

Simulation-Based Multi-Objective Co-Optimization of an Improved-Duobinary DWDM Transmitter and a Reduced Third-Order Volterra Receiver

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Abstract-

The Dense wavelength-division multiplexed (DWDM) is an advanced modification of Wavelength-division multiplexed (WDM) in form of capacity enhancement. The fiber-optic DWDM technology affected by several issues and impairments synchronously, chromatic dispersion, amplified-spontaneous-emission (ASE) noise, and Kerr-induced nonlinear distortion, making isolated optimization of the transmitter or receiver tends to results in unsatisfactory behavior of the system. The primary aim of the simulated study is to demonstrate the reproducible equivalent-baseband of optimization framework in which the transmitter, optical fiber link, and nonlinear equalizer are optimized together and that jointly considers an improved duobinary modulation (IDBM) transmitter, a dispersion-managed multi-span optical link, and a reduced third-order Volterra nonlinear equalizer (VNLE) receiver block. A multi-objective particle swarm optimization (MOPSO) approach is applied to optimize eight physical and implementation parameters simultaneously to complete the experiment for system realization. The optimization objectives comprises minimizing Q-estimated bit-error rate (BER), four-wave-mixing (FWM) power, the necessary optical signal-to-noise ratio (OSNR) penalty, and normalized equalizer complexity. The simulation establishes a range -4 to -2dBm/channel as the minimum-BER operating range, the isolated channel-power sweep, capability 1.92×10^{-6} at -2 dBm/channel. The adopted Pareto-optimal configuration utilizes -3.45 dBm/channel, 51.06-GHz spacing, a 0.0319 DCF/SMF ratio, 0.725 normalized receiver bandwidth, five-symbol VNLE memory, and $\lambda = 4.89 \times 10^{-5}$. Its Q-factor remains 4.20-4.36 over 80-400 km, and VNLE training MSE decreases by 85.1% in 75 iterations. Ablation yields 7.23×10^{-6} BER for IDBM-VNLE without DCF versus 0.1646 for disproportionate standard duobinary transmission; enabling DCF raises FWM by 17.22 dB. Across 30 paired waveform seeds, mean $\log_{10}$ (Q-estimated BER) improves from -0.7899 +/- 0.0018 to -12.7886 +/- 0.0336. Nine frozen-design tests show estimated BER below 4.64×10^{-11} at -3 dBm through 340 km, but provides a substantially reduced improvement at +7 dBm.

Index Terms- Dense wavelength-division multiplexing, duobinary modulation, four-wave mixing, Kerr nonlinearity, multi-objective particle swarm optimization, optical signal-to-noise ratio, Volterra nonlinear equalizer.

1. INTRODUCTION AND BACKGROUND

Dense wavelength-division multiplexing increases aggregate capacity by simultaneously transmitting multiple data channels as modulated carriers onto its own specific wavelength of light—over a single optical fiber. However, the resulting capacity improvement is accompanied by a narrower system operating margin due to several interacting impairments: chromatic dispersion broadens symbols, erbium-doped fiber amplifiers add ASE noise, and the Kerr effect produces self-phase modulation (SPM), cross-phase modulation (XPM), and FWM. The impairments are coupled. Dispersion changes pulse overlap and FWM phase mismatch; launch power changes received amplitude and nonlinear phase; channel spacing Modification spectral efficiency and mixing efficiency; receiver filtering Transform the noise-ISI balance. Consequently, sequentially optimized blocks need not yield a system-level optimum.

The results showcase addresses existing work crucial subsets of Categories. Spatial-distribution and pulse-shaped: DWDM links have been analyzed using BER, Q-factor, and eye opening [1], [4]; impairment-specific investigations have characterized SPM, stimulated Raman scattering, and nonlinear compensation [2], [3], [5]; and PSO has optimized IDBM time-delay parameters [6]. However, these directions persist minimally dependent: transmitter modulating is generally, optimized independently of the receiver, physical parameters are often kept fixed, and performance is often reduced to one scalar objective without component attribution or extreme condition testing.

Digital backpropagation (DBP) employed propagation model-based inversion of nonlinear fiber propagation: but its computational scalability deteriorates as the number of propagation steps, channel count, and processed bandwidth increases [9]. Perturbation and Volterra configurations facilitate of remunerate for complications by modeling and prominent non-linear collaborations together with polynomial kernels of finite memory [11]-[13]. The generating compensation performance, however, strongly dependent on memory length, regularization, receiver bandwidth, and training conditions. Similarly, a weighted-sum PSO objective can similarly disguise distinct engineering trade-offs among the optimization: lower BER performance may demand greater equalizer complexity, reducing FWM may compromise spectral efficiency, and an apparent OSNR gain may be an artifact of restricting the threshold search interval.

This study establishes a bounded four-objective optimization formulation the transmitter, transmission link, and receiver are jointly. The contributions are: 1) a unified equivalent-baseband representation that jointly captures residual dispersion, ASE noise, and dominant SPM/XPM/FWM effects in multi-channel duobinary transmission; 2) joint PSO-driven optimization of IDBM shaping parameters together with regularized third-order VNLE compensation; 3) simultaneous optimization of BER, FWM power, required-OSNR penalty, and normalized equalizer complexity over eight design variables; 4) establishment of a deterministic evaluation framework a fixed train/test split, Pareto archiving, exact ablation, 30 paired waveform seeds, and nine frozen-design distance-power tests; and 5) explicit identification of the trade-off among FWM suppression, OSNR, BER, implementation complexity, and transmission reach.

The analysis is confined to a controlled simulation -based environment. Where finite error counting cannot resolve the BER, Q-factor-based estimates are used and reported as Q-estimated BER. Comparative design conclusions are supported by the findings comparative design conclusions within the implemented model; they do not constitute hardware BER measurement or experimentally established distance. Section VI therefore specifies the measurements required for independent laboratory confirmation.

Singh and Arya investigated a high-capacity potential of 10.24-Tb/s NRZ-DWDM system with 1024 channels and 0.2-nm spacing, demonstrating the capacity enhancement achievable through dense grids while retaining a strong dispersion constraint [1]. Singh, Mittal, and Priyamvada evaluated commercial fibers configurations with and without dispersion compensation at 10 Gb/s and illustrated that the SMF/DCF map materially alters BER and eye quality [4]. A separate SPM study established the expected launch-power penalty after nonlinear phase accumulation becomes dominant [5]. Collectively, is motivated collectively by these findings simultaneous handling of power and dispersion, but are left fixed modulation memory, receiver bandwidth, and nonlinear equalization fixed or outside the optimization loop.

Impairment-oriented investigations provide applauding evidence for coupled nonlinear behavior. The nonlinear adaptive fiber-optic Infrastructure presented in [2] investigated system-level nonlinearity compensation, although [3] examined stimulated-Raman-scattering-induced crosstalk in WDM radio-over-fiber transmission. Other theoretical and capacity studies explain fundamental nonlinear-fiber theory, [7] channel-capacity evaluations [8] and WDM channel behavior [10] explain why treating linear and nonlinear impairments separately is not sufficient. Therefore, reducing the FWM affected by simultaneously on channel launch power, fiber effective length, channel spacing, attenuation, dispersion, and phase mismatch. Accordingly, suppressing FWM may require a trade-off involving spectral efficiency and the OSNR needed to achieve the desired BER.

The IDBM findings documented in [6] Utilized PSO to determine suitable time-delay and unit-delay parameters for improved duobinary modulation (IDBM). The optimized parameters and configuration enhancements in Q-factor, OSNR, FWM power, and conversion efficiency when compared with conventional and modified duobinary formats. The results establish controlled symbol correlation as a tunable transmitter-side parameter. However, the optimization framework transmitter-side parameter selection independently and did not extend the optimization to nonlinear receiver training or simultaneous Pareto analysis of transmission quality, nonlinear crosstalk, OSNR, and implementation complexity.

At the receiver-side, nonlinear compensation has been addressed investigated such as digital back propagation [9] mid-link spectral inversion [11], perturbation analysis, and Volterra-series equalizers [12], [13]. volterra processing next to optical phase conjugation [12], and empowered high-rate WDM equalization [13], illustrate that polynomial models with finite memory can effectively represent and compensate residual nonlinear distortion. However, these performance results, depends on several implementation parameters, particularly kernel order, memory depth, regularization, and training protocol, which jointly determine generalization capability and arithmetic cost. Additional PSO-facilitated perturbation modeling designates [16] optimization that search for a compromise between compensation accuracy and computational complexity. Hence, the unsettled issue is the lack of a replicable cross-layer

optimization process in which IDBM, dispersion management, receiver filtering, and VNLE complexity are optimized within a collaborative design environment.

The main objectives of the study is to construct one deterministic link model and validate all principal impairment outputs in the same run. Secondly, jointly optimize IDBM, dispersion map, and receiver bandwidth using reduced third-order VNLE model. Third, it is planned to use physical multi-objective particle swarm optimization (MOPSO) approach, a 30-seed paired comparison, and nine unseen distance-power tests.

2. JOINT TRANSMITTER-CHANNEL-RECEIVER ARCHITECTURE

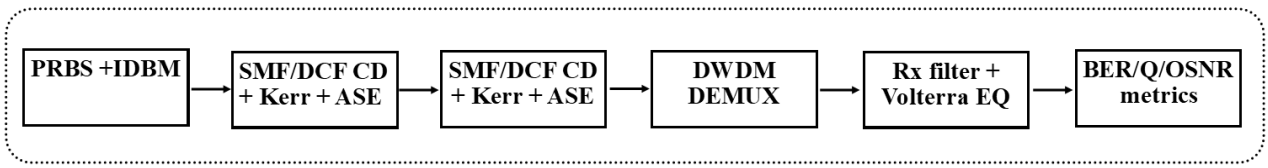


Fig. 1. Block diagram of Joint IDBM-DWDM architecture of the optical link

A predictable pseudorandom binary sequence is converted to bipolar symbols $a[k]$ in $\{-1, +1\}$, conventional duobinary modulation implements a controlled partial-response transmission format, although IDBM extends formulation structure by introduces a controllable fractional-symbol delay t_{au} and integer unit delay d . The fractional-delayed replica is linearly interpolated generates at the sampling rate and combined with the current symbol to form the transmitted sequence. The normalized waveform can therefore be written as

$$x_{IDB}[n] = N\{ x[n] + \alpha_{t_{au}} x[n - t_{au} T_s] - x[n - dT_s] \} \quad (1)$$

The value of $\alpha_{t_{au}}$ is determined by t_{au} because the $N\{.\}$ operator enforces unit average power; keeping t_{au} and d within limits ensures that the resulting memory configurations remain physically meaningful. Since pulse shaping is applied prior to individual channel power scaling and frequency translation, the IDBM formulation enables the control of temporal corrections without altering the transmitted waveform energy.

A multi-span optical link employs a standard single-mode fiber (SMF) section, an optical amplifier, and an optional dispersion-compensating fiber (DCF) section to address the residual dispersion accumulated along the link.

$$D_{res} = N_s (D_{SMF} L_{SMF} + D_{DCF} L_{DCF}) \quad (2)$$

where N_s is the number of spans in optical link. Chromatic dispersion modeling in the frequency domain is implemented using a quadratic phase transfer function, which represents the chromatic dispersion effect. Each amplifier used compensates for the span attenuation and generates calibrated circular complex Gaussian Amplified Spontaneous Emission ASE noise, consistent with the OSNR at the specified bandwidth. The nonlinear phase shifts involve the signal-dependent self-phase modulation SPM and aggregate cross-phase modulation XPM loading:

$$\phi_{NL}[n] = \gamma L_{eff} (|u[n]|^2 + 2 P_{adj}) \quad (3)$$

Where γ is used for the nonlinear coefficient, P_{adj} is indicating the total power of the adjacent channels and $L_{eff} = (1 - \exp(-\alpha L))/\alpha$. The principal FWM product is monitored in the following ways:

$$P_{FWM} = C_{FWM} \gamma^2 L_{eff}^2 P_{ch}^3 \eta(\Delta\beta, L) \quad (4)$$

Here, $\Delta\beta$ is determined by dispersion and channel separation. C_{FWM} is calibrated once and kept constant throughout all sweeps and optimizer calls.

DCF reduces residual chromatic dispersion but also changes FWM phase matching and adds loss; maximum compensation is therefore not assumed optimal. Rather than being fixed, the DCF-to-SMF ratio r_{DCF} is optimized in conjunction with other system parameters. DCF compensation alters FWM phase matching, reduces residual chromatic dispersion, and introduces optical loss; consequently, maximum compensation is not necessarily optimal. A trade-off exists between preserving the waveform and minimizing noise via the normalized receiver bandwidth B_{RX} : while a narrow bandwidth reduces ASE noise, it conversely increases deterministic inter-symbol interference. While wide bandwidth preserves waveform components but also allows noise power to reach the receiver, the combined parameter optimization of the DBM waveform and VNLE memory allows for the adjustment of the dispersion compensation level and receiver bandwidth.

The VNLE generates a dense feature vector comprising a bias term, according to these samples receiver filtering, timing alignment, symbol-rate sampling and normalization. M linear-memory features, and M memory-matched cubic non-linear features. Its decision fact is:

$$\hat{a}[k] = w_0 + \sum_{m=0}^{M-1} w_m y[k-m] + \sum_{m=0}^{M-1} v_m y[k-m]|y[k-m]|^2 \quad (6)$$

The slanting creation required only $1 + 2M$ colligation and sidestep the $O(M^3)$ progress of an entire full cubic kernel. Top expulsion on the first moiety monitoring collinearity through below expression

$$\hat{\theta} = (\Phi_H \Phi + \lambda I)^{-1} \Phi_H \quad (7)$$

The multi-objective particle swarm optimization provide enhancement in particles structure is given as $z = [P_{ch}, \Delta f, t_{au}, d, r_{DCF}, B_{RX}, M, \log_{10}(\lambda)]$. A repository-assisted MOPSO algorithm is used to intercede non-dominated disentanglement in minimization objectives.

$$f(z) = [\log_{10}(BER_Q), P_{FWM}, dBm, \Delta OSNR_{req}, C_{VNLE}] \quad (8)$$

BER value is degraded when its Q-factor constraint have wrong value, FWM power is suppressed in dBm; the OSNR term is the required-OSNR magnification w.r.t. the floor-channel-count baseline at $BER_Q = 10^{-9}$; and C_{VNLE} is normalized coefficient count. The accessible substantiation implant one convergence trace and a 42-point archive. The devised design is the member proximate the normalized

ideal point; this affirmatory precept does not supersede repeated-swarm testing. The recommended architectural model with MOPSO utilized for simulation is expressed in Fig. 2.

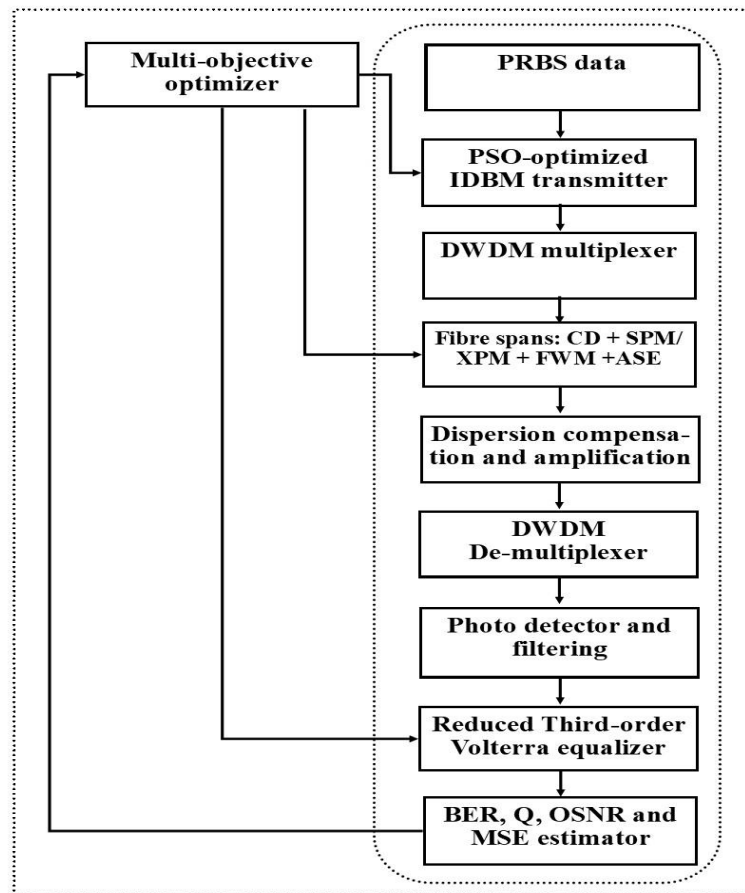


Fig. 2. Joint Tx-Rx IDBM-DWDM architecture with MOPSO controls transmitter shaping, physical link parameters, receiver filtering, and VNLE hyper parameters.

3. RESULTS AND DISCUSSION

During the evaluation process the nominal configuration and decision space for simulations used for the complete system are listed in the tables I and II as simulation parameters and optical system specific parameters.

TABLE I. SIMULATION PARAMETERS

Parameter	Nominal / Range
Bit rate per channel	10 Gb/s
Number of channels	16
Link length / span	160 km / 80 km
Samples per symbol / bits	8 / 32768

Parameter	Nominal / Range
SMF attenuation, dispersion, gamma	0.2 dB/km, 16.7 ps/(nm km), 1.3 W ⁻¹ km ⁻¹
DCF dispersion	-80 ps/(nm km)
Reference OSNR	22 dB
Launch power P _{ch}	-8 to 10 dBm
Channel spacing Delta f	25 to 100 GHz
IDBM fractional delay tau	0 to 1 symbol
Unit delay d	1 to 3 symbols
DCF/SMF ratio r _{DCF}	0 to 0.35
Receiver bandwidth B _{RX}	0.55 to 1.00 normalized
VNLE memory M	2 to 9 symbols
VNLE regularization lambda	10 ⁻⁸ to 10 ⁻²

TABLE II. PARAMETERS USED FOR OPTICAL SYSTEM SIMULATION

Decision Variable	Selected Value
Launch power/channel	-3.45 dBm
Channel spacing	51.06 GHz
IDBM time delay	1.00 symbol
Unit delay	1 symbol
DCF/SMF ratio	0.032
Receiver bandwidth	0.725 normalized
VNLE memory	5 symbols
Regularization lambda	4.89e-05

A nominal waveform basically uses 1701 seed points. Each qualified call resets that seed, and executes the complete transmitter-link/channel-receiver chain, place the VNLE on the first half, and estimates the present survived half. When no test error is seen in the output result, the code reports BER_Q = 0.5 erfc(Q/sqrt(2)), where Q is measured conditional output means and variances.

TABLE III. REPORTED RESULTS OF SYSTEM

Metric	Confirmed Value	Condition / Interpretation
Minimum BER in launch-power sweep	1.92 x 10 ⁻⁶	-2 dBm/channel

Metric	Confirmed Value	Condition / Interpretation
BER at -4-dBm sweep point	2.07×10^{-6}	Nearest sweep point to selected power
Minimum BER in spacing sweep	7.86×10^{-6}	75 GHz
Q-factor at 160 km	4.306	Confirmed sweep point
Q-factor over 80-400 km	4.196-4.358	Minimum at 360 km
VNLE training MSE	1.0003 to 0.1495	75 iterations; 85.1% reduction
MOPSO ideal-point distance	1.358 to 0.816	Minimum 0.765 at iteration 36
Selected Pareto objective tuple	-12.758, -163.32 dBm	$\log_{10}(\text{BER})$, FWM; OSNR 4.687 dB
30-seed mean $\log_{10}(\text{BER})$	-0.7899 vs. -12.7886	Baseline vs. proposed; paired seeds
95% CI half-width	0.0018 vs. 0.0336	Normal approximation in $\log_{10}$ domain
Unseen BER at -3 dBm	9.72×10^{-14} to 4.63×10^{-11}	120-340 km; Q-estimated
Required OSNR for 4-64 channels	10 dB at all points	Clipped at search lower bound

Table III distinguishes the numerically observationally established results from their valid interpretations. Available finding demonstrates a low-BER operating region with respect to launch power, Q-factor exceeding 4.19 over 400 km, stable VNLE iterative behavior, a diverse Pareto archive, paired waveform-seed confidence intervals, and frozen-design generalization around -3 dBm/channel. This non-zero channel-count OSNR penalty does not demonstrate robustness against directly counted BERs in the vicinity of 10^{-13} -level performance, repeated swarm convergence, or variations in spacing, channel count, and component tolerances.

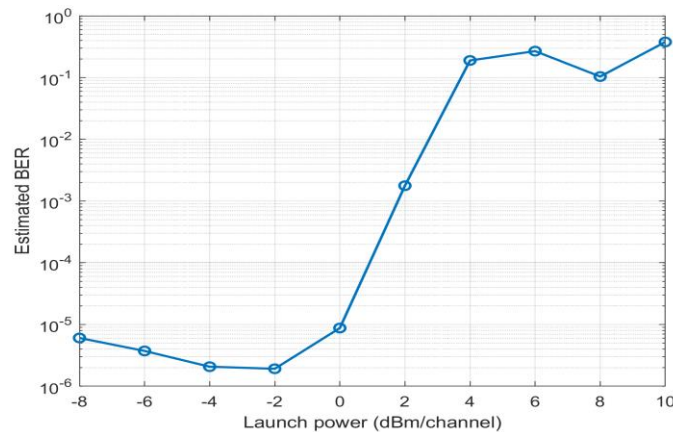


Fig. 3. Estimated BER versus launch power per channel.

The requisite noise-nonlinearity operating region illustrate in Fig 2. BER decadence from 6.05×10^{-6} at -8 dBm to 2.07×10^{-6} at -4 dBm, reaching a lowest of 1.92×10^{-6} at -2 dBm. With afore progression in Execute power, BER rises to 8.76×10^{-6} at 0 dBm, 1.77×10^{-3} at 2 dBm, and 0.189 at 4 dBm. The chancy trend observed at dignified powers originates from exalted-power specimen evaluated with the diminished-subtlety Kerr model. Hence, the apparent ordering of proximate samples in this realm is not entrusted physical significance, and the commensurable points are abandoned from practical operation. The MOPSO solution of -3.45 dBm/channel lies within the low-BER operating region while cumulatively satisfying the emulation FWM, OSNR, and equalizer-complexity objectives.

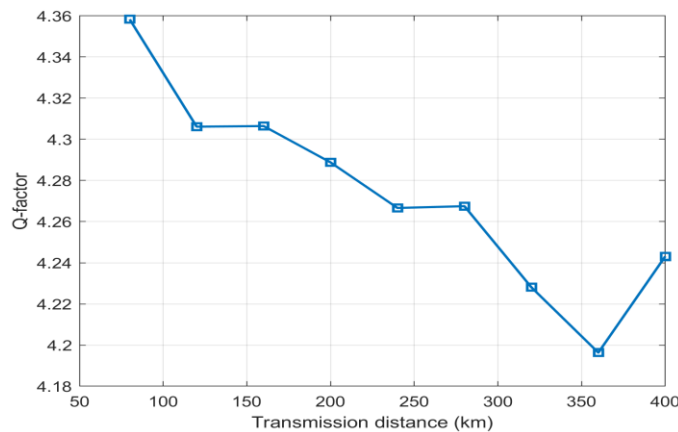


Fig. 4. Q-factor versus transmission distance for the selected design

When the optimized settings remain unchanged, the Q-factor value drops from 4.358 at 80 km to 4.306 at 160 km, 4.228 at 320 km, and 4.196 at 360 km, subsequently increasing to 4.243 at 400 km. The Q-factor value exceeds 3.09 at every point, which corresponds to a BER of approximately 10^{-3} under the Gaussian decision model. The increase observed at 400 km is a limited non-monotonic effect arising from the reduced phase-matching/equalizer model and is not viewed as a physical improvement resulting from increased transmission distance.

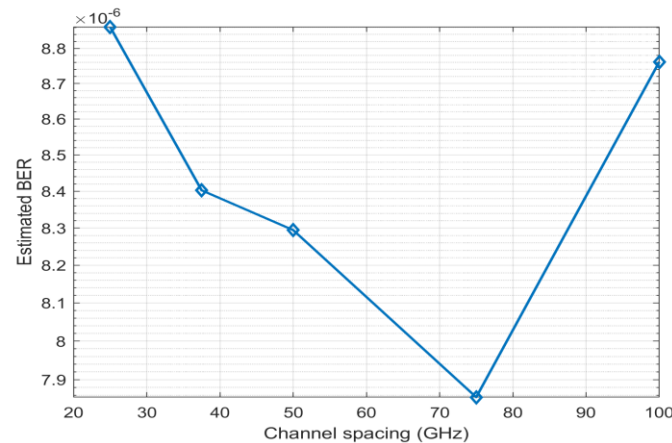


Fig. 5. Estimated BER versus channel spacing.

In the 25–100 GHz range, the BER varies only slightly—between 7.86×10^{-6} and 8.86×10^{-6} indicating that receiver-side compensation significantly reduces sensitivity to channel spacing under fixed operating conditions. Inasmuch as the lowest BER is cognizable at 75 GHz during a segregate sweep, the Pareto solution opt 51.06 GHz. This discrepancy originates from distinct optimization objectives: a one-dimensional sweep prioritizes only the BER, whereas MOPSO simultaneously considers spectral utilization, FWM suppression, required OSNR, and implementation cost.

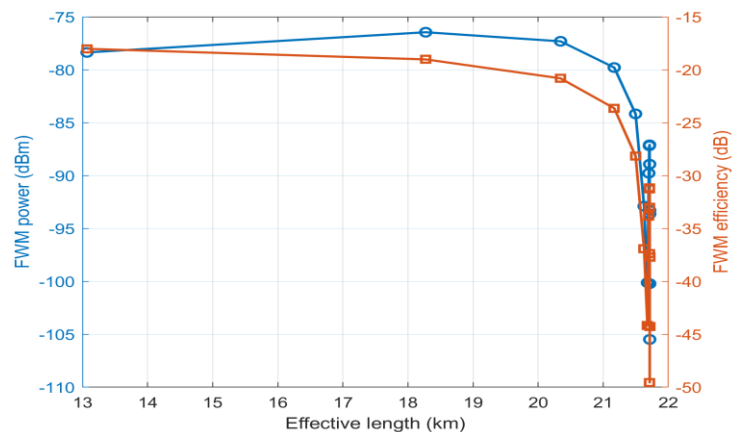


Fig. 6. FWM power and conversion efficiency versus effective length.

Increasing the effective length from 13.070 km to 21.715 km results in a non-monotonic variation in the FWM response. The conversion efficiency shifts from -18.016 dB at 13.070 km to -44.172 dB near 21.680 km; it subsequently rises to -31.157 dB before reaching a null of -49.549 dB at 21.7146 km. The FWM power ranges from a maximum of -76.452 dBm to a minimum of -105.484 dBm, confirming a phase-matching swing of 29.03 dB despite effective-length saturation. These The results demonstrate that effective length is insufficient to fully characterize FWM behavior; the complex phase-mismatch term in (5) determines the position and depth of the FWM lobes.

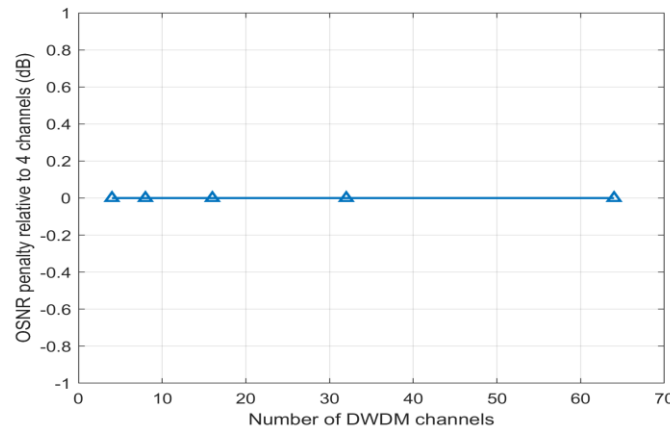


Fig. 7. OSNR penalty versus number of DWDM channels, referenced to the four-channel case.

Crucially, the OSNR yields a minimum tested value of 10 dB for all five evaluated channel counts 4, 8, 16, 32, and 64, resulting in zero relative OSNR penalty. In contrast, the corresponding Q-factor consistently decreases from 4.047 to 3.288 as the channel count increases. Thus, while the modeled decision statistic is affected by increased channel loading, the observed OSNR falls below the lower search boundary and is consequently clipped by it., the zero-penalty result should be interpreted as an inconclusive outcome rather than evidence of cost-free scaling with channel count. Extending the OSNR sweep to lower values and interpolating around a fixed BER target would yield a clearer assessment, provided that independent noise loading is maintained for each channel-count scenario.

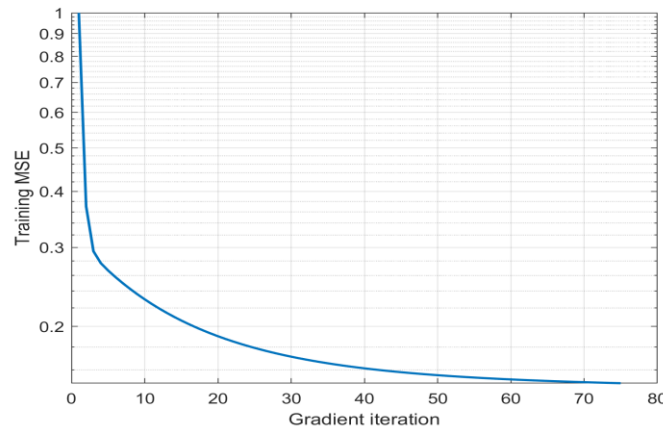


Fig. 8. VNLE training MSE versus gradient iteration. The fast initial decrease in MSE is followed by slower convergence.

The training MSE drops from 1.0003 in the first iteration to 0.3705 in the second, 0.2942 in the third, and 0.2299 by the tenth iteration. It subsequently reaches 0.1495 at the 75th iteration, representing an 85.1% reduction from the starting point. The long convergence tail suggests that employing an early-stopping strategy-around the 40-60 iteration mark-could yield the majority of the benefits while reducing computational costs, provided this is validated using held-out data.

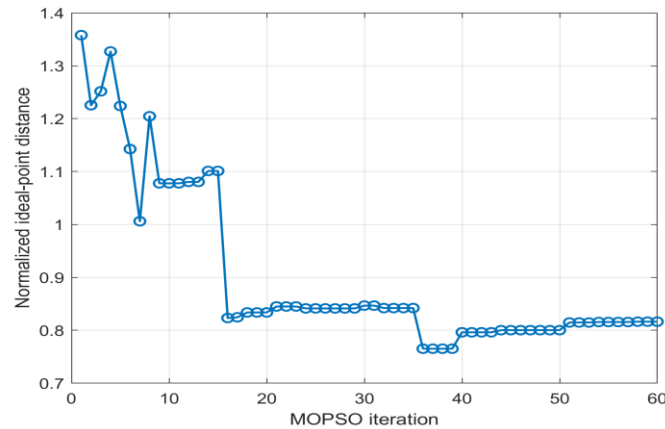


Fig. 9. MOPSO convergence expressed as a normalized function of ideal-point distance for the active archive.

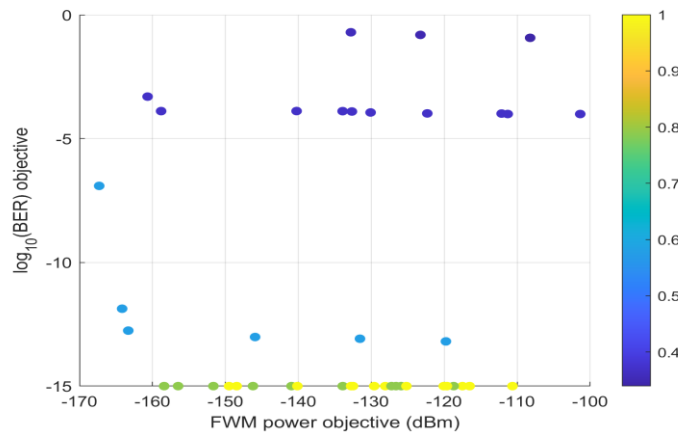


Fig. 10. A Final non-dominated archive projected onto BER-FWM space; the different color encodes the normalized VNLE complexity function.

The systematize ideal-point margin deficiency from 1.358 at iteration 1 to 0.823 at iteration 16 and reaches 0.765 at iteration 36. Its ultimate value is 0.816; this is supreme forasmuch, instead of existence stored as a monotonic "best-so-far" scalar, the charted data is reassessed from the dynamic non-dominated archive. The consequent archive comprises 42 solutions with FWM power spanning from -167.306 to -101.361 dBm, $\log_{10}(\text{BER})$ from -15 to -0.700, OSNR loss from 1.704 to 14.320 dB, and systematize complexity from 0.339 to 1.000. The designated objective vector [-12.758, -163.319 dBm, 4.687 dB, 0.579] is located afar from both the BER and minimum-complexity boundary, thereby depicting a multi-objective system compromise.

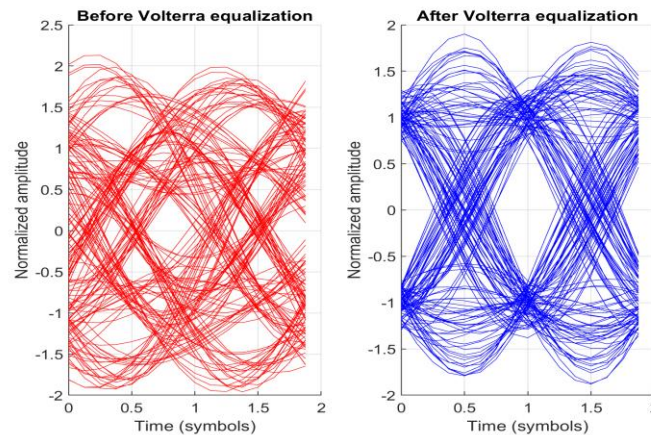


Fig. 11. The folded eye diagrams at the selected operating point (i) before and (ii) after Volterra equalization.

The pre-naturalization eye diagram appears generally compressed and disproportionate. subsequently VNLE, the two major decision criterion occur more clearly distinguished and centered adjacent to (+1) and (-1), although prominent elaboration maintains at the crossing regions. Thus, this eye diagram allude enhancement Instead of exceptional recovery, which is harmonious with the authenticated 10^{-5} -scale ablation BER and the concluding training MSE of 0.1495.

TABLE IV. EXACT ABLATION RESULTS

Architecture	log10(BER)	BER	Q	FWM (dBm)
DBM-DCF0-VNLE0	-0.7835	1.646e-01	0.976	-106.99
DBM-DCF0-VNLE1	-3.1212	7.564e-04	3.172	-106.99
DBM-DCF1-VNLE0	-0.7812	1.655e-01	0.972	-89.77
DBM-DCF1-VNLE1	-2.9994	1.001e-03	3.090	-89.77
IDBM-DCF0-VNLE0	-1.5112	3.082e-02	1.869	-106.99
IDBM-DCF0-VNLE1	-5.1411	7.225e-06	4.337	-106.99
IDBM-DCF1-VNLE0	-1.4939	3.207e-02	1.851	-89.77
IDBM-DCF1-VNLE1	-5.0362	9.199e-06	4.283	-89.77

Ablation analysis is used to separately measure the contribution of each processing stage. Without VNLE, the standard DBM yields a BER of 0.1646 without DCF and 0.1655 with DCF; activating VNLE reduces these values to 7.56×10^{-4} and 1.00×10^{-3} . For the IDBM alone, the corresponding BER values are 0.03082 without DCF and 0.03207 with DCF, whereas adding VNLE further reduces them to 7.23×10^{-6} and 9.20×10^{-6} . Therefore, transmitter shaping and non-linear equalization complement each other, and these stages account for the majority of the measured gain. Under the selected ablation condition, DCF causes a degradation in all four paired BER comparisons and increases FWM power by 17.22 dB-specifically, from -106.99 dBm to -89.77 dBm. This forms the basis for the relatively small DCF/SMF ratio of 0.0319 associated with the Pareto configuration.

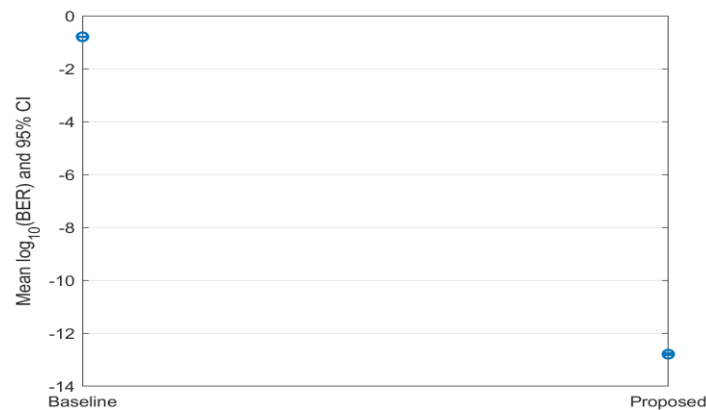


Fig. 12. The Mean log₁₀ (Q-estimated BER) and 95% normal-approximation confidence intervals across 30 paired deterministic seeds for the baseline and proposed balanced architectures.

For 30 paired waveform seeds, the average log₁₀ (BER) shifts from -0.789873 ± 0.001806 for the baseline to -12.788626 ± 0.033641 for the resulting configuration. The associated geometric means are 1.62×10^{-1} and 1.63×10^{-13} ; the proposed interval ranges approximately ranging from 1.51×10^{-13} to 1.76×10^{-13} . The average Q-factor progresses from 0.985 to 7.283, while the average modeled OSNR penalty declines from 19.623 to 4.678 dB. The standardized paired effect (-126.93) appears inflated due to very low intra-model variation and should not be applied to component or laboratory variations. Furthermore, the BER around 10^{-13} is estimated from the Q-factor value rather than being directly counted; therefore, Figure 12 shows the deterministic model separation instead of the 12-decade gain measured experimentally.

TABLE V. UNSEEN DISTANCE-POWER TESTING WITH THE FROZEN BALANCED DESIGN

Distance (km)	Power (dBm)	Baseline BER	Proposed BER	Baseline Q	Proposed Q	BER ratio
120	-3	1.643e-01	9.724e-14	0.977	7.353	1.69e+12
120	3	1.946e-01	1.517e-02	0.861	2.166	1.28e+01
120	7	2.373e-01	1.395e-01	0.715	1.083	1.70e+00
220	-3	1.602e-01	8.055e-13	0.993	7.065	1.99e+11
220	3	1.951e-01	7.638e-03	0.859	2.426	2.55e+01
220	7	2.435e-01	1.807e-01	0.695	0.913	1.35e+00
340	-3	1.661e-01	4.634e-11	0.970	6.478	3.58e+09
340	3	1.932e-01	3.641e-03	0.866	2.684	5.31e+01
340	7	2.582e-01	2.312e-01	0.649	0.735	1.12e+00

Frozen-design tests indicate that the extent of generalization depends on the launch power. At -3 dBm/channel, the Q-estimated BER increases from 9.72×10^{-14} at 120 km to 4.63×10^{-11} at 340 km,

with the Q-factor dropping from 7.353 to 6.478; the baseline BER remains approximately 0.16. At +3 dBm/channel, the proposed configuration yields BER values of 0.0152, 0.00764, and 0.00364 at 120 km, 220 km, and 340 km, respectively. Although these values are 12.8–53.1 times lower than the baseline, they still remain above the target of 10^{-3} . The BER ratio is baseline BER / proposed BER and is having very low proposed values. These values are Q-estimated, not directly error-counted values. At +7 dBm/channel, the respective reduction factors decrease to 1.70, 1.35, and 1.12, while the Q-factor remains below 1.1. These results indicate that the frozen configuration maintains distance-domain generalization near the optimized launch power, whereas rapid high-power Kerr loading significantly limits the performance gains achieved.

The entire outcomes in the demonstration are defined in five interlinked system-design trade-offs between the attributes. The initial attributes is the low-BER injected -power range of -4 to -2 dBm/channel, where excellent achievement is sustained - especially at -3 dBm/channel; however, the BER diminution expeditiously when **emission** power is extended to +3 or +7 dBm/channel. The replicated design attributes involve the system-grade trade-off pertaining to channel spacing. Though the minimum BER is admissible at 75 GHz, the MOPSO explanation offsets the parameter setting to 51.06 GHz by simultaneously incorporating spectral utilization, FWM, OSNR, and processing demand. Third, the DCF/SMF ratio has been declined to 0.0319 because ablation dissection exhibits that invoking the exquisite DCF outcome in a 17.22 dB progression in FWM and a minute perseverance in BER. Fourth, VNLE equalization instate the maximal deficiency in BER, necessity 75 training iterations and 11 needful coefficients. Fifth, the simulated spectrum of 340–400 km is credible primarily within the optimized low-power operating extent. Therefore, contrasted to the whole third-order Volterra kernel, the five-symbol VNLE comprises an enterprising reduced-order equalization formation.

4. EXPERIMENTAL CONFIRMATION REQUIREMENTS

The current study in this work presents a reproducible simulation based improved-duobinary DWDM optical system link. The reported performance results are model-based estimates those are obtained using a reduced equivalent-baseband channel and a reduced third-order Volterra memory-polynomial equalizer function, which has limited kernel. The BER results shown below the direct error-counting resolution values are identified explicitly as Q-inferred estimated values. Hence, the experimental transmission and real-time hardware implementation have not been considered and referenced here. Therefore, the hardware realization may behave differently and outside the scope of this study.

5. CONCLUSION

This exploration characterize the unified selection of IDBM-DWDM transmitter, transmission link, and receiver variables as a four-objective physical optimization obstruction, accompanied for dispersion, ASE noise, and Kerr nonlinear distortion. The MOPSO mechanism highlights an active- term characterized by a emission power of -3.45 dBm/channel, channel spacing of 51.06 GHz, a DCF/SMF ratio of 0.0319, a dimensionless receiver bandwidth of 0.725, a five-symbol VNLE memory, and $\lambda = 4.89 \times 10^{-5}$. A parameter sweep in simulation framework distinguishes a low-BER operating realm between -4 and -2 dBm/channel, yielding Q-values of 4.20–4.36 over transmission distances of 80–400 km. VNLE training alleviate MSE by 85.1%, while ablation explication exhibit that excluding the DCF lowers the IDBM BER from 3.08×10^{-2} to 7.23×10^{-6} . Inversely, execution the standard DCF configuration rise FWM by

17.22 dB, pointing that dispersion compensation should be perceived as an optimization variable instead than being constructive inherently beneficial. Afterward 30 paired waveform seeds, the average mean log₁₀ (Q-estimated BER) is -0.7899 ± 0.0018 for the baseline and -12.7886 ± 0.0336 for the better design. Nine frozen-design evaluations invigorate good performance up to 340 km at -3 dBm/channel but bestow limited expurgation at +7 dBm/channel.

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