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A Comparative Study of Capacity Scaling Strategies for Future Optical Transport Networks

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ABSTRACT The exponential rise in bandwidth demand from cloud services, real-time streaming, and emerging AI workloads is rapidly exhausting the scalability headroom of today's optical transport networks. Conventional advances in coherent transceivers and C-band systems are nearing saturation, underscoring the need for new capacity-scaling strategies. This paper provides a comparative analysis of three orthogonal approaches: (i) transceiver evolution, (ii) spectral expansion through multi-band transmission, and (iii) spatial scaling via space-division multiplexing (SDM). Using a statistical network assessment of the German core network, we quantify their individual and combined impacts on capacity, efficiency, and long-term scalability. Results show that transceiver upgrades alone improve per-fiber throughput by up to 66% (400G to 1.2T) but yield diminishing returns under fixed spectrum. Multi-band operation increases per-fiber capacity by more than 150% when extending from C-band to full C+L+S operation, though it requires band-specific amplification and inter-band power equalization. SDM provides nearly linear scaling, delivering up to a 56-fold increase with six parallel fibers, albeit at higher infrastructure costs. A forward-looking 10-year projection under 25% annual traffic growth reveals that C-band-only systems saturate within 4–6 years, whereas hybrid strategies combining multi-band expansion with SDM sustain multi-petabit traffic, extending scalability by more than fivefold compared to single-band operation. These findings highlight that future-ready optical infrastructures must jointly exploit transceiver efficiency, ultra-wideband photonics, and spatial parallelism to ensure sustainable long-term growth.

INDEX TERMS Optical transport networks, coherent transceivers, multi-band transmission, space-division multiplexing (SDM), network scalability, spectral efficiency, fiber capacity scaling, future network trends.

I. INTRODUCTION

THE EXPONENTIAL growth of data-driven services, such as cloud computing, real-time streaming, and AI workloads, has pushed optical transport networks toward their scalability limits. Although individual advances in transceivers (TRxs), spectrum utilization, and spatial multiplexing have extended network capacity, their combined and long-term effects on system-level scalability remain underexplored. Despite significant advances in coherent transceiver technology and spectrum utilization, most existing studies investigate capacity scaling along individual dimensions, either transceiver evolution, spectral expansion, or spatial multiplexing, without evaluating their combined or long-term impact on network-level scalability [1], [2]. Moreover, current research largely concentrates on component- or link-level enhancements, such as amplifier optimization and power equalization, without establishing how these physical-layer improvements translate into sustainable, system-wide performance gains under realistic deployment conditions [3], [4]. To bridge this gap, an integrated assessment framework is developed here that jointly examines transceiver advancements, ultra-wideband

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operation, and spatial parallelism within a unified core-network model. Building on this framework, the paper presents a comprehensive and comparative analysis of three orthogonal capacity scaling strategies: transceiver advancements, multi-band transmission, and space-division multiplexing (SDM), within the framework of a realistic core network model. Recent industry analyses further underscore this urgency. According to Nokia's Global Network Traffic Report [5], global Internet Protocol (IP) traffic is projected to grow at a compound annual growth rate (CAGR) of 22–25% through 2030, with high-adoption scenarios (e.g., extended reality and cloud gaming) pushing this figure up to 32%. Such excessive growth trajectories are expected to saturate the scaling headroom provided by conventional optical systems, thereby necessitating a holistic rethinking of capacity expansion approaches.

Technological advances such as coherent detection, polarization-division multiplexing enabling dual-polarization (DP) multi-level modulation formats, and the extension of wavelength-division multiplexing (WDM) transmission into the L-band have been instrumental in scaling optical network capacity over the past decade. However, these methods are nearing saturation. Although coherent optical TRxs continue to evolve, their incremental performance gains yield diminishing returns under fixed spectral and spatial constraints. To meet future capacity demands, especially beyond the early 2030s, there is a growing need to explore complementary scaling strategies enabling parallelization [1] that extend the capabilities of existing technologies in a cost-effective and adaptable manner.

To address the saturation limits of current optical systems, two orthogonal capacity-scaling solutions have been identified: (1) SDM, a general technique that exploits parallel spatial channels, here considered in the form of multiple parallel single-mode fibers; and (2) band-division multiplexing (BDM), which extends the usable spectrum into the L- and S-bands, enabled by advanced amplifier technologies [6] such as thulium-doped fiber amplifiers (TDFAs) [7]. These two dimensions, spectral and spatial, provide complementary scaling mechanisms. Their combined impact on network capacity and efficiency requires systematic investigation. While erbium-doped fiber amplifiers (EDFAs) efficiently support the C and L bands, TDFAs are employed to extend amplification into the S band due to their favorable gain profiles and compatibility with standard single-mode fibers [3]. BDM enables network operators to leverage the extended transmission window of standard single-mode fibers, effectively increasing capacity without the need for additional fiber deployment [8], [9], [10]. Concurrently, upgrading TRx technology is critical to support next-generation capacity demands. The industry has already transitioned from 100G to 400G TRxs, and current advancements are pushing the boundaries further with commercially available 800G and development-stage 1.2T coherent TRxs. These TRxs utilize advanced modulation formats, high symbol rates, and sophisticated digital signal processing (DSP) techniques to optimize performance over both short- and long-reach optical paths. Thus, the combination of SDM, BDM, and next-generation TRxs forms a robust technological foundation to ensure the scalability, flexibility, and future-readiness of optical transport networks in the face of relentless traffic growth.

This study provides a comprehensive evaluation of three fundamental scaling strategies for optical transport networks: TRx evolution, multi-band spectral expansion, and spatial scaling through parallel fiber deployment. The key contributions are as follows. First, the study offers a systematic comparison of TRx configurations, spectral allocations, and spatial dimensions using a unified simulation framework based on the analysis of the German core network. Second, it quantifies network-level capacity gains across a wide range of configurations, including full C, L, and S band operation combined with 400G, 800G, and 1.2T coherent TRxs. Third, the analysis includes a decade-long projection of capacity requirements under a realistic traffic growth model. This projection evaluates the sustainability of each scaling approach under increasing demand. Finally, the study highlights system-level considerations for component support in scalable network deployments, particularly the need for band-specific amplification, compatibility with multi-band ROADM architectures, and power equalization techniques suitable for SDM and ultra-wideband transmission.

II. OPTICAL CAPACITY SCALING

The capacity of optical transport networks can be scaled along three fundamental and independent dimensions: enhancing the performance of coherent optical TRxs, expanding the usable optical bandwidth beyond the conventional C and L bands, and leveraging spatial parallelism through space-division multiplexing.

A widely adopted baseline for accurate yet simple analysis of physical-layer effects is the approximation of transparent lightpaths (LPs) as additive Gaussian noise (AGN) channels. This model is consolidated and extensively validated in the C-band, [10], [11] The capacity of optical transport networks can be scaled along three fundamental and independent dimensions: enhancing the performance of coherent optical TRxs, expanding the usable optical bandwidth beyond the conventional C and L bands, and leveraging spatial parallelism through SDM.

Accordingly, the performance of LPs employing DP coherent TRxs can be characterized by the generalized signal-to-noise ratio (GSNR), which accounts for all Gaussian noise sources impacting transparent propagation. These include amplified spontaneous emission (ASE) noise from optical amplifiers, nonlinear interference (NLI) from fiber propagation, and, potentially, linear crosstalk introduced by ROADM-based optical switching nodes.

The following subsections examine each of these strategies: (i) upgrade TRxs, (ii) use of multi-band, and (iii) SDM in detail, highlighting their respective potential, challenges, and role in supporting future network scalability.

A. CAPACITY SCALING THROUGH COHERENT OPTICAL TRANSCEIVER EVOLUTION

The capacity scaling enabled by coherent optical TRxs is central to expanding the capacity of modern optical networks. Since their introduction, coherent detection combined with polarization-division multiplexing and higher-order modulation formats has enabled the commercial deployment of high-capacity DP TRXs operating at 100 Gb/s, 400 Gb/s, and beyond [12], [13], [14]. These TRXs achieve higher capacities by increasing the symbol rate and employing advanced modulation formats such as 16-quadrature amplitude modulation (QAM) and 64-QAM. While this enhances spectral efficiency (SE), it also introduces stricter GSNR requirements and greater vulnerability to nonlinear transmission effects and filtering penalties from network components such as ROADMs and wavelength-selective switches (WSSs). These advances have significantly increased optical transmission systems' SE. Thanks to the AGN approximation of transparent LPs, we can apply the Shannon theory for additive white Gaussian noise (AWGN) conditions giving:

$$\mathrm{SE} = 2\log_2(1 + \mathrm{SNR}) \tag{1}$$

where the factor of two accounts for dual-polarization transmission. However, practical systems are subject to implementation penalties, including forward error correction (FEC), framing overheads, and internal noise from the TRx. To account for practical system imperfections, two parameters are introduced. The first is the coding gap (Γ), representing implementation penalties such as framing overhead, FEC, and digital signal processing (DSP) inefficiencies. The second is the transceiver signal-to-noise ratio ($\mathrm{SNR_{TRx}}$), which captures electrical and optical noise contributions from the transmitter and receiver [15], [16], [17]. With the introduction of these two impairments, a more realistic model is given as:

$$\mathrm{SE} = 2\log_2\left(1 + \frac{\mathrm{SNR}}{\Gamma}\right) \tag{2}$$

Eq. (2) defines the net SE of a coherent optical TRx system. Compared to the ideal Shannon capacity (Eq. (1)), this model provides a more realistic estimation of SE achievable in commercial systems. The effective SNR in Eq. (2) is given as:

$$\frac{1}{\mathrm{SNR}} = \frac{1}{\mathrm{GSNR}} + \frac{1}{\mathrm{SNR_{TRX}}} \tag{3}$$

where the $\mathrm{SNR_{TRX}}$ is the transceiver SNR.

With practical design parameters such as a Γ_{dB} of up to 4 dB and $\mathrm{SNR_{TRX,dB}}$ values exceeding 20 dB [11], current-generation coherent TRxs can operate within approximately 90% of the theoretical Shannon capacity across diverse optical network conditions [2].

Improving SE alone cannot accommodate traffic growth rates exceeding 22% CAGR, and increasing SE in finer granularity (e.g., increments of 0.25 bits/s/Hz) yields diminishing returns, particularly when constrained by fixed client port rates such as 100 Gb/s and 400 Gb/s [14], [16]. Additionally, while optical regeneration can enhance the GSNR by dividing long-haul links into shorter segments, its overall effectiveness is ultimately limited by the maximum SE achievable by transponders and internal noise sources [2].

Consequently, while advancing coherent TRx technology remains essential, the long-term scalability of optical core networks will also require architectural enhancements enabling more spectral regions such as multi-band and parallel fiber transmission systems.

B. CAPACITY SCALING THROUGH MULTI-BAND TRANSMISSION BEYOND THE C-BAND

One of the most direct ways to enhance network capacity without installing new fibers is to extend the usable optical bandwidth. This approach capitalizes on the existing single-mode fiber infrastructure, allowing operators to postpone expensive trenching or duct installation while still achieving a significant capacity increase.

Historically, optical transmission has relied almost exclusively on the C-band (1530–1565 nm), owing to its low attenuation and the mature performance of EDFAs. The subsequent adoption of the L-band (1565–1625 nm) effectively doubled the available spectrum, enabling total per-fiber bandwidths approaching 10 THz [18]. C+L-band systems are now commercially mature, supported by reliable amplifiers and wavelength-selective components specifically designed for these windows [19]. Beyond these conventional ranges, other wavelength regions such as the O-band (1260–1360 nm) and S-band (1460–1530 nm) have attracted research interest. The O-band, with its low chromatic dispersion, is suited to short-reach, non-coherent links such as data-center interconnects. The S-band, on the other hand, was historically constrained by higher fiber loss and the absence of efficient amplification [20], [21]. Recent progress in TDFAs and gain-flattened multi-band amplification schemes has mitigated these issues, making the S-band a practical candidate for coherent long-haul transmission [3], [22].

Extending transmission from C+L to C+L+S bands increases the total usable spectrum to more than 15 THz, enabling up to 384 WDM channels at 50 GHz spacing. Realizing this potential, however, requires careful launch-power equalization and inter-band management to suppress effects such as stimulated Raman scattering (SRS), NLI, and ASE noise accumulation. When these parameters are optimized, multi-band transmission achieves GSNR uniformity across the spectrum and can yield capacity comparable to, or greater than, that obtained through SDM over multiple fibers [3].

Another avenue for bandwidth scaling involves using optical super-channels, where multiple tightly spaced carriers are co-routed as a single logical unit [23], [24], [25]. This technique reduces guard band overhead and allows for more efficient spectrum utilization. However, the net gain in capacity from super-channels is modest compared to the potential increase offered by complete multi-band transmission. The

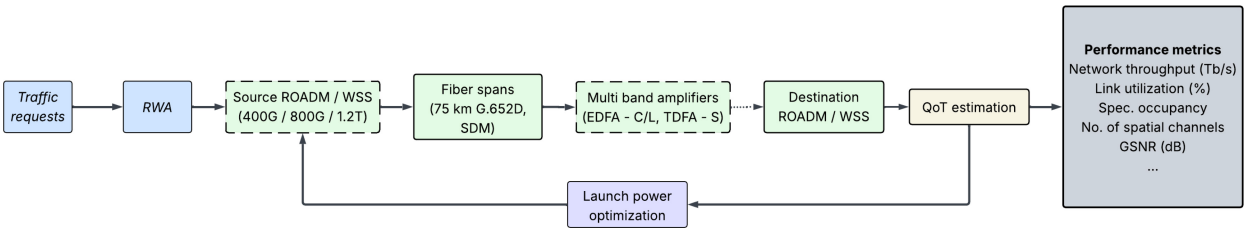

FIGURE 1. SNAP-based network architecture for capacity evaluation.

practical deployment of multi-band systems depends largely on the availability of band-compatible transceivers and amplifier modules. An interim alternative is optical wavelength conversion, which shifts signals between bands to reuse existing TRxs hardware [26], [27]. While attractive for transitional upgrades, such solutions introduce additional optical complexity and may increase power consumption.

Overall, ultra-wideband transmission across the S-, C-, and L-bands provides a technically and economically sound path for future capacity scaling. Supported by integrated photonic technologies and intelligent power-control mechanisms, multi-band architectures enable substantial per-fiber capacity gains and extend the life of existing optical infrastructure before spatial replication becomes unavoidable.

C. CAPACITY SCALING THROUGH SPATIAL MULTIPLEXING

A direct and scalable approach to increase network capacity involves deploying multiple parallel fiber systems between nodes. Since the aggregate capacity scales linearly with the number of fiber pairs, this approach remains one of the most scalable options. However, it is also among the most cost-intensive, especially in long-haul deployments where obtaining rights-of-way or trenching new ducts can be economically or logistically restrictive [4].

Despite the associated costs, deploying parallel single-mode fibers often termed multi-rail fiber links is already used in practice and is expected to gain further adoption as traffic surges. To address cost constraints and space limitations, significant research has focused on SDM, which seeks to enhance capacity by duplicating fibers and developing advanced transmission technologies that operate across multiple spatial paths. This includes the use of multicore fibers [28], few-mode fibers, spatial couplers, and amplifiers tailored for spatial channels [29], [30].

SDM-based systems are expected to become commercially viable once their cost-per-bit undercuts that of conventional single-mode fiber replication. In the interim, parallel single-mode fibers remain the dominant solution for near-term scaling. As networks scale to include multiple fiber pairs per route, node architectures must evolve accordingly. Classical colorless and directionless (CD) or contentionless (CDC) ROADM designs face limitations in their ability to scale switching functions across many fibers due to WSS port constraints [31].

To address this, architectural enhancements, such as introducing inner or outer fiber/band circuit switching layers,are under investigation [2]. These enable efficient signal routing at coarser granularity (e.g., entire fibers or bands), reducing the complexity and cost of WSS-based switching as the number of parallel fibers increases [31]. Such hybrid nodes can manage fiber-switched or band-switched traffic with wavelength-switched paths, offering a scalable and cost-effective migration strategy for future SDM-enabled networks.

Overall, parallel fiber deployment, using traditional single-mode links or novel SDM architectures, remains the most direct path to large-scale capacity increases. However, realizing its full potential requires rethinking node designs and network control to ensure flexibility, resiliency, and cost-efficiency as spatial parallelism becomes more prevalent.

III. NETWORK MODELING AND ARCHITECTURE

To evaluate the scalability of future optical transport networks using a unified modeling framework, we examine the impact of three independent capacity enhancement strategies: (i) scaling coherent TRxs, (ii) expanding the usable optical bandwidth through multi-band transmission, and (iii) increasing spatial capacity via parallel fiber deployment. To this end, the Statistical Network Assessment Process (SNAP) [22] is adopted to evaluate system-level degradations across a realistic core topology. SNAP operates at the physical layer and evaluates the degradation of the quality of transmission (QoT) introduced by each network element. A disaggregated physical-layer abstraction is adopted, where every network component introduces gain, loss, or Gaussian noise. This includes ASE noise from optical amplifiers and NLI arising from fiber propagation effects. Under this model, the GSNR for the i-th WDM channel is given by:

$$\mathrm{GSNR}_i = \frac{P_{S,i}}{P_{\mathrm{ASE}}(f_i) + P_{\mathrm{NLI},i}(f_i)} \tag{4}$$

where $P_{S,i}$ is the launch power of the signal, $P_{\mathrm{ASE}}(f_i)$ is the ASE noise power, and $P_{\mathrm{NLI},i}(f_i)$ is the nonlinear interference power at frequency f_i.

To provide a detailed overview, Fig. 1 illustrates the SNAP-based network architecture adopted in this study. The workflow begins with the generation of incremental traffic requests between source–destination (s–d) pairs based on a uniform traffic demand model. During each simulation, up to $N_{\max}$ requests are progressively loaded into the network.

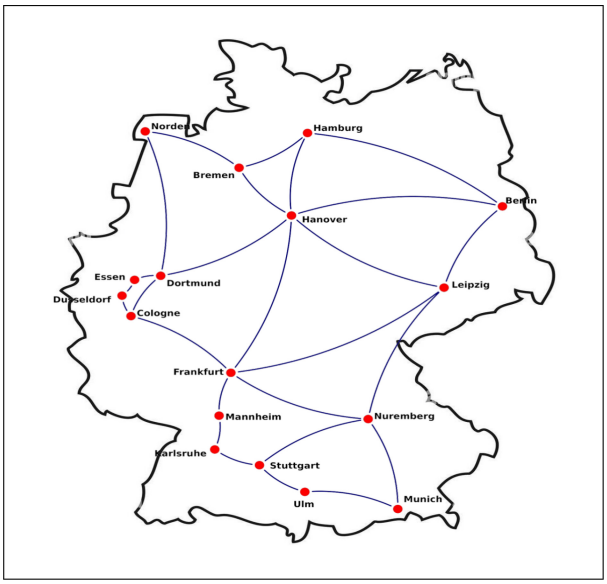

FIGURE 2. German network topology.

Each new source-destination pair is drawn independently from the predefined traffic matrix. To capture the stochastic variability of traffic realizations, the analysis is repeated over 1000 independent Monte Carlo runs, each with a different random seed. The loaded traffic requests are handled by the Routing and Wavelength Assignment (RWA) module. The RWA identifies up to k shortest paths per request using the k-shortest path algorithm with $k = 5$, and it uses the first-fit scheme for spectrum allocation. To minimize the deployment of new LPs, the simulation attempts to perform end-to-end traffic grooming by utilizing idle capacity on existing LPs.

When a new LP is required, the optical controller dynamically selects the modulation format and channel parameters based on the estimated QoT and the required GSNR (RGSNR) of the transceiver [32]. The source ROADM/WSS node then configures the appropriate TRx based on the target capacity and selected modulation format. Three main TRxs systems are considered in this analysis: 400 G, 800 G, and 1.2 T. The TRxs operate according to band-specific parameters: C-, L-, and S-band TRxs use the ITU-T 100 GHz WDM grid with a symbol rate of $R_s = 60$ GBaud for 400 G transmission [33], and the 150 GHz WDM grid with $R_s = 120$ GBaud for 800 G transmission [34]. Similarly for 1200 G transmission, a 150 GHz WDM grid with a symbol rate of $R_s = 130$ GBaud is considered [35].

The optical signal subsequently propagates through fiber spans consisting of standardized 75 km G.652D single-mode fiber segments, which may be extended to support SDM configurations. The analysis also considers a reasonably loaded multi-band scenario with FSR = 150 GHz, supporting a total of 105 WDM channels: 25 in the C-band (≈4 THz), 40 in the L-band (≈6 THz), and 40 in the S-band (≈6 THz).

After signal propagation through each fiber span, the signal is amplified by band-specific optical amplifiers: the C- and L-band channels are amplified by commercial EDFAs, while the S-band channels are amplified using TDFAs. These are independently tuned to ensure flat gain and low noise across the extended spectrum. At the destination ROADM/WSS node, the received signal is evaluated by the QoT estimation module, which computes the QoT in terms of GSNR per channel as expressed in Eq. (4).

Furthermore, the study employs a span-by-span launch power optimization approach using the LOGO algorithm, which feeds QoT (GSNR) results back to adjust span-wise input power, thereby maximizing GSNR and ensuring balanced performance across the C, L, and S bands [33].

Finally, network evaluation is performed on the German topology, illustrated in Fig. 2, which consists of 17 optical nodes (red dots) representing ROADM sites and 26 fiber links (blue lines) with in-line amplifiers. The topology exhibits an average node degree of 3.1, an average inter-node distance of 207 km, and a maximum link length of 300 km.

IV. NETWORK-LEVEL PERFORMANCE EVALUATION AND ANALYSIS

This section presents a comparative evaluation of the proposed capacity scaling strategies through detailed network statistical network performance analysis [36] across various TRx configurations, spectral bands, and transmission architectures. Building on the previously defined simulation and optimization framework, the study investigates system behavior with 400G, 800G, and 1200G TRxs under both single- and multi-band scenarios (C, C+L, and C+L+S), as well as comparing SDM and BDM strategies.

Results are presented for the real German optical network topology, capturing realistic node and link characteristics to evaluate system-level performance. Key performance indicators such as traffic-carrying capacity,link utilization, and blocking probability are reported. At any instance, the blocking probability is computed as the ratio between the number of blocked requests and the total number of generated requests. The following subsections outline the trade-offs and comparative performance of modulation scaling, spectral expansion, and transmission architecture choices to inform the design of future optical transport networks.

A. IMPACT OF TRANSCEIVER SCALING UNDER C-BAND CONSTRAINTS

Fig. 3 presents the network-level evaluation of blocking probability as a function of traffic demand for three coherent TRx configurations operating over the C-band: 400G, 800G, and 1200G. Each curve corresponds to a single-fiber, C-band-limited configuration. The results indicate a clear capacity scaling trend associated with increasing TRx data rates. As shown in Fig. 3, a traffic load of approximately 75 Tbps can be accommodated using 400G TRxs before the blocking probability reaches 10^{-2}. With 800G TRxs, the network can sustain up to 95 Tbps under the same blocking threshold. The 1200G configuration extends this

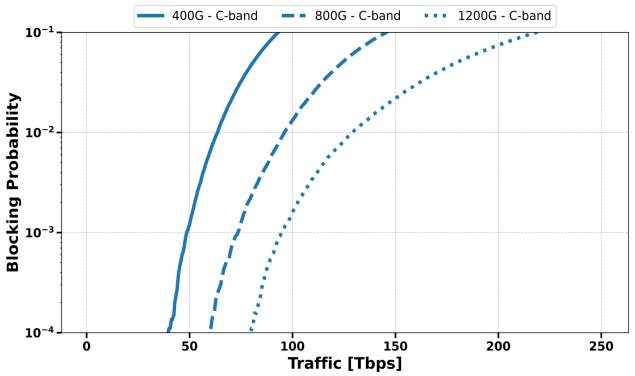

FIGURE 3. Blocking probability vs. traffic load for 400G, 800G, and 1.2T transceivers over C-band.

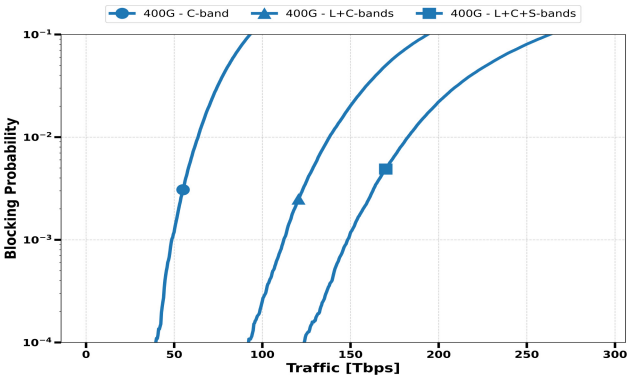

FIGURE 4. Traffic load capacity with 400G transceivers over C, C+L, and C+L+S bands.

capacity further, supporting up to 130 Tbps of traffic before encountering similar levels of blocking.

The right-shift of the curves demonstrates that higher-capacity TRxs enhance network throughput within the given (C-band) by transmitting more bits per channel through higher symbol rates and advanced modulation formats. However, as data rates approach the terabit-per-wavelength range, the incremental gain diminishes due to stricter GSNR requirements and increased sensitivity to nonlinear effects and filtering penalties, which ultimately constrain further efficiency improvements. A more detailed evaluation of TRx scaling, in conjunction with spectral and spatial dimensions, is presented in the subsequent sections.

B. EFFECT OF SPECTRAL EXPANSION UNDER FIXED TRANSCEIVER CONFIGURATIONS

While Section IV-A examined network scalability through TRx upgrades under fixed spectrum and spatial conditions, this section focuses on the impact of expanding the usable optical bandwidth from the conventional C-band to C+L and C+L+S band configurations. To isolate the spectral scaling dimension, we fix the TRx configuration to 400G and the fiber count to one per link.

Fig. 4 illustrates the network blocking probability curves for three configurations, C-band only, C+L bands, and the full C+L+S multi-band transmission under a consistent 400G TRx setup. As the usable spectral window increases, a clear horizontal shift in the blocking curves is observed, confirming that capacity scales proportionally with available optical bandwidth. Quantitatively, the maximum supported traffic at a blocking probability of 10^{-2} increases from approximately 75 Tbps under C-band to about 130 Tbps in C+L-band and exceeds 175 Tbps with full C+L+S-band transmission. This trend is attributable to the increase in the number of WDM channels made available by broader spectral occupancy, doubling the capacity from C-band ($\approx$ 4 THz) to C+L ($\approx$ 10 THz), and further extending to $\approx$ 15 THz with the inclusion of the S-band. The results demonstrate that spectral scaling offers a powerful and cost-effective strategy for enhancing network throughput without additional fiber infrastructure. It is important to note that the full benefits of multi-band transmission depend on the availability of band-specific amplifiers (e.g., EDFAs and TDFAs) and TRxs that are spectrally compatible. The integration of such components in future ROADMs and network nodes is a critical enabler for practical multi-band deployment.

The next section explores spatial scaling by increasing parallel fibers across all spectral bands and different TRx.

C. SPATIAL SCALING VIA PARALLEL FIBERS (SDM)

Fig. 5 presents blocking probability trends for 400G, 800G, and 1.2T TRxs over the C-band, as the fiber count is incrementally increased from 1 to 6. Each subplot corresponds to a specific transceiver configuration, and each curve within those plots represents a different number of parallel fibers.

The results show a clear and nearly linear capacity improvement with each additional fiber. For instance, using 400G TRxs, increasing from 1 to 6 fibers enhances the supported traffic load (at 10^{-2} blocking) from $\approx$75 Tbps to over 430 Tbps. With 800G, this capacity scales from $\approx$ 95 Tbps to $\approx$625 Tbps, and for 1.2T, the network can carry nearly 1150 Tbps with 6 parallel fibers. This near-linear trend occurs because each fiber provides an independent optical path that replicates the full spectral capacity, producing an additive gain with minimal inter-fiber interference. Minor deviations from perfect linearity arise from unequal link utilization and routing constraints at high network load.

Fig. 6 extends the spatial scaling analysis to C+L band transmission, comparing network performance across 400G, 800G, and 1.2T TRxs with increasing fiber counts from 1 to 6. Compared to Fig. 5 (C-band only), the addition of the L-band nearly doubles the usable optical bandwidth, which when combined with SDM, amplifies capacity gains substantially. For example, with 400G TRxs, the supported traffic increases from $\approx$ 152 Tbps with 1 fiber to $\approx$ 880 Tbps with 6 fibers. In the 800G and 1.2T cases, the maximum supported traffic jumps to approximately 1480 Tbps and 2850 Tbps, respectively, under the same spatial scaling. This underscores that multi-band spectral expansion and spatial multiplexing work synergistically, delivering multiplicative throughput improvements.

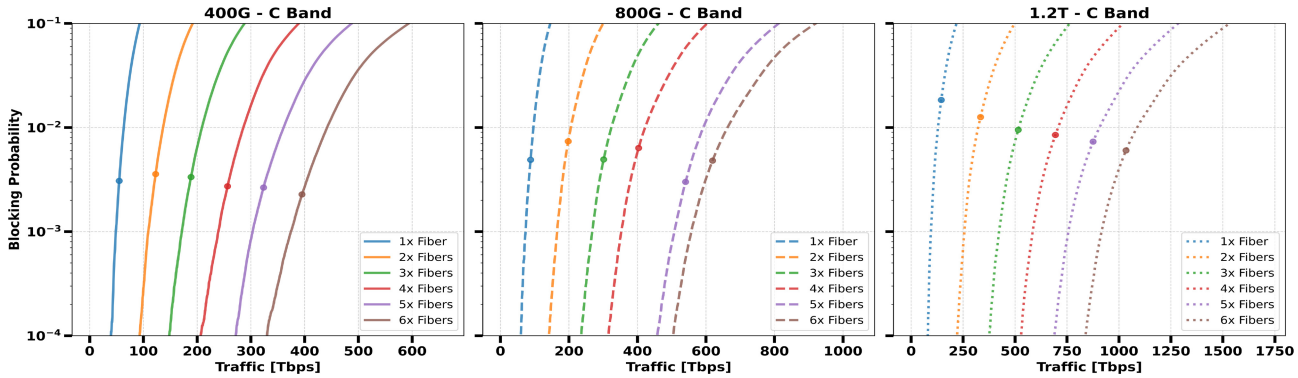

FIGURE 5. Traffic load scaling with 400G, 800G, and 1.2T transceivers over the C-band with increasing spatial multiplexing.

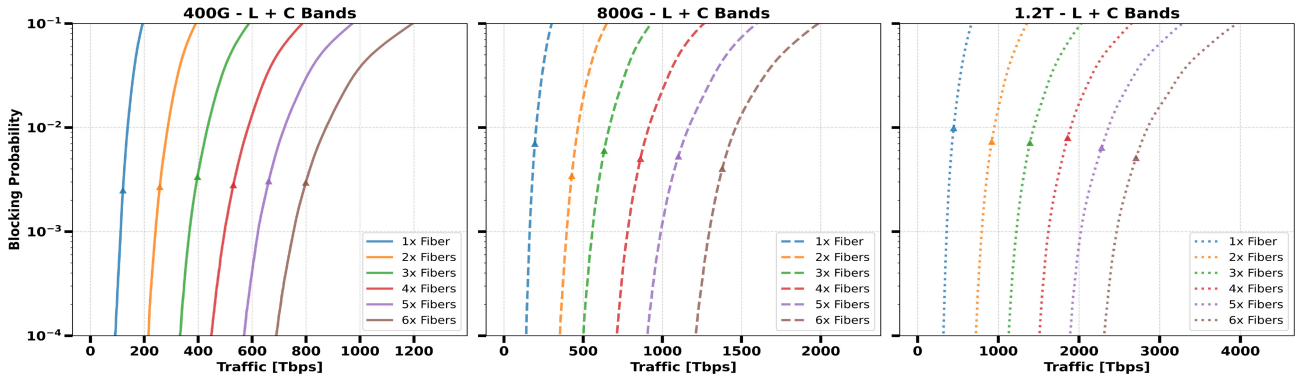

FIGURE 6. Traffic load scaling with 400G, 800G, and 1.2T transceivers over the C+L bands with increasing spatial multiplexing.

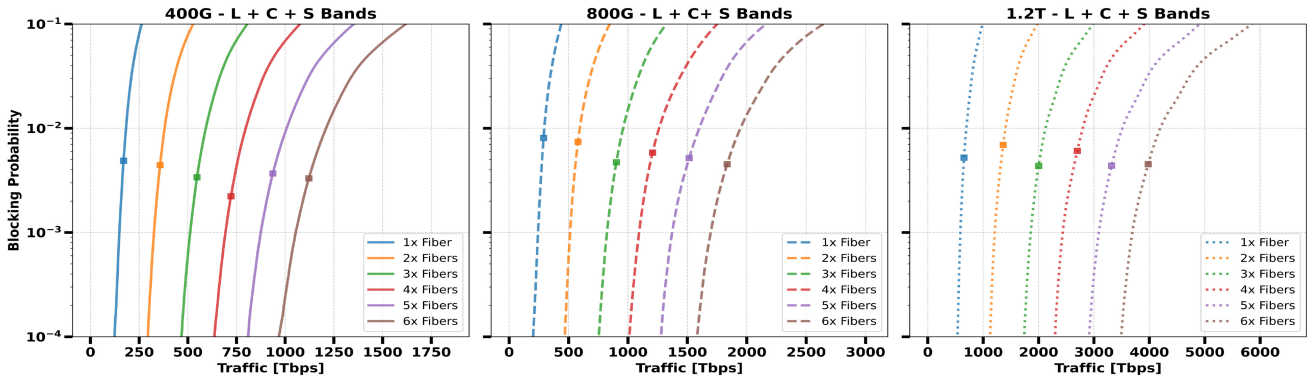

FIGURE 7. Traffic load scaling with 400G, 800G, and 1.2T transceivers over the C+L+S bands with increasing spatial multiplexing.

The right-shift of the blocking curves in each subplot also reveals that higher-order TRxs make more efficient use of each additional fiber, especially in broader spectral windows. These results reflect realistic scenarios in which operators upgrade both fiber infrastructure and spectrum availability to accommodate exponential traffic growth. Fig. 7 presents the most comprehensive configuration, full C+L+S-band transmission across all considered TRx rates and fiber counts. This setup utilizes the full spectrum supported by current amplifier and TRx technologies, thus offering the highest potential capacity both per fiber and across spatially multiplexed links. Under this configuration, the network supports approximately 195 Tbps to 1200 Tbps using 400G TRxs, 310 Tbps to 1900 Tbps with 800G TRxs, and 600 Tbps to over 4200 Tbps when employing 1.2T TRxs, as the number of parallel fibers increases from 1 to 6. In continuity with the preceding analyses, Fig. 7 confirms that when spectral expansion and spatial multiplexing are jointly applied, the resulting capacity gain becomes multiplicative rather than incremental. The extended C+L+S bandwidth increases per-fiber channel availability, while parallel fibers replicate this full spectrum independently, yielding an almost linear aggregate improvement.

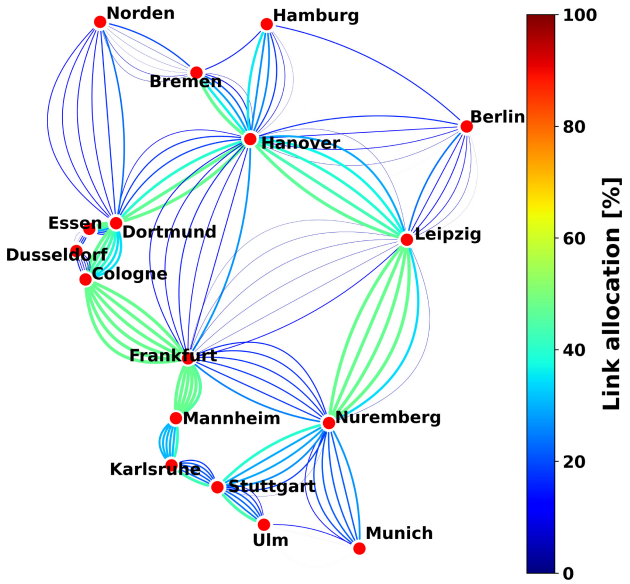

FIGURE 8. Normalized link-level fiber occupancy with 800G transceivers over the C+L+S bands under spatial multiplexing (up to 6 fibers).

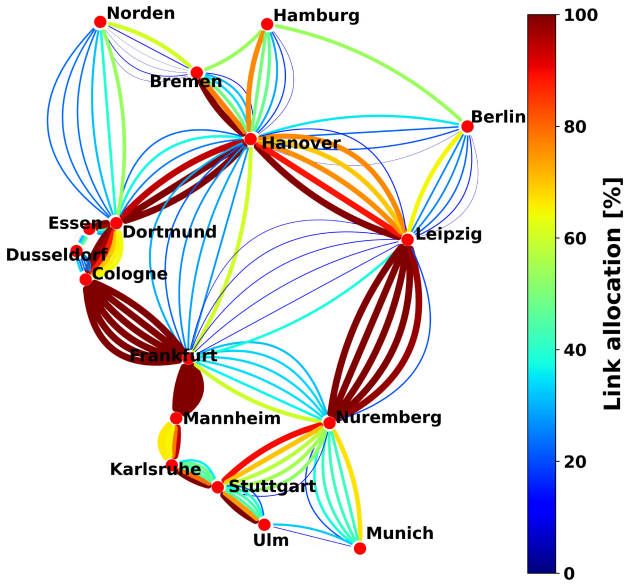

FIGURE 9. Normalized link-level fiber occupancy with 1.2T transceivers over the C+L+S bands under spatial multiplexing (up to 6 fibers).

Figs. 8 and 9 offer a comparative view of spatial resource utilization across the network under SDM-enabled conditions, visualized through heatmaps that capture normalized link-level fiber occupancy. Both configurations assume full C+L+S-band operation and six parallel fibers per link. The color scale in these heatmaps reflects the degree of spatial utilization, with red indicating maximum fiber usage (normalized to the highest value observed in the 1.2T case), and blue or cooler tones representing relatively lower link occupancy. Under this normalization, 1.2T transceiver exhibits widespread presence of high-occupancy links, denoted by deep red hues, indicating that traffic flows under 1.2T operation fully exploit the available spatial resources across critical paths in the network.

In contrast, 800G transceiver shows a broader distribution of blue and green regions, reflecting lower relative link occupancy when compared against the 1.2T reference. While traffic is distributed across more links in the 800G case, the overall spatial utilization remains lower in magnitude. This indicates that 1.2T TRxs, due to their higher per-channel traffic demands and constrained routing options, drive more aggressive consumption of SDM resources, leading to greater fiber utilization.

This scaling behavior is fundamentally rooted in two key mechanisms. First, extending the spectral occupancy to the full C+L+S band significantly increases the total number of available WDM channels, thereby enhancing the per-fiber throughput. Second, spatial multiplexing via parallel fibers provides a linear and modular path to capacity expansion, as each fiber independently supports the entire spectral load without requiring additional modulation complexity or advanced coding schemes.

The observed trends across Fig. 5 through Fig. 9 illustrate that full-spectrum transmission and spatial scaling are not only complementary but also multiplicative in effect. High-capacity TRxs such as 1.2T demonstrate superior utilization of both spectral and spatial resources, owing to their elevated symbol rates and improved SE. When deployed over wider optical bands and multiple fibers, these TRxs unlock substantial system-level gains.

Together, these findings reaffirm that scalable optical transport must consider a balanced integration of spectral and spatial dimensions. Leveraging multi-band transmission increases per-fiber capacity without additional physical infrastructure; however, it necessitates enhancements across the photonic layer. Specifically, amplifiers must support multiband gain profiles, WSS devices must maintain flat spectral performance over wider bandwidths, and ROADMs must be re-engineered to handle signal routing beyond the conventional C-band, with minimal inter-band crosstalk and signal distortion. Conversely, spatial scaling through SDM offers a conceptually simpler yet capital-intensive path by replicating full-spectrum transmission over multiple parallel fibers. This approach preserves component design within the C-band but incurs higher costs related to fiber deployment, trenching, and spatially-aware switching infrastructure. As traffic continues to scale toward the multi-petabit regime, the choice between spectral or spatial scaling or an optimized hybrid thereof will depend on a range of factors including available infrastructure, economic constraints, photonic integration maturity, and regional deployment models.

To summarize the key results from the preceding analyses, Table 1 provides a consolidated overview of how each scaling dimension, TRx scaling, spectral expansion, and spatial multiplexing, individually and in combination, influences the total optical transport capacity. The results highlight the cumulative capacity gains that can be achieved through

TABLE 1. Comparative analysis of optical transport capacity scaling via transceiver evolution, spectrum expansion, and spatial multiplexing strategies under 10^{-2} blocking constraints.

Scaling Strategy	Configuration	Spectral Bandwidth (THz)	Fiber Count	Aggregate Network Capacity @ 10^{-2} Blocking (Tbps)	Relative Capacity Gain (vs. Baseline)
Baseline	400G, C-band only	4	1	75	1×
Transceiver Scaling	800G, C-band only	4	1	95	1.27×
	1.2T, C-band only	4	1	125	1.67×
Spectrum Expansion	400G, C+L	10	1	152	2.03×
	400G, C+L+S	16	1	195	2.66×
Transceiver + Spectrum	800G, C+L+S	16	1	310	4.1×
	1.2T, C+L+S	16	1	690	9.2×
Spatial Scaling (SDM)	400G, C+L+S	16	6	1201	16×
	800G, C+L+S	16	6	1936	25.8×
	1.2T, C+L+S	16	6	4200	56×

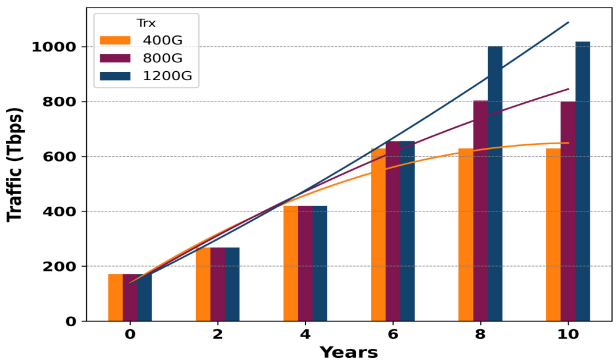

FIGURE 10. Projected network throughput evolution under C-band operation for different TRx configurations.

higher-order transceivers, multi-band spectrum utilization, and parallel fiber deployment using SDM.

V. LONG-TERM SCALABILITY AND FUTURE EVOLUTION TRENDS

To understand how core optical networks can evolve over the next decade under increasing traffic demand, this section extends the analysis to investigate future scaling trends using multi-band spectrum expansion and SDM, for different TRxs. As global IP traffic continues to grow, driven by cloud services, 8K/VR media, and emerging AI workloads, optical transport systems must adopt scalable strategies that go beyond current single-band, single-fiber constraints. Such analysis is critical for determining which scaling dimensions can sustainably address future traffic demands, while minimizing infrastructure and operational overhead. It provides valuable insights into the relative efficiency and viability of different scaling strategies, guiding network operators and equipment vendors in planning future deployments and upgrades.

The analysis is performed by applying a projected annual traffic growth rate of 25%, which reflects compound increases in user demand over time [2]. This projection allows us to evaluate how different TRx configurations (400G, 800G, and 1.2T) will perform under future loads and what levels of physical infrastructure (spectrum and fiber count) will be required to maintain acceptable network performance. Traffic growth over time is modeled using a standard exponential projection, where the total traffic load in year n is calculated as:

$$\text{Traffic}_{\text{Year } n} = \text{Traffic}_{\text{Year } 0} \times (1.25)^n$$

Here, $\text{Traffic}_{\text{Year } 0}$ is set to 400 Gbps per demand, representing current network conditions, and n is the number of years since deployment. The projection spans a 10-year horizon to assess long-term network scalability under realistic infrastructure and performance constraints.

The simulations are conducted on the same German network topology used throughout the study. Three classes of TRxs, 400G, 800G, and 1.2T, are considered, each with fixed symbol rates, modulation formats, and spectral occupancy as defined in previous sections. To explore the impact of spectral scaling, three spectrum configurations are analyzed: C-band only (≈4 THz), extended C+L bands (≈10 THz), and the full C+L+S spectrum (≈16 THz). Across Figs. 10–Fig. 12,the total requested traffic, derived from the 25% annual growth projection, is implicitly represented by the 1.2 T TRx configuration. Since the 1.2T TRx remains unsaturated throughout the 10-year horizon under all spectral conditions (C, C+L, and C+L+S), its supported throughput effectively equals the requested traffic in each year. Consequently, the 400 G and 800 G TRx results can be interpreted relative to this reference, where any deviation from the 1.2 T trend indicates unmet demand due to modulation or spectral limitations.

Fig. 10 illustrates how traffic-carrying capacity evolves over a 10-year period when constrained to the conventional C-band (≈4 THz of optical spectrum), across three different TRx configurations: 400G, 800G, and 1.2T. Each bar represents the total supported traffic (in Tbps) at discrete year intervals (0, 2, 4, 6, 8, and 10 years), assuming a 25% compound annual growth in demand per connection. The overlaid lines indicate the fitted trend lines for each TRx configuration, obtained by interpolating the discrete simulation results to visualize the continuous

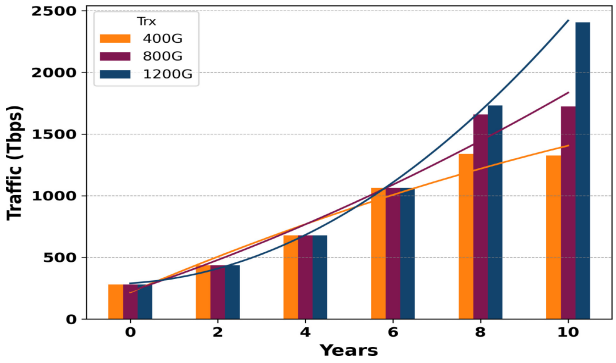

FIGURE 11. Projected network throughput evolution under C+L- bands operation for different TRx configurations.

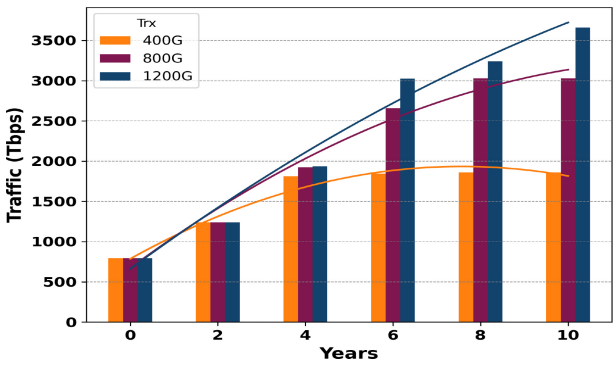

FIGURE 12. Projected network throughput evolution under C+L+S- bands operation for different TRx configurations.

growth behavior. In the initial phase (Years 0–4), all three TRxs demonstrate comparable performance. During this period, the traffic demand remains moderate, and the available spectral bandwidth within the C-band is sufficient to accommodate requests without significant contention. However, as traffic continues to grow exponentially beyond Year 4, the limitations imposed by both TRx capacity and the fixed spectral bandwidth become more pronounced. By Year 10, the differences in performance become substantial. The 1.2T TRx configuration achieves a projected throughput of approximately 1050 Tbps, while the 800G and 400G configurations are limited to about 800 Tbps and 620 Tbps, respectively. This indicates that the 1.2T TRxs outperform the 800G by approximately 23.8% and the 400G by 40.9% in terms of total supported network capacity. These gains are attributed to the higher spectral efficiency and symbol rate supported by the 1.2T TRxs, which enable more data per Hz of available spectrum.

In Fig. 11, the available spectral bandwidth provides a significant improvement over the C-band-only case, allowing all TRxs to fully accommodate traffic demands without notable blocking for the first six years. During this period, the throughput performance remains comparable across TRx types. However, as traffic volume increases exponentially in the latter half of the decade, the impact of TRx capacity becomes more evident. By Year 10, the 1200G TRx configuration supports approximately 2400 Tbps, while the 800G and 400G configurations support 1700 Tbps and 1350 Tbps, respectively. This corresponds to a 29.17% and 43.1% performance gap compared to the 1.2T case. The observed gap is primarily due to the differences in SE and modulation format limitations at lower TRx rates. The additional 6 THz of bandwidth from the L-band effectively delays spectral saturation, enabling better utilization of high-capacity TRxs like 1.2T in long-term scaling.

Fig. 12 presents the scenario where the full C+L+S spectrum (≈16 THz) is available, representing the maximum possible spectral expansion in current fiber systems. As expected, this significantly boosts the network's capacity to support long-term traffic growth across all transceiver types. In the initial 0–4 years, all three TRx configurations scale efficiently with minimal differentiation. However, the divergence becomes apparent after year 6. By Year 10, the 1.2T TRxs enable the network to carry approximately 3650 Tbps, while the 800G and 400G configurations reach 3030 Tbps and 1900 Tbps, respectively. This translates to a 17% and 47.9% performance advantage for the 1.2T configuration over the 800G and 400G options. Even with the full C+L+S-band available, the lower-capacity TRxs begin to exhibit saturation due to coarser spectral packing and higher slot usage per demand. The higher-rate TRxs provide more efficient spectrum utilization, enabling better alignment with the available frequency grid and thus greater overall throughput.

These results demonstrate that while spectrum expansion, moving from C-band to C+L and eventually to full C+L+S operation, provides substantial improvements in network capacity, its effectiveness is tightly coupled with TRx capabilities. Higher-capacity TRxs (e.g., 1.2T) consistently deliver superior performance due to their higher SE and better utilization of available bandwidth. However, even with full multi-band deployment (≈16 THz in C+L+S), lower-rate TRxs begin to show signs of saturation under continued exponential traffic growth (400G trend line). These trends confirm that spectral scaling alone cannot indefinitely support long-term network evolution, especially as traffic demand accelerates over years. The system's physical limitations, such as fixed spectrum granularity and increasing fragmentation with lower-rate TRxs, lead to inefficiencies and early blocking. Therefore, to sustain traffic growth beyond what multi-band spectrum can offer, it becomes necessary to consider spatial scaling strategies, such as SDM, which adds capacity by provisioning additional fiber paths per link.

Fig. 13 illustrates the projected demand for fiber pair scaling in an SDM-based optical transport network over a 10-year horizon, assuming the spectral resources remain fixed to the C-band and 1.2T TRxs are used. The vertical bars represent the average number of fiber pairs required across the German core network, while the orange curve on the secondary y-axis indicates the relative growth factor compared to the initial setup.

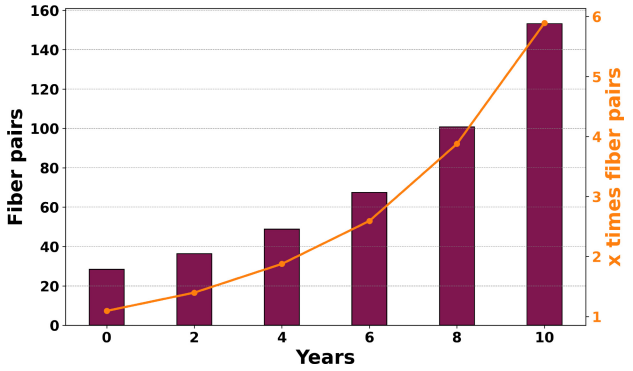

FIGURE 13. Projected increase in required fiber pairs for SDM-based scaling over a 10-year period.

The network begins with 26 fiber pairs, representing the baseline needed to support current traffic loads under single-band operation. As the network evolves and traffic volumes increase year after year, the number of required fiber pairs grows significantly. By Year 2, approximately 36.3 fiber pairs are needed, reflecting a 1.4× increase over the initial configuration. By the end of the 10-year period, this number rises to about 153 fiber pairs, marking nearly a 5.9-fold increase in spatial resource requirements. This projection underscores the effectiveness of SDM in accommodating long-term traffic scaling under a fixed spectral bandwidth regime. With spectrum confined to the C-band and TRx characteristics held constant, increasing the number of parallel fiber pairs emerges as the primary means to extend network capacity. The observed trend demonstrates that SDM offers a straightforward and predictable scaling approach, where capacity can be linearly increased in proportion to fiber availability. This makes SDM a compelling solution for future networks that must sustain traffic growth when further spectral or modulation enhancements are constrained.

However, the results also highlight key trade-offs associated with large-scale fiber deployment. Scaling through SDM requires substantial physical infrastructure investments, including additional fiber installations, increased switching complexity, and higher amplification overhead per link. While SDM presents a theoretically unbounded path to capacity growth, its practical implementation must carefully balance the benefits of increased throughput against the operational and economic burdens of deploying and managing a vastly expanded spatial layer.

VI. CONCLUSION

This paper presented a comprehensive evaluation of capacity scaling strategies for future optical transport networks in response to the exponential growth of IP traffic. By systematically analyzing the interplay between TRx performance, spectral bandwidth utilization, and spatial multiplexing, the study highlights the necessity of adopting a multidimensional approach to scalability. Performance evaluation revealed that upgrading coherent transceivers from 400 G to 1.2 T within the C-band raises supported network traffic from 75 Tbps to 125 Tbps (+66%). Extending spectrum from C (≈4 THz) to full C+L+S (≈16 THz) lifts single-fiber capacity from 75 Tbps (400 G) to 195 Tbps (+160%) and reaches 690 Tbps with 1.2T transceivers. Under a 25% annual traffic growth model, C-band-only configurations reach the 10^{-2} blocking threshold within ≈4–6 years, whereas C+L/C+L+S postpones saturation toward the late decade (depending on TRx). Spatial scaling via SDM is near-linear: increasing from 1 to 6 fibers multiplies capacity by ≈7× at fixed TRx and spectrum (e.g., 1.2 T C+L+S: 600 to 4200 Tbps). Combining multi-band, higher-rate TRx, and SDM yields an overall 56× gain relative to the 400 G, single-fiber, C-band baseline. Looking ahead, the results underscore the importance of designing future networks with flexibility to integrate multiple scaling dimensions. Operators must consider trade-offs between SE, infrastructure cost, and operational complexity to achieve sustainable growth. A hybrid strategy that jointly exploits multi-band spectrum and SDM stands out as the most viable path to future-proof optical infrastructure.

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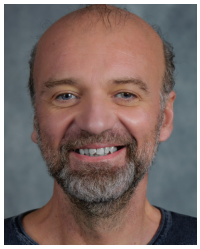

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