Hybrid Optical Packet and Circuit Switching in Spatial Division Multiplexing Fiber Networks

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- Integrated OPS and OCS
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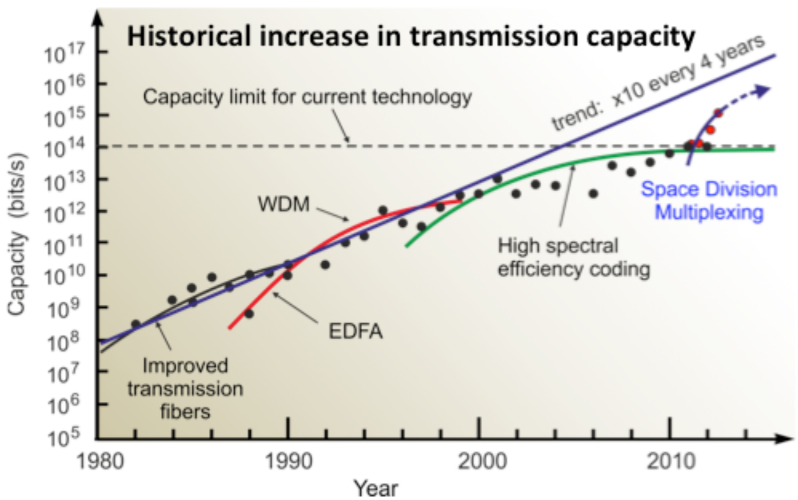
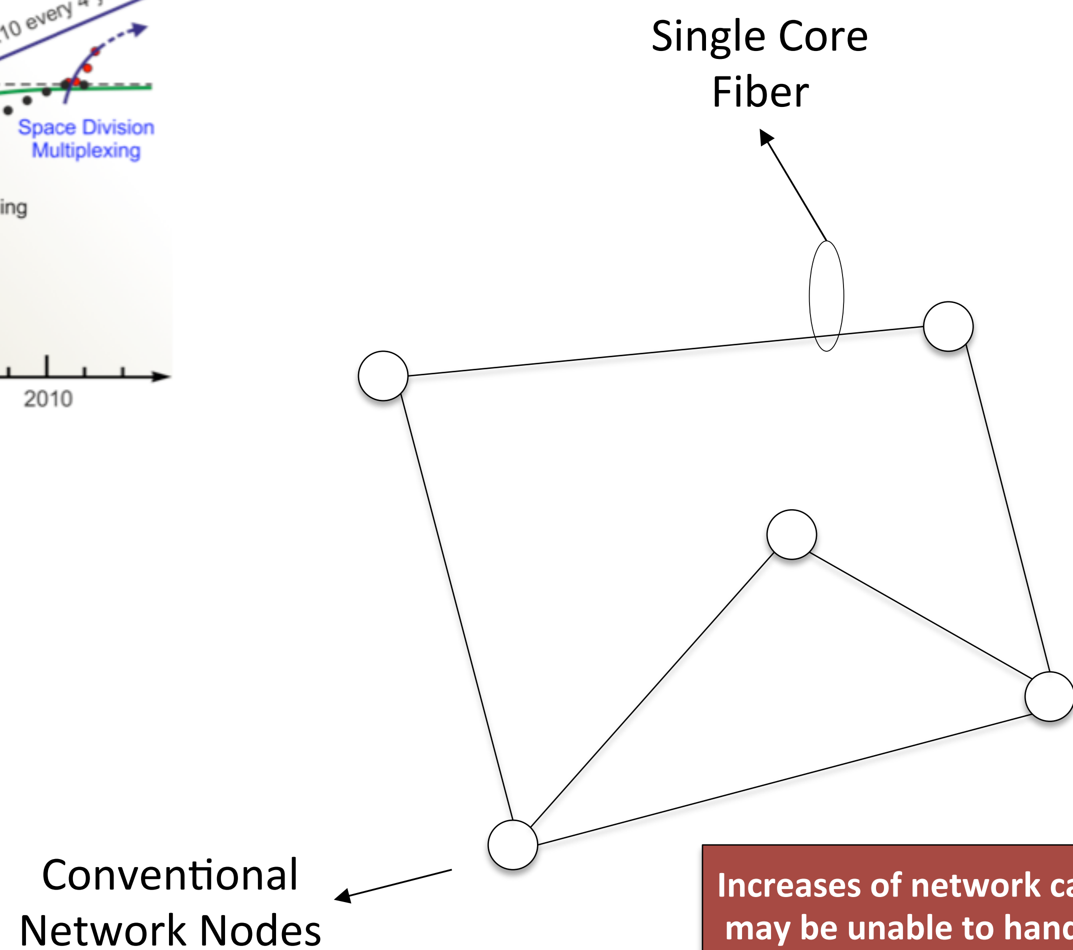
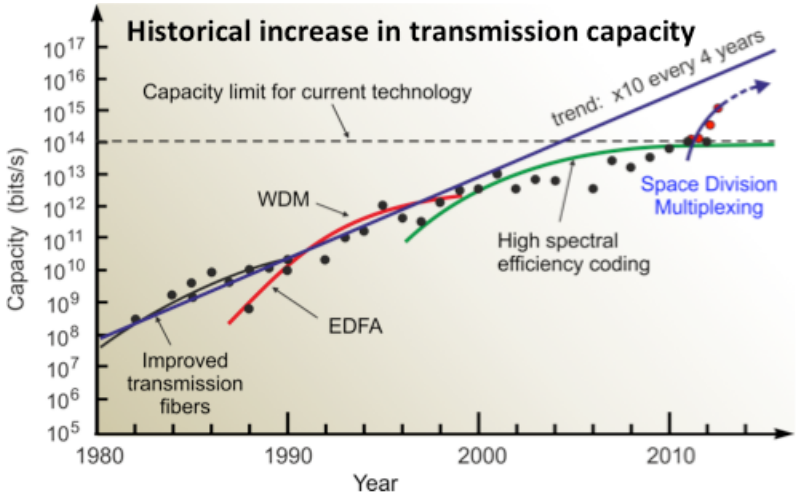
SDM Networks

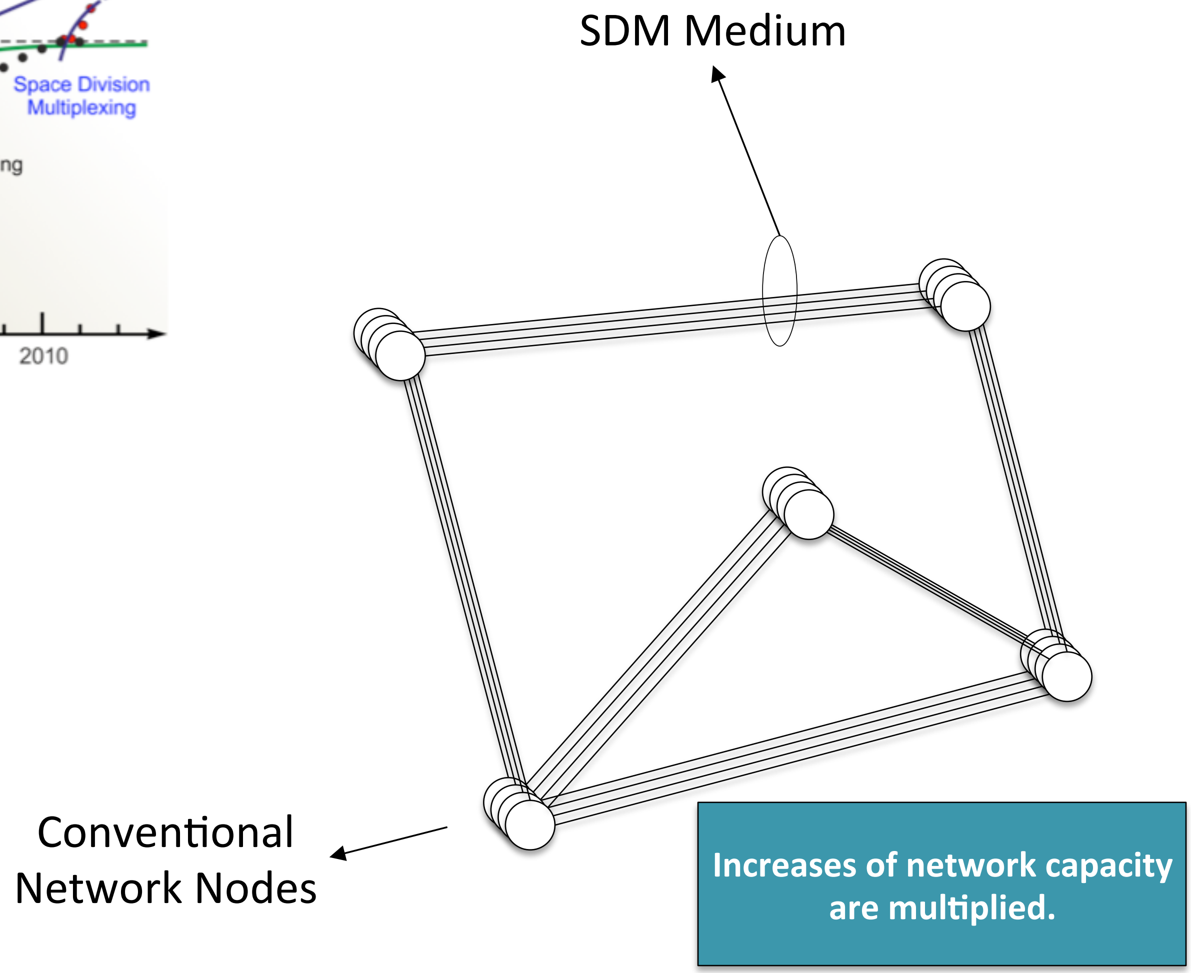




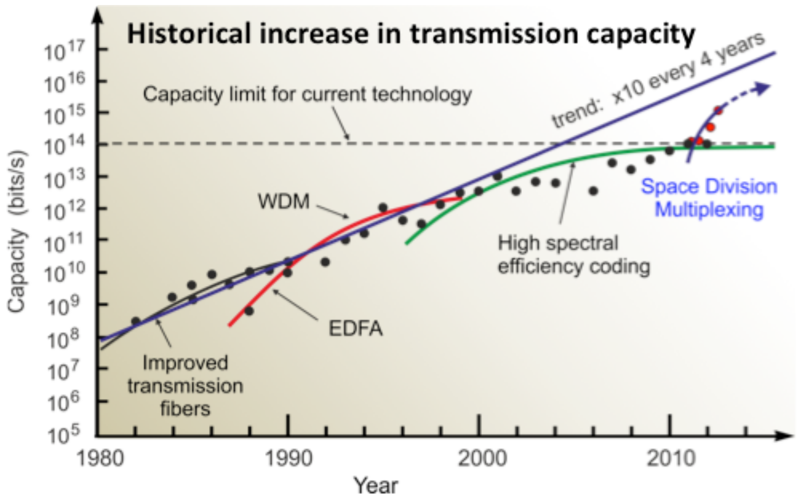
Increases of network capacity may be unable to handle the increase in traffic demand!

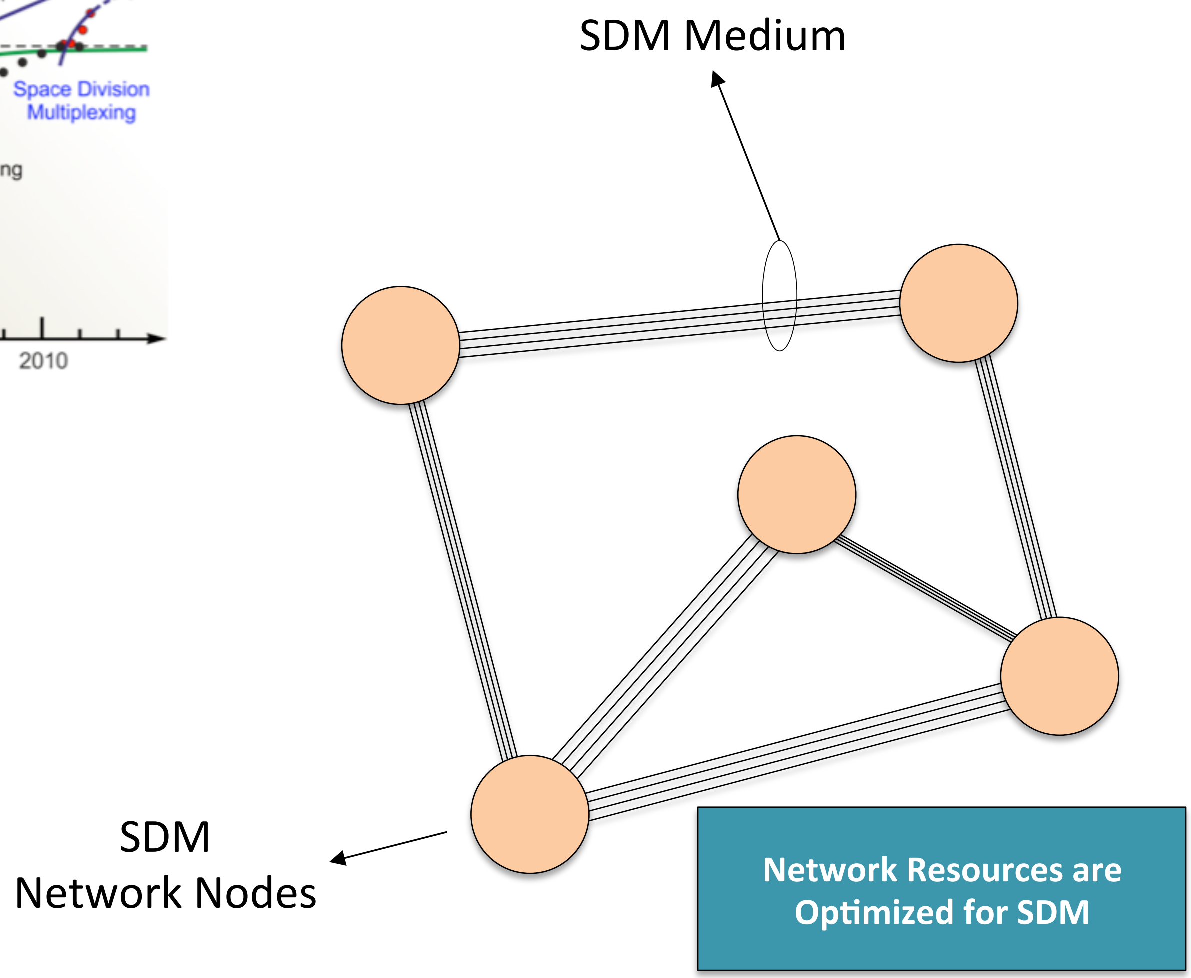
SDM Networks



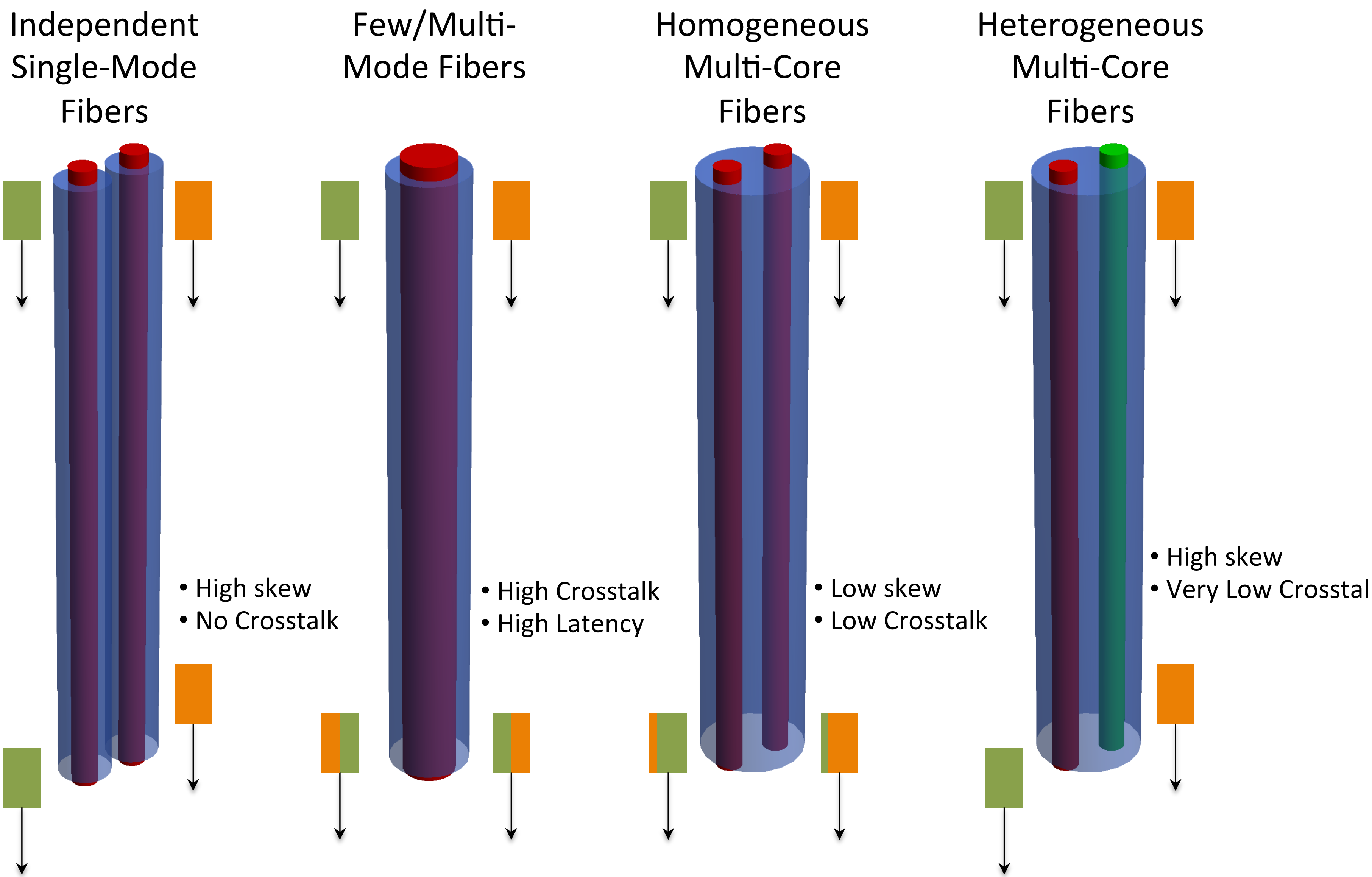


SDM Networks





SDM Networks Using Homogeneous MCFs



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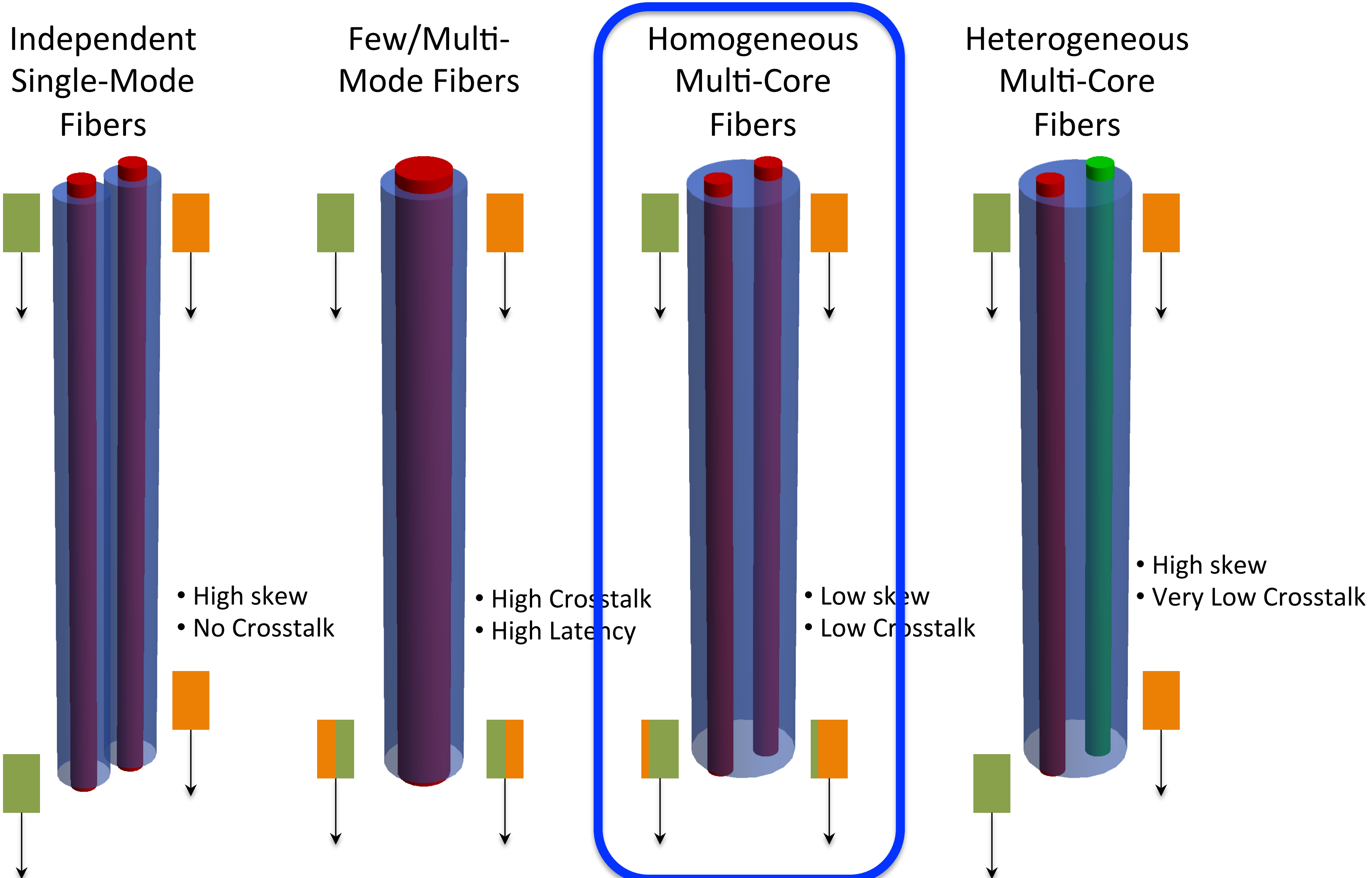
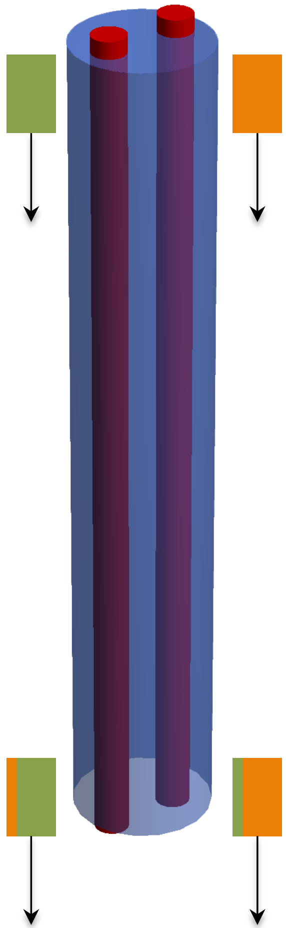


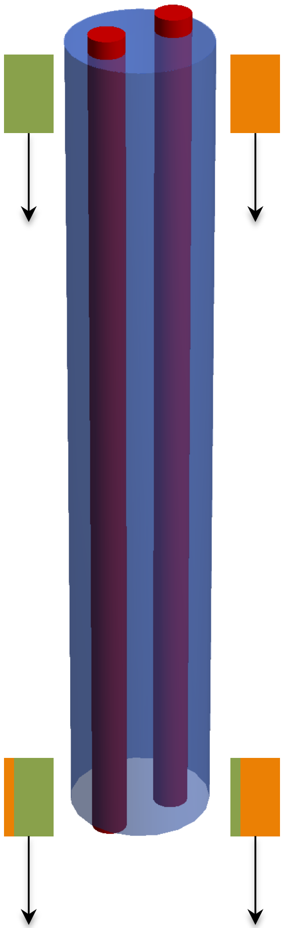
SDM Networks Using Homogeneous MCFs

Homogeneous
Multi-Core
Fibers

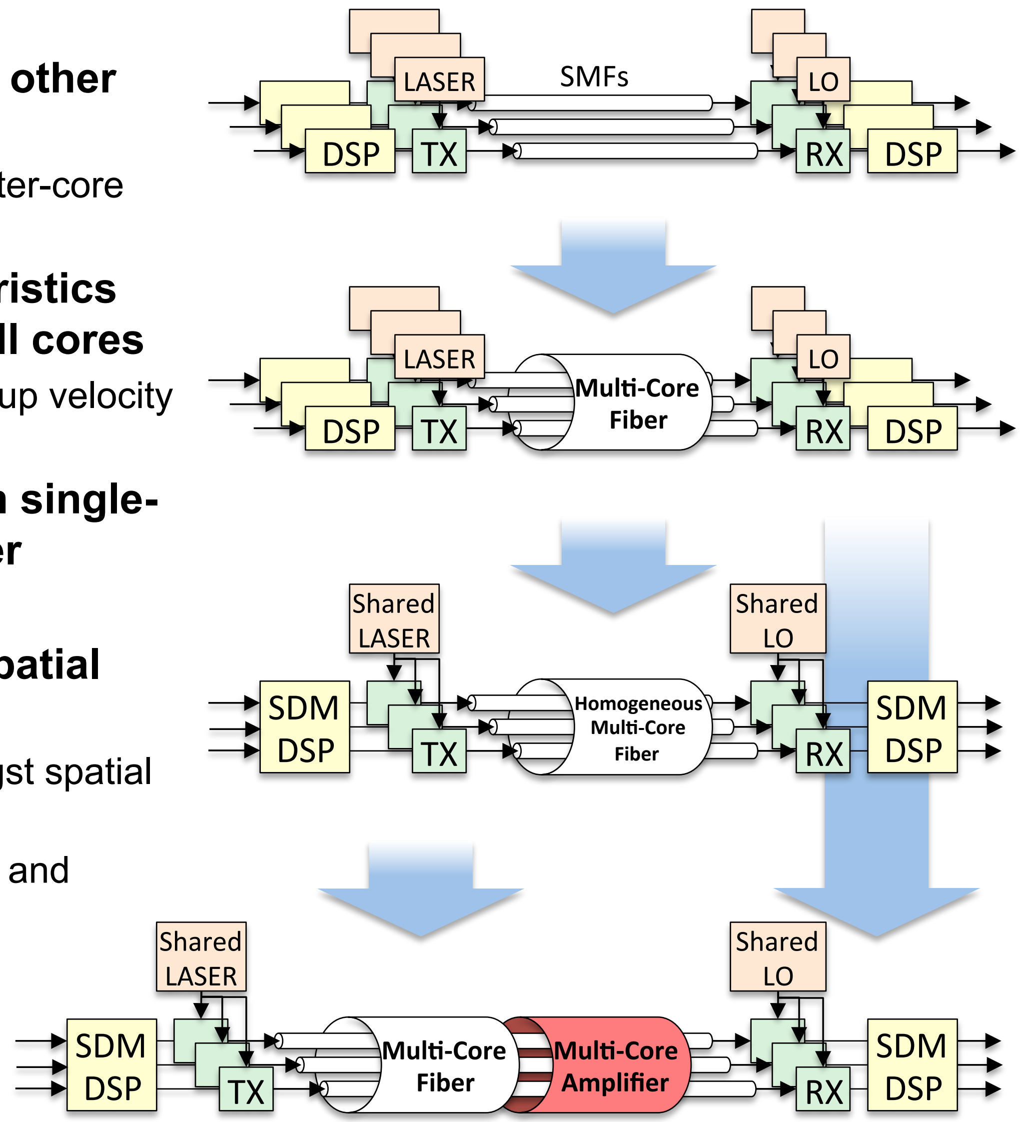


SDM Networks Using Homogeneous MCFs

Homogeneous Multi-Core Fibers



- **Light on each core is "uncoupled" from the other cores**
  - Residual coupling yields inter-core crosstalk
- **Propagation characteristics are similar amongst all cores**
  - Residual differences in group velocity yield inter-core skew
- **Simple transition from single-core to multi-core fiber systems**
- **Nearly time-aligned Spatial Super-Channels**
  - Simple shared DSP amongst spatial channels
  - Spatial modulation formats and Spatial coding
  - Self-Homodyne Detection



Crosstalk-Limited Spectral Efficiency

Assumptions:

- Crosstalk behaves as an AWGN with power proportional to the signal power (high symbol rates and/or long distances and signals w/ null carrier)
- Average crosstalk depends only on the fiber geometry
- Similar launch power on all fiber cores
- Linear transmission
- Spectral Efficiency:

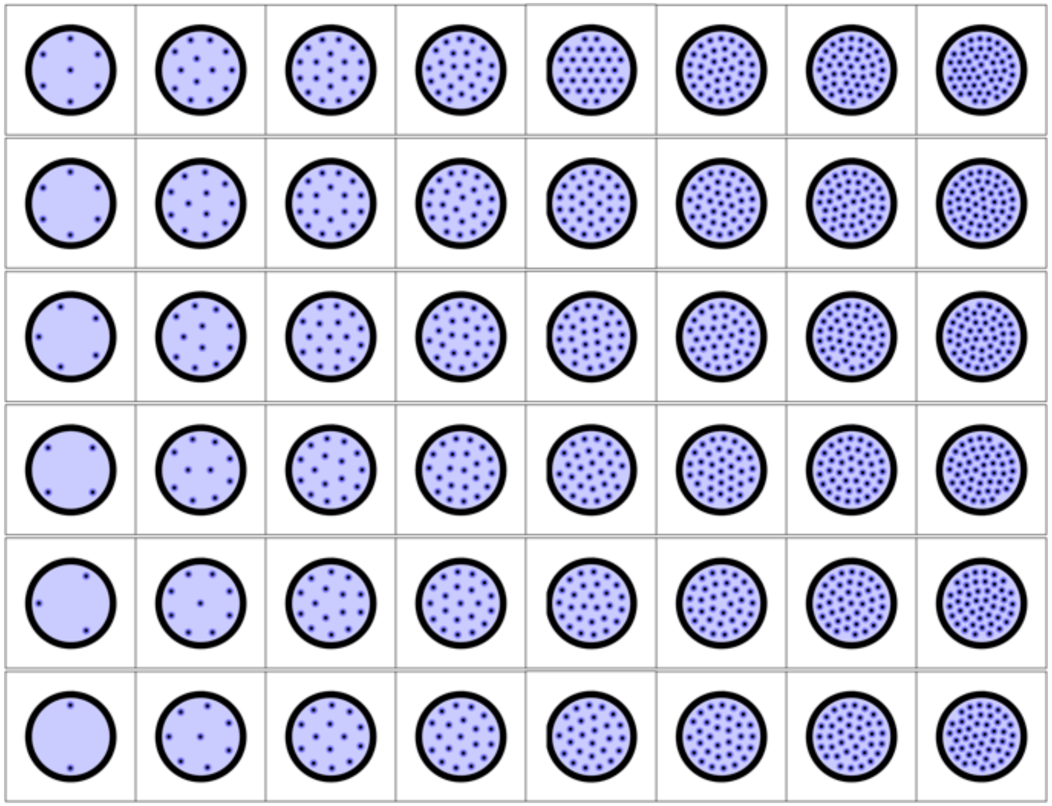
$$SE_{\mathrm{core}\,k} = \log_2\left[1 + \left(SNR^{-1} + XT_k\right)^{-1}\right]$$

$$SE = \sum_k SE_{\mathrm{core}\,k}$$

Crosstalk – Ratio between avg. crosstalk and signal powers

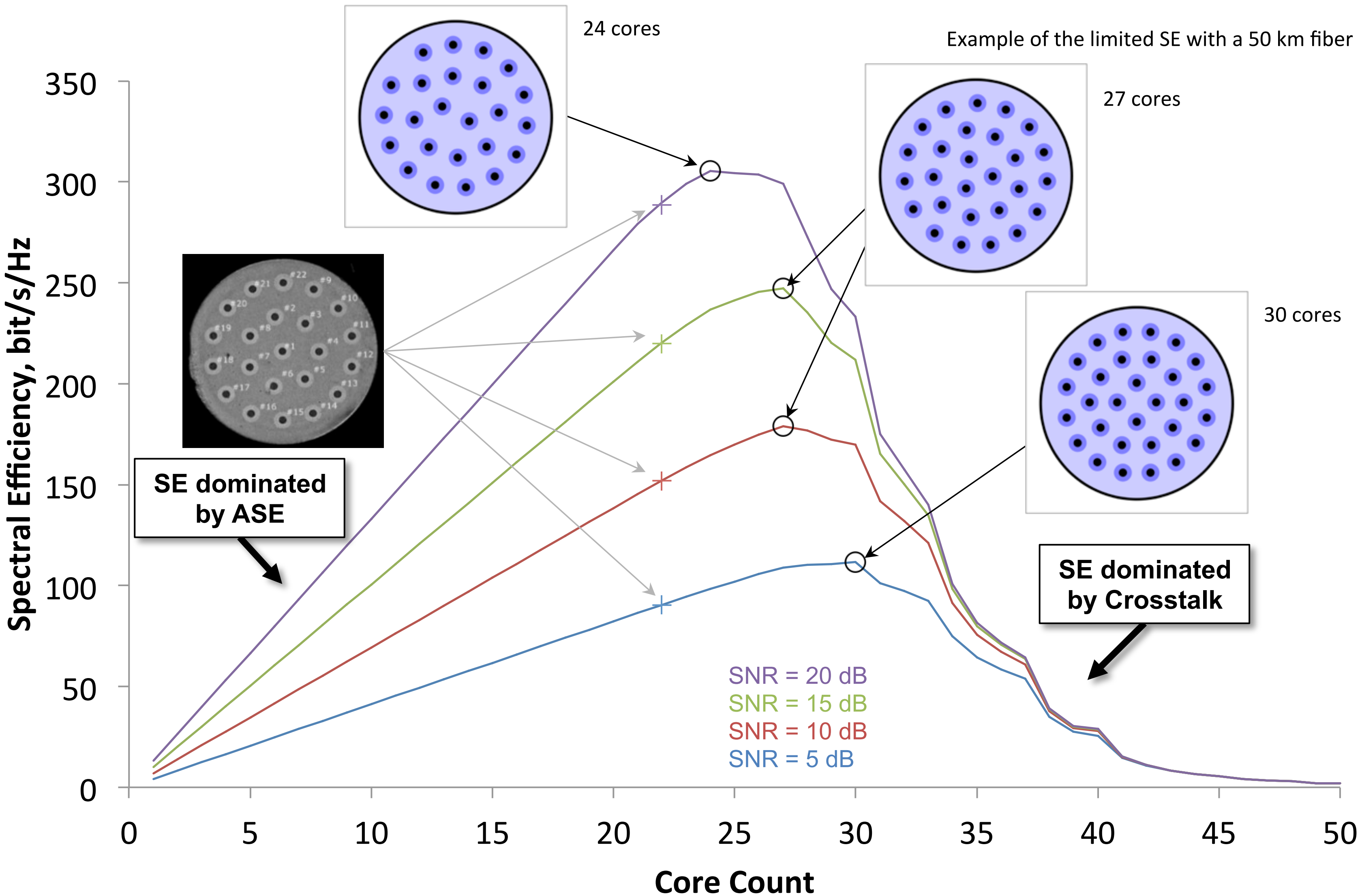
SNR in the absence of crosstalk

Considered core arrangements to maximize core pitch[2]



[1] B. J. Puttnam, et al., ECOC, PDP.3.1, 2015
[2] E. Specht, http://www.packomania.com
[3] F. Ye, et al., Optics Express **22**(19), 23007, 2014

Crosstalk-Limited Spectral Efficiency



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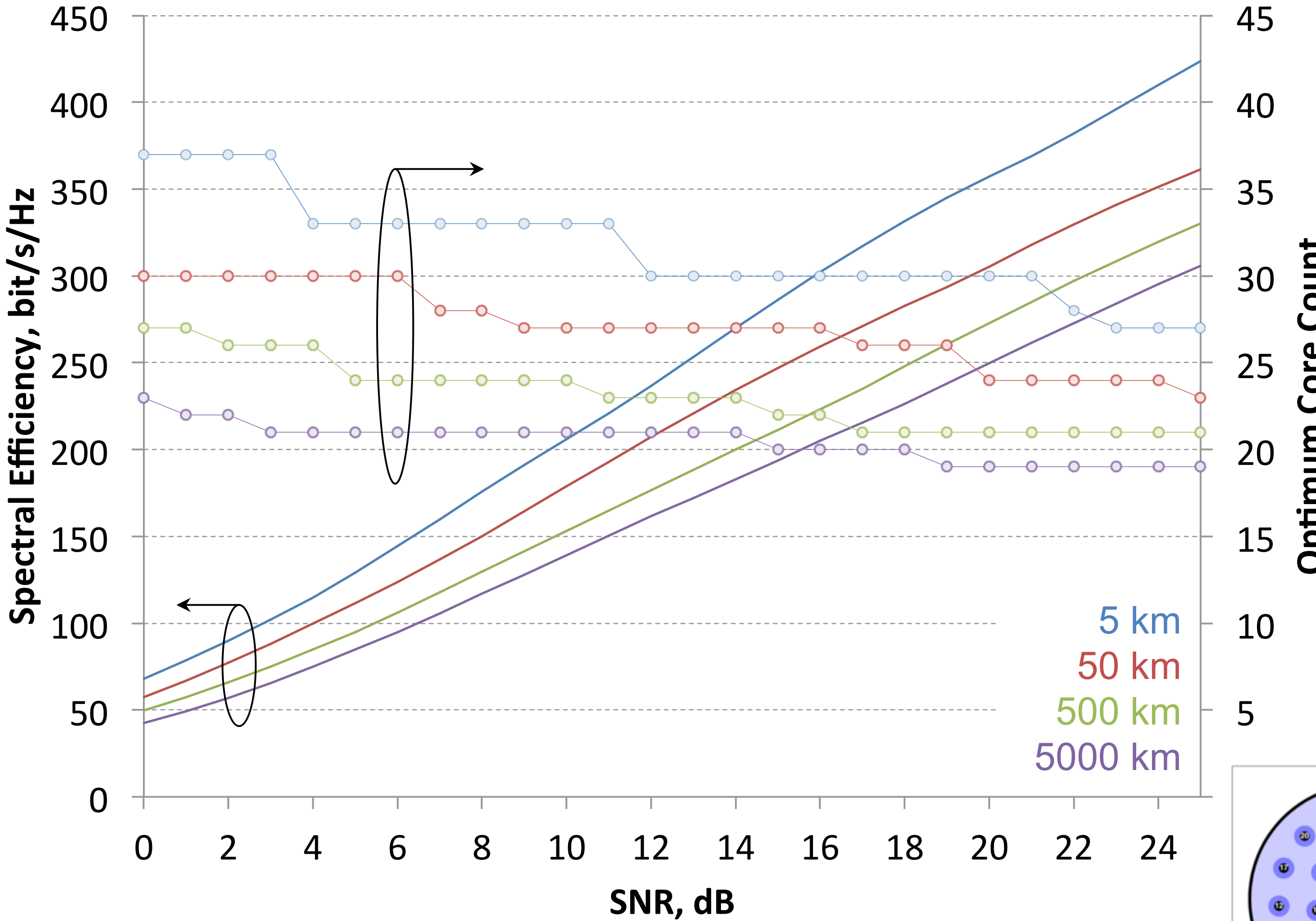

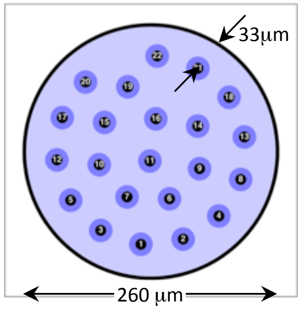

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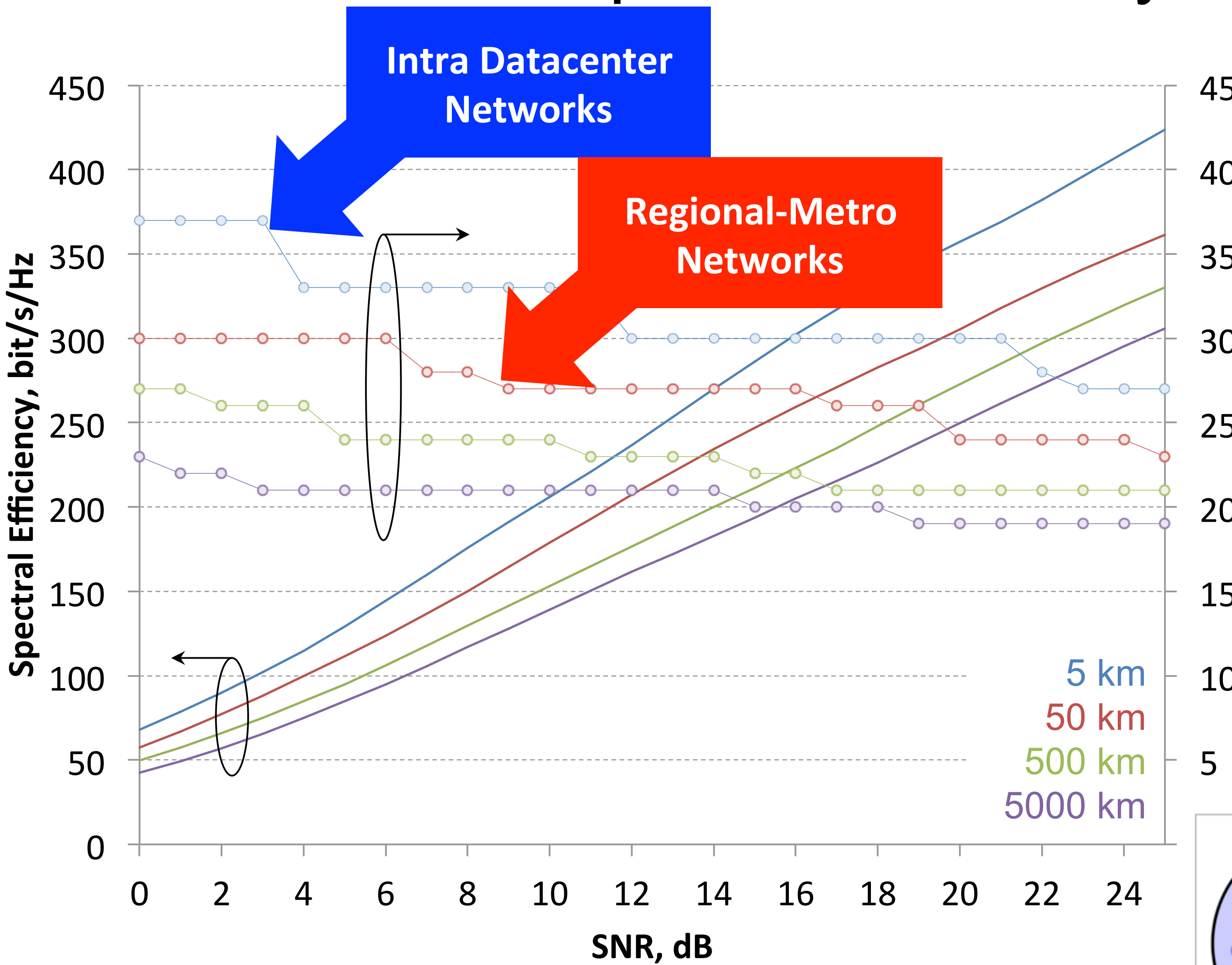
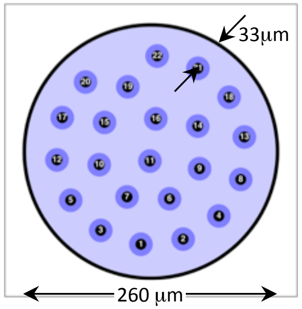
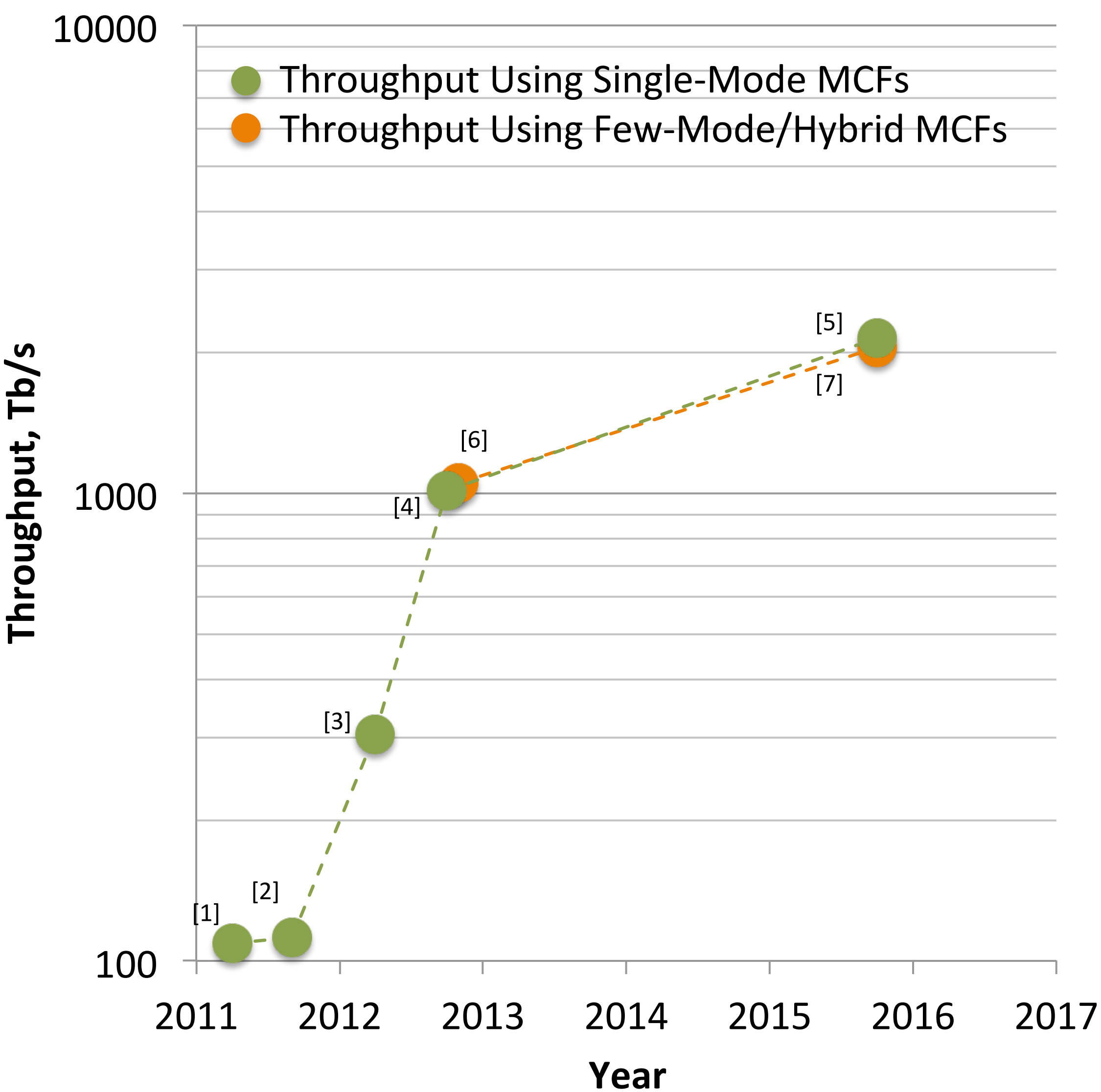
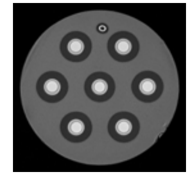


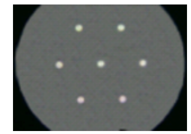


SDM Networks Using Homogeneous MCFs

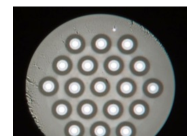




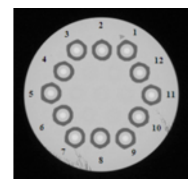
[1] J. Sakaguchi, et al., OFC 2011 PDPB6



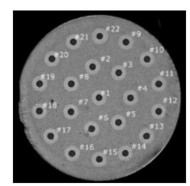
[2] B. Zhu, et al., OPEX, 19(17), 2011



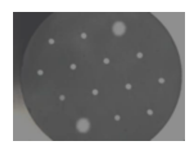
[3] J. Sakaguchi, et al., OFC 2011 Th5C.1



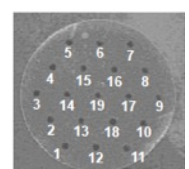
[4] H. Takara, et al., ECOC 2012, Th3C.1



[5] B. Puttnam, et al., ECOC 2015, PDP.3.1



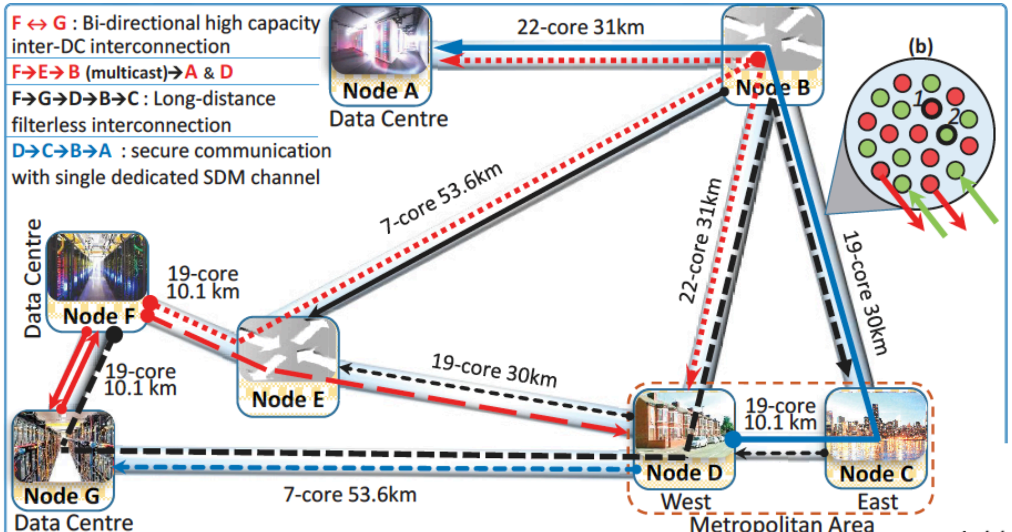
[6] D. Qian, et al., FIO 2012 FW6C.3



[7] D. Soma, et al., ECOC 2015, PDP.3.2

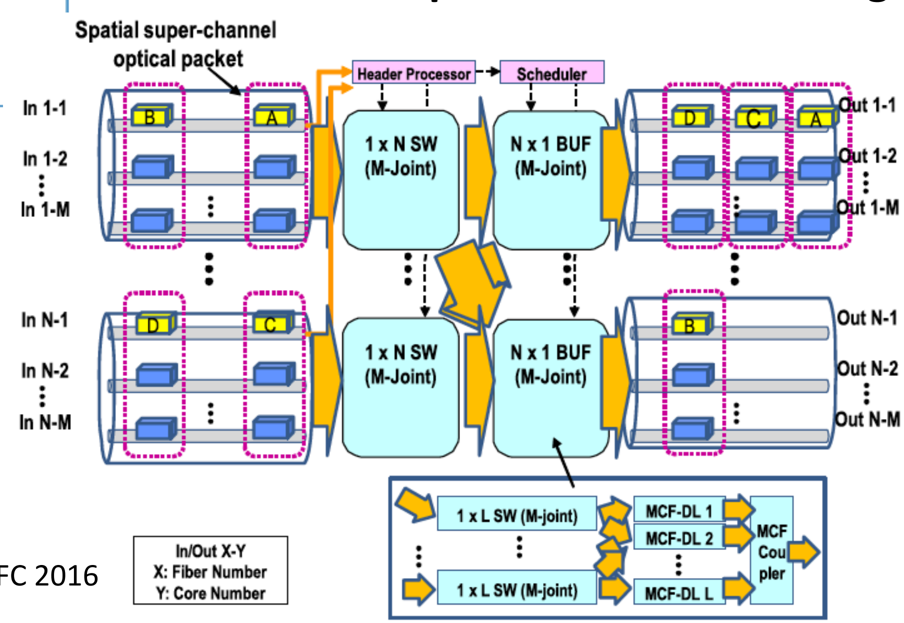
SDM Networks Using Homogeneous MCFs

Architecture on Demand experimental demonstration



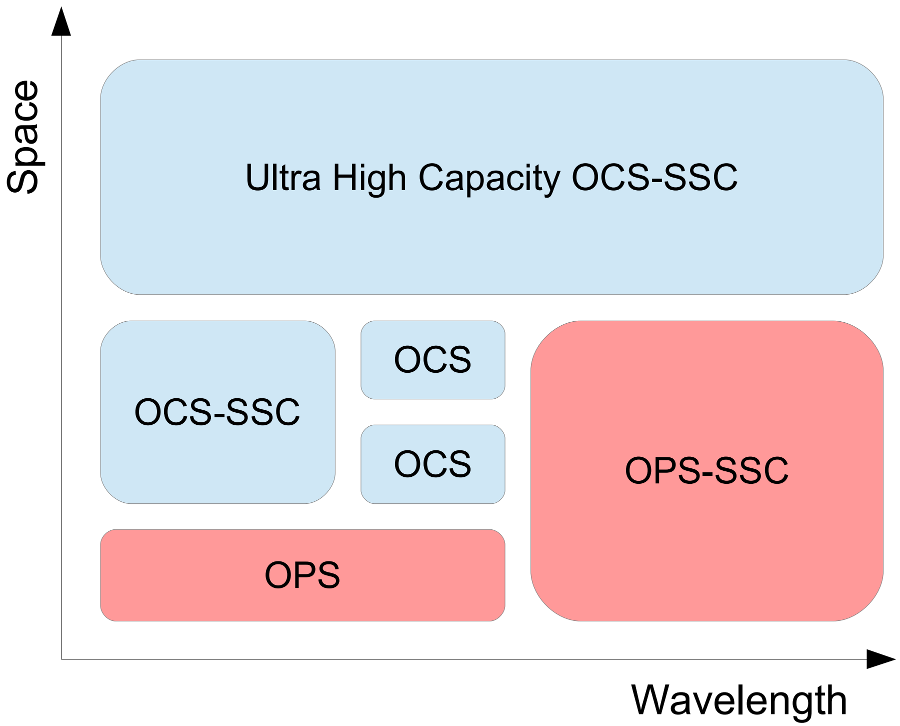
G. Saridis et al., ECOC 2016

Joint Spatial Packet Switching



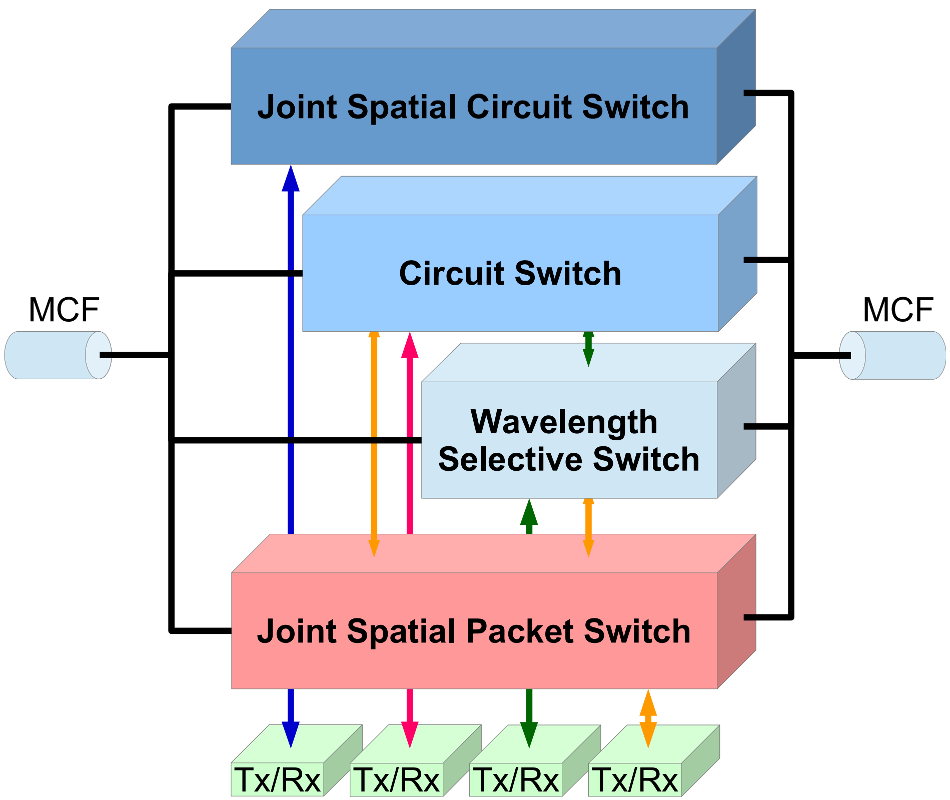
H. Furukawa et al., OFC 2016

Integrated OPS and OCS SDM Networks



- Optical packet switched (OPS) and Optical circuit switched (OCS) links can be flexibly established
- OCS Spatial super channels (SSC) provide ultra-high capacity
- OPS-SSC provide granularity
- Arbitrary combinations of spatial channels and wavelengths are possible
- **Joint spatial circuit and/or packet switching** may reduce hardware requirements

Integrated OPS and OCS SDM Networks



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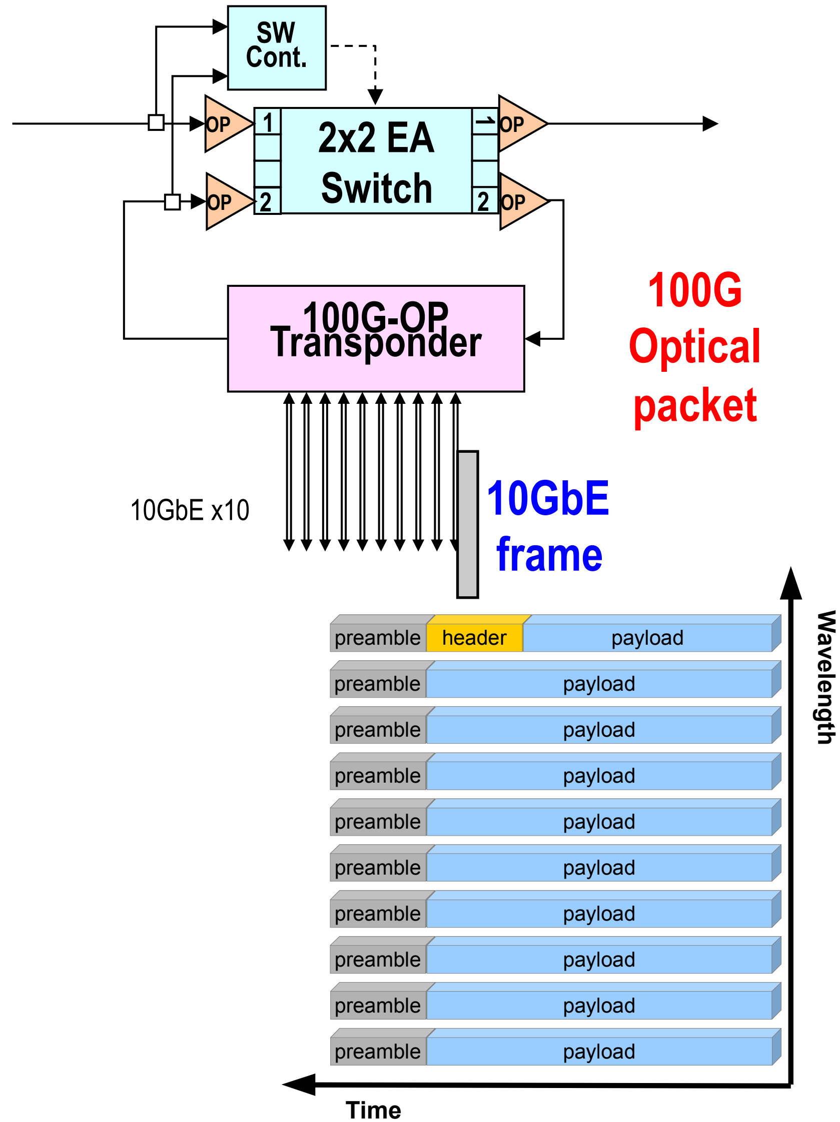
Optical Packet Switch

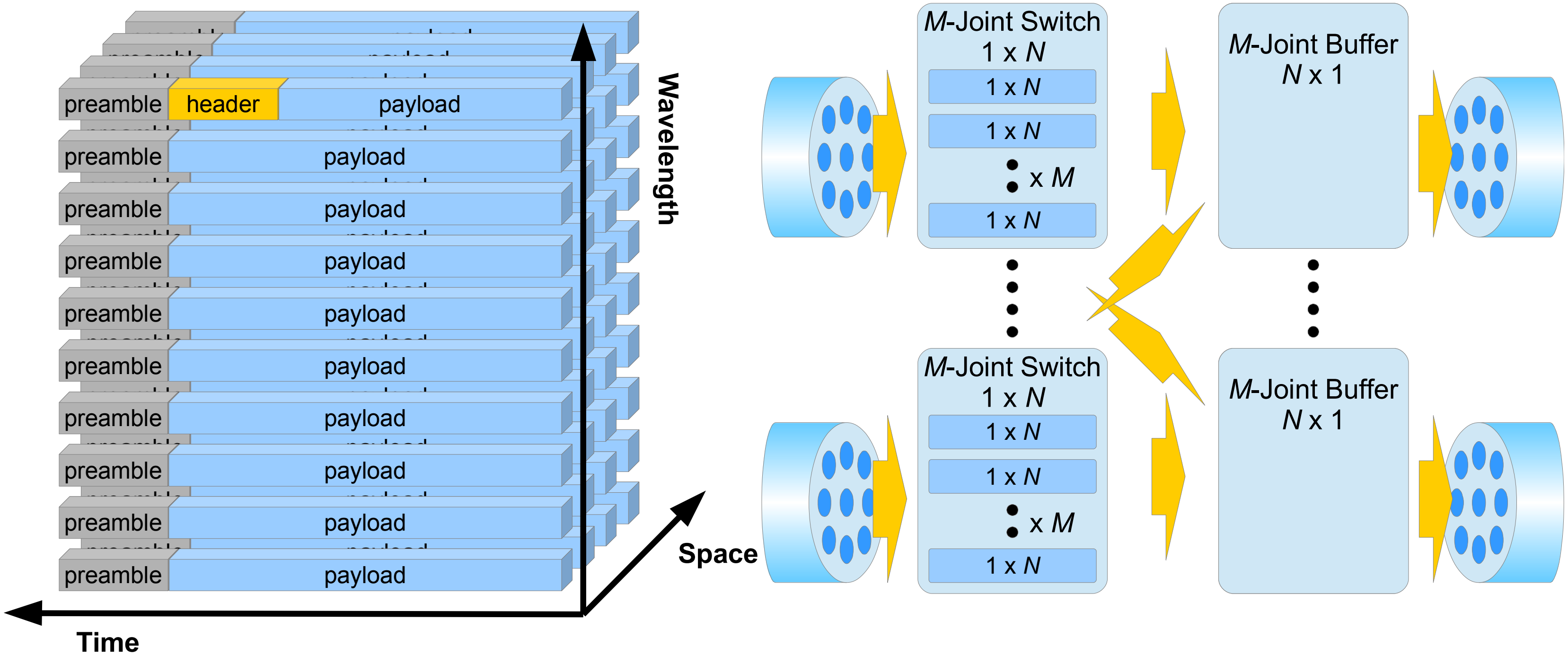
100G OTN Transponder | OCS (ROADM) | OPS

H. Furukawa, et.al, P.4.16, ECOC2015.

- Electro-absorption switches
- 100 Gb/s multi-wavelength packets
- Optical-Label Processing
- Burst-mode amplification

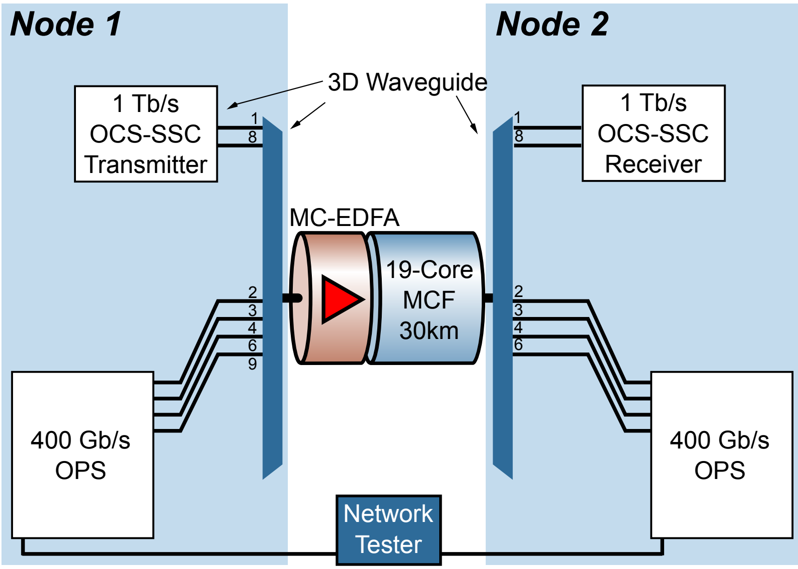


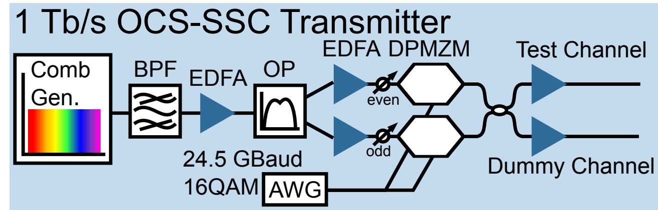
Joint Spatial Optical Packet Switch

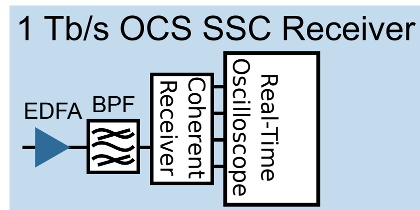


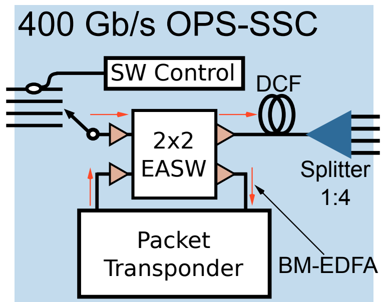
- Electro-absorption switches
- 400 Gb/s multi-wavelength spatial packets
- Optical-Label Processing – Core 1
- Burst-mode amplification

Experimental Demonstration

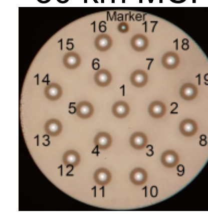




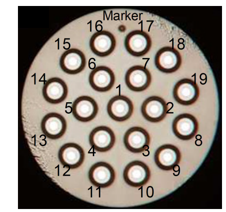


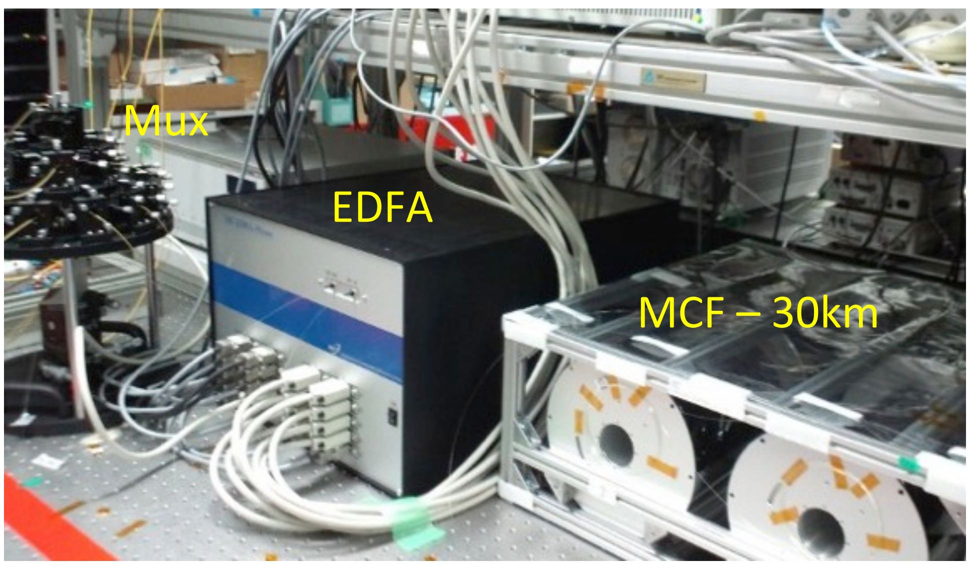


19-Core 30 km MCF



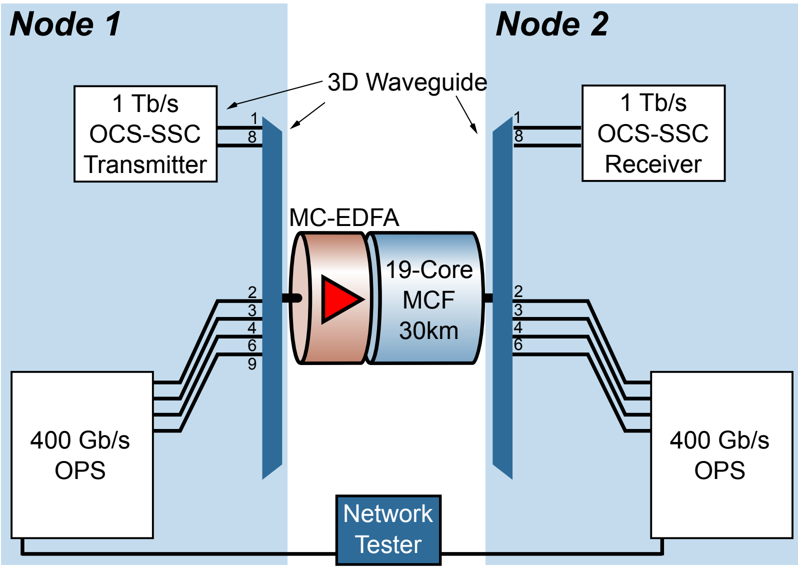
19-Core MC-EDFA

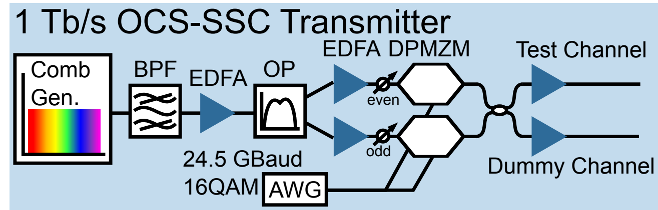


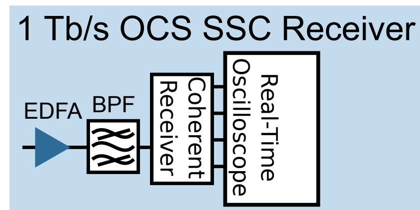


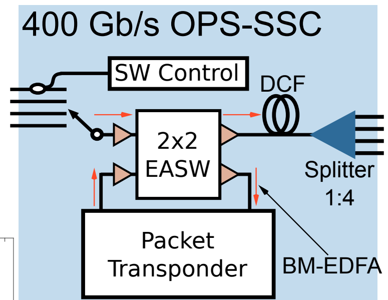
- 19-Core 30 km MCF
- 19-Core MC-EDFA

Experimental Demonstration









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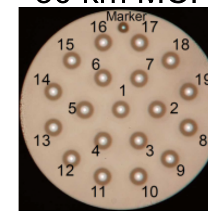

19-Core
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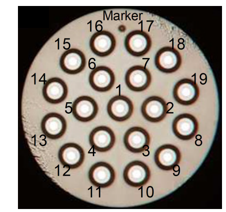
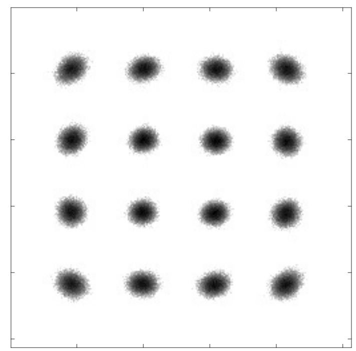
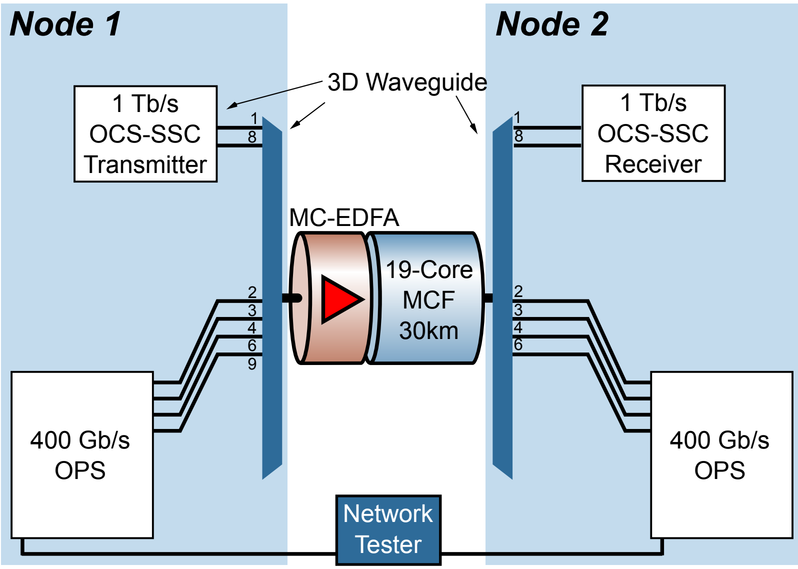
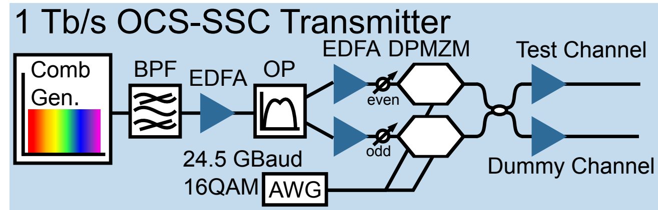


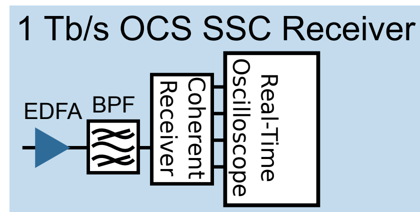


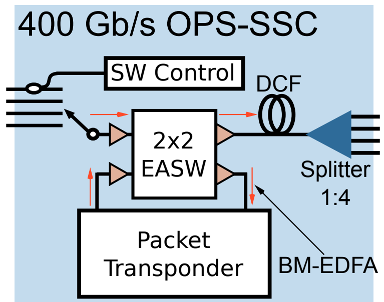
- 1 Tb/s OCS-SSC
  (2 cores x 3 wavelengths)
- PDM-16QAM at 24.5 Gbaud
- Ultra-wideband frequency comb generator
  (up to 400 wavelengths)

Experimental Demonstration









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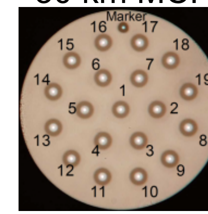

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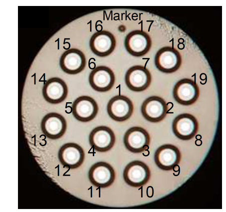
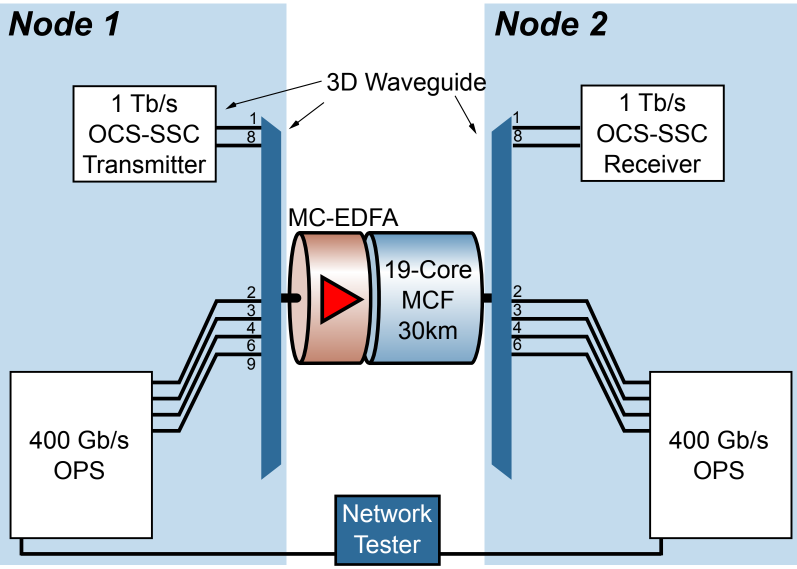
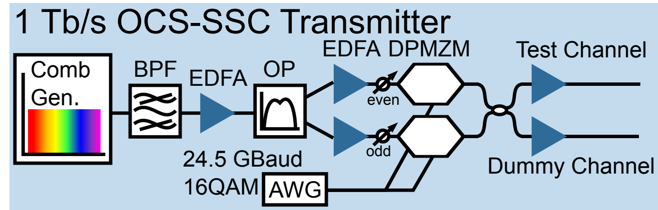
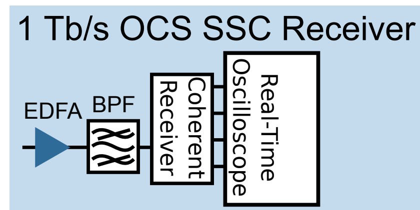


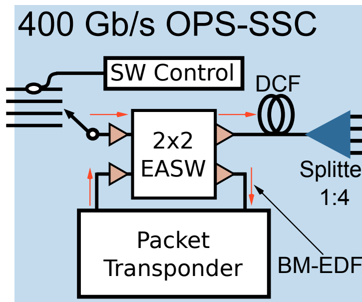
- 400 Gb/s OPS-SSC
- Emulated Joint Packet Switching

Experimental Demonstration









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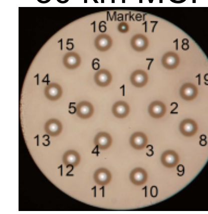

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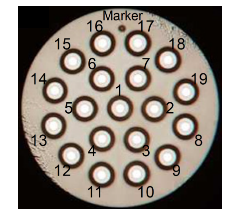
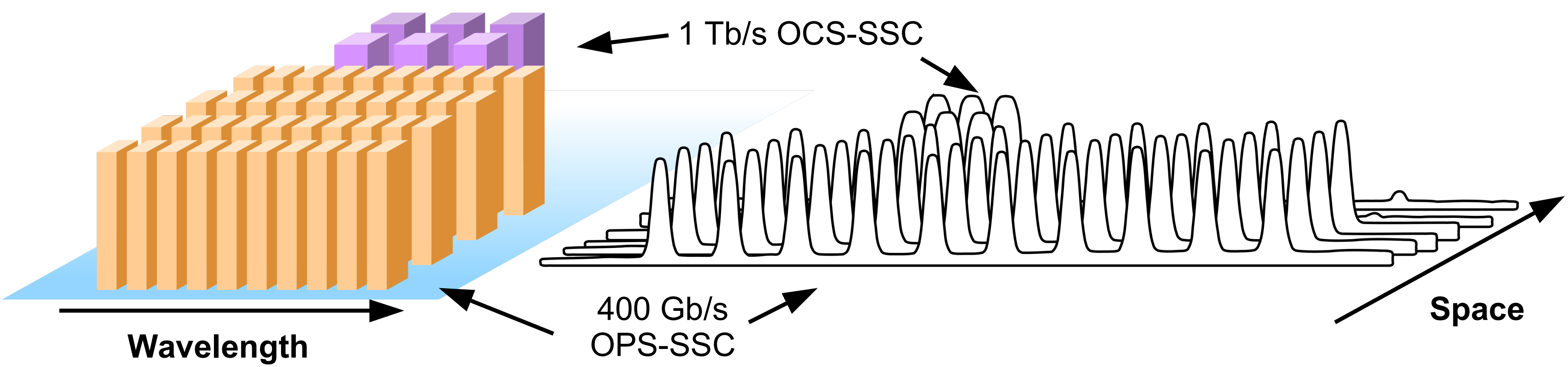


Allocated Channel Plan **Measured Channel Plan**



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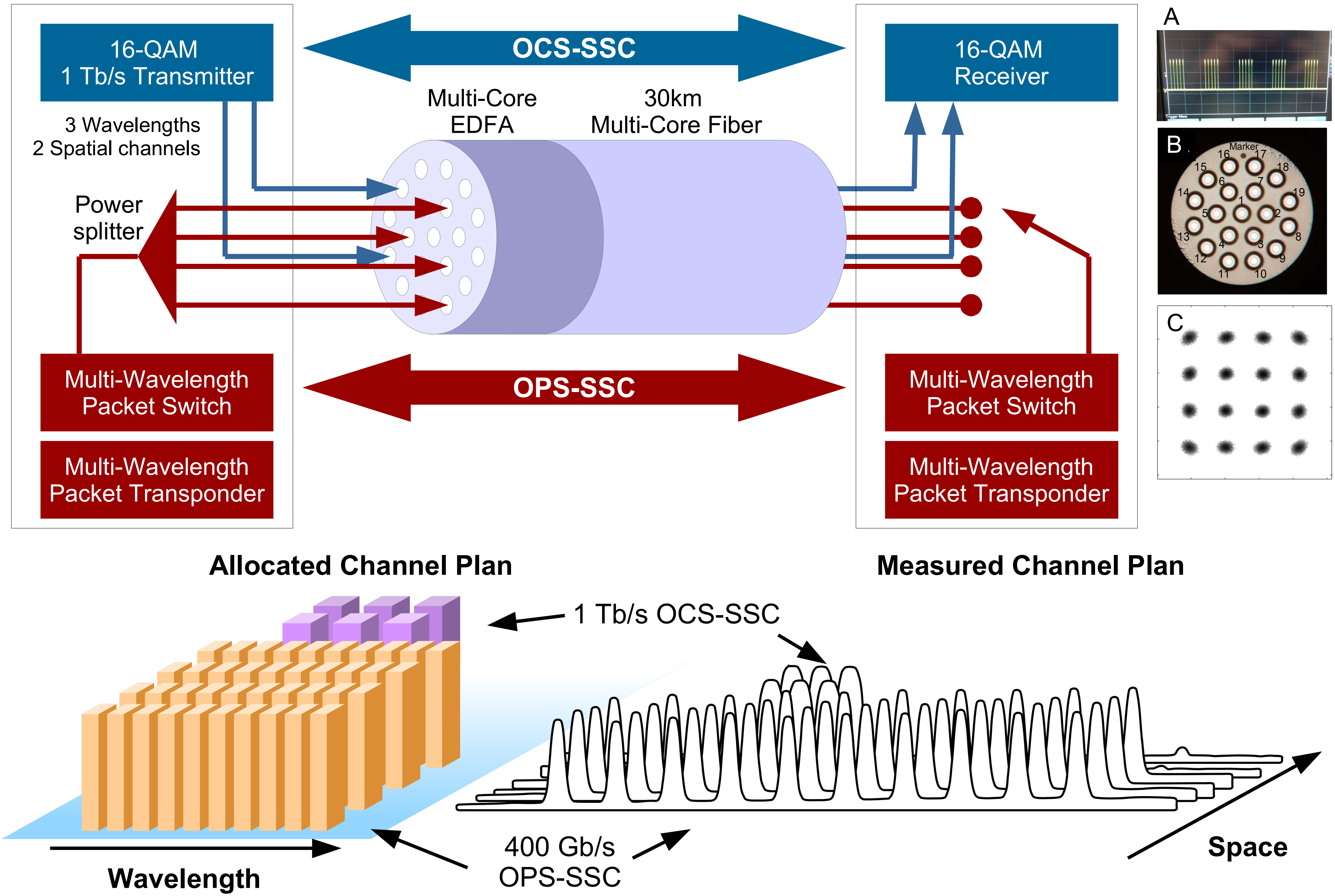

Conclusion

- Addressed the physical aspects of the use of homogeneous multi-core fibers in SDM networks
- Made the case for a hybrid spatial packet and circuit switching architecture for SDM networks
- Experimentally demonstrated a SSC-OPS + SSC OCS system using joint optical packet switching, multi-core fiber and multi-core amplification
- Future work: Including joint spatial circuit switching; network management and control; higher throughput

Acknowledgement

The authors acknowledge the efforts of the NICT technical staff on the experimental demonstration

- Takeshi Makino
- Takahiro Hashimoto
- Michie Kurihara

Thanks for your attention!

Questions?