

Performance Evaluation of a 112-Gbps Dual-Polarization 16-QAM Coherent Optical Fiber Link with DSP-Enabled OSNR and Reach Optimization

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Abstract

This paper presents a numerical investigation of a 112 Gbps dual-polarization (DP)-16-quadrature amplitude modulation (QAM) coherent optical fiber link employing a digital signal processing (DSP) chain that includes dispersion and nonlinearity compensation, adaptive equalization, frequency-offset estimation, and carrier-phase estimation. First, back-to-back performance is compared for 16-QAM, 32-QAM, and 64-QAM using bit error rate (BER) and error vector magnitude (EVM) as functions of optical signal to noise ratio (OSNR), showing that 16-QAM reaches the forward error correction (FEC) threshold of $\log(\text{BER})$ of -2.42 corresponding to a typical soft-decision FEC overhead of about 20% in coherent optical systems with EVM less than 16% at an OSNR of about 17 dB, whereas 32-QAM and 64-QAM require approximately 26 dB and 29 dB, respectively. For 80 km single-mode fiber (SMF) transmission, the proposed DP-16-QAM system achieves $\log(\text{BER})$ of -4.04 and 12.5% EVM at 20 dB OSNR, indicating only a modest OSNR penalty compared with the back-to-back case. Distance-swept simulations further reveal that, at 20 dB OSNR, $\log(\text{BER})$ degrades from -4.82 (back-to-back) to -2.08 at 160 km, while EVM increases from 11.0% to 17.9%, still remaining within typical soft-decision FEC limits. A fixed-OSNR reach analysis shows that at 18 dB OSNR the link can sustain near-threshold operation up to about 120 km, whereas at 24 dB OSNR the usable range extends to approximately 170 km before $\log(\text{BER})$ rises above -2.42 and EVM exceeds 20%.

Keywords - Coherent optical communication, QAM signals, Digital signal processing, Polarization division multiplexing.

1. Introduction

With the continued expansion of data traffic generated by cloud services, high definition video streaming, 5G and emerging 6G networks and data center interconnects, optical information transport systems are being pushed to ever increasing capacity and reach (Dhasarathan et al., 2020; Sivakumar et al., 2020). For long-haul and metro-regional links, coherent optical communication is currently the preferred solution which relies on high-order modulation formats, polarization-division multiplexing (PDM) and powerful

digital signal processing (DSP) to deliver very high spectral efficiency and robust impairment compensation (Agalliu & Lucki, 2016; Du et al., 2025; Kakati & Arya, 2019). In this context, the quadrature amplitude modulation (QAM) formats (16-QAM, 32-QAM, and 64-QAM) have been extensively investigated for bit rates within 100 Gbps and higher, because of the possibility of providing several bits per symbol or symbol pairs for the modulation while keeping the required optical signal to noise ratio (OSNR) reasonable, and the tolerance to linear and nonlinear effects in the fiber link.

There are two major approaches used to scale beyond the original 100 Gbps generation of coherent systems: increasing the symbol rate and increasing the modulation order, or both in combination with PDM (Li et al., 2018). An increasing symbol rate leads to an increasing occupied bandwidth and constrains both electronic components and optical front end, while increasing to higher-order QAM makes symbols smaller and requires higher OSNR and more complicated DSP to achieve the same bit-error-rate (BER) (Zhu et al., 2018). However, in many practical deployments, particularly over installed standard single mode fiber (SMF), the OSNR is constrained by amplifier noise, span design and power limits. In these circumstances, many interests arise to find modulation formats and DSP configurations that provide for high capacity at moderate OSNR and for realistic link distances.

A critical technique to double the capacity of a single optical carrier without expanding the spectral occupancy is called PDM (Lu et al., 2025; Yi et al., 2025). By transmitting independent data streams on two orthogonal states of polarization, a dual-polarization (DP) coherent transceiver can, in principle, double the bit rate at a fixed baud rate. For instance, a DP-16-QAM signal with 28 Gbaud has 4 bits/symbol/pol, which gives a line rate of 112 Gbps. This architecture, in conjunction with coherent detection, which is possible using an 8 GHz InGaAs InP detector pair, and DSP, can provide full field reconstruction in both polarizations, and compensate for laser phase noise, frequency offset, polarization mode dispersion, and chromatic dispersion in the digital domain (Yi et al., 2018).

Simultaneously, the DSP functionality has progressed from impairment management into a key enabler of modulation format flexibility and performance optimization (He et al., 2022; Zhong et al., 2018; Zhao et al., 2019). DSP can be used to shape pulses and pre-compensate predictable distortions at the transmitter, and to resample, recover timing, demultiplex in polarization, adaptively equalize, estimate the frequency offset (FOE) and estimate the carrier phase (CPE) as well as to monitor errors at the receiver. By creating a combination of fiber dispersion cancellation and nonlinearity cancellation along with cancelling hardware imperfections, these blocks can enable higher-order DP-QAM formats to operate at lower OSNR as discussed in Rizzelli & Gaudino (2024). But the complexity and convergence characteristics are highly sensitive to the modulation format and the noise and impairment environment, and there is ongoing need to quantify the performance and reach that can be achieved under realistic conditions (Weng et al., 2019; Xie et al., 2023).

The performance of the different M-QAM formats in coherent optical links has been studied in the past, and it has been demonstrated that, in principle, the spectral efficiency can be improved by using 16-QAM, 32-QAM or 64-QAM, but at the expense of several dB increase in OSNR required for the same target BER (Hao et al., 2024). This OSNR penalty in the long haul links can substantially reduce the transmission reach or force the use of more complicated and power consuming coding schemes due to cascaded erbium-doped fiber amplifiers (EDFA) and nonlinear noise accumulation. Besides, higher-order QAM constellations are more susceptible to phase noise and residual dispersion, which places emphasis on FOE, CPE and adaptive equalizers. For this reason, many deployed systems still prefer to use DP-QPSK or DP-16-QAM for line rates of 100–200 Gbps, while higher-order QAM is reserved for short-range, high-OSNR applications, such as data-center interconnects.

In this light, it is of great interest to analyze the performance limits of DP-16-QAM at around 112 Gbps under such practical OSNR and fiber-impairment conditions with the state of the art DSP. A comparison with the back-to-back operation and with the transmission over standard SMF of DP-32-QAM and DP-64-QAM can help understand the amount of OSNR margin and reach that can be achieved by a preference for 16-QAM; and how far the gap can be closed with DSP for higher-order formats. The advanced DSP modules enable the characterization of the dependence of OSNR, transmission distance and quality metrics like BER and error vector magnitude (EVM).

Although comparative studies of DP-QAM formats are available in the literature, the novelty of the present work lies in its unified system-level evaluation of DP-16-QAM, DP-32-QAM, and DP-64-QAM under the same 112 Gbps coherent receiver and DSP chain. Unlike prior studies that typically emphasize a single modulation format, BER-only metrics, or a limited transmission scenario, this work jointly evaluates BER and EVM, covers back-to-back and 80 km transmission cases, extends the analysis to distance-swept performance up to 160 km, and determines fixed-OSNR reach limits. The resulting framework offers practical design insight into OSNR margin, reach penalty, and modulation-format selection for coherent optical transport.

In this work, a 112 Gbps DP coherent optical transmission system based on 16-QAM is designed and simulated, and its performance is systematically evaluated using a detailed DSP chain. For the proposed 112 Gbps DP-16-QAM system operating at 28 Gbaud, the ideal gross spectral efficiency is 8 b/s/Hz, since 16-QAM carries 4 bits per symbol per polarization and polarization multiplexing doubles the throughput. The system model incorporates a polarization-multiplexed transmitter, a standard SMF channel including chromatic dispersion and nonlinear effects, and a coherent receiver with polarization-diversity front-end. At the receiver, the sampled signals are processed through dispersion and nonlinearity compensation, adaptive equalization for polarization demultiplexing and residual inter-symbol interference (ISI) removal, FOE, and CPE, followed by symbol decision and error counting. In this work, three main evaluations are conducted. First, a comparative analysis of DP-16-QAM, DP-32-QAM, and DP-64-QAM is carried out in back-to-back configuration and after 80 km transmission, with $\log(\text{BER})$ and EVM plotted as functions of OSNR. Second, a focused investigation on DP-16-QAM examines the impact of transmission distance on performance for OSNR values between 8 and 20 dB, covering back-to-back and fiber lengths up to 160 km. Third, a fixed OSNR reach analysis is carried out at the OSNR level of 18 dB and 24 dB to find the maximum distance over which a target $\log(\text{BER})$ of -2.42 (which corresponds to a typical soft-decision forward error correction (FEC) threshold) can be achieved.

This paper can then be summarized as follows: First, it presents a detailed comparison of DP-16-QAM, DP-32-QAM and DP-64-QAM at the same 112Gbps rate, with OSNR gain of the 16-QAM shown in both BER and EVM for realistic FEC threshold. Second, it allows for a complete assessment of the performance of DP-16-QAM transmission over standard SMF over a distance of up to 160 km, along with estimation of OSNR penalties and constellation diagram evolution at various DSP stages. Third, it sets realistic upper bound constraints on the fixed OSNR values of 18 dB and 24 dB, which allow the system designers to trade off modulation format, OSNR budget and target distance in coherent optical networks. The insights provide an advantage for choosing DP 112 Gbps 16-QAM, with advanced DSP, as an appealing solution for long haul and metro-regional optical transport.

2. System Design

The practical design of 112 Gbps DP-*M*-QAM coherent transmission system, which consists of an optical transmitter, SMF link, coherent receiver and coherent DSP chain is shown in **Figures 1** and **2**.

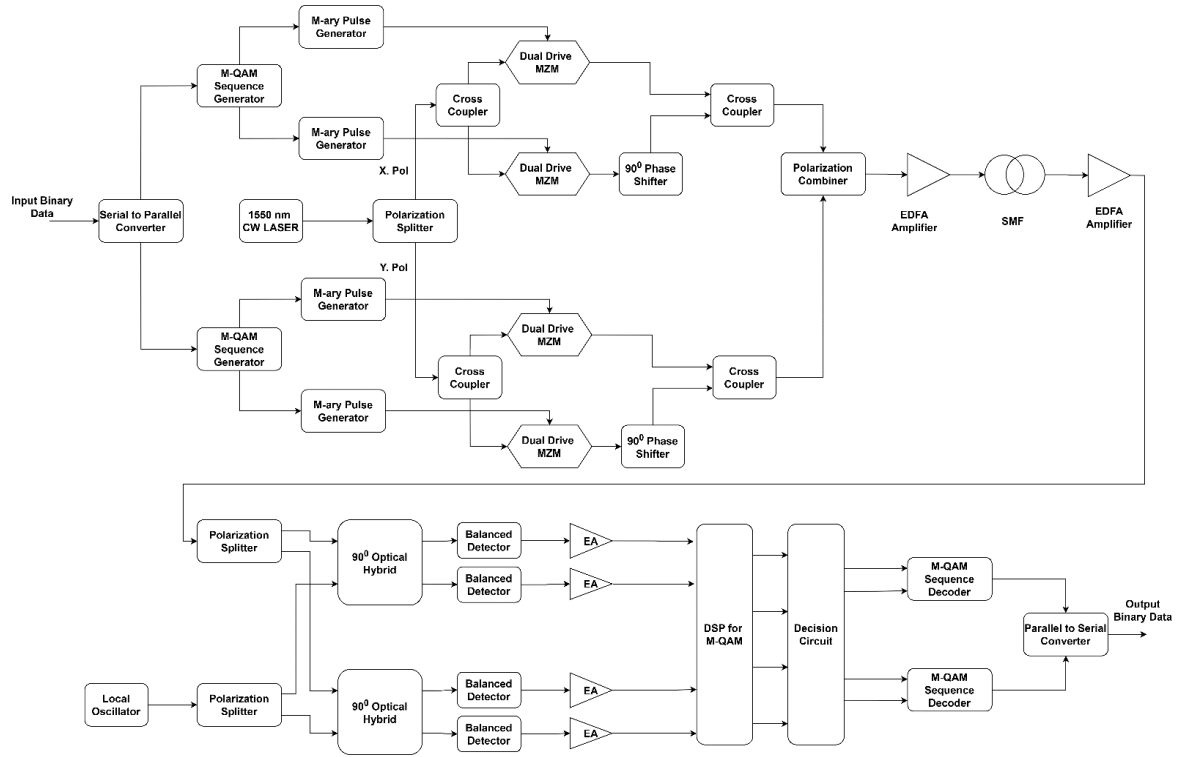


Figure 1. Schematic of DP-M-QAM transmission over SMF using DSP at the receiver.

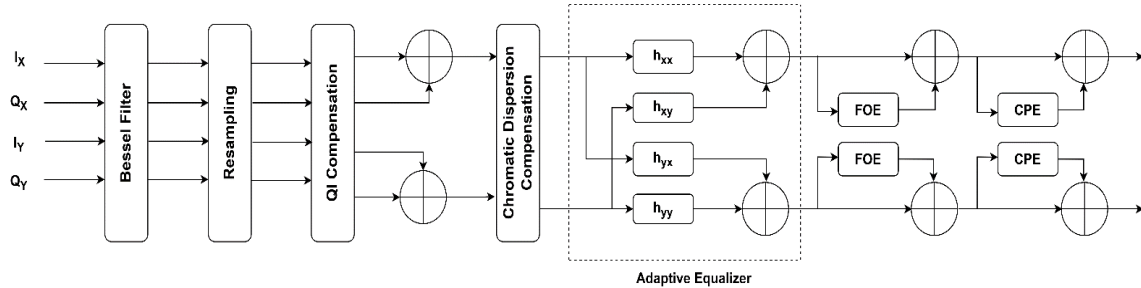


Figure 2. Schematic of DSP algorithm at the receiver.

The system starts with a 112 Gbps aggregate line rate binary data stream. Bits are initially serially to parallel converted to create two data tributaries for the X- and Y-polarization branches. They are each connected to an M -QAM sequence generator (where, $M = 16, 32$ or 64 is determined by the scenario), which encodes groups of bits into complex symbols based on the selected constellation. Both the in-phase (I) and quadrature (Q) components of each of these complex sequences are then sent to M -ary pulse generators, where the shaping functions are root-raised-cosine with a roll-off factor of 0.2, used to limit the spectrum occupied and reduce ISI. Dual drive Mach-Zehnder modulators (MZMs) are used to modulate a narrow linewidth 1550 nm continuous wave (CW) laser with pulse shaped electrical waveforms. The dual drive MZMs and 90° RF phase shifter are combined in the polarization branches to implement complex field

modulation as IQ modulators. The I and Q arms are then cross coupled together to create a single complex optical signal for each polarization. Then a polarization splitter and combiner structure is used to implement the PDM, in which the X- and Y-polarized complex signals are multiplexed into one optical carrier with DP-M-QAM, as shown in **Figure 1**. This polarization multiplexed signal is amplified to the required launched power by an EDFA before being launched into an SMF link.

The transmission medium is a standard SMF operating in C-band. The standard SMF channel was simulated by the split-step Fourier method (SSFM) with the consideration of chromatic dispersion, attenuation and Kerr nonlinearity, and a nonlinear coefficient γ of $1.3 \text{ W}^{-1}\text{km}^{-1}$. Propagation interval was subdivided to sufficiently small values to maintain numerical stability and to represent the nonlinear phase accumulation. The fiber model contains attenuation, chromatic dispersion and Kerr nonlinearity, which all result in power loss, temporal broadening and nonlinear phase rotation of the transmitted symbols. The total link length is varied from back-to-back (0 km) up to 200 km. Amplified spontaneous emission (ASE) noise from the EDFAs is added to the signal, and the OSNR at the receiver is adjusted over the required range by tuning the amplifier gain and input power.

Upon reception, the incoming DP signal is first divided into two components of orthogonal polarization by a polarization beam splitter. Each polarization is then passed through a 90° optical hybrid where it is combined with a local oscillator (LO) laser with a nominal wavelength equal to the transmitter but phase and frequency independent. The optical hybrid generates four outputs for the I and Q components of both polarizations. Balanced photodiodes detect these outputs, convert the optical fields to electrical currents and reject common-mode noise. The X and Y polarization electrical signals are then amplified by transimpedance amplifiers, and sampled by high speed analog-to-digital converters. The sampling rate is considered as 2 samples per symbol and the analog-to-digital converter have 8 bit resolution to ensure that adequate temporal sampling and quantization accuracy would be obtained for subsequent DSP processing. The resulting four sampled streams, denoted as I_X , Q_X , I_Y , and Q_Y are transmitted over to the DSP module shown in **Figure 2**.

The function of the DSP chain is to compensate for any receiver front-end imperfections, fiber-induced impairments, and recover the transmitted symbols with as high fidelity as possible. In addition to the chromatic-dispersion compensation, adaptive equalization, FOE, CPE, and digital backpropagation (DBP) for nonlinear impairment compensation are included in the DSP chain. The initial step in the digital processing is the application of Bessel low-pass filters to each of the 4 input branches as shown in **Figure 2**. This filter will reject high-frequency noise and reduce the effective bandwidth to the bandwidth of the modulated signal. A resampling block is then used to synchronize the sampling moments onto the symbol grid and impose an adequate sampling rate, so subsequent algorithms can work with the time synchronized data. After re-sample a quadrature-imbalance (QI) compensation module is used to compensate amplitude and phase imbalance between the I and Q branches of each polarization. This step minimises imperfections caused by non-ideal IQ modulators, optical hybrids and electrical front-end.

The chromatic-dispersion compensation block then numerically inverts the accumulated dispersion of the SMF link, usually through a frequency-domain filter or time-domain finite-impulse-response equalizer, thereby restoring the temporal alignment of the pulses. The main segment of the DSP receiver is the adaptive polarization-demultiplexing and equalization stage. This is implemented as a 2×2 multiple-input multiple-output (MIMO) filter with four complex sub-filters h_{xx} , h_{xy} , h_{yx} , and h_{yy} that jointly process the X and Y polarization components. The 2×2 MIMO adaptive equalizer was implemented with 15 taps per branch and a step size of $\mu = 10^{-3}$. The equalizer operated in a two-stage mode, using the constant modulus algorithm (CMA) for blind convergence and switching to decision-directed least mean squares

(DD-LMS) for steady-state tracking and residual ISI suppression. The equalizer iteratively adapts its coefficients using a decision-directed or constant-modulus-type algorithm to cancel residual chromatic dispersion, polarization-mode dispersion, and ISI, while also separating the two polarization tributaries. After convergence, the two complex outputs correspond to the recovered X- and Y-polarization signals. Downstream of the adaptive equalizer, a FOE stage removes the residual frequency mismatch between the transmitter laser and LO. This is typically done by measuring and compensating a common frequency shift on the recovered symbols. Finally, CPE tracks and corrects the time-varying phase noise introduced by both lasers and by nonlinear propagation. The CPE module can be realized using blind phase search or decision-directed phase-locked techniques, and it is applied separately to each polarization tributary. After FOE and CPE, the corrected symbols are de-rotated to the nearest ideal 16-QAM constellation points in a decision circuit. The detected symbols are passed through 16-QAM sequence decoders to remap them into binary words for each polarization. A parallel-to-serial converter then recombines the two tributaries into the recovered 112 Gbps bit stream. BER and EVM metrics are finally computed by comparing the recovered bits and symbols with the transmitted reference sequences over a sufficiently long observation window. The key simulation parameters are briefly listed in **Table 1**.

Table 1. Simulation parameters.

Parameter	Value	Unit
Data rate	112	Gbps
Symbol rate	28	Gbaud
Sampling rate	2	Sample/symbol
Modulation Format	M -QAM ($M = 16, 32, 64$)	-
Bits per symbol	4 (16-QAM); 5 (32-QAM); 6 (64-QAM)	-
Laser wavelength	1550	Nm
Fiber type	SMF	-
Fiber Dispersion	17	ps/(nm-km)
Fiber differential group delay	0.2	ps/ $\sqrt{km}$
Kerr nonlinear coefficient γ	1.3	$W^1 km^{-1}$
CW laser power	0	dBm
Laser line width	0.1	MHz
EDFA gain	16	dB
EDFA noise figure	4	dB
Fiber attenuation	0.2	dB/km
Transmission distance	0 - 200	km
OSNR range	8 - 32	dB
PIN detector responsivity	0.8	A/W
PIN detector dark current	10	nA
ADC resolution	8	bits
RRC roll-off factor	0.2	-
Equalizer tap length	15	Taps/branch
Equalizer adaption	CMA + DD-LMS	-

The received complex samples after analog-to-digital conversion are represented as:

$$\mathbf{x}(n) = \begin{bmatrix} x_X(n) \\ x_Y(n) \end{bmatrix} \quad (1)$$

where, $x_X(n)$ and $x_Y(n)$ denote the samples in the two orthogonal polarization tributaries. The polarization demultiplexing and equalization stage is implemented using a 2×2 MIMO adaptive filter, written as

$$\mathbf{y}(n) = \mathbf{W}^H(n)\mathbf{x}(n) \quad (2)$$

where, $\mathbf{W}(n)$ is the complex tap-weight matrix and $(\cdot)^H$ denotes Hermitian transpose. For the blind acquisition stage, the filter coefficients are updated by the constant modulus algorithm (CMA) according to

$$\mathbf{W}(n+1) = \mathbf{W}(n) + \mu \mathbf{x}(n)e^*(n) \quad (3)$$

with

$$e(n) = (R - |y(n)|^2)y(n) \quad (4)$$

where, μ is the adaptation step size, R is the constant-modulus reference, and $(\cdot)^*$ denotes complex conjugation. After initial convergence, the equalizer switches to a decision-directed least mean squares (DD-LMS) mode, for which the update rule becomes

$$\mathbf{W}(n+1) = \mathbf{W}(n) + \mu \mathbf{x}(n)[\hat{\mathbf{d}}(n) - \mathbf{y}(n)]^H \quad (5)$$

where, $\hat{\mathbf{d}}(n)$ is the decided symbol vector. This two-stage strategy provides blind polarization separation during acquisition and improved residual ISI suppression during tracking.

After equalization, the residual carrier frequency offset is estimated from the phase evolution of successive symbols. A convenient estimator is:

$$\Delta f = \frac{1}{2\pi T_s} \angle \left(\sum_{n=1}^{N-1} z(n+1)z^*(n) \right) \quad (6)$$

where, $z(n)$ denotes the equalized complex symbol stream, T_s is the symbol period, and N is the observation window length. The frequency-compensated signal is then obtained as:

$$z_f(n) = z(n)\exp(-j2\pi\Delta f n T_s) \quad (7)$$

Finally, CPE is performed to remove the residual laser phase noise. If blind phase search is used, the phase estimate is obtained by minimizing the decision error over a discrete set of candidate phases, i.e.

$$\hat{\phi}(n) = \arg \min_{\phi \in \Phi} \sum_{k=-K}^K |z_f(n+k)e^{-j\phi} - Q[z_f(n+k)e^{-j\phi}]|^2 \quad (8)$$

where, Φ is the phase-search set, K is the block half-length, and $Q(\cdot)$ denotes the nearest-constellation decision operator. The phase-corrected output is then

$$\tilde{z}(n) = z_f(n)e^{-j\hat{\phi}(n)} \quad (9)$$

The detected symbols are finally mapped back to binary data, and BER and EVM are computed by comparing the recovered and transmitted sequences over the observation window.

The relationship between BER, EVM, and OSNR can be interpreted analytically through the signal-to-noise ratio (SNR). For approximately Gaussian noise conditions, the root-mean-square EVM is related to SNR by

$$\text{EVM}_{\text{rms}} \approx \frac{1}{\sqrt{\text{SNR}}} \quad (10)$$

so that

$$\text{SNR} \approx \frac{1}{\text{EVM}_{\text{rms}}^2} \quad (11)$$

For square M -QAM under high-SNR operation, the BER can be approximated by

$$\text{BER} \approx \frac{4}{\log_2 M} \left(1 - \frac{1}{\sqrt{M}}\right) Q \left(\sqrt{\frac{3 \log_2 M}{M-1}} \text{SNR} \right) \quad (12)$$

where, $Q(\cdot)$ is the Gaussian Q -function. Combining these expressions shows that BER decreases rapidly as OSNR increases, because higher OSNR reduces noise variance, lowers EVM, and increases the decision margin between adjacent constellation points.

3. Results and Discussion

Figures 3 to 8 summarize the back-to-back performance of the DP 16-QAM, 32-QAM, and 64-QAM formats in terms of $\log(\text{BER})$ and EVM as a function of OSNR at the receiver. For all three modulations, an increase in OSNR leads to a clear reduction in BER and EVM, confirming that the coherent receiver and DSP chain efficiently suppress noise and ISI in the absence of fiber transmission impairments. The rate of improvement, however, strongly depends on the modulation order and directly reflects the different OSNR sensitivities of 16-QAM, 32-QAM, and 64-QAM.

Figure 3 shows the B2B results for the proposed DP-16-QAM signal. At low OSNR of 8 dB, the system exhibits a BER of approximately 3.5×10^{-1} ($\log(\text{BER}) \approx -0.45$) and a relatively high EVM of about 28.8%, indicating that the received constellation is still strongly affected by ASE noise. As OSNR increases, both metrics improve rapidly: at 14 dB the BER drops to about 2.2×10^{-2} ($\log(\text{BER}) \approx -1.65$) with EVM reduced to 20.6%, and at 18.5 dB the BER further decreases to roughly 4.9×10^{-4} ($\log(\text{BER}) \approx -3.31$) with $\text{EVM} \approx 13.3\%$, which is compatible with typical soft-decision FEC thresholds for 112-Gbps coherent links. At 20 dB OSNR, the system operates in a very robust regime, achieving a BER on the order of 1.5×10^{-5} ($\log(\text{BER}) \approx -4.82$) and EVM near 11.3%, demonstrating that DP-16-QAM can meet stringent BER and EVM requirements with relatively relaxed OSNR in the B2B configuration. **Figure 4** shows the constellation at 17 dB OSNR for B2B transmission using 16-QAM signals demonstrating $\log(\text{BER}) \approx -2.42$ (i.e. FEC threshold limit) and $\text{EVM} \leq 16\%$. The EVM limit of 20% is adopted here as an indicative design benchmark for acceptable constellation quality in the simulated coherent 16-QAM link, alongside the adopted FEC threshold.

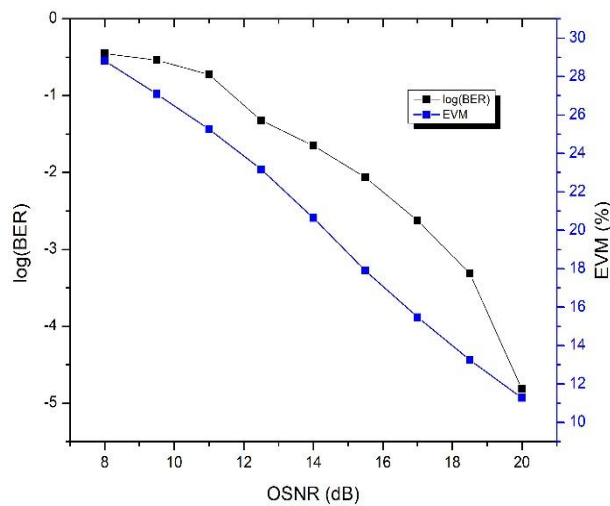


Figure 3. $\log(\text{BER})$ and EVM% versus OSNR for B2B transmission using 16-QAM signals.

As shown analytically in Section 2 (Equations (10)–(12)), the reduction in EVM with OSNR is accompanied by a corresponding improvement in BER, consistent with the simulation results here. **Figure 5** presents the corresponding B2B characteristics for DP-32-QAM. At 8 dB OSNR, the BER is approximately 4.6×10^{-1} ($\log(\text{BER}) \approx -0.34$) and the EVM is about 21.1%, already lower than the initial EVM of 16-QAM due to the different symbol mapping and scaling, but still outside the acceptable range for reliable detection. A noticeable improvement is observed when OSNR increases to 17 dB, where the BER reduces to roughly 1.96×10^{-1} ($\log(\text{BER}) \approx -0.71$) and EVM falls to 15.8%; however, the BER remains significantly higher than that of 16-QAM at similar OSNR. Only at around 23–26 dB OSNR does DP-32-QAM approach a pre-FEC regime, achieving BER values between 1.2×10^{-2} and 2.2×10^{-3} ($\log(\text{BER}) \approx -1.93$ to -2.66) with EVM improving to ≈ 11.8 – 10.1% , which is several dB more OSNR than required by DP-16-QAM to reach comparable BER and EVM. **Figure 6** shows the constellation at 26 dB OSNR for B2B transmission using 32-QAM signals demonstrating $\log(\text{BER}) \approx -2.42$ and $\text{EVM} \leq 11\%$.

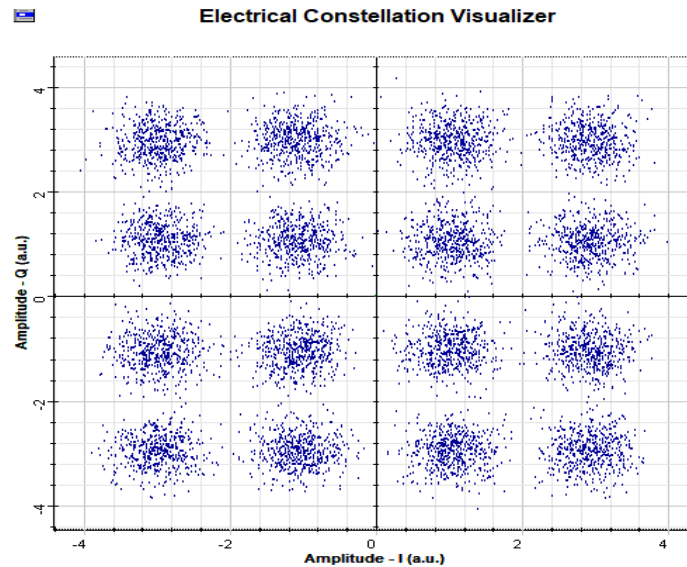


Figure 4. Constellation at 17 dB OSNR for B2B transmission using 16-QAM signals.

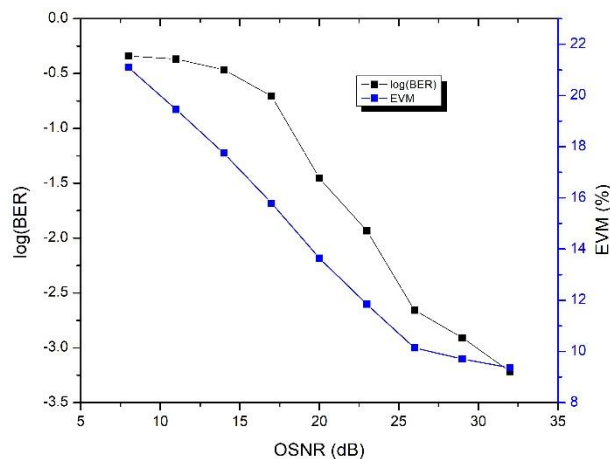


Figure 5. $\log(\text{BER})$ and EVM% versus OSNR for B2B transmission using 32-QAM signals.

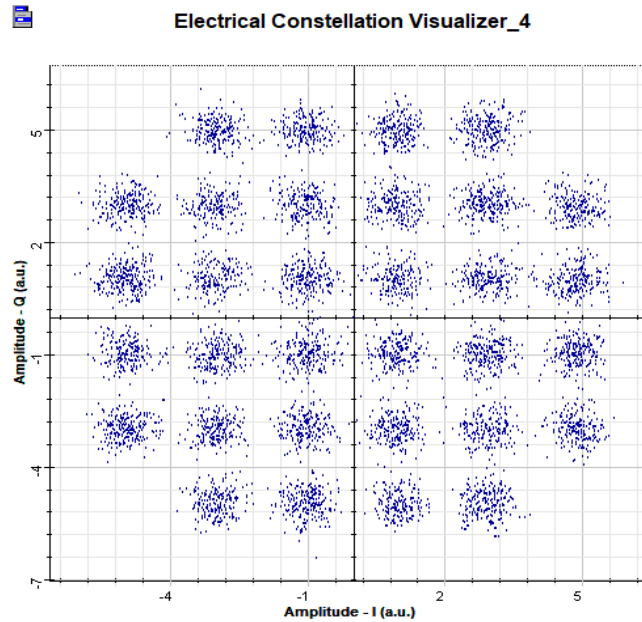


Figure 6. Constellation at 26 dB OSNR for B2B transmission using 32-QAM signals.

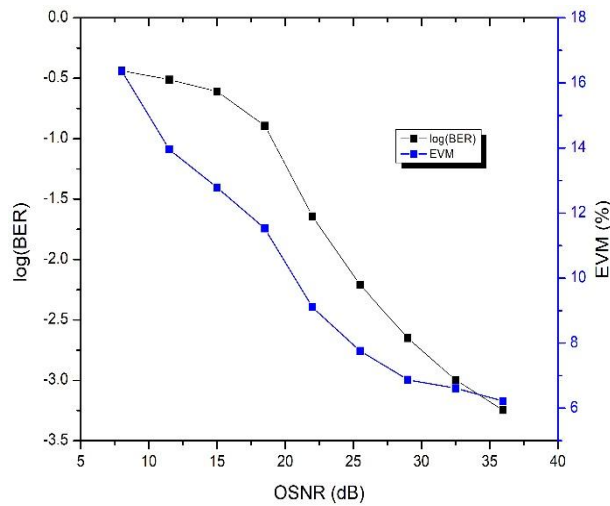


Figure 7. log(BER) and EVM% versus OSNR for B2B transmission using 64-QAM signals.

Figure 7 reports the B2B performance for DP-64-QAM. At 8 dB OSNR, the BER is about 3.65×10^{-1} ($\log(\text{BER}) \approx -0.44$) with an EVM of 16.4%, indicating that the dense 64-QAM constellation is highly sensitive to noise at low OSNR. As OSNR increases to 22 dB, the BER and EVM improve to approximately 2.3×10^{-2} ($\log(\text{BER}) \approx -1.64$) and 9.1%, respectively; nonetheless, this still corresponds to a weaker BER performance compared with 16-QAM at only 18.5–20 dB OSNR. The system reaches BER values around 5.6×10^{-4} ($\log(\text{BER}) \approx -3.25$) and $\text{EVM} \approx 6.2\%$ only when OSNR is increased up to 36 dB, clearly highlighting the much tighter OSNR requirement of DP-64-QAM to achieve a signal quality level

comparable to lower-order formats. **Figure 8** shows the constellation at 29 dB OSNR for B2B transmission using 64-QAM signals demonstrating $\log(\text{BER}) \approx -2.42$ and $\text{EVM} \leq 7\%$.

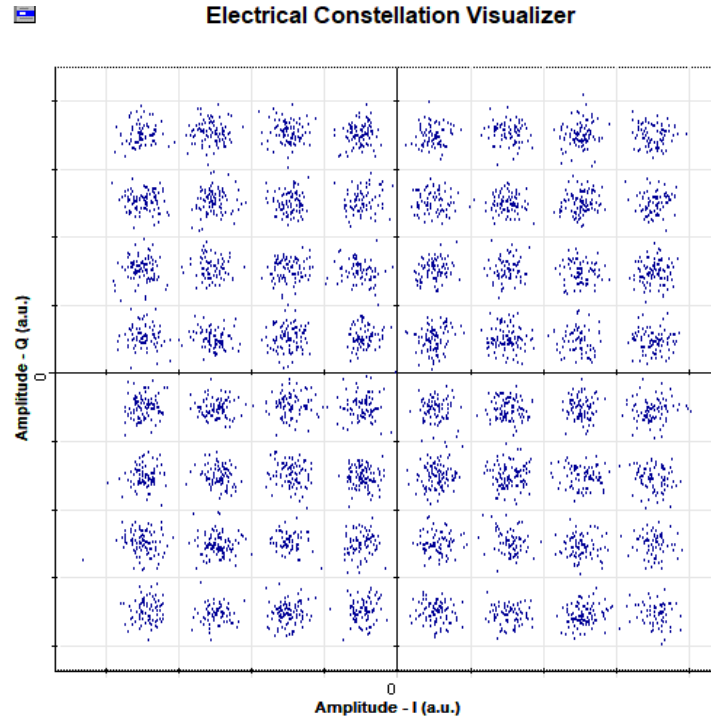
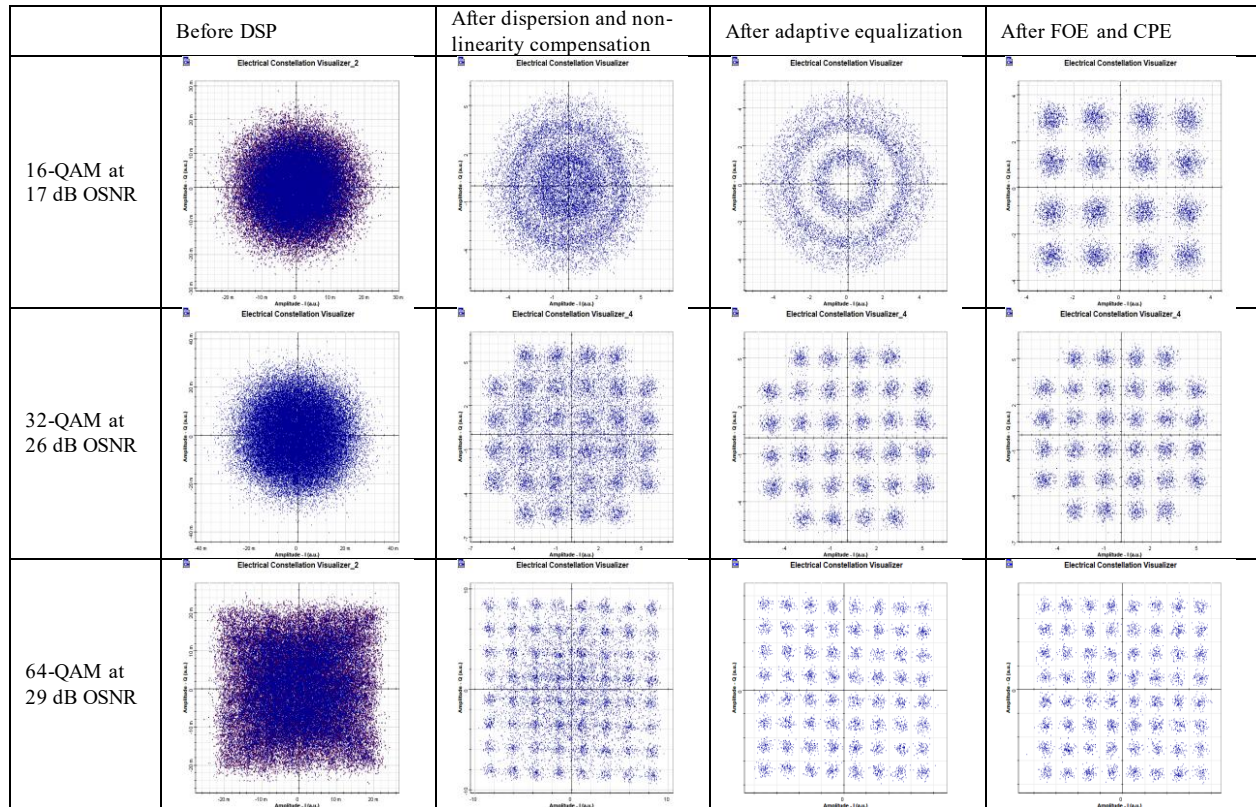


Figure 8. Constellation at 29 dB OSNR for B2B transmission using 64-QAM signals.

A direct comparison of **Figures 3 to 8** demonstrates that, for a given target BER and EVM, the required OSNR scales with the modulation order, in agreement with the reduced minimum Euclidean distance between constellation points in higher-order QAM. For example, to reach a BER on the order of $10^{-3} - 10^{-4}$ with EVM below about 15%, DP-16-QAM requires an OSNR of approximately 17 dB, whereas DP-32-QAM needs around 26 dB and DP-64-QAM must operate close to or above 29 dB. These results clearly show that, in the proposed 112-Gbps DP coherent system, 16-QAM offers the most favorable OSNR-to-performance trade-off in back-to-back operation, making it an attractive choice when the available OSNR is limited or when additional OSNR margin is desired to accommodate fiber-induced impairments in long-haul transmission.

A qualitative comparison of the recovered constellations for B2B transmission for DP-16-QAM, DP-32-QAM and DP-64-QAM is carried out at the OSNR values, where the target $\log(\text{BER})$ of -2.42 (corresponding to the adopted FEC threshold) is achieved and the results are summarized in **Table 2**. The constellations are displayed in each of the four key stages throughout the coherent receiver DSP: before, after the nonlinear distortion compensation, after adaptive equalization and after FOE and CPE. The following diagram illustrates the successive processing of the noisy received symbols by the DSP blocks and the progressive nature of the separation of the symbols into distinct clusters, and the dependence of this processing on the modulation order. Overall, it is verified in **Table 2** that each DSP stage is important to restore the constellation quality and reach the target FEC threshold for all three formats, and that 16-QAM is the most important in terms of low OSNR requirement, followed by 32-QAM and then 64-QAM.

Table 2. Comparative analysis of 16-QAM, 32-QAM, and 64-QAM signals of the X-polarization tributary at successive DSP stages; the Y-polarization exhibits similar behavior and is not separately shown for clarity.



As far as a practical design is concerned, the three formats have different trade-offs between spectral efficiency and receiver complexity. The gross spectral efficiency for proposed 112 Gbps DP-16-QAM system with 28 Gbaud is calculated as 8 b/s/Hz. Alternatively, when using higher-order formats, the nominal spectral efficiency can be higher, however, the OSNR penalty is more severe, the constellation spacing is less, the sensitivity to residual phase noise is higher, and the DSP convergence requirements are higher. The required OSNR for the system performance to meet the FEC threshold increases with the modulation order from 16-QAM to 32-QAM and 64-QAM, and the margins for the operation of the equalizer and phase-recovery blocks need to be tightened. Thus, while higher order QAM may be beneficial in theory, the 112 Gbps coherent link studied shows best balance of robustness, reach and implementation complexity with 16-QAM.

Figures 9 to 14 show the log(BER) and EVM performance of the proposed DP 16-QAM, 32-QAM, and 64-QAM formats after 80 km SMF transmission as a function of OSNR at the receiver. For all three formats, increasing OSNR again leads to a monotonic reduction in BER and EVM, indicating that the coherent receiver and DSP chain are able to mitigate linear fiber impairments and noise accumulation over 80 km, although with a clear OSNR penalty compared with the back-to-back case. **Figure 9** shows the 80 km performance of DP-16-QAM. At 8 dB OSNR, the BER is about 2.9×10^{-1} ($\log(\text{BER}) \approx -0.54$) and the EVM is $\approx 29.2\%$, confirming that the signal is still strongly noise-limited at low OSNR. As OSNR increases to 14 dB, the BER improves to roughly 3.0×10^{-3} ($\log(\text{BER}) \approx -1.52$) with EVM reduced to 21.5%; at 17 dB OSNR, the BER falls further to approximately 4.5×10^{-3} ($\log(\text{BER}) \approx -2.34$) with EVM $\approx 16.6\%$,

which is already close to typical soft-decision FEC limits for coherent links. At 20 dB the system reaches BER of 9.2×10^{-5} ($\log(\text{BER}) \approx -4.04$) and $\text{EVM} \approx 12.5\%$, demonstrating that DP-16-QAM can still achieve stringent BER and EVM targets after 80 km with only a modest OSNR increase compared with the back-to-back case. **Figure 10** shows the constellation at 18 dB OSNR for 80 km transmission using 16-QAM signals demonstrating $\log(\text{BER}) \approx -2.42$ and $\text{EVM} \leq 16\%$.

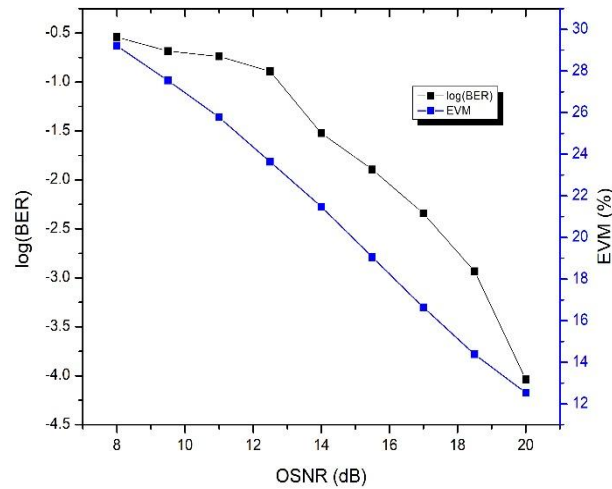


Figure 9. $\log(\text{BER})$ and $\text{EVM}\%$ versus OSNR for 80 km transmission using 16-QAM signals.

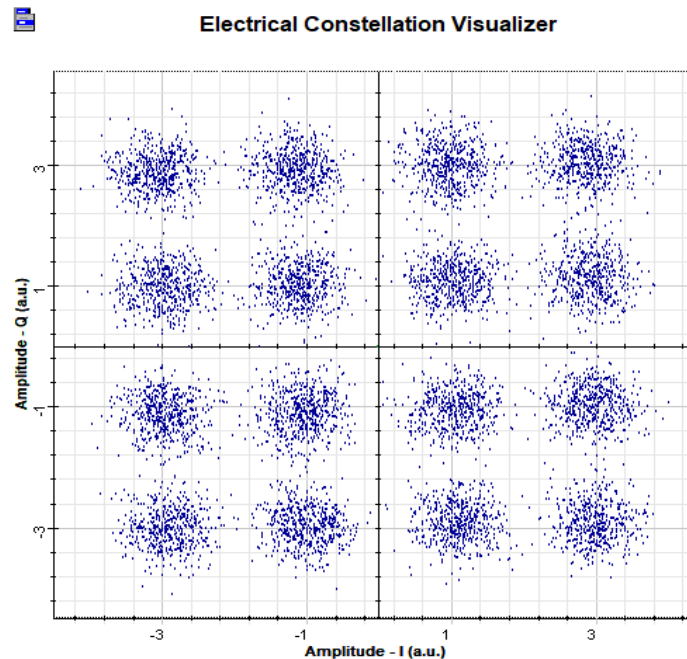


Figure 10. Constellation at 18 dB OSNR for 80 km transmission using 16-QAM signals.

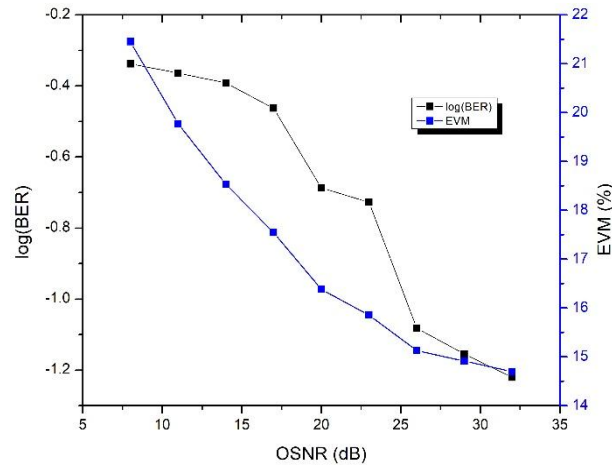


Figure 11. log(BER) and EVM% versus OSNR for 80 km transmission using 32-QAM signals.

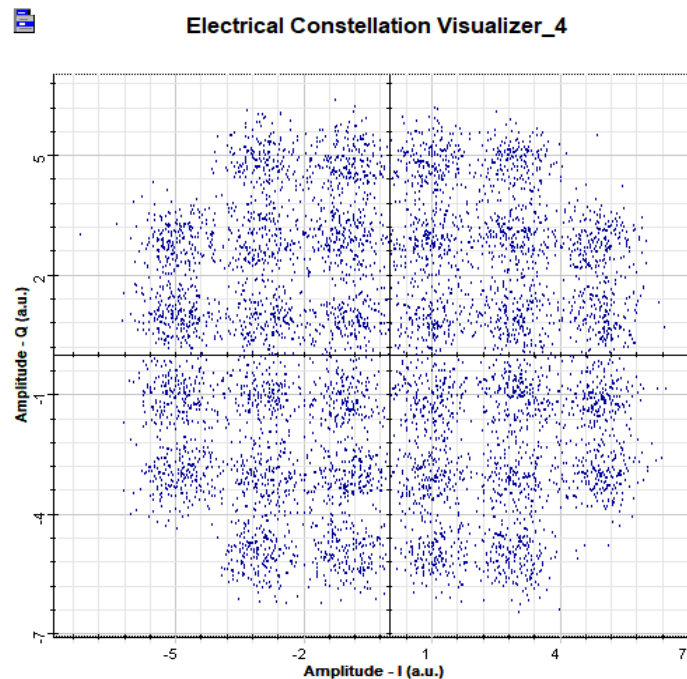


Figure 12. Constellation at 32 dB OSNR for 80 km transmission using 32-QAM signals.

Figure 11 presents the corresponding results for DP-32-QAM over 80 km. At 8 dB OSNR, the BER is approximately 4.6×10^{-1} ($\log(\text{BER}) \approx -0.34$) with an EVM of 21.4%, which remains outside the acceptable region for reliable detection. When OSNR is raised to 17 dB, the BER improves to about 3.5×10^{-2} ($\log(\text{BER}) \approx -1.08$) and EVM decreases to 15.1%, but the system still operates above typical pre-FEC BER limits. Only at around 20–23 dB OSNR does DP-32-QAM approach a quasi-FEC regime, with BER values around $2.1 \times 10^{-2} - 1.9 \times 10^{-2}$ ($\log(\text{BER}) \approx -0.69$ to -0.73) and $\text{EVM} \approx 16.4\text{--}15.9\%$, which is several dB more OSNR than required by DP-16-QAM to reach similar EVM and substantially

lower BER. **Figure 12** shows the constellation at 32 dB OSNR for 80 km transmission using 32-QAM signals.

Figure 13 reports the 80 km performance of DP-64-QAM. At 8 dB OSNR, the BER is about 3.6×10^{-1} ($\log(\text{BER}) \approx -0.44$) with an EVM of 15.7%, illustrating that the dense 64-QAM constellation is highly sensitive to the combined effects of ASE noise and fiber impairments. Increasing OSNR to 22 dB reduces the BER to roughly 1.3×10^{-1} ($\log(\text{BER}) \approx -0.88$) and EVM to about 11.5%, but these values still remain well above those of 16-QAM at considerably lower OSNR. Even at 36 dB OSNR, the BER only reaches about 5.1×10^{-2} ($\log(\text{BER}) \approx -1.30$) with $\text{EVM} \approx 10.1\%$, clearly indicating that DP-64-QAM over 80 km requires a much higher OSNR than the lower-order formats and still struggles to enter a strict pre-FEC regime. **Figure 14** shows the constellation at 36 dB OSNR for 80 km transmission using 64-QAM signals.

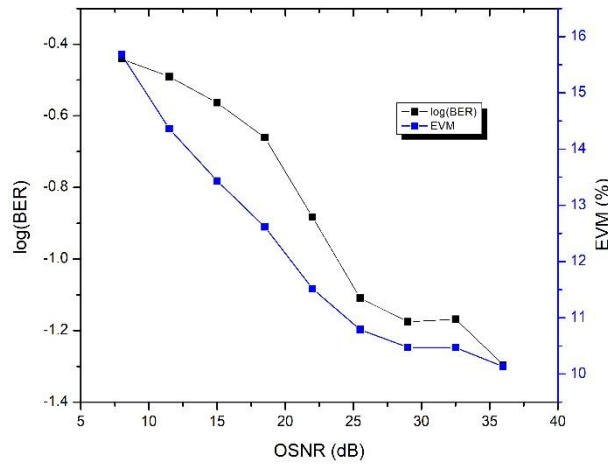


Figure 13. $\log(\text{BER})$ and EVM% versus OSNR for 80 km transmission using 64-QAM signals.

A comparative inspection of **Figures 9 to 14** confirms that, after 80 km transmission, the required OSNR for a given BER/EVM target again increases with modulation order, and the relative OSNR gaps between 16-QAM, 32-QAM, and 64-QAM become even more pronounced than in the back-to-back case. For example, to approach a BER in the $10^{-3} - 10^{-4}$ range with EVM below about 15%, DP-16-QAM needs an OSNR of only about 18–20 dB, whereas DP-32-QAM does not reach comparable performance within the considered OSNR window and DP-64-QAM performs significantly worse even at 36 dB OSNR. These observations demonstrate that, in the proposed 112-Gbps dual-polarization coherent system, 16-QAM not only offers the best OSNR-to-performance trade-off in back-to-back operation but also preserves this advantage after 80 km of fiber, making it the most suitable format when both high spectral efficiency and robust long-haul transmission are required.

Note that from **Figures 11 to 14**, both DP-32-QAM and DP-64-QAM fail to achieve the adopted FEC limit of $\log(\text{BER}) \approx -2.42$ after 80 km transmission in the range of the OSNR investigated, 8–36 dB. This means, with the current link intensity and the current DSP configuration, the higher order modulation formats are still not sensitive enough to the combined effect of the ASE noise, the residual dispersion, the nonlinear phase rotation and the phase-recovery limitations to achieve pre-FEC operation. In other words, they might provide higher spectral efficiency, but they would need significantly higher OSNR, more powerful FEC, shorter reach or more sophisticated transmitter/receiver processing to be suitable for 80 km SMF. It is

evident from the result that DP-16-QAM has the advantage of robustness in the considered system and shows the relationship between spectral efficiency and reliability of transmission.

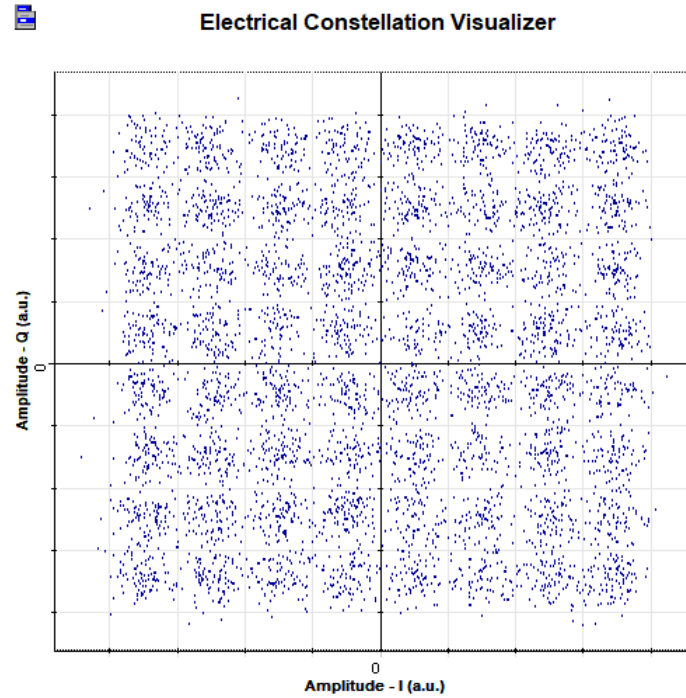


Figure 14. Constellation at 36 dB OSNR for 80 km transmission using 64-QAM signals.

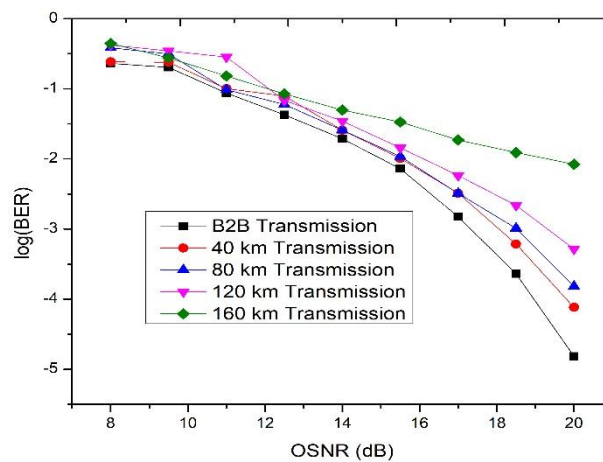


Figure 15. $\log(\text{BER})$ versus OSNR for DP-16-QAM transmission at different fiber lengths.

For a more effective evaluation of the proposed system, the $\log(\text{BER})$ and EVM performance are shown in **Figures 15** and **16**, respectively, for various transmission distances, namely B2B, 40 km, 80 km, 120 km and 160 km of standard SMF. The results show the effect of chromatic dispersion, fiber nonlinearities and

cumulative ASE noise on the quality of the signal with distance and how the coherent receiver DSP chain can effectively mitigate the impact up to 160 km.

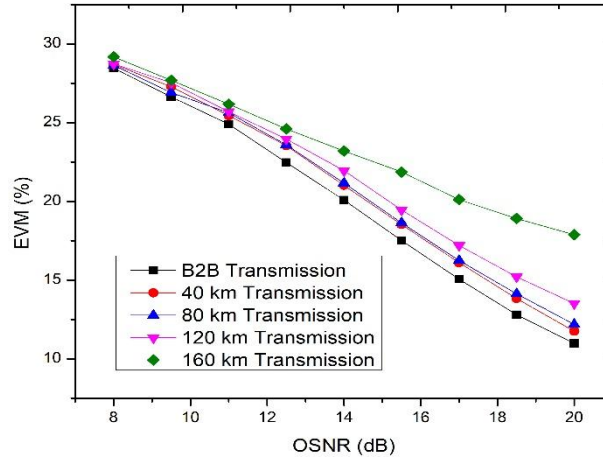


Figure 16. EVM% versus OSNR for DP-16-QAM transmission at different fiber lengths.

The results of $\log(\text{BER})$ plotted against OSNR are shown in **Figure 15** with all five transmission scenarios. The BER of B2B is monotonically improved with increasing OSNR with $\log(\text{BER}) \approx -4.82$ at 20 dB OSNR, as reported earlier. For an extended transmission distance of 40 km, a slight OSNR penalty is observed: when OSNR is 20 dB, the B2B BER of 1.5×10^{-5} becomes about 7.7×10^{-5} ($\log(\text{BER}) \approx -4.12$); this is mainly due to the fact that fiber causes linear and nonlinear impairments to start degrading performance. The OSNR penalty is more noticeable at 80 km, with BER growing up to approximately 1.5×10^{-4} ($\log(\text{BER}) \approx -3.82$) at 20 dB OSNR, which is still a reasonable BER for soft decision FEC. In the BER degradation case with 120 km transmission, the degradation is even greater, of the order of 5.2×10^{-4} ($\log(\text{BER}) \approx -3.28$) for 20 dB OSNR, about 35 times higher than the B2B case with the same OSNR. However, the DSP chain is still able to cope with the effect of dispersion and non-linearity such that a BER near the FEC threshold is maintained. The BER at 20 dB OSNR is around 8.4×10^{-3} ($\log(\text{BER}) \approx -2.08$) at the maximum distance analysed (160 km), which means there is enough cumulative impairment to prevent error correcting codes from recovering the data. Importantly, BER curves in all cases follow a similar declining trend towards lower BER as OSNR increases, indicating the stability and effectiveness of the DSP algorithms for equalizing the channel and recovering the phase even in the more demanding long distance propagation conditions.

The EVM performance shown in **Figure 16** is for the same distance of the transmission. The EVM is around 28.5% at B2B and 8 dB OSNR, which rises slightly to around 28.7–29.2% for 40 km–160 km transmission at the same low OSNR, indicating that EVM at very low OSNR is strongly related to ASE noise and not much related to fiber impairments. The differential effects of transmission distance are more apparent at higher values of OSNR (e.g., 17 dB or greater). For the DP-16-QAM signal at 17 dB OSNR, the EVM increases from approximately 15.1% in the B2B configuration to approximately 20.1% after 160 km of transmission, reflecting the combined effect of chromatic dispersion and fiber nonlinearity on symbol positioning. Compared with 160 km transmission the B2B EVM is at 11.0% at 20 dB OSNR, which is a degradation of approximately 6.9%. By comparing the BER and EVM with a systematic approach for all the distances, we can easily observe the occurrence of quantitative OSNR penalty as a function of fiber length. The required OSNR increases from about 17 dB at B2B to 18 dB at 40 km, 18.5 dB at 80 km, 19

dB at 120 km and about 20+ dB at 160 km with an incremental OSNR penalty of ~ 0.25 - 0.75 dB/40 km of transmission. This relatively shallow penalty slope further demonstrates the effectiveness of the chromatic dispersion and nonlinearity compensation using the DSP to minimize fiber-induced penalty and achieve the desired performance over long distances. **Table 3** summarizes the OSNR needed for the adopted FEC threshold in DP-16-QAM transmission over the various SMF lengths, including the OSNR penalty compared to the B2B case, to give a clearer idea of a system-level comparison. As the transmission distance increases, the required OSNR gradually increases as chromatic dispersion, nonlinear effects and ASE noise increase along the way. In particular, the penalty becomes about 3 dB at a distance of 160 km, and 2 dB at 120 km, 1.5 dB at 80 km and 0 dB in the B2B case, which verifies the effect of the implemented DSP chain to reduce but not completely eliminate the distance-dependent OSNR degradation.

Table 3. Consolidated OSNR penalty required to reach the adopted FEC threshold for DP-16-QAM transmission over different SMF lengths.

Transmission condition	OSNR at FEC threshold (dB)	OSNR penalty vs. B2B (dB)
B2B	17.0	0.0
40 km	18.0	1.0
80 km	18.5	1.5
120 km	19.0	2.0
160 km	20.0	3.0

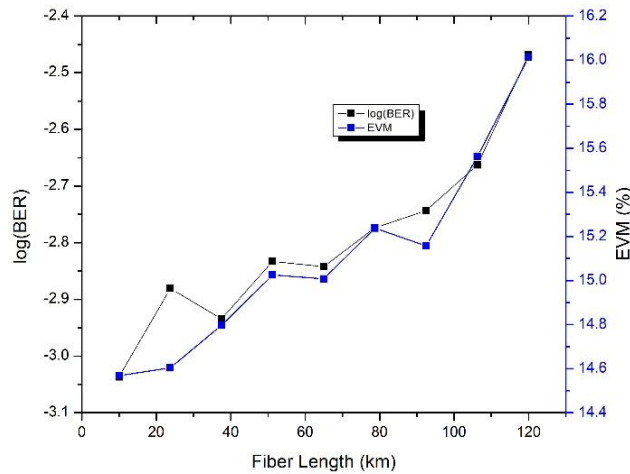


Figure 17. log(BER) and EVM% versus fiber length for DP-16-QAM signal at 18 dB OSNR.

The performance of 112Gbps DP-16-QAM system when the fiber length is varied while keeping the fixed OSNR at 18 dB and 24 dB, respectively, are shown in **Figures 17** and **18** by plotting the log(BER) and EVM. The BER is below FEC limit $\log(\text{BER}) \approx -2.42$ at 18 dB OSNR and is below this limit up to approximately 80-100 km, and the BER is from -3.04 at 10 km up to about -2.74 at 92.5 km while EVM is around 14.6–15.2%. Beyond this range, the combined effects of chromatic dispersion, nonlinearities and ASE noise create a gradual yet noticeable degradation: at 106.25 km, the BER is $\log(\text{BER}) \approx -2.66$ with $\text{EVM} \approx 15.6\%$ and at 120 km, the BER is $\log(\text{BER}) \approx -2.47$ with EVM increasing to around 16.0%. These values show that the link is approaching the FEC limit around 100-120km, and comfortable operation is possible with relatively high margin up to the length of 80-100km.

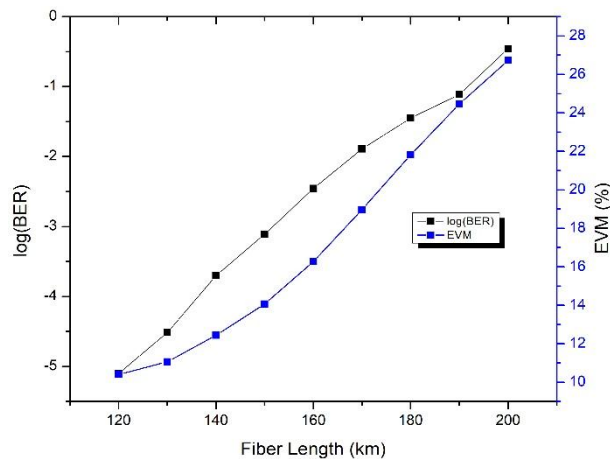


Figure 18. log(BER) and EVM% versus fiber length for DP-16-QAM signal at 24 dB OSNR.

The system has a much greater transmission reach at the same BER and EVM constraints at 24 dB OSNR (**Figure 18**). At 120 km, the BER is on the order of 8×10^{-6} ($\log(\text{BER}) \approx -5.10$) with $\text{EVM} \approx 10.4\%$, indicating very robust operation. Performance gradually degrades as the fiber length increases, at 150 km, $\log(\text{BER}) \approx -3.11$, with $\text{EVM} \approx 14.1\%$ and at 170 km, $\log(\text{BER}) \approx -1.89$, with $\text{EVM} \approx 19.0\%$ which remains close to but above the FEC point. The performance of the accumulated impairments becomes predominant beyond 170–180 km, with a BER of $\log(\text{BER}) \approx -0.46$ and EVM of $\approx 26.7\%$ at 200 km, well outside the range of acceptable performance for reliable 16-QAM detection. From these trends, it can be concluded that the DP-16-QAM system can support $\log(\text{BER}) \leq -2.42$ and EVM of approximately 20% up to a link length of 160–170 km with an OSNR of 24 dB compared to 18 dB. In conclusion, the fixed OSNR reach analysis validates the close interaction between OSNR and maximum achievable distance of the proposed system. For moderate OSNR (18 dB), DP-16-QAM can support error corrected transmission over metro scale spans of approximately 80–100 km and a 6 dB increase in OSNR is required for reliable operation over regional/long haul spans of up to 160–170 km. The results are in accordance with the distance swept analysis and is also another evidence that the implemented DSP chain, when used with DP-16-QAM, provides a good combination of spectral efficiency, OSNR tolerance and reach for 112 Gbps coherent optical links.

4. Conclusion

A detailed performance evaluation of a high-speed, dual-polarization 16-QAM coherent optical fiber system using advanced DSP technology has been conducted and the results are compared with performance of higher-order QAM systems with regard to OSNR and reach. The study reveals that 16-QAM achieves higher OSNR efficiency compared to 32-QAM and 64-QAM, and also achieves lower OSNR at the same OSNR efficiency, without compromising on EVM performance and with well-shaped constellations after the FEC, both in the B2B and 80 km transmission cases. The dispersion/nonlinearity compensation and carrier recovery algorithms have been implemented and tested by distance-dependent and fixed-OSNR reach measurements at 18 dB and 24 dB, respectively, that the system is capable of reliably supporting 100 km metro scale links at moderate OSNR and reaching 170 km with sufficient OSNR margin. Overall, it is found that DP-16-QAM with the implementation of the impairment mitigation enabled by DSP is a promising candidate for next generation 112 Gbps coherent optical transport networks that can be robustly operated with manageable OSNR and reach penalties and offer design margin for practical deployment and future system upgrades. The present study relies on a numerical simulation and

is thus not taking into account several practical impairments that may impact real deployed systems such as polarization-dependent loss, stimulated Raman scattering and inter-channel crosstalk. The effects of these may limit achievable OSNR margin and reach in a practical implementation and will be taken into consideration in future works.

Conflicts of Interest

The authors declare no conflict of interest.

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AI Disclosure

The authors confirm that no generative AI or AI-assisted writing tools were used in the preparation, drafting, or revision of this manuscript, including its text, figures, and data analysis.

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