Impact of Waveband and Wavelength Switching in the
Next-Generation Optical Networks

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***Abstract*—The rapid and significant increase in Internet traffic, driven by developments in 5G/6G mobile communications, video streaming, cloud computing, and other high-bandwidth applications, challenges the capabilities of existing optical network infrastructures. This progress necessitates the creation of optical networks that can be expanded, have large capacity, and are affordable. This article evaluates the performance of a new multi-band optical cross-connect (OXC) architecture that uses waveband (WB) switching technologies at the network level. WB switching, a technique that combines many wavelengths into larger bands for more efficient routing, is a potential solution to overcome future optical networks' scalability and complexity issues. WB switching streamlines network design and decreases operating costs by decreasing the number of necessary switching components, in contrast to standard wavelength (WL) switching, which treats each wavelength as a separate route. Our study, using extensive simulation evaluations, demonstrates the possibility of this design to provide the extensive parallelism and bandwidth capacity required for next-generation bandwidth-intensive optical networks. The results suggest that WB switching can greatly improve network performance by providing a simplified yet effective method for managing increasing data traffic. This represents a feasible way to achieve bandwidth-rich and highly parallel optical networks for the 6G era and beyond. This contribution establishes the foundation for future studies on enhancing optical network designs to address the increasing requirements of global communication without going into the details of routing and spectrum assignment schemes.**

***Index Terms*—Hierarchical optical network; Waveband paths; Multi-band transmission.**

I. Introduction

The exponential growth in Internet traffic, driven by recent technological advancements such as 5G/6G mobile communications, high-bandwidth applications including video streaming services, virtual reality (VR), augmented reality (AR), and the increasing reliance on cloud computing [1], presents significant challenges to the underlying network infrastructure. This surge in data traffic necessitates the development of cost-effective, bandwidth-abundant optical networks capable of supporting massive data capacities while ensuring high levels of reliability and energy efficiency.

Current optical switching systems, predominantly based on reconfigurable optical add-drop multiplexers (ROADMs) and optical cross-connects (OXCs) [2], utilize wavelength-selective switches (WSSs) that are limited in their port count, typically maxing out at 35 [3]. This limitation poses a substantial network scalability and flexibility bottleneck, particularly as we edge closer to the 6G era, characterized by ultra-high-speed, dense communication networks. The traditional approach to overcoming the port count limitation involves cascading multiple WSSs, a method that increases the system's complexity and cost and introduces additional transmission losses [4]. These losses necessitate the use of more optical amplifiers, further complicating the network architecture and degrading the signal quality through added noise. A potential solution to these challenges lies in adopting WB switching technology [5]. Unlike conventional WL switching, which routes optical signals based on their individual wavelengths, WB switching aggregates multiple wavelengths into a single WB, allowing them to be routed as a unified entity. This aggregation reduces the number of switching components required, simplifying the network architecture, reducing costs, and minimizing transmission losses. However, this method introduces a coarse granular routing limitation, which, while posing a slight performance penalty, can be mitigated using sophisticated routing and spectrum assignment strategies [6].

In this paper, we perform a networking performance analysis of an optical node switching system for multi-band optical networks that realizes switching in two steps: grouping WLs and switching them as WB paths. For each input port, a set of multiple continuous WLs are grouped and form WB. This work considered the OXC architecture proposed in [7], in which small-port-count WSSs for two frequency bands (C+L) are used as dynamic optical filters to form WBs. In this investigation, instead of using separate WSSs for the (C+L) bands, we considered a single modular multi-band WSS that can operate in the low-loss region, i.e., C+L+S bands [8]. The analysis performed in this work shows that conventional WL

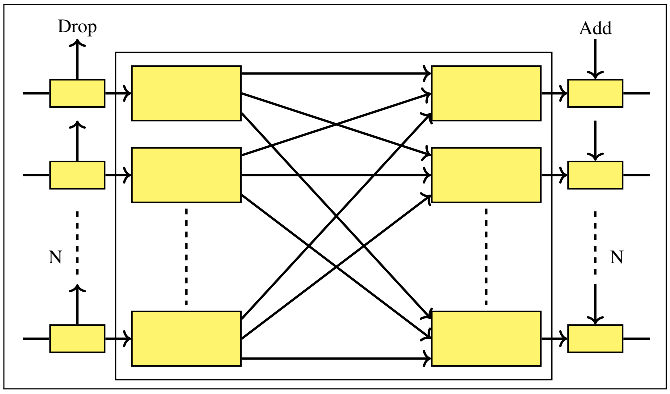

Fig. 1: Wavelength enabled node architecture

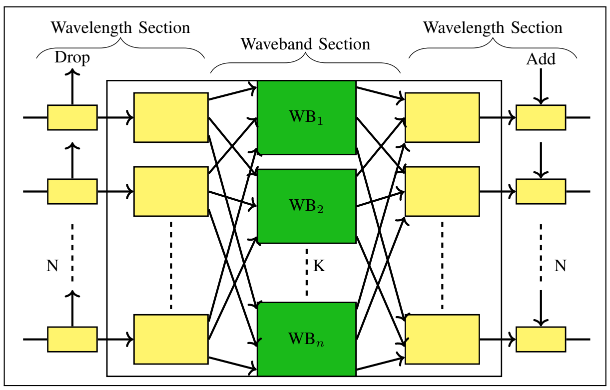

Fig. 2: Waveband enabled node architecture.

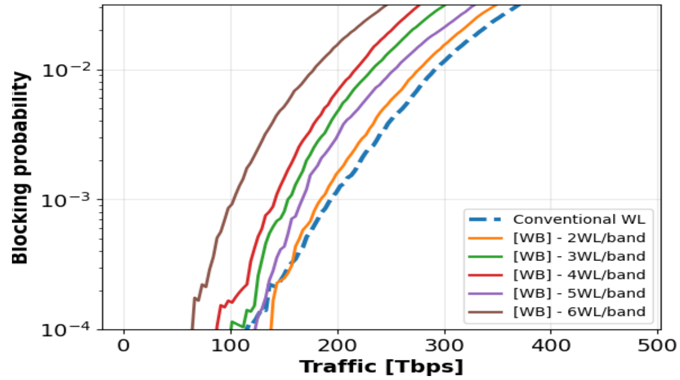

Fig. 3: Blocking probability vs. traffic for wavelength and waveband enabled network.

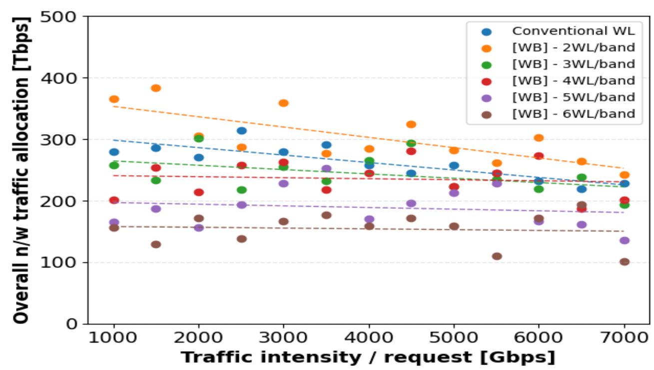

Fig. 4: Impact of waveband size (M) on overall Network Traffic

routing is no longer feasible for the upcoming bandwidth-abundant optical networks where routing bandwidth increases and eventually reaches full band or fiber routing; the potential alternative to traditional WL routing is cost-effective and simple WB routing.

II. Simulation Setup for Waveband-Enabled Network

Fig. 1 shows the OXC architecture, which depicts the conventional WL-based switching system that utilizes the wavelength-granular routing method. In parallel, Fig. 2 shows the coarse-granular routing scheme, WB routing. In this granularity of the WB, the routing operation involves three main steps: optical paths from the incoming fibers are initially grouped into M WBs. The construction of WB follows WL continuity and contiguity constraints. Then, the M WBs are independently routed to the connected outgoing fiber port. Lastly, the WBs that arrive at any fiber port are coupled to deliver the WBs to more outgoing fibers. This work only performs the networking-level analysis of OXC architecture, in which we assess the effect of WL and WB routing on the networking scale; the device-level functionality is out of the scope of this article. The device-level study has already been performed in [9].

The network performance is examined to discover the effect of the WL and WB architectures on the optical transport system. For this purpose, the statistical network assessment process (SNAP) [10] is utilized, which operates on the physical layer of the tested network and is based on the degradation in quality of transmission (QoT) caused by each network element. The simulation is performed for the multi-band optical system. The multi-band transmission system requires different networking components, mainly optical amplifiers [11]. The amplifiers considered for this analysis are commercially available erbium-doped fiber amplifiers (EDFAs) for the C- and L-band and thulium-doped fiber amplifiers (TDFAs) for the S-band [12]. The fiber in the amplified lines is a standard single-mode fiber with a span length of 75 km. In this work, we examined a 1600 G transmission system employing a transceiver with a free spectral range (FSR) of 220 GHz and a symbol rate of 200 GBaud [13]. The input power for each band is optimized, following a span-by-span strategy using the local optimization global optimization (LOGO) algorithm based on maximizing QoT [14]. The simulation considered a total spectrum of almost 16 THz C-band 18-channels ($\approx$4 THz), L-band 27-channels ($\approx$6 THz), and S-band 27-channels ($\approx$6 THz).

In addition to this, for the conventional WL switching system, every channel is routed. On the other hand, in the WB switching architecture, WLs are initially grouped up, keeping continuity constraints; the minimum 2WL/band ($M = 2$)

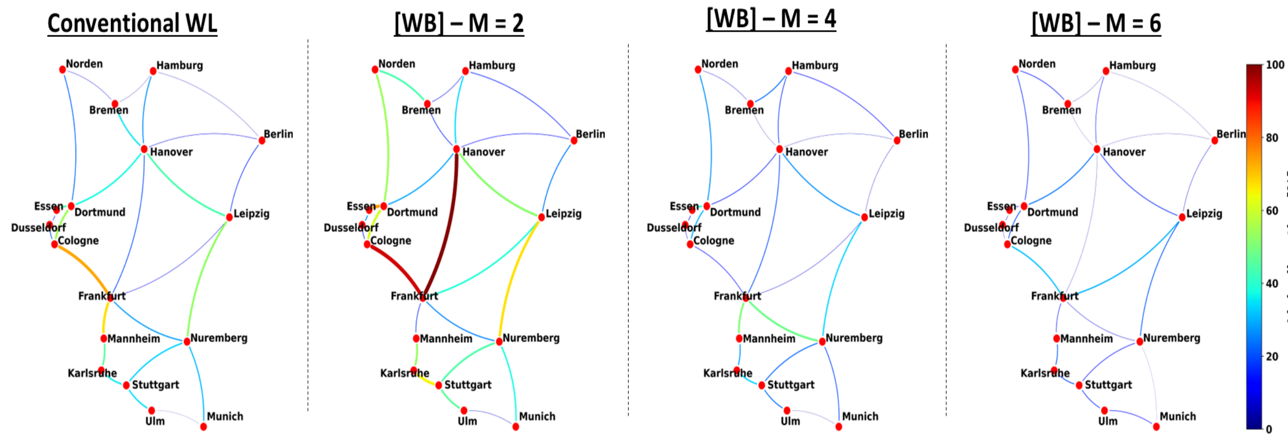

Fig. 5: Heat map of traffic distribution for wavelength - WL and waveband - WB $(M = 2, 4, 6)$ enabled network.

and maximum 6WL/band ($M = 6$) are considered. The clustered WL are routed together as a single WB at a given time. Furthermore, the analysis considers the German network topology of 17 optical nodes and 26 edges. OXCs are regarded as optical nodes where traffic requests are added/dropped. The edges represent the optical line systems, including fiber pairs and inline amplifiers. Moreover, the average node degree of a German network is 3.1 with an average inter-node distance of 207 km and a maximum link length of 300 km [15]. Finally, a uniform traffic distribution for all nodes of the network is considered for this simulation.

III. Results and Conclusion

To assess the impact of the WB architecture on networking performance relative to the conventional WL architecture, we performed comprehensive simulations across various network scenarios and uniform traffic profiles. Fig. 3 illustrates the allocation of network traffic as a function of blocking probability (BP) for both the conventional WL ($M = 1$) and the WB architectures over a range of values for M, specifically $M = 2-6$, and a fixed uniform traffic profile of 3500 Gbps per request. For this specific traffic profile, keeping $BP = 10^{-2}$, the WL case allocates $\approx$ 290 Tbps. In contrast, the WB case ($M = 2$) allocates $\approx$ 273 Tbps (5% lesser). For $M = 3, 4, 5, 6$, the overall traffic allocation is $\approx$ 243 Tbps (16.21% lesser), $\approx$ 217 Tbps (25.5% lesser), $\approx$ 252 Tbps (12.07% lesser), $\approx$ 178 Tbps (38.27% lesser), respectively. For M = 2,3,4,5, and 6, the traffic allocation is lesser than the M =1 case due to the spectrum wastage at 3500 Gbps traffic profile.

Fig. 4 illustrates the network performance regarding overall traffic allocation across a range of traffic intensities for $BP = 10^{-2}$. As the traffic intensity per request increases, a decline is observed in the overall allocation of network traffic for the WB architecture across varying values of M ranging from 2 to 6. A comparison between the conventional WL and WB cases reveals a notable distinction: the steeper slope in the conventional WL leads to an earlier occurrence of traffic request blocking, attributed to the constraints imposed by limited channel bandwidth. However, the WL has a steeper slope in the overall network traffic allocation, and the trend shows that the WB cases will surpass the WL case for greater intensity.

Fig. 5 depicts the traffic allocation per link in the context of the conventional WL architecture compared to WB with $M = 2, 4, 6$. This specific scenario involves a fixed traffic profile, and a heat map is used to visualize the data, where blue represents 0% allocation and red represents 100% traffic allocation per link. In the WB ($M = 2$) case, the maximum traffic allocated for this scenario reaches 18.7 Tbps on the Frankfurt-Hanover link. All instances are normalized to facilitate comparison based on this highest traffic allocation.

The findings of our study underscore the viability of WB switching in addressing the bandwidth scalability challenges posed by next-generation optical networks. This approach not only demonstrates a notable improvement in network performance but also presents a scalable and cost-effective alternative to conventional WL switching mechanisms. With the advancement of optical networks to meet the increasing needs of 6G and future generations, the importance of scalable and efficient network architectures becomes crucial. The implementation of WB switching represents a substantial advancement in the pursuit of this objective. Ensuring seamless interoperability between different network components and across various network layers is crucial for the widespread adoption of WB switching. Efforts should be made to establish comprehensive standards and protocols that facilitate interoperability and enable a smooth transition from existing WL-based architectures.

IV. Conclusion and Future Work

This paper has presented a comprehensive analysis of the impact of WB and WL switching in next-generation optical networks. Our findings highlight the superiority of WB switching in terms of network performance and cost-effectiveness, making it an attractive option for future bandwidth-abundant and massively parallel optical networks. As we stand on the cusp of the 6G era, it is imperative to continue exploring innovative optical networking technologies that can meet the escalating demands for high-speed, reliable communication infrastructures. The path forward will undoubtedly require a concerted effort from researchers, industry stakeholders, and policymakers to realize the full potential of these groundbreaking technologies.

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