Evaluation of Adaptive Against Fixed Modulation in Ring-Core Fibre OAM-Based SDM/WDM Transmission: A Benchmarking Perspective

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ABSTRACT

The exponential increase in data traffic has raised a high demand for ultra-high-capacity optical transmission networks. Orbital Angular Momentum-based Space and Wavelength Division Multiplexed (OAM-SDM/WDM) optical communication systems serve as a promising strategy for meeting this demand. However, these systems typically adopt fixed modulation formats and coding schemes. This limits their ability to exploit spatial-spectral signal-to-noise ratio (SNR) variations across channels. A study titled "High spectral-efficiency, ultra-low MIMO SDM transmission over a field-deployed multi-core OAM fibre" serves as the architectural benchmark for this study. The benchmark reference deployed a 7-core Ring-Core Fibber system adopting fixed 8-Quadrature Amplitude Modulation and an effective Forward Error Correction rate of approximately 0.83, achieving an aggregate spectral efficiency of 403.2 bits/s/Hz and a throughput of 201.6 Tb/s. This paper presents a systematic spectral efficiency (SE) benchmarking study comparing an adaptive modulation and coding (MODCOD) scheme against a fixed-modulation baseline. The adaptive framework dynamically assigns modulation orders from 8-QAM to 1024-QAM and Forward Error Correction (FEC) code rates from 0.60 to 0.95 per channel based on instantaneous SNR estimates, augmented by probabilistic amplitude shaping. Simulation results demonstrated a peak aggregate spectral efficiency of 550.8 bits/s/Hz per direction and a net bidirectional throughput of 528.8 Tb/s with a post-FEC bit error rate of 1×10^{-15}. The results confirm that per-channel adaptive modulation and coding improves spatial-spectral resource utilization in OAM-SDM/WDM systems without altering the physical fibre infrastructure.

KEYWORDS

Orbital angular momentum, space division multiplexing, wavelength division multiplexing, adaptive modulation and coding, spectral efficiency, throughput

I. INTRODUCTION

The rapid development of fibre optics communication systems is mainly due to an exponential increase in global data traffic as a result of the emergence of recent technologies such as cloud computing, high-definition video streaming, and other high-data demanding multimedia applications. By 2030, the data traffic demand is expected to force optical communication systems to operate in the Peta-bit-per-second transmission capacity domain [2]. Capacity enhancement in optical fibre is traditionally achieved by employing multiplexing techniques on single-mode fibre (SMF), including Time Division Multiplexing (TDM), Wavelength Division Multiplexing (WDM), and Frequency Division Multiplexing (FDM), often coupled with advanced coherent detection technology [3]. However, fundamental physics constrains the technological development of SMF systems due to the capacity crunch phenomenon. Theoretically, SMF systems reach their peak transmission capacity at about 100 Tbps/fibre [4] [5], arising from the nonlinear properties of silica optical fibres where increasing signal power to improve SNR results in nonlinear phase shift and distortion [6] [7]. Space Division Multiplexing (SDM) is considered a promising candidate technology proposed to overcome this capacity limit [3] [8] [9]. Within SDM, the integration of Orbital Angular Momentum (OAM) modes provides a specialized form of Mode Division Multiplexing (MDM). OAM modes comprise helical phase fronts characterized by topological charge l, and their effective refractive indices are separated from neighbouring modes to ensure propagation stability when guided in ring-core fibres (RCF) [10][11]. This propagation stability enables uncoupled channels, resulting in ultra-low complexity MIMO-based MDM transmission, which makes SDM highly promising for improved channel spectral efficiency (SE) and transmission capacity [12][13].

Most OAM-SDM/WDM systems reported in the literature adopt a fixed modulation format and code rate uniformly across all channels. Although this is operationally convenient, the channel conditions are not uniform across the whole link. Different spatial-spectral channels within a multicore RCF experience different SNR levels. This is due to the presence of residual crosstalk, nonlinear interference, and amplifier noise [14] [15]. Consequently, the fixed-scheme system cannot fully utilise channels with high SNR margins, or optimally protect those with poor link quality. To address this, there should be an adaptive modulation and coding (MODCOD) framework that can dynamically assign per-channel modulation order and FEC rate that its instantaneous SNR can support, maintaining the target post-FEC BER while maximising per-channel throughput [16].

This paper aims to examine the extent to which adaptive modulation and coding can improve the spectral efficiency and throughput of an OAM-SDM/WDM optical communication system when compared with a fixed-format reference architecture. The objectives of this work are as follows:

- Development of an adaptive MODCOD framework that selects the modulation order and FEC code rate of each spatial-spectral channel based on the estimated SNR condition.
- Evaluating the spectral efficiency and throughput of the proposed adaptive framework using the field-deployed 7-core RCF OAM-SDM/WDM system of Liu et al. [1] as the benchmark reference.
- Quantifying the SE and throughput gain obtained relative to the fixed-format benchmark.

The comparison is therefore not intended as a strict identical-distance replication of the benchmark experiment. Rather, it is a benchmark-referenced evaluation designed to show how adaptive per-channel MODCOD can improve spatial-spectral resource utilization under a longer simulated link condition while retaining the same 7-core RCF channel structure.

The remainder of this paper is organized as follows. Section II reviews related literature on SDM, OAM multiplexing, and adaptive modulation. Section III describes the system model and key equations. Section IV presents the benchmarking methodology and findings. Section V concludes the paper.

II. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

A. OAM-SDM/WDM Systems and Fixed Modulation

Research titled "High Spectral-Efficiency, Ultra-low MIMO SDM Transmission over a Field-deployed Multi-core OAM Fibber" [1] demonstrated an OAM-based SDM/WDM transmission over a field-deployed 7-core RCF, achieving high SE in a real field experiment. The system achieved a net throughput of 201.6 Tbsp. and aggregate SE of 403.2 bits/s/Hz, representing the highest reported SE for a field-deployed SDM fibre system at the time of publication. This high aggregate SE is realized through parallelization across 84 OAM modes, 40 WDM channels, with 7-core RCF, making a total of 3,360 logical channels per direction. The system utilized fixed 12-Gbaud 8-QAM modulation and evaluated the measured BER against a 20% soft-decision FEC threshold, corresponding to an effective FEC rate of approximately 0.83. While the research successfully demonstrated the potential of OAM-based SDM/WDM systems to achieve high data transmission capacity with low MIMO DSP complexity [17][18], the utilization of fixed modulation format and FEC code rate renders the system unable to account for the uneven SNR variation across the spatial-spectral channels, leaving per-channel bandwidth utilization sub-optimal.

Other notable fixed-modulation SDM demonstrations include [2], which demonstrated 1.01 Pbps SDM/WDM transmission but applied fixed PDM-64-QAM uniformly with rate selection performed offline, leaving a documented gap between achieved and GMI-estimated capacity. In the domain of probabilistic shaping, [19] combined PAS with per-channel rate variation but fixed the modulation order at PDM-1024-QAM and performed selection offline. To the best of the authors' knowledge, no prior work has directly benchmarked SE and throughput gains from closed-loop per-channel adaptive MODCOD against a fixed-format reference within the same OAM-SDM/WDM spatial architecture.

B. Adaptive Modulation and Coding in Optical Systems

The integration of adaptive modulation schemes in SDM/WDM systems under fluctuating channel conditions results in significant improvement in system SE [16] [20] [21]. This approach involves a dynamic evaluation of the individual channel quality through the SNR or other parameters such as Generalized Mutual Information (GMI). Based on this, the system will adjust the modulation formats and coding rates to maintain a target post-FEC BER [16]. To improve the raw BER and ensure the link integrity, adaptive FEC schemes, particularly soft-decision FEC utilizing Low Density Parity Check (LDPC) codes are employed [22][23]. The integration of Probabilistic Amplitude Shaping (PAS) optimizes the signal constellation to operate near the Shannon limit. This improves the achievable transmission capacity through offering a good matching between achievable rates and channel SNR variations in SDM fibres [19] [24] [25]. These principles form the basics of the adaptive framework developed in this study. The framework integrates per-channel SNR-based

MODCOD selection, LDPC-based FEC rate adaptation, and SNR-dependent PAS gain thereby maximizing spectral efficiency across 3360 spatial-spectral channels.

III. STUDIES AND METHODS

A. System Architecture

The adaptive system implements a hybrid SDM/WDM architecture using a 7-core Ring-Core Fibber (RCF), with each core supporting 6 OAM mode groups with dual polarization, giving 84 spatial streams [11][12]. Each spatial stream carries 40 DWDM wavelength channels equally spaced in the C-band at a symbol rate of 12 Gbaud, yielding 3,360 spatial-spectral channels per direction; identical to the benchmark spatial-spectral channel structure of [1]. The transmission link is 10 km, compared to the 5 km span in [1], to evaluate the adaptive framework under slightly more rigorous attenuation and noise conditions while maintaining the short-reach transmission regime. The receiver employs a 4x4 MIMO equalizer with TDE below 15 taps per mode group, consistent with [1] [17] [18], after which the FEC decoder produces the post-FEC BER estimate and the SNR estimate that drives the adaptive MODCOD selection cycle. The block diagram of the proposed bidirectional adaptive OAM-based SDM/WDM system is shown in Fig. 1.

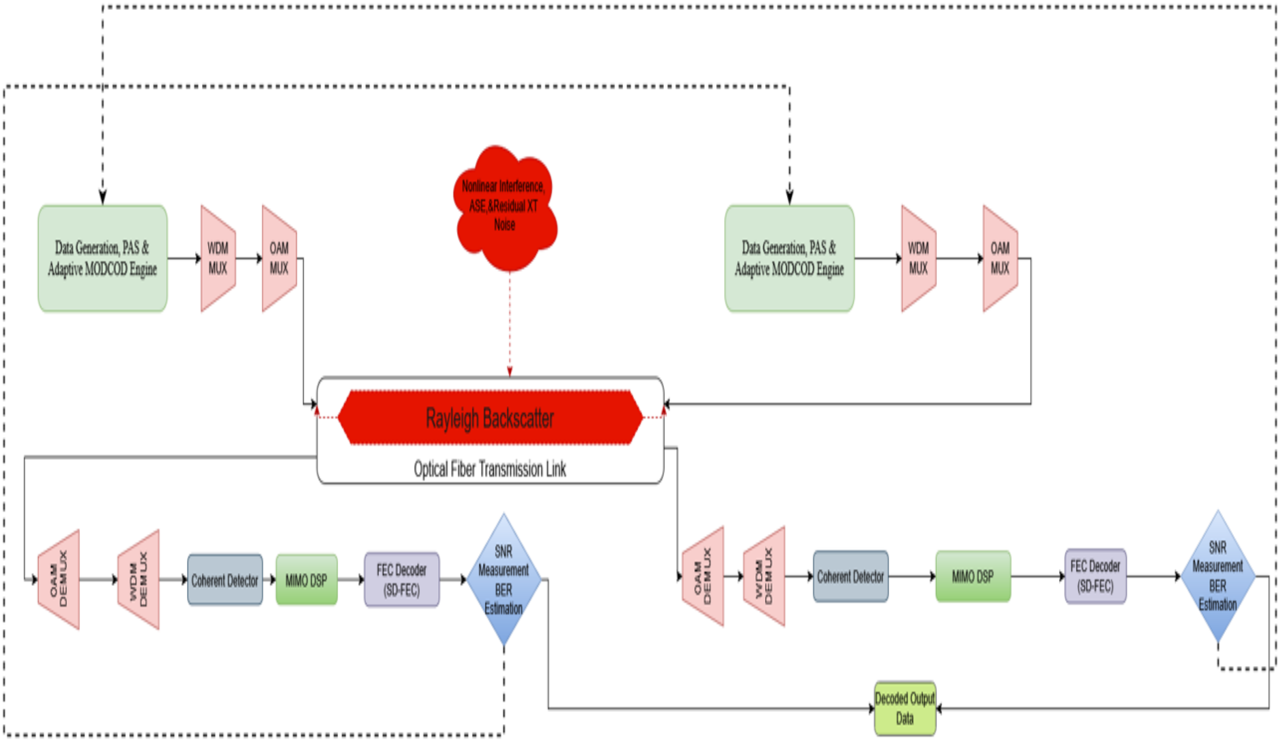

Figure. 1: Block Diagram of Bidirectional Adaptive OAM-Based SDM/WDM Optical Communication System

Table 1 summarises the key simulation parameters of both the proposed adaptive system and the benchmark system of [1].

Table 1. Key Simulation Parameters

Parameter	Adaptive System	Benchmark [1]
Fibber type	7-core RCF, 178 um cladding	7-core RCF, 178 um cladding
Fibber length	10 km	5 km
Spatial streams (Nsp)	84	84
WDM channels	40	40
Total channels per direction	3,360	3,360
Symbol rate per channel	12 Gbaud	12 Gbaud
Modulation format	Adaptive 8-QAM to 1024-QAM	Fixed 8-QAM
FEC code rate	Adaptive 0.60 to 0.95	Effective rate ~0.83
MIMO DSP	4x4, TDE < 15 taps	4x4, TDE < 15 taps
NLI coefficient (eta)	1x10^-26 W^-2	Physical measurement
RB penalty	1.5 dB (rho_RB = 0.412)	Measured experimentally
PAS gain (max)	0.35 bits/symbol	Not applied
Post-FEC BER target	1x10^-15	BER below 20% SD-FEC threshold

B. SNR Estimation Model

The effective electrical SNR for each channel k is estimated by accounting for four independent noise contributions [26] [27]. The total noise variance is:

$$\sigma_{tot,k}^2 = \sigma_{ASE,k}^2 + \sigma_{NLI,k}^2 + \sigma_{XT,k}^2 + \sigma_{RB,k}^2 \qquad (1)$$

where $\sigma_{(ASE,k)}^2$ is the ASE noise variance from EDFA amplification; $\sigma_{(NLI,k)}^2$ is the nonlinear interference variance modeled using the Gaussian Noise (GN) approximation [26][27] as $\sigma_{(NLI,k)}^2 = \eta \times P^3 ch,k$, with $\eta = 1\times10^{-26}$ W^{-2}; $\sigma_{(XT,k)}^2$; is the residual inter-modal crosstalk variance modeled as a Gaussian-distributed SNR perturbation with mean -18 dB [28][29]; and $\sigma_{(RB,k)}^2$ is the Rayleigh backscattering noise contribution derived from a 1.5 dB equivalent SNR penalty yielding $\rho RB = 0.412$ [30].
The effective SNR is then:

$$\gamma_k = \frac{P_{r,k}}{\sigma_{tot,k}^2} \qquad (2)$$

Where $P_{(r, k)}$ is the received power per channel.

C. Adaptive MODCOD Selection and SE Computation

The adaptive MODCOD algorithm dynamically assigns the optimal modulation order Mk and coding rate Rk for each channel k to maximize per-channel spectral efficiency subject to a pre-FEC BER constraint [16][20]. The system accepts a candidate MODCOD pair (Mk, Rk) if the pre FEC BER of the channel, BERpre, k , is equal to or below the decoding threshold Berth(Rk) derived from the LDPC coding gain curves [22][23]. When a candidates failed to satisfy this pre-FEC BER constraint, the algorithm falls back to the most robust configuration

(8-QAM with rate-0.60 FEC). This preserves link reliability. Below is the pseudo code used to implement the adaptive MODCOD selection?

```
OUTPUT: M_k, R_k, SE_shaped,k for each channel k
FOR each channel k = 1 to N_total DO
    best_SE  <- 0
    best_M   <- 8       // fallback modulation
    best_R   <- 0.60    // fallback code rate
    FOR each (M, R) in MODCOD_set DO
        Compute BER_pre(M, gamma_k) using M-QAM formula
        IF BER_pre(M, gamma_k) <= BER_thr(R) THEN
            SE_raw    <- R x log2(M)
            SE_shaped <- SE_raw + G_PAS(gamma_k)
            IF SE_shaped > best_SE THEN
                best_SE <- SE_shaped
                best_M  <- M
                best_R  <- R
            END IF
        END IF
    END FOR
    Assign M_k <- best_M
    Assign R_k <- best_R
    Assign SE_shaped,k <- best_SE
END FOR
Compute SE_avg  = (1/N_WDM) x SUM(SE_shaped,k)
Compute T_total = 2 x SE_avg x B x N_sp
```

The algorithm selects the pair yielding the highest shaped SE:

$$SE_{shaped,k} = SE_{raw,k} + G_{PAS}(\gamma_k) \qquad (3)$$

Where $G_{PAS}(\gamma_k)$ is an SNR-dependent shaping gain ranging from 0 to 0.35 bits/symbol [19] [24] [25]. The average aggregate SE per direction and the throughput are calculated as:

$$SE_{avg} = \frac{1}{N}\sum_{k=1}^{N} R_k log_2(M_k) \qquad (4)$$

The net throughput per channel is:

$$T_k = R_k log_2(M_k) B_{ch} \qquad (5)$$

The aggregate bidirectional throughput is calculated as:

$$T_{total} = \sum_{k=1}^{N} T_k \qquad (6)$$

Where N is the number of channels.

D. Benchmarking Methodology

The field-deployed OAM-SDM/WDM system reported by Liu et al. [1] was adopted as the benchmark reference for this study. This choice is appropriate because the reported system provides a well-documented fixed-format implementation based on a 7-core ring-core fibre architecture. These features make it a suitable reference point for assessing the benefit of introducing adaptive modulation and coding into a comparable OAM-SDM/WDM spatial-spectral structure.

The proposed system retained the same 7-core RCF channel structure, giving 84 spatial streams and 3360 spatial-spectral channels per transmission direction. The fixed benchmark configuration was also reproduced using fixed 12-Gbaud 8-QAM under the reported FEC condition, which yields an aggregate spectral efficiency of 403.2 bits/s/Hz. This confirmed that the reference model was consistent with the performance reported by Liu et al. [1].

It should be noted that while the benchmark experiment was demonstrated over a 5 km field-deployed link, the proposed adaptive framework was evaluated over a 10 km simulated link. Hence, this comparison is not treated as a strict distance-identical replication. It is a benchmark-referenced evaluation aimed at examining the spectral efficiency gain obtained when the fixed per-channel modulation strategy is replaced with SNR-driven adaptive MODCOD. In the fixed benchmark, each channel is limited to the spectral efficiency of 8-QAM under the reported FEC condition, while the adaptive framework allows channels with sufficient SNR to operate with higher-order modulation formats, up to 1024-QAM with a rate-0.95 FEC configuration.

IV. FINDINGS AND RESULTS

Two main metrics, aggregate spectral efficiency, expressed in bits/s/Hz and net bidirectional throughput, expressed in Tb/s, are used to compare the proposed adaptive system with the fixed-format benchmark. The results are presented using the simulated OSNR range, selected modulation formats, spectral efficiency values, and throughput values.

A. Selected Modulation Formats

The distribution of modulation formats across the spatial-spectral channels in the adaptive system for a launch power ranging from -4 dBm to +12 dBm per wavelength is shown in Fig. 2. At each launch-power point, the total number of spatial–spectral channels remain 3360, but the allocation among the different modulation formats varies with the estimated channel condition.

At the lower launch-power levels, most channels are assigned to the lower-order formats, particularly 8-QAM and 16-QAM. As the launch power increases, the share of channels using these lower-order formats gradually decreases, while 32-QAM, 64-QAM, and 128-QAM become more prominent. At the upper end of the launch-power range, a larger proportion of channels is assigned to 256-QAM and 1024-QAM, provided that the required pre-FEC BER condition is satisfied.

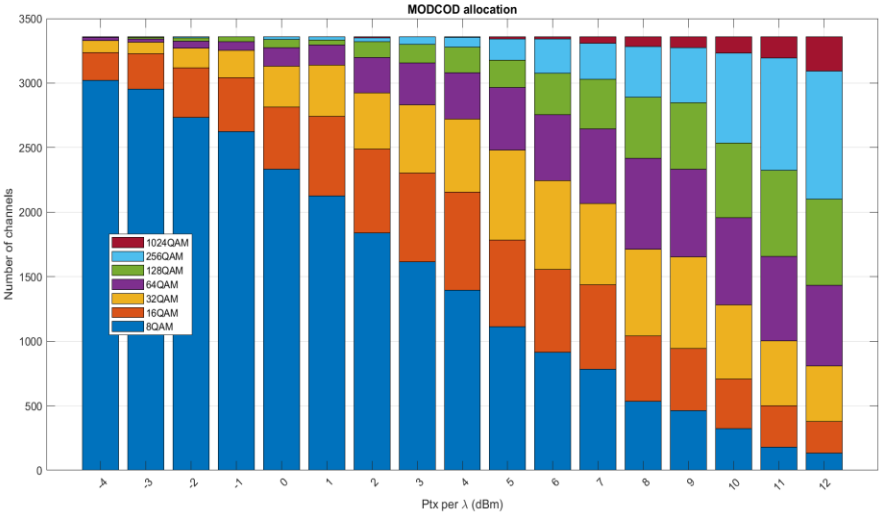

Figure. 2: Distribution of modulation formats selected across the simulated launch-power range

B. Spectral Efficiency Performance

The aggregate spectral efficiency of the proposed adaptive OAM-SDM/WDM system varied with the average OSNR and the selected modulation format. At lower OSNR range 23–28 dB, the adaptive algorithm selected mainly 8-QAM, 16-QAM, and 32-QAM. Within this OSNR range, the spectral efficiency was between 185 and 256 bits/s/Hz per direction. At an average OSNR range of 30–36 dB, the selected modulation formats adjusted to 64-QAM and 128-QAM. The corresponding spectral efficiency increased from approximately 304 to 403 bits/s/Hz per direction. This range also included the point where the adaptive system reached a spectral efficiency level comparable to the fixed-format benchmark value. At OSNR values above 37 dB, the algorithm selected higher-order modulation formats, mainly 256-QAM and 1024-QAM, for channels satisfying the required BER threshold. In this region, the spectral efficiency increased from approximately 452 to 550 bits/s/Hz per direction. The peak aggregate spectral efficiency recorded by the proposed adaptive system was 550.8 bits/s/Hz per direction, as shown in Fig. 3.

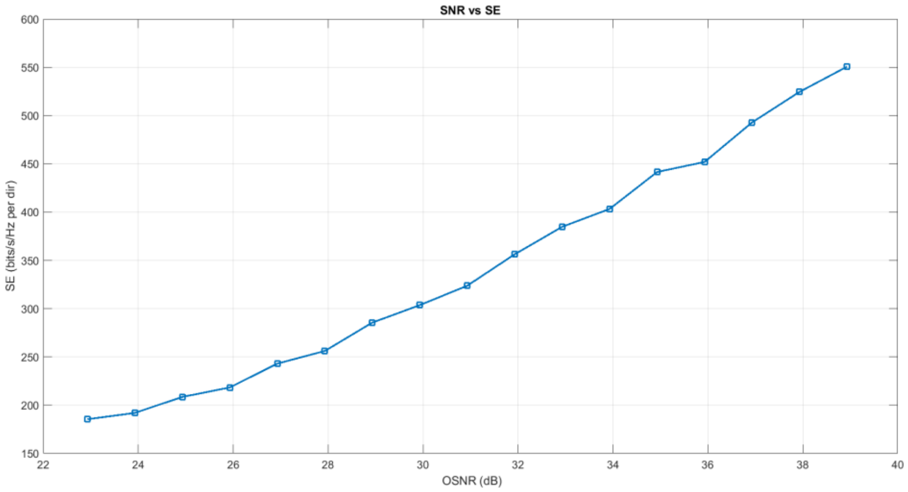

Figure. 3: Spectral Efficiency and the OSNR Trend

C. Throughput Performance

The net bidirectional throughput was computed from the aggregate spectral efficiency and the transmission bandwidth used in the simulation. The trend shows an increase in the throughput with an increase in OSNR across the simulated operating range. At the lower OSNR range of 23–30 dB, the net bidirectional throughput was between 180 and 291 Tb/s. At higher OSNR values, the selection of higher-order modulation formats resulted to higher throughput values. The throughput increased to approximately 504 Tb/s when the OSNR exceeded 38 dB and reached a peak value of 528.8 Tb/s at an average OSNR of 38.9 dB, as shown in Fig. 4.

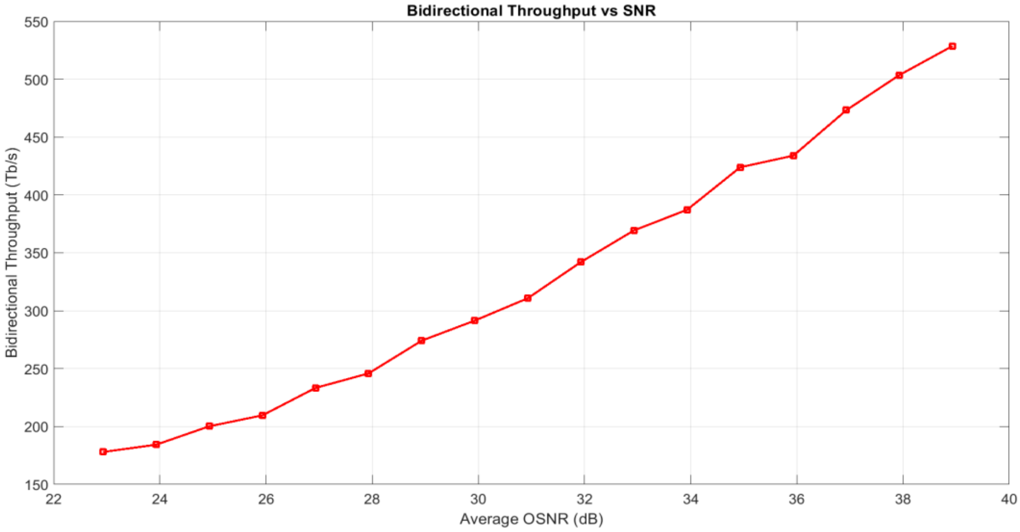

Figure. 4: Bidirectional Throughput and OSNR Trend

D. SE and Throughput Benchmarking Summary

The comparison of SE and throughput between the benchmark system [1] and the proposed adaptive system is presented in table 2. While the benchmark system exhibits a uniform per channel SE of 2.4 bits/s/Hz, the adaptive system achieves an average SE of approximately 6.5 bits/s/Hz per channel. This corresponds to a factor of 2.7 improvement at the per-channel level.

Table 2. SE and Throughput Benchmarking Results

Metric	Benchmark [1]	Adaptive System	Gain
Modulation format	Fixed 8-QAM	Adaptive 8-1024-QAM	--
FEC code rate	Effective rate ~0.83	Adaptive 0.60-0.95	--
Per-channel SE	2.4 bits/s/Hz	Up to 9.5 bits/s/Hz	Up to 4x
Aggregate SE	403.2 bits/s/Hz bidirectional	550.8 bits/s/Hz Per direction	Different directional basis
Net bidirectional throughput	201.6 Tb/s	528.8 Tb/s	+2.62x
Total spatial-spectral channels	3,360	3,360	Identical

V. DISCUSSION

The adaptive framework achieved a peak aggregate SE of 550.8 bits/s/Hz per direction and a net bidirectional throughput of 528.8 Tb/s. The improvement is mainly due to per-channel MODCOD selection, which allows high-SNR channels to support higher-order modulation while lower-SNR channels retain more robust configurations. This suggests that the fixed 8-QAM configuration used in the benchmark leaves part of the available channel capacity unexploited, particularly in channels with higher SNR margins. The improvements in SE and throughput confirm that the per-channel adaptive MODCOD is an effective and infrastructure-efficient strategy for improving spectral utilization in OAM-SDM/WDM systems. This demonstrates the potential of per-channel adaptive MODCOD as an efficient capacity-enhancement strategy for OAM-SDM/WDM transmission. However, the result should be interpreted with the comparison basis in mind: the benchmark system was demonstrated over a 5-km field-deployed link, whereas the proposed adaptive framework was evaluated over a 10-km simulated link. The comparison is therefore best understood as a benchmark-referenced evaluation rather than a strict identical-distance replication.

VI. CONCLUSION

This paper has presented a focused spectral efficiency and throughput benchmarking study comparing an adaptive MODCOD OAM-SDM/WDM system against the field-deployed fixed-format reference of Liu et al. [1]. The proposed adaptive system, operating over a 7-core ring-core fibre with 3,360 spatial-spectral channels per direction, achieved a peak aggregate SE of 550.8 bits/s/Hz per direction and a net bidirectional throughput of 528.8 Tb/s. Compared with the benchmark throughput of 201.6 Tb/s, this corresponds to a 2.62× throughput improvement under the benchmark-referenced simulation framework.

The results confirm that spatial-spectral heterogeneity in OAM-SDM architectures represents an under-exploited resource when fixed modulation formats are employed. The adaptive framework dynamically assigns modulation orders up to 1024-QAM where channel conditions permit, approaching the achievable information-theoretic bound more efficiently while maintaining a consistent post-FEC BER of 1×10^{-15} across all channels. Future work should focus on hardware implementation and DSP-level validation using real-time coherent receivers, and on the integration of machine learning-based adaptive control to enable real-time predictions toward highly efficient Tbps-to-Pbps optical transmission networks [31] [32].

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