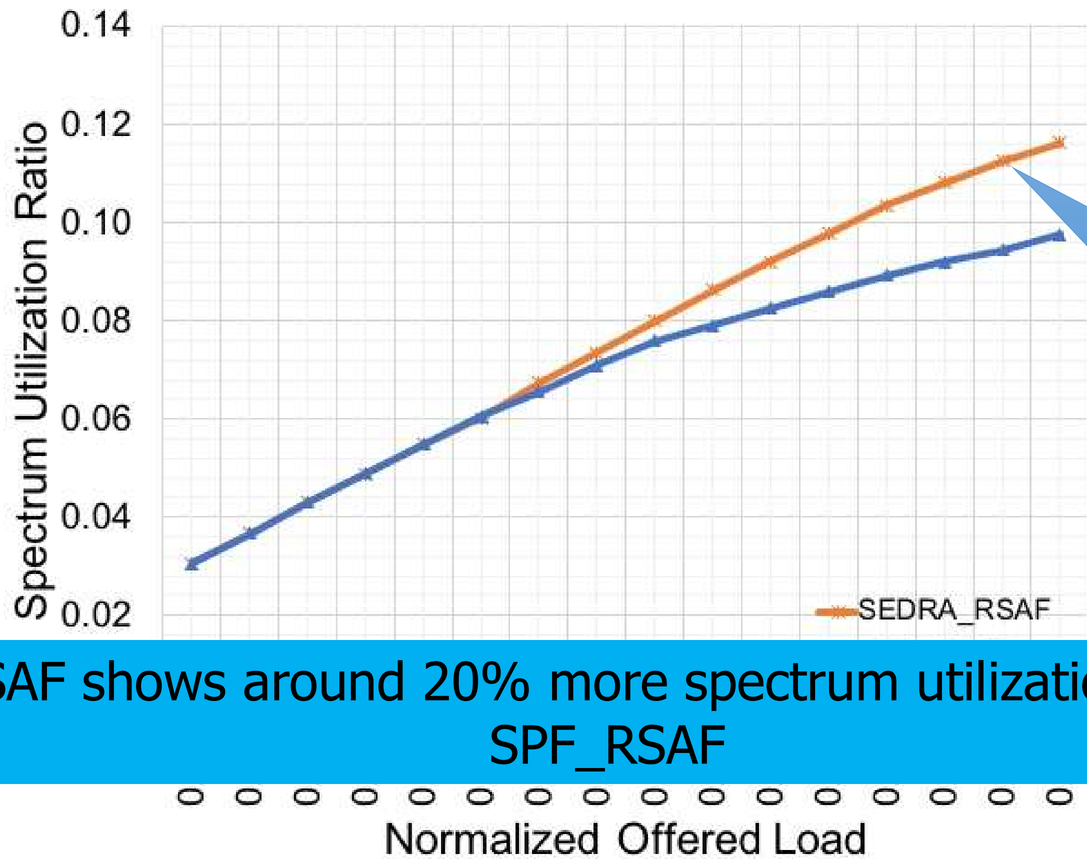
Results: Spectrum Utilization vs. Offered Load

- Shortest Path First (SPF)
- Spectrum Efficient Dynamic Route and spectrum Allocation (SEDRA)
- Reusable Spectrum Allocation First (RSAF)



BBR at 22% load of SPF_RSAF 0.11 SEDRA_RSAF 0.09

SEDRA-RSAF shows around 20% more spectrum utilization compared to SPF_RSAF

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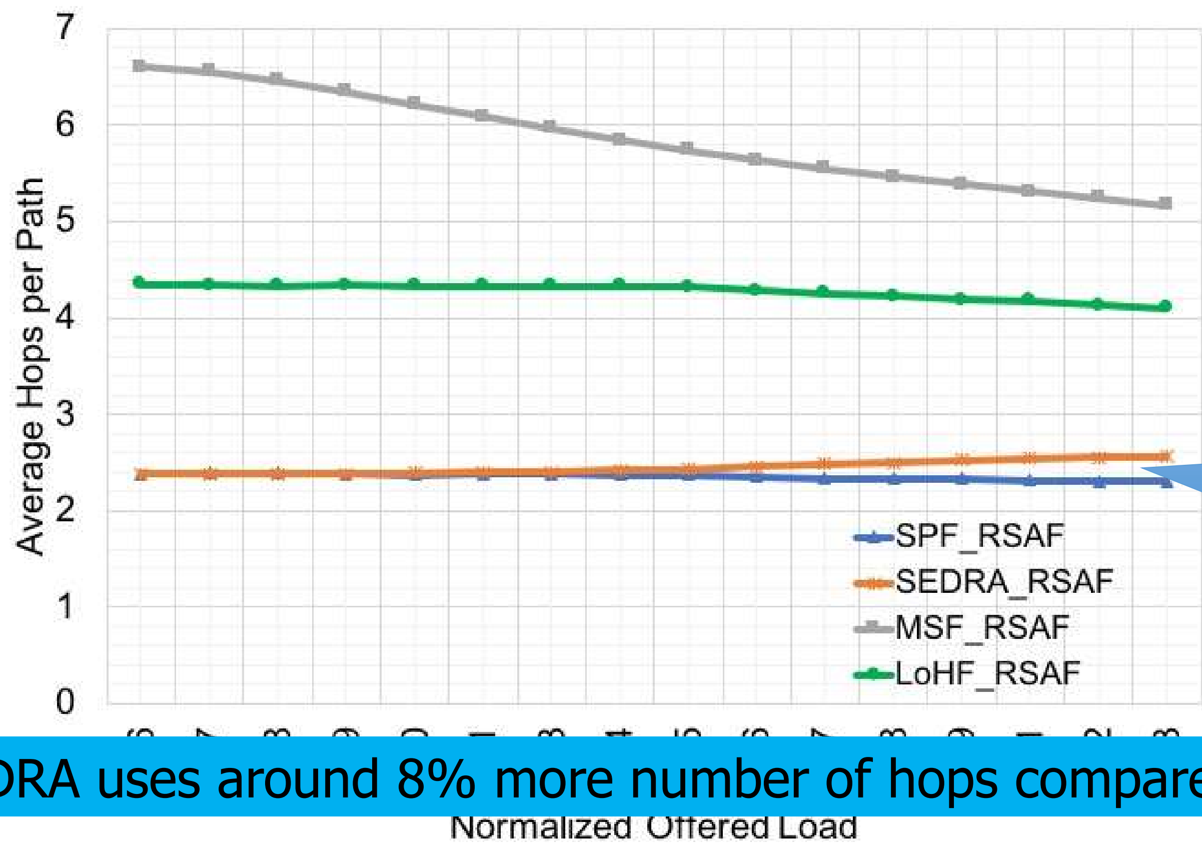
Results: Average Hop Count vs. Offered Load

- Shortest Path First (SPF)
- Most Slots First (MSF)
- Largest Slot-over-Hops First (LSoHF)
- Spectrum Efficient Dynamic Route and spectrum Allocation (SEDRA)
- Reusable Spectrum Allocation First (RSAF)



Avg. hop count at 22% load
SPF 2.3
SEDRA 2.5

SEDRA uses around 8% more number of hops compared to SPF

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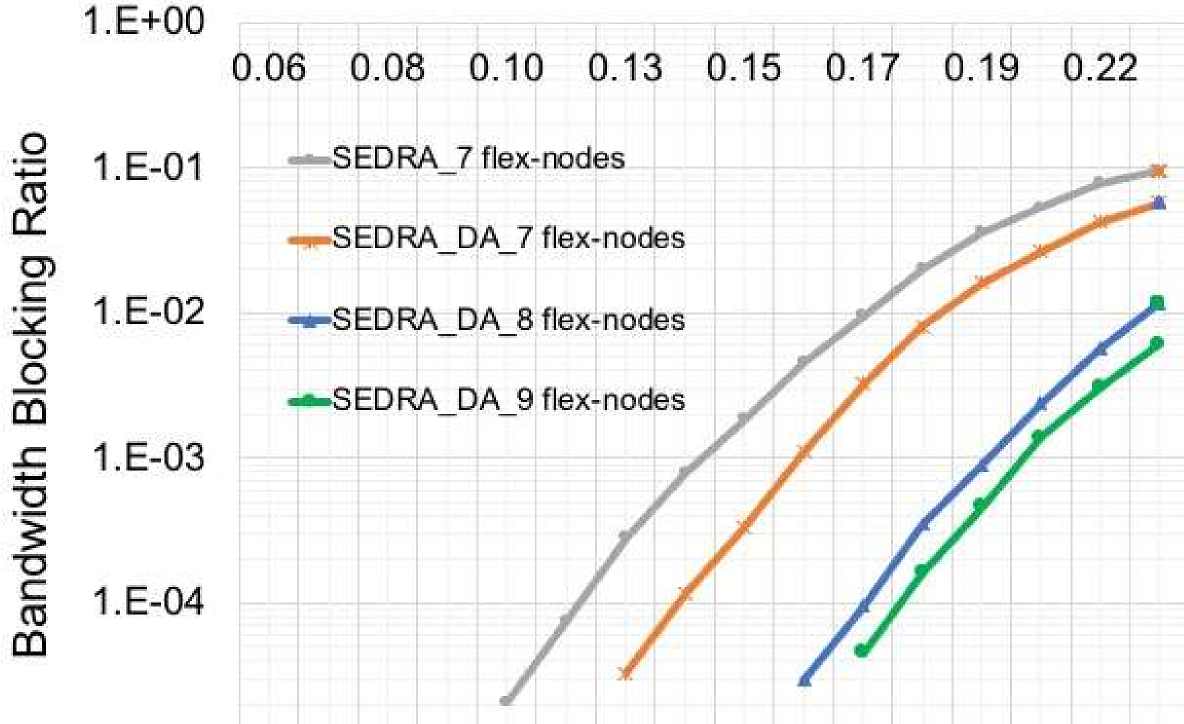
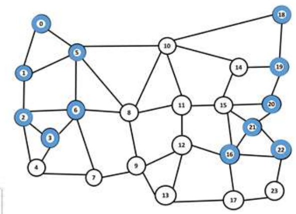
Results: BBR vs. Offered Load (varying no. of flex-grid nodes)

- Spectrum Efficient Dynamic Route and spectrum Allocation (SEDRA)
- Distance-adaptive modulation (DA)

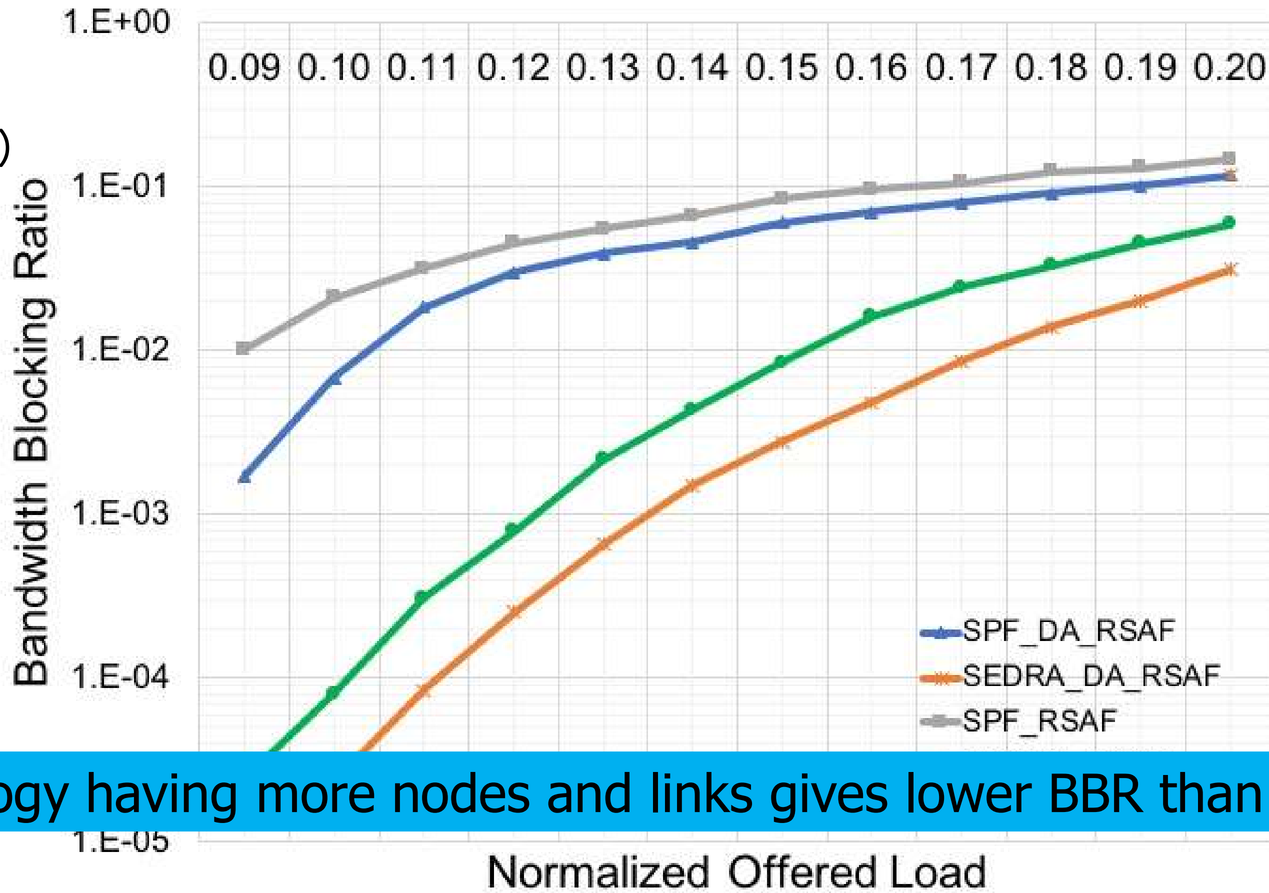


BBR decreases with increases number of flex-grid nodes

Results: BBR vs. Offered Load (Usnet-24)



- Shortest Path First (SPF)
- Spectrum Efficient Dynamic Route and spectrum Allocation (SEDRA)
- Reusable Spectrum Allocation First (RSAF)



Usnet-24 topology having more nodes and links gives lower BBR than NSFnet-14

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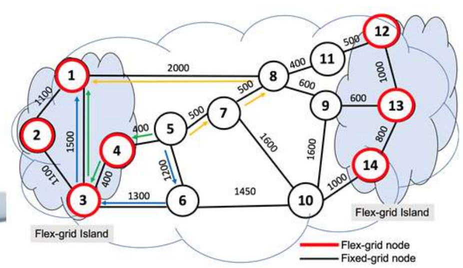
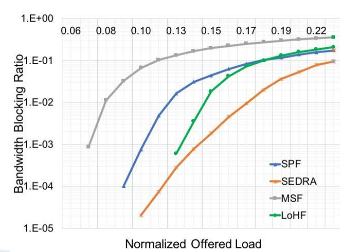
Summary and Future Research Ideas

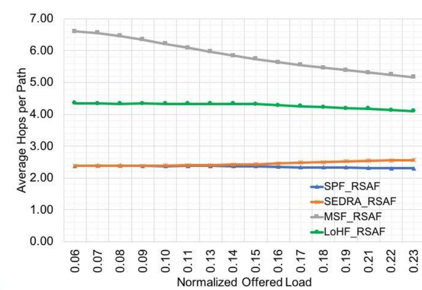
- A mixed-grid-aware spectrum-efficient solution called SEDRA is proposed for a dynamic traffic scenario
- Illustrative results show **80%** BBR reduction with cost of **8%** increased hop count is achieved compared to SPF for NSFnet-14 network
- **20%** of spectrum utilization is obtained using SEDRA compared to SPF NSFnet network

Future work:

- Applying insights gained from analysis of SEDRA to take migration decisions







Publications

- T. Ahmed, S. Rahman, M. Tornatore, X. Yu, K. Kim and B. Mukherjee, "Dynamic Routing and Spectrum Assignment in Co-Existing Fixed/Flex-Grid Optical Networks," *Proc., Advanced Networks and Telecommunications Systems (ANTS)*, Indore, India, Dec. 2018.
- T. Ahmed, S. Rahman, S. Ferdousi, M. Tornatore, A. Mitra, B. C. Chatterjee, and B. Mukherjee, "Dynamic Routing, Spectrum, and Modulation Format Assignment in Co-Existing Mixed-Grid Optical Networks," to be submitted to *Journal of Optical Communications and Networking*.

Outline

- Introduction
- Contribution I: High-precision time synchronization techniques for optical datacenter networks and a zero-overhead microsecond-accuracy Solution
- Contribution II: Dynamic routing, spectrum, and modulation format assignment in co-existing fixed/flex-grid optical networks
- Conclusion and future research ideas

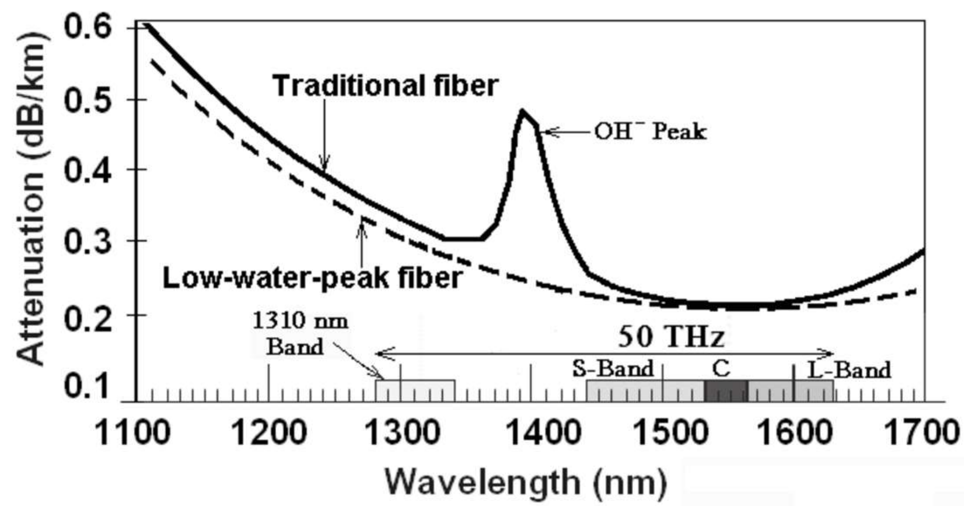
Outline

✓Multiband optical line systems
✓Spectrally–spatially flexible optical networks
✓Spectrum trading in virtual optical networks

Multiband Optical Line Systems

C-band: 1530 nm to 1565 nm (Conventional) Lowest fiber loss

L-band: 1565 nm to 1625 nm (Long Band) Low attenuation



Source: B. Mukherjee, "Optical WDM Networks," *Springer Science & Business Media*, 2006.

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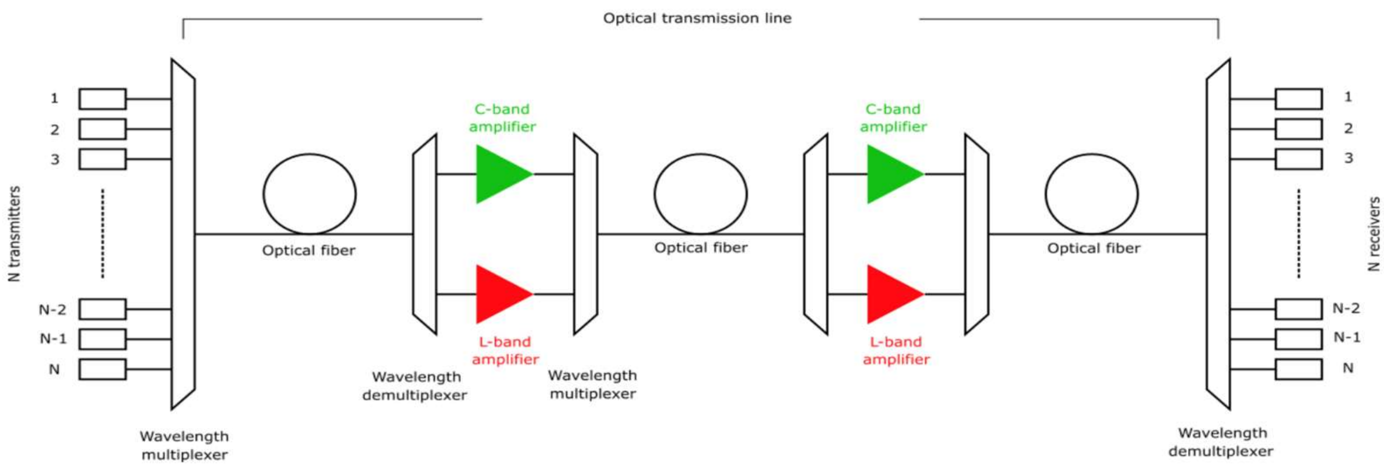
Challenges of Using Multiband Transmission

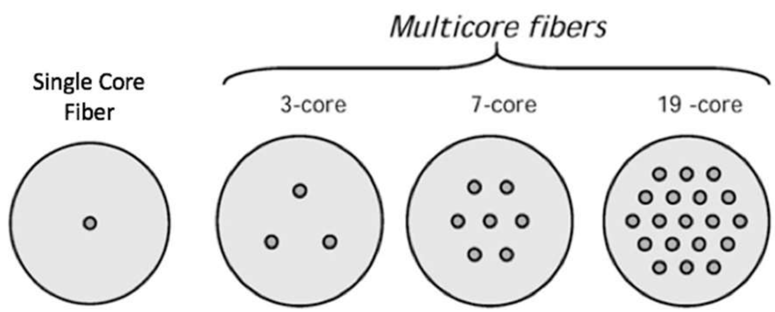
- Attenuation is higher than C band
- Quality-of-transmission estimator (QoT-E)
    1. Amplified spontaneous emission (ASE) noise
    2. Nonlinear impairments



Source: https://www.fiberlabs.com/glossary/long-wavelength-band/

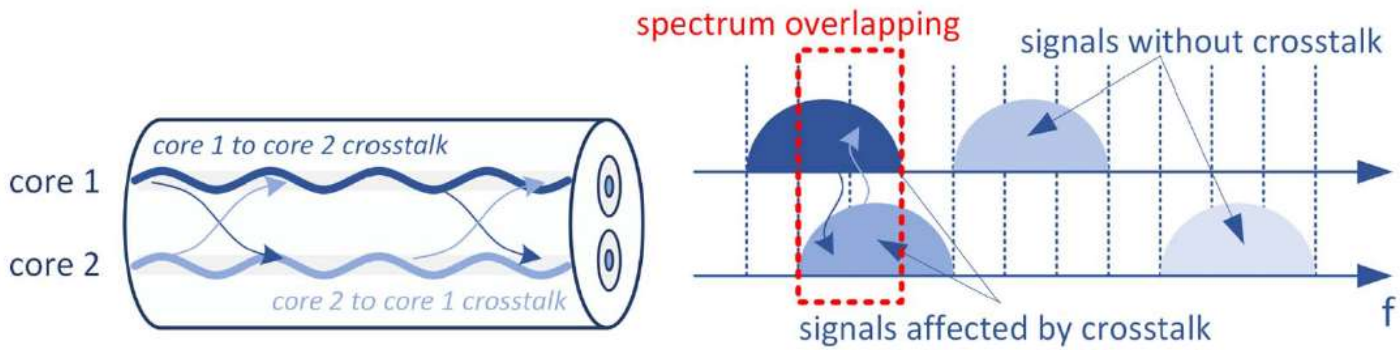
Spectrally–Spatially Flexible Optical Networks

1. Routing
2. Spectrum
3. Modulation format
4. Core



Courtesy: Andrea Marotta, Networks lab, UC Davis

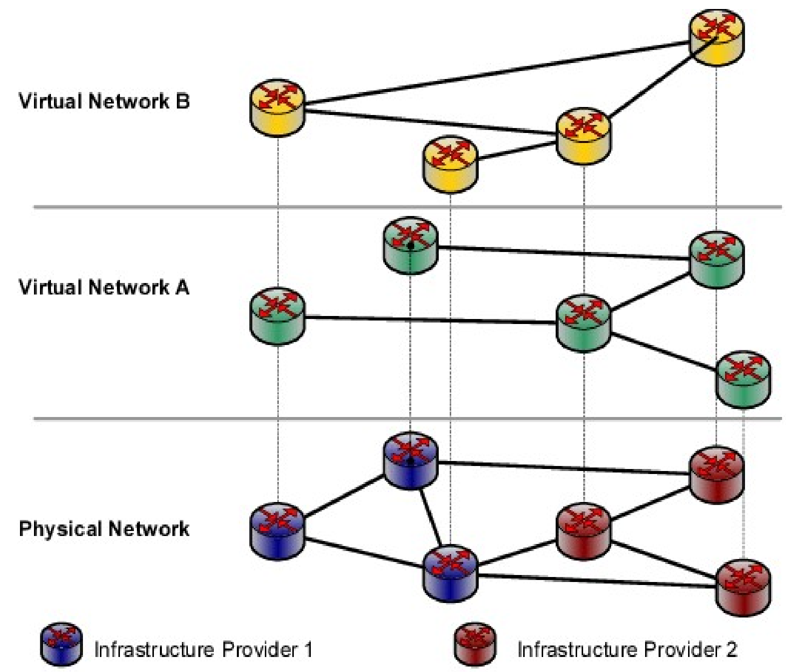
Spectrally–Spatially Flexible Optical Networks



M. Klinkowski and G. Zalewski, "Dynamic Crosstalk-Aware Lightpath Provisioning in Spectrally–Spatially Flexible Optical Networks," *Journal of Optical Communications and Networking*, vol. 11, no. 5, pp. 213–225, May 2019.

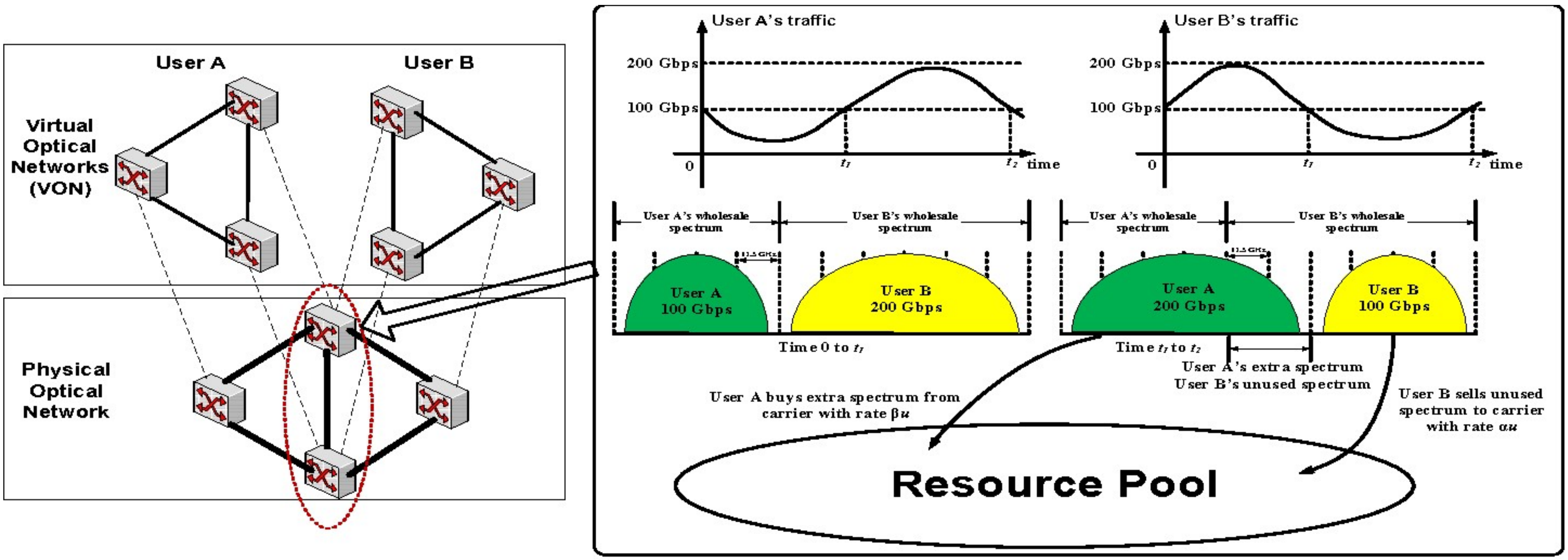
Spectrum Trading

- Network virtualization splits capacity of a physical network into multiple independent virtual optical networks (VONs)
- Allocated with fixed capacity
- Real-time capacity fluctuation
- Large idle capacity & capacity shortage is observed on virtual links



S. Ding, X. Fu, B. Jiang, S. K. Bose, and G. Shen, "Spectrum Trading between Virtual Optical Networks Embedded in an Elastic Optical Network," *Proc., Optical Fiber Communication Conference*, Mar. 2019.

Spectrum Trading



W. Xie, J. Zhu, C. Huang, M. Luo, and W. Chou, "Dynamic resource pooling and trading mechanism in flexible-grid optical network virtualization," *Proc., Cloud Networking*, pp. 167-172, Oct. 2014.

Conclusion

- Importance of flexible network architecture
- Ultra low latency (sub-microsecond) is achievable in a distributed system like a datacenter using data plane transmission and PTP time synchronization protocol
- A mixed-grid-aware resource provisioning technique can obtain high spectrum efficiency by allocating lightpaths considering all the interoperability challenges

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THANK
YOU!

Appendix

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Photonic Frame

OTS			ETSH		ETSP
OTg	OTfe	OTSt	OTSre	PF Preamble	PF Payload

OTS: Optical Time Slot

ETS: Electrical Time Slot

ETSH: ETS Header

ETSP: ETS Payload

PF: Photonic Frame

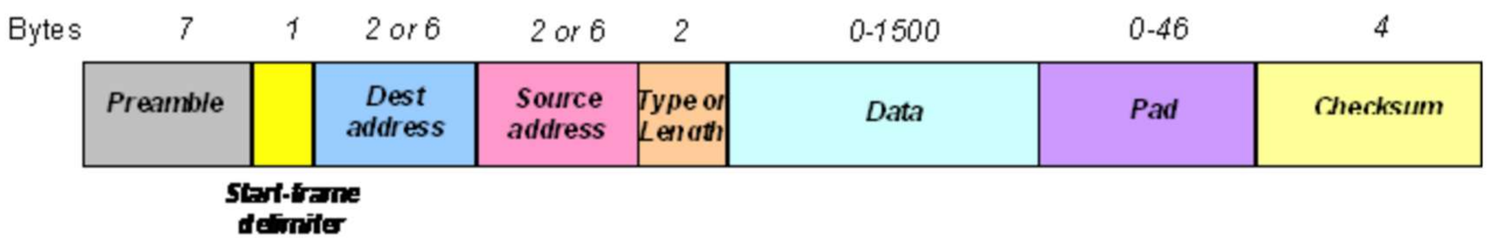
OTg: Optical guard time

OTfe: Optical Falling Edge time

OTSt: Optical wavelength Switching Time

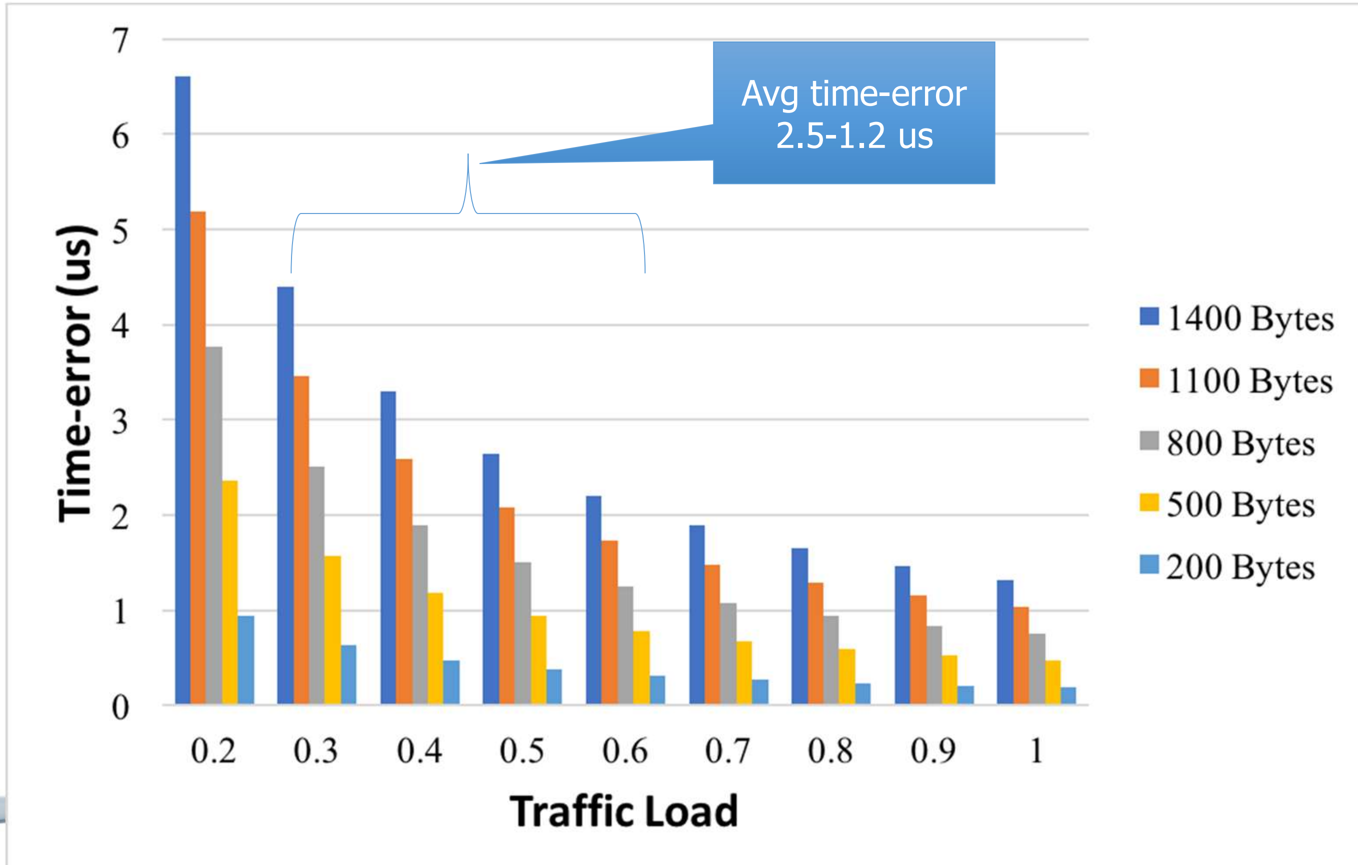
OTSre: Optical Rising Edge time

Ethernet Frame



Source: http://www.dcs.gla.ac.uk/~lewis/networkpages/m04s03EthernetFrame.htm

Results: Time-error vs. Load (Pareto)



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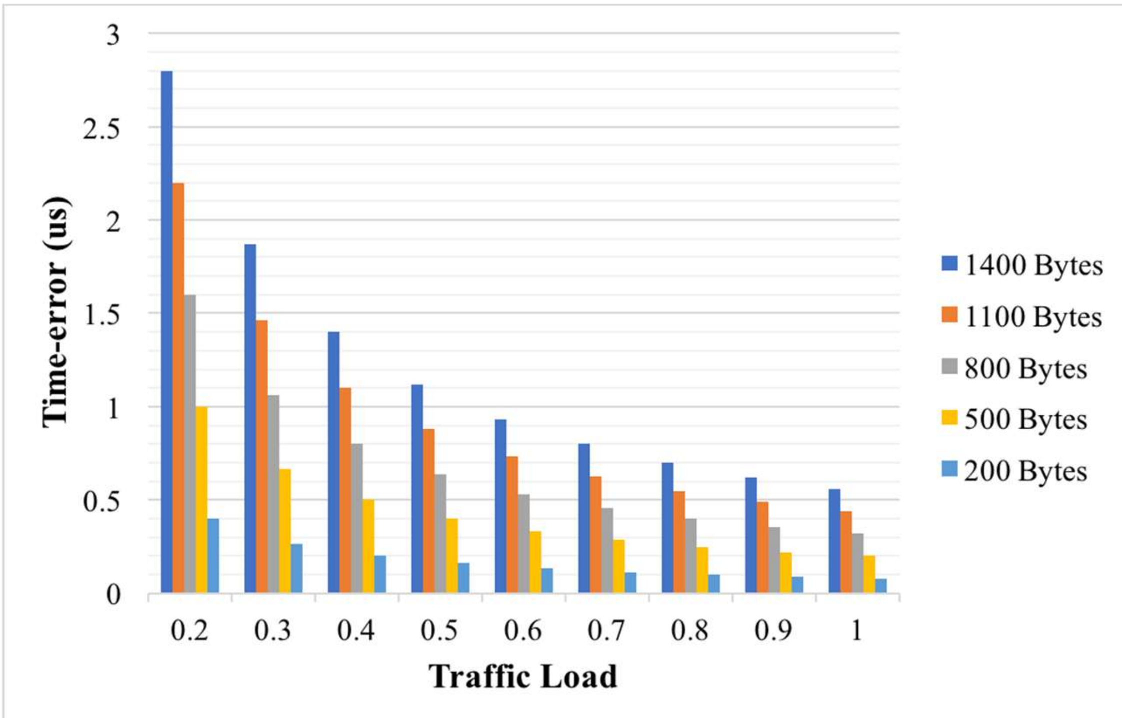
Results: Time-error vs. Load (Uniform)



Performance Evaluation Metrics

Offered load

= arrival rate * avg request size * avg holding time* Avg path length/Network Capacity

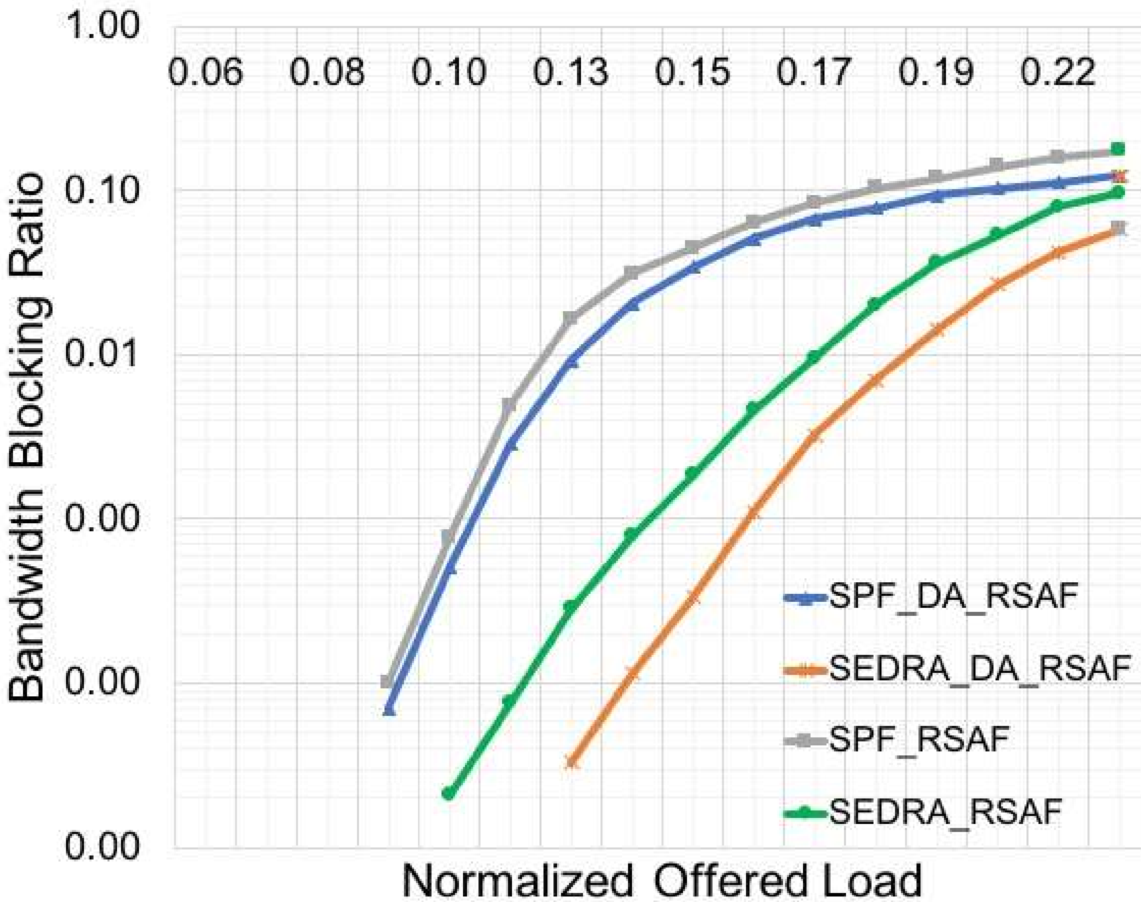
Network Capacity

= #fixed links * channel capacity in GHz * Spectral Efficiency of fixed grid + #flex link * channel capacity in GHz * Spectral Efficiency of flex-grid

Spectral Efficiency of fixed grid = 100/50 = 2 bits/sec/Hz

Spectral Efficiency of fixed grid = 100/37.5 = 2.6 bits/sec/Hz

Results: BBR vs. Offered load



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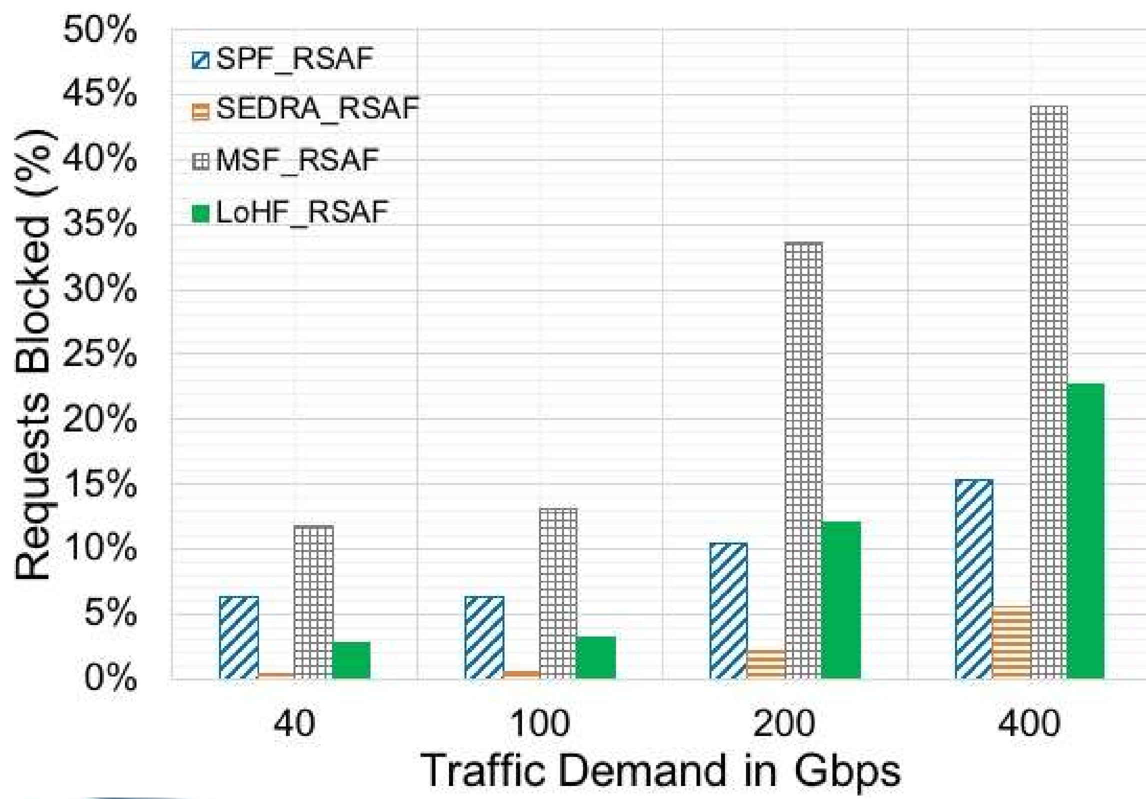
Results: Request Blocked vs. Traffic Demand



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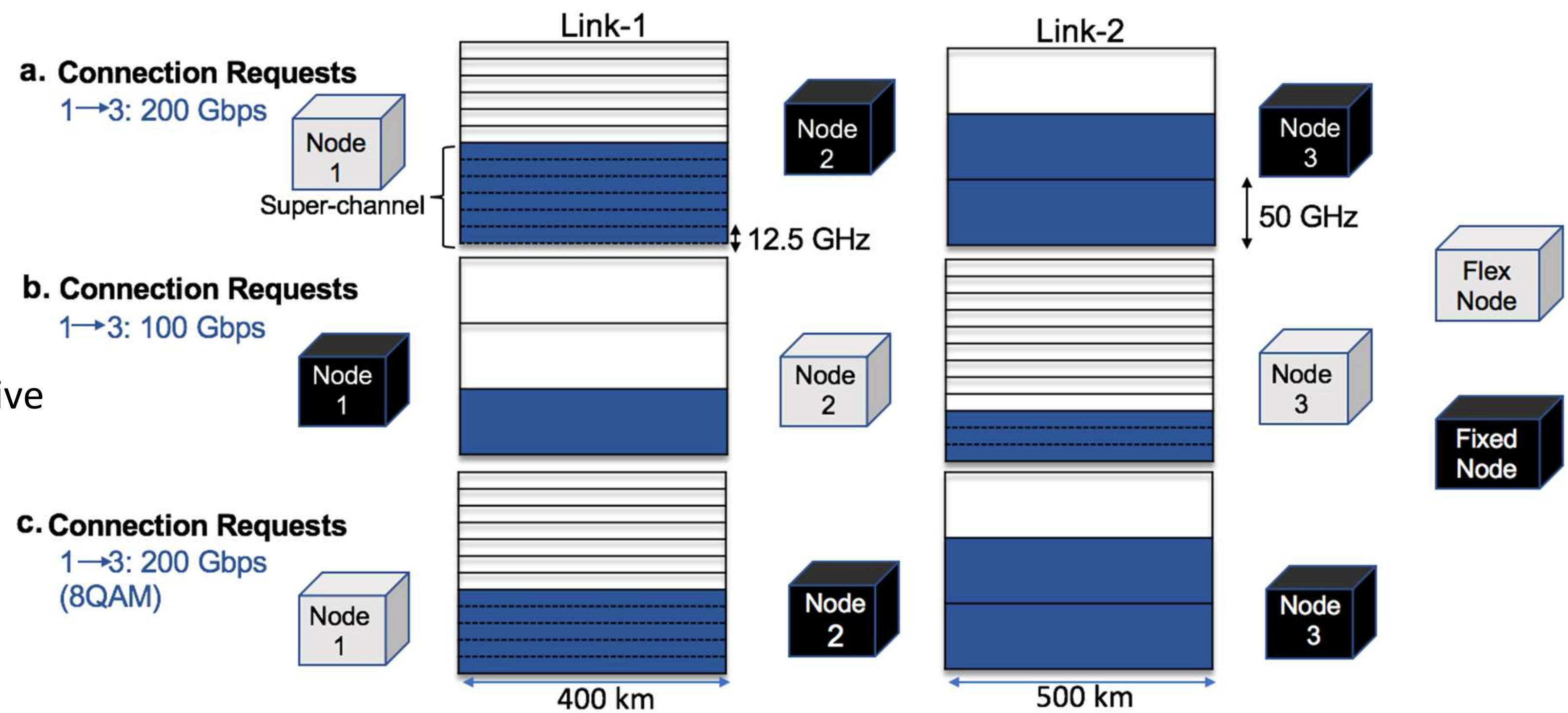
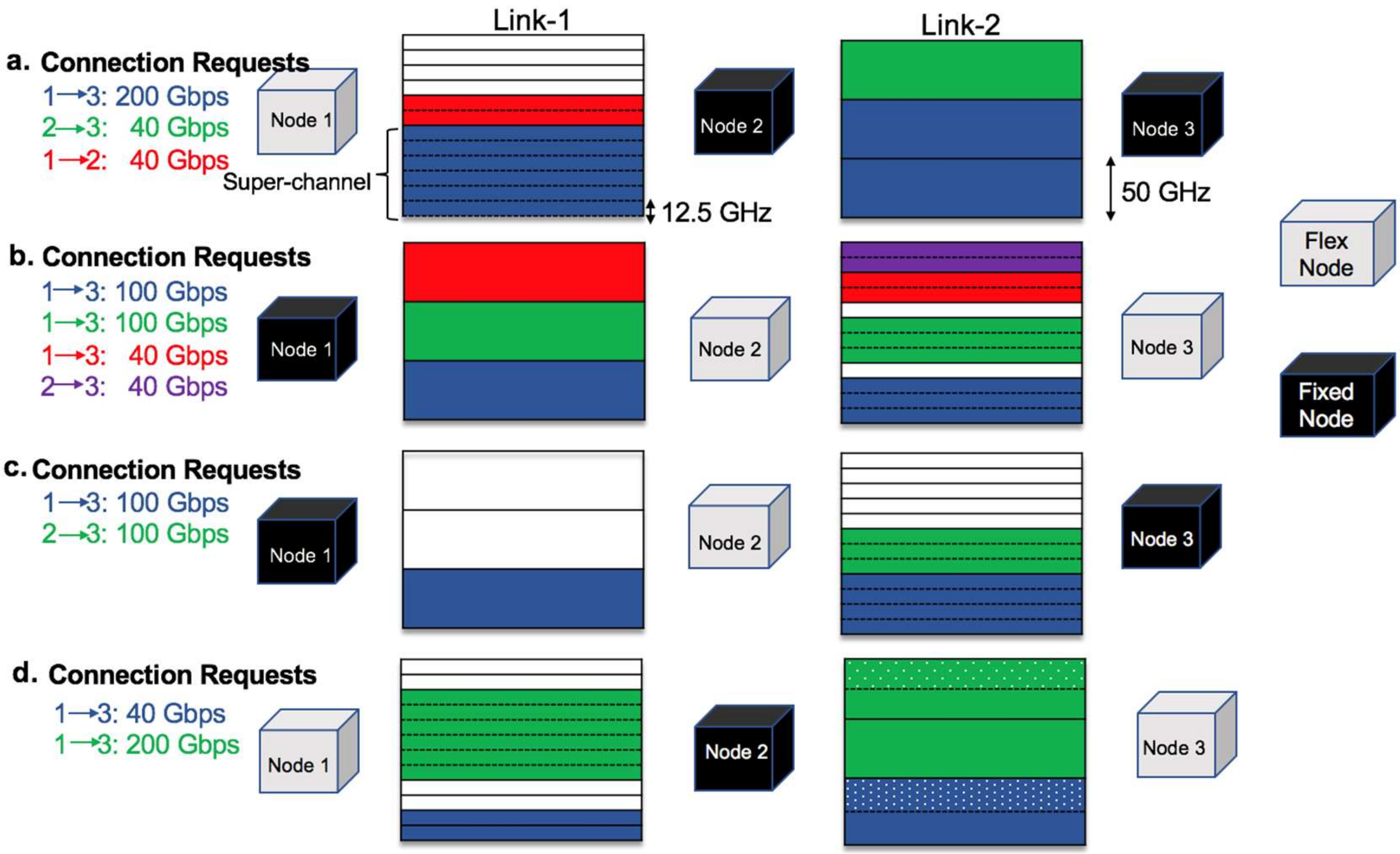
Spectrum and Modulation Format Assignment: Mixed-grid

With QPSK

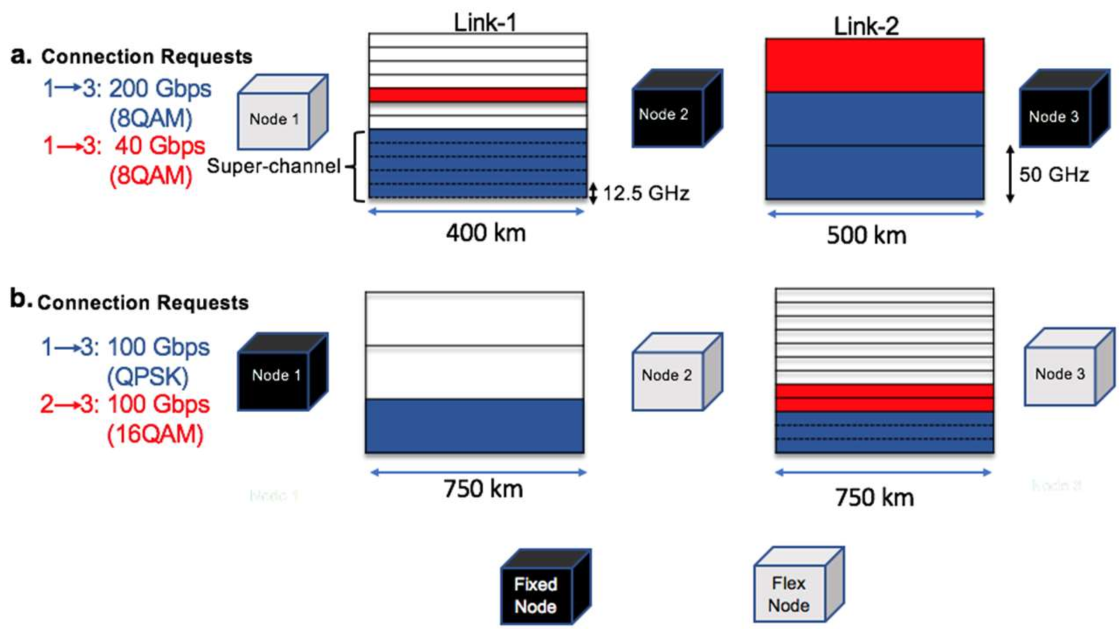
With Distance adaptive modulation format



Spectrum and Modulation Format Assignment: Mixed-grid



Spectrum and Modulation Format Assignment: Mixed-grid

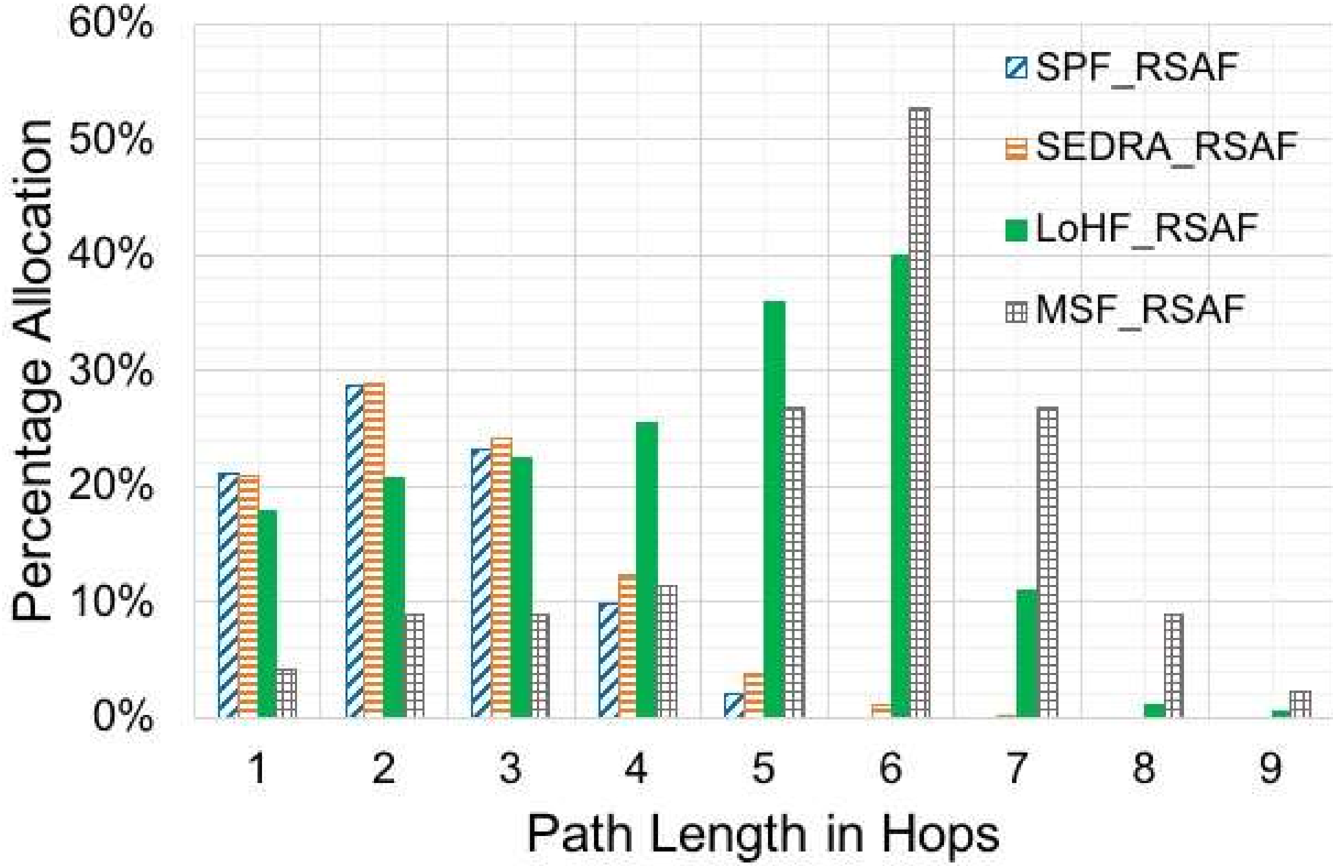


Traffic Profiles

Traffic Profiles

Traffic Demand (Gb/s)	Profile 1	Profile 2	Profile 3
40	50%	20%	0%
100	30%	50%	40%
200	15%	20%	40%
400	5%	10%	20%

Spectrum and Modulation Format Assignment: Mixed-grid



Proposed Algorithm

Algorithm 1 Spectrum Efficient Dynamic Route and Spectrum Allocation (SEDRA)

Input: $N(V, E), p_{s,d}, \alpha_{s,d}$;
Output: Route, Spectrum, and Modulation Format;
for each connection request $(\alpha_{s,d})$ **do**
    $P_{s,d} \leftarrow$ find set of k-shortest paths $\alpha_{s,d}$;
        $\triangleright$ list of candidate paths with available spectrum
    for each $p_{s,d}$ **in** $P_{s,d}$ **do**
        if $(spectrum\_avail(p_{s,d}, \alpha_{s,d}) == True)$ **then**
            $\kappa_{s,d} \leftarrow \kappa_{s,d} \cup p_{s,d}$;
        end if
    end for
    for each $p_{s,d}$ **in** $\kappa_{s,d}$ **do**
        $m \leftarrow modulation\_format(p_{s,d}, \alpha_{s,d})$;
        $\gamma_T^p \leftarrow calculate\_spectrum(p_{s,d}, \alpha_{s,d}, m)$;
            $\triangleright$ find path requiring least spectrum for $\alpha_{s,d}$
        if γ_T^p is lowest **then**
            $\gamma_{min}^p \leftarrow \gamma_T^p$;
            $p_{s,d}^{best} \leftarrow p_{s,d}$;
            $m^{best} \leftarrow m$;
        end if
    end for
    Allocate lightpath on $p_{s,d}^{best}$ using modulation format m^{best} to achieve minimum spectrum allocation of γ_{min}^p;
end for

Proposed Algorithm

Algorithm 2 spectrum_avail()

Input: $p_{s,d}, \alpha_{s,d}$;
Output: Boolean, spectrum available or not;
$m \leftarrow modulation\_format(p_{s,d}, \alpha_{s,d})$;
for each link l **in** $p_{s,d}$ **do**
    $\gamma_l^p \leftarrow mixed\_grid\_spectrum(s, l_s, l_e, \alpha_{s,d}, m)$;
    Requested no. of slots, $n \leftarrow \gamma_l^p / W_{fl}$;
        ▷ find n contiguous slots on link l
    if $\psi_l^n == false$ **then**
        return $false$;
    end if
end for
return $true$;

Proposed Algorithm

Algorithm 3 mixed_grid_spectrum()

Input: $s, l_s, l_e, \alpha_{s,d}, m$;
Output: γ_l^p;
if $\phi_s == 0$ **then**
    if $\phi_{l_s} == 0$ **then**
        $calculate\_spectrum(0, \alpha_{s,d}, m)$
        ▷ check node type: fixed/flex-grid;
    else if $(\phi_{l_s} == 1 \;\; \& \; \phi_{l_e} == 0)$ **then**
        $calculate\_spectrum(0, \alpha_{s,d}, m)$;
    else if $(\phi_{l_s} == 1 \;\; \& \; \phi_{l_e} == 1)$ **then**
        $calculate\_spectrum(1, \alpha_{s,d}, m)$;
    end if
else
    if $\phi_{l_s} == 1$ **then**
        $calculate\_spectrum(1, \alpha_{s,d}, m)$;
    else if $(\phi_{l_s} == 0 \;\; \& \; \phi_{l_e} == 1)$ **then**
        $calculate\_spectrum(0, \alpha_{s,d}, m)$;
    else if $(\phi_{l_s} == 0 \;\; \& \; \phi_{l_e} == 0)$ **then**
        $calculate\_spectrum(0, \alpha_{s,d}, m)$;
    end if
end if
return γ_l^p;

Proposed Algorithm

Algorithm 4 calculate_spectrum()

Input: $\phi_v, \alpha_{s,d}, m$;
Output: γ_T^p;
$\gamma_T^p \leftarrow 0$;
for each link l **in** $p_{s,d}$ **do**
    $\gamma_l^p \leftarrow$ find minimum required spectrum for $\alpha_{s,d}$ and modulation format m from Table I and II;
    $\gamma_T^p \leftarrow \gamma_T^p + \gamma_l^p$;
end for
return γ_T^p;

Algorithm 5 modulation_format()

Input: $p_{s,d}, \alpha_{s,d}$;
Output: m;
$p^l \leftarrow$ find path-length of path $p_{s,d}$;
$p^{fixed} \leftarrow$ find if $p_{s,d}$ has all fixed-grid nodes;
if $p_{fixed} == True$ **then**
    return QPSK;
else
    return highest modulation format with reach p^l for $\alpha_{s,d}$ using II;
end if