Exascale Virtualized and Programmable Distributed Cyber Resource Control

-Software Defined Elastic Optical Network for Petabit Data Movements on Demand-

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Driving Needs for Intelligent Optical Network Infrastructure

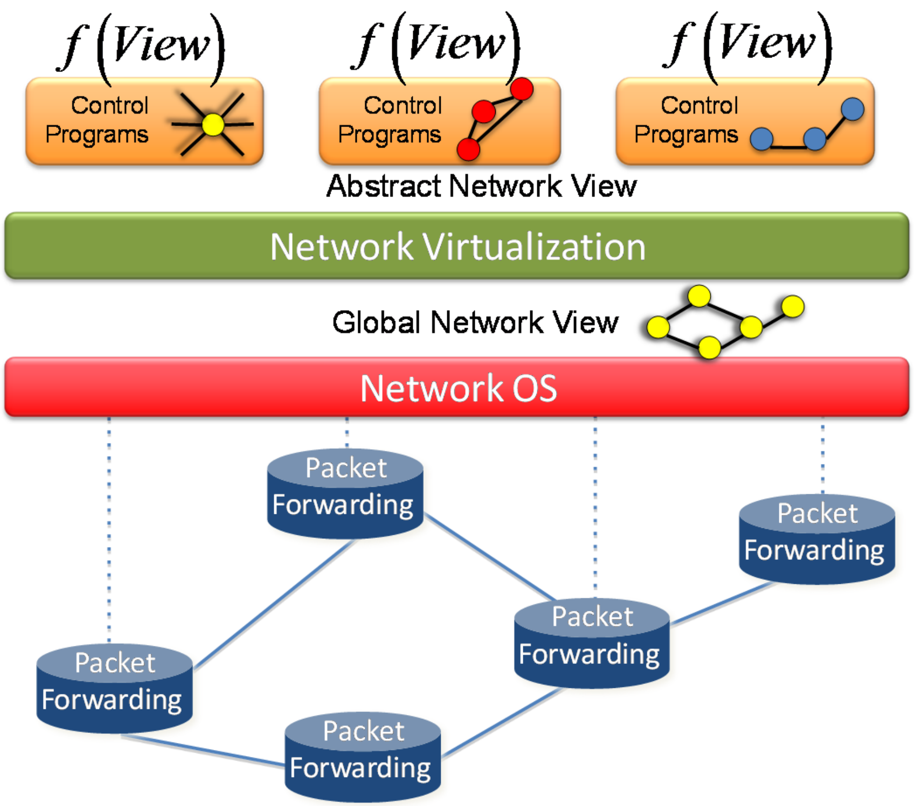
- **Big Data (Data-intensive science)**
- **Extreme-Scale Computing**
- **Network complexities and Scalability**

Software Defined Elastic Optical Networking with Exascale Virtualized and Programmable Distributed Cyber Resource Control

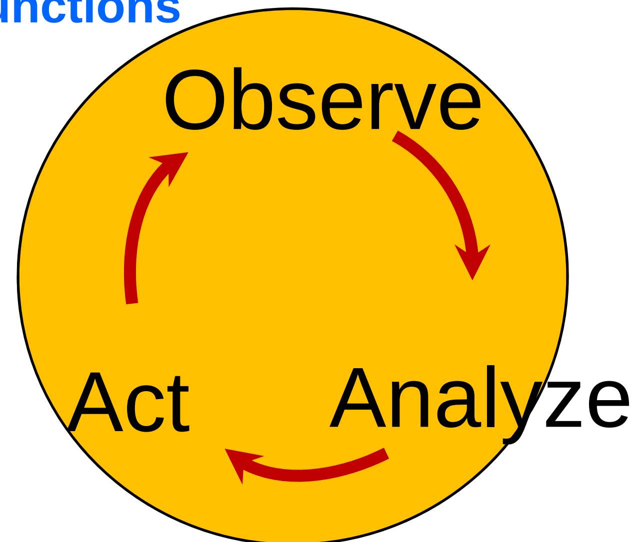
- **Dynamic Assignment of Large Bandwidth On-Demand**
- **Service Automation**
- **Application Aware & Impairment Aware Adaptive Networking**
- **High-Availability and Optimized Operation**
- **Programmability**
- **Virtualized Resource Control**
- **Interoperability and Vendor Neutrality**
- **End-to-End Principle with Intra-domain and Inter-domain Optimization**

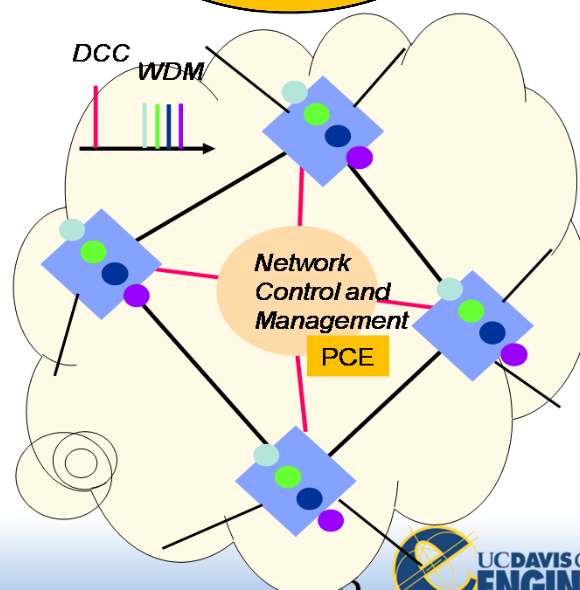
Software Defined Networking =>
Cognitive/Knowledge Plane Optical Networking

Separation of Control Plane and Data Plane
Separation of Forwarding functions and Routing functions
Virtualization of Lower Layer Functions



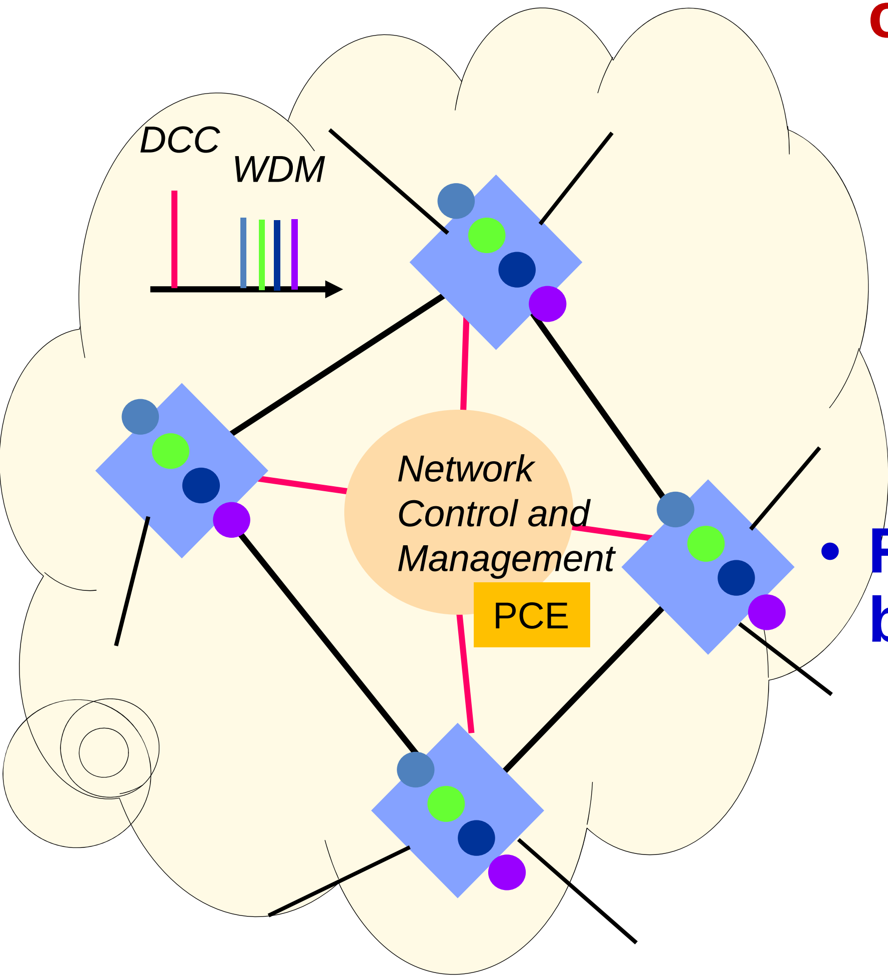
McKeown et al





Hierarchical Intelligent Control & Management

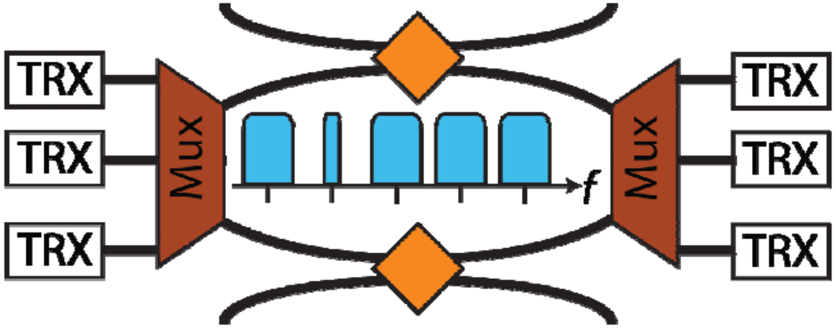
(from 1997 Optical Label Switching SJBYoo)



- **Brain: Interelement Control (out-of-band DCC)**
  - **Slow but elaborate**
  - **Overall abstracted view of network**
  - **Performance monitoring based on labels or abstracted attributes**
  - **Anomaly detection (global)**
  - **Listens and instructs to the Reflex**
- **Reflex: Distributed Control (in-band DWDM, Label based)**
  - **Rapid and reflex-like**
  - **Local view of network (details)**
  - **Packet forwarding using labels**
  - **Anomaly detection (local)**
  - **Reports and listens to the Brain**

Transitioning from *DWDM Networking* to *Elastic Optical (Flex Grid) Networking*

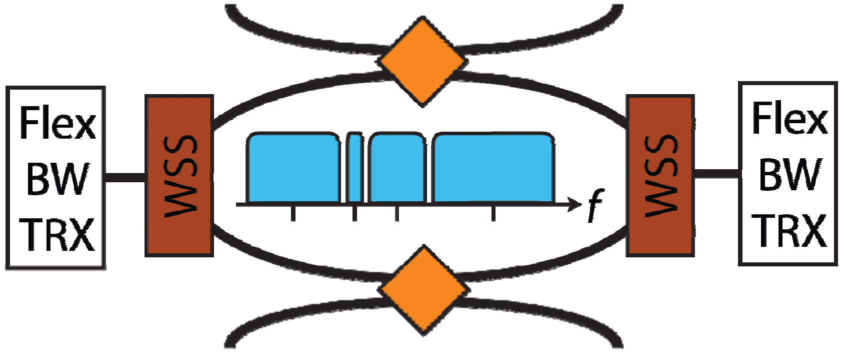
Conventional DWDM Network



TRX = Transmitter and Receiver

- **Limited achievable spectral efficiency due to spectral guard bands**
- **Single channel bandwidths limited by frequency grid spacing**
- **Sub-wavelength and super-wavelength channels difficult**
- **Stranded bandwidth problem**

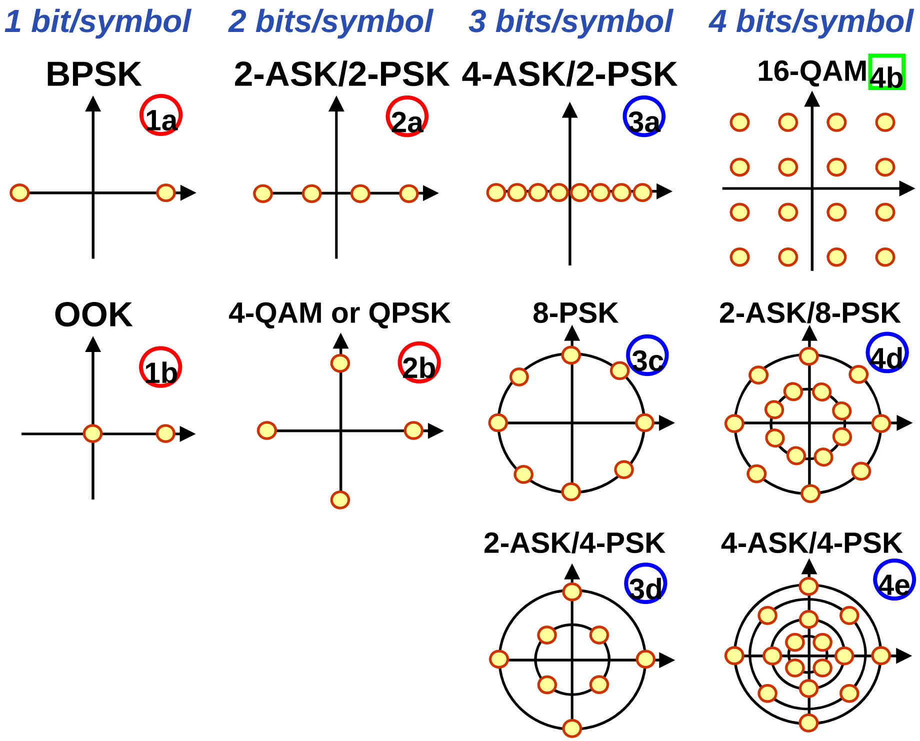
Flexible Bandwidth Network

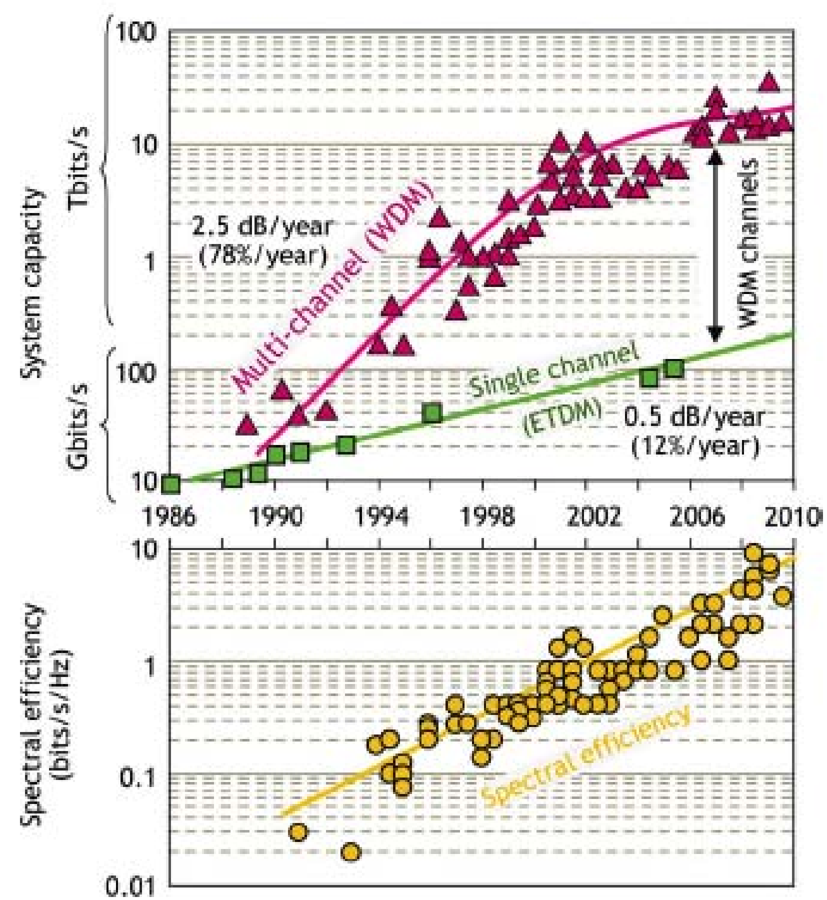


Flex BW TRX = Flexible Bandwidth Transmitter and Receiver

- **Spectral efficiency no longer limited by network architecture**
- **Arbitrary channel bandwidth capable**
- **Arbitrary modulation format capable**
- **Capable of sub-wavelength and super-wavelength channels**

Advanced Modulation Formats for High Spectral Efficiency

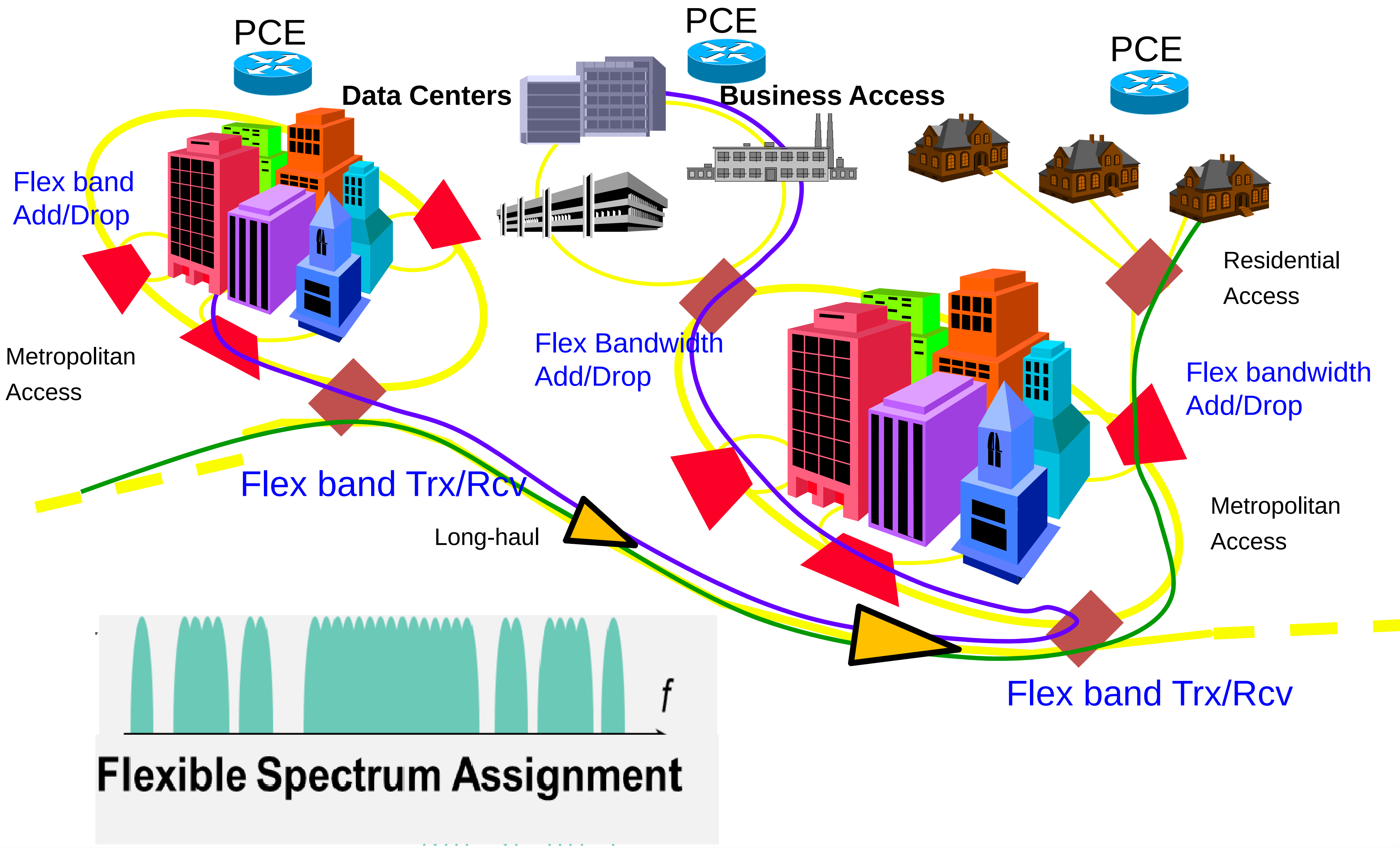




The more information bits the modulation format contains, the more SNR and energy it requires

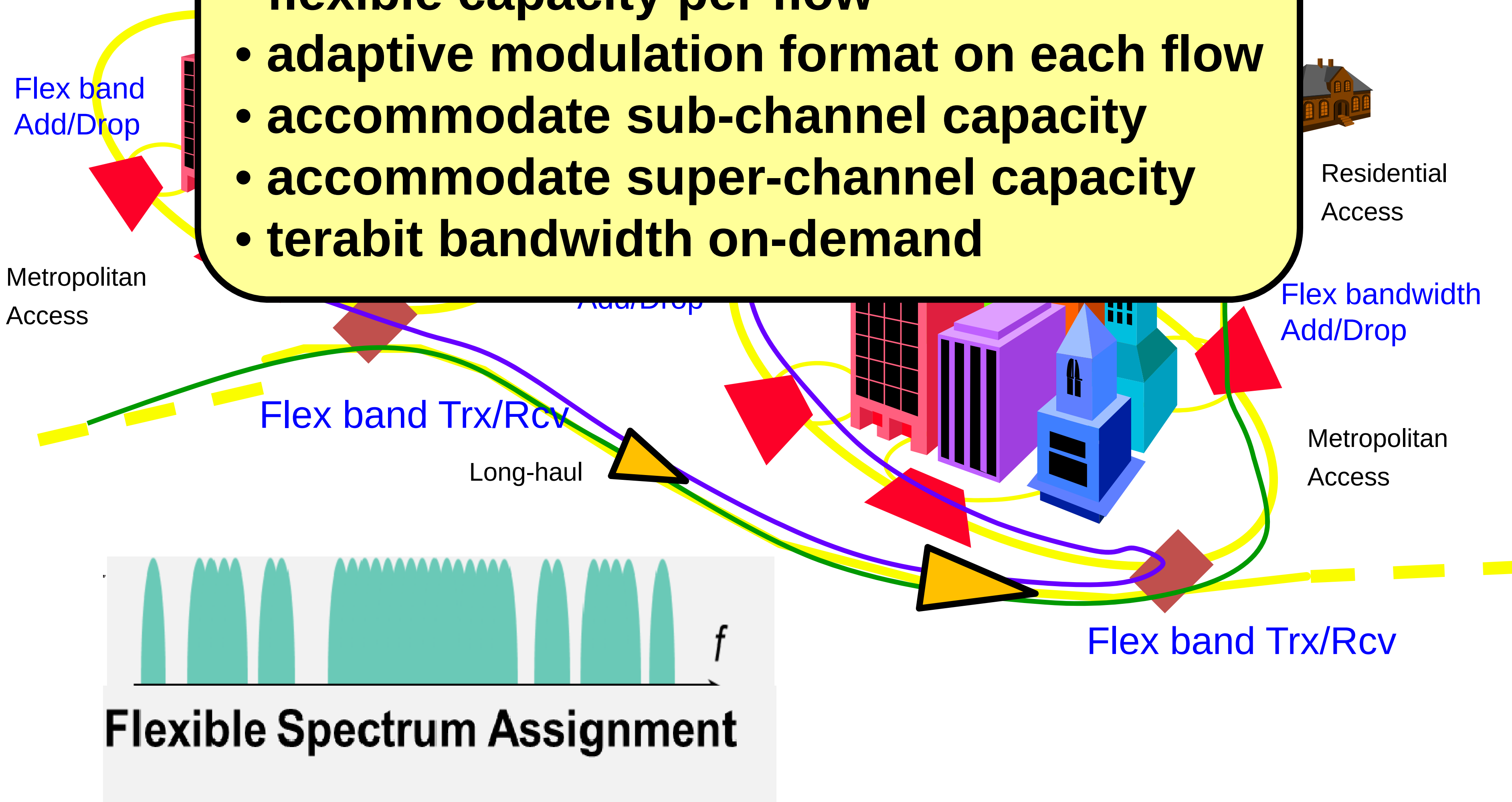
From: Essiambre, Alcatel-Lucent "Capacity Limit of Fiber-Optic Communications," OFC 2009, also JLT 2010

Elastic Optical Networking



Elastic Optical Networking

- efficient use of spectrum (~30% savings)
- flexible capacity per flow
- adaptive modulation format on each flow
- accommodate sub-channel capacity
- accommodate super-channel capacity
- terabit bandwidth on-demand

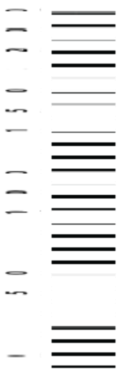


Key Approaches to Elastic Optical Networking

- **Routing Spectrum Modulation Format Assignment (RSMA) with Defragmentation in Temporal, Spectral, and Spatial Domains**
- **QoS-Aware & Impairment-Aware Networking**
- **Automatic & Adaptive Operation of Networks**
- **Use Supervisory Channel & Optical Performance Monitoring for EON with Observe-Analyze-Act**
- **Interoperability and backward-compatibility for Seamless Upgrades**
- **SDN with Virtualized Resource Control**
- **Support of Big Data transfer upon demand with efficient resource management.**
- **Multi-domain SDN with brokers**
- **SDN-EON Testbed Studies**

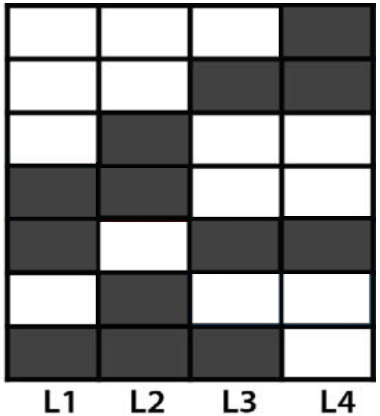
Challenges in EON: Fragmentation increases blocking probability

- Non-contiguous spectrum slots in fiber links (spectral domain fragmentation). Caused by:



  - Non-optimized routing and spectrum assignment algorithms make random or biased use of the spectral resources.
  - Dynamic establishment and tear-down of the end-to-end connections.

- Misaligned unused spectrum slots in the neighboring links (spatial domain fragmentation between links, non-continuous). Caused by:
  - Neighboring links are used by different light path connections.
  - The lack of wavelength conversion capability raises the wavelength continuity constraints.



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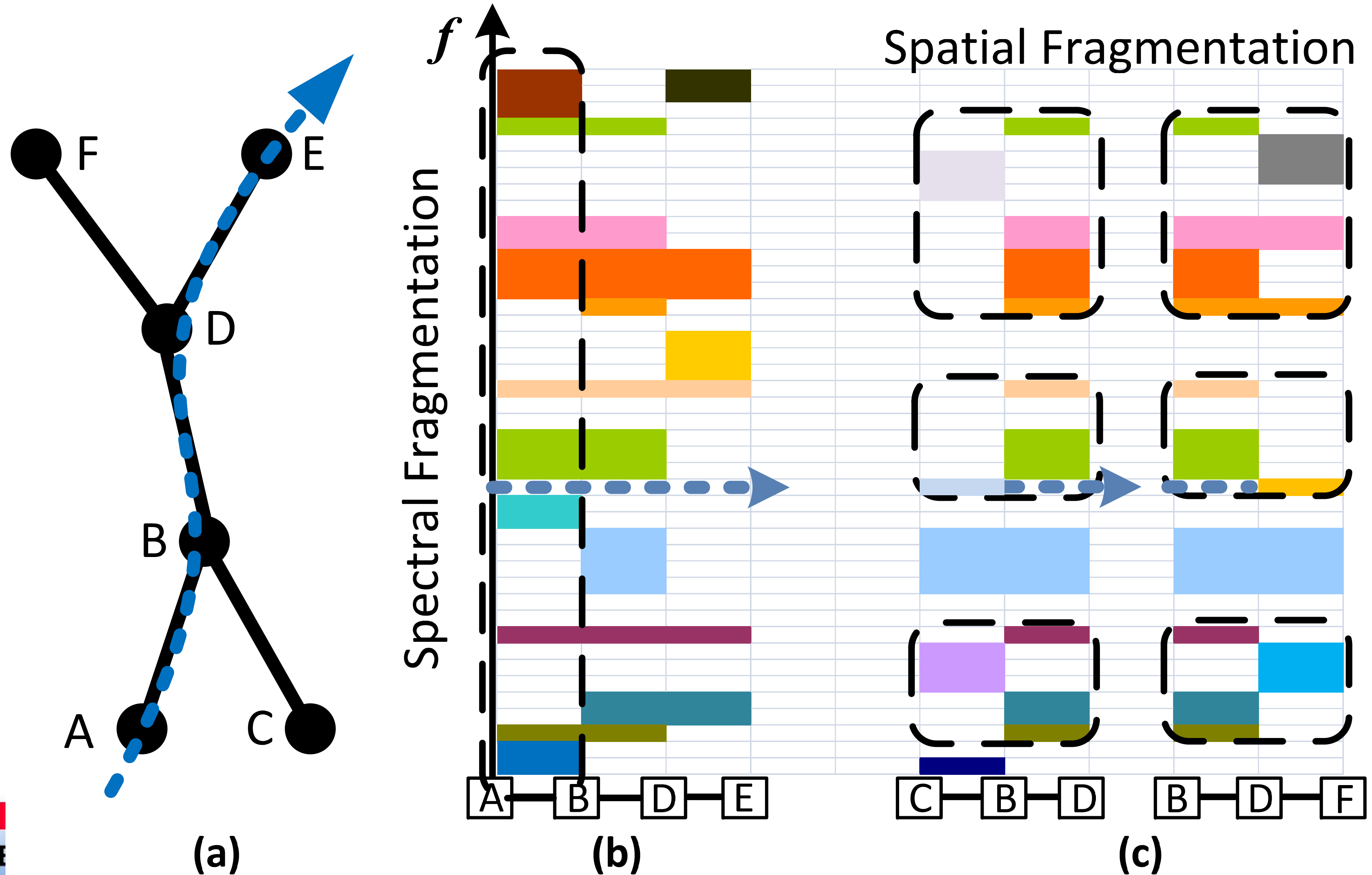
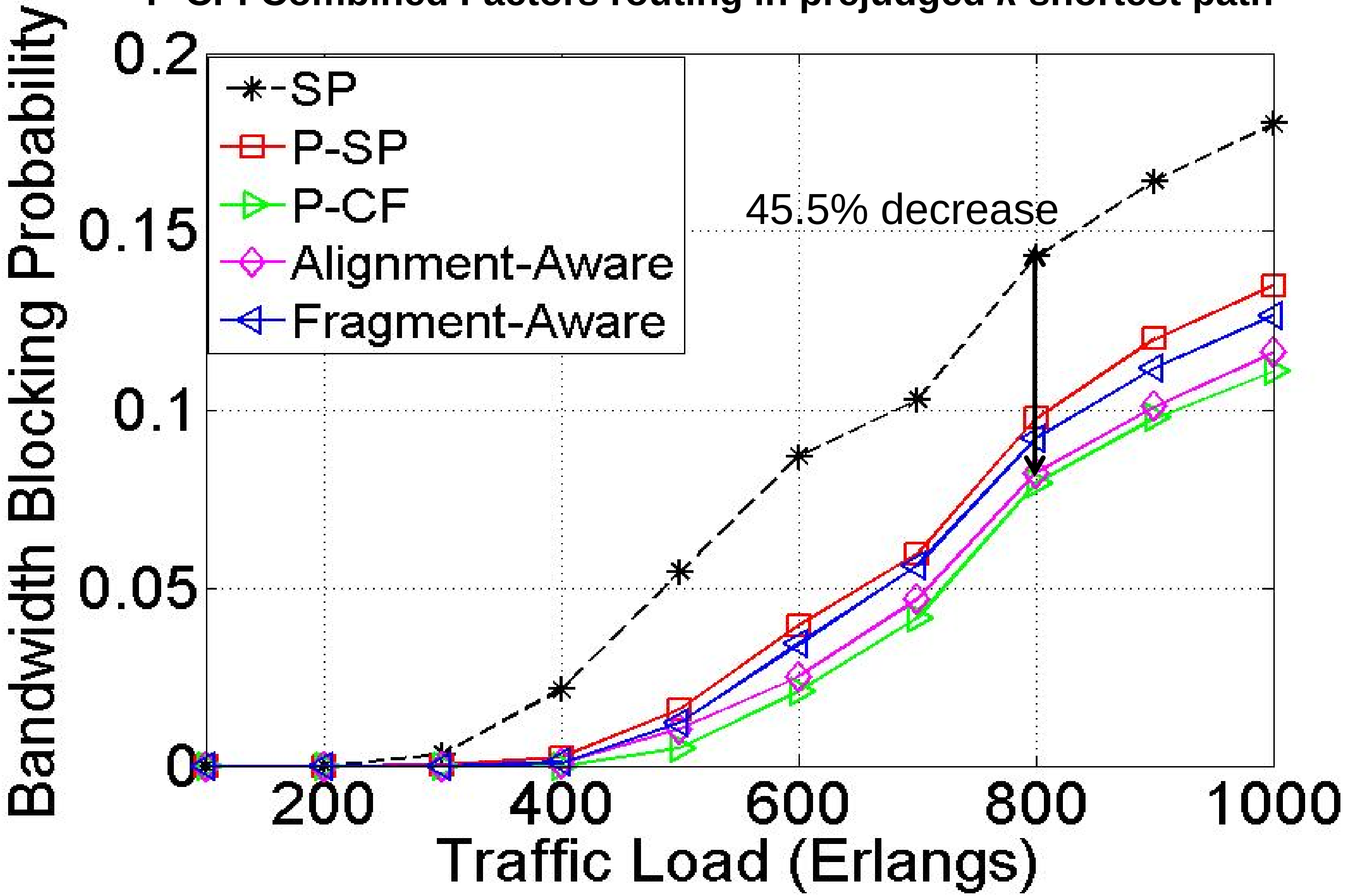
Challenges in EON: Fragmentation increases blocking probability



Fragmentation-Aware and Misalignment Aware RSMA: Simulation Results (Spatio-Spectral Domains)

- **SP: Shortest path routing**
- **P-SP: Shortest path routing in prejudged *k* shortest path**
- **P-CF: Combined Factors routing in prejudged *k* shortest path**



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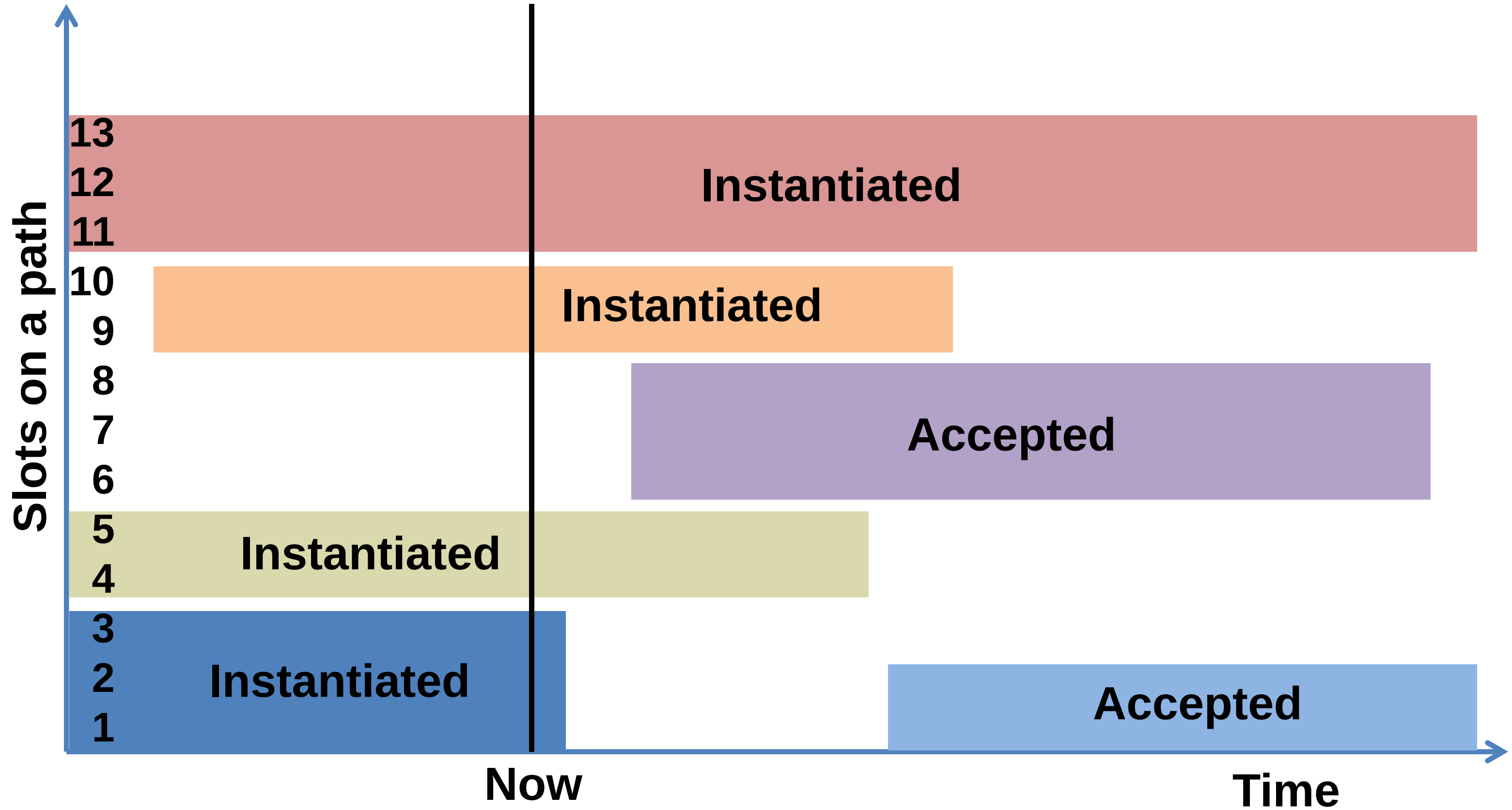
Advanced Reservations of RSMA

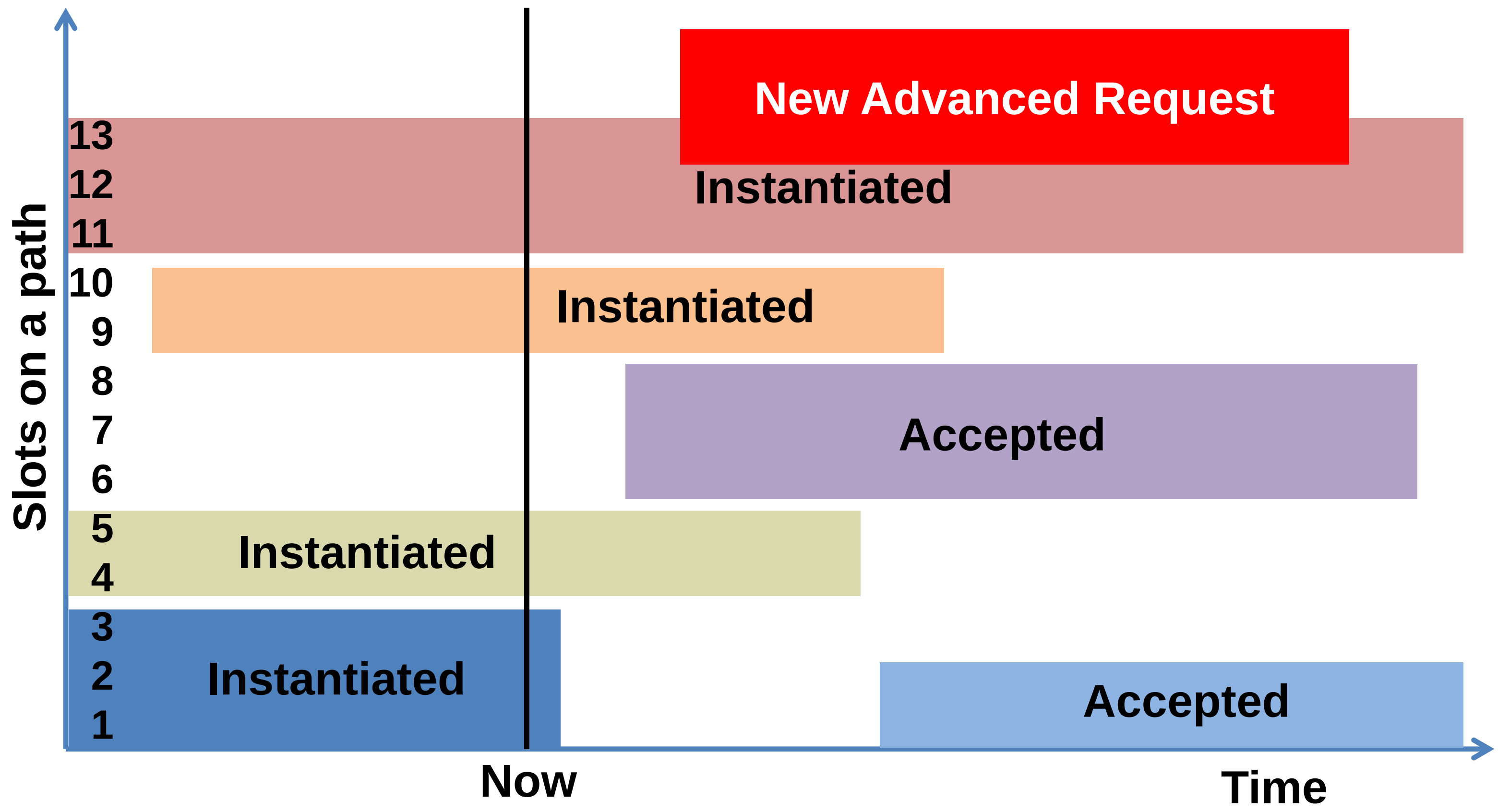
- Resources allocated in the future when an Advanced Reservation is accepted
- Leads to temporal and spatial fragmentation



Ref) X.Yang, T. Lehman, et al., "On M-concurrency path computation and its application in dynamic service Multi-Layer Networks," *ONDM 2010*

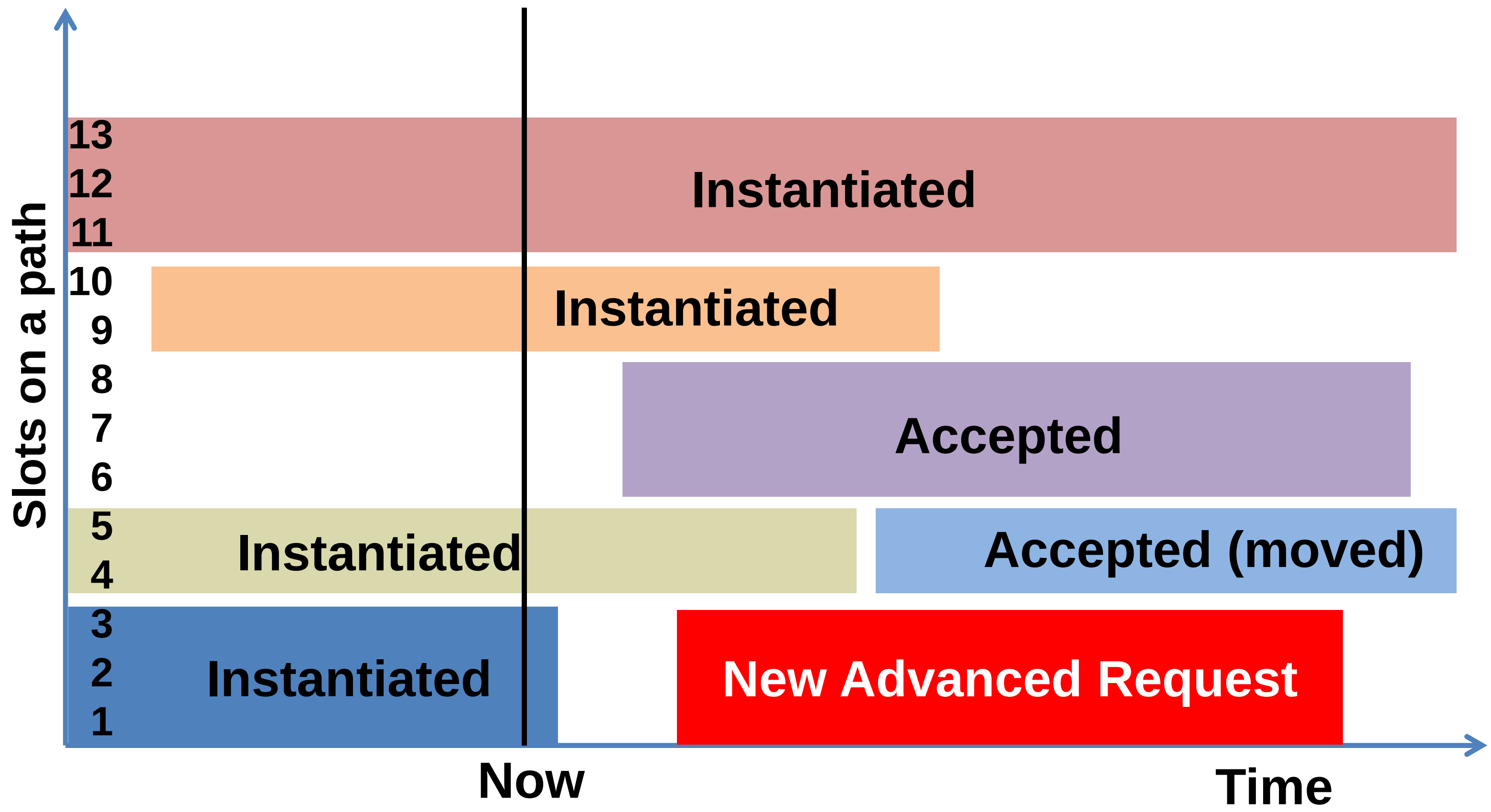
Advanced Reservations of RSMA

- **New Advanced Request may be blocked due to how resources were allocated to earlier Advanced Reservations**

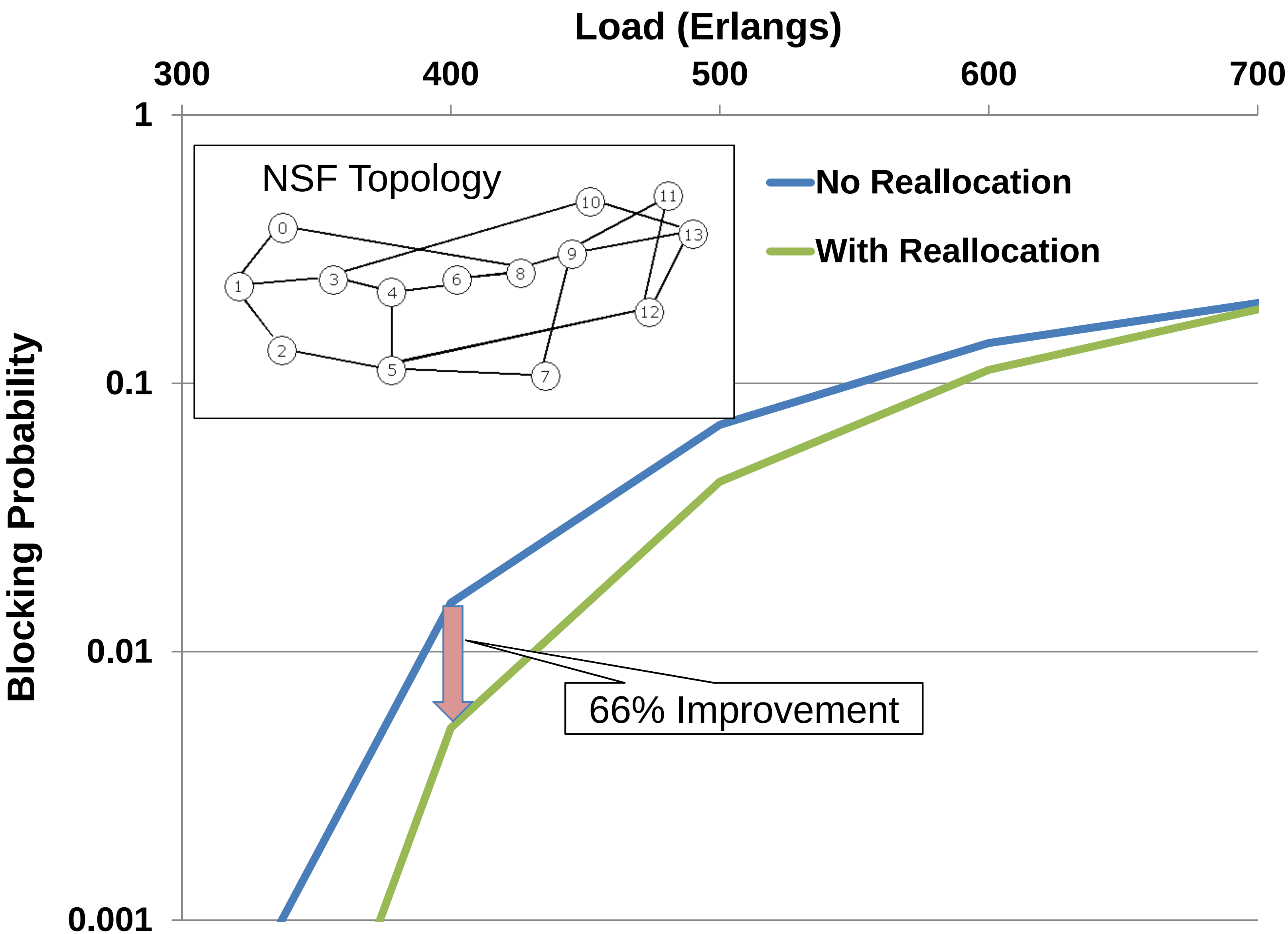


Advanced Reservations of RSMA

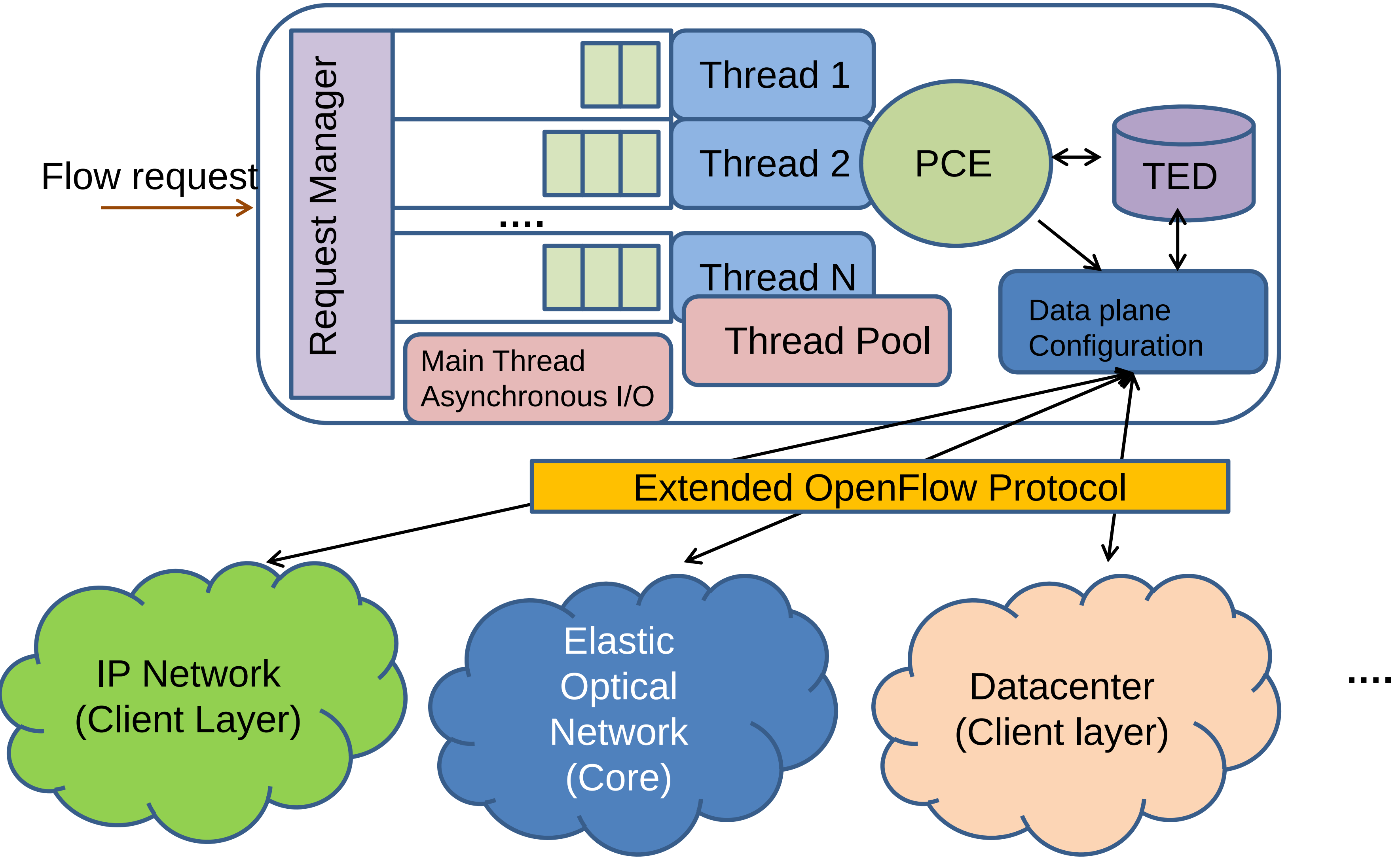
- **Reallocating resources to already accepted reservations can decrease blocking probability**



Temporal-Domain Fragmentation Aware RSMA

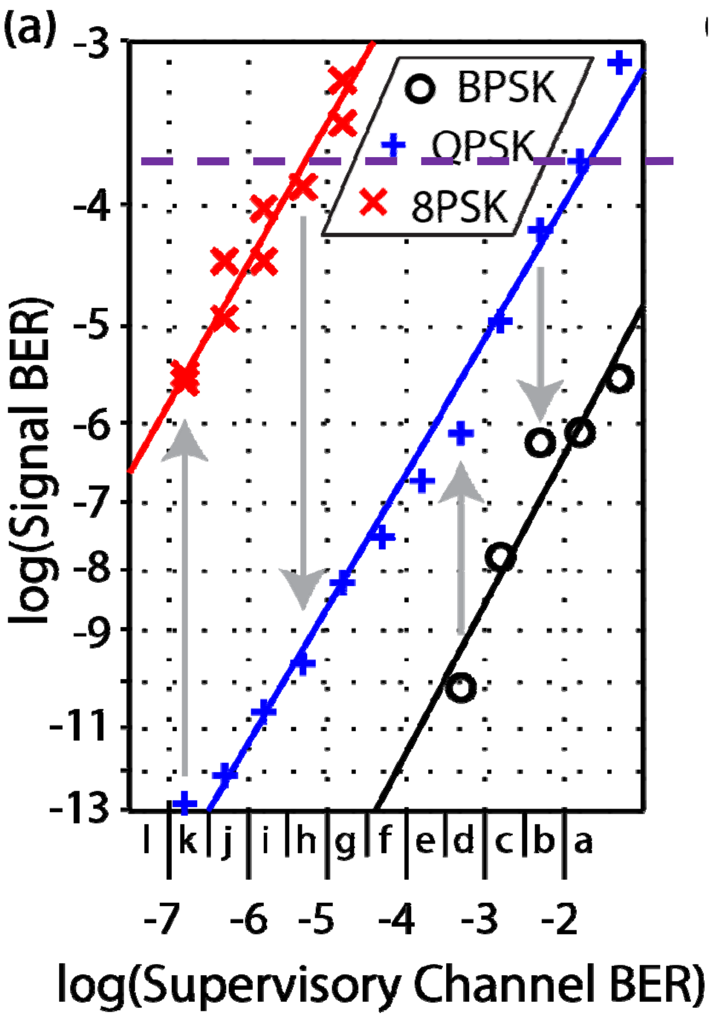


SDN/OpenFlow Controller Design and Implementation

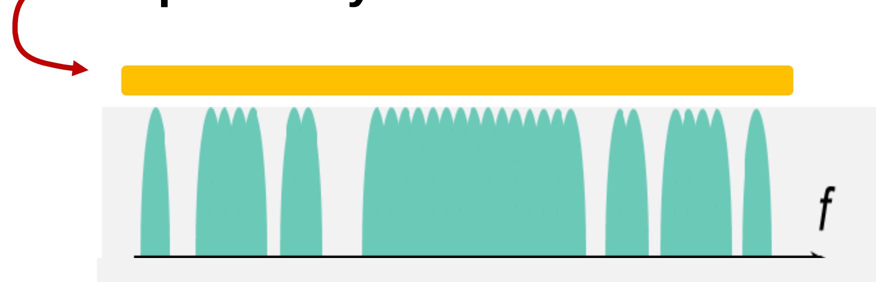


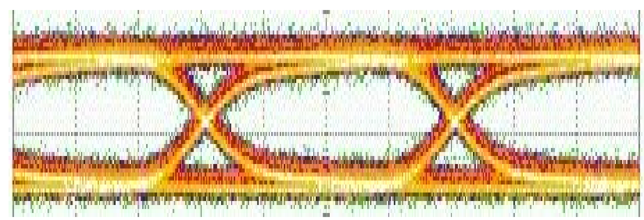
Optical Supervisory Ch. with Performance Monitoring

- **Mapping between low speed supervisory channel BER and high speed signal (360Gb/s) BER**



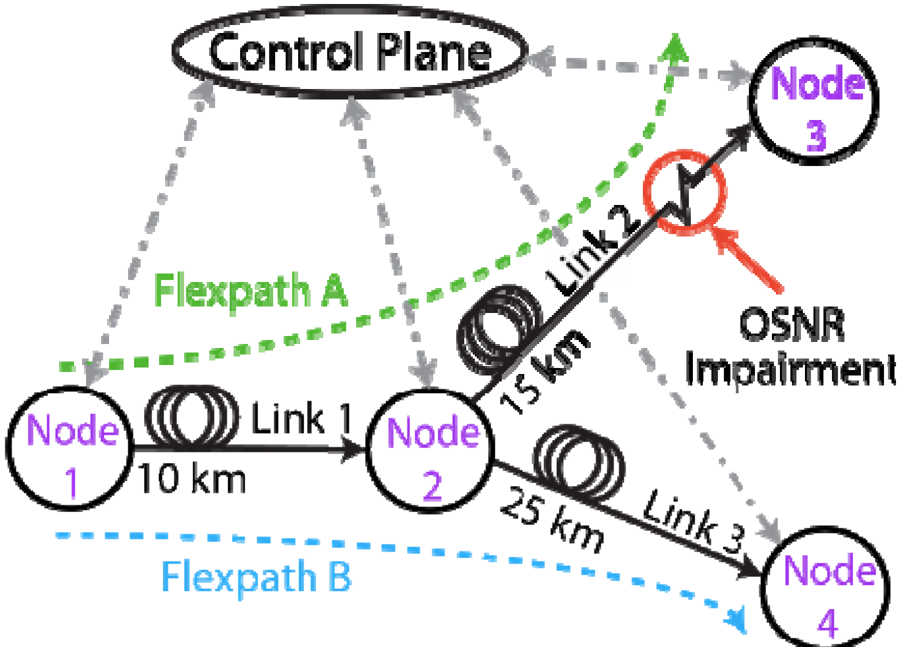
Spread Spectrum Optical Supervisory channel: 2^{31}-1 PRBS

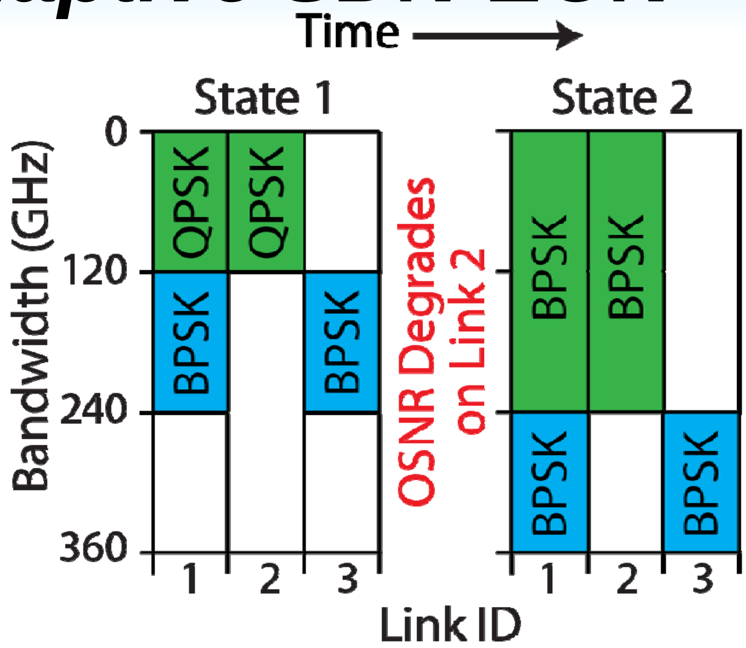


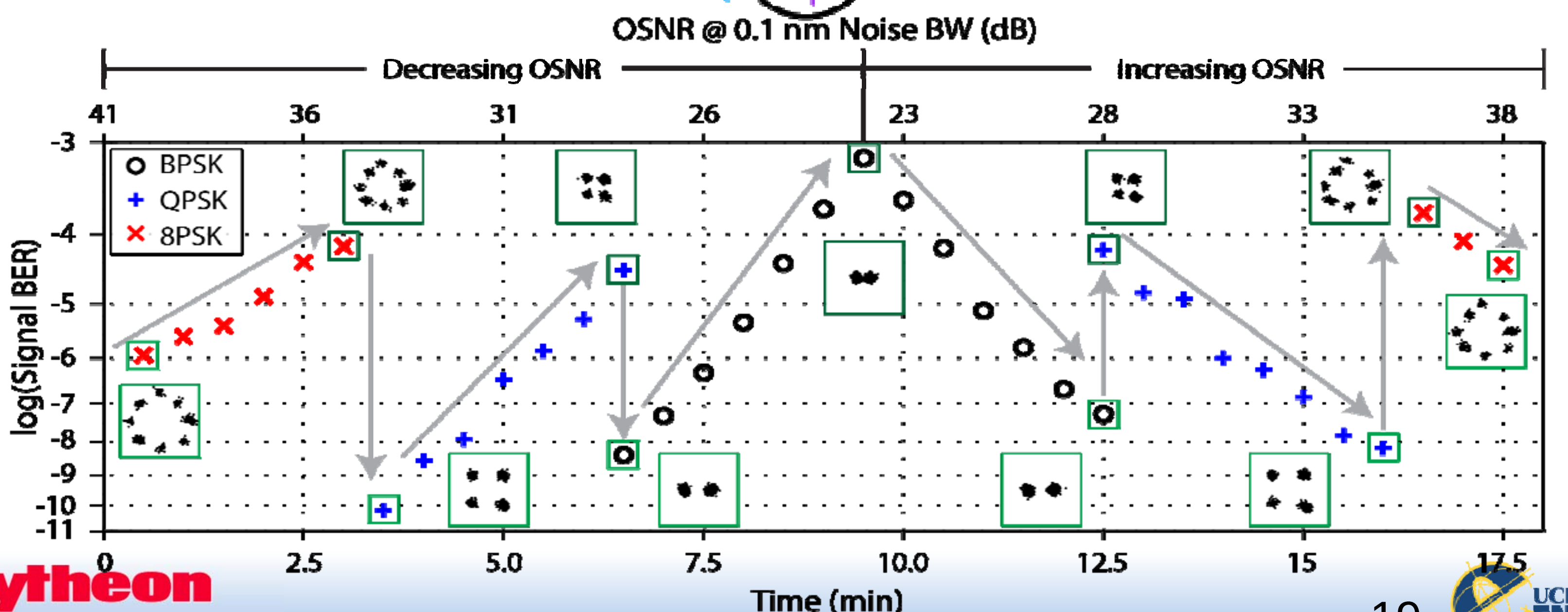


- **The FPGA supervisory channel 1.25 Gb/s PRBS 2^{31} -1 NRZ OOK**
- **BER monitoring at FPGA**
- **If BER fails to meet QoT requirement, modulation format is adjusted**

Real-time, Automatic Adaptive SDN-EON

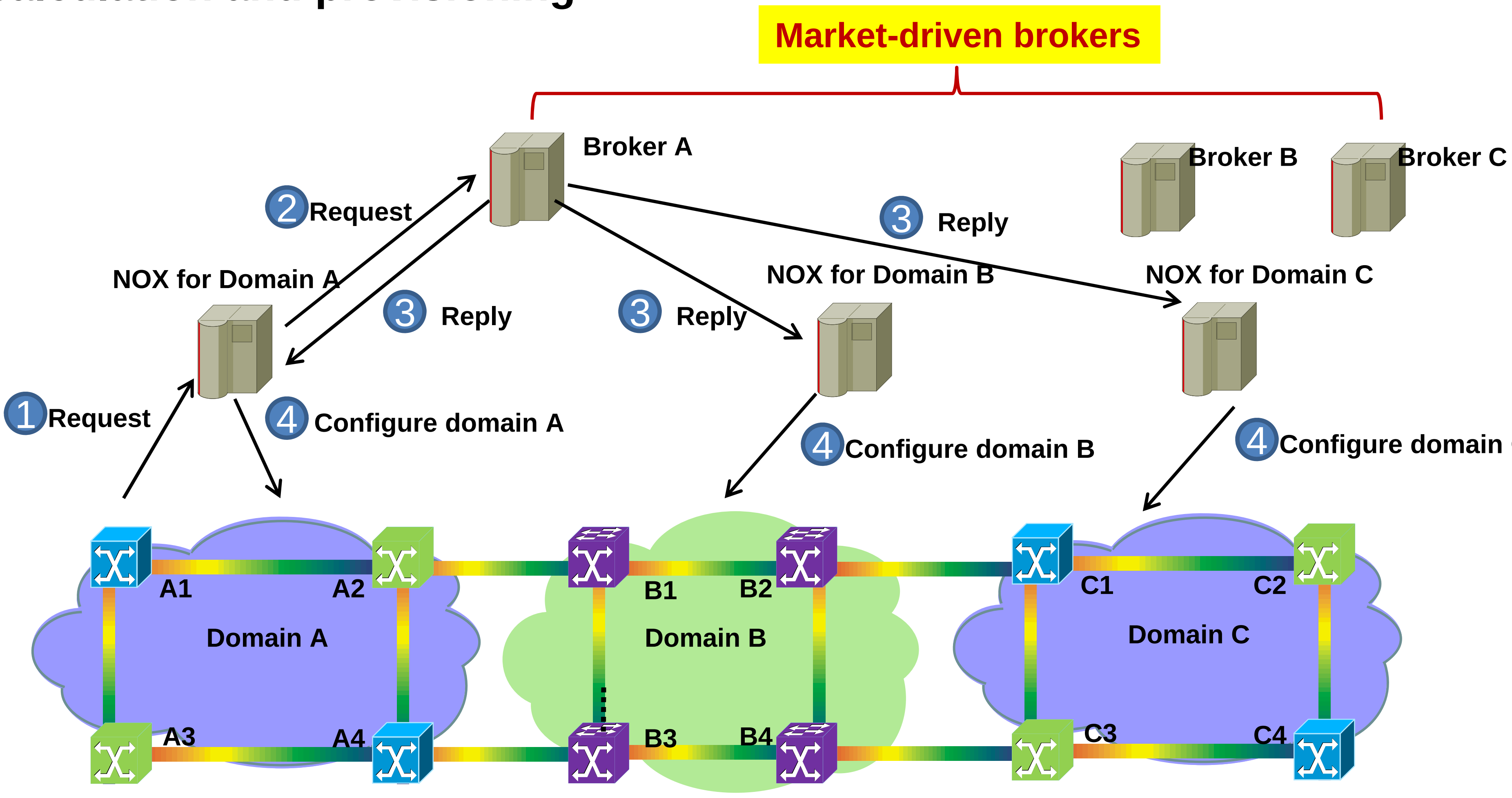






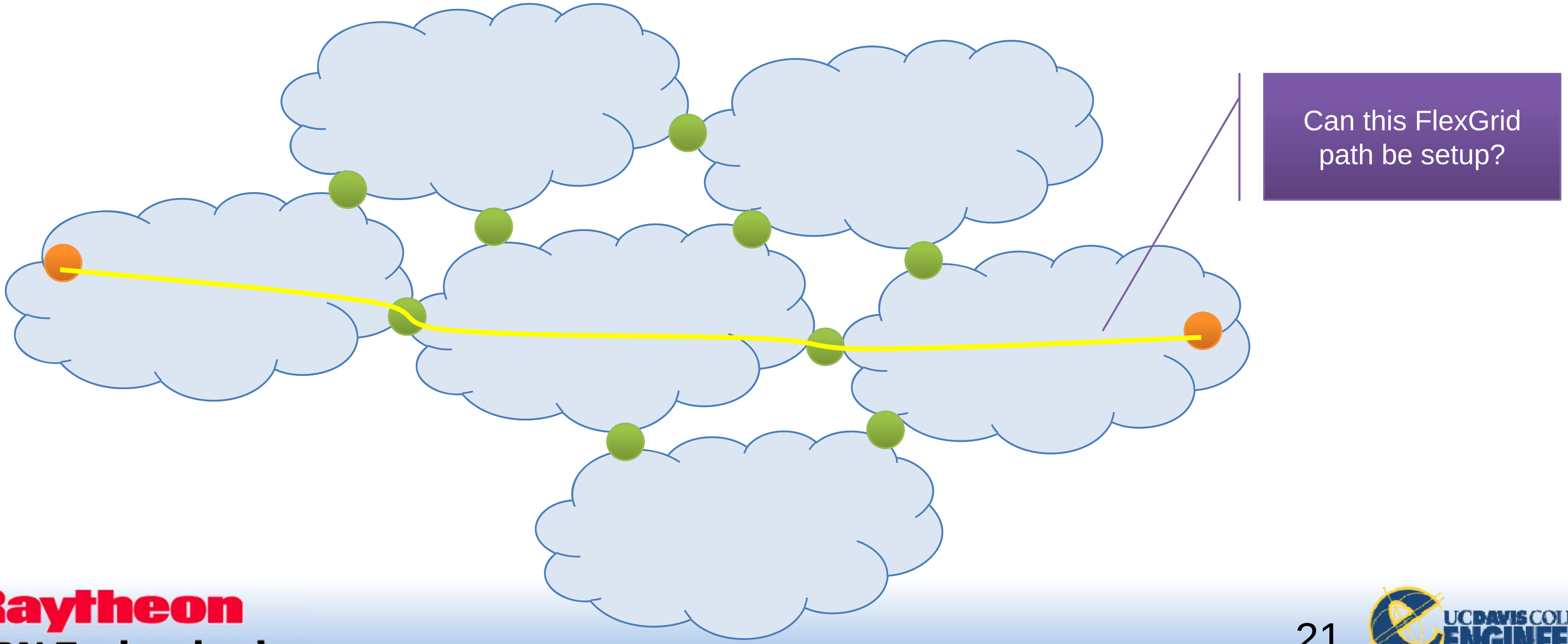
Inter-domain control framework

Broker-based solution: using a broker to coordinate inter-domain path calculation and provisioning



Domain Virtualization

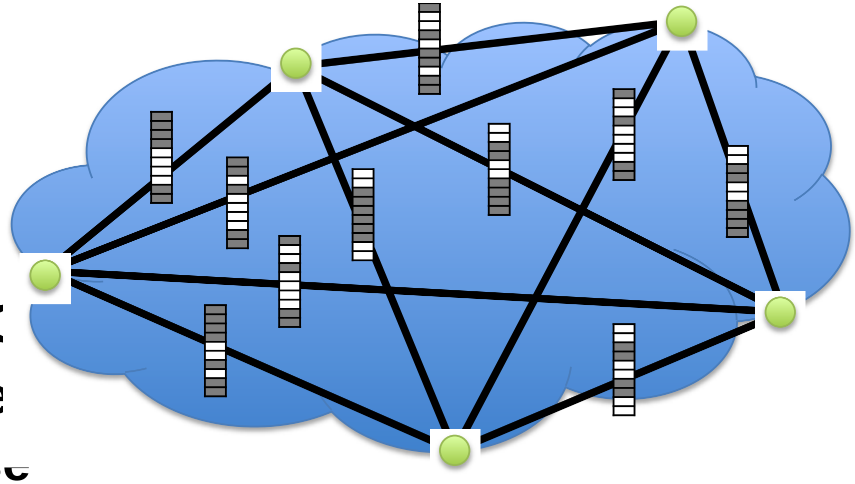
- **Domain manager provides virtualized resources:**
  - **Spectral resources**
  - **Path resources including gateways**
  - **Time resources**
- **Broker selects domains and gateways for setting up path**



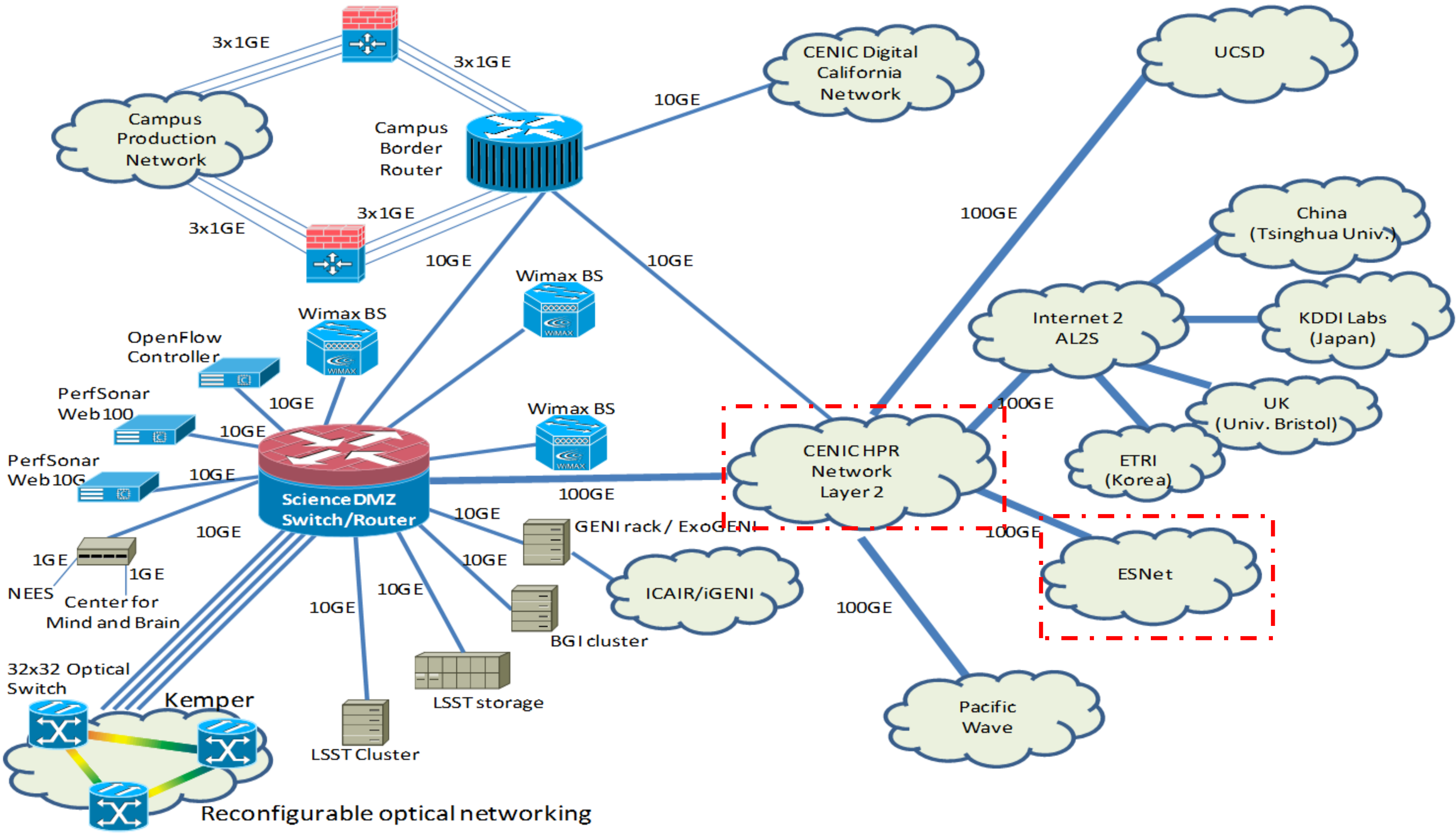
Domain Virtualization for EON

- **Broker provides domain controllers with time interval associated with new request**
- **Domain manager**
  - **Defines virtual links between gateway pairs**
  - **Finds path(s) between each pair of gateways**
  - **Determines spectral channel availability on each path between gateway pairs**
  - **Reports availability on a per-virtual link basis**
- **Broker uses virtual links to**
  - **Determine which domains to use**
  - **Determine which gateways to use**

when setting up an end-to-end circuit



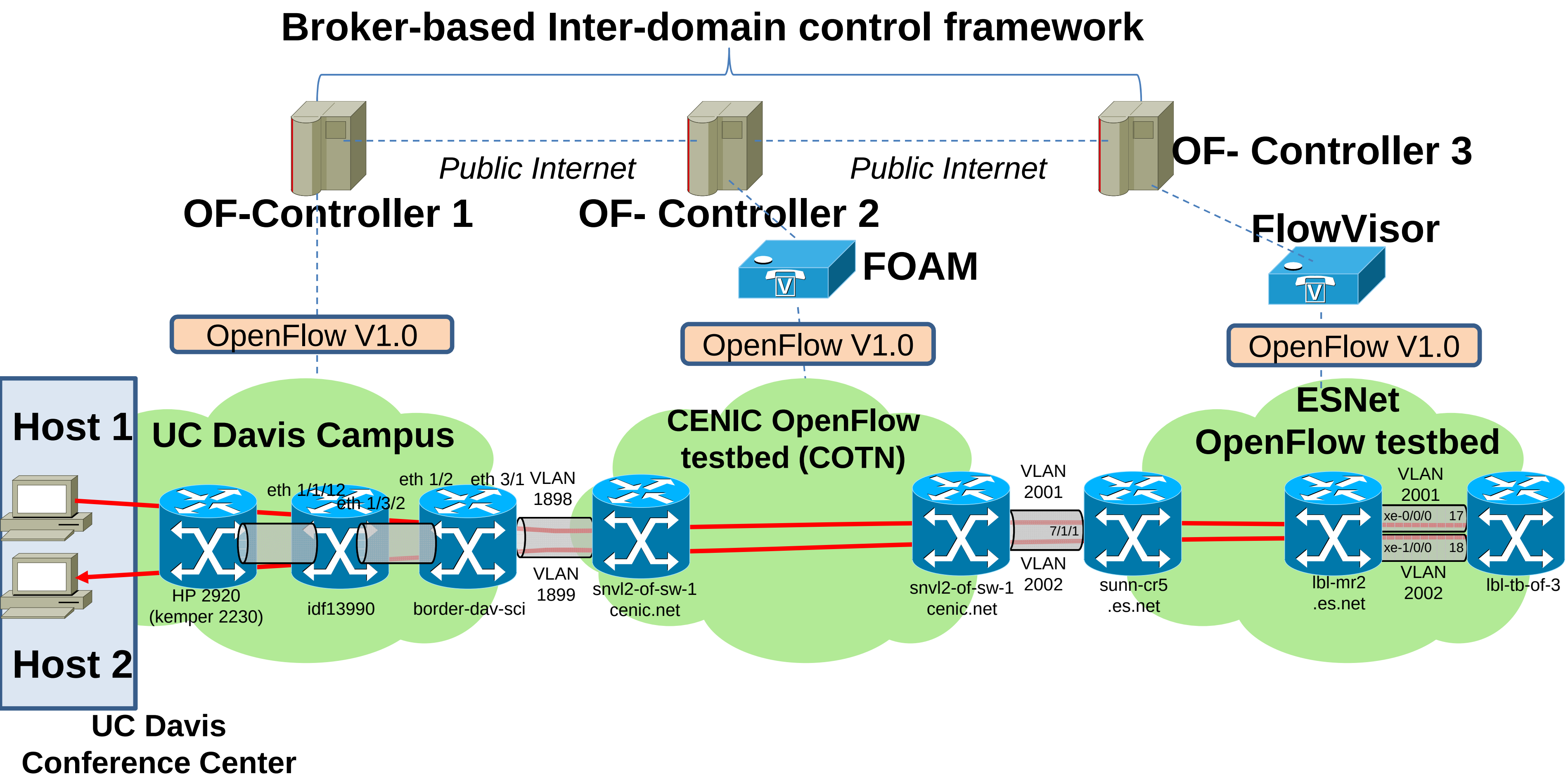
SDN experiments across UC Davis- CENIC (COTN)-ESnet



UC Davis Campus Network and its Connectivity

Multi-domain UCD-COTN-ESNet SDN demo

Dynamic end-to-end multi-domain path creation and flow transmission by using our broker-based inter-domain control framework



Next Steps

- **Integrate algorithms for defragmentation in spectral-spatial-temporal domains**
- **Extend RSMA to incorporate cross-layer optimization**
- **More on Resource and Domain Virtualization**
- **Implement FlexGrid RSMA within OSCARS**
- **Develop multi-domain FlexGrid RSMA using virtualized resource model and brokers**
- **Testbed experiments with multi-domain OpenFlow controller with brokers and resource virtualization**

What question does your research motivate you to now ask?

- **What is the DoE's requirements/specs for multi-domain optical networking?**
- **Can application-network integration achieved with our distributed resource control tools?**
- **Can end-to-end performance effectively enhanced across multiple administrative domains?**