# A Digital Twin-Driven Framework for Cost-Effective Upgrading from C-Band to Multi-Band Optical Networks


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## ABSTRACT

The transition from C-band to ultra-wideband (C+L+S-band) optical networks is essential to meet escalating traffic demands but poses significant technical and economic challenges. This paper presents a digital twin (DT)-driven framework to evaluate and guide Pay-as-You-Grow (PaYG) migration strategies, enabling flexible and low-risk spectrum expansion. The proposed optical network digital twin (ONDT) accurately models inter-channel stimulated Raman scattering (ISRS), generalized signal-to-noise ratio (GSNR), and dynamic service reconfiguration to assess upgrade impacts in a virtual environment. We evaluate five PaYG strategies on the USB14 ultra-long-haul network using 64 GBaud transceivers and 20 THz total spectrum. Simulation results show that the most aggressive approach, PaYG-WAR (with all reconfigurations), achieves up to 17% higher throughput and 70% lower CAPEX per 100 Gbps of traffic compared to conservative strategies, while minimizing hardware upgrades. The ONDT-guided approach ensures cost-effective, scalable, and non-disruptive multi-band migration, making it a robust tool for future optical backbone evolution.



**Keywords:** Multi-band; Digital Twin; Techno-economic, What-if Analysis, Network Upgrading.


## 1. INTRODUCTION

As the demand for bandwidth continues to grow, expanding the optical spectrum beyond the conventional C-band (4.8 THz) to multi-band configurations like C+L (12 THz) or C+L+S (20 THz) becomes essential [1, 2]. Operators typically choose between two migration strategies: full “Day-One” deployment or the more flexible “Pay-as-You-Grow” (PaYG) approach, which incrementally adds bands based on traffic growth [3, 4]. While PaYG improves scalability and cost efficiency, it also introduces operational complexity and risk—particularly service disruption due to inter-band nonlinearities such as Inter-Channel Stimulated Raman Scattering (ISRS), which can destabilize existing C-band traffic during upgrades. To mitigate these risks, Optical Network Digital Twins (ONDTs) have emerged as a promising approach for evaluating ”what-if” scenarios [5]. A synchronized digital replica of the physical network allows for realistic modeling of impairments, service behavior, and migration scenarios without impacting live operations. Operators can virtually evaluate migration plans—including amplifier settings, traffic rerouting, and power optimization—and safely apply validated configurations to the live network [6]. Several studies have analyzed multi-band evolution strategies, comparing C+L versus multi-fiber upgrades, or proposing GSNR-aware planning models that consider ISRS effects [3, 7–9]. Incremental strategies, including partial and progressive provisioning, have been explored to reduce CAPEX while maintaining service continuity [3, 7]. Meanwhile, ONDT research has demonstrated applications in network monitoring, fault prediction, and QoT-aware provisioning using realistic Reconfigurable Optical Add-Drop Multiplexer (ROADM) and Erbium-Doped Fiber Amplifier (EDFA) models [5]. Despite these advancements, the use of ONDTs for evaluating “what-if” multi-band migration scenarios remains underexplored. This paper addresses that gap by proposing a digital twin-driven PaYG methodology for upgrading optical networks from the C-band to the C+L-band, and subsequently to the C+L+S-band. The method includes a techno-economic analysis and a reprovisioning mechanism to ensure cost-effective, QoT-compliant, and non-disruptive network evolution.

## 2. Enabling “what-if” Planning with ONDT: Architecture and Capabilities

The Optical Network Digital Twin (ONDT) is an ideal platform to conduct “what-if” scenario simulations in preparation for multi-band spectrum upgrades, such as migration from C-band to C+L or C+L+S band systems. This capability is vital for operators seeking to scale capacity while minimizing risk, cost, and service disruption. The proposed ONDT architecture introduces a comprehensive, multi-layered framework designed to mirror, monitor, and intelligently control optical communication networks in near real-time. This architecture facilitates a shift toward autonomous and predictive network operation by integrating physical-layer telemetry, analytical modeling, and AI-driven decision-making. The ONDT is composed of five logical layers.

The Data Collection Layer interfaces directly with optical network elements (e.g., ROADMs, EDFAs, transponders) and monitoring systems (e.g., OTDR, OSNR probes) using telemetry protocols such as gNMI, Netconf, and SNMP, collecting critical KPIs including OSNR, BER, CD/PMD, power levels, and latency. These data serve as the empirical foundation for the Digital Twin Core Layer, which replicates both the topology and physical-layer behaviors of the network. It includes modules for path computation (e.g., using EGN or GNPy), amplifier and span modeling, and service-to-lightpath mapping. The AI and Analytics Layer (it is not addressed in this work) provides intelligent insights through anomaly detection, predictive maintenance, reconfiguration for routing and resource optimization, and cost/energy-aware upgrade scenario evaluation. Notably, this layer also enables what-if scenario simulation, allowing operators to safely evaluate the impact of adding new traffic demands, migrating to multi-band systems (e.g., C to C+L or C+L+S), or reconfiguring amplifier settings, without disrupting live services. The Visualization and Control Layer supports interactive exploration of these scenarios through real-time dashboards and simulation panels, while integration with SDN controllers allows automated or semi-automated implementation of validated strategies. Lastly, the Integration and Orchestration Layer ensures interoperability with OSS/BSS systems, cloud platforms, and external applications via northbound APIs, making the ONDT a scalable and extensible solution. By embedding what-if analysis as a core capability, this architecture empowers telecom operators to optimize migration strategies, mitigate risks associated with ISRS and other nonlinear effects, and adopt data-driven decisions with minimal disruption to existing services. The integration of cloud and edge computing within the ONDT architecture, particularly at the orchestration and integration layer, plays a pivotal role in enabling scalability, real-time analytics, and distributed intelligence.

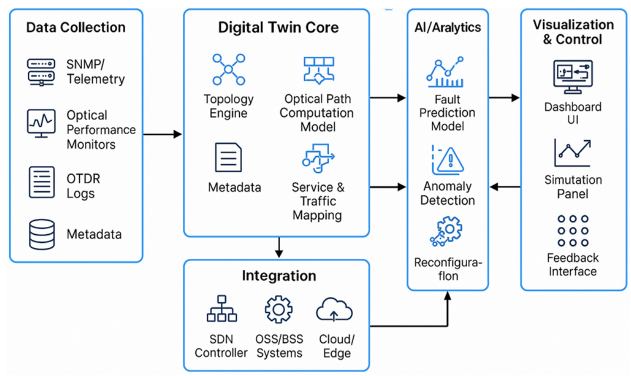


Fig. 1: Block diagram of the proposed ONDT.

## 3. Methodology and Algorithms

Fig. 2 illustrates the flow of the proposed digital twin-enabled “what-if” migration scenario analysis. The algorithm begins by analyzing the legacy network topology, fiber parameters, and infrastructure elements such as ROADM-on-Blade (RoB), multicast switches (MCS), inline amplifiers (ILA), and line card interfaces (LCI). For each source-destination pair, it selects the three shortest paths and precomputes per-span GSNR and optimal launch powers for C-, C+L-, and C+L+S-band scenarios using the fiber resource planning (FRP) algorithm proposed in [10]. These span-level GSNRs are aggregated to compute end-to-end GSNRs, which are used to determine the modulation format and bit rate per channel without relying on fixed transmission distances. Once pre-processing is complete, the algorithm attempts to serve demands using spectrum resources in the C-band, prioritizing grooming and first-fit spectrum assignment. If C-band resources are insufficient, links are selected for upgrade based on their current occupancy and physical length, and then re-evaluated in the digital twin. This “migration plan” undergoes feasibility checks through recalculation of GSNRs and channel capacities. Lightpaths exceeding updated thresholds are reconfigured by reassigning channels or grooming residual capacity. If the new configuration meets all capacity and GSNR constraints, the demand is accepted and the upgrade is finalized. Otherwise, the algorithm attempts to reconfigure other links in the candidate paths. This iterative process continues until the blocking ratio ($B_{\mathrm{R}}$) drops below the predefined threshold ($B_{/textthr}$). Throughout, lightpaths are confined to their assigned frequency bands (C, L, or S), avoiding any mid-route band-switching and preserving seamless transmission via matching amplifiers and switches.

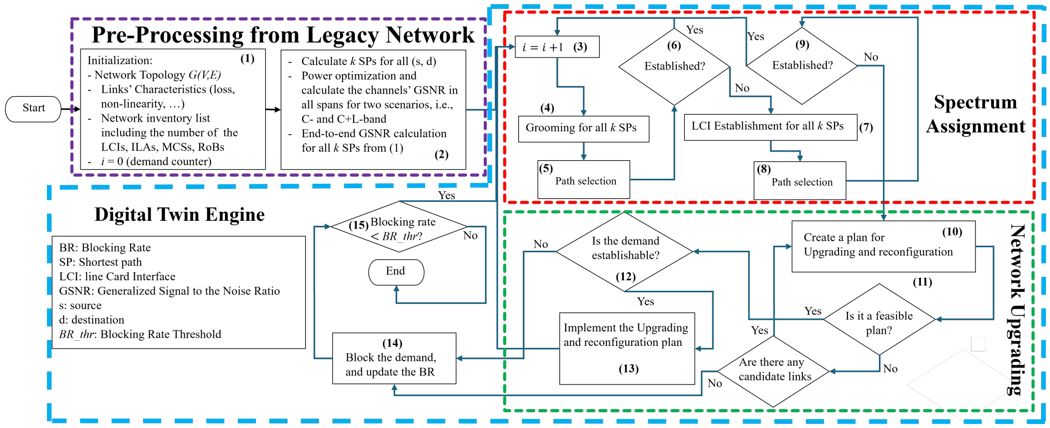


Fig. 2: The flowchart of the proposed Digital Twin-Enabled PaYG method.

## 4. Physical Layer Modeling and Different PaYG Scenarios

The generalized signal-to-noise ratio (GSNR) for a lightpath (LP) in uncompensated multi-band optical links can be modeled using the incoherent Enhanced Generalized Gaussian Noise (EGGN) model [10, 11]. The GSNR in dB for channel $i$ is given by:

$$GSNR^{i}_{\mathrm{LP}}|_{\mathrm{dB}} = 10\log_{10}\left[\left(SNR^{-1}_{\mathrm{ASE}} + SNR^{-1}_{\mathrm{NLI}} + SNR^{-1}_{\mathrm{TRx}}\right)^{-1}\right] - \sigma_{\mathrm{Flt}}|_{\mathrm{dB}} - \sigma_{\mathrm{Ag}}|_{\mathrm{dB}}, \tag{1}$$

where $SNR_{\mathrm{ASE}} = \Sigma_{s\in S} P^{s+1,i}_{\mathrm{tx}}/P^{s,i}_{\mathrm{ASE}}$ and $SNR_{\mathrm{NLI}} = \Sigma_{s\in S} P^{s+1,i}_{\mathrm{tx}}/P^{s,i}_{\mathrm{NLI}}$. Moreover, $P^{s+1,i}_{\mathrm{tx}}$ is the launch power at the beginning of span $s+1$, $P^{s,i}_{\mathrm{ASE}} = n_{\mathrm{F}} h f^{i}(G^{s,i}-1)R_{\mathrm{ch}}$ is noise power caused by the EDFA equipped with the dynamic gain equalizer, and NLI noise power ($P^{s,i}_{\mathrm{NLI}}$) is calculated from (2) in [11]. Moreover, $n_{\mathrm{F}}$, $h$, $f^{i}$, $G^{s,i} = P^{s+1,i}_{\mathrm{tx}}/P^{s,i}_{\mathrm{rx}}$, $S$, and $R_{\mathrm{ch}}$ are the EDFA's noise figure, Plank's coefficient, channel frequency, frequency center of the spectrum, EDFA's gain, set of spans, and channel symbol rate, respectively. $P^{s,i}_{\mathrm{rx}}$ is the received power at the end of span $s$. $SNR_{\mathrm{TRx}}$, $\sigma_{\mathrm{Flt}}$, $\sigma_{\mathrm{Ag}}$ are the transceiver SNR, SNR penalty due to wavelength selective switches filtering, and SNR margin due to the aging. In multi-band optical networks, transitioning from C-band to C+L-band or C+L+S-band causes GSNR degradation due to ISRS, possibly lowering GSNR below the modulation format threshold. This necessitates modulation reconfiguration to avoid bit rates penalties. The resulting unserved residual traffic (URT) is defined as: $C_{\mathrm{URT}} = C_{\mathrm{Req}} - C_{m}$, where $C_{\mathrm{Req}}$ is the required capacity and $C_{m}$ is the capacity supported by the downgraded modulation format. Efficient upgrade and reconfiguration strategies are critical to maintaining service reliability in multi-band optical networks during capacity expansion. In this study, five PaYG strategies are proposed for the seamless and cost-effective migration of optical networks from C-band to C+L+S-band operation. Unlike the traditional Day-One approach, which upgrades the entire network upfront, PaYG methods incrementally scale the network based on real demand, optimizing CAPEX. The **PaYG-MinG** approach uses the minimum GSNR across bands to avoid future reconfiguration, albeit at the cost of lower initial capacity. **PaYG-WoR** estimates GSNR assuming a fully loaded C+L+S-band network from the outset to prevent reconfigurations, leading to early underuse of C-band resources. **PaYG-WPR** introduces partial reconfiguration by shifting only the unserved residual traffic to the L-/S-band, while retaining the remainder in the C-band. **PaYG-WFR** performs full reconfiguration of affected lightpaths, often reallocating them entirely to the L-/S-band to free up C-band spectrum. Finally, **PaYG-WAR** aggressively reconfigures both affected and unaffected lightpaths to the L-/S-band, maximizing future C-band availability.

## 5. Simulations, Results, and Conclusions

The simulation results for the USB14 network—a representative ultra-long-haul optical backbone in the United States with 14 nodes and 22 links—validate the effectiveness of the proposed PaYG strategies for scalable C+L+S-band optical network migration. This topology features an average link length of 927 km and routing path distances of approximately 1966 km, 2713 km, and 3308 km for the three shortest paths. Simulations were conducted using flexible coherent transceivers operating at 64 GBaud with variable modulation formats ranging from 100 to 600 Gbps, soft-

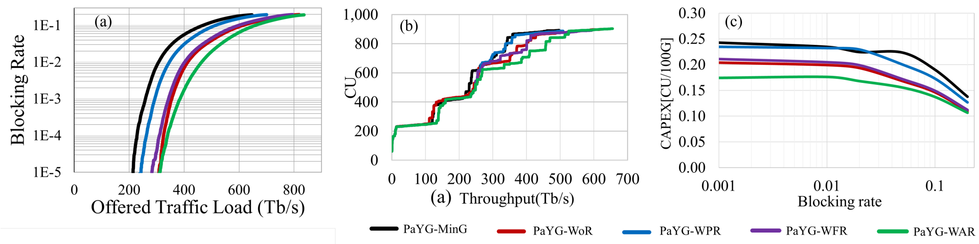


Fig. 3: Fig. 3. Performance of PaYG strategies. (a) blocking rate, (b) CAPEX growth, (c) Normalized CAPEX per 100 Gbps.

decision forward error correction, and a 2 dB transceiver aging margin. The total spectrum considered was 20 THz, distributed as 6 THz for the C-band, 6 THz for the L-band, and 8 THz for the S-band, with 500 GHz guard bands between adjacent bands. EDFAs with realistic noise figures—4.5 dB (C-band), 5.5 dB (L-band), and 6 dB (S-band)—were used, and GSNR thresholds corresponding to six modulation formats were applied (3.45–19.34 dB). The CAPEX is ultimately reported as the cost unit (CU) per 100 Gb/s versus the established traffic (Throughput). Calculations are based on the cost model proposed in [2]. CAPEX includes the cost of LCIs, ROADM-on-Blade cards, MCSs, and ILAs with respective CUs of 2.5, 1.9, 0.8, and 0.7. The premium factor for L-band components is set at 20%. Among all tested algorithms, the PaYG-WAR (With All Reconfigurations) strategy consistently yields the best performance. As shown in Fig. 1(a), PaYG-WAR achieves the highest throughput at a 1% blocking rate, supporting 17% more demand than PaYG-WoR and 40% more than PaYG-MinG. This is due to its aggressive yet optimized reconfiguration strategy, where both affected and unaffected lightpaths are shifted to the L- and S-bands upon each upgrade, maximizing available C-band capacity for future demands. In terms of capital expenditure (CAPEX), PaYG-WAR significantly reduces costs, as illustrated in Fig. 1(b), which presents the CAPEX growth curve in terms of cost units (C.U), and Fig. 1(c), which shows the normalized CAPEX per 100 Gbps of established traffic. PaYG-WAR outperforms PaYG-WFR, WPR, WoR, and MinG by 15% to 70% in cost efficiency.

Overall, PaYG-WAR presents the best trade-off among the proposed strategies, offering the highest throughput, lowest CAPEX, and most efficient infrastructure deployment. Its ability to adaptively and incrementally upgrade the network while leveraging the full 20 THz spectrum makes it a powerful solution for future-proofing long-haul optical backbones like the USB14 network.

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