Demonstration of Multigranular-Routing Layered Network with Impairment-Aware Modulation Format Selection

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Abstract: We demonstrate the validity of our multigranular-routing layered network architecture that adopts optical bypass. Network simulations show OXC cost reduction by 17% / 21%, while transmission experiments confirm a transmittable distance increase of 500 km. © 2025 The Authors

1. Introduction

The recent evolution of generative artificial intelligence applications using large language models has significantly accelerated traffic growth. To accommodate this ever-increasing demand, it is essential to enhance the capacity of optical transport networks. Current networks typically use wavelength cross-connects (WXCs) based on wavelength selective switches (WSSs). While WSSs offer the necessary operation with path granularity, their relatively large insertion loss and band-pass filtering degrade optical signal quality. Additionally, commercially available WSSs are limited to a degree of approximately 1×50, so WXCs face scalability issues. To address this scalability problem, coarse granularity routing has been explored [1-4], where multiple paths are bundled and routed as a single entity. A common configuration for such networks is the hierarchical optical cross-connect (OXC), where WXCs and coarse granularity routing optical cross-connects (CG-OXCs) are stacked and connected via intra-node fibers. In this setup, WXCs handle add/drop, grooming, and channel power equalization, while CG-OXCs manage express routing. If CG-OXCs could efficiently accommodate large numbers of optical paths, hierarchical OXCs would offer a more cost-effective solution than conventional WXCs. However, the average number of links traversed by optical signals in typical topologies is relatively small, ranging between two and four, which challenges this assumption. Furthermore, the use of intra-node fibers for grooming operations increases the number of OXC components that optical signals must pass through, leading to further signal degradation.

We recently proposed a novel multi-layered network architecture in which the layers adopt different routing granularities [5]. The finest-granularity routing layer, composed of WXCs, manages all path-level operations, including add, drop, express, grooming, and channel power equalization. Coarse-granularity routing layers provide optical bypasses for the finest-granularity routing layer. Since we do not assume an OXC hierarchy within a node, WXCs and CG-OXCs are not interconnected at the same node. Instead, these layers are bridged by inter-node fibers, allowing WXCs and CG-OXCs at different nodes to be connected. This shift from the conventional OXC hierarchy to a network-layer hierarchy minimizes the number of OXC components traversed by optical signals. Consequently, we can reduce transmission impairments while maintaining the cost-efficiency of CG-OXCs, with only marginal network capacity degradation, as all nodes are equipped with WXCs. Our previous work used numerical simulations, to validate the concept, assuming static path allocation.

In this paper, we demonstrate, through both network analysis and transmission experiments, the performance of our layered networks with impairment-aware (IA) modulation format selection targeting the software-defined networking era. By utilizing CG-OXCs, signal quality is enhanced, allowing the use of higher-order modulation formats and subsequently increasing network capacity. Extensive simulations indicate a network capacity improvement of 3.3% compared to a network composed solely of WXCs, while retaining the cost-effectiveness of the CG-OXCs. The effectiveness of this approach is validated through transmission experiments on 128-wavelength 32 Gbaud dual-polarization (DP) QPSK/16QAM signals on a 37.5 GHz grid.

2. Multigranular-Routing Layered Network and its Design Algorithm

For notational simplicity, we make the following assumptions: Optical paths fall on the ITU-T flexible grid, and their modulation formats are adaptively selected based on impairment level. Wavelength conversion and 3R regeneration are not considered. Each network link consists of bundled single-core single-mode fibers (SMFs); however, the following discussion can be generalized to networks using spatial division multiplexing. Figures 1 and 2 illustrate our

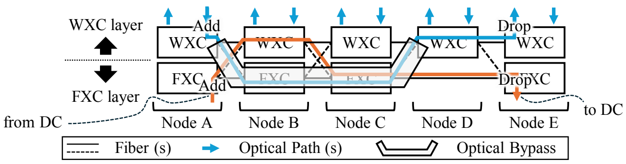

Fig. 1. Our proposed architecture with WXCs and FXCs configuration.

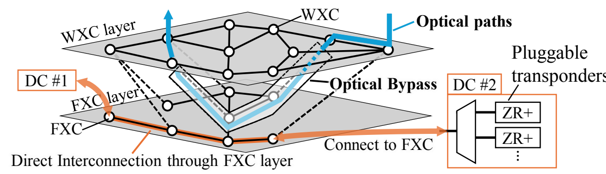

Fig. 2. Layered network model.

recently proposed multigranular-routing layered network architecture. The finest-granularity routing layer, i.e., the WXC layer, handles all path-level operations as described earlier. The coarse-granularity routing layers provide optical bypass functions for the WXC layer. CG-OXCs are placed only where necessary, allowing for sparse distribution. A typical example of CG-OXCs is the use of optical matrix switches as fiber cross-connects (FXCs) and automated-fiber-patches. The WXC and FXC layers are primarily connected by inter-node fibers, as indicated by the dotted lines in Figs. 1 and 2; this inter-node inter-layer connection avoids the need for intra-node fibers. This design minimizes the number of OXC components that optical signals must traverse. Reducing the number of OXC traversals, along with WXC cut-through, mitigates transmission impairments such as loss and spectrum narrowing at nodes. Although not thoroughly discussed in the simulation below, we can also accommodate optical signals emitted directly from pluggable transponders, such as 400ZR+, whose compatibility with wavelength routing networks was demonstrated in a recent study [6]. Although these signals have lower impairment tolerance, our architecture provides impairment-mitigated transmission links by direct connection through the FXC layer (see Fig. 2). This approach offers a cost-effective implementation of data center (DC) interconnections.

The primary advantage of our proposed layered network is improved transmission quality by offloading traffic to the FXC layer. However, in fixed-grid networks using a single modulation format, the full potential of this architecture cannot be realized. To assess the impairment suppression offered by the proposed layered network, we introduce the use of a flexible grid network with IA modulation format selection. This approach allows the gain from offloading to FXCs to be applied toward increasing the modulation order, thereby enhancing the efficiency of network resource utilization. The following method designs layered networks for given traffic distributions.

<Design of Layered Networks with Impairment-Aware Modulation Format Selection>

Derive a WXC-based network for given expected traffic distribution through a static network design process; routes that minimize the number of fibers deployed on the links are selected. Estimate the impairment levels for each path and assign appropriate modulation formats accordingly. Search for sequences of fibers across multiple consecutive links that carry the same optical paths. If found, convert these fiber sequences into optical bypasses through the coarse-granularity routing layer. Remove all paths, keeping the fibers unchanged, and then reallocate the paths. If necessary, install new fibers to accommodate the traffic demands. Repeat this procedure until no further bypass conversions occur or the increase in the number of fibers relative to the initial network exceeds a given threshold, δ [5].

3. Numerical Simulations

We conducted numerical simulations to evaluate the performance of our layered network under dynamic path operation. First, we designed a two-layered configuration with WXCs and FXCs, as described in Section 2. Data rates for each path were randomly set at 100, 400, or 800 Gbps, with modulation formats adaptively chosen based on the receiver SNR, which was calculated using an amplifier chain model to determine the system noise figure (NF) [7]. The SNR at the transmitter side was set to 48 dB. Table 1 presents the required slots for each modulation format. The receiver SNR thresholds were set to 14.91 dB, 12.38 dB, and 8.33 dB, in descending order of modulation order. The frequency range was set to 4.8 THz, divided into 384 slots, and the maximum repeater span was 80 km. The losses were set to 0.2 dB/km for fiber, 7 dB for WSS, and 1 dB for $N\times N$ optical matrix switches. The amplifier NF was assumed to be 6 dB. We used WXCs with the route-and-select (R&S) configuration and FXCs consisting of $N\times N$ switches. For each path setup request, we selected the route with consideration for link load balancing, and established the path through the coarser routing layer whenever possible. The spectrum was assigned using a first-fit approach. The WXC-based network with the same fiber configuration was served as the baseline for comparison.

Figure 3 presents the data-rate-weighted blocking ratio for two tested topologies: Japan JPN25 and Italia [8,9]. Our proposed architecture outperforms the baseline scheme by 3.3% / 1.6% when the target blocking ratio is set

Table 1. The number of slots needed for each path.

	100 Gbps	400 Gbps	800 Gbps
DP-QPSK	4 slots	14 slots	26 slots
DP-8QAM	3 slots	9 slots	18 slots
DP-16QAM	3 slots	8 slots	14 slots

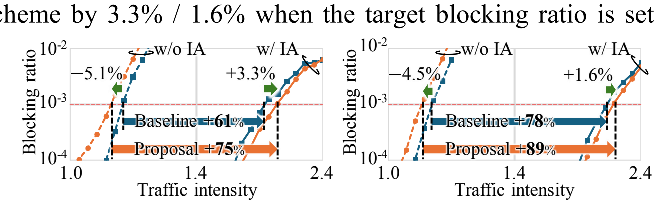

Fig. 3. Blocking ratio weighted with data rate on JPN25 (left) and Italia (right).

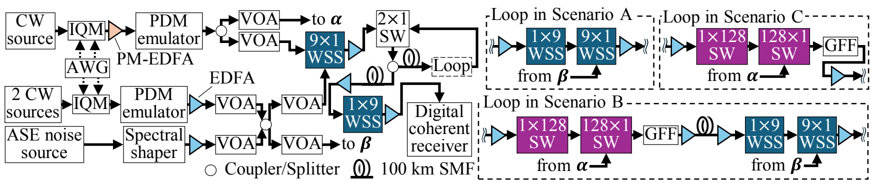

Fig. 4. Experimental setup.

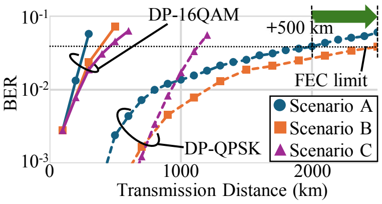

Fig. 5. BER versus transmission distance.

to 10^{-3}, even though the baseline scheme has no routing constraints. In addition, by replacing some WXCs with low-cost FXCs, the total OXC cost reduction compared to the baseline reaches 17% / 21% when the FXC port cost is 0.02 times that of the WXC port [5]. This reduction in hardware costs of the proposed scheme is achieved by accepting certain routing constraints. However, the integration of IA modulation format selection allows the proposed architecture to not only compensate for the penalties imposed by these routing restrictions but also enhance overall network capacity. As proof of that, while the proposed scheme underperforms the baseline without considering impairment levels, it outperforms the baseline with IA modulation format selection. This improvement is driven by the availability of spectrally efficient higher-order modulation formats for the optical paths that utilize optical bypasses provided by the FXC layer, which experiences fewer impairments than the WXC layer. Notably, the amplifier chain model considers only transmission link losses; thus, the performance gap in favor of the proposed architecture would likely widen if other impairments, such as spectrum narrowing, were taken into account. Consequently, our proposed architecture, in conjunction with IA modulation format selection, offers even higher cost-performance efficiency.

4. Transmission Experiments

We experimentally confirmed the transmission performance of the proposed network. Figure 4 illustrates the experimental setup. A 32 Gbaud DP-QPSK/16QAM signal was generated using an IQ modulator (IQM) driven by an arbitrary waveform generator (AWG), with polarization division multiplexing (PDM) realized by the split-delay-combine method. Two non-target signals, with wavelengths adjacent to the target signal, were generated using the same process. Additionally, 125-wavelength signals aligned on a 37.5 GHz grid were emulated using an amplified spontaneous emission (ASE) noise source and a spectral shaper. After adjusting signal power with variable optical attenuators (VOAs) and erbium-doped fiber amplifiers (EDFAs), all signals were combined via a 2×2 coupler and a 9×1 WSS, resulting in 128-wavelength signals emulating ultra-dense WDM across the full extended C-band. The signals then entered a recirculating fiber loop. Tests considered three scenarios: In Scenario A, the loop consisted of a 100 km SMF, EDFAs, and an R&S configuration WXC. Scenario B, representing our proposed architecture, added an FXC and a gain-flattening filter (GFF) to the loop configuration of Scenario A, with the FXC consisting of a 1×128 MEMS switch and a 128×1 MEMS switch. Scenario B corresponds to the most frequent case in the numerical simulations. In Scenario C, the loop consisted of a 100 km SMF, EDFAs, an FXC, and GFF. After multiple circuits of the loop, the target signal was dropped using a 1×9 WSS and coherently detected. It is important to note that the target signal experienced spectrum narrowing at each WXC traversal.

Figure 5 plots the BER versus transmission distance for the three scenarios. Comparing Scenarios A and B, we confirmed that offloading optical signals from the WXC to the FXC enhanced signal quality due to the FXC's lower loss and reduced spectrum narrowing at the WXC. However, in Scenario C, despite using the FXC at every node traversal, signal quality deteriorated compared to Scenario B over longer distances. This degradation was attributed to the collapse of signal gain flatness during the experiments, even though initial flatness was set within 0.5 dB using the GFF. In contrast, in Scenario B, signal power flatness can be maintained since WXCs are inserted at appropriate intervals. These results indicate that the combined use of FXCs and WXCs, which are connected with inter-node fibers, provides the most effective solution from both hardware cost and transmission performance perspectives.

5. Conclusion

In this paper, we conducted numerical simulations and transmission experiments to verify the performance of our proposed layered network. The results demonstrate that our proposed layered network can achieve both low hardware cost and good spectral efficiency. Additionally, our layered network is capable of accommodating various modulation formats and traffic demands, making it a versatile solution for future optical transport systems.

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