# Dual-Polarization Multi-Band OFDM versus Single-Carrier DP-QPSK for 100 Gbps Long-Haul WDM Transmission over Legacy Infrastructure

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**Abstract:** *We experimentally compare the performance of coherent dual-polarization multi-band OFDM (DP-MB-OFDM) and QPSK (DP-QPSK) for 100 Gbps long-haul transport over legacy infrastructure combining G.652 fiber and 10 Gbps WDM system. We show that DP-MB-OFDM and DP-QPSK have nearly the same performance at 100 Gbps after transmission over a 10x100 km fiber line.*

## Introduction

Even if coherent dual-polarization quaternary phase shift keying (DP-QPSK) is today the industrial solution for 100 Gbps long-haul transport [1], coherent dual-polarization multi-band OFDM (DP-MB-OFDM) has been also proposed in the past few years for 100 Gbps application [2], and remains today a very interesting candidate for WDM transmission at 400 Gbps and 1 Tbps. However, a debate exists over the capacity of OFDM to be as efficient as QPSK for long-haul WDM transmission due to its supposed higher sensitivity to fiber nonlinearities.

After having answered to this question in the reference [3] for the particular case of DCF-free transmission line, we address in this paper the case of legacy transport infrastructure mixing G.652 fiber and 10 Gbps WDM system. We carry out an experimental performance comparison of DP-MB-OFDM and DP-QPSK at 100 Gbps in such realistic transmission conditions. Through the simultaneous propagation of the two DP-MB-OFDM and DP-QPSK channels in a 78x10 Gbps NRZ WDM system using a 10x100-km dispersion-managed (DM) G.652 fiber line, we show that DP-MB-OFDM is nearly as robust as DP-QPSK for 100 Gbps transmission.

## Experimental set-up

The nominal data rate of 100 Gbps, increased up to 124.4 Gbps to account for the various transmission overheads (7% for FEC, 7.03% for cyclic prefix, 6% for training symbols, and 2.3% for pilot tones), is split between four polarization-multiplexed OFDM sub-bands. Each sub-band carries 31.1 Gbps in a bandwidth of ~ 8 GHz while the sub-band spacing is 10 GHz. Fig. 1 shows the experimental set-up of our 100 Gbps DP-MB-OFDM transmitter. A comb of optical carriers spaced by 10 GHz (shown in the first inset of Fig. 1) is generated by using an external cavity laser (ECL) and driving a dual-arm Mach-Zehnder modulator (MZM) with a 10 GHz RF frequency according to the recommendations of reference [4]. The required four optical carriers are selected at the transmitter output by a square flat-top optical band-pass filter (BPF) of ~ 40 GHz bandwidth. Before that, a combination of 20 GHz and 40 GHz polarization-maintaining delay line interferometers (PM-DLI) splits into four groups of carriers spaced by 40 GHz the initial comb of 10-GHz-spaced optical carriers. Each of the four generated combs is modulated by a complex-MZM (CMZM) and combined by a 4:1 polarization-maintaining (PM) coupler. The details over the generation of the OFDM signal are given in reference [5]. Thanks to two arbitrary waveform generators (AWG), data carried by neighboring sub-bands are totally decorrelated, provided that AWG 1 generates the first and third sub-bands while AWG 2 generates the second and fourth sub-bands. A polarization-maintaining Erbium-doped fiber amplifier (PM-EDFA) balances the losses introduced by the MZM, DLIs, CMZMs and coupler and feeds a 1-symbol-delay polarization-multiplexing module. The spectrum of our 100 Gbps DP-MB-OFDM signal is shown in the second inset of Fig. 1.

Our previously described 124.4 Gbps DP-MB-OFDM transmitter operating at 1552.93 nm is then combined with one channel at 1548.11 nm carrying a 112 Gbps DP-QPSK signal and a multiplex of 78 wavelengths spaced by 50 GHz and modulated at 10.7 Gbps by NRZ-OOK. The DP-QPSK channel is fed by an ECL to limit the impact of laser phase noise,

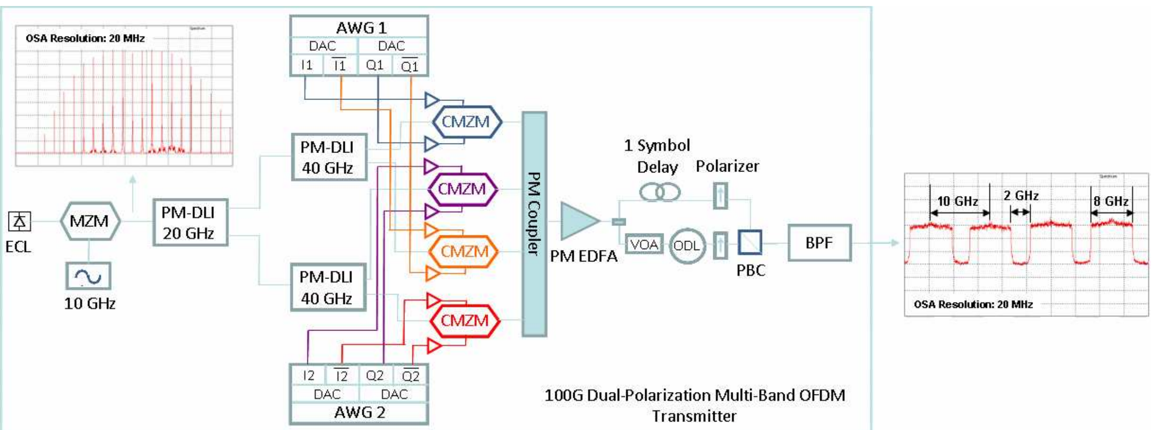


**Fig. 1:** Set-up of the 124 Gbps DP-MB-OFDM transmitter with PBC (polarization beam combiner), ODL (optical delay line), VOA (variable optical attenuator). In insets are represented the spectrum of the 10-GHz-spaced optical carriers at the MZM output, and the spectrum of the 124 Gbps DP-MB-OFDM signal at the transmitter output.

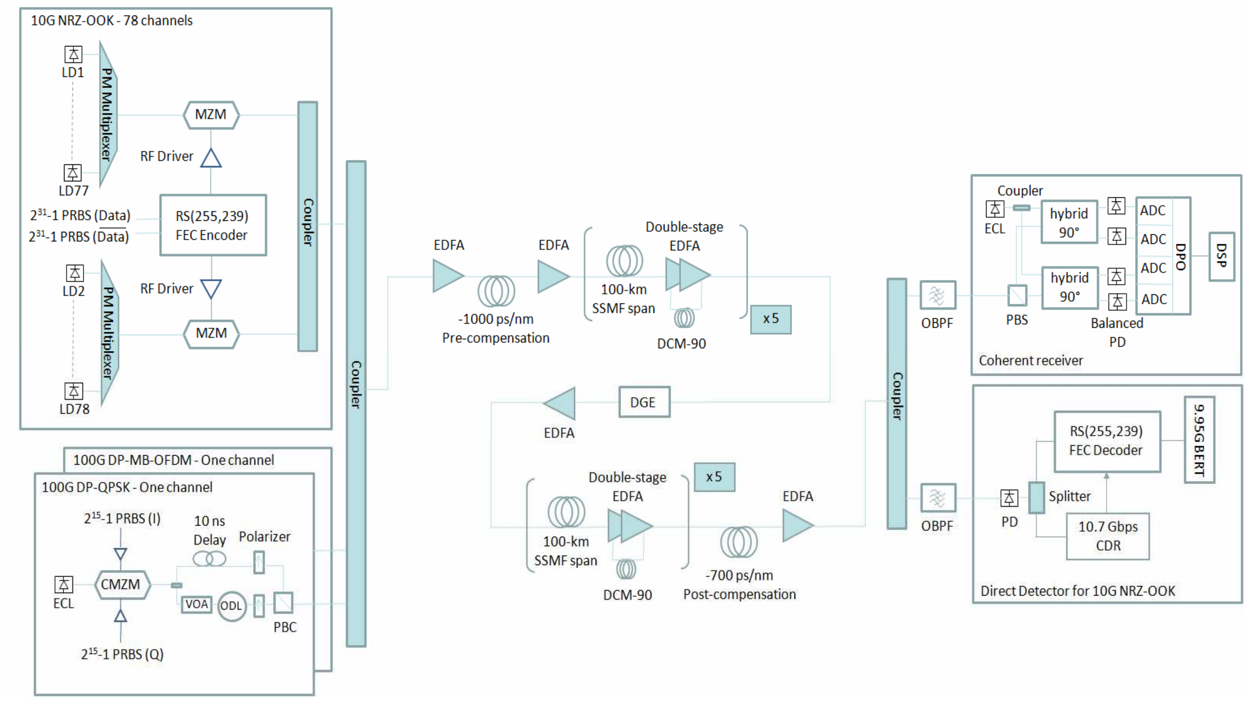


**Fig. 2:** Set-up of the 124.4 Gbps DP-MB-OFDM, 112 Gbps DP-QPSK, 10.7 Gbps NRZ-OOK transmitters, 10x100 km G.652 fiber transmission line, coherent receiver and direct detector with PM (polarization-maintaining), PBS (polarization beam splitter), ADC (analog-to-digital converter), RS (Reed-Solomon), PD (Photodiode).

while the 78 NRZ channels at 10.7 Gbps are fed by standard laser diodes (LD) with wavelengths ranging from 1529.16 nm to 1560.61 nm. Decorrelated $2^{15}$-1 pseudo-random bit sequences (PRBS) at 28 Gbps are used to drive the I and Q ports of the CMZMs, which generate QPSK constellation. A 10-ns timing delay is introduced between the two replica of the QPSK signal into the polarization-multiplexing module in order to generate the DP-QPSK signal. The 78 odd and even 10 Gbps channels are firstly encoded thanks to a RS(255, 239) forward error correction (FEC) code, separately multiplexed, independently modulated with decorrelated $2^{31}$-1 PRBS, and then coupled with the two 100 Gbps channels.

The DM transmission line shown in Fig. 2 is constituted of a pre-compensation stage of -1000 ps/nm at 1550 nm, followed by ten spans of 100 km of G.652 standard single-mode fiber (SSMF), separated by double-stage EDFAs with 30 dB gain and 5.5 dB noise figure, whose inter-stage is equipped with dispersion compensation module (DCM) adapted to 90-km SSMF spans. In the middle of our transmission line, a dynamic gain equalizer (DGE) is inserted in order to flatten the multiplex power after 1000 km. A post-compensation stage of -700 ps/nm brings back to ~ 0 ps/nm the cumulated dispersion of the channel at 1550 nm.

At the receiver side, the 100 Gbps DP-MB-OFDM and DP-QPSK signals are selected by a square flat-top optical band-pass filter (OBPF) of 0.4 nm bandwidth, and detected by a polarization diversity coherent receiver using a ~100 kHz bandwidth ECL as local oscillator (LO). The signals are converted back to the digital domain thanks to a 50 GSa/s real-time oscilloscope (DPO). In the DP-MB-OFDM detection case, the LO wavelength is tuned to the centre of the OFDM sub-band under measurement. The "off-line" digital signal processing (DSP) is then performed with four basic steps: synchronization according to the algorithm developed by Minn & Bhargava [6], which also permits to compensate a frequency offset in the range of ± 2Δf (Δf being the sub-carrier spacing); compensation of the remaining part of the frequency offset by determining the frequency shift that the last filled OFDM sub-carrier experiences [5]; separation of the two polarization components thanks to the zero-forcing MIMO equalizer [7]; and finally compensation of the common phase noise generated by the ECLs thanks to the method of the pilot sub-carriers described in [8]. In the DP-QPSK case, the "off-line" DSP is based on blind equalization, and more particularly on the constant modulus algorithm (CMA) which carries out polarization separation and residual chromatic dispersion (CD) compensation [9]. Frequency offset compensation and carrier phase estimation are done by the methods described in [10]. To avoid cycle slips, the detection is differential. The 10.7 Gbps NRZ channel under measurement is selected by a Gaussian OBPF of 0.25 nm bandwidth, detected by a 10 GHz photo-receiver, which feds the FEC decoder and 10.7 GHz clock and data recovery (CDR). The FEC card sends the decoded $2^{31}$-1 PRBS to a 9.95 Gbps bit-error-rate tester (BERT).

## Results and discussion

Two various configurations have been evaluated in Fig. 3. In the first one ("Single-Channel" configuration) used as reference, the wavelengths were not modulated except the channels at 1552.93 nm and 1548.11 nm, which carry the 100 Gbps channels. The second one ("with 10G" configuration) corresponds to the experimental set-up already described above, for which several schemes have been investigated. Firstly, no guard band (GB) is inserted between our two 100 Gbps channels and the 10 Gbps multiplex ("No GB" configuration). As observed in Fig. 3 for this scheme, the 100 Gbps DP-QPSK and DP-MB-OFDM channels do not work after 10x100 km of G.652 fiber line, as BERs largely exceed the FEC limit (fixed here at $2x10^{-3}$).

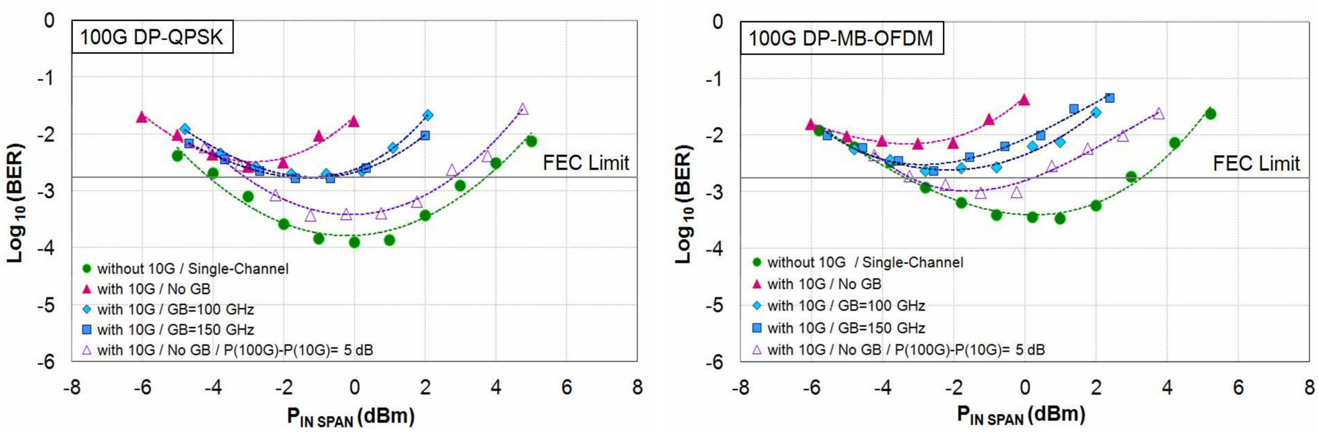


**Fig. 3:** BER versus span input power per channel after the dispersion-managed 10x100-km G.652 fiber line for the 112 Gbps DP-QPSK and the 124 Gbps DP-MB-OFDM signals for the various configurations under study.

In order to limit the impact of cross-phase modulation (XPM) and its cross-polarization modulation (XPolM) corollary between the 10 Gbps NRZ channels and the 100 Gbps ones [11], a first scheme consisting in inserting a guard band of 100 GHz and 150 GHz, corresponding to one and two 10 Gbps channels stopped from each side of the measured 100 Gbps channels ("GB=100 GHz" & "GB=150 GHz" configurations), have been tested. This option slightly improves the BER of 100 Gbps channels while increasing the optimum span input power per channel of both 100 Gbps DP-QPSK and DP-MB-OFDM, but not sufficiently to be below the FEC limit. Note as well that increasing the GB width from 100 GHz to 150 GHz does not further improve transmission performance.

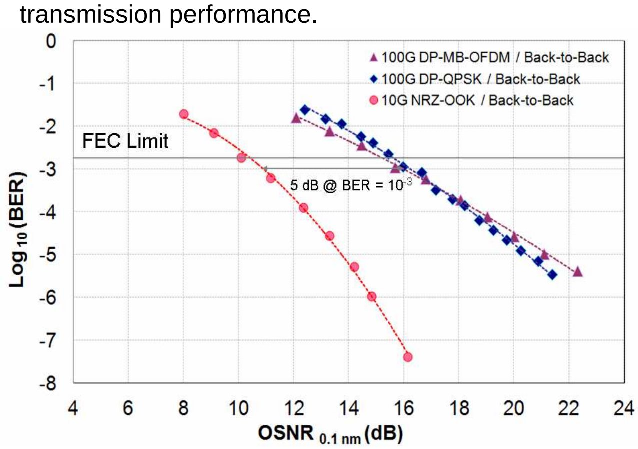


**Fig. 4:** BER versus OSNR (in 0.1 nm) measured in back-to-back for the 124 Gbps DP-MB-OFDM,112 Gbps DP-QPSK, and 10.7 Gbps NRZ-OOK signals.

Then, provided that the 10 Gbps NRZ channels have an advantage of 5 dB in terms of back-to-back OSNR sensitivity over both 100 Gbps DP-MB-OFDM and DP-QPSK signals (as it is shown in Fig. 4), we have intentionally reduced, in the transmitter, the 10 Gbps channel power of 5 dB with respect to that of the 100 Gbps signals ("P(100G)-P(10G)= 5 dB" configuration). This solution improves significantly the BER of 100 Gbps DP-QPSK and DP-MB-OFDM: nearly one decade is gained. In the same time, the optimum span input power per channel is enhanced of 3 dB for DP-QPSK and 2 dB for DP-MB-OFDM when compared to the "No GB" configuration, pointing out a better robustness to nonlinearities. This configuration permits to recover system margins and to ensure an error-free 1000-km transmission, confirming that the 10 Gbps channel power reduction option is the most credible solution to limit the impact of XPM and XPolM in such legacy infrastructure. Nonetheless, we do not recover the BER obtained in the "Single-Channel" configuration, in which intra-channel nonlinearities only are excited. Note that no error has been detected for the two 10 Gbps nearest neighbors of the 100 Gbps DP-MB-OFDM and DP-QPSK channels (at the optimum span input power per channel over the curves of Fig. 3).

Fig 3 also points out that 100 Gbps DP-QPSK shows a slightly higher performance than 100 Gbps DP-MB-OFDM, which is less than half a BER decade in the various configurations under study. The optimum span input power per channel is also slightly higher (up to 1 dB) in the DP-QPSK case, indicating an upper resistance of DP-QPSK over DP-MB-OFDM to XPM and XPolM.

## Conclusion

We have shown here that 100 Gbps DP-QPSK and DP-MB-OFDM transmission over legacy infrastructure is possible over 10x100 km of G.652 fiber, by decreasing the 10 Gbps channel power with respect to 100 Gbps channels by 5 dB. In such realistic conditions, 100 Gbps DP-MB-OFDM and DP-QPSK have nearly similar performance.

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[1] Alcatel-Lucent 1830 PSS brochure, www.alcatel-lucent.com; Ciena 6500 product data sheet, www.ciena.com.
[2] www.ofidium.com/technology.
[3] J. Karaki et al., accepted to SPPCom, Colorado Springs (2012)
[4] T. Sakamoto et al., Opt. Lett., Vol. 32, n°11, pp. 1515-1517 (2007).
[5] J. Karaki et al., CLEO 2012, Paper CF1F.3, San Jose (2012).
[6] H. Minn et al., IEEE Comm. Lett., Vol. 4, n°7, pp. 242-244 (2000).
[7] S.L. Jansen, et al., J. Opt. Networking, Vol. 7, n°2, pp.173-181 (2008).
[8] X. Yi et al., IEEE Photon. Technol. Lett., Vol. 19, n° 12, pp. 919-921 (2007).
[9] S.J. Savory, Opt. Express, Vol. 16, n°2, pp. 804-817 (2008).
[10] D.S. Ly-Gagnon et al., J. Lightwave Technol., Vol. 24, n°2, pp.12-21 (2008); A. Leven et al., IEEE Photon. Technol. Lett., Vol. 19, n°6, pp. 366-368 (2007).
[11] C. Xie, Opt. Express, Vol. 17, n°6, pp. 4815-4823 (2009)