Implications of deploying Optical Phase Conjugators (OPCs) to reduce DSP overhead in a dynamic WDM coherent optical network

Boyang Hu*, Mrudula Krishna†, Deepa Venkitesh† and Byrav Ramamurthy*
*School of Computing, University of Nebraska–Lincoln, Lincoln, NE 68588-0115, USA
Email: boyang.hu@huskers.unl.edu, ramamurthy@unl.edu
†Department of Electrical Engineering, Indian Institute of Technology Madras, Chennai, India
Email: ee19d017@smail.iitm.ac.in, deepa@ee.iitm.ac.in

***Abstract*—This paper introduces a novel approach to optimizing dynamic Wavelength Division Multiplexing (WDM) optical networks by deploying Optical Phase Conjugators (OPCs). Optical networks, central to modern communication infrastructures, face significant challenges in managing signal impairments due to fiber dispersion and nonlinearity. These impairments often require extensive Digital Signal Processing (DSP), increasing operational costs and energy consumption. Our research proposes a new network architecture incorporating OPCs, utilizing mid-span spectral inversion (MSSI) to mitigate these impairments effectively. The placement of OPCs is crucial, ideally at the mid-span of the signal path, to ensure complete all-optical dispersion and nonlinearity compensation. However, this presents a challenge in dynamic networks where link routes vary, affecting the distance from the mid-span and the associated equalizer requirements. Addressing this gap, our work provides a comprehensive analysis of a network architecture incorporating OPCs, which is used to reduce digital signal processing overhead while maintaining signal integrity. Through simulations of two network topologies, we explore the practical implications and trade-offs of OPC implementation. Our results highlight the potential of OPCs in enhancing network performance, particularly in reducing operational costs and energy consumption. This paper significantly contributes to the field by showcasing the feasibility and benefits of OPC integration in dynamic optical networks, offering insights into creating more efficient and sustainable communication infrastructures.**

***Keywords*—Optical network simulation, Coherent optical networks, Optical phase conjugators, Digital signal processing**

I. Introduction

Optical networks, the backbone of modern telecommunications, rely on advanced technologies to maintain signal integrity, manage bandwidth, and enhance network flexibility. Advanced modulation techniques, regenerators, Wavelength Converters (WCs), and Optical Phase Conjugators play pivotal roles among these technologies. Each of these components serves a unique function in combating signal degradation, managing wavelength resources, and improving overall network performance. Advanced modulation formats like Quadrature Phase Shift Keying (QPSK) and m-Quadrature Amplitude Modulation (mQAM) have become feasible in optical communication systems, thanks to efficient Digital Signal Processing at both transmitters and receivers. This development is crucial in today's information era, where there's a constant demand for transmitting higher data rates. These advanced formats achieve this by encoding information in the electric field's amplitude, phase, and polarization. However, data transmitted through such coherent modulation formats often faces impairments. These include phase noise from the transmitter and local oscillator lasers, frequency offsets between lasers, polarization mixing, chromatic dispersion, and fiber nonlinearities. Among these, chromatic dispersion compensation demands the highest DSP overhead [1]. To mitigate fiber nonlinearities, optical power control, and advanced machine learning algorithms are often employed [2], although these approaches also introduce significant signal processing overheads.

Regenerators are crucial for restoring signal integrity through re-amplification, re-shaping, and potentially re-timing, but they involve O/E/O conversions, adding complexity and power consumption [3]. Wavelength Converters enhance network flexibility and wavelength management, available in O/E/O or all-optical forms, with considerations for shared or dedicated deployment impacting availability and resource efficiency [4]. Optical Phase Conjugators [5] provide advanced all-optical signal restoration capabilities, particularly effective for long-haul transmissions by compensating for dispersion and nonlinearities, albeit with inherent conversion losses and efficiency considerations. Both optical wavelength conversion and OPC utilize four-wave mixing, with Semiconductor Optical Amplifiers (SOA) being the preferred nonlinear medium due to their high efficiency, compact size, and integration capability in photonic circuits [6]–[8]. However, wavelength conversion and OPC roles in a network differ substantially. Conventional conjugate generation involves a nonlinear medium like an SOA, where the signal and a strong pump beam at different wavelengths are introduced. SOAs, gaining prominence for their potential ability to induce nonlinearities at low input power levels [9] and their suitability as amplifiers, enable compact designs conducive to photonic circuit integration. This adaptability makes SOAs ideal for compact and integrable phase conjugation applications within photonic circuits.

978-3-903176-62-1 © 2024 IFIP

All-optical techniques, particularly Optical Phase Conjugation with Mid-Span Spectral Inversion, have demonstrated effectiveness in compensating for both dispersion and nonlinearity-induced impairments in fibers [9]. As symbol rates scale up, the importance of dispersion compensation intensifies due to the inversely proportional increase of equalizer taps with the square of the sampling period [10]. Additionally, as the number of constellation points rises, so do the Signal-Noise Ratio (SNR) and vertical resolution demands of the analog-to-digital converters in the receivers. Consequently, the significance of Optical Phase Conjugation becomes increasingly apparent in advanced transceivers characterized by higher symbol rates and denser constellations.

While there have been successful field demonstrations of multi-wavelength, point-to-point links with mid-span OPCs, the application of OPC within a network context remains less explored [11]. Some previous studies, like [12], focused on network layer optimization, introduce Bit Error Rate (BER) based call-admission algorithms that account for various physical layer impairments, demonstrate its substantial influence on the performance of realistic wavelength-routed optical networks. Another research, [4] focused on all-optical wavelength conversion and network implementation strategies, but the constraints on the network with OPC implementation are quite different. Our paper aims to bridge this gap by exploring potential network architectures incorporating OPC, supported by simulations on two sample networks, to highlight the trade-offs in OPC network implementations.

The structure of the paper is as follows: Section II explores the historical development of Optical Phase Conjugation and its applications in Coherent WDM Networks. It also reviews related literature, discussing recent advancements and potential challenges. Section III elaborates on our proposed network architecture and highlights the challenges in OPC implementation. Section IV introduces our OPC Position Identification algorithm. Section V presents our simulation results and key findings, providing insights into the implications of the study. The paper concludes with Section VI, which summarizes our contributions and suggests directions for future research.

II. OPC in Coherent WDM Networks

OPC has been widely studied and implemented for dispersion compensation in optical fibers in the context of Coherent WDM Networks. The phase-conjugated signal can counteract the dispersion-induced pulse broadening, allowing for clearer signal transmission over long distances [13]. Optical fibers exhibit nonlinear characteristics, especially at high power levels, leading to signal distortion. OPC helps mitigate these nonlinear effects, thereby maintaining the integrity of the transmitted signal [14]. The need for electronic dispersion compensation and complex optical amplification can be reduced by employing OPC, leading to simpler and potentially more cost-effective optical network architectures [15]. Studies [16] have shown that incorporating OPC in optical networks can improve overall system performance, including improved signal-to-noise ratios and extended transmission distances without the need for regeneration.

In recent years, technological advancements have enabled more practical and efficient implementations of OPC in optical networks. The integration of OPC with advanced modulation formats and coherent detection technologies has opened up new possibilities for further enhancing the capacity and reach of optical communication systems. Research continues to explore novel materials and techniques for OPC, aiming to overcome current limitations and unlock the full potential of this technology in future optical networks. Optical Phase Conjugation has evolved from a theoretical concept to a practical tool in optical communications, offering unique solutions to some of the most challenging problems in long-distance fiber optic transmission. As optical network technologies continue to advance, the role of OPC is likely to become increasingly significant in achieving higher capacities and longer transmission distances in the global communication infrastructure.

For effective all-optical dispersion and nonlinearity compensation through OPC, its placement must be exact, ideally at the mid-span of the signal path. Network routes can present challenges like differential distances from the mid-span, influencing the requirement for equalizer taps. These factors, crucial in assessing the cost-effectiveness and energy efficiency of OPC, have not been adequately studied.

Despite the advantages of the implementation of OPC in coherent WDM networks, there are some challenges that we need to consider, including nonlinear media, system complexity, and noise management. The successful integration of OPC into coherent WDM networks requires careful consideration of the nonlinear media, system complexity, and noise management. As research and technology advance, OPC remains a key area of interest for overcoming the limitations of current optical communication systems and paving the way for next-generation high-capacity networks.

III. Proposed network architecture with OPC and network implications

The utilization of Optical Phase Conjugation for compensating dispersion and nonlinearity, along with the necessary operating conditions, is illustrated in Figure 1a.

When a phase-modulated signal (field, A) passes through a fiber of length L_1, the accumulated phase is determined by the product of second order dispersion parameter ($\beta_{2(1)}$) and the length L_1, as well as the nonlinearity coefficient (γ_1) and the instantaneous power (P_1). If the conjugate of the signal (A^*) is transmitted through a second fiber segment of length L_2, and the specific conditions outlined in Figure 1(a) are met, then the accumulated phase can be fully compensated all-optically. Fig. 1(a) also shows the corresponding nonlinear Schrodinger equations leading to these conditions. For the sake of simplicity, this study assumes that all fibers in the network share similar values of β_2 and power (P). OPC implementations rely on four-wave mixing (FWM), and we propose to use SOAs as the nonlinear media. These SOAs can function both as OPC in the presence of a pump laser and

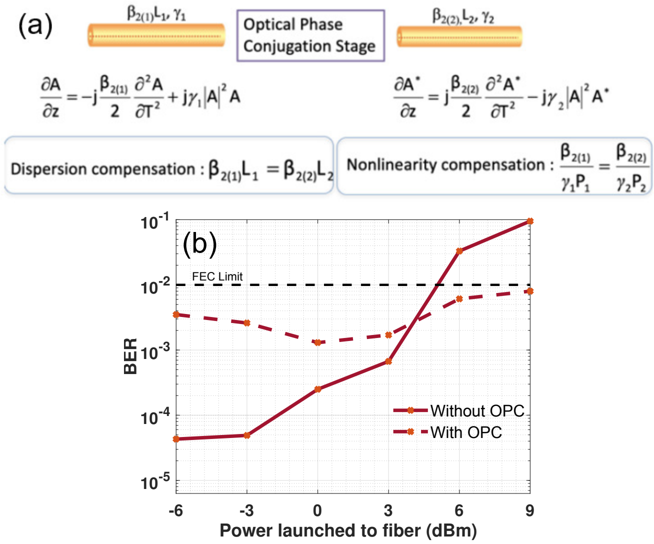


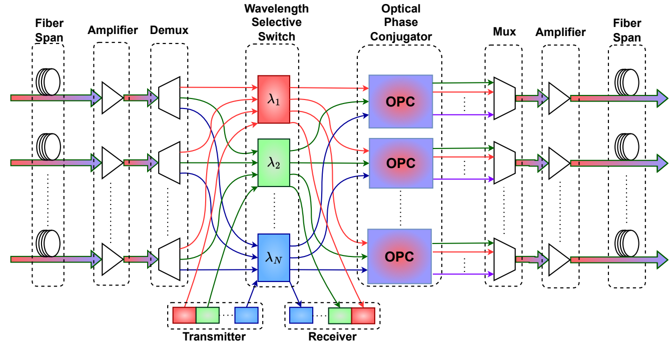
Fig. 1: (a) Working principle of OPC-based compensation (b) BER performance of SOA-based phase conjugator.

as amplifiers as required. Fig.1(b) shows the experimentally measured BER performance with OPC (dashed line) and without (solid line) OPC in an SOA-based setup, connecting two 50 km fiber spans for 160 Gbps PM-16QAM data, which clearly indicates that OPC helps in launching more power into the fiber by compensating the fiber nonlinearities. In scenarios where OPC is not employed, DSP algorithms are used to counteract dispersion and nonlinearity-induced phase shifts. SOAs provide higher efficiencies and smaller footprints than other nonlinear media and can be integrated into a photonic circuit [9].

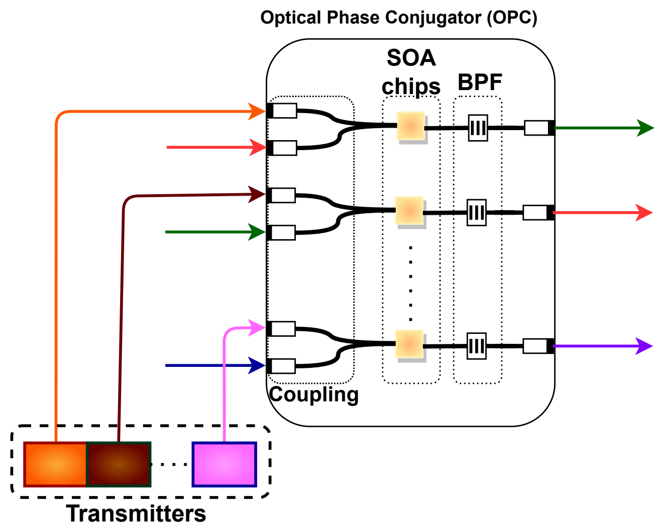
The proposed architecture for the wavelength routing node or reconfigurable optical add-drop multiplexer (ROADM) is as shown in Fig. 2(a). This wavelength routing node operates as the stage between fiber spans in an optical network and is responsible for wavelength switching/routing.

The front-end optical amplifiers in our proposed architecture initially compensate for span loss. This is followed by an array of demultiplexers segregating incoming signals, directing them to the optical wavelength-routing switches (WRS) or wavelength-selective switches (WSS). After this, the OPC stage is implemented before the signals are multiplexed. Our proposed design for the OPC chip is detailed in Fig. 2(b). Each incoming signal is coupled with a specific pump wavelength on the chip to generate the desired conjugate wavelength. This conjugate is then selectively filtered using a bandpass filter as needed. The filtered conjugate proceeds through the wavelength multiplexer and is amplified before its onward transmission.

The efficiency of conjugate generation and its optical signal-to-noise ratio (OSNR) is decided by the pump-signal detuning [9] and therefore, we propose an SOA bank with multiple pump wavelengths to handle all WDM channels. It's crucial that the wavelength spacing between the pump



(a)



(b)

Fig. 2: Proposed architecture for (a) wavelength routing node (b) phase conjugator in photonic integrated chip.

and signal matches the WDM channel spacing, ensuring that the conjugate spacing also adheres to the International Telecommunications Union (ITU) grid spacing, either 50 GHz or 100 GHz.

The WRS in our system is equipped with transmitters and receivers for reconfigurable add-drop multiplexing. The multiplexed signal suffers losses from the demultiplexer, WSS, and multiplexer, which are then compensated by a second amplifier. The boosted WDM signal is then ready for transmission over the next fiber span. The system also includes the capability to add and remove wavelengths, allowing for the modification of data transmission from one wavelength to another.

The energy consumption of a single SOA for phase conjugation, including the pump laser used for FWM, is less than 1W, regardless of the modulation formats employed. Notably, SOAs can also function as amplifiers for signals when required. This energy usage per bit is substantially lower than DSP, particularly at higher bit rates.

However, one critical aspect in the network implementation of OPC is its placement. Ideally, the WRS for conjugation should be activated precisely at the midpoint of the chosen path, ensuring that the conjugate wavelength is accessible throughout the remainder of the path. Yet, a significant challenge arises since, for any given source and destination in a network, finding a route with a router exactly at the mid-span might not always be feasible. Consequently, when OPC is implemented in a network, residual dispersion and nonlinear phases may require further compensation. Despite this, the all-optical approach to dispersion compensation still offers considerable energy savings. The overall power consumption of an SOA is notably low, under 1 W. Additionally, the flexibility of SOAs to serve dual roles as either amplifiers or OPC devices further enhances their utility in network configurations.

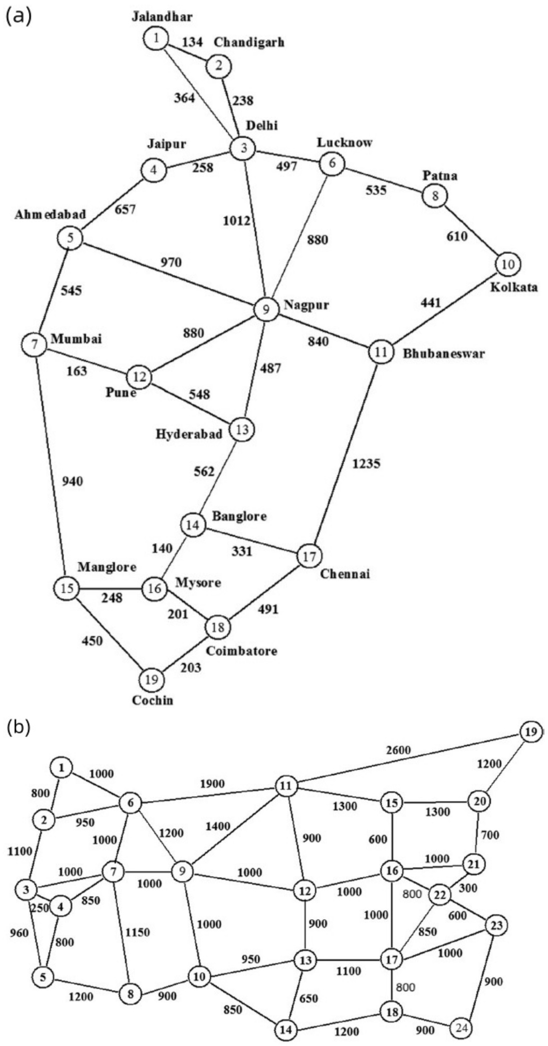


Fig. 3: Network Topologies (a) 19-nodes RailTel Network (b) 24-nodes USNET.

IV. OPC Position Identification Algorithm

The OPC will be deployed in all the nodes in the topology. Ideally, only the OPC at the middle point of the light path can be activated to compensate for the dispersion and mitigate the

---

Algorithm 1 OPC Position Identification

Input: Network topology N as a graph, potential paths P, distance function D
Output: Optimal OPC node position and unbalanced distance for each path

procedure INITIALIZE
  for each path $p \in P$ **do**
    Initialize variables for optimal OPC position and minimum unbalanced distance
  end for
end procedure

procedure PATH ANALYSIS
  for each path $p \in P$ **do**
    Compute total distance of p
    Identify midpoint of p in terms of distance
    Initialize cumulative distance $cumDist = 0$
    for each node $n \in p$ until midpoint is surpassed **do**
      $cumDist \leftarrow cumDist +$ distance to next node
    end for
  end for
end procedure

procedure OPC POSITION IDENTIFICATION
  for each path $p \in P$ **do**
    Identify nodes n_{before} and n_{after} surrounding the midpoint
    Calculate absolute value of unbalanced distance D_{before} for n_{before}
    $D_{before} = |p - 2 * D_{n_{before}}|$, ($D_{n_{before}}$ is distance from source to n_{before})
    Calculate unbalanced distance D_{after} for n_{after}
    $D_{after} = |p - 2 * D_{n_{after}}|$, ($D_{n_{after}}$ is distance from source to n_{after})
    if $D_{before} \leq D_{after}$ **then**
      Optimal OPC position $\leftarrow n_{before}$
    else
      Optimal OPC position $\leftarrow n_{after}$
    end if
  end for
end procedure

procedure OUTPUT
  for each path $p \in P$ **do**
    Record optimal OPC position and corresponding unbalanced distance
  end for
end procedure

nonlinearities fully. In a given static network topology, the exact middle point is often unavailable; thus, finding the node closest to the middle point and measuring the residual distance is important. The OPC Position Identification algorithm aims to determine the most suitable node for placing an OPC device in a network topology, focusing on minimizing the unbalanced distance of the network's paths, thereby enhancing the network's performance by effectively mitigating dispersion and nonlinearities. We assume homogeneity in fiber properties across the network. Our proposed Algorithm is outlined in Algorithm 1. It takes into account the network's topology (N), a set of potential paths (P). Then, it employs a function (D) to calculate the unbalanced distance of a path. It first identifies two nodes surrounding the midpoint of the path, labeled as n_{before} and n_{after}. It then calculates the unbalanced distance for the node before the midpoint D_{before}, which is the absolute difference between the total path length p and twice the distance from the source to n_{before}. Similarly, it calculates the unbalanced distance for the node after the midpoint D_{after}. The algorithm compares these unbalanced distances, and the node with the smaller unbalanced distance is selected as the optimal position for OPC placement. If D_{before} is less than or equal to D_{after}, the node before the midpoint is chosen; otherwise, the node after the midpoint is selected. This process is repeated for each path within the network to determine the best OPC placement positions.

V. Simulation Results and Discussion

This section provides a detailed comparative analysis of OPC efficacy in enhancing network performance, specifically focusing on the metric of residual distance. Our analysis employs the advanced SIMON coherent model [17] for simulations, enabling a precise examination of the average mid-span residual distances across various routes. The statistical interpretation of these results provides a nuanced understanding of OPC's impact on network efficiency.

In this study, we conducted an in-depth analysis of two network topologies [18]: Fig. 3(a), a 19-node RailTel India network featuring 28 bidirectional links with distances ranging from 134 km to 1235 km and Fig. 3(b), a larger 24-node US-NET network with 43 bidirectional links with link distances extending from 250 km to a substantial 2600 km.

Fig. 4(a) illustrates the residual distance distribution across two network topologies, highlighting the variability in network performance and the impact of OPC. Fig. 4(b) delves into the shortest path distances between all source-destination pairs, showcasing a broader distribution in the US topology relative to the Indian one. This disparity underscores the increased challenges in OPC deployment within networks characterized by longer inter-node distances, primarily due to the heightened complexity in compensating for dispersion effects. Furthermore, Fig. 4(c) displays the distribution of unbalanced distances (the absolute difference between the distances from the source to the OPC location and from the OPC to the destination) in both networks, sorted by ascending unbalanced distance. Excluding adjacent locations, the Indian network has 286 paths with shorter unbalanced distances, in contrast to the US network's 465 paths, which typically cover longer distances, highlighting the greater complexities of OPC implementation in networks with extended link lengths.

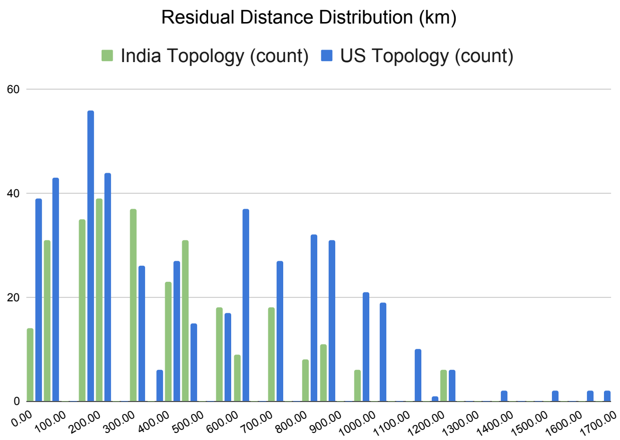
The statistical analysis of the residual distances for the India and US network topologies yields the following insights. **Count**: There are 286 paths in the India topology and 465 paths in the US topology, indicating a larger number of potential paths in the US network. **Mean**: The average residual distance is **388.81** for the India topology and **492.56** for the US topology, suggesting that, on average, paths in the US network have longer residual distances. **Standard Deviation**: The standard deviation for the India topology is **272.65**, while for the US topology, it is **369.67**, indicating a wider spread of residual distances in the US network. **Min/Max**: Both topologies have paths with a minimal **0** residual distance, but the maximum residual distance is **1200** for the India topology and **1680** for the US topology, further highlighting the longer paths in the US network. **Quartiles**: The 25th, 50th (median), and 75th percentiles further illustrate the distribution of residual distances within each network. The US topology shows higher values at each quartile, reinforcing the trend of longer residual distances.

This analysis not only elucidates the distribution and variability of residual distances across both topologies but also highlights the nuanced challenges in optimizing OPC deployment, especially in networks with expansive inter-node distances.

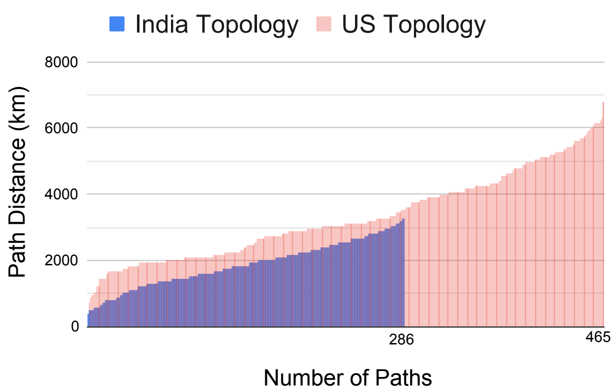
VI. Conclusions and Future Work

In this study, we introduced an innovative nodal architecture design aimed at minimizing DSP overhead within Coherent WDM optical networks. By integrating OPCs and SOAs in the all-optical network, our analysis illuminated the significant potential for energy savings that OPC offers in optical network communications. A critical aspect of our research involved addressing the challenges of mid-span OPC deployment through the development of an OPC Position Identification algorithm. This algorithm is designed to identify the optimal placement of OPC devices within the network, thereby enhancing network performance by mitigating dispersion and nonlinearity effects over extended transmission distances. Our analysis, underscored by statistical and comparative evaluations of residual distances in diverse network topologies, highlighted the complexities and considerations necessary for effective OPC implementation. The findings from the Indian and US network topologies underscore the increased challenge of deploying OPC in networks with longer inter-node distances, revealing the nuanced balance between network design and the operational benefits of OPC.

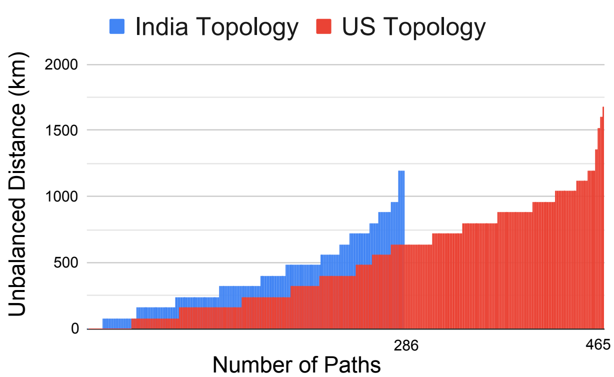
In our future work, we will quantify the effects of OPC on both Capital Expenditures (CapEx) and Operational Expenditures (OpEx), providing a holistic view of the economic and technical benefits of OPC integration.



(a) Residual distance distribution of two network topologies



(b) Shortest path distances across all source-destination pairs



(c) Unbalanced distances for each path

Fig. 4: (a) Residual distance distribution of two network topologies, cumulative histogram of (b) Shortest path distances across all source-destination pairs, and (c) Unbalanced distances for each path.

VII. Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant Number CNS-1817105 in the US as well as the Department of Science and Technology (DST) and IITM Pravartak in India.

References

[1] R. A. Soriano, F. N. Hauske, N. G. Gonzalez, Z. Zhang, Y. Ye, and I. T. Monroy, "Chromatic dispersion estimation in digital coherent receivers," *Journal of Lightwave Technology*, vol. 29, no. 11, pp. 1627–1637, 2011.

[2] A. Amari, X. Lin, O. A. Dobre, R. Venkatesan, and A. Alvarado, "A machine learning-based detection technique for optical fiber nonlinearity mitigation," *IEEE Photonics Technology Letters*, vol. 31, no. 8, pp. 627–630, 2019.

[3] O. Leclerc, B. Lavigne, E. Balmefrezol, P. Brindel, L. Pierre, D. Rouvillain, and F. Seguineau, "Optical regeneration at 40 gb/s and beyond," *Journal of lightwave technology*, vol. 21, no. 11, pp. 2779–2790, 2003.

[4] B. Ramamurthy and B. Mukherjee, "Wavelength conversion in WDM networking," *IEEE Journal on selected areas in communications*, vol. 16, no. 7, pp. 1061–1073, 1998.

[5] R. A. Fisher, *Optical phase conjugation*. Academic press, 2012.

[6] A. D'Ottavi, F. Girardin, L. Graziani, F. Martelli, P. Spano, A. Mecozzi, S. Scotti, R. Dall'ara, J. Eckner, and G. Guekos, "Four-wave mixing in semiconductor optical amplifiers: a practical tool for wavelength conversion," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 3, pp. 522–528, 1997.

[7] D. Geraghty, R. B. Lee, M. Verdiell, M. Ziari, A. Mathur, and K. Vahala, "Wavelength conversion for WDM communication systems using four-wave mixing in semiconductor optical amplifiers," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 3, pp. 1146–1155, 1997.

[8] F. D. Mahad, A. Supa'at, S. M. Idrus, and D. Forsyth, "Analyses of semiconductor optical amplifier (SOA) four-wave mixing (FWM) for future all-optical wavelength conversion," *Optik*, vol. 124, pp. 1–3, 2013.

[9] A. Sobhanan, A. Anthur, S. O'Duill, M. Pelusi, S. Namiki, L. Barry, D. Venkitesh, and G. P. Agrawal, "Semiconductor optical amplifiers: recent advances and applications," *Advances in Optics and Photonics*, vol. 14, no. 3, pp. 571–651, 2022.

[10] T. Xu, G. Jacobsen, S. Popov, J. Li, E. Vanin, K. Wang, A. T. Friberg, and Y. Zhang, "Chromatic dispersion compensation in coherent transmission system using digital filters," *Optics express*, vol. 18, no. 15, pp. 16 243–16 257, 2010.

[11] M. Pelusi, F. Luan, D.-Y. Choi, S. Madden, D. Bulla, B. Luther-Davies, and B. Eggleton, "Optical phase conjugation by an As(2)S(3) glass planar waveguide for dispersion-free transmission of WDM-DPSK signals over fiber," *Optics express*, vol. 18, no. 25, pp. 26 686–26 694, 2010.

[12] B. Ramamurthy, D. Datta, H. Feng, J. Heritage, and B. Mukherjee, "Impact of transmission impairments on the teletraffic performance of wavelength-routed optical networks," *Journal of Lightwave Technology*, vol. 17, no. 10, pp. 1713–1723, 1999.

[13] S.-R. Lee, "Dispersion management and optical phase conjugation in optical transmission links with a randomly distributed single-mode fiber length," *Journal of information and communication convergence engineering*, vol. 11, no. 1, pp. 1–6, 2013.

[14] S. Shimizu, T. Kobayashi, T. Umeki, T. Kazama, K. Enbutsu, R. Kasahara, and Y. Miyamoto, "Channel arrangement design in lumped amplified WDM transmission over NZ-DSF link with nonlinearity mitigation using optical phase conjugation," *IEICE Transactions on Communications*, vol. 105, no. 7, pp. 805–813, 2022.

[15] B. Badar and A. Anisha, "Simulative analysis and compensation of dispersion in WDM optical systems," *Int J Eng Res Technol*, vol. 4, no. 1, pp. 721–725, 2015.

[16] R. Sabella and E. Iannone, "Long distance optical communication systems adopting wavelength conversion by four-wave mixing in semiconductor amplifiers," *Journal of optical communications*, vol. 18, no. 3, pp. 109–113, 1997.

[17] B. Hu, K. Mrudula, D. Venkitesh, and B. Ramamurthy, "Integrating physical layer modeling in the simulation of dynamic WDM optical networks with direct and coherent detection," in *2023 IEEE Future Networks World Forum (FNWF 2023)*, Baltimore, US, Oct. 2023.

[18] R. J. Pandya, V. Chandra, and D. Chadha, "Simultaneous optimization of power economy and impairment awareness by traffic grooming, mixed regeneration, and all optical wavelength conversion with an experimental demonstration," *Journal of Lightwave Technology*, vol. 32, no. 24, pp. 4768–4779, 2014.