# Applicability of Multi-wave-modulation Loading Scheme and ASE Dummy Loading Method in 40G PDM-PSK Coherent Systems for Full-capacity Performance Evaluation

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**Abstract:** We propose a multi-wave-modulation loading scheme (MWML) for full-capacity performance evaluation and verify its feasibility over two types of dispersion-managed (DM) 40G polarization-division-multiplexed binary phase shift keying (PDM-BPSK) coherent systems by comparing with the systems using line cards. ASE loading scheme is not very suitable for DM coherent systems but is still applicable to un-compensated systems.

## 1. INTRODUCTION

Emergence and proliferation of bundles of bandwidth-hungry applications are driving telecom operators to pursue maximum transmission capacity to cover potential demands for the future and enhance their competitive positioning. Parallel to the increase in demand, new technologies including phase shift keying modulation (PSK) with polarization multiplexing (PDM) and coherent detection with digital signal processing are maturing, becoming an important enabler for the maximization of system capacity.

To validate the system design capacity, full-capacity performance usually needs to be evaluated in the laboratory test before the system is manufactured, and subsequently needs to be further confirmed when the system is installed. However, the initial effective capacity is usually operated much lower than the designed capacity in the light of initial demand, leading to scant facilities for full-capacity test at the pre-validation stage. It has been shown that dummy loading provides a cost-effective way to solve this problem in 10G/40G non-coherent systems.

For the ease of future upgrade, it is preferable for each dummy light to have the same power as the signal channel and generate the inter-channel interference that is as close to the full-capacity case as possible. The beauty of this lies in simplifying upgrade process by conveniently replacing any dummy loading with a signal channel with the same power. In this context, the loading scheme with few high-power loading tones [1] or with uniformly allocated continuous waves [2] is obviously excluded from our considerations due to the unequal powers or the underestimation of inter-channel interference. Other dummy loading schemes such as uniformly allocated ASE dummies are also widely used as the adjacent neighbours of a small number of signal channels for predicting transmission performance of 10G full-loaded non-coherent systems [3]. However, most of these researches focus on keeping the channel power and gain shape the same as those in the full-loaded case. Only very few studies refer to the impact of dummy schemes on the signal performance, but they are mainly for non-coherent systems [3]. Reference [4] discusses the insufficiency of the odd/even de-correlation method in emulating cross phase modulation characteristics of a DWDM coherent system, but it did not clarify whether the enhanced method can provide consistent results with the systems using terminal equipment (line card), and what is the impact of the polarization de-correlation. In addition, what is the applicable condition of the existing ASE loading scheme and whether there is a better dummy loading method in submarine scenarios to achieve correct evaluation of full-capacity performance are still indefinite.

We will fill the gap in this paper by proposing a multi-wave-modulation loading scheme (MWML) for a full-capacity performance evaluation and experimentally comparing different dummy loading schemes with the full-capacity case by the use of coherent-based 40G PDM binary PSK (BPSK) over both dispersion-managed (DM) and un-compensated systems. The impact of polarization de-correlation is investigated by simulations.

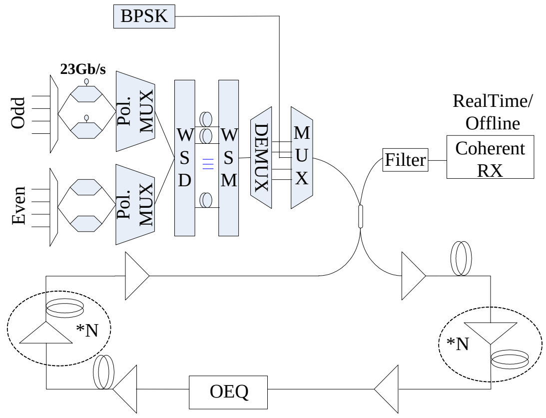


Figure 1: DWDM Coherent transmission experiment with MWML scheme.

## 2. MWML Scheme

The simplified schematic of our proposed MWML scheme used for the comparison of different dummy schemes is shown in Fig.1. The setup consisted of an independently modulated tunable signal channel and N distributed feedback lasers (DFB) spaced by 50GHz. These DFB lasers were separated into two spectrally-interleaved combs. Each comb was split and modulated with two BPSK modulators, corresponding to the modulations on two polarizations. Each modulator was fed by a 23Gb/s random data source including 7% forward error correction (FEC) and protocol overhead. The output from BPSK modulator then passed through a return-to-zero (RZ) pulse carver to generate RZ-BPSK signal. Polarization multiplexing was finally performed through a polarization beam combiner (PBC). To reduce inter-channel nonlinear crosstalk, temporal polarization bit interleaving (BI) was also adopted by inserting a polarization maintaining delay line before PBC to generate half a symbol period offset between the two orthogonal polarization tributaries, producing 46Gb/s BI-RZ-PDM-BPSK channels. The odd and even channels were then spectrally interleaved by a 50GHz interleaver. Independent modulators only ensure the de-correlation between odd and even channels, further de-correlation need to be done within odd set and even set to correctly emulate the reality, where all the channels are uncorrelated. This was achieved by dividing the combined odd and even signals into nine groups through a 9-port wavelength selective switch demultiplexing unit (WSD), which can route any wavelength from any port to any other port. The nine groups passed through nine different short SMFs, respectively. The lengths of the nine SMFs increased monotonically with a fixed step size of 5m which was large enough to achieve time de-correlation among different groups. The delayed signals are multiplexed by a wavelength selective switch multiplexing unit (WSM), and finally coupled with the test channel by a DWDM Mux/Demux pair, then launching into our recirculating loop. To verify the feasibility of this loading scheme, we set a baseline by replacing the nearest four neighboring dummies of the test channel with corresponding independently modulated line cards on each side, and call this the baseline line-card scheme.

All the experiments presented in this paper were based on our two types of recirculating loop configurations. One was so-called hybrid configuration (case A): it was based mainly on sixteen hybrid spans, each combining two types of fibers with effective areas of 70 $\mu m^2$ and 50 $\mu m^2$, respectively. The average dispersion coefficient of each hybrid span was adjusted at -3.3ps/nm.km. Periodic dispersion compensation was achieved by using two spans of large core fibers characterized by 101 $\mu m^2$ of effective area and chromatic dispersion of 18.7ps/nm.km at 1550nm. The loop length in this case was about 1139km, with an average span length of 65km. Twenty EDFAs with 14dBm output power were used to compensate for the fiber loss and loop-specific loss. The other was dispersion-slope-matched fiber (DSMF) configuration (case B): the loop was composed of sixteen DSMF spans, each being constructed with D+ and D- fibers. The dispersions were about +20.5 ps/nm/km for the D+ fiber, and - 44 ps/nm/km for the D- fiber, providing an average span dispersion of -2.3ps/nm.km. The loop length was about 1214km with an average span length of 76km (16dB span loss). To manage a real-time performance test, three fiber spans of 90.4km dispersion compensation fibers were placed at both the input and output of the loop, achieving 2800ps/nm residual dispersion at 1550nm after 6600km transmission. 24 EDFAs in total with 16dBm output powers were used in this case. An optical gain equalizer (OEQ) was placed in the middle of each of the two loops to provide in-line compensation of the uneven spectral gain profiles of the EDFAs.

At the receiver end, the test channel was extracted by a narrow-bandwidth optical filter and sent into a coherent receiver. The receivers used in our experiments were either real-time or offline type. The real-time receiver was from a line card, which consisted of a local oscillator, an integrated coherent detector and an ASIC for the digital signal processing (DSP). The DSP ASIC is the critical element in the real-time coherent receiver since it must perform, in real time, all the required algorithms to track and retrieve the incoming phase and polarization state of the signal, consequently allowing a real-time error counting and bit-error-ratio (BER) computing accordingly. The algorithms involved chromatic dispersion estimation and compensation, clock recovery, polarization tracking, differential group delay compensation and carrier phase recovery. The main difference between offline receiver and real-time receiver lies in whether the digitizing and subsequent estimation and compensation algorithms were processed on the chips of a real product in real time or processed offline on a computer. The real-time measurement in recirculating loop systems is not easy, which has been hindered by the mismatch of algorithm processing time and the roundtrip time of the loop. This difficulty was finally partially solved by our careful selection and adjustment of DSP functionalities.

## 3. CORRECTNESS VERIFICATION OF MWML SCHEME

In DM coherent systems, the combination of dense wavelength division multiplexing (DWDM) and polarization multiplexing makes inter-channel nonlinear interaction depend not only on the powers but on the state of polarization (SOP). These two types of dependences are so-called cross-phase modulation (XPM) and cross-polarization modulation (XPolM). Recent studies have shown that, with homogeneous PDM-PSK channels, XPolM exhibits the dominant nonlinear impact on transmission performance in DM coherent systems [5], and this impact strongly depends on the correlation status among channels [4]. Hence, eliminating the inter-channel correlation to the most extent is the key for our loading scheme to correctly emulate the full-capacity field scenarios in reality, where all channels are un-correlated.

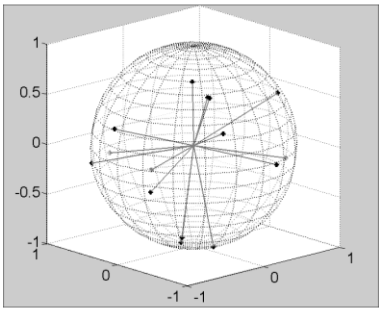

Figure 2: Random scattering of output SOPs on the Poincare sphere.

Our MWML scheme achieved the inter-channel de-correlation in odd or even tributaries via two key procedures: one was to increase the walk-off of neighbouring channels by inserting wavelength selective switches together with several groups of unequal lengths of short fibers; the other was to randomize the SOPs of neighbouring channels by using a DWDM Mux-Demux pair. This Mux-Demux pair makes different channels go through different paths, resulting in the channel SOPs randomly scattering on the Poincare sphere. The measured output SOPs were shown in Fig.2. We investigate the contribution of the SOP randomization at the transmitter side to the reduction of the cross-nonlinearities by simulations in case A with 31 channels in total over 4500km. Three cases are considered in the simulations: (1) same data stream and SOPs; (2) same data stream but random SOPs (3) different data stream (the counterpart of experimental line card case); By taking the difference in optical signal-to-noise ratio (OSNR) penalty at the BER level of 1E-3 between simulations and the experimental line card case, we compare above three cases in Fig. 3, concluding that the SOP randomization can greatly reduce cross-nonlinearities, which makes system performance close to the line card case.

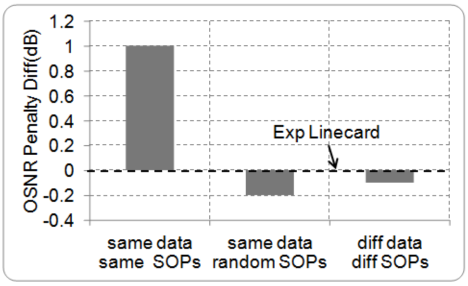


Figure 3: Contribution of SOP randomization to the reduction of cross-nonlinearity

The feasibility of our MWML scheme was finally verified by the performance comparison between our MWML scheme and the baseline in both A and B cases. The measured OSNR difference as a function of BER under these two configurations over 4500km transmission with optimal pre-dispersion compensation is depicted in Fig. 4. We observed very small discrepancies (<0.3dB) between the two cases, indicating the feasibility of the MWML scheme.

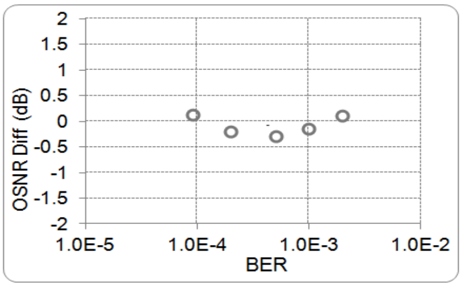


Figure 4: BER vs. OSNR difference for hybrid configuration

The feasibility was also verified in case B, where 64 channels were launched into the loop, and the test channel and its line card neighbours were moved to the blue, central and red bands, respectively, for full C-band experimental study. Fig. 5 shows that the difference in the OSNR penalty after

 

6600km transmission between the MWML scheme and the line card scheme was no larger than 0.1dB, giving clear evidence that the MWML scheme is very suitable for accurate performance evaluation of full-loaded systems.

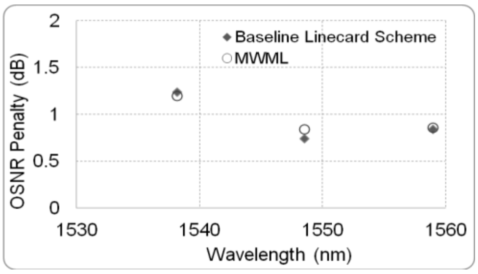


Figure 5: Comparison of OSNR penalty after 6600km transmission between MWML scheme and line card scheme

## 4. ASE LOADING SCHEME VS. MWML SCHEME

We also investigated the performance discrepancy between the ASE dummy scheme and the MWML scheme in case B and a 6100km dispersion uncompensated system which is fully constructed with G.654B compliant fiber. The ASE dummies were obtained by slicing the continuous ASE spectrum from an EDFA into tens of combs with a 100GHz Mux/Demux pair and a 25GHz or a 50GHz interleaver, generating 25G-spaced or 50G-spaced ASE loadings, respectively. We compared the transmission penalties at blue band for both cases. To highlight the discrepancy, the penalty in ASE loading case was normalized with respect to the MWML case. Our studies show that, with 50GHz channel spacing, the ASE dummy scheme led to larger penalty than MWML scheme, overestimating cross nonlinear interaction in the DM system. In contrast, in a dispersion-uncompensated system, the impact of ASE dummy on the signal light is close to the MWML case, and therefore is applicable to the full-capacity performance evaluation, shown in Fig.6. In addition, by comparing the 25G-spaced and 50G-spaced ASE loading schemes, we also observed that, broadening the optical spectrum of an ASE dummy channel while maintaining the power unchanged helped to slightly reduce the penalty of the signal light induced by ASE dummy channels.

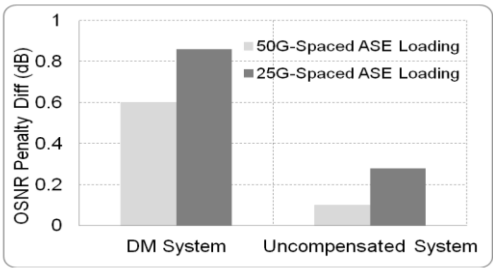


Figure 6: Impact of spectral width of ASE dummy channel in DM systems and uncompensated systems

## 5. CONCLUSIONS

We propose a MWML scheme for full-capacity performance evaluation and verify its feasibility over two types of dispersion-managed 40G PDM-BPSK coherent systems by comparing with the systems using line cards. The ASE loading scheme induces larger penalty than full-capacity case, overestimating cross-nonlinearities in coherent DM systems, but this sign is not pronounced in un-compensated systems.

## 6. REFERENCES

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