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

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Abstract: We propose four strategies for TDHMF Tx operation. *BER* minimization permits PM-QPSK/PM-16QAM performance similar to PM-8QAM's. In TDHMF nonlinear propagation, predistortion and/or polarization interleaving enables the maximum reach predicted by GN-model.

OCIS codes: (060.1155) All-optical networks; (060.1660) Coherent communications;

1. Introduction

The evolution of optical networks goes towards the maximum time-flexibility, so it becomes beneficial for transceivers to be able to maximize spectral efficiency (*SE*) by adapting to the actual conditions of the network and data rate for each given traffic demand [1]. For such a scenario, to simplify transceiver implementation it is convenient to keep the channel spectral allocation Δf and symbol rate R_S as constants. The use of *standard* modulation formats with given bit-per-symbol (*BpS*) fails in satisfying such requirements as $SE=BpS\cdot\Delta f/R_S$. A possible solution could be the use of flexible transceivers that can operate on demand with *N* different modulation formats, but the flexibility should be still quantized at *N* values corresponding to the modulation format *BpS*'s.

A solution giving a finer granularity to *SE* – and consequent trade-off with reach – within a given range is the use of the time-division hybrid modulation formats (TDHMF) [2] based on transmission of alternated frames of two modulation formats. Feasibility of TDHMF has been positively tested in several experiments based on a pair of modulation formats in the PM-mQAM family [2-9]. Moreover, it has been shown that nonlinear propagation seems to induce larger impairments on TDHMF with respect to *standard* formats [9]. Regarding the strategy in setting the transmitter (Tx) operation for TDHMF, a clear assessment has not been presented yet.

First purpose of this work is to list the possible strategies for setting the operation of the Tx for TDHMF, describing the choice of parameters and displaying the performance vs. optical signal to noise ratio (*SNR*[1]). Then, we suppose to use a TDHMF based on PM-QPSK and PM-16QAM. This choice is motivated by the characteristics of these formats allowing I/Q data separation and threshold-based decision at the receiver. We show that the PM-QPSK/PM-16QAM TDMHF with $BpS=6$ bits with the optimal Tx setup does not present any back-to-back penalty with respect to PM-8QAM, assuming operation at $BER=2\cdot 10^{-2}$. We test the nonlinear propagation of such a format within a Nyquist-WDM (NyWDM) channel comb on uniform uncompensated links. We show that in absence of any countermeasure it experiences a small penalty with respect the GN-model [10] predictions, that can be recovered with a proper amount of predistortion or partially recovered using the polarization interleaving [8].

2. Strategies for transmitter operation

In general, TDHMF's are characterized by periodic frames of *M* symbols: first M_1 symbols refer to the first modulation format (F_1) and the second M_2 symbols are second modulation format's (F_2). Both F_1 and F_2 operate at R_S. Tx time-evolution is pictorially described in Fig. 1 together with the definitions of main parameters. Both F_i's (i=1,2) are characterized by BpS_i, by the individual average power P_i and individual SNR_i, given the overall average power P_{Tx}, the power ratio *PR* and the format ratio *FR*. Hence, the overall bit-error-rate (*BER*) is:

$$BER=\frac{1}{\left(1-\frac{FR}{100}\right)\cdot BpS_1+\frac{FR}{100}\cdot BpS_2}\cdot\left\{\left(1-\frac{FR}{100}\right)\cdot BpS_1\cdot\Phi_1\left[\frac{SNR}{\left(1-\frac{FR}{100}\right)+\frac{FR}{100}\cdot PR}\right]+\frac{FR}{100}\cdot BpS_2\cdot\Phi_2\left[PR\frac{SNR}{\left(1-\frac{FR}{100}\right)+\frac{FR}{100}\cdot PR}\right]\right\} \quad (1)$$

where $\Phi_1(x)$ and $\Phi_2(x)$ [10] are functions of *SNR* giving *BER* for F_1 and F_2, respectively. As it does not appear in Eq. (1), the frame length *M* affects only propagation and does not modify the back-to-back performance.

Once the pair of modulation formats is chosen, using Eq. (1), *PR* and *FR* parameters must be settled. The choice of the overall *BpS* in the range $[BpS_1;BpS_2]$ fixes *FR*, and consequently defines the overall *SE*, given the channel spacing Δf. Thus, the remaining degree of freedom for setting the transmitter operation is the choice of the power ratio *PR*. To this purpose, the following four different strategies can be implemented.

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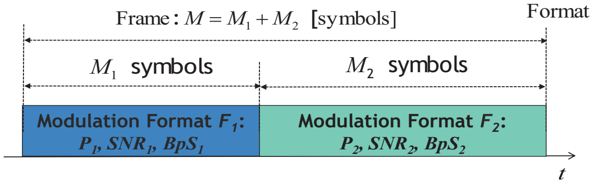
[1] In this work, we consider the optical signal-to-noise ratio *SNR* as referred to the noise bandwidth $B_N=R_S$.



$$\text{Format ratio}: FR = 100\frac{M_2}{M} \quad \text{Power ratio}: PR = \frac{P_2}{P_1}$$

$$P_{Tx} = \left(1 - \tfrac{FR}{100}\right) \cdot P_1 + \tfrac{FR}{100} \cdot P_2$$

$$SNR = \left(1 - \tfrac{FR}{100}\right) \cdot SNR_1 + \tfrac{FR}{100} \cdot SNR_2$$

$$\text{Bit-per-symbol}: BpS = \left(1 - \tfrac{FR}{100}\right) \cdot BpS_1 + \tfrac{FR}{100} \cdot BpS_2$$

$$\text{Spectral efficiency}: SE = BpS\frac{\Delta f}{R_s}$$

Fig. 1: Time-frame of a generic time-division hybrid modulation format and definition of the fundamental parameters.

1. ***PR*=0 dB**: it keeps constant power during transmission ($P_1=P_2=P_{Tx}$). Only the highest-cardinality modulation format operates at the FEC cliff, while the other format is practically working error free.
2. **$d_1=d_2$**: the minimum Euclidean distance d_i (i=1,2) is kept equal for both the modulation formats. Also in this case *PR* is a constant depending only on the chosen pair of modulation formats.
3. **$BER_1=BER_2$**: both modulation formats are forced to operate at the same *BER*. *PR* is consequently defined and depends both on the pair of modulation formats through the functions Φ_i, and on the target *BER*.
4. **Min *BER***: *PR* is obtained minimizing *SNR* in Eq. (1), given *BER*. Hence, *PR* varies with the target *BER*.

In order to test the four strategies for setting the Tx operation, we considered the TDHMF proposed in Sec. 1, i.e., F_1=PM-QPSK, F_2=PM-16QAM, *FR*=50% (*BpS*=6 bits) and target *BER* ($BER_T=2\cdot 10^{-2}$). For each of the four options we evaluated the value of *PR* vs. *BER* and then we calculated the required *SNR* for each *BER* level.

In Fig. 2a, *PR* at different target *BER* is plotted. Strategies 1 and 2 imply constant *PR* set to 0 and 7 dB, respectively. For the other two strategies, *PR* tends to the "$d_1=d_2$" level (7 dB) for small *BER*, while it decreases with the increasing of *BER*. At $BER_T=2\cdot 10^{-2}$, we found *PR*=6.5 dB for "$BER_1=BER_2$" and *PR*=5 dB for "Min *BER*". Fig. 2b shows the *SNR* required to have a certain *BER* for the four strategies, together with the curve referred to the PM-8QAM, as standard modulation format reference with *BpS*=6 bits. Except for the "*PR*=0 dB" option, the other three strategies present very similar performances with "Min *BER*" being the optimal choice, as expected. At $BER=2\cdot 10^{-2}$, with "Min BER" the TDHMF requires $SNR_T\approx 10.5$ dB as the standard PM-8QAM does, while choosing "$d_1=d_2$" or "$BER_1=BER_2$" a roughly 0.1 dB penalty can be observed. The suboptimal choice is "*PR*=0 dB" that needs $SNR_T\approx$ 11.9 dB. It is interesting to observe that using a TDHMF based on PM-QPSK and PM-16QAM with *FR*=50% we have a modulation format with *BpS*=6 bits with the same *SNR* requirement (10.5 dB) at $BER_T=2\cdot 10^{-2}$ as the PM-8QAM does. Envisioning FEC coding with higher performance, the TDHMF can even overperform PM-8QAM as it can be observed in the upper part of Fig. 2b.

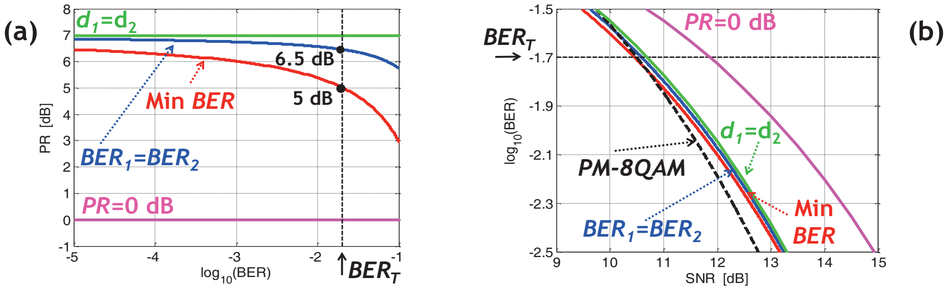


Fig. 2: *PR* vs. *BER* (a) and *BER* vs. *SNR* (b) for all the considered Tx operation strategies In (b), PM-8QAM curve is plotted as a reference.

3. Nonlinear propagation: benefits of pre-distortion and polarization interleaving

The subsequent analysis was the evaluation of the nonlinear propagation performances for the chosen TDHMF at R_s=32 Gbaud. We set the Tx according to "Min *BER*" (*PR*=5 dB), being the optimal choice. We simulated propagation on uncompensated uniform multi-span links with span length L_s=100 km and EDFA's with *NF*=5 dB recovering span losses. Channel comb was made of 9 ideal NyWDM channels spaced 33.6 GHz. A standard receiver was followed by an LMS equalizer and threshold-based decision. We considered two fiber types: SSMF and NZDSF with (α_{dB}=0.22 dB/km, *D*=16.7 ps/nm/km, γ=1.3 1/W/km) and (α_{dB}=0.22 dB/km, *D*=3.8 ps/nm/km, γ=1.5 1/W/km), respectively. We swept P_{Tx} looking for the max number of spans N_{span}[2] still giving *BER* below $BER_T=2\cdot 10^{-2}$.

The frame length is supposed to influence propagation impairments, therefore, first, we tested its effect considering *M*=2, 4, 8, 32 and 128 symbols. Results are plotted in Fig 3a as maximum N_{span} giving $BER\leq BER_T$ vs. P_{Tx}. GN-model [10] predictions based on SNR_T and P_{Tx} are plotted as a reference. It can be observed that with the increasing of *M* the nonlinear impairments grow, consequently reducing the reach. Such a behavior is summarized in Fig. 3b as maxima $N_{span,MAX}$ of Fig. 3a curves vs. *M*. The best performance is reached reducing the frame to the

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[2] In order to avoid quantized results we considered also fractional spans obtained through interpolation of *BER* measurements.

minimum. Even with M=2, TDHMF channels experience some amount of penalty with respect to the GN-model predictions, estimated as reach reduction of 14% (0.7 dB) and 9% (0.4 dB) for NZDSF and SSMF, respectively

In order to counteract the nonlinear propagation impairments we tested the effect of predistortion for the case M=2 only. We simulated propagation on both fiber types progressively introducing some amount of chromatic dispersion D_{pre}, up to 20000 ps/nm, and we evaluated $N_{span,MAX}$ for each D_{pre} showing results in Fig. 3c together with the GN-model predictions. Predistortion enables to reach the GN-model predictions with D_{pre}=10000 ps/nm for NZDSF and with D_{pre}=20000 ps/nm for SSMF. The other possible countermeasure to the nonlinear impairment is the polarization interleaving (PI) proposed in [8]. We simulated propagation for the case M=2 on both fiber types with PI showing results in Fig. 3d as $N_{span,MAX}$ vs. P_{Tx} together with the GN-model predictions and results without PI. PI reduces nonlinear impairments but leaves some reach penalty: 9% (0.4 dB) and 3% (0.1 dB) for NZDSF and SSMF, respectively. Hence, using PI some predistortion is still required to reach GN-model predictions. In particular, we should apply D_{pre}=2000 ps/nm for NZDSF and D_{pre}=4000 ps/nm for SSMF.

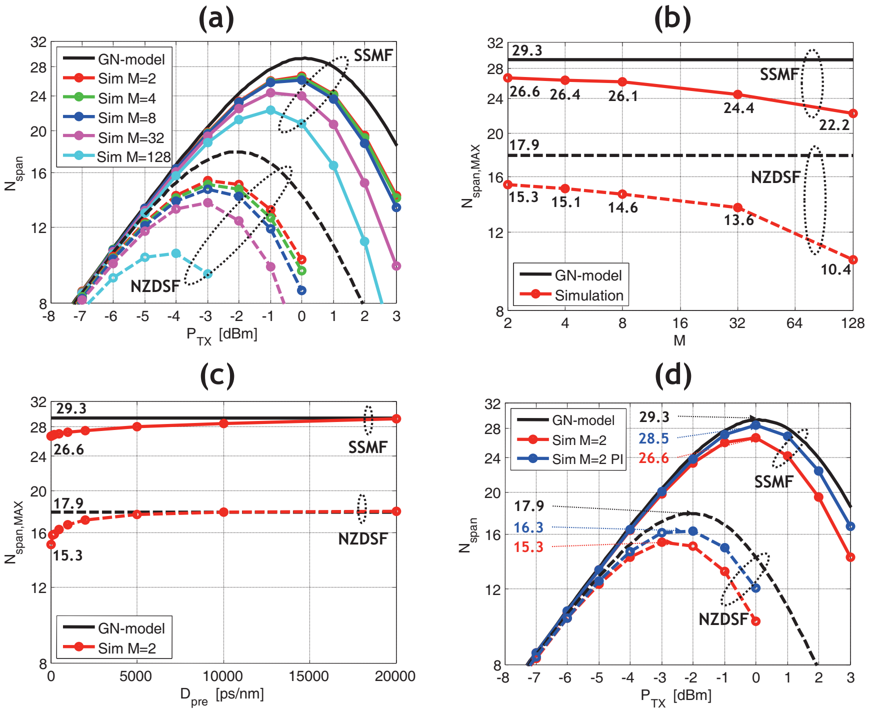

Fig. 3: Max reach vs. P_{Tx} with different M (a). Maxima of max reach curves vs. M (b). Results of predistortion with M=2 as $N_{span,MAX}$ vs. D_{pre} (c). Results of PI with M=2 as Max reach vs. P_{Tx} with and without PI (d). In all figures black lines refer to the GN-model predictions.

4. Comments and conclusions

We assessed four different strategies for setting the TDHMF Tx, showing that best performances are obtained with the "Min *BER*" one. We show that the FR=50% PM-QPSK/PM-16QAM TDHMF (BpS=6) set at "Min *BER*" presents the same back-to-back performances (SNR_T=10.5 dB at $BER_T=2\cdot 10^{-2}$) of the PM-8QAM modulation format carrying BpS=6 as well. We tested nonlinear propagation on uncompensated uniform links of such a TDHMF showing that it experiences a limited extra penalty with respect to the GN-model [10] predictions. The penalty can be completely recovered by predistortion or partially recovered applying polarization interleaving.

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References

[1] Ori Gerstel *et al*.," Time Elastic Optical Networking: A New Dawn for the Optical Layer?," Comm. Mag., **Feb,** S12-S20 (2013).
[2] Wei-Ren Peng *et al*.," Hybrid QAM Transmission Techniques…," OECC 2011, 824-825 (2011).
[3] Xiang Zhou *et al*.," 400G WDM Transmission on the 50 GHz Grid for Future Optical Networks," JLT, **30,** 3779-3792 (2012).
[4] Qunbi Zhuge *et al*.," Time Domain Hybrid QAM Based Rate-Adaptive …," OFC/NFOEC 2013, Paper OTh4E.6 (2013)
[5] Xiang Zhou *et al*.," 12,000km Transmission of 100GHz Spaced…," OFC/NFOEC 2013, Paper OTu2B.4 (2013)
[6] Xiang Zhou *et al*.," High Spectral Efficiency 400 Gb/s Transmission…," JLT, **31,** 999-1005 (2013).
[7] Qunbi Zhuge *et al*.," Spectral Efficiency-Adaptive Optical Transmission…," JLT, **31,** 2621-2628 (2013).
[8] R. Rios-Muller *et al*.," Experimental Comparison between Hybrid-QPSK/8QAM…," ECOC 2013, Paper Th.2.D.2 (2013)
[9] Han Sun *et al*.," Comparison of Two Modulation Formats…," ECOC 2013, Paper Th.2.D.3 (2013)
[10] A Carena *et al*.," Modeling of the Impact of Nonlinear Propagation Effects…," JLT, **30**, 1524-1539 (2012)