Space Division Multiplexing (SDM) Technology

Prof: Mounia Lourdiane

Group member:
Abdennour Ben Terki
Moatasim Mahmoud
Puyuan HE
Zhe WANG

Outline

- SDM basic concepts.
- SDM Devices & Components.
- SDM Experimental.
- SDM Challenges & Application.

- **SDM basic concepts.**
- SDM Devices & Components.
- SDM Experimental.
- SDM Challenges & Application.

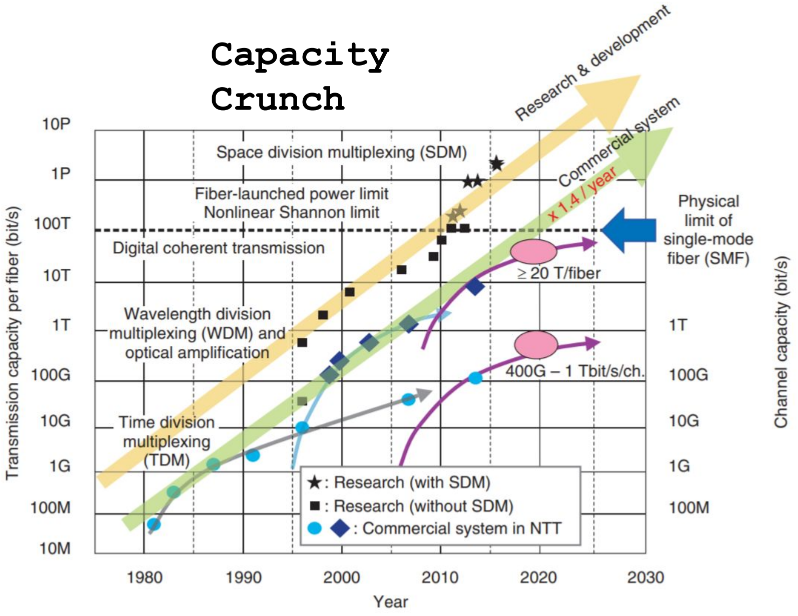
FROM WDM, TDM, ... to SDM

SDM (Spacing Division Multiplexing)

SDM refers to the use of orthogonal channels in multiple spaces to transmit signals at the same time to achieve expansion

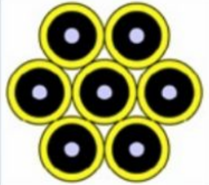
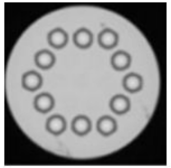
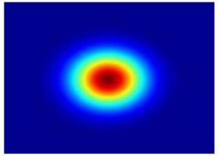
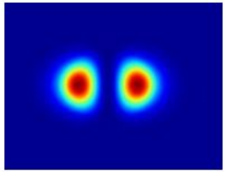
Low loss single mode fiber, EDFA, TDM, WDM and PDM → Time, frequency, polarization state, orthogonality

Capacity Crunch



"Space Division Multiplexing Optical Transmission Technology to Support the Evolution of High-capacity Optical Transport Networks" [8]

Common SDM optical transmission technology

	PSM	MCF	MDM	OAM
fiber type	Fiber array	Multi-core fiber	Few Mode Fiber	Eddy current fiber
channels num.	>100	Max. ~37	Max. ~6	Max. ~12
legend	 	 	 	 

*
PSM : parallel sign-mode fiber
MCF : multi-core fiber
MDM: Mode Division Multiplexing
OAM : Orbital Angular Momentum

*
OAM technology originated from the concept of electronic spin angular momentum in wireless communication, and was later introduced into space optical communication to achieve multiplexing [9].

Advantages and drawbacks

Multi-core	Multi-mode solid core	Multi-mode hollow core
+ Highest data rates achieved so far	+ Potentially lowest system cost	+ Lowest latency (<-30%)
+ Enabling higher density of integration for transponders and amplifiers	+ Enabling higher density of integration for transponders and amplifiers, ROADMs	+ Enabling higher density of integration for transponders and amplifiers
+ Can be combined with multi-mode	+ Higher reach due to lower nonlinearity	+ Lowest potential loss (<0.1dB/km) @ 2 µm
- No advantage in reach (same loss, nonlinearity)	+ More efficient pumping than multi-core	+ 4 x bandwidth @ 2 µm
- Same bandwidth as SSMF	- Same bandwidth as SSMF	+ Very low nonlinearity
- Fiber crosstalk needs to be further reduced	- Equalization of mode cross talk required in DSP	- Mode dependent loss is intrinsic and leads to performance degradation
- No ROADM integration	- Mode dependent loss can lead to performance degradation	- Very high differential group delay requires huge DSP complexity for mode multiplexing
	- Scalability to higher number of modes is tough	- No long reaches demonstrated so far (record reach <1 km)
		- Losses so far are well above SSMF

Space division mulplexing: a new milestone in the evolution of fiber optica communication [10]

Question

1. which one can better increase the capacity of the optical transmission system and have better performance?

    a. MDM

    b. MCF

- SDM basic concepts.
- **SDM Devices & Components.**
- SDM Experimental.
- SDM Challenges & Application.

SDM Devices and Components

-SDM Fiber Technologies

-SDM Tx and Rx

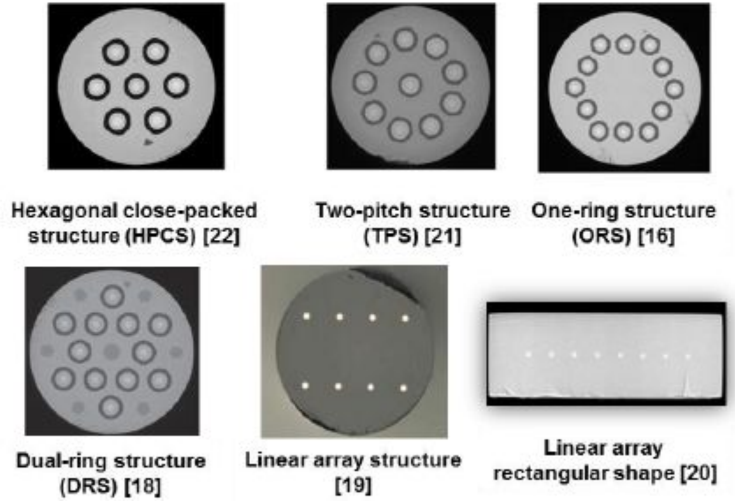
-SDM Amplifiers

-SDM Mux/DeMux

-SDM Switches

-SDM ROADM

100Gbps AOC (25Gbps×4 channels) using multi-mode fiber transmission technology.[5]*



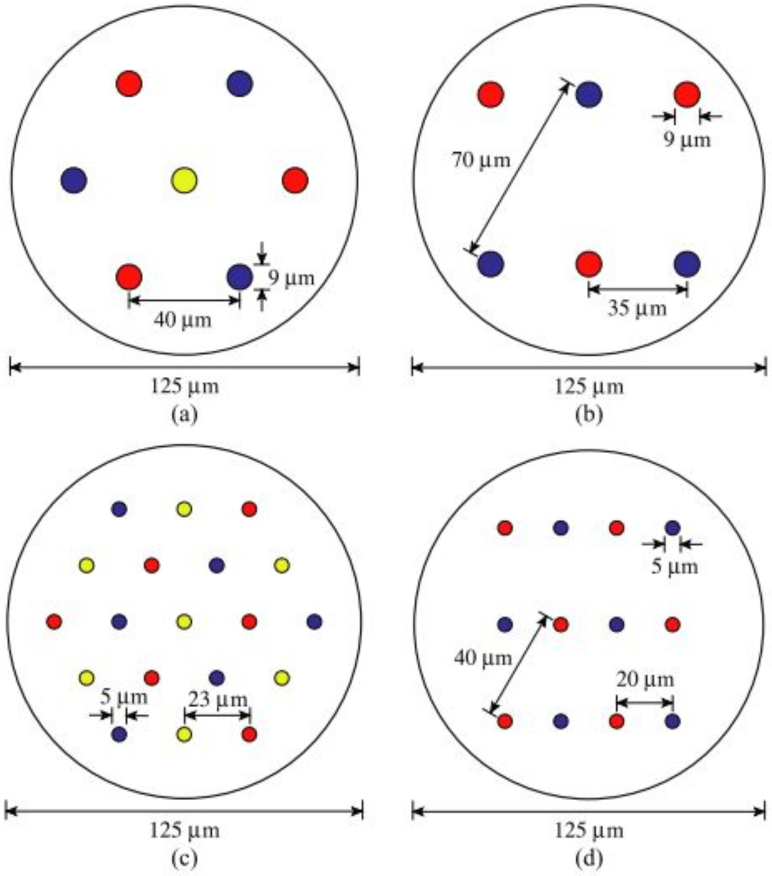
Different MCF Core Arrangement Designs[1]

**AOC: Active Optical Cable*

Hetrogeneous MCF

The maximum power transferred between non-identical cores is lower than between identical cores.

This allows more closely packed cores in definite space compared to the conventional homogeneous MCF.

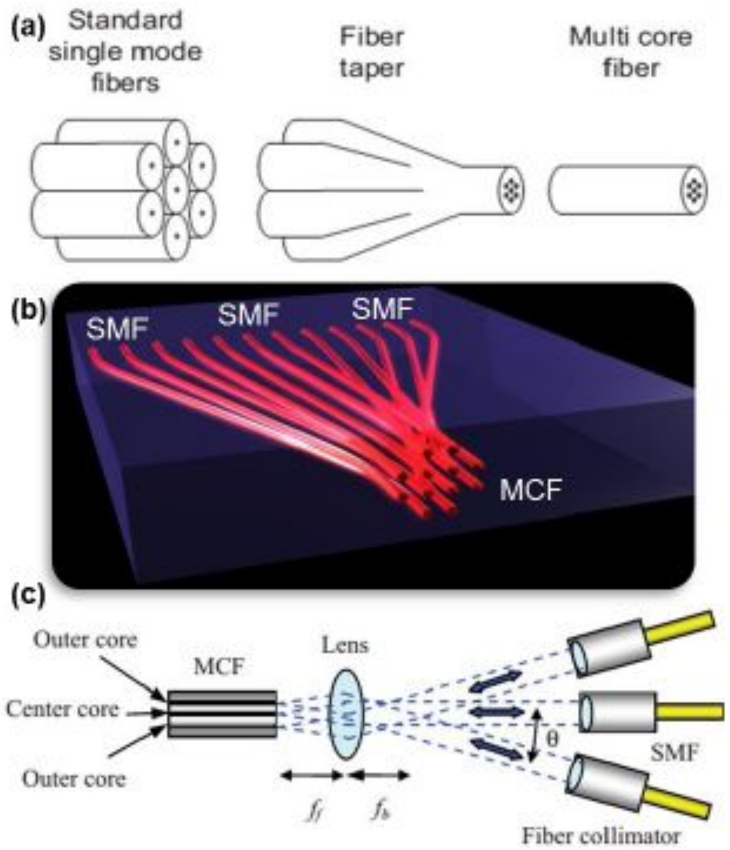


Heterogeneous MCFs with Different Number of Cores.[4]

MCF Mux/DeMux

- Direct coupling: implements waveguide-optics interface that directly couples the MCF to the SMFs.

- Indirect Coupling: a free space optics solution that relies on lens system.

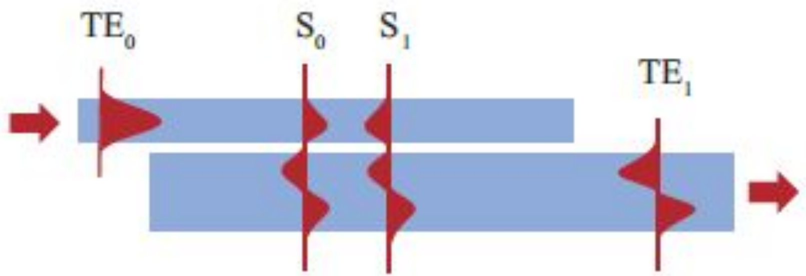


MCF Multiplexing Solutions. (a) Tapered cladding. (b) Waveguid coupling. (c) Lens system.[1]

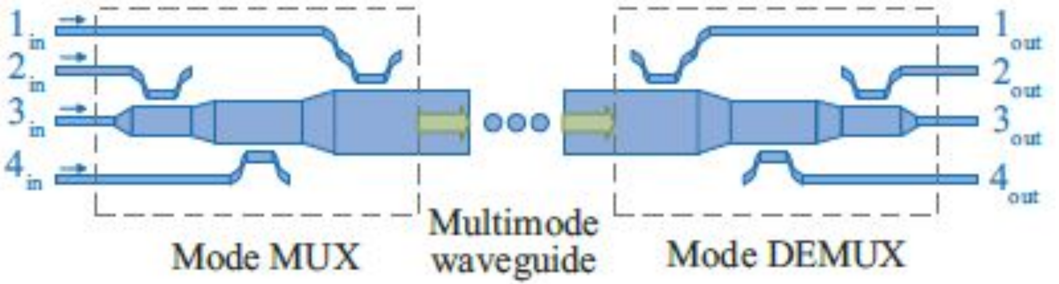
Multimode Mux/DeMux

One way to achieve mode multiplexing is by cascading asymmetric directional couplers (ADCs) which are used to convert the fundamental modes to higher order modes.

In ADC, two waveguides with identical effective refractive index are placed closley to supports super modes.



Mode Conversion (TE0 to TE1) in an ADC[2]

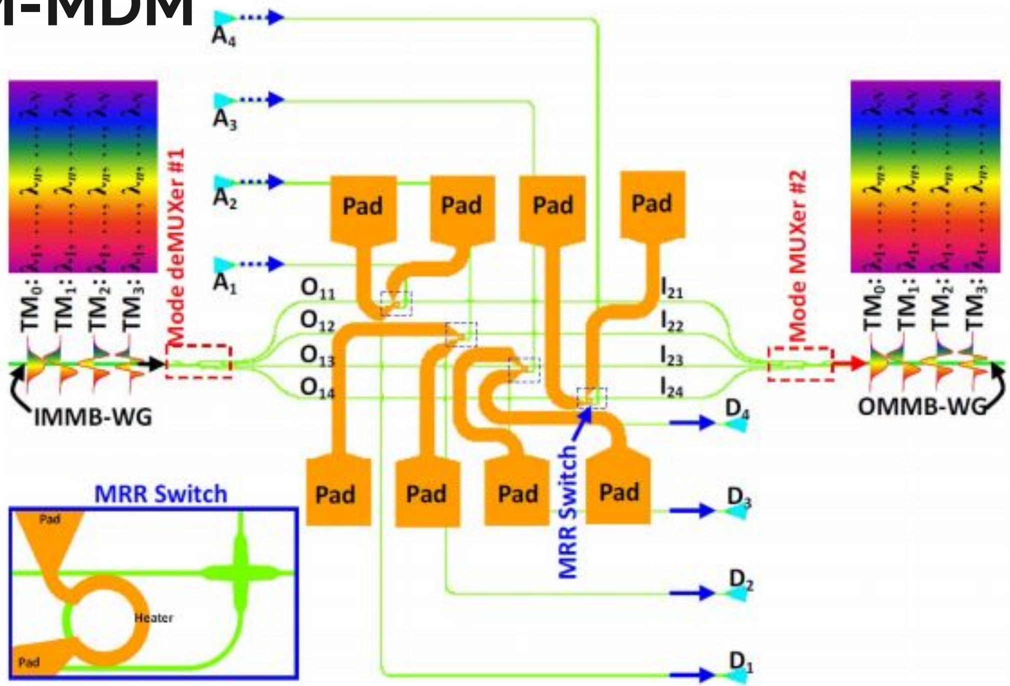


Schematic of Multimode Mux based on ADC[2]

IMMB-WG: Input Multimode Bus-Waveguide
OMMB-WG: Output Multimode Bus-Waveguide
MRR: Microring Resenator
WSS: Wavelength Selective Switch

ROADM for Hyprid WDM-MDM

- Arriving data is demultipexed into 4 modes by deMux#1.
- For each one of the four groups, one of the wavelength channels (λ_n) can be dropped and a local signal can be added to the same wavelength. This is done by MRR-based WWSs.
- The four groups are multeplexed to the four mode channels by mode deMux#2.



Configration of a ROADM for Hyprid WDM-MDM System[3]

Quetion

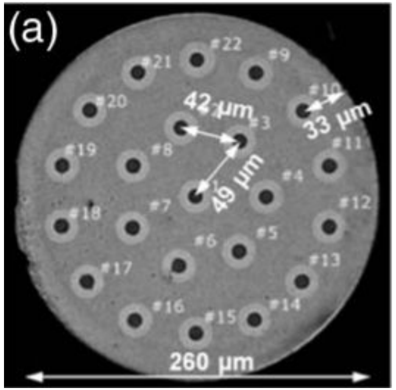
Question: Which MCF design results in **less** interference between the cores?

A. Homogeneous MCF (identical cores)

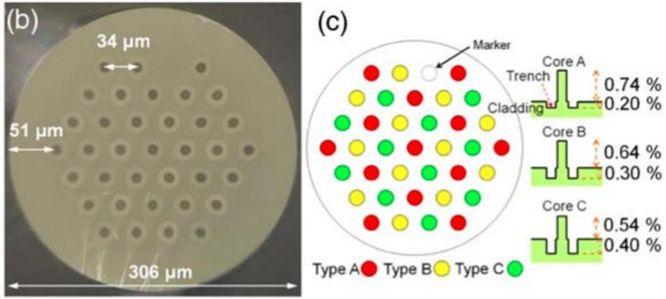
B. Hetrogeneous MCF (non-identical cores)

- SDM basic concepts.
- SDM Devices & Components.
- **SDM Experimental.**
- SDM Challenges & Application.

SDM Experimental



Homogeneous SM- MCF [6]



Heterogeneous FM- MCF [6]

SDM Experimental

- ❖ The first successful demonstration of transmitting data rates exceeding 100 Tb⁄s in 2011 using the seven-core MCF [7].
- ❖ In early 2012 a 19-core MCF carrying 305 Tb⁄s was reported [7].

- ❖ by the end of 2012 the capacities exceeding 1 Pb⁄s.
  - ➢ 52 km 12-core homogeneous MCF carrying in each core 222 channel WDM signals with PDM and 32QAM [8].
  - ➢ 3 km 14-core heterogeneous MCF that employed a combination of 12 single-mode cores carrying PDM-32QAM-OFDM signals and two three-mode cores carrying PDM-QPSK signals [9].

SDM Experimental

- ❖ In 2015, the data rate record was doubled to 2 Pb⁄s:
    - ➢ 31.4 km 22-core single-mode MCF [10].
    - ➢ 9.8 km 19-core six-mode MCF where each mode carried 360 channels, carrying 50 Gb⁄s PDM-QPSK signals [11].

Question

What is the achieved data rate using SDM:

A. 1 Gb/s.
B. 1 Tb/s.
C. 1 Pb/s.
D. 2 Pb/s.

- SDM basic concepts.
- SDM Devices & Components.
- SDM Experimental.
- **SDM Challenges & Application.**

Challenges in SDM technology

For large-scale topologies, SDM networks based on multi-core fibers show significantly better performance than multi-mode fibers.

The challengages:

1. How to mitigate the crosstalk is the major problem
2. The development of suitable equipments
3. Production of equipment with a low financial cost

Crosstalk inside a multi core fiber

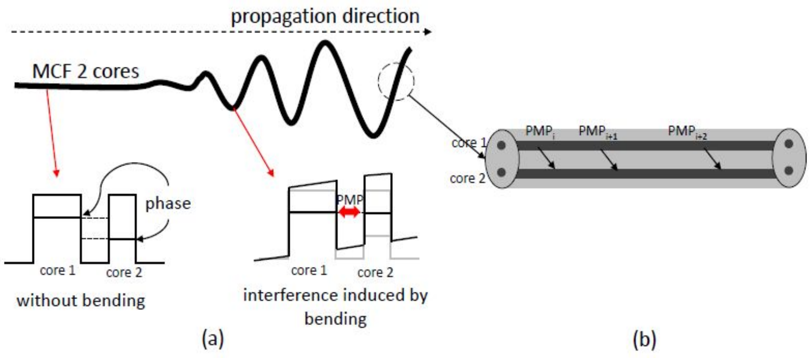
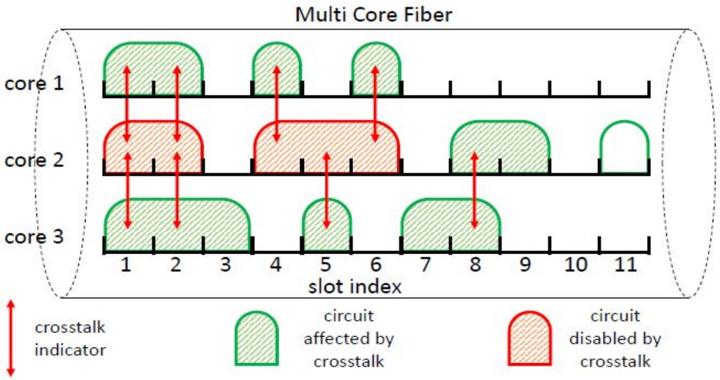


Figure 6: (a) Crosstalk occurence in a PMP, adapted from [8] and (b) different PMPs along the fiber.



(figure from [12])

Possible solutions:

1.Reasonably design the structure of multi-core fiber

2.Reasonably arrange the circuit slot for neighbouring cores

The evaluation of Crosstalk (XT):

$$XT = \frac{n - n.exp[-(n+1).2hL]}{1 + n.exp[-(n+1).2hL]} \qquad h = \frac{2k^2 r}{\beta w_{tr}}$$

Question

What’s superchannel?

A.Multiple, coherent optical carriers are combined to create a unified channel of a higher data rate

B. Multiplexing a number of optical carrier signals onto a single optical fiber by using different wavelengths

Application: Spatial superchannels

Def: A super-channel is an evolution in Dense Wavelength Division Multiplexing (DWDM) in which multiple, coherent optical carriers are combined to create a unified channel of a higher data rate, and which is brought into service in a single operational cycle.

We can also use this conception in spatial domain, it's called Spatial superchannels (SSC)

Advantages:

1. It can share hardware and DSP resources for each subset.
2. It can be extended to new spatial modulation formats that enable
3. greater design flexibility

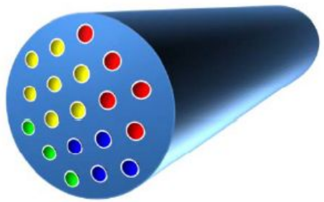


Fig. 7. Example of four sliced spatial superchannels.

(figure from [13])

Application : SDM in self-homodyne detection (SHD)

A transmitted pilot-tone (PT) originating from the transmitter laser is space-multiplexed in the MCF with the data signal and used as a local oscillator for coherent reception, as shown in the figure.

So the local oscillator (LO) laser at the receiver side is not necessary, the impact of laser phase noise can be reduced.

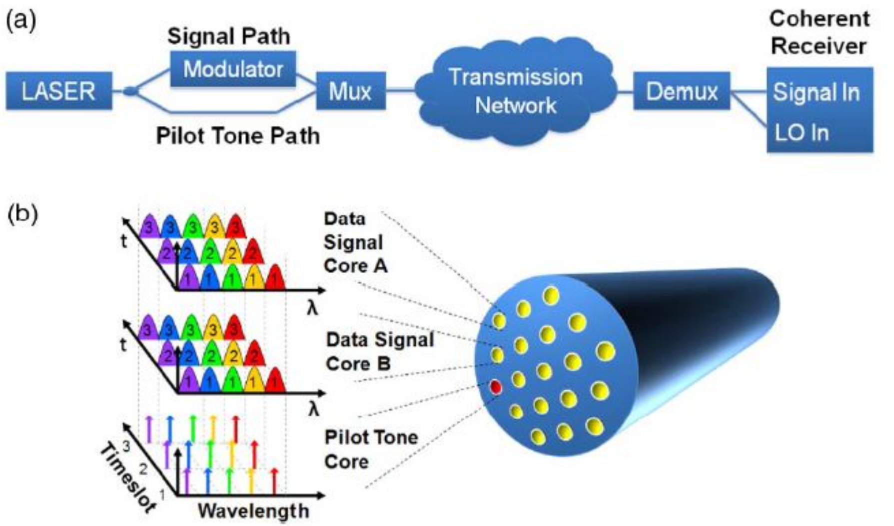


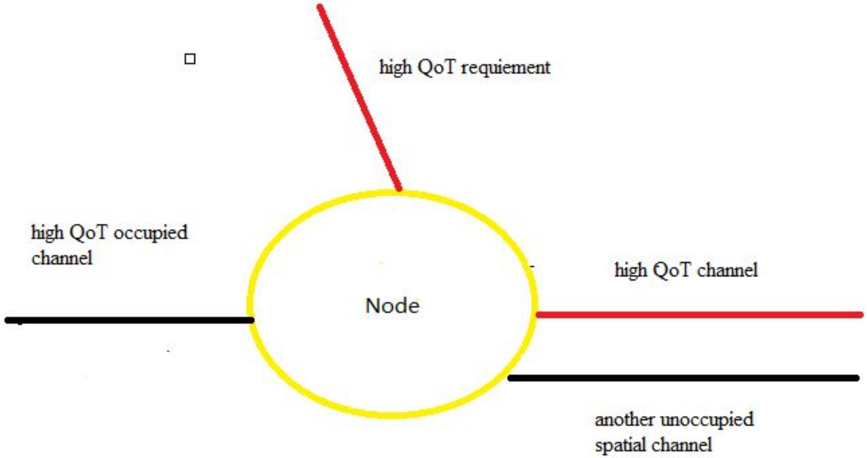
Fig. 8. (a) Schematics of a self-homodyne transmission system. (b) Signal distribution in data-signal cores and the pilot-tone core.

(figure from [13])

Application: wavelength contention management

RWA: Routing and wavelength assignament, need to be done by using OEO now.

Goal: Realize RWA in optical domain by using SDM



References

1. G. M. Saridis, D. Alexandropoulos, G. Zervas and D. Simeonidou, "Survey and Evaluation of Space Division Multiplexing: From Technologies to Optical Networks," in IEEE Communications Surveys & Tutorials, vol. 17, no. 4, pp. 2136-2156, Fourthquarter 2015, doi: 10.1109/COMST.2015.2466458.
2. Yu, Y., Sun, C. & Zhang, X. Silicon chip-scale space-division multiplexing: from devices to system. Sci. China Inf. Sci. 61, 080403 (2018). https://doi.org/10.1007/s11432-017-9449-4.
3. Shipeng Wang, Xianglian Feng, Shiming Gao, Yaocheng Shi, Tingge Dai, Hui Yu, Hon-Ki Tsang, and Daoxin Dai, "On-chip reconfigurable optical add-drop multiplexer for hybrid wavelength/mode-division-multiplexing systems," Opt. Lett. 42, 2802-2805 (2017).
4. Koshiba, M., Saitoh, K. and Kokubun, Y., 2009. Heterogeneous multi-core fibers: proposal and design principle. IEICE Electronics Express, 6(2), pp.98-103.
5. Fujitsu.com. 2021. Fujitsu to Exhibit World's First 100Gps Multi-Mode QSFP28 Active Optical Cable - Fujitsu United States. [online] Available at: <https://www.fujitsu.com/us/about/resources/news/press-releases/2014/fcai-20140304-1.html> [Accessed 21 February 2021].
6. Klaus et al. "Advanced Space Division Multiplexing Technologies for Optical Networks". VOL. 9, NO. 4/APRIL 2017/J. OPT. COMMUN. NETW. C1
7. J. Sakaguchi, Y. Awaji, N. Wada, A. Kanno, T. Kawanishi, T. Hayashi, T. Taru, T. Kobayashi, and M. Watanabe, "109-Tb/s (7 x 97 x 172-Gb/s SDM/WDM/PDM) QPSK transmission through 16.8-km homogeneous multi-core fiber," in Optical Fiber Communication Conf. (OFC), 2011, paper PDPB6.
8. H. Takara, A. Sano, T. Kobayashi, H. Kubota, H. Kawakami, A. Matsuura, Y. Miyamoto, Y. Abe, H. Ono, K. Shikama, Y. Goto, K. Tsujikawa, Y. Sasaki, I. Ishida, K. Takenaga, S. Matsuo, K. Saitoh, M. Koshiba, and T. Morioka, "1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) crosstalk-managed transmission with 91.4-b/s/Hz aggregate spectral efficiency," in European Conf. on Optical Communications (ECOC), 2012, paper Th.3.C.1.
9. D. Qian, E. Ip, M.-F. Huang, M.-J. Li, A. Dogariu, S. Zhang, Y. Shao, Y.-K. Huang, Y. Zhang, X. Cheng, Y. Tian, P. N. Ji, A. Collier, Y. Geng, J. Liñares, C. Montero, V. Moreno, X. Prieto, and T. Wang, "1.05Pb/s transmission with 109b/s/Hz spectral efficiency using hybrid single- and few-mode cores," in Frontiers in Optics, 2012, paper FW6C.3.
10. B. J. Puttnam, R. S. Luís, W. Klaus, J. Sakaguchi, J.-M. Delgado Mendinueta, Y. Awaji, N. Wada, Y. Tamura, T. Hayashi, M. Hirano, and J. Marciante, "2.15 Pb/s transmission using a 22 core homogeneous single-mode multi-core fiber and wideband optical comb," in European Conf. on Optical Communications (ECOC), 2015, paper PD3.1
11. D. Soma, K. Igarashi, Y. Wakayama, K. Takeshima, Y. Kawaguchi, N. Yoshikane, T. Tsuritani, I. Morita, and M. Suzuki, "2.05 peta-bit/s super-Nyquist-WDM SDM transmission using 9.8-km 6-mode 19-core fiber in full C band," in European Conf. on Optical Communications (ECOC), 2015, paper PD3.2.
12. GEORG RADEMACHER,* RUBEN S. LUÍS, BENJAMIN J. PUTTNAM, YOSHINARI AWAJI, AND NAOYA WADA, "Crosstalk dynamics in multi-core fibers"
13. Werner Klaus, Benjamin J. Puttnam, Ruben S. Luís, Jun Sakaguchi,,José-Manuel Delgado Mendinueta, Yoshinari Awaji, and Naoya Wada Advanced Space Division Multiplexing Technologies for Optical Networks

Thank you for your attention