On Optical Add/Drop Multiplexing Architecture for Hyperscale Backbone Networks

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Abstract: *We analyze Optical Add/Drop Multiplexing architecture trade-offs for Cloud Content Providers focusing on G-SNR, operations, reliability, and cost/power. We show that as coherent baud-rates increase, directly attaching transponders to the WSS satisfies all key metrics.*
Keywords: *Optical Add/Drop Multiplexing, coherent pluggable, backbone networks, cloud content providers.*

I. INTRODUCTION

The proliferation of cloud computing and distributed artificial intelligence workloads has catalyzed an unprecedented growth in global IP traffic. Cloud Content Providers (CCPs) are racing to accommodate these data flows on three fronts: by building more fiber infrastructure between data-centers or inter-regions, on-boarding the L-Band in Dense Wavelength Division Multiplexing (DWDM) line systems, and consuming low-power interoperable coherent pluggables (ZR/ZR+, [1]); while adhering to the following stringent design principles: 1) diversity by using multiple geographically diverse paths to provide physical redundancy for connectivity, 2) minimal failure impact with fast and automatic physical protection and reroute via traffic engineering, 3) securing connections based on hardware encryption at wire speed, and 4) automation to deal with the immense scale and to accelerate repair times. The advancements in both packaging and manufacturing at the transistor level, enabled Original Equipment Manufacturers (OEMs) to provide higher-baud rate coherent pluggables. In Fig. 1, we explore the relationship between the number of ports, i.e., wavelengths, required in the muxing and demuxing structures of OADMs versus the ZR generation when fully filling the C-Band spectrum. It is worth noting that for all these generations, the total capacity is 25.6Tbps per Fiber Pair (FP) for one span in the case of ZR [1] as OEMs are focusing on optimizing for the power to fit into the strict power envelope rather than on spectral efficiency. In this paper, we compare two Optical Add/Drop Multiplexing (OADM) architectures, shown in Fig. 2, based on WSS available from OEMs (up to 16 ports in this case to accommodate 1600ZR). Additionally, we discuss the impact on the end-to-end G-SNR for a standardized channel plan to operate a backbone at scale.

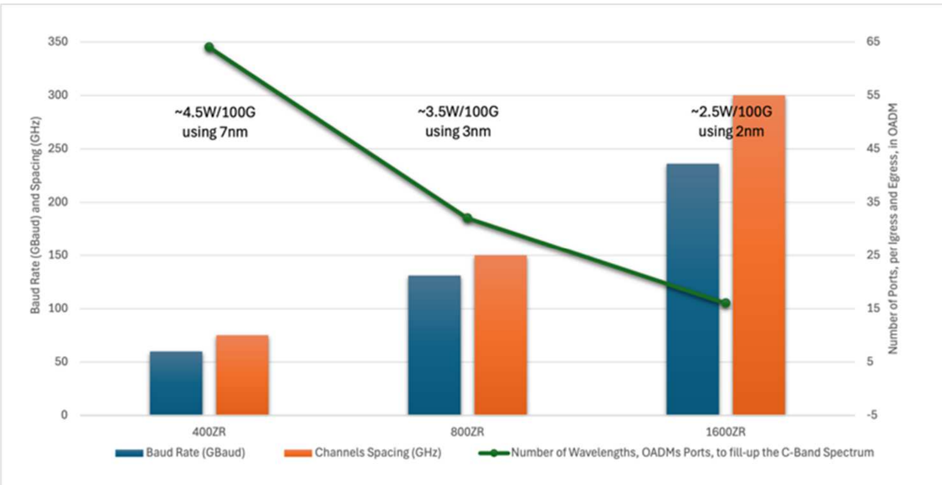

Fig. 1. Evolution of low-power pluggable coherent modems and its impact on the number of wavelengths at add/drop.

While Colorless-Directionless-Contentionless (CDC) add/drop architectures offer full software-driven reconfigurability via multicast switches (MCS) or M×N WSS fabrics, they impose significant penalties in power consumption, footprint, and upfront capital cost due to the mandatory switch-fabric electronics, Fiber Interconnect Modules (FIM), and dedicated internal Erbium Doped Fiber Amplifier (EDFA) stages [2, 3]. For CCP backbone networks operating predominantly on point-to-point linear topologies with predictable, static traffic patterns, the operational flexibility of CDC is largely unnecessary. This motivates our focus on CDA and TDA as practical, cost-effective architectures optimized for hyperscale deployments where power efficiency, reliability, and scalability are paramount. In

Section II, we will present the configurations of interest. Then Section III will present quantitative results based on simulation, and Section IV will conclude the paper.

II. CONFIGURATIONS OF INTEREST

The choice of add/drop architecture directly dictates the physical link budget, component reliability, and the Total Cost of Ownership (TCO). Network operators are currently faced with a critical design trade-off between maximizing optical performance and spectral efficiency and minimizing Capital/Operational Expenditures (CAPEX/OPEX), power consumption, and operational complexity. When using WSS for power balancing and branching/express functionality, if applicable, there are two options: 1) Colorless Direct Attached (CDA), where transponders are aggregated using a colorless module, and amplified to compensate for the high insertion loss of the combiner/splitter, then connected to the WSS; 2) Transponder Direct Attached (TDA), where the transponder is plugged into the WSS port directly. CDA and TDA end-to-end block diagrams are shown in Fig. 2 and 3, respectively. In TDA, the network treats each transponder as a fixed media channel (MC) that traverses the network independently. This simplifies Network Media Channel (NMC) management and overall channel planning, as each path is isolated, but limits flexibility in channel spacing, constraining it to a fixed grid (even if the line WSS is flex-grid). In contrast, CDA enables dynamic pooling of MCs. This aggregation impacts the NMC by introducing shared infrastructure (e.g., amplifier noise, Colorless Mux Combiner (CMC) and egress of Colorless DeMux Splitter (CDS) losses in blocks 1 and 4 in Fig. 2). At the same time, CDA allows for better utilization of available line GSNR to granularly optimize channel spacings and avoid WSS's guard-bands, i.e., potentially increasing capacity as is the case in subsea cables. However, this also introduces an impact on the end-to-end GSNR due to noise funnelling and linear cross-connect between transponders. This complicates the operational aspect of using CDA at scale when aiming to optimize channel plans per link.

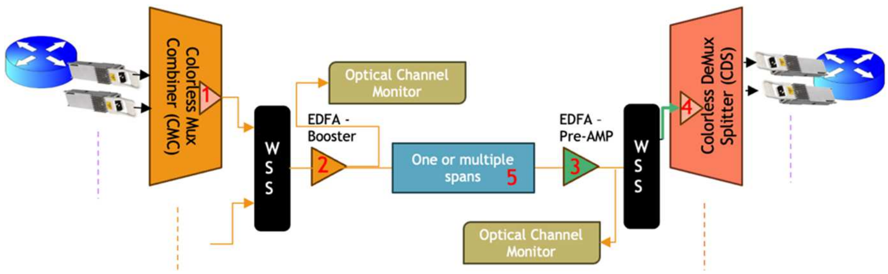

Fig. 2. The structure of CDA configuration

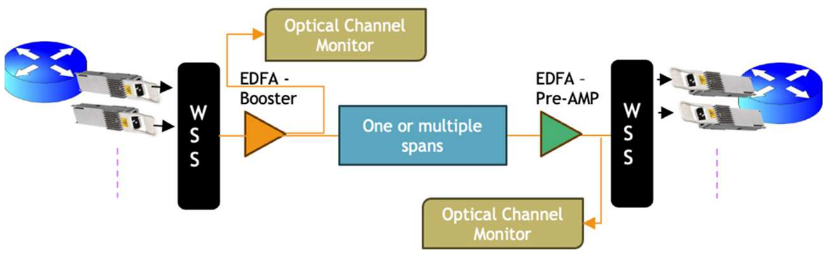

Fig. 3. The structure of TDA configuration, bypassing CMC and CDS

From an optical power budget perspective, the CDA architecture introduces a splitter/combiner loss of approximately $10 \cdot \log_{10}(N) + L\_excess$ (dB) at the CMC and CDS stages, where N is the fan-out and L_excess accounts for non-ideal coupling (typically 0.5–1.5 dB). For a 1×8 fan-out, this yields approximately 10.5–11 dB of additional insertion loss that must be compensated by dedicated EDFA stages in blocks 1 and 4, adding amplified spontaneous emission (ASE) noise to the signal path. In contrast, TDA bypasses these passive aggregation stages entirely, incurring only the WSS insertion loss (typically 5–7 dB), thereby preserving a cleaner signal path with fewer noise contributors and enabling a direct G-SNR advantage that scales with the number of cascaded spans.

It is worth noting that, compared to passive channel mux/demux (CMD)-based ROADMs, both TDA and CDA offer the capability to introduce ASE noise loading when partially filling an optical line system (OLS). ASE noise loading is indispensable for securing both immediate channel stability and long-term performance predictability. When a link is under-filled on Day 1, injecting dummy ASE noise into the unpopulated spectrum ensures that EDFAs operate at their nominal, fully saturated design target for total output power. This constant-power operation locks the amplifier's inversion level, effectively neutralizing dynamic gain tilt, spectral ripple variations, and transient power surges that would otherwise jeopardize active traffic during channel upgrades. Furthermore, by forcing the line system to maintain its exact end-of-life (EOL) operating conditions, noise loading provides a reliable physical proxy for the system's eventual nonlinear and noise environments; this allows engineers to precisely verify baseline SNR and OSNR margins under true operational constraints long before the transponder footprint is fully populated. However, if the traffic demand is high where a fiber pair is always filled on Day 1, it is worth investigating passive-CMD-based OADMs.

III. Simulations and Discussions

Assuming a point-to-point linear topology, we simulated the following three cases: 1) Full-fill of 12 wavelengths per CMC in CDA, 2) Reducing the number of wavelengths at the ingress of each CMC and egress of CDS, i.e., 2/3 full-fill compared to case 1, and 3) TDA. We modelled two line systems with single-span and 6-span configurations, deploying Non-Dispersion Shifted Fiber (NDSF) with an effective area of 80 μm² and dispersion of 17 ps/nm/km, and each span is 80 km long with a loss coefficient of 0.2 dB/km. In Fig. 4, it is shown that the OADM configuration has a major impact on GSNR. Comparing "CDA – Full-fill" to "TDA", the improvement in GSNR can be used to increase capacity by more than 2 Tb/s in the case of "6xSpans" or as end-of-life (EoL) margin to account for line/modem ageing. As the line system lengthens, noise accumulation from inline amplifiers becomes increasingly dominant, reducing the impact of the OADM configuration. "CDA – 2/3 Full" helps in improving GSNR due to less funnelling and better SNR at the output of the CMC. Beyond the GSNR advantage, on the photonics side per FP, without the traffic modules, TDA offers reductions on three fronts: 25% in cost, 15% in power, and 1 rack unit per shelf. In terms of availability, the fewer optical components cascaded (such as the amplifiers in blocks 1 and 4), the fewer failures in the line. TDA has a better overall system availability with both the amplifiers in CMC and CDS removed. Furthermore, as CCPs' backbone networks expand and the addition of L-Band ramps up, having a defined channel plan will control the scope of link budgeting parameters (nonlinearity due to cross-phase modulation and stimulated Raman scattering), ease the operational aspects of both deployment and troubleshooting. It is worth noting that CDA will allow for a smaller WSS radix, potentially as low as 2×1 in a point-to-point topology, which will help recover the savings in cost, power, and space.

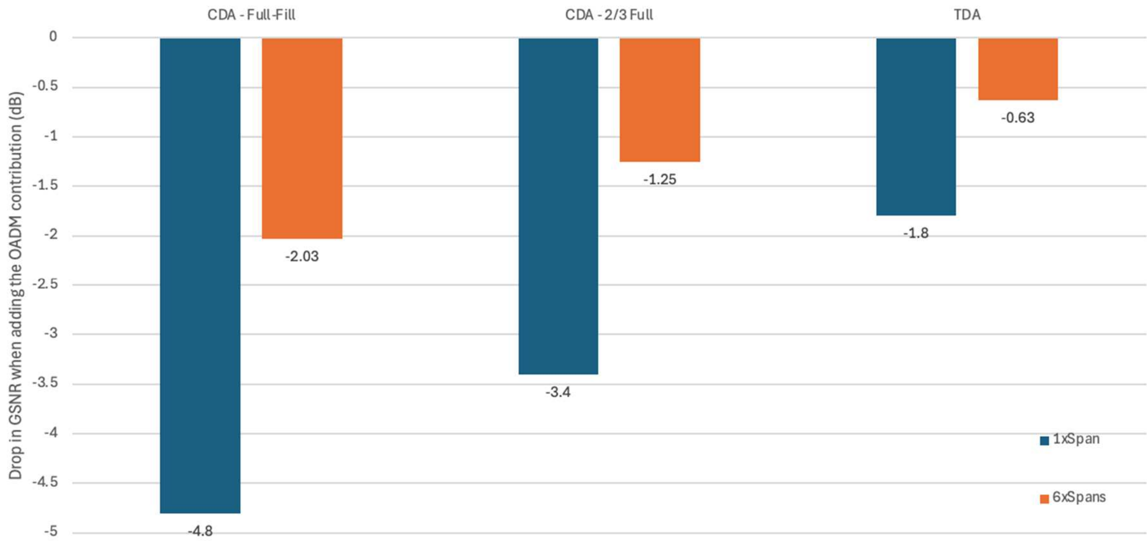

Fig. 4. End-to-end G-SNR comparison showing the drop, in dB, due to various OADM configurations using two links

IV. Conclusion

We discussed the trade-offs between two OADM configurations to provide practical guidance for network architects. We demonstrated that when aiming to standardize the channel plan and automate the provisioning of wavelengths in CCPs' hyperscale backbones, TDA provides many advantages across power, space, and availability while still offering more than 4 Tb/s of additional capacity in a C&L-Band system compared to CDA for a fixed channel plan.

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