Optimization of Pulse Shaping Scheme and Multiplexing/Demultiplexing Configuration for Ultra-Dense WDM based on mQAM Modulation Format

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Abstract: In this paper, we discuss the optimization of the spectrum shaping technology and multiplexing/demultiplexing configuration considering linear and nonlinear penalty based on the QAM modulation format. Q performance of DP-8QAM and DP-16QAM signal with 37.5 GHz or 33.3GHz channel spacing under back-to-back and transmission condition are analyzed through several simulations. Finally, we experimentally evaluate the transmission performance of DP-16QAM using the straight transmission line with the optimized spectrum shaping and multiplexing/demultiplexing configuration.

1. INTRODUCTIONS

The capacity of the submarine cable system has expanded by the adoption of 100 Gb/s DP-QPSK signal which is enabled by the polarization multiplexing and coherent digital signal processing in the past few years [1,2]. However, because of the explosive growth of the internet traffic, the demand for larger capacity of the submarine cable system is getting much higher. In order to achieve higher spectral efficiency, increasing the bit rate per wavelength and multiplexing signals in narrower channel spacing are necessary. Therefore, the QAM modulation format and Nyquist pulse shaping have been the focus of recent studies [3,4].

In this paper, we discuss how the simultaneous optimization of spectrum shaping and the multiplexing/de-multiplexing (Mux/DeMux) configuration can be used to minimize the linear penalty on the QAM modulation format. First, we evaluate the performance of the shaped signal and Mux/DeMux method with 37.5 and 33 GHz channel spacing. Moreover, we discuss the non-linear effects which are important factor for the long haul transmission. We demonstrate the impact of the spectrum shaping and Mux/DeMux configuration on non-linear impairments and the transmission performance by using a straight transmission line. Finally, we propose the most appropriate pulse shaping method and the Mux/DeMux architecture to maximize the transmission performance and transmission distance.

2. PULSE SHAPING SCHEME AND MULTIPLEXING/DEMULTIPLEXING CONFIGURATION

The Nyquist pulse shaping is known as a technology to realize narrower channel spacing since an ideal Nyquist pulse has a rectangular spectrum which allows for neighboring channels to be placed arbitrarily close, while the signals remain free from inter-symbol interference (ISI) [5]. Therefore, an optical coupler is one of the candidates for the multiplexing. In practice, a perfect rectangular shape cannot be achieved, nor desired, since as the shape of the signal becomes closer to a rectangle in the spectral domain, the portion of the signal that remains ISI-free in time domain becomes vanishingly small which makes signals vulnerable to small imperfections in the clock recovery [5]. Instead, a family of pulse shapes known as root raised

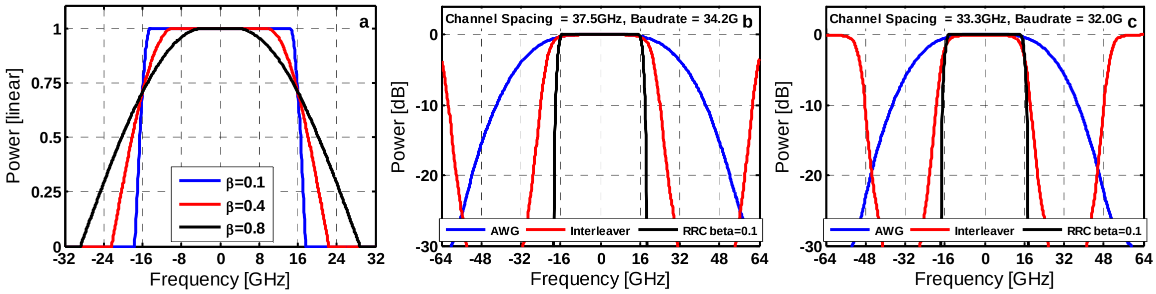

Figure 1: RRC shapes with different roll-off factors at 32 Gbaud (a). Transmittance profile of the AWG (blue) and Interleaver (red) in comparison with RRC profile with a roll-off factor of 0.1 (black) for channel spacings of (b) 37.5 GHz, and (c) 33 GHz

cosine (RRC) are used more commonly. The spectrum of a signal with an RRC shape can be defined by a single parameter, the roll-off factor β which is a measure of the portion of the spectrum that remains outside the Nyquist bandwidth. As an example, Fig. 1a shows the RRC shapes for three different roll-off factors. By tuning the roll-off factor, one can arbitrarily optimize the trade-off between the required channel spacing and the sensitivity to hardware limitations. Such RRC shapes and others can be easily generated with digital transmitters.

An alternative to using digital pulse shaping to manage inter-channel cross-talk is to use optical filters such as interleavers and AWGs as the Mux/DeMux as it has been the common practice so far. However, these multiplexers cannot have features as sharp as that can be obtained by digital filters. As a result the Nyquist shaped waveforms can be distorted which can lead to ISI. Therefore, performance comparison between the semi-Nyquist shaped WDM signal combined by optical couplers and WDM signals multiplexed by an interleaver and/or AWG is interesting when filtering penalty and cross-talk penalty are considered.

3. LINEAR PENALTY

In order to verify the linear penalty, back-to-back simulation analysis was conducted. As an example of dense WDM configuration we picked 34.2 Gbaud DP-8QAM signals over 37.5 GHz channel spacing corresponding to 91% filling ratio, where the filling ratio is defined as the ratio of the baud rate to the channel spacing. Figure 1b shows the envelope of the optical spectrum of a 34.2 GBaud DP-8QAM signal with β=0.1 and transmittance profile of the 37.5 GHz interleaver and AWG which we have used in the simulation. The AWG has sufficiently wider bandwidth than the interleaver in order to combine the WDM channels in odd and even fashion with limited additional distortion.

Figure 2 shows the OSNR tolerance where we plotted the performance of the center channel in a 3 WDM signal configuration. WDM channels are prepared with different roll-off factors from β=0.1 to 0.8 to compare tolerance of different pulse shapes to different Mux/Demux configurations which consists of either an optical coupler or both an interleaver and an AWG at the multiplexer and either just an AWG or both an interleaver and an AWG at the demultiplexer. The OSNR tolerance is evaluated under similar conditions both in experiment, as shown in the upper row, and in simulation, as shown in the lower row of Fig. 2. Figure 2a shows that if only a coupler is used as the WDM multiplexer, the roll-off factor should be less than 0.3 to avoid significant cross-talk penalty.

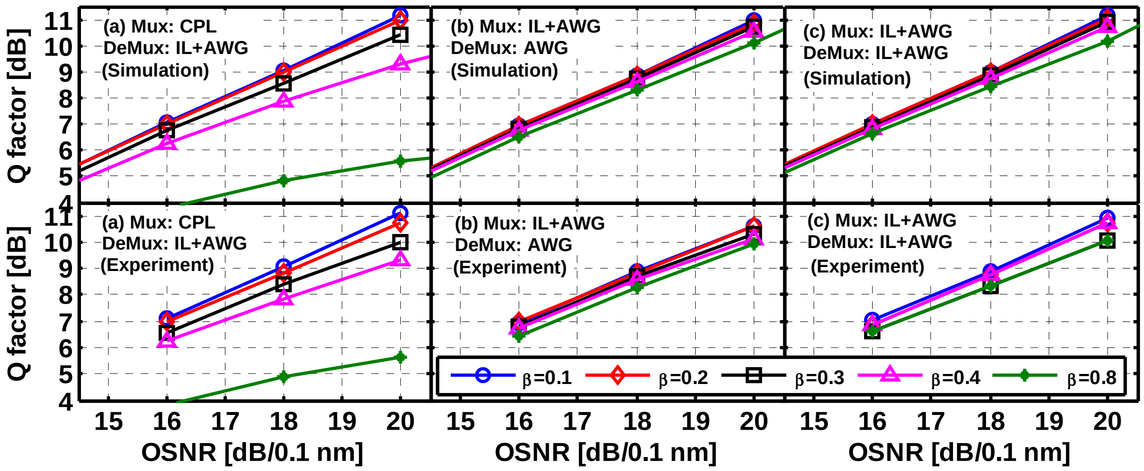

Figure2: OSNR sensitivity for different roll-off factors β, in simulation (top row) and by experiment (bottom row) for 34.2 Gbaud 8QAM with 37.5 GHz channel spacing. (a) Mux: CPL, DeMux: IL+AWG, (b) MUX: IL+AWG, DEMUX: AWG, (c) MUX: IL+AWG, DEMUX: IL+AWG

However, by using an appropriate combination of interleaver and AWG as the multiplexer the cross-talk penalty can be virtually eliminated even for the largest roll-off factor considered. On the other hand, there is negligible difference in the performance between the optical coupler and the combination of the interleaver and AWG for the multiplexer with β = 0.1 and 0.2. In terms of the demultiplexer, using only AWGs and using interleaver+AWG show similar performance if interleaver+AWG is used for multiplexing.

In order to see the impact of a higher filling ratio, namely 97%, we repeated the simulations with 32 Gbaud DP-8QAM over 33.3 GHz channel spacing. To compare the sensitivity of different QAM constellations, the simulations are also conducted for DP-16QAM modulation with the same baud rate and channel spacing. The spectral profile of a 32 Gbaud signal with β = 0.1 and the optical Mux/DeMux filters for 33.3 GHz spacing are shown in Figure 1c for reference. The upper row and the lower row in Fig3 shows the OSNR sensitivity for the DP-8QAM and DP-16QAM signals, respectively. In each case, simulation is repeated under different Mux/DeMux configurations and the roll-off factor is varied from 0.1 to 0.4. In Fig3a, where only couplers are used as multiplexer, and only an AWG is used for the demultiplexer cross-talk penalty increases dramatically as the roll-off factor is increased, which is expected when the filling ratio is large. Similarly, 16QAM is slightly more sensitive to cross-talk. When optical filters are used at the multiplexer side as shown in Fig3b, the cross-talk penalty reduces for all roll-off factors especially for larger values. Finally, little improvement is obtained by using interleavers in addition to AWGs for demultiplexing.

4. NONLINEAR PENALTY

In addition to cross-talk penalty that was considered in the previous section, pulse shape also affects the nonlinear penalty. In general, the nonlinear penalty reduces as the channel bandwidth and roll-off factor is increased [6]. To verify the influence of pulse shaping and Mux/DeMux configuration, transmission simulations are conducted. In the simulation 14 WDM channels with 33.3 GHz channel spacing and 12 WDM channels with 37.5 GHz channel spacing with 32 Gbaud DP-16QAM modulation are propagated over

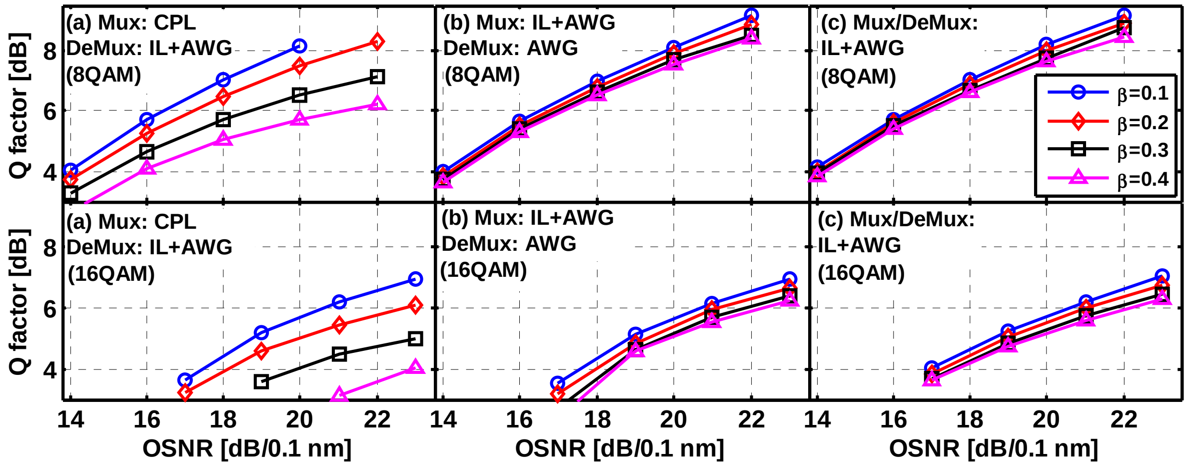

Figure 3: OSNR sensitivity for 32 Gbaud signals with 33 GHz channel spacing for DP-8QAM (top row) and DP-16QAM (bottom row) (a) Mux: CPL, DeMux: IL+AWG, (b) MUX: IL+AWG, DEMUX: AWG, (c) MUX: IL+AWG, DEMUX: IL+AWG

2600 km. Transmission fibers consist of 50 km spans with 0.155 dB/km attenuation, 20.5 ps/nm/km dispersion, 130 μm^2 effective area and 2.2x10^{-20} m^2/W of nonlinear coefficient. At the receiver the center channel is filtered and the Q factor is estimated by BER counting by emulating a coherent receiver followed by standard offline digital signal processing.

Figure 4 summarizes the results of the simulation. In view graphs a to c the Q factor as a function of power per channel are shown under different Mux/DeMux configurations. In column a of Fig.4, only couplers are used for multiplexing and only AWGs are used for demultiplexing. The impact of cross-talk penalty is clear as the roll-off factor is increased beyond $\beta=0.1$ which is expected based on the OSNR penalty results. Adding interleaver to the demultiplexer side as shown in column b improves the Q factor slightly. Finally using a combination of AWG and interleaver as both multiplexer and demultiplexer as shown in column c brings additional improvement, especially for roll-off factors larger than $\beta=0.2$. However, the nonlinear penalty does not improve noticeably with larger roll-off. As the roll-off factor is increased, the linear cross-talk becomes the dominant factor, which requires the use of AWG-interleaver pairs. When AWG and interleavers are used, the spectrum is shaped mostly by interleavers rather than the roll-off factor. Therefore a reduction in the nonlinear penalty is not observed for larger β which is evident in Fig.4 where the optimum power remains close to -2 dBm regardless of β.

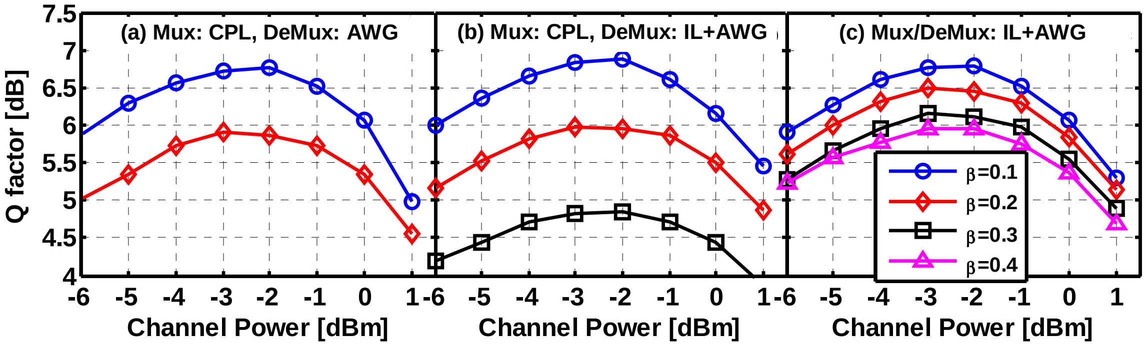

Figure 4: Q vs channel power for 32Gbaud DP-16QAM signal with 33 GHz channel spacing after 2600 km. (a)Mux: CPL, DeMux: AWG, (b) MUX: CPL, DEMUX: IL+AWG , (c) MUX: IL+AWG, DEMUX: IL+AWG

5. TRANSMISSION EVALUATION

We demonstrated the transmission performance of 33.3 GHz channel spaced 32 Gbaud DP-16QAM signal with a straight line over 2,000 km. Figure 5 shows the configuration of the transmission evaluation.

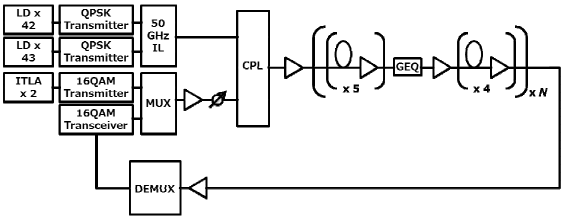

Figure 5: Setup for transmission evaluation

The measured DP-16QAM signal generated by a real-time 16QAM transceiver is combined with adjacent 2x32 Gbaud DP-16QAM signals and 50 GHz spaced 85xDP-QPSK signals. Transmission line consists of SMF fibers, EDFAs and gain equalizers. The span length, fiber attenuation and output power of EDFA are 60 km, 0.157 dB/km and +17 dBm, respectively. At receiver side, the measured signal is selected by DeMux and the Q factor is calculated by BER counting by the 16QAM transceiver.

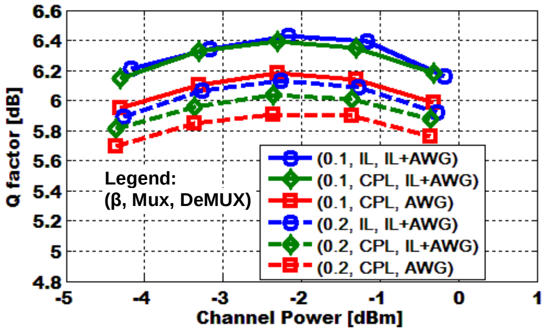

Figure 6: Channel power dependence after 2,040 km (33.3GHz spacing)

Figure 6 shows the channel power dependence of 33.3 GHz spaced signal after 2,040 km with several β and Mux/DeMux configuration. The legends indicate the combination of {β, Mux, DeMux}. From Fig.6 it is found that the performance with β = 0.1 is better than β = 0.2 under all Mux / DeMux conditions and the optimal performance is obtained with combination of β = 0.1, interleaver as Mux and interleaver + AWG as DeMux, same as the simulation.

6. CONCLUSIONS

Through simulations and real-time experimental verification we show that high order modulation formats such as DP-8QAM and DP-16QAM are sensitive to cross-talk penalty at tight channel spacing configurations such as 34.2 Gbaud over 37.5 GHz channel spacing and 32 Gbaud over 33.3 GHz channel spacing. The cross-talk penalty can be managed by using digital pulse shaping or equally well by using optical filters such as AWG and interleavers.

7. REFERENCES

[1] E. Yamazaki et al., “Fast optical channel recovery in field demonstration of 100-Gbit/s Ethernet over OTN using real-time DSP”, Optics Express, vol. 19, 13179-13184 (2011).

[2] M. Arikawa et al., “WDM Transmission of 127 Gb/s PM-QPSK Signal over 3,350 km SMF-only Line with Chromatic Dispersion Compensation using Real-Time DSP-LSI,” NFOEC 2012, NTH1I.4 (2012).

[3] F. Yaman et al., “First Quasi-Single-Mode Transmission over Transoceanic Distance using Few-mode Fibers,” OFC2015 Th5C.7 (2015).

[4] F. Buchali et al., “Experimental Demonstration of Capacity Increase and Rate-Adaptation by Probabilistically Shaped 64-QAM,” ECOC2015 PDP3.4 (2015).

[5] R. Schmogrow et al., “Real-time Nyquist pulse generation beyond 100 Gbit/s and its relation to OFDM,” optics Express, vol. 20, 317-337 (2011).

[6] E. Torrengo et al., “Influence of Pulse Shape in 112-Gb/s WDM PDM-QPSK Transmission,” IEEE Photon. Technol. Lett., vol. 22 1714-1716 (2010).