Comparing Different Options for Flexible Networking: Probabilistic Shaping vs. Hybrid Subcarrier Modulation

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Abstract *Multi-subcarrier frequency-domain hybrid modulation formats (MSC-FDHMF) are experimentally compared against single-carrier probabilistic-shaped (SC-PS) 64QAM to achieve 12.5G bit-rate granularity at 32 Gbaud. We found maximum reach gains of SC-PS over MSC-FDHMF in the range of 0.4–1 dB.*

Introduction

Spectral efficiency and data-rate flexibility are two major drivers for future high-capacity optical networks[1]. However, the joint optimization of these two requirements poses new challenges in terms of signal design. Standard single-carrier (SC) QAM has limited scalability in terms of delivered data-rate versus required signal-to-noise ratio (SNR). To enhance data-rate flexibility at the physical layer, several advanced modulation techniques have been proposed[2,3]. Multi-subcarrier (MSC) transmission, in which the signal is split into closely spaced low baudrate subcarriers, has been widely addressed in recent papers due to its increased robustness against nonlinearities, resulting from the phenomenon of symbol-rate optimization (SRO)[4]. In addition, employing frequency-domain hybrid modulation formats (FDHMF) across subcarriers also provides an additional degree of freedom to improve bit-rate flexibility[2].

Alternatively to standard QAM-based uniform constellations, probabilistic shaping (PS) allows to adjust the symbol probability of the transmitted signal in order to minimize the QAM shaping loss, thus benefiting from increased sensitivity in AWGN channels[5]. Another prominent advantage of PS is the ability to adjust the delivered data-rate with arbitrary granularity, by tuning probability distribution of the symbols in the constellation[3].

In this work, we perform a 21-channels WDM experimental comparison between MSC-FDHMF and SC-PS to achieve a bit-rate granularity of 12.5G in the range of 200G and 250G. MSC-FDHMF is based on the mixing of PM-16QAM and PM-32QAM, while SC-PS is based on the adaptive shaping of a PM-64QAM constellation.

Signal design and experimental setup

Table 1 shows the set of flexible modulation formats tested in this paper. Considering a total symbol-rate of $R_s = 32$ Gbaud and a total overhead of 28%, 200G and 250G transmission can be achieved by SC PM-16QAM and PM-32QAM, respectively. To exploit their enhanced performance in linear and nonlinear regimes, PS and MSC signals (8×4 Gbaud) are also tested at 200G and 250G. Intermediate bit-rates with 12.5G granularity are then achieved by MSC-FDHMF or alternatively by adjusting the entropy and shaping parameter of the SC-PS signal. In the case of FDHMF transmission, the power-ratio between subcarriers is optimized in order to equalize performance over frequency. Assuming ideal FEC, the mutual information (MI) threshold, $\mathrm{MI_{th}}$, for error-free transmission is given by,

$$\mathrm{MI_{th}} = \frac{R_b}{2R_s}\frac{1+\mathrm{OH_{tot}}}{1+\mathrm{OH_{fec}}}, \tag{1}$$

where 200 Gb/s$\leq R_b \leq$ 250 Gb/s is the net bit-rate, $\mathrm{OH_{fec}} = 0.2$ is the overhead reserved for FEC and $\mathrm{OH_{tot}} = 0.28$ is the total overhead, also including the additional protocol overhead.

In order to provide a fair comparison at the same net data-rate and FEC overhead, the entropy, H, of the PS signals encoded using the scheme described in[3] is given by,

$$H = \mathrm{MI_{th}} + \log_2(M_{\mathrm{PS}})\frac{\mathrm{OH_{fec}}}{1+\mathrm{OH_{fec}}}, \tag{2}$$

where $M_{\mathrm{PS}} = 64$ is the constellation size of the QAM constellation over which PS is applied.

Tab. 1: Flexible modulation options adopted in this work. R_b is in Gb/s, H and $\mathrm{MI_{th}}$ are in bits per QAM symbol.

R_b	**Config.**	N_{sc}	Constellation Size	H	$\mathrm{MI_{th}}$
200	PS	1	64	4.33	3.33
	SC	1	16	4	
	MSC	8	16 16 16 16 16 16 16 16	4	
212.5	PS	1	64	4.54	3.54
	MSC	8	16 16 16 32 32 16 16 16	4.25	
225	PS	1	64	4.75	3.75
	MSC	8	16 16 32 32 32 32 16 16	4.5	
237.5	PS	1	64	4.96	3.96
	MSC	8	16 32 32 32 32 32 32 16	4.75	
250	PS	1	64	5.17	4.17
	SC	1	32	5	
	MSC	8	32 32 32 32 32 32 32 32	5	

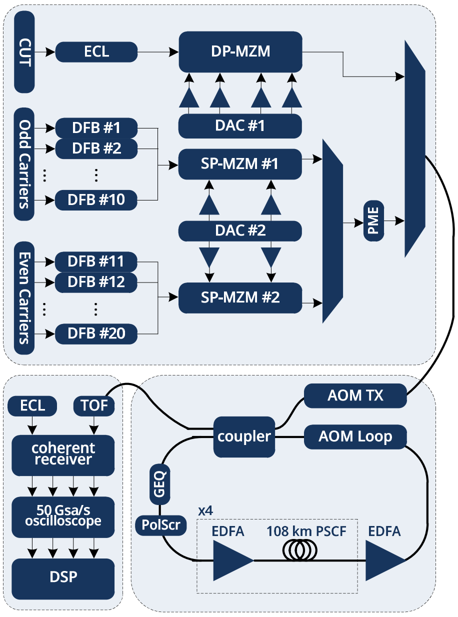

Fig. 1: Laboratorial setup.

Experimental results

The experimental setup is shown in Fig. 1. The channel under test (CUT) is generated by an external cavity laser (ECL) and modulated in a dual-polarization Mach-Zehnder modulator (DP-MZM) fed by a 64 Gsa/s digital-to-analog converter (DAC), while the remaining 20 interferers are generated by distributed feedback (DFB) lasers in groups of odd and even carriers and modulated in single-polarization MZMs, fed by a second 4-port DAC. Polarization multiplexing for the interferer channels is then optically performed by means of a polarization multiplexing emulator (PME). The recirculating loop is controlled by acousto-optic modulators (AOMs) and is composed of 4 spans of pure silica core fiber (PSCF) ($D = 20.17$ ps/(nm.km) and $\alpha = 0.16$ dB/km) with average length of 108 km and EDFA-only amplification (5.4 dB of noise figure). A gain-equalizer (GEQ) and a polarization scrambler (PolScr) are utilized every loop to flatten the optical gain and to statistically average the polarization effects. The CUT is then filtered by a tunable optical filter (TOF) at the coherent receiver, where a second ECL is utilized as local oscillator. The digital signal is acquired by a 50 Gsa/s oscilloscope with 33 GHz of electrical bandwidth.

The offline digital signal processing (DSP) is applied in data-aided mode and consists of i) a 2×2 CMA-based butterfly filter with 5 taps for polarization demultiplexing, ii) Viterbi&Viterbi carrier-phase estimation with fixed block length of 100 samples, iii) a real-valued 4×4 (SC and PS) or 8×8 (MSC) least-mean squares (LMS)-based adaptive linear equalizer with 51 taps to eliminate transmitter skew and perform matched filtering. The system performance is measured in terms of the MI of the received constellation after DSP. Note that for the case of MSC signals, we consider the average MI among all subcarriers.

The obtained experimental results for all considered bit-rates and signal modulation formats are shown in Fig. 2, both in terms of back-to-back (B2B) performance and maximum reach (MR) after propagation in the recirculating loop. A summary of all results is also provided in Table 2, highlighting the relative B2B and MR gains provided by PS and MSC over SC transmission, for the 200G and 250G cases, or simply by PS over MSC-FDHMF, where SC configurations are not supported. The required SNR of SC and MSC is exactly aligned in B2B.

This guarantees that the SRO effect can be observed without the interference of different implementation penalties. The impact of SRO for the 200G and 250G cases was found to be in the range of 0.2–0.3 dB in terms of MR gain. Note however that in this work we use a fixed number of subcarriers ($N_{\mathrm{sc}} = 8$) and a fixed CPE block length (100 taps) that may be suboptimal in terms of nonlinear mitigation via SRO[4]. Nevertheless, in this paper we have chosen to fix these parameters in order to keep our analysis more simple and general, providing a clear fair comparison among all considered flexible modulation options. The B2B SNR gains provided by PS-64QAM were found to be in the range of ~1–1.2 dB, directly translating into MR gains of ~0.75–1.1 dB. In contrast with MSC, whose MR gains come entirely from their enhanced nonlinear robustness (note that the MR curves of MSC and SC in Fig. 2d are practically overlapped in the linear regime and detach only when approaching the optimum power), the MR gain provided by PS actually comes from its improved B2B performance, staying almost stable across all powers. This can be an interesting advantage for network operators that may prefer to operate in the linear regime with a few dBs of power margin.

To summarize all results, Fig. 3 shows the

Tab. 2: Summary of the obtained experimental results.

R_b (Gb/s)	Config.	Req. SNR (dB)	B2B Gain (dB)	MR (km)	MR Gain (dB)
200	SC	11.3	–	6176	–
	MSC	11.3	0	6636	0.31
	PS	10.3	1	7365	0.76
212.5	MSC	12.3	–	4695	–
	PS	11.1	1.2	5932	1.01
225	MSC	13	–	4271	–
	PS	11.8	1.2	5098	0.76
237.5	MSC	13.7	–	3651	–
	PS	12.5	1.2	4367	0.77
250	SC	14.3	–	2937	–
	MSC	14.3	0	3084	0.21
	PS	13.3	1	3795	1.11

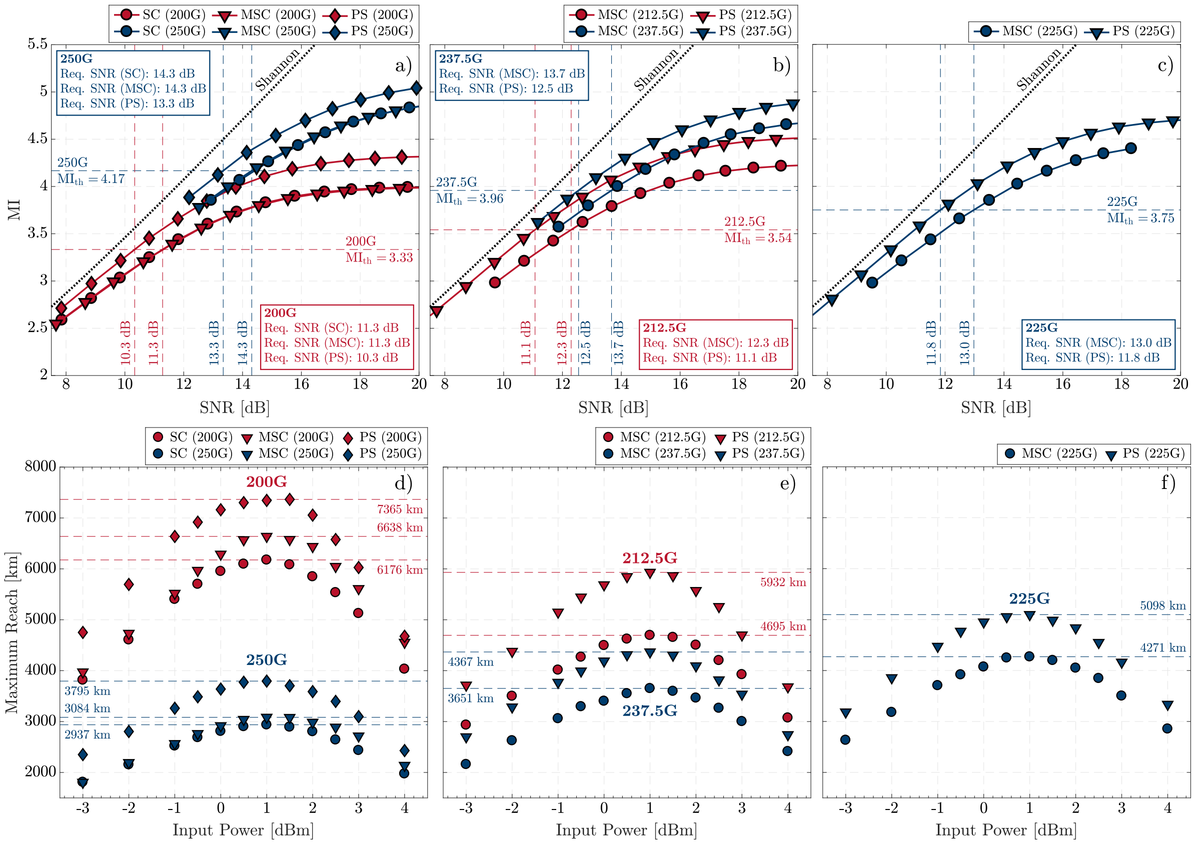

Fig. 2: Experimental results obtained with SC, MSC and PS signals. a), b) and c) show the B2B characterization for each configuration, while d), e) and f) show the maximum reach results after propagation in the recirculating loop.

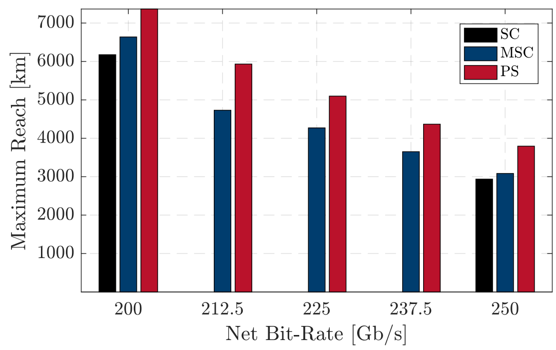

Fig. 3: Maximum reach versus net bit-rate.

MR provided by each modulation scheme at the corresponding net bit-rate. The benefit of MSC-FDHMF and PS over SC in terms of bit-rate flexibility becomes apparent, enabling to fill the 50G gap between the PM-16QAM and PM-32QAM SC solutions. Despite of some additional propagation penalty, the best performance is always obtained with the bit-rate adaptive SC-PS solution.

Conclusions

We experimentally compared flexible modulation schemes based on multi-subcarrier frequency-domain hybrid modulation formats (PM-16QAM and PM-32QAM) and single-carrier probabilistic shaped PM-64QAM. Multi-subcarrier signaling together with FDHMF allows to increase the bit-rate granularity while keeping the inherent advantages of symbol-rate optimization, which were found to be in the range of 0.2–0.3 dB, for the considered case of 8 electronic subcarriers with fixed CPE block length of 100 taps. In turn, probabilistic shaping 64QAM was found to provide 1–1.2 dB advantage in terms of B2B required SNR, translating then into 0.75–1.1 dB of maximum reach improvement. It can be therefore concluded that, even if PS gain may be slightly reduced after propagation, its gains still tends to overcome those provided by SRO. The results indicate that the implementation of PS over MSC signals may be a promising way of further improving the system performance while providing arbitrary bit-rate flexibility.

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