Time-Division Hybrid Modulation Formats: Tx Operation Strategies and Countermeasures to Nonlinear Propagation

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Motivation and outline

- Symbol-rate and wavelength grid given: continuity of reach vs. spectral efficiency
- Use of reduced-complexity “squared” constellations
- Flexible network optimization
- Transmitted frame and operation-setting parameters
- Strategies to define the Tx operation and b2b performance
- Nonlinear propagation of NyWDM channels on SSMF and NZDSF
  - Effects of frame length
  - Benefits of predistortion
  - The polarization interleaving technique
- Comments and conclusions
**Tx frame and operation-setting parameters**

- Frame: \( M = M_1 + M_2 \) [symbols]
- \( M_1 \) symbols
- \( M_2 \) symbols
- Modulation Format \( F_1 \): \( P_1, \text{SNR}_1, \text{BpS}_1 \)
- Modulation Format \( F_2 \): \( P_2, \text{SNR}_2, \text{BpS}_2 \)

**Format ratio**: \( FR = 100 \frac{M_2}{M} \)

**Power ratio**: \( PR = \frac{P_2}{P_1} \)

- OSNR in \( R_s \): \( SNR = \left( 1 - \frac{FR}{100} \right) \cdot \text{SNR}_1 + \frac{FR}{100} \cdot \text{SNR}_2 \)
- Average power: \( P_{Tx} = \left( 1 - \frac{FR}{100} \right) \cdot P_1 + \frac{FR}{100} \cdot P_2 \)

**Overall bit-per-symbol**
- \( \text{BpS} = \left( 1 - \frac{FR}{100} \right) \cdot \text{BpS}_1 + \frac{FR}{100} \cdot \text{BpS}_2 \)

**Overall BER**
- \( BER = \frac{1}{\left( 1 - \frac{FR}{100} \right) \cdot \text{BpS}_1 + \frac{FR}{100} \cdot \text{BpS}_2} \left( \frac{\text{SNR}}{\left( 1 - \frac{FR}{100} \right) \cdot \text{BpS}_1 + \frac{FR}{100} \cdot \text{BpS}_2} \right) \cdot \Phi \left( \frac{PR}{\left( 1 - \frac{FR}{100} \right) + \frac{FR}{100} \cdot PR} \right) \)

**Strategies for Tx working point**

Given \( F_1, F_2 \) and \( FR \), \( PR \) is the parameter to set according to one of the following strategies:

- **a)** Min BER: \( PR \) is obtained minimizing \( SNR \) in BER equation \( \Rightarrow \) \( PR \) varies with the target BER

- **b)** \( BER_1 = BER_2 \): both \( F_1 \) and \( F_2 \) are forced to operate at the same BER \( \Rightarrow \) \( PR \) is consequently defined

- **c)** \( d_1 = d_2 \): the minimum Euclidean distance \( d_i (i=1,2) \) is kept equal for both \( F_1 \) and \( F_2 \) \( \Rightarrow \) \( PR \) is a constant depending on constellations

- **d)** \( PR = 0 \) dB: it keeps constant power during transmission \( (P_1 = P_2 = P_{Tx}) \) \( \Rightarrow \) the highest-cardinality modulation format operates at the FEC cliff, the other is working error free
**PR vs. BER for different strategies**

F1: PM-QPSK, F2: PM-16QAM, BpS=6 \(\rightarrow\) FR=50%

\[ d_1 = d_2 \]

\[ \text{Min } BER \]

\[ \text{BER}_1 = \text{BER}_2 \]

\[ PR = 0 \text{ dB} \]

\[ \text{BER}_T = 2 \cdot 10^{-2} \]

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**BER vs. SNR for different strategies**

F1: PM-QPSK, F2: PM-16QAM, BpS=6 \(\rightarrow\) FR=50%

\[ \text{BER}_T = 2 \cdot 10^{-2} \]

\[ PR = 0 \text{ dB} \]

\[ d_1 = d_2 \]

\[ \text{PM-8QAM} \]

\[ \text{BER}_1 = \text{BER}_2 \]

\[ \text{Min } BER \]

**Very similar behavior**
Combining the first “squared” constellations...

Very small penalty using $BER_1=BER_2$ or $d_1=d_2$

... and the fiber propagation?

- F1: PM-QPSK, F2: PM-16QAM with “Min BER” Tx
- BpS=6 $\Rightarrow$ $FR=50\%$
- $R_s=32$ Gbaud
- 9-channel NyWDM comb @ $\Delta f=33.6$ GHz=$1.05 \cdot R_s$
- $BER_T=2 \cdot 10^{-2}$
- Multispan link with $L_s=100$ km, EDFA with $NF=5$ dB
- Two typical fiber types:
  - SSMF
    - $\alpha_{dB}=0.22$ dB/km, $D=16.7$ ps/nm/km, $\gamma=1.3$ $1/W/km$
  - NZDSF
    - $\alpha_{dB}=0.22$ dB/km, $D=3.8$ ps/nm/km, $\gamma=1.5$ $1/W/km$
Maximum reach vs. GN-model

FR=50%, F1: PM-QPSK, F2: PM-16QAM, BER_T=2·10^{-2}

Power per channel

The frame length does matter!

Predistortion: Max Reach vs. D_{pre}

FR=50%, F1: PM-QPSK, F2: PM-16QAM, BER_T=2·10^{-2}

Proper predistortion enables GN-model-predicted reach
Polarization Interleaving (PI)

In order to keep constant power...

PI helps and reduces the required predistortion.
Comments and conclusions

- Strategies for Tx setup giving b2b performance
- Combining “squared” constellation \( \Rightarrow \) continuity in spectral efficiency w/o substantial b2b penalties with respect to specific modulation formats
- Nonlinear propagation: the shorter the frame length, the better
- Predistortion enables to obtain GN-model predictions
- Polarization interleaving helps and substantially reduces the required predistortion

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