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

R. S. Luis, H. Furukawa, G. Rademacher, B. J. Puttnam, and N. Wada
Photonic Network System Laboratory – National Institute of Information and Communications Technology - Japan

rluis@nict.go.jp
Contents

• SDM Networks Using Homogeneous MCFs

• Integrated OPS and OCS SDM Networks

• Experimental Demonstration

• Conclusions
SDM Networks

Historical increase in transmission capacity

- Capacity limit for current technology
- Trend: x10 every 5 years
- WDM
- Space Division Multiplexing
- High spectral efficiency coding
- Improved transmission fibers
- EDFA

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

Single Core Fiber

Conventional Network Nodes
SDM Networks

Increases of network capacity are multiplied.
SDM Networks

SDM Medium

Network Resources are Optimized for SDM

SDM Network Nodes

Historical increase in transmission capacity

Capacity (Gbit/s)

Year

1980 1990 2000 2010

SDM Networks

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SDM Networks Using Homogeneous MCFs

- **Independent Single-Mode Fibers**
  - High skew
  - No Crosstalk

- **Few/Multi-Mode Fibers**
  - High Crosstalk
  - High Latency

- **Homogeneous Multi-Core Fibers**
  - Low skew
  - Low Crosstalk

- **Heterogeneous Multi-Core Fibers**
  - High skew
  - Very Low Crosstalk
SDM Networks Using Homogeneous MCFs

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SDM Networks Using Homogeneous MCFs

Homogeneous Multi-Core Fibers
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:

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

\[
SE = \sum_k SE_{\text{core } k}
\]

Considered core arrangements to maximize core pitch\(^2\)

SNR in the absence of crosstalk

Crosstalk – Ratio between avg. crosstalk and signal powers

1 B. J. Puttnam, et al., ECOC, PDP.3.1, 2015
3 F. Ye, et al., Optics Express 22(19), 23007, 2014
Crosstalk-Limited Spectral Efficiency

Example of the limited SE with a 50 km fiber

- SNR = 20 dB
- SNR = 15 dB
- SNR = 10 dB
- SNR = 5 dB

SE dominated by ASE

SE dominated by Crosstalk
Crosstalk-Limited Spectral Efficiency
Crosstalk-Limited Spectral Efficiency

SNR, dB

Optimum Core Count

Spectral Efficiency, bit/s/Hz

5 km
50 km
500 km
5000 km

Intra Datacenter Networks

Regional-Metro Networks

Intra Datacenter Networks

Regional-Metro Networks

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SDM Networks Using Homogeneous MCFs

Throughput, Tb/s

- Throughput Using Single-Mode MCFs
- Throughput Using Few-Mode/Hybrid MCFs

Year

10000

1000

100


References:
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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
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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

- 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
Experimental Demonstration

- 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

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

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Experimental Demonstration

Node 1
- 1 Tbps OCS-SSC Transmitter
- 3D Waveguide
- 19-Core MCF 30km
- Network Tester
- 400 Gbps OPS

Node 2
- 1 Tbps OCS-SSC Receiver
- MC-EDFA
- 400 Gbps OPS

1 Tbps OCS-SSC Transmitter
- Comb Gen.
- BPF
- EDFA
- OP
- 24.5 Gbaud
- 16QAM
- AWG
- DPMZM
- Test Channel
- Dummy Channel

1 Tbps OCS-SSC Receiver
- EDFA
- BPF
- Coherent Receiver
- Oscilloscope
- Real-Time

400 Gbps OPS-SSC
- SW Control
- DCF
- 2x2 EASW
- Packet Transponder
- Splitter 1:4
- BM-EDFA

Allocated Channel Plan
- Wavelength
- 1 Tbps OCS-SSC
- 400 Gbps OPS-SSC

Measured Channel Plan
- Space
- 1 Tbps OCS-SSC
- 400 Gbps OPS-SSC
Experimental Demonstration

- **16-QAM 1 Tb/s Transmitter**
  - 3 Wavelengths
  - 2 Spatial channels

- **Multi-Core EDFA**
- **30km Multi-Core Fiber**

- **Power splitter**

- **Multi-Wavelength Packet Switch**
- **Multi-Wavelength Packet Transponder**

- **OCS-SSC**

- **Multi-Wavelength Packet Switch**
- **Multi-Wavelength Packet Transponder**

- **16-QAM Receiver**

- **Allocated Channel Plan**
  - 1 Tb/s OCS-SSC

- **Measured Channel Plan**
  - 400 Gb/s OPS-SSC
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
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Questions?