ACHIEVING FINE BIT-RATE GRANULARITY WITH HYBRID SUBCARRIER MODULATION

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OUTLINE

- Motivations
- The proposed technique
  - Frequency Division Hybrid Modulation Formats (FDHMF)
- Simulations results
  - Comparing FDHMF and TDHMF
- Conclusions
- Reach can be traded off with capacity
- Standard Polarization Multiplexed Square M-QAM modulation formats have a coarse bit-rate granularity
  - Steps of 4 bit/symbol
MOTIVATION: TDHMF

- A possible solution: Time-Domain Hybrid Modulation Format

- Drawbacks: extra DSP complexity due to time-dependent modulation
Thanks to the EGN it has been shown that NLI can be minimized through Symbol Rate Optimization (SRO)

- Recent experiments confirmed it
- Optimal symbol rate are usually too small to be implemented as single wavelength → SubCarrier Multiplexing is a viable solution
We propose to use frequency domain hybrid modulation formats (FDHMF). It is a hybrid subcarrier modulation.
**TRANSMITTER**
- $R_s = 32$ Gbaud
- 15 channels
- Roll-off = 0.05
- $\Delta f = 37.5$ GHz

**LINK**
- Fiber: SMF
  - $\alpha = 0.2$ [dB/km]
  - $\gamma = 1.3$ [1/W/km]
  - $D = 16.7$ [ps/nm/km]
- EDFA
  - Gain recover fiber loss
  - $F = 5$ dB

**RECEIVER**
- Coherent receiver
- ADC
  - 2 SpS (64 GSa/s)
- DSP:
  - DA-LMS with training sequence

**100 km Fiber span**

**EDFA**

**SIMULATION SETUP**
- We consider FDHMF obtained mixing PM-16QAM and PM-64QAM, spanning from 8 to 12 Bits per Symbol (200G to 300G)

- Optimal symbol-rates are:
  - 4 GBaud for PM-16QAM
  - 8 GBaud for PM-64QAM

- We define a FDHMF configuration composed of 8 subcarriers, enabling a net bit-rate granularity of up to 12.5 Gb/s
FDHMF transceivers can be operated in difference modes

- Power ratio between formats depends on them

We used the “same BER” approach

- Power ratio is set to 5.83 dB between PM-16QAM and PM-64QAM

We considered three configurations

1. frequency interleaving of the low- and high-cardinality formats

2. allocating the low-cardinality format to the edge subcarriers and the high-cardinality format to the center subcarriers

3. applying the reverse of 2
We restrict our simulation analysis to a 25 Gb/s granularity

- 225G: 6SC x PM-16QAM + 2SC x PM-64QAM
- 250G: 4SC x PM-16QAM + 4SC x PM-64QAM
- 275G: 2SC x PM-16QAM + 6SC x PM-64QAM

The maximum reach is calculated taking into account the average BER among all subcarriers.

In order to assess the performance of each modulation format, we also plot the average BER of each set of subcarriers associated with PM-16QAM and PM-64QAM modulation formats.
FDHMF MAXIMUM REACH: 225G

- linear
- IGN
- PM-16QAM
- PM-64QAM
- HYBRID
- interleaved
- edge\textsubscript{16} / center\textsubscript{64}
- edge\textsubscript{64} / center\textsubscript{16}

Max. Reach [km]

Input Power Per Subcarrier [dBm]

INTERLEAVED

225G
FDHMF MAXIMUM REACH: 225G

Max. Reach [km]

-15 -14 -13 -12 -11 -10 -9 -8

Input Power Per Subcarrier [dBm]

- linear
- IGN
- PM-16QAM
- PM-64QAM
- HYBRID
- interleaved
- edge\textsubscript{16} / center\textsubscript{64}
- edge\textsubscript{64} / center\textsubscript{16}

INTERLEAVED

EDGE\textsubscript{16}/CENTER\textsubscript{64}

EDGE\textsubscript{64}/CENTER\textsubscript{16}
FDHMF MAXIMUM REACH: 225G

\[ \frac{P_{64QAM}}{P_{AVG}} = 3.5 \text{ dB} \]
FDHMF MAXIMUM REACH: 250G

\[ \frac{P_{64QAM}}{P_{AVG}} = 2.0 \text{ dB} \]

**Graph:**
- **X-axis:** Input Power Per Subcarrier [dBm]
- **Y-axis:** Max. Reach [km]
- **Curves:**
  - **linear**
  - **IGN**
  - **PM-16QAM**
  - **PM-64QAM**
  - **HYBRID**
- **Points:**
  - **interleaved**
  - **edge_{16} / center_{64}**
  - **edge_{64} / center_{16}**

**Bar Charts:**
- **INTERLEAVED**
- **EDGE_{16}/CENTER_{64}**
- **EDGE_{64}/CENTER_{16}**

**Note:**
- The graph shows the maximum reach for different modulation schemes and input power levels.
- The ratio of peak power to average power is 2.0 dB.
- The 1.5 dB improvement is indicated by the arrow.
FDHMF MAXIMUM REACH: 275G

\[ \frac{P_{64QAM}}{P_{AVG}} = 0.9 \text{ dB} \]

Graph showing the relationship between input power per subcarrier and maximum reach for different modulation schemes. The graph includes data points for linear, IGN, PM-16QAM, PM-64QAM, and HYBRID modes. The graphs indicate a maximum reach of 275G at 1 dB power level.
For TDHMF, in order to keep power level constant symbol by symbol, polarization interleaving has been proposed:
  - It helped improve system performance.
We similarly applied it also to FDHMF to equalize power in the frequency domain.

Polarization Interleaving
COMPARING WITH TDHMF

![Graph comparing maximum reach with bit rate](image)

- **TDHMF (32 Gbaud)**
- **TDHMF-PI (32 Gbaud)**
- **FDHMF (4 Gbaud)**
- **FDHMF-PI (4 Gbaud)**
- **Incoherent GN**

**Legend:**
- **mean BER**
The impact of PI on the average BER performance is negligible
The impact of PI on the average BER performance is negligible

FDHMF reaches performances similar to TDHMF
Although the impact on the average BER performance is negligible, PI is shown to significantly reduce the gap between the best and worst performing subcarriers.
We proposed a new format to achieve fine bit-rate granularity: FDHMF

FDHMF performs similarly to the previously introduced TDHMF solution

FDHMF being time invariant has significant advantages for the DSP implementation

Polarization Interleaving has been shown to be an effective technique to mitigate BER differences between subcarrier after non-linear propagation
THANK YOU!

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