Space-Division Multiplexing on the fiber: from idea to innovation

Ghaya Rekaya-Ben Othman

LTCI Research Day - October 2022

Part I

Space Division Multiplexing on the fiber

Optical Fiber Transmission Systems

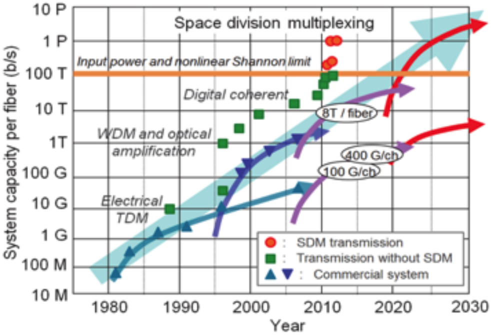
Systems

- Datacenter Interconnects
- Access & Metropolitan Networks
- Core & Submarine Networks

Challenges

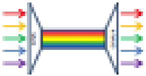
- Throughput >100 Terabits
- Very good performance ($Pe \backsimeq 10^{-15}$)
- Less energy consumption

Optical Fiber Communication Evolution

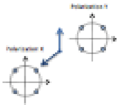


[T.Mizuno et al., J. Lightwave Technology, 2015]

- 1990s’ Wavelength Division Multiplexing



- 2000s’ Polarization Multiplexing

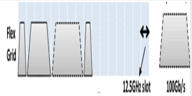


More Capacity on the fiber

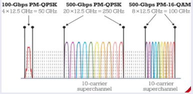
$$C = \underset{\text{spectral}\nearrow}{B} * \underset{\text{spatial}\nearrow}{M} * log_2(SNR)$$

DENSE WDM

- FlexGrid Systems

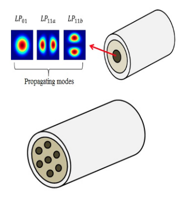


- Super channels



Space Division Multiplexing

- Multi-Mode Fiber (MMF)
- Multi-Core Fiber (MCF)

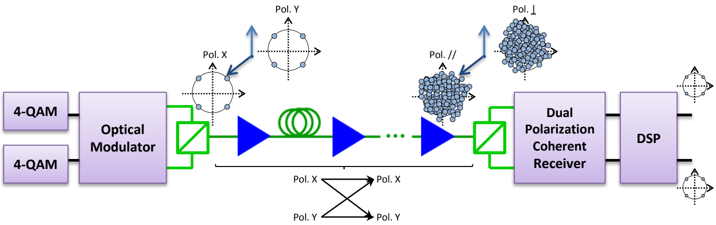


Outline

Space Division Multiplexing on the fiber

1. PolMux Fiber
2. Multi-Mode Fiber
3. Multi-Core Fiber

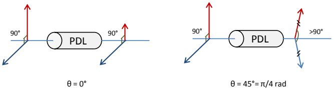
Polarization Division Multiplexing



- Coherent detection gives access to amplitude, phase & polarization
- Higher bitrate over longer distances with SSMFs
- **Channel effects** : Polarization crosstalk, polarization mode dispersion (PMD), **polarization dependent loss (PDL)**

Polarization Dependent Loss Channel Model

- PDL induces loss of orthogonality & OSNR inequalities



- The transfer matrix of a PDL element is given by:

$$H_{PDL} = R_\theta \begin{bmatrix} \sqrt{1+\gamma} & 0 \\ 0 & \sqrt{1-\gamma} \end{bmatrix} R_\theta^{-1}$$

  where R_θ is a random rotation describing polarization states and principal polarization states axes mismatch.

- PDL is defined as :

$$\Gamma_{\mathrm{dB}} = 10 \log_{10} \frac{1+\gamma}{1-\gamma}$$

Optical channel as MIMO channel

MIMO : **M**ulti-**I**nput **M**ulti-**O**utput.

- The received signal is: $Y_{2\times T} = H_{2\times 2}.X_{2\times T} + W_{2\times T}$
  - T is the temporal codelength.
  - H is the channel matrix
  - W is the AWGN noise.
  - X is the transmitted codeword called “Space-Time Code”
- A Space-Time code bring dependency between space and time domain by sending linear combination of information symbols:

$$X_{ST,2\times T} = \begin{bmatrix} x_1(t_1) & x_1(t_2) & \dots \\ x_2(t_1) & x_2(t_2) & \dots \end{bmatrix} = \begin{bmatrix} f_1(s_1 \dots s_{N_S}) & f_2(s_1 \dots s_{N_S}) & \dots \\ f_3(s_1 \dots s_{N_S}) & f_4(s_1 \dots s_{N_S}) & \dots \end{bmatrix}$$

with $N_S \leq 2T$ modulated symbols & a rate $r_{ST} = \frac{N_S}{T}$ symbols/cu

Classical channels behavior

- For **AWGN Channel**, an upper bound of the error probability is :

$$P_e(\Lambda) \leq \overline{N_{min}} \cdot exp\left(-\frac{d_{E,min}^2}{4\sigma_w^2}\right)$$

where $\overline{N_{min}}$ is the average number of neighbors, $d_{E,min}$ is the minimum euclidean distance of the constellation.

- For **Rayleigh channel**, the pairwise error probability is upper bounded by:

$$\mathrm{Prob}(X \to Z) \leq \left(\prod_{i=1}^{r} \lambda_i\right)^{-n_r} \left(\frac{1}{\frac{E_S}{8N_0}}\right)^{r \cdot n_r}$$

λ_i are singular values of $B = (X - Z)^H (X - Z)$ and r its rank.

PolMux Optical channel

- The pairwise error probability is upper bounded by:

$$\Pr(X \to Z) \leq \exp\left(-\frac{\|\mathbf{X}_\Delta\|^2}{8N_0}\right) I_0\left(\frac{\gamma_{eq}}{8N_0}\sqrt{a^2+b^2}\right)$$

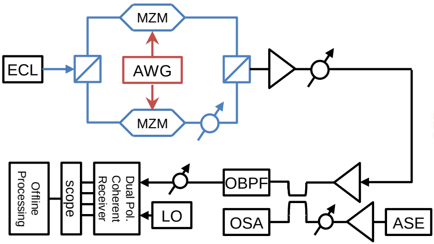
  - $X_\Delta = Z - X = \begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{pmatrix}$, $a = \|\mathbf{x}_2\|^2 - \|\mathbf{x}_1\|^2$, $b = 2\Re(\langle \mathbf{x}_1, \mathbf{x}_2 \rangle)$,
  - $I_0(k)$: 0^{th} order modified Bessel function of the first kind.
- At high SNR, the pairwise error probability is upper bounded by :

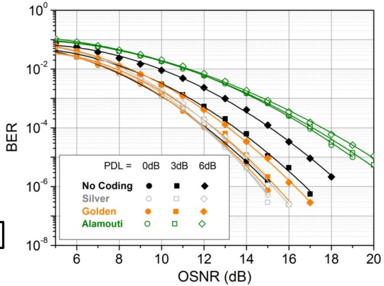
$$\Pr(X \to Z) \leq \exp\left(-\frac{\|X_\Delta\|^2 - \gamma_{eq}\sqrt{a^2+b^2}}{8N_0}\right)$$

- **Gaussian behavior**, with a different minimum distance which depends on the PDL value

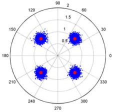
$$d_{min} = min\left(\|X_\Delta\|^2 - \gamma_{eq}\sqrt{a^2+b^2}\right)$$

Theoretical / Numerical /Experimental Validation

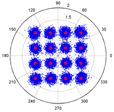




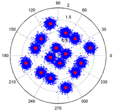
No Coding (4-QAM)



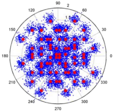
Alamouti (16-QAM)



Golden code



Silver code



Space Division Multiplexing on the fiber

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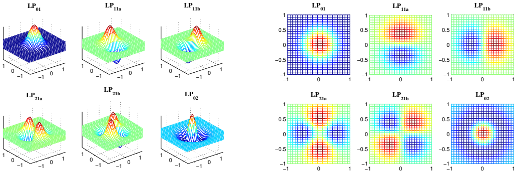
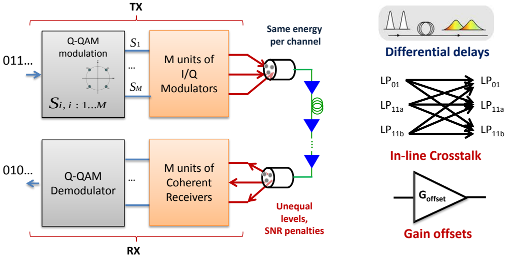
2. Multi-Mode Fiber
3. Multi-Core Fiber

Mode Multiplexing

6 mode profiles





TX

011...

Q-QAM modulation

$S_{i,\ i\ :\ 1\ldots M}$

S_1

...

S_M

M units of I/Q Modulators

Same energy per channel

010...

Q-QAM Demodulator

M units of Coherent Receivers

Unequal levels, SNR penalties

RX

Differential delays

LP_{01} LP_{11a} LP_{11b} → LP_{01} LP_{11a} LP_{11b}

In-line Crosstalk

G_{offset}

Gain offsets

Mode Dependant Loss Channel model

- **Mode dependent Loss (MDL)**
    - Different attenuations for modes
    - Local MDL induced by optical components (as amplifiers)
    - Inline distributed MDL induced by fiber Bends, fiber misalignment...
- Multi-mode channel matrix is :

$$H_{MDL} = \sqrt{L} \cdot D \cdot U$$

    - D is a diagonal matrix with entries uniformly drawn from $[\lambda_{min}, \lambda_{max}]$ representing the imbalanced attenuations of modes.
    - U is a random unitary matrix describing mode coupling.
- MDL is defined as :

$$MDL_{\mathrm{dB}} = 10 \log_{10} \frac{\lambda_{max}}{\lambda_{min}}$$

Upper bound on the error probability

- The pairwise error probability is upper bounded by:

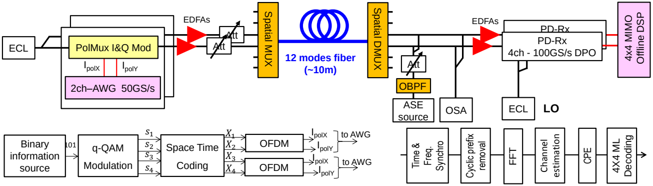
$$\Pr(X \rightarrow Z) \leq N_1 \cdot \exp\left(-\frac{d^2_{min}}{8N_0}\right) + N_2 \cdot \exp\left(-\frac{d^2_{min}}{8N_0 \cdot \frac{\lambda_{max}}{\lambda_{min}}}\right)$$

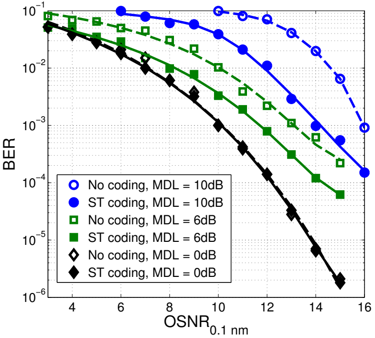
  - $d^2_{min} = \underset{\mathbf{x}_i \neq \mathbf{x}_j}{min} \|\mathbf{x}_i - \mathbf{x}_j\|^2$ is minimal distance between two codewords
  - N_1 is the average number of closest neighbors of $\mathbf{x}_i$ such that $\mathbf{x}_i - \mathbf{x}_j$ is orthogonal.
  - N_2 is the average number of closest neighbors of $\mathbf{x}_i$ such that $\mathbf{x}_i - \mathbf{x}_j$ is non orthogonal.

Code construction criterion

To minimize the error probability, the code should maximize the number of closest neighbors of $\mathbf{x}_i$ such that $\mathbf{x}_i - \mathbf{x}_j$ is orthogonal.

Theoretical / Numerical /Experimental Validation

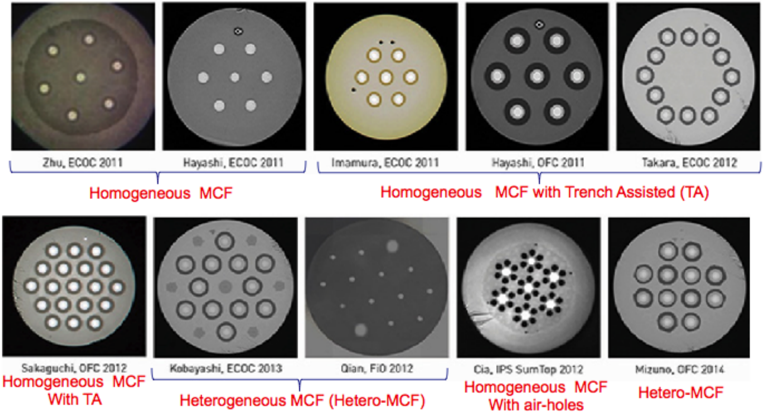




Space Division Multiplexing on the fiber

1. PolMux Fiber
2. Multi-Mode Fiber
3. Multi-Core Fiber

Multi-Core Fiber configurations



[P.J. Winzer , "Optical Fiber Networks challenges and solutions"]

Core Dependant Loss Channel Model

- **Core dependent Loss (CDL)**
  - Different attenuations for the cores
  - CDL induced by crosstalk between the cores
  - Distributed CDL induced by fiber Bends, fiber misalignment ...
- CDL channel matrix is :

$$H_{CDL} = \sqrt{L} \cdot \prod_{k=1}^{K} ((H_{XT})_k \cdot M_k)$$

  - H_{XT} is the **crosstalk** matrix function of core configuration
  - M is a diagonal matrix representing to a random gaussian **misalignment** of a fixed variance.
- CDL is defined as :

$$CDL_{\mathrm{dB}} = 10 \log_{10} \frac{\lambda_{max}}{\lambda_{min}}$$

where λ_{min} and λ_{min} are min and max singular values of HH^* respectively.

Proposed MCF Channel Model

- The equivalent channel H can be expressed as :

$$H = U \cdot \begin{bmatrix} r_1 & & \\ & \ddots & \\ & & r_c \end{bmatrix} \cdot V \quad r_i = (XT_i)^K \prod_{l=1}^{K} \alpha_i^l$$

- The singular values are **log-normally distributed** with parameters :

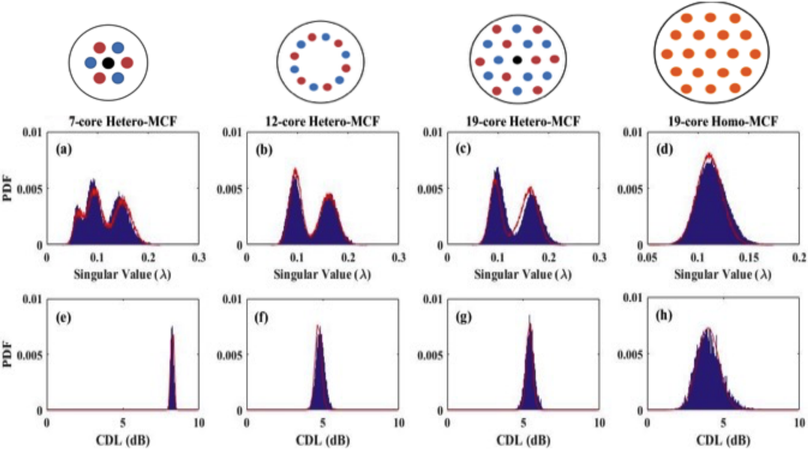
$$\mu_{r_i} = exp\left(\mu + \frac{\sigma_z^2}{2}\right) = exp\left(2Kb_i\left(b_i\sigma^4_{(x,y)i} - \sigma^2_{(x,y)i}\right)\right)$$

$$\sigma^2_{r_i} = \left(exp\left(\sigma_z^2\right) - 1\right) \cdot \mu^2_{r_i} = \left(exp\left(4Kb_i^2\sigma^4_{(x,y)i}\right) - 1\right) \cdot \mu^2_{r_i}$$

- **CDL has gaussian distribution** :

$$CDL = \mathcal{N}\left(\frac{20}{ln(10)} \cdot \left(K \cdot ln\left(\frac{XT_{\lambda_{max}}}{XT_{\lambda_{min}}}\right) + \left(\mu_{z,\lambda_{max}} - \mu_{z,\lambda_{min}}\right)\right), \left(\frac{20}{ln(10)}\right)^2 \cdot \left(\sigma^2_{z,\lambda_{max}} + \sigma^2_{z,\lambda_{min}}\right)\right)$$

Proposed MCF Channel Model validation



Simulated and Theoretical PDF of singular values and CDL

IQ-Code Performance

- We have proposed several solutions as Space-time code, scrumbling, core selection, pre-coding ...
- We have developed a new code, **IQ-Code**, that average the levels of losses and crosstalk in each polarization and core (or mode, or sub-band) without using OFDM
- We are now submitting a collaborative project to run an experiment of the IQ-Code on MCF and MMF fibers.

Part II

MIMOPT Technology

Idea

- 13 years of research work have resulted in a portfolio of 14 patent families
- Worldwide recognition of our results
- A great expertise on the domain
- **An observation**: Optical communications are in the midst of a digital revolution

Project pre-maturation

- **Telecom Paris “pre-maturation project”**, 2018-2019:
  - Structure of our results
  - Prepare a draft of the business model
- **Market study 2019-2020**:
  - A firm specialized in photonic communications
  - Market investigation
  - Verdict: **It’s the right "Time to market”**

MIMOPT Technology- April 2021

Ghaya Rekaya
CEO/ MIMOPT

- Professor at Telecom Paris
- Expert on Digital Communication
- More than 100 publications, and 50 patents.
- Research Topics : Coding and Decoding for MIMO systems, Physical Layer Network Coding and Coding for Optical Fiber Communications

Akram Abouseif
CTO/ MIMOPT

- PhD on Signal processing on space-division multiplexing, Telecom Paris.
- MSc Optical Network and Photonic Systems, Saclay University.
- Engineering diploma in Electrical and Computer Engineering , Cairo University.

Yves Jaouën
Expert/ MIMOPT

- Professor at Telecom Paris
- Expert on Optical Communication
- More than 250 publications, and 15 patents.
- Research topics : high-bit rate coherent-based optical systems, new characterization techniques for advanced photonic devices.

Our Scope

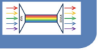
MIMOPT develops and commercializes innovative Digital Signal Processing solutions for optical fiber communication systems.

Patent Clusters

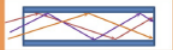
EP US JP

Group 1 : Polarisations

Group 4: Wavelengths



Group 2 : Modes



Group3: Cores

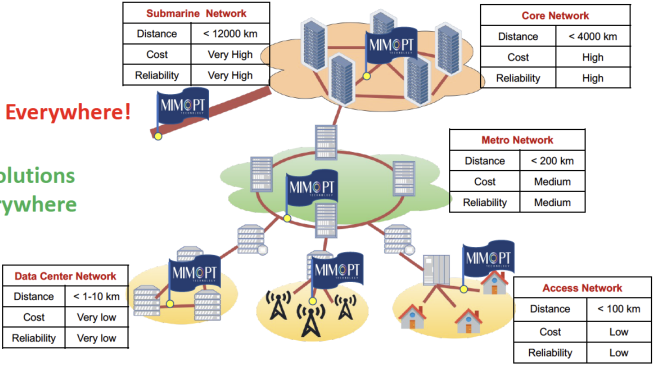
Our Market

Optical Fiber is Everywhere!

and

MIMOPT solutions

can be Everywhere



Submarine Network	
Distance	< 12000 km
Cost	Very High
Reliability	Very High

Core Network	
Distance	< 4000 km
Cost	High
Reliability	High

Metro Network	
Distance	< 200 km
Cost	Medium
Reliability	Medium

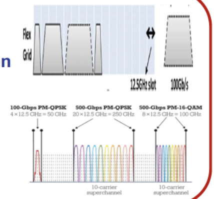
Data Center Network	
Distance	< 1-10 km
Cost	Very low
Reliability	Very low

Access Network	
Distance	< 100 km
Cost	Low
Reliability	Low

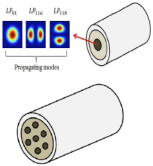
Our Innovation

Innovative DSP Solutions

Our coding schemes make **spectral allocation densification possible** by canceling inter-channel interference.



WDM systems with
Flex Grid and Superchannels

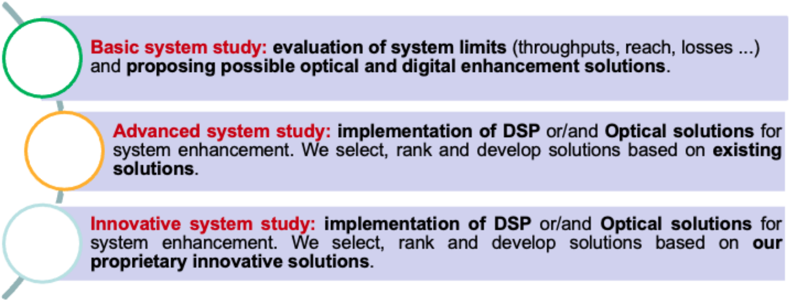


Our coding solutions allow an optimal use of all degrees of freedom in the fiber in: **polarization**, **wavelength, mode** and **core**.

SDM systems with
multi-mode and multi-core fibers

Our Offer

For companies that own optical communication systems can benefit from MIMOPT's knowledge, expertise, and simulation to design or upgrade their optical communications system.



Basic system study: **evaluation of system limits** (throughputs, reach, losses ...) and **proposing possible optical and digital enhancement solutions**.

Advanced system study: **implementation of DSP** or/and **Optical solutions** for system enhancement. We select, rank and develop solutions based on **existing solutions**.

Innovative system study: **implementation of DSP** or/and **Optical solutions** for system enhancement. We select, rank and develop solutions based on **our proprietary innovative solutions**.

Thank you for your attention !