

A Flat Long-Reach of WDM-PON and Optical Switching for Future National Data Center Interconnects: A Review

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Abstract

The national fiber backbone requires continuous upgrading due to the increasing demand for data transfers between datacenters and end users, resulting in congestion and delays. This paper presents a structured review of national-scale flat Long-Reach Wavelength Division Multiplexing Passive Optical Network (LR WDM-PON) architectures. These architectures are integrated with optical switching technologies for distributed Data Center Interconnects (DCI) to enhance the performance of optical networks. The study analyzes the evolution of WDM-PON toward extended-reach operations and highlights the role of Optical Add-Drop Multiplexers (OADMs) in wavelength-level routing. Additionally, we discuss key challenges that limit optical transmission, such as chromatic dispersion accumulation, nonlinearities, and Optical Signal-to-Noise Ratio (OSNR) degradation caused by cascaded amplification. Special attention is given to dispersion compensation strategies, such as the deployment of dispersion-compensating fiber (DCF), and their impact on Bit Error Rate (BER) performance in extended-reach scenarios. This review synthesizes recent experimental and theoretical studies to explain the primary design frameworks and physical constraints involved in scaling transparent optical networks to a national level.

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1. Introduction

Data traffic inside and between data centers has grown rapidly, largely driven by the expansion of cloud services, Internet of Things (IoT) applications, real-time analytics, high-definition video streaming, and virtualization [1]. Electrically switched networks face challenges in terms of scalability and energy efficiency [2]. Repeated Optical-Electrical-Optical (OEO) hops increase end-to-end latency [3], [4] and power consumption. For instance, a single 25-Tbit/s core router utilizing legacy interfaces can require up to 768 converters and consume over 12,000 Watts [5]. For this reason, optical interconnection is increasingly considered a more suitable alternative. Maintaining signals in the optical domain during switching between data centers can considerably improve performance and energy efficiency. Consequently, it represents the most attractive solution for large-scale next-generation architecture[6].

Beyond speed, the primary challenge in current networks is their architectural complexity across different network levels. Traditional data moves through several hierarchical layers (Access, Metro, and Core), and each layer adds more processing time and hardware costs. Extension of passive optical networks (PON) to longer than normal access distances has been a topic of much research. Different experimental and analytic studies have shown that the long-reach WDM-PON and TWDM-PON structures can be used significantly beyond the traditional access limits by using optical amplification and wavelength-multiplexing techniques [7], [8], [9]. These long-range strategies are usually floated to limit the central offices and to cover greater service areas.

The increase in the transmission distance also increases the susceptibility of the system to cumulative transmission impairment and tough power-budget limitations. The chromatic dispersion effect builds up with long fiber spans and causes pulse broadening, and with higher levels of optical power, the nonlinear propagation effects get more pronounced [10], [11]. Amplified spontaneous emission (ASE) noise is detrimental to the Optical Signal-to-Noise Ratio (OSNR) and directly affects signal quality and Bit Error Rate (BER) performance [12], [13]. Therefore, dispersion-management plans, such as dispersion-compensating fiber (DCF), are explored to maintain the transmission in long-reach situations [14].

Despite literature on long-reach WDM-PON systems and optical switching, most studies consider the two as independent. Research has been mostly devoted to transmission performance, and optical switching has been dedicated to a device-level or data-center scale deployment. As a result, a complete framework that considers long-reach WDM-PON, switching integration, and physical layer limits in a co-packaged national-scale flat architecture is conspicuously rare. It is this gap that forms the basis of the motivation for an organized review that conforms to architectural design decisions with transmission-performance values.

This paper offers a concise review of the national-scale flat LR WDM-PON architecture. This review differs from earlier ones with a strong focus on the use of optical switching technologies for distributed Data Center Interconnects (DCI) in a variety of application areas, including 5G/6G fronthaul, IoT, and edge computing. This paper distills recent experimental and theoretical work to offer a comprehensive design perspective to overcome physical layer limitations for scaling optical networks. The flat architecture removes the long processing delays of OEO conversions, as it does not require the traditional Metro and Core levels to enable transparent connections. To offer a comprehensive and rigorous analysis, this review presents the basic mathematical expressions of physical impairments, compares the proposed flat architecture with hierarchical networks by considering several physical and network performance metrics (BER, OSNR, Q-factor, power consumption, and latency), and focuses on the interactions among architecture, switching, and transmission constraints.

The rest of the review is divided into four major parts. First, we discuss optical switching technologies for data center and metro network settings. Second, we follow the development of PON to long-reach operations, and also discuss impairments of the physical layer that limit the transparent transmission of long distances. Third, we give a detailed discussion of the integration issues and architectural trade-offs of scaling these transparent networks to the national level. Finally, we identify unresolved research questions and provide potential future research directions.

2. Review Methodology

We performed a comprehensive literature review on Optica, SpringerLink, IEEE Xplore, Elsevier, and De Gruyter, spanning 2002 to 2025, to include both theoretical foundations and the latest developments in large-scale optical networks. The keywords used were "Long-Reach WDM-PON", "Optical Switching", "DCI", "OADM", and "Dispersion Compensation". We selected peer-reviewed papers that addressed limitations of the physical layer and optical DCI networks, excluding upper-layer protocols and wireless-only networks. Out of 109 records, 73 key papers were chosen.

3. Optical Switching Technologies

Several switching approaches are available, each one performing differently in terms of speed, scalability, and power consumption [15]. When optical switching is considered for national-scale networks, these differences become important, since practical deployments usually involve compromises between performance and efficiency rather than an ideal solution.

3.1 Device-Level Optical Switching Mechanisms

Optical switching works by using various physical phenomena to direct light signals using a variety of materials. Of particular importance among these is silicon photonic switches that are compatible with complementary metal-oxide-semiconductor (CMOS) technology, which facilitates mass production at low cost [16]. One major challenge to using them in long-reach WDM-PON systems is that they require significant power for control when deployed on a large scale.

The silicon switches described by Chen, Lin, and Wang [16] are mainly based on the thermo-optic effects (TO) and carrier-dispersion effects (CD), where the former needs substantial amounts of static power to phase shifts and the latter provides only a limited change in the refractive index. As both are generally non-latching and need a constant electric bias, recent work has analyzed phase-change materials (PCMs) as a more energy-efficient, stable option to integrated switching. Scholars have also shifted attention to new architectural designs in order to attain high-density scalability, like the thermo-optic waveguide lens (TOWL). A huge 1x576 optical switch on a small multimode polymer waveguide platform was reported by Chen et al. [17]. This experimental setup was able to isolate crosstalk to less than -30 dB without having to deal with sophisticated management schemes that can be found in traditional Mach-Zehnder Interferometer (MZI) or Micro-Electro-Mechanical Systems (MEMS) solutions. This defines a very scalable method of applying energy-conscious wavelength routing in data center and access settings. MEMS switches with mirror-based design are switches that offer mechanical, electrical, and optical operations [18], which have been fabricated by batch-process microelectronic methods. Ma and Kuo [15] indicate that these switches should be selected based on balancing scalability and speed. These switches are highly ported and have very low insertion loss, yet operate at a low speed of between 1 and 10 milliseconds. Such speed is not enough to support dynamic packet switching but is ideal in

one or two special Long-Reach applications, such as fiber cut protection and Optical Add-Drop Multiplexers (OADM), where signal consistency is much more important than switching speed.

Regarding the field of semiconductor switching, Sasikala et al. [19] indicate that the principal purpose is to enhance the speed, though without damaging the signal. Semiconductor Optical Amplifier (SOA) may also be used to create logic gates based on nonlinear effects, but in optical routing and WDM networks, SOAs act as nanosecond ON/OFF gate switches by quickly switching the bias current [20]. This linear gating enables the switching speed in the nanosecond range, and the internal optical gain of the SOA is a direct counterpart of the attenuation of the Long-Reach systems. The accumulation of Amplified Spontaneous Emission (ASE) noise is the trade-off [21].

This noise puts a limit on the number of switches that can be cascaded. Although photonic crystals have been proposed as a remedy to these stability issues, their complicated fabrication is a serious impediment [19].

In an attempt to improve light-matter interaction on a new level, Tavana et al. [22] suggested an electro-optical switch based on anisotropic graphene sheets integrated in a one-dimensional photonic crystal. A localized light at 1552.4 nm is produced by this structure, and this increases the interaction of the light and matter. In contrast to the traditional phase-shifting devices, this mechanism is realized through the process of electro-absorption; when an external voltage is applied, the chemical potential of the graphene layers changes and will transform the device into a transparent or absorbing device. The simulation results that have been reported show a high extinction ratio of 14.26 dB and a low insertion loss of 0.18 dB.

The use of Microring resonators (MRRs) has the potential to facilitate energy-efficient switching, but due to their sensitivity to thermal changes and fabrication variations, it makes scaling them a challenge. In an attempt to overcome these constraints on stability, Li et al. [23] introduced a 3D multi-layer design that exhibits a vertical integration strategy, alleviating the limitations of planar silicon, and also showing that MRR-based fabrics can be scaled successfully at reduced insertion loss. A review of these technologies shows that there is a disintegration of performance standards. As shown by Pareto analysis, Cheng et al. [24] prove that modern architectures are not able to meet all the performance measures at the same time. Liu et al. [25] confirm that MEMS is stable in hyperscale commercial applications since their response time of milliseconds makes them inappropriate in the context of packet-level switching. The slowdown is not necessarily optical. Xue et al. [20] state that the real bottleneck is not necessarily the optical material itself but the delay of the electronic control plane.

The difference between the maximum switching speed and the system-level throughput sets the comparison framework portrayed in Table 1.

Table 1. Performance comparison of optical switching technologies (Speed, Power, and Loss)

Technology	Switching Speed	Power Consumption >(W/port)	Insertion Loss	Typical Applications	Reference
MEMS	1–10 ms	Low (1-5)	Low (0.5–2 dB)	Large-scale optical switching networks	[15],[25]
SOA	< 1 ns	High (5-10)	Zero / Net Internal Gain (~0 dB)	High-speed switching in data centers	[20],[24]
Silicon Photonics	< 1 ns to ~1 μ s	Low(2-8)	Low to Medium	Switching in integrated photonic circuits	[24]
Hybrid (III-V/Si)	< 1 ns	Medium(4-8)	Low (1–3 dB)	Hybrid and hierarchical switching applications	[24]

Choice of a switching fabric is determined by domain-specific criteria, not by a universal standard. The sub-microsecond latency of data centers is fundamentally different than the loss-budget constraint of long-reach WDM-PON.

3.2 Optical Switching Paradigms

Performance environments experience severe latency bottlenecks with bursty traffic at interface speeds of 400 Gb/s [26]. As a result, the dilemma of switching speed versus signal integrity presents a challenge [27]. Optical Circuit Switching (OCS) offers reliable, low-loss connections with millisecond-scale MEMS but lacks the flexibility of packet-level, nanosecond-scale operation. On the other hand, Optical Packet Switching (OPS) provides nanosecond-speed switching but is physically unrealizable due to the lack of stable optical Random Access Memory (RAM) for packet buffering [27]. In response, Optical Burst Switching (OBS) has been devised as a practical compromise. Imran et al. [28] showed that an OBS architecture (based on the use of fast optical switches and a two-way reservation protocol) can address the unacceptable connection-setup time

problem associated with OCS under heavy data-center traffic. This flexibility positions OBS as an ideal solution to deal with bursty upstream traffic in the next-generation long-reach WDM-PONs.

3.3 System-Level and Reconfigurable Switching

Optical switching integration at the system level displays a basic synchronization problem. The optical data plane may be operated at timescales of nanoseconds, but the electronic control plane is usually slower in reaction. Photonic switching devices can transition between states very rapidly, as explained by Xue et al. [20], but in general, system throughput is often limited by the latency of the control-plane, the lack of convenient optical buffering, and the complexity of high-rate Clock and Data Recovery (CDR).

To reduce such a discrepancy, Xue et al. [20] suggested a combined switching and control structure, which would help in synchronizing the rate of hardware to the speed of control responsiveness. Their prototype was able to reconfigure the switch in approximately 43.4 ns, which was aided by a CDR module running around 3.1 ns. Their framework not only demands faster switching but also controls the contention between packets and the timeline. This effectively demonstrated that it never comes down to a device-level problem as far as attaining speeds on the nanosecond scale is concerned.

This indicates that reconfigurable optical networks cannot be dependent on faster switching material or better photonic hardware only. Instead, these system-level enhancements cannot be achieved without a collaborative approach to designing the optical hardware and electronic control algorithms. Scheduling logic based on fast scheduling, accurate synchronization, and effective contention resolution mechanisms is the necessary ingredient to make full use of the nanosecond switching platforms.

3.4 AWGR-Based Switching

The interconnection topology in the data centers is experiencing a very serious scalability bottleneck in which merely raising cabling density is no longer viable due to power and latency considerations. Ye et al. [29] refer to this as a 'cabling bottleneck' that makes it very difficult to maintain server systems and prevent thermal noise.

To overcome the contention problems of such designs with static designs, Shukla et al. [30] proposed a WDM-based switch design that uses Fiber Delay Lines (FDLs) in addition to the AWG. This combination forms an optical buffer that helps a great deal in counteracting the loss of packets in bursty traffic situations.

Building on this buffering idea, Singh et al. [31] presented an architecture with an optical add-drop feature. They confirmed the design of FDLs in simulations that (BER) is achievable with standard C-band operations, and they robustly reduced the percentage of packet drops with different traffic loads, despite addition of 1X2 Wavelength-Selective Switch, while preserving the use of a folded AWG structure Kraemer et al. [32] However, this machine has extraordinarily attained error free O, S, C and L-band routing with OSNR penalties less than 2 dB.

These results show that multi-band Wavelength Selective Switches (WSS) modules that are integrated are a viable option for scalable and flexible wavelength routing in current access systems and upcoming WDM-PON designs. Even though this static implementation may require rigidity, it has been demonstrated that the architecture is scalable in terms of additional ports. The results indicate the benefits of AWG-based designs to route the wavelength and resolve contention in high-speed, low-latency networks. It is noteworthy that the physical layer of the future access networks can be enhanced by knowing these switching features. The following section examines this with regard to WDM-PONs.

3.5 Relevance to WDM-PON and Long-Reach Architectures

WDM-PON and long-reach are evolving and changing according to the needs of bandwidth. There have been a number of efforts to serve a huge number of people with the same transmission medium [33]. The optical switching gives fine control of wavelength routing, and this makes the device innovations more practical to access and metro services. To increase WDM-PON scalability, flexibility, and performance, a metropolitan ring simulated by Essa, Asker, and Sedeeq [33] is based on OADM. They showed that with a 1.6 Tb/s configuration with Non Return to Zero (NRZ) and Return to Zero (RZ) coding, OADM nodes would be able to efficiently route signals that had a high constant power output, and the gain varied much less than when operating with a return to zero (RTZ) coded signal. This paper has set a crucial threshold on how optical nodes are capable of sustaining terabit-scale traffic with the signal integrity necessary for large-scale integration.

Recent studies have been shifting the emphasis to flexibility in networks. Mkhwanazi et al. [34] believe that the movement towards the Reconfigurable OADMs (ROADMs) will inevitably approach the contemporary traffic. They emphasized the fact that automatic redirection or addition of wavelengths is not simply a feature but a requirement in linking local access networks with regional layers to ensure that they have capacity as well as network survivability.

Proving this idea at long distances, Rani et al. [35] established that this flexibility is also valid at long distances. In the experiments, 40 Gbps of traffic was supported by the architecture on 16 channels and a 780 km path. Throughout this, the system was able to sustain good Q-factors and BER to 300 km, even with 64 channels. This affirms the fact that ROADM-based designs have the strength to directly interconnect regional nodes to the national backbone.

On the hardware side, Htwe in [36] researched the trade-off in active WSS. This comparison has shown a drastic difference. In contrast to photonic crystal switches, which have breathtaking speeds of 0.5 ps combined with much higher

insertion loss (2 dB vs. 16 dB), electro-optic switches are slower (requiring 5 ns) with much lower insertion loss (2 dB). We discovered that optimum delay time, i.e., the addition of 3 ns delay to the electro-optic switch, allowed crosstalk distortion to be minimized and power budget to be improved by 3 dB with both 10 Gbps and 40 Gbps systems.

These investigations implied that the application of optical switching is not solely based on crude velocity. It must identify the optimal engineering compromise between switching response and signal integrity for the next generation of long-reach WDM-PON.

4. Passive Optical Networks (PON) Evolution and Scalability.

We discuss the development of Passive Optical Networks (PONs), which comprise the transport infrastructure of an access and metro access setting. In the last 20 years, PON architectures have changed a lot, in terms of scale, with the growing bandwidth requirements, split ratio requirements, and service coverage requirements. This evolution is important to understand the manner in which the long-reach and switching integration can be implemented on a national scale.

4.1 Evolution of PON Standards

The historic development of PONs has been strongly connected with the continuing increase in broadband data usage in residential and mobile access settings. Initial large-scale fiber systems, which were mostly Gigabit-class, like GPON and EPON, were standardized by the ITU-T and IEEE, respectively. With the ever-growing traffic demand, 10 Gigabit-class technologies such as XG-PON1 and 10G-EPON were launched to improve the downstream and upstream capacity without interfering with the previous systems [37].

Abbas and Gregory [38] characterise the PON standards evolution as a changing of multiplexing paradigms. Whereas the legacy and NG-PON1 technologies were bound by the physical limits of Time Division Multiplexing (TDM), Stage 2 (NG-PON2) redefined the paradigm. It adopted Time and Wavelength Division Multiplexing (TWDM); this multiplexed multiple wavelengths onto a single fiber and overcame previous constraints.

A key step in the ITU-T roadmap was the launch of the Higher-Speed PON (HS-PON) project, which defined the 50G-PON standard in the G.9804.x series. According to Bonk et al. [39], 50G-PON is the first significant upgrade after 10G-PON, contributing a fivefold increase in line rate while still compatible with existing GPON and XGS-PON on the same Optical Distribution Network (ODN). The system enhances Digital Signal Processing (DSP) equalization with improved forward-error correction capabilities and offers more flexible wavelength planning. However, the strong dependency on highly sophisticated DSP modules in the optical network unit (ONU) can increase power consumption and heat generation.

New fronthaul requirements are also becoming more influential in the development of PON standards. Fayad et al. [40] in Toward 6G Optical Fronthaul present the stricter latency and synchronization requirements of future mobile architectures as being beyond the requirements of the traditional TDM-based access systems. The paper notes that next-generation fronthaul has to be able to accommodate heterogeneous traffic patterns with tight delay budgets and enhanced functional split flexibility.

This observation supports the shift of pure TDM to wavelength-aware and hybrid architectures. Although the capacity of higher line rates (e.g., 50G-PON) is enhanced, the fronthaul viewpoint indicates that deterministic wavelength assignment and low-delays control systems also become important. Scalability, therefore, does not just have throughput as its characteristic anymore but also has timing accuracy as well as architectural flexibility.

Moving beyond 50G standards reveals a physical bottleneck, Feng [41], using DSP and advanced multiplexing to stabilize Beyond-100G transmissions. However, relying on complex DSP increases equipment costs and power consumption at the user side (ONU). Therefore, balancing high data rates with low-cost hardware remains a major challenge.

The researchers have also studied hybrid data transmission techniques in order to enhance the scaling of networks with the changes in ITU-T standards of TDM GPON to the TWDM NG-PON2. Through simulations, for example, Hamadouche et al. [42] demonstrate that the hybrid WDM/TDM PON with 128 users is more stable in the Q-factors as compared to either TDM or WDM, especially in higher split ratios and longer fiber lengths.

It is restricted to network distances of 60 km and does not consider integration with national networks of long distances, where issues such as signal dispersion and noise gain greater significance.

PON standards are being updated to make networks more flexible. According to Montalvo et al. [43], the move towards Software Defined PON (SD-PON) with hardware and software separated and different PON types supported. SD-PON allows the control system to be virtual, and allows operators to field open white box OLTs capable of operating both with G-PON and with XGS-PON, or with Combo-PON (C-PON).

Demonstrates that disaggregated architectures are capable of round-trip delays of approximately 1 ms and use less power per port than conventional OLT systems. The access layer is enhanced with this method, and long-distance issues like chromatic dispersion and ASE noise in networks are not addressed on a large scale.

Another aspect in NG-PON2 research was delay performance rather than just line rate. In the study by Zaouga et al. [44], the authors analyzed the conventional 125 μ s frame structure used in NG-PON2 and showed that it may not be suitable for services that require very low delay, such as 5G fronthaul. They proposed splitting the upstream frame into smaller sub-frames to reduce queuing time for high-priority traffic. Their simulations showed that upstream delay could be held to less than the 250

μ s fronthaul threshold. This method has a cost: it adds overhead in the form of guard time and complexity in the form of reporting, which inevitably would result in a slight reduction in the bandwidth efficiency. It should also be noted that their evaluation was performed over a typical 20 km access distance, so the impact of this approach under extended or long-reach conditions remains unclear.

However, virtualization also has latency threats. solved by demonstrating the inability of standard DBA algorithms to fulfill the requirements of 5G. Their optimized DBA on NG-PON2 specifically focuses on the time-slot allocation process, and the fact that software-defined control is the only solution available to ensure low latency in the process of dense networks is proven.

The main milestones, multiplexing techniques, and improvements in performance of PON generations have been summarized in Table 2.

Table 2. Evolution of PON Standards and Their Relevance to Long-Reach WDM-PON Architectures

System / Study	Capacity	Multiplexing	Key Contribution
EPON / GPON [37].	1–2.5 Gb/s	TDM	Foundational FTTH standards; basic optical budget.
XG-PON / XGS-PON[37].	10 Gb/s	TDM	Higher data rates; asymmetric/symmetric coexistence with GPON.
NG-PON2 [38]	40 Gb/s	TWDM	Wavelength stacking; tunable transceivers.
50G-PON (G.9804) [39]	50 Gb/s	Enhanced TDM + DSP	Higher-rate optics; improved FEC (LDPC); coexistence support.
Beyond-100G Technologies [41]	≥ 100 Gb/s	WDM / SDM + Advanced Modulation	DSP-based impairment mitigation; ultra-high capacity.
Hybrid WDM/TDM-PON [42]	>10 Gb/s	Hybrid (WDM/TDM)	Improved performance under high split ratios (e.g., 128 ONUs).
Next-Generation Light Sources [45]	10–100 Gb/s	Component-level	Improved source stability; enhanced optical budgets.
Multi-PON / SDN[43]	Standard-dependent	Multi-domain	Disaggregated white box hardware; software-defined control.
Advanced DBA [44]	Standard-dependent	TDM / TWDM	Low-latency dynamic bandwidth allocation.

Developments of 10G-PON based on EPON and GPON, further development through hybrid multiplexing, and future 100G-and-beyond research development are a progressive trend of higher capacity, more flexibility, and service integration. Long-reach optical access networks are designed based on these developments, and current WDM-PON systems are formed on them.

Using these technologies, compared to the conventional hierarchical multi-layered high-switching electronic networks (with energy-intensive electronic switching and multiple O-E-O conversions, as illustrated in Figure 1), the proposed transparent flat WDM-PON networks for a national-scale network have less energy consumption and delay. While conventional DCI networks are hard to scale due to the limited capacity in routers, with transparent optical designs, wavelength routing is achievable over a long distance, making them a better choice for high-capacity national-scale backbones.

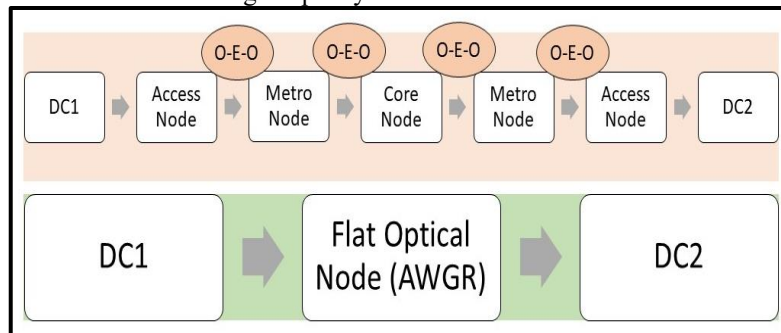


Figure 1: Comparison between traditional multi-tier hierarchical architecture and the proposed flat Long-Reach WDM-PON architecture

4.2 WDM-PON and Wavelength Scalability

To handle the growing spectral demands of next-generation access systems, WDM-based architectures have been implemented as an alternative to pure TDM approaches. Optical transmission systems wavelength grids are classified by the channel spacing as Coarse WDM (CWDM) and Dense WDM (DWDM). Recommendation ITU-T G.694.1 defines the nominal

central frequencies and allows channel spacing for DWDM systems fixed at 193.1 THz, supporting spacings from 12.5 GHz up to 100 GHz and more [46].

In the context of WDM-PON, each ONU is typically assigned to a dedicated wavelength channel. This effectively creates a virtual point-to-point optical link between the OLT and the user [47], enabling direct communication between the OLT and each ONU without complex upstream scheduling mechanisms, which simplifies resource management compared to conventional TDM-based systems [48].

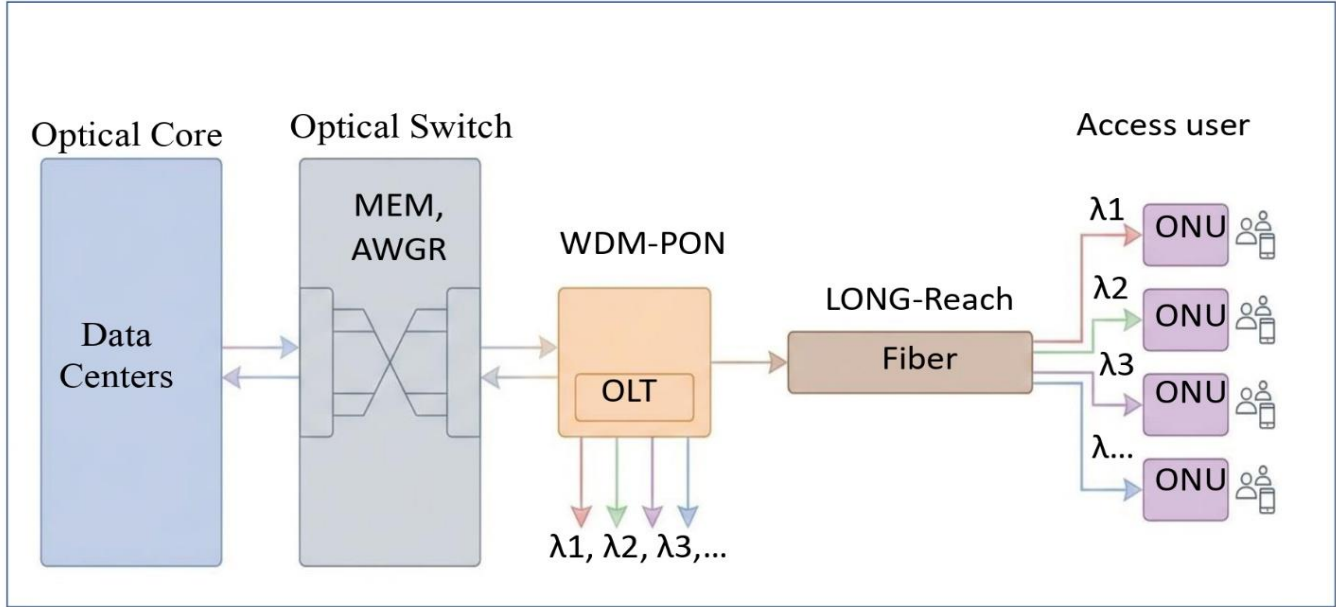


Figure 2. Proposed scalable WDM-PON architecture integrating Optical Switching and AWG-based wavelength routing

Wavelength routing is usually achieved by a passive AWGR deployed at the remote node, as described in the schematic (Figure 2). The AWGR merely demultiplexes and directs single wavelengths to the corresponding ONUs, using no active switching equipment. This principle of wavelength-selective routing is consistent with the architectural principles in [47] and other studies of interconnection using AWGR. Capacity scaling is then possible through the activation of more wavelengths or OLT ports and does not require any changes to the passive distribution network.

Even though WDM-PON provides dedicated channels for each channel per ONU, it has been linked to the high cost of components and stringent engineering choices. Specifically, the high density of channels makes them susceptible to nonlinear effects and needs careful power control, which can be done by optical amplification.[49]. In addition to traditional definitions of CWDM and DWDM grids, wavelength scalability in access networks is closely associated with the evolution of optical multiplexing approaches in general. Wavelength division multiplexing is not the only dimension of capacity scaling, as explained in Optical Multiplexing Techniques [50]. In the literature, multiplexing is divided into temporal (TDM), spectral (WDM), spatial (SDM), and combinations of all of them, as each addresses various physical and architectural limitations.

Although TDM is more cost-effective due to statistical sharing, WDM is a deterministic bandwidth allocator that isolates users on a spectral basis. Nevertheless, mixed-method hybrids based on both wavelength and time domains [9] are also seen to become more scalable to dense deployments, as feeder fiber capacity is used as a constraint. The big picture shows that the size of WDM-PON is not whether it should increase the number of wavelengths, but rather it should select the appropriate dimension of multiplexing based on the distance that it has to cover, the number of users it needs to cover, and the impairment that it can tolerate.

In a direct performance comparison of WDM-PON and CWDM-PON, Kherici et al [49] found that WDM performance will start to deteriorate beyond 60 km under 10 Gbps operation due to the nonlinear interaction being enhanced by dense spacing, whilst the CWDM configuration was able to control the nonlinear interaction to ensure acceptable Q-factor and OSNR factors up to 100 km in their simulation scenario [49]. There is a design tradeoff here in that by having WDM channels packed into proximity, the system becomes highly susceptible to nonlinear phase-matching issues such as Four-Wave Mixing (FWM). Thus, the identified limitation is both physical and architectural, but not only implementation-dependent.

Later work challenges the perception of strict reach boundaries. Verma et al. [51] provide the 80 Gbps total capacity over 80 km, and because of the NRZ modulation, the Q-factor is 3.46, and the BER is 2.48×10^{-11} . This implies that the issue of reach extension in WDM-PON is largely a challenge in power-budget and impairment management. Other than the distance

of transmission, architectural flexibility has been investigated [50]. The key difference lies in system optimization, including transmitter power selection and receiver configuration, rather than in wavelength density alone.

Architectural flexibility has also been investigated beyond the distance of transmission. Yeh et al. [47] proposed a ring-based WDM-PON enabling 28 Gbps symmetrical access while supporting a 3 Gbps inter-ONU VPN without routing traffic through the OLT. This proves the fact that wavelength isolation can also support differentiation of the service layer, rather than just capacity scaling. But the demonstrated reach was not very large (less than normal access distances of 25 km SMF), and much of the performance of long-reach systems in overlay cases had not been studied.

Scalability has also been explored in the spatial domain. Goyal et al. [52]. studied how using Space Division Multiplexing (SDM) with multicore or multimode fibers can boost total upstream capacity and reduce the need for feeder fibers [52]. While SDM helps overcome limits in wavelength density, it also makes mode coupling management and receiver design more complex, which makes real-world deployment in access networks more challenging.

Collectively, the literature suggests that the scalability of WDM-PON is based on three factors that interact, namely spectral density, power budget engineering, and architectural topology. The reported limits of the reach are sometimes indicative of conservative system design, as opposed to real wavelength limitations. This difference is especially pertinent when considering long-reach architectures that seek to expand the customary access boundaries.

4.3 Physical Layer Impairments in Long-Reach PON

PON is the best choice for such types of access networks [52]. Chromatic dispersion accumulation is a major challenge in long-reach networks. Chromatic dispersion causes pulse broadening as different wavelength components propagate at different velocities. The resulting pulse broadening factor (Δt) is mathematically defined as [13]. $\Delta t = D \cdot L \cdot \Delta \lambda$ (1)

To mitigate this impairment, dispersion-compensating fibers (DCF) are widely used. In this approach, the lengths (L) and slopes (S) of the DCF are carefully matched with the standard single-mode fiber (SMF) to satisfy the fundamental conditions [53], $(S_{SMF} \times L_{SMF}) + (S_{DCF} \times L_{DCF}) \approx 0$ (2)

thereby ensuring minimal residual dispersion across the transmission spans.

While fiber attenuation, mainly caused by Rayleigh scattering, reduces the received optical power [12], to reduce these effects, several techniques have been developed, most notably the deployment of optical amplifiers like EDFAs. To achieve span power transparency ($P_{in} \approx P_{out}$), the gains (G_1, G_2) of the amplifiers must be precisely allocated to counter the losses of both SMF and DCF segments, following the relation:

$$P_{out} = P_{in} - (\alpha_{SMF} \times L_{SMF}) + G_1 - (\alpha_{DCF} \times L_{DCF}) + G_2 \quad (3)$$

This strategy ensures a stable power level throughout the long-reach link while minimizing the buildup of ASE noise. The wavelength routing passive optical network (WR-PON) is investigated by Kachhatiya and Prince [54]. They used the OptiSystem-13 simulation tool to study NG-PON2 by comparing power-split and wavelength-routing architectures.

They compared conventional G.652 fibres with 40 km ranges and sophisticated G.655 fibres with 60 km ranges and discovered that the fibre type is the key to long-range performance. Although the standard fibers have worked well at shorter distances, the G.655 fibers had high signal quality at 60 km, indicating that dispersion, fiber nonlinearity, and splitting loss are all limiting downstream performance and are to be addressed when choosing modulation formats and compensation schemes.

Nonlinear impairments pose a greater threat than dispersion in dense architectures. Pagare et al. [55] modeled the worst-case effects of Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), and FWM on N1-class NG-PON2 systems. Their simulation data shows that the most important variable in terms of stability is the power of fiber launch control. They used standard G.652 fibers to provide a signal over 50km by limiting the launch power to 3 dBm. This particular design allowed symmetric 80 Gbps services over a splitting ratio of up to 1:1280 and was capable of complying with the requirements of ITU-T G.989.2 without special cabling needed.

At 100G-class, the passive components are not sufficient to meet the power budget. Reza et al. [8] addressed this by inserting an SOA at the Remote Node. Their experiment was able to transmit 112.5 Gb/s PAM-4 signals to cover a distance of 50 km. The configuration provided a power budget of 31 dB (Class N2), which indicates that active amplification can cause the loss gap in long ODNs to be bridged and the BER to be within the Hard-Decision Low-Density Parity-Check (HD-LDPC) limit.

Designers of national backbone networks should balance two physical constraints: limiting power to minimize nonlinearities (as noted by Pagare) while using active amplification to overcome attenuation (as demonstrated by Reza).

4.4 Dispersion and Power Compensation Techniques

Dispersion-compensating fiber (DCF) has been experimentally studied to reduce the dispersion-induced penalty in dense multi-channels. Akram et al. [56] experimentally tested the DCF-enabled compensation in the ultra-dense WDM systems with special focus on the reduction of FWM. They obtained a result of 32.1804 when using Carrier-Suppressed Return-to-Zero (CSRZ) modulation and DCF, which gave them a better Q-factor as compared to the conventional RZ and NRZ schemes in identical conditions with a 15 dBm launch power. This method, instead of removing nonlinearities, illustrates how a setting of modulation compensation pairing can greatly reduce the FWM-induced high-power system.

The setting of amplifiers is also a very important factor in signal integrity. Lazem et al. [12] stressed that high optical power caused by excessive amplifier gain may enhance nonlinear effects such as FWM, which eventually reduces the Q-factor and raises the BER. Their findings demonstrate the importance of coordinated gain optimization and dispersion control, specifically, in the long-reach deployments. Other FBGs-based compact dispersion compensation schemes other than DCF have been explored. Other than DCF, fiber Bragg gratings (FBGs)-based compact dispersion compensation methods have been investigated. Abdulla et al. [9] showed that the FBGs at the optical line terminal (OLT) and optical network unit (ONU) in TWDM-PON schemes enhanced the high-speed transmission and supported 160/80 Gb/s transmission. What it means is that when local dispersion correction is done at the network endpoints, it is possible to support high aggregate capacities without necessarily requiring long compensation spans.

Moreover, the importance of cumulative dispersion is also critical for system performance, which is verified by simulation-based studies. As an example, Mohammed et al. in [57] examined the adverse impact of pulse broadening in long transmission distances and confirmed that successful dispersion compensation methods (including both DCF and FBG) are necessary to maintain signal integrity in high-speed WDM links.

Besides dispersion, optical power management is also more imperative in high-speed systems based on WDM-PON. In addition to fiber impairments, transmitter-side stability and amplification strategy have a direct effect on Q-factor and BER performance. Amiri et al. [45] have shown that a directly modulated laser of 40 Gb/s with a 20 km length could reach a Q-factor of 14.98 and a BER of 3.55×10^{-51} was possible with proper optical amplification and filtering. In spite of the fact that the distance under evaluation does not exceed the traditional access limits, the results indicate the value of coordinated source control and gain management in maintaining high signal integrity. These results confirm the argument that dispersion compensation is not enough unless optical power is closely controlled. Khair et al. in [11] researched the implementation of DCF in a 16-channel DWDM-PON with a current data rate of up to 40 Gb/s and found that the implementation of DCF is more susceptible to degradation due to dispersion, and that the launch power and amplifier setup must be cautiously optimized to allow operation at reasonable levels of BER. High-speed burst-mode transmission is challenged further by the recent high-speed developments. The next-generation PON systems at 100 Gb/s per wavelength were investigated by. Jamali et al. [21] investigated SOA-based optical burst power equalization. This technique removes the need for complex digital signal processing strategies to compensate for the large packet-to-packet power variations in order to simplify receiver design and improve scalability to dense high-speed deployments. Besides, it has been demonstrated that the combination of dispersion compensation fiber (DCF) and erbium-doped fiber amplification (EDFA) is highly effective to enhance the Q-factor as well as to extend the transmission range of high-speed PON systems by Htwe et al. in [36], and that the coordinated dispersion and power control is still a key aspect of stable operations. On the system-level, Garg et al. in [58] provided a flexible WDM-PON architecture that would allow dedicated and broadcast downstream transmission and direct inter-ONU communication. The architecture proves that optimizing architecture can be used to mitigate physical-layer compensation methods to minimize latency, operational expenditure (OPEX), and energy usage in dense access networks. The general literature concurs that dispersion compensation and power management are design parameters and not mechanisms that should be left to independently develop. With the increasing per-wavelength data rates of 50-100 Gb/s, coordinated optimization of modulation format, DCF or FBG implementation, amplifier gain control, and optical burst equalization is necessary to maintain acceptable values of the BER and Q-factor of long-reach WDM-PON systems.

4.5 Long-Reach and Extended-Reach PON

It has already become a strategic goal of operators to extend the use of PON systems further than the conventional 20 km limit to consolidate the central offices and expand the coverage areas [59]. A longer transmission distance, however, necessarily increases attenuation, chromatic dispersion, and amplified noise, which decrease signal margin and worsen the BER and Q-factor performance. Regarding the amplification side, Reza et al. [60] showed how to use Quantum-Dot Semiconductor Optical Amplifiers (QD-SOAs) to transmit 100 Gb/s upstream and 150 Gb/s downstream over 20 km simultaneously. Their quoted power budgets of 32.3 dB (uplink) and 29 dB (downlink) are confirmatory of the fact that QD-based amplification is suitable in high-speed access, although the range of the tests is within the conventional distance of access. In order to overcome prolonged transmission, Hamadouche [61] tested the gain dynamics of EDFA in a 32-user WDM-PON with a range of 100 km. These findings demonstrated that one-stage amplification is ineffective at longer lengths, and a cascaded EDFA-EDFA design achieves a scale of BER of less than 10^{-9} over a distance of 100 km. This implies that the reach of long-reach is influenced not only by the presence of amplifiers but also by the amplification strategy. Scalability of architecture has been explored as well. Randhawa [62] suggested a hybrid WDM/TDM system with an area of 96 users on a feeder fiber of 96 km. The system was operating at 10 Gb/s NRZ with all the subscribers recording Q-factor values of over 6. In comparison to only physical-layer compensation, it can be argued that multiplexing architecture plays an important role in determining the reach and density of subscribers. However, the dispersion is a preponderant impairment. Mustafa et al. [14] demonstrated that cascaded FBG compensation, especially when duobinary modulation is used, compensates pulse broadening better than conventional NRZ at 10 Gb/s. Likewise,

At the standard access level, real-world deployment experiments provide additional stability verification of standard GPON designs. Sapundzhi et al. [63] described the design and deployment of a GPON-based FTTH network in a small town, using cascaded splitters (1:4 and 1:16), organized OLT planning, and the verification of optical power budget in detail. They showed consistent performance up to the 20km limit of GPON and can be scaled to 64-128 users per OLT port.

But the architecture is still restricted to classical access ranges and fails to support long-range extensions (beyond 40 km) and incorporation of dynamic optical switching planes. It is established in the study that splitter configuration and optical budgeting can be used to assure consistent performance at the metro/access scale, but wavelength-routing interactions, cascaded switching impairments, and national-scale transmission difficulties are not considered. This underscores the difference between access-level-optimization and large-scale backbone-integrated WDM-PON architectures.

Verma and Garg [48] have indicated acceptable BER performance to about 60 km with Avalanche Photo Diode (APD) receivers, with a degradation evident at around 70 km through the built-up dispersion and power loss. These results suggest that the received sensitivity improvements may be limited to a range of achievable physical limits. In addition, there are protocol constraints.

A more flexible solution to extended reach was shown by Liao et al. [64], who incorporated the short-to-long reach fiber transmission in a WDM-PON design with periodic AWG routing to compensate for the upstream and downstream wavelengths and reduce Rayleigh backscattering. The study established that reach can be flexibly extended by wavelength engineering and optimization of power budget instead of only through dispersion compensation by assigning various modulation rates (2.5-28.2 Gb/s) based on fiber length (15-75 km). Nevertheless, even though it is a useful design that offers insight into the practicality of multi-rate adapting and wavelength-level control, its assessment is limited to access-level reach, and to implement wavelength-aware strategies on a backbone scale, coordinated switching, amplification staging, and protocol-conscious control mechanisms are required. As Sachdeva et al. [65] emphasized, at high loads, the probability of burst blocking is higher with a more significant round-trip time (RTT) in long-reach PON because the dynamic bandwidth allocation (DBA) is broken. Therefore, despite the success of optical compensation, latency and schedule inefficiencies can be used to constrain scalability. In general, it is indicated in the literature that long-reach PON extension is not a one-layered maximization issue. Hybrid multiplexing Randhawa [62], amplification (Reza et al. [60]), or dispersion compensation Mustafa et al. [14] or receiver enhancement Verma and Garg [48] are add-ons. Nevertheless, none of them alone can ensure stable performance at distances of over 80-100km when heavy traffic is observed. The combination of physical and protocol constraints inspires the need to seek more flexible optical-layer routing and switching solutions for longer-distance deployments.

5. Optical Data Center Networks (ODCN)

The intensive development of data traffic within the modern data centers is conditioned by the presence of data-intensive applications implemented in the edge and cloud modes [59]

Under such conditions, traditional electrical switching architectures are growing susceptible. Abdulmahdi et al. [27] considered the structural constraints of electrical topologies and pointed out that even though OCS is potentially less power-consuming than electrical interconnects, it lacks scalability to highly dynamic traffic because it can be quite slow to reconfigure. Their discussion explains that the traditional reconfigurable optical networks (RONs) and, in particular, the RONs with fixed routing structure like Fat-Tree, find it difficult to deal with blocking probability when using static optical configurations.

In order to overcome this shortcoming, Imran et al. [66] suggested a hybrid optical switching architecture that was specifically developed to be used with ODCNs. They used OMNet++ to simulate a hybrid network. In this model, ongoing data flows go through power-efficient MEMS switches, while short bursts are sent to fast SOAs switches that work at nanosecond speeds. Such traffic-conscious segregation causes the MEMS ports in slower traffic to have less congestion, and the load handling is enhanced in the presence of realistic data center traffic patterns.

Scalability is also mainly determined by the choice of switching technology. The MEMS and Liquid Crystal on Silicon (LCOS) technologies were compared by Nance Hall et al. [67]. Their analysis revealed that MEMS has a reduced insertion loss in large-scale crossing slang, but LCOS is more appropriate in WSS by its non-mechanical composition. Notably, they stressed that scalability can be constrained by hardware only, but it is also subject to the scheduling horizon of the control plane, i.e., the possibility of computing interference-free configurations within the reconfiguration time window.

Mahdian et al. [4] moved the debate more recently to the integrated photonic switch fabrics. Their contribution suggests that silicon photonic platforms with micro-ring resonators (MRRs) are needed to support AI next-generation workloads and high-performance computing workloads. These integrated solutions have high port density, reduced latency, and better scaling.

5.1 Production-Scale Optical Switching in Data Centers

Optical switching is no longer a prototype undertaking in the laboratory but a reality in a production set-up. Liu et al. in [25] wrote about the Lightwave Fabrics of Google, which is one of the first large-scale implementations of optical circuit switching in machine-learning and cloud clusters. Their design makes use of WDM transmission and optical circulators to enable

bidirectional high-bandwidth communication across single fibers, which forms an efficient and reconfigurable optical fabric using less energy.

On the same note, Urata et al. [68] introduced "Mission Apollo," which reported extensive implementation of 3D-MEMS-based OCS in Google data centers. They found that optical circuit switching can meet hyperscale workloads in active environments, as opposed to being a research idea.

In addition to pure OCS fabrics, Teh and Zhao [69] proposed the METTEOR architecture, which is based on inverse multiplexing. They do not use a single optical link with ultra-high speed; their implementation combines several moderate-rate circuits into dynamically high-capacity circuits. With this approach, the bandwidth can be scaled with the demand without any upgrades in the data rate per link or the replacement of physical infrastructure. Their assessment indicates better performance in the presence of different traffic conditions, especially when there is a change in the patterns of the traffic.

5.2 Architectural and Physical Layer Challenges in Data Center Networks

Despite the advantages of optical switching, modern optical data center networks face sharply coupled constraints across traffic dynamics, signal integrity, and energy consumption (as summarized in Figure 3).[2], [24].

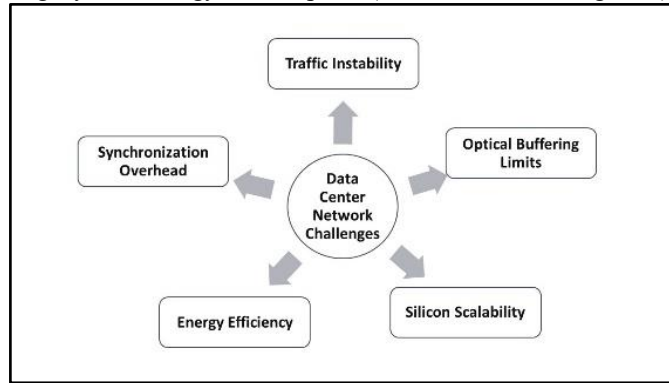


Figure 3: Primary architectural and physical-layer challenges in optical Data Center Networks

In contrast to purely electronic systems, an optical data center network needs to meet sharply coupled constraints that cut across traffic dynamics, buffering constraints, silicon integration density, and synchronization overhead. Traffic instability is one of the main issues. In M/M/1 queuing models, Shukla et al. [70] demonstrated that the cloud traffic arrives stochastically with bursty behavior. They analyze that random bursts of high intensity can surpass the reaction speed of centralized planes of control, resulting in temporary congestion at Top-of-Rack (ToR) switches. This indicates that the one way to remove blocking when there are no better traffic management systems is by increasing the link capacity. Optical buffering is one of the possible mitigation measures. The constraints of recirculating fiber-loop buffers were, however, quantified by Sinha et al. [6], and the authors illustrate that with each circulation, more ASE noise is introduced. Although the loss of packets is decreased by the deeper buffering, noise that builds up gradually decreases the OSNR, which gives a practical upper limit to the buffering time. This points to a trade-off between delay tolerance and signal integrity. Also, on the device level, silicon photonic scalability creates additional constraints. According to Cheng et al. [71], crosstalk between neighboring waveguides increases with the density of integration to the range of terabit-per-second. According to their findings, miniaturization is not necessarily a panacea to scale because excessive port density is sufficient to degrade signal quality. Energy efficiency is also another structural constraint. Traffic pattern has been studied by Yoo [2] in modern data centers and found that most of the traffic is East-West (server-to-server) traffic. This traffic route causes the data to go over several switching layers, which causes OEO conversions to be repeated. Yoo states that much of the energy consumed in switching logic is not associated with switching logic itself but with line cards and transceiver modules needed to process OEO. These results imply that flattening of architectures, and not step-by-step increases in switch speeds, could make a more sustainable change in efficiency. At last, the bottleneck appears in the form of synchronization overhead, which is not so visible but still critical. Xue et al [72]. investigated the Clock and Data Recovery (CDR) behavior of optical switching systems and demonstrated that traditional CDR circuits can take microsecond-scale locking times. Such locking delays can be a major detrimental factor to effective throughput when the duration of packets is in the dozens of nanoseconds range. Their work stresses the need for burst-mode CDR methods with much higher-phase acquisition rates to sustain high efficiency in packet-level optical switching is stressed in their work.

6. Critical Synthesis and Research Gaps

In contrast to other previously conducted studies, which consider photonic switching and long-reach WDM-PON systems as two different streams of research, the current review places the two fields under one analytical frame. It integrates

switching technology, wavelength routing technology, dispersion compensation technology, and amplification technology in the transport of long-range networks of optical access.

Instead of discussing device speed, transmission distance alone, etc., this paper emphasizes the interaction of the insertion loss, amplification noise, and scalability of the wavelength at a system level. Focusing on cascaded OADM configurations and their practicability in long-reach conditions where BER, Q-factor, and power budget margins are of concern. The review will attempt to offer a systematic structure for designing scalable, low-latency, and physically resilient national-scale WDM-PON infrastructures by structuring the literature in terms of architectural integration, as opposed to individual elements.

6.1 Review of Long-Reach WDM-PON Studies

Much research has been done on how to extend the range of transmission of Passive Optical Networks beyond the traditional 20km access limit. Some of the studies have mainly dealt with physical-layer limitations like chromatic dispersion, attenuation, and amplified noise build-up. As an illustration, Lazem et al. [12] tested a 48-channel DWDM system with a distance of between 240 and 300 km with SMF, DCF, and cascaded EDFA amplification, and studied the effects of launch power and dispersion compensation on Q-factor and BER performance. Equally, Htwe et al. [36] established that DCF, when used together with optimized EDFA stages, helps to improve the stability of transmission within high-speed PON mediums significantly.

Naim et al. [73] implemented a 32-channel DWDM-PON that uses 10 Gb/s per channel and 100 GHz spacing with SMF, DCF, and EDFA amplification. Their analysis of OptiSystems compared NRZ, RZ, and duobinary modulation format distance to 120 km. The findings indicated that duobinary coding got the best BER (2.66×10^{-19}) and Q-factor of 8.9 at an altitude of 100 km, exceeding the performance of NRZ and RZ in the same conditions. Although the study validates the technique of dispersion compensation and optimized modulation format in their effectiveness, the assessed reach is still in the range of metro-spans (less than 120 km) and is not subject to multi-span cascaded amplification or dynamic wavelength routing. Therefore, has not been validated under nationwide-scale cascaded switching architectures.

Sensitivity to receivers and effects of modulation were investigated in other works. Verma and Garg [48] have reported that NRZ-based WDM-PON architectures give acceptable performance of BER to about 60-70 km before dispersion and power loss will lead to poor signal quality. Recent simulation studies of TWDM-PON, including in Látal [74], have been able to meet long-reach operation down to 60 km with high split ratios; they mostly focus on physical-layer optimization, including amplification and dispersion compensation. Although these results validate the viability of long-range transmission, the evaluation does not extend to dynamic network operation or integrated system-level performance considerations.

On the backbone level, Rani et al. [35] tested an ROADM-based DWDM system with a transmission distance of 780 km and 16 channels. Though these studies show that ultra-long-haul is feasible, they do not combine access-layer switching logic and test wavelength routing interactions in PON structures.

Simultaneously, architectural scalability has been considered in the data-center and metro setting (e.g., Ye et al. [29]; Shukla et al. [30]), but the works seldom investigate physical impairments in long fiber distances. Consequently, two serious gaps are created. First, there is a functional gap: functional studies of long-reach PONs rarely include dynamic optical switching or wavelength-routing functionality other than in the case of simple OADM architectures. Second, a scalability discontinuity: the current benchmarks usually break at metro-scale ranges, and the interdependence between cascaded optical switching planes and ultra-long-haul fiber impairments has not been well studied.

The overall evidence of previous studies proves that it is possible to have longer optical transmission. Nevertheless, a system-level architecture that combines long-reach physical limitations with cascaded switching architectures that are appropriate to deploy to nationwide WDM-PON deployments is understudied.

6.2 Identified Research Gap

Despite the significant advances in long-reach PON transmission and optical switching fabrics being investigated independently, their convergence on the system level is not studied properly. The literature will generally discuss (i) physical-layer amplification methods to extend reach to (ii) optical switching scalability in metro and data-center systems, but rarely both of these altogether as a national-scale system.

Precisely, three dimensions are not sufficiently discussed at the same time:

- Long-distance (>1000 km) transmission distances reflective of national backbones,
- High-access user scalability,
- Different rates (e.g., 10G/40G) on a cascade-based switching architecture.

Although other surveys, like Abdulmahdi et al. [27], consider possibilities of optical switching integration, they do not offer simulation-based validation of ultra-long-distance integration with cascaded switching nodes integrated within WDM-PON architectures.

As a result, there are still no end-to-end models that assess the behavior of optical switching fabrics deployed over statewide fiber distances, where the interactions between dispersion accumulation, OSNR loss, and nonlinear processes, and wavelength-sorting logic and cascaded amplification schemes interact.

Also, at least to the best of our knowledge, no previous study combines the study of PON technologies, optical switching integration, and deploying PON technologies at regional or even national-scale coverage at the same time within a single coherent architecture.

To illustrate these limitations, Table 3 provides a summary of recent studies. It demonstrates that although individual works are dedicated to specific areas (e.g., PON, optical switching, or long-reach transmission), none of them combine all these vital parameters into a single study.

Table 3. Summary of Studies and Identification of the Research Gap

Author(s)	PON Tech.	Optical Switching	DCN Application	Long-Reach	Performance Analysis	Key Takeaway from the Study
[9]	√	X	X	√	√	Demonstrated 160/80 Gb/s TWDM-PON using FBG; dispersion compensation is essential for maintaining BER/Q-factor beyond long distances.
[20]	X	√	√	X	√	Achieved a 43.4-ns photonic switching system; establishes state-of-the-art for nanosecond reconfiguration.
[30]	X	√	√	X	√	Proposed a large-capacity optical switch architecture using AWG + FDL; showed switching performance depends on topology and buffering strategy.
[33]	X	√	X	X	√	Evaluated an OADM-based metropolitan network at 1.6 Tb/s, demonstrating effective wavelength add/drop performance with high Q-factor and low BER.
[36]	√	√	X	X	√	Investigated the effect of switching delay time and crosstalk using Wavelength Selective Switches (WSS) in flexible WDM-PON networks.
[49]	√	X	X	√	√	Showed that BER degrades sharply beyond ~60 km without dispersion mitigation, highlighting the limits of long-reach PON.
[56]	X	X	X	√	√	Demonstrated that DCF + repeaters stabilize DWDM signals over >400 km; useful analogy for national-scale long-distance fiber links.
[68]	X	√	√	X	√	Real-world demonstration of large-scale OCS proves optical switching is practical and production-ready.
[73]	√	X	X	X	√	Explored WDM-based multi-wavelength provisioning; reinforces the scalability of WDM long fiber.

To overcome this key challenge, a holistic and layered design approach is needed. Our integrated design approach for flat national-scale Long-Reach WDM-PON is shown in Figure 4. The framework shows the design process from architectural flattening (eliminating unnecessary O-E-O conversions) to the choice of suitable transparent switching technologies (such as AWGR and Hybrid MEMS-SOA). Then, we take physical-layer mitigation measures to ensure signal quality and performance over the long distances of a national-scale network.

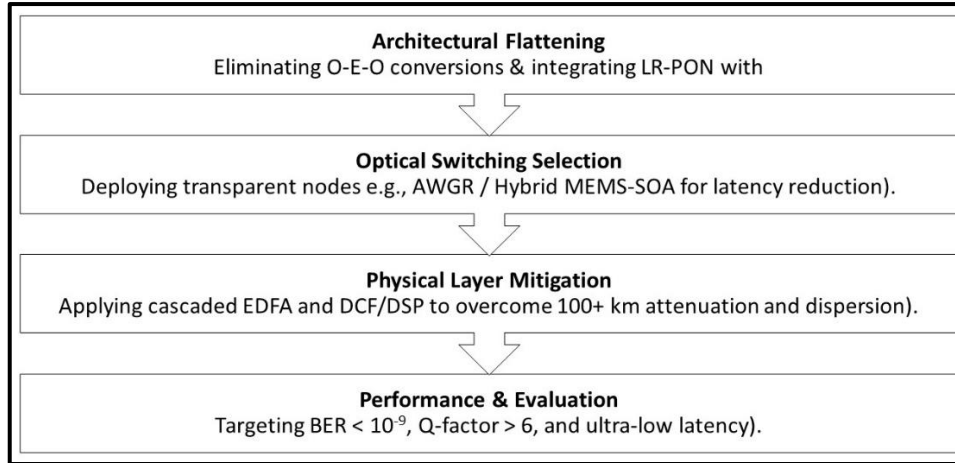


Figure 4: The proposed integrated design framework for a national-scale flat Long-Reach WDM-PON

7. Conclusion

This review shows that the current trend to national-scale Long-Reach WDM-PON architectures is not just a capacity boost, but relatively an architectural transformation of optical networking itself. The classical hierarchical designs have difficulties in the consumption of power, the accumulation of latency, and the limitations in scalability, especially when the traffic patterns are changed to dense and burst-based. These proposed designs and solutions are especially important for high-performance applications and domains, such as distributed Data Center Interconnects (DCI) and 5G/6G mobile backhauling. The comparison of switching technologies proves the fact that there is no one optimal optical switching mechanism that meets all the performance metrics at the same time. Passive components AWG and OADM are offering stability at the wavelength scale and also deterministic routing in the edges of the access and metro, whereas MEMS-based optical switches provide scalable circuit switching capability for large switching fabrics. Contrastingly, SOA-based switching is critical in dealing with bursty traffic that is fast and needs nanosecond-responsiveness. Therefore, Hybrid switching appears to be a promising and practical direction, which trade-offs include the loss due to insertion, switching speed, scalability, and energy consumption. Nonetheless, the cumulative chromatic dispersion, attenuation, nonlinear effects, and OSNR degradation are introduced by extending WDM-PON to long-haul or national ranges. To solve these anomalies, the use of DCF cascading, EDFA amplification, and power optimization must be combined. It has been demonstrated throughout the literature that a bare physical-layer enhancement is not sufficient in the absence of architectural awareness. The subsequent national optical infrastructures will not merely be based on quicker equipment, but system-model approaches that integrate optical switching allotment, wavelength direction consciousness, and physical-layer constraints across extended distances to a unified coherent architectural system. For future work, there is an interesting opportunity for development in the direction of suggesting smart approaches, for instance, using the combination of SDN and Machine Learning (ML), to dynamically handle these physical limitations to improve the network performance. The greatest research direction that should bridge this gap of integration to establish a scalable, energy-efficient, and latency-conscious deployment of WDM-PON in the country is the development of integrated architectures that collectively mitigate optical switching flexibility issues and physical-layer transmission constraints as envisioned by the architectural framework in this review.

8. Declarations

8.1 Ethics approval and consent to participate

Not applicable. This study is a systematic literature review and does not involve any human participants, animals, or clinical trials.

8.2 Consent for publication

Not applicable. This manuscript does not contain any individual person's data, images, or videos.

8.3 Availability of Data and Materials

Not applicable. All data analyzed and synthesized during this study are included within this published review article and its cited references.

8.4 Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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دراسة مرجعية لشبكات الألياف الضوئية السلبية طويلة المدى بالتقسيم الموجي (WDM-PON) المسطحة والتحويل الضوئي لربط مراكز البيانات الوطنية

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المستخلص:

تتطلب البنية التحتية الوطنية للألياف الضوئية تحديثاً مستمراً نظراً للطلب المتزايد على نقل البيانات بين مراكز البيانات والمستخدمين النهائيين، والذي أدى إلى حدوث اختناقات وتأخيرات. تقدم هذه الورقة مراجعة منهجية لمعماريات شبكات الألياف الضوئية السلبية طويلة المدى بالتقسيم الموجي (LR WDM-PON) المسطحة على المستوى الوطني. يتم دمج هذه المعماريات مع تقنيات التبديل (التحويل) الضوئي لربط مراكز البيانات الموزعة (DCI) بهدف تعزيز أداء الشبكات الضوئية. تحلل الدراسة تطور شبكات WDM-PON نحو عمليات الوصول الممتد (المدى الطويل)، وتسلط الضوء على دور المُجَبِّعات الضوئية للإضافة والإسقاط (OADMs) في التوجيه على مستوى الطول الموجي. بالإضافة إلى ذلك، نناقش التحديات الرئيسية التي تحد من الإرسال الضوئي، مثل تراكم التشننت اللوني، والتأثيرات غير الخطية، وتدهور نسبة الإشارة الضوئية إلى الضوضاء (OSNR) الناتج عن التكبير المتسلسل للمقويات. يُعطى اهتمام خاص لاستراتيجيات تعويض التشننت، مثل استخدام ألياف تعويض التشننت (DCF)، وتأثيرها على أداء معدل خطأ البت (BER) في سيناريوهات الوصول الممتد. تجمع هذه المراجعة بين الدراسات التجريبية والنظرية الحديثة لشرح أطر التصميم الأساسية والقيود الفيزيائية المرتبطة بتوسيع نطاق الشبكات الضوئية الشفافة لتغطي المستوى الوطني.