ADVANCED NOTIFICATION-BASED DATA TRANSMISSION IN HIGH-SPEED OPTICAL FIBER NETWORKS FOR COMPUTING SYSTEMS

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ABSTRACT

The exponential growth of data-intensive computing systems has intensified demand for high-throughput, low-latency network infrastructure. Optical fiber networks, underpinned by Wavelength Division Multiplexing (WDM) and Space Division Multiplexing (SDM), represent the dominant transmission substrate for modern computing environments. This study investigates Advanced Notification-Based Data Transmission (ANDT) as a proactive traffic-management paradigm within high-speed optical fiber networks. By dispatching control signals ahead of primary data bursts, ANDT enables network nodes to pre-allocate bandwidth, reduce queuing delays, and minimize packet loss in high-traffic computing environments. The study evaluated throughput and latency improvements achievable through notification-based mechanisms relative to conventional protocols, and assessed system-level efficiency gains in computing infrastructure. A quantitative experimental methodology was adopted using simulated Optical Burst Switching (OBS) scenarios benchmarked against ITU and IEEE standards. Statistical hypothesis testing confirmed that ANDT achieves significant reductions in latency and packet loss. Findings indicate up to 69.6% latency reduction and 91.6% improvement in burst loss rate, positioning ANDT as a viable next-generation transmission strategy for computing systems globally.

Keywords: *Optical Fiber Networks[1], Notification-Based Transmission[2], Wavelength Division Multiplexing[3], High-Speed Computing[4], Latency Optimization[5]*

1. INTRODUCTION

The international virtual setting is experiencing an outstanding evolution, powered via cloud computing, synthetic intelligence, and the proliferation of interconnected devices. Optical fiber networks are an essential part of this emerging infrastructure, providing unique characteristics of high-speed, long-distance, low-loss data transport near the speed of light. Currently worth an estimated USD 8.07 billion in 2023, the fiber optics industry is on the path to continued growth fueled by an ever-increasing hunger for bandwidth across enterprise, residential, and scientific computing axes (Brackett, 1990). This growth has created a need for new paradigms of data transmission that go beyond legacy reactive packet-switching architectures and their legacy congestion limitations. Traditional transmission methods in optical fiber networks are reactive data transmission takes place, network congestion is identified after-sending, and then remedies are taken after-the-fact. In a scene where deterministic, low-latency delivery are key to orchestration workloads, distributed processing and inter-processor communications manifests a significant inherent inefficiency. However, under peak-hour congestion conditions, the application performance throughput can be negatively impacted by latency values well in excess of 50,000 microseconds due to queuing observed under 10G link speeds (Asaba et al., 2023). Unpredictable latency profiles like these cannot maintain acceptable performance for high-performance computing clusters, AI training environments, or real-time data pipelines.

This limitation is overcome by Advanced Notification-Based Data Transmission (ANDT), consisting of a proactive control layer derived from Optical Burst Switching (OBS). The OBS protocol reserves the network resources through sending the burst control packet before the data payload between the intermediate nodes in the OBS network. Extending this idea to fast optical computing networks, efficient networking architecture with notification-driven transition (ANDT) sends a notification signal which contains metadata such as the duration of the burst, its priority class, its destination address and its bandwidth (to allow switching matrices to effectively pre-configure before the primary data burst arrives) (Saridis et al. 2015). It overcomes reactivity-based queuing delays and also minimizes the contention at optical crosspoints immensely. This is especially true for data center scenarios, which gives ANDT an extra layer of relevance. A systemic study on optical interconnects concluded that the electronic packet switches characterizing current data center networks present a severe power drawback and grow intractable for meeting the ever-increasing application communication bandwidth demands of next-generation datacenters; optical interconnects been seen as a promising alternative, providing high throughput, low latency, and energy-efficient solutions (Kachris & Tomkos, 2012). These recent advances validate the enormous capability of physical fiber far beyond current use specifically the 22.9 Petabit-per-second transmission recorded by NICT in 2023 with extreme space-wavelength multiplexing over a single optical fiber (Puttnam et al 2023).

In addition, new developments in Dense Wavelength Division Multiplexing (DWDM) that can support as many as 96 simultaneous wavelength channels per fiber with a data rate of 400 Gbps per channel represent an ideal environment for achieving notification-based reservation schemes without degrading aggregate data throughput (Brackett, 1990; Xu et al., 2023).

2. LITERATURE REVIEW

The development of optical fiber transmission has been characterized extensively in both experimental and theoretical literature. Liu outlined a complete trajectory of the transition of fiber-optic transmission to the 5G era, hypothesising that the commercial per-fiber capacity was in the vicinity of 64 Tb/s through multi-band Erbium-Doped Fiber Amplifier amplification and advanced optical digital signal processing algorithms. Their assessment provides valuable context for the operatic conditions under which notification-based systems are expected to function. In the optical network architecture, Soma et al. conducted a record of 10.16 Pb/s using 6-mode, 19-core fiber over the C+L transmission band. Their work was instrumental in providing experimental confirmation that Space Division Multiplexing significantly increases the capacity above that of conventional single-mode fiber. Saridis et al. conducted an appraisal of the seminal survey and evaluation of SDM within this complete context, stratifying the technologies from multi-cores to few-mode fibers and explored their in-principle integration into a complete functional network. The assessment supports the premise that SDM and WDM form the implementable route to a scalable petabit-class network. Brackett formally established the distance-based limitations of DWDM scaling, with single channel capacities limited at about 100 Gb/s. Their work provides initiating guidelines for spacing, amplification, and protocol transparency requirements complete relevant. The properties of these WDM systems sets, including dispersion management and long-haul traffic distances and signal reflashes, were charcoaled in Bergano and Davidson. Their work saw wide use in the context of programmable DWDM system design.

In addition, Basch et al., conducted an architectural tradeoff analysis on reconfigurable DWDM systems. (2006), which formed the design lexicon of today's flexible optical networks through their assessment of optical add-drop multiplexers and cross-connect configurations. With respect to the chip scale, for example, Dong (2016) showed that silicon photonic integrated circuits allow wavelength-division multiplexing at the computing nodes, allowing for coming-very-close-multiplexing to the processor and notification-based control signaling at unprecedented small spatial granularity. We conclude the section by discussing implications for ANDT of recent advances in protocol-level control. Under the Internet Engineering Task Force (IETF) RFC 9331 designated low-latency, low-loss, scalable throughput (L4S) Explicit Congestion Notification (ECN) protocol, De Schepper and Briscoe (2023) formalized a signaling framework through which network nodes communicate congestion state prior to full queue saturation. Sengupta et al. (2022) showed that a millisecond-plus network telemetry delay can be achieved in deployed networks, as the authors used programmable data planes to continuously monitor round-trip time in-network.

Performance measurement studies have confirmed the operational levers targeted by ANDT. Asaba et al. (2023) illustrated and measured throughput and latency of optical fiber communication networks running in the field, establishing link congestion during peak hours leads to non-compliant low-latency in addition to low throughput. Drainakis et al. In (2023), they drew their low-latency optimization skills to the field of optical access network and, specifically, to TCP Prague concepts for time-sensitive services as well as to the impetus for proactive notification protocols. Trevisan et al. A recent five-year longitudinal study of internet performance at the ISP level by (2020) establishes baseline performance trends to which one must measure protocol improvements. Using eBPF for continuous latency monitoring therefore enables real-time protocol tuning, which directly relates to ANDT feedback loops. Established hardware capacity for ANDT, whose photonic chip microcomb transmission of 1.84 Pb/s verified the notion of dedicated spectral resources for notification channels.

3. Objectives

1. To evaluate the impact of Advanced Notification-Based Data Transmission (ANDT) on throughput and latency performance in high-speed optical fiber networks compared to conventional data transmission protocols.

2. To assess the computing system efficiency gains specifically in packet loss reduction and resource utilization achievable through ANDT deployment in optical fiber data-center network environments.

4. METHODOLOGY

A quantitative experimental design was employed in this study to simulate notification-based data transmission to high-speed optical fiber networks. The research utilized an experimental architecture for optical burst switching (OBS) design that sends control notification packets ahead of data bursts 5 ms. before enabling intermediate nodes in the network to pre-allocate switching resources. Peer nodes then read the notification payload consisting of destination address, burst duration, priority class and required bandwidth, allowing optical crosspoints to configure their selection of a wavelength switching matrix in advance of signal burst arrival. There were six simulated network topology scenarios in the sample, each systemically varied in three dimensions: fiber link speed (10G, 100G, and 400G), numbers of active DWDM wavelength channels (32, 64, and 96), and number of concurrent computing workload intensity (low, medium, and high). For each configuration, there are 1,000 simulation runs per scenario, yielding a total of 6,000 data points per protocol condition when evaluated assuming conventional transmission and ANDT.

Network simulation engine designed based on ITU-T G.709 OTN standards and IEEE 802.3 Ethernet framing parameters the main data collection instrument We collected performance metrics such as: throughput (Mbps/Gbps), one-way end-to-end latency (μs/ms), packet/burst loss rate (%), resource utilization efficiency (%) and control-plane setup overhead (ms). Secondly, the data were obtained from published experimental studies providing the real optical fiber network performance. Methods used were descriptive statistics for measures of central tendency and dispersion, independent-samples t-tests at $\alpha = 0.05$ comparing ANDT to conventional transmission performance, and effect size by Cohen's d statistic. Performance metrics were tabularized to depict across all the scenario categories. We checked for data normality through Shapiro-Wilk test before making the parametric analysis, and the outcomes were cross-validated against performance benchmarks calculated based on IEEE 802.3 and ITU-T G.8201.

5. RESULTS

Table 1: Global Optical Fiber Transmission Capacity Milestones (2018–2023)

Year	Record Capacity	Technology Used	Reference
2018	10.16 Pb/s	6-mode, 19-core SDM/WDM (C+L band)	Soma et al. (2018)
2022	1.84 Pb/s	Photonic chip microcomb ring resonator	Jørgensen et al. (2022)
2022	22 Tbps/pair	Grace Hopper subsea cable (16 fiber pairs)	Rademacher et al. (2023)

2023	301 Tbps	E+C+L band over commercial SMF	Rademacher et al. (2023)
2023	22.9 Pb/s	38-core 3-mode MCF + 750-channel WDM	Puttnam et al. (2023)

Exponential growth trajectory of optical fiber transmission capacity milestones from 2018 and 2023 recorded in Table 1. Starting from the 10.16 Pb/s record broken in 2018 via 6-mode 19-core SDM/WDM (Soma et al., 2018) capacity increased to more than doubly the amount of bit by bit in 2023, reaching a total of 22.9 Pb/s via extreme space-wavelength multiplexing (Puttnam et al., 2023). These benchmarks underscore substantial if not nearly limitless overhead space from which ANDT notification channels can be drawn from existing spectral resources without incurring significant capacity penalties on primary data wavelengths.

Table 2: Latency and Throughput Performance in Optical Fiber Links Against IEEE/ITU-T Standards

Test Condition	Link Speed	Measured Latency (µs)	Throughput (%)	Standard Compliance
Peak-hour congestion	10G	50,000–64,000	<90%	Non-compliant
Off-peak stable	10G	37,000	100%	Compliant
Peak-hour congestion	100G	76,000–92,000	95%	Non-compliant
Zero active traffic	100G	0	—	—
Singapore avg. fiber	1G	4,000	205 Mbps upload	Compliant (best-in-class)

The relationship between network load conditions and latency performance as extracted from operational optical fiber links is summarized in Table 2. And it is the data showed that the 100G link had latencies during peak-hour congestion of 76000–92000 µs and IEEE/ITU-T compliance thresholds were violated (Asaba et al., 2023). The best around the world is in Singapore, where 1G latency is at 4,000 µs maximum. These results directly illustrate the disparity that proactive notification based pre-allocation must eliminate to ensure consistent performance standards compliance during computing workloads with high demand.

Table 3: DWDM Channel Configuration and Network Capacity Specifications

WDM Technology	Max Channels	Per-Channel Rate	Total Capacity	Distance Support
CWDM	18	10 Gbps	180 Gbps	<80 km
Standard DWDM	80	100 Gbps	8 Tbps	>1,000 km

Advanced DWDM	96	400 Gbps	38.4 Tbps	>1,000 km
SDM + Multi-band DWDM	38 cores × 750 ch	>1 Pbps/fiber	22.9 Pbps	13 km (lab)

DWDM channel layouts with corresponding density assignment are shown in Table 3. Currently, three-dimensional wavelength-division multiplexing (DWDM) systems are based on 96 separate wavelength channels in the 1550-nm region, each having a 400 Gbps data capacity, contributing toward 38.4 Tbps of aggregate capacity per fiber (Brackett 1990; Xu et al, 2023). In controlled conditions, the SDM+DWDM configuration reached 22.9 Pbps (Puttnam et al., 2023). Confirmation of these specifications shows that dedicating one or two specific notification channels for ANDT control signaling incurs a negligible overhead of less than 1.3% of total channel capacity, while allowing for network-wide pre-allocation coordination.

Table 4: ANDT vs. Conventional Transmission Comparative Performance Metrics(N = 6,000 runs)

Performance Parameter	Conventional	ANDT Protocol	Improvement (%)
Average Latency (ms)	18.4 ± 3.2	5.6 ± 1.1	69.6%
Burst/Packet Loss Rate (%)	3.8 ± 0.6	0.32 ± 0.07	91.6%
Throughput Efficiency (%)	68.3 ± 4.1	89.7 ± 2.8	31.3%
Resource Utilization (%)	63.5 ± 5.4	87.2 ± 3.1	37.3%
Setup Overhead (ms)	12.6 ± 2.0	7.8 ± 1.3	38.1%

The core comparative performance results between traditional transmission and ANDT over 6,000 simulation runs is summarized in table 4. Across all the five parameters tested, conventional protocols did not beat ANDT. Latency experienced a significant drop of 69.6%, from 18.4 ms to 5.6 ms; meanwhile burst loss-rate dropped from 3.8% to 0.32%, showing an impressive 91.6% improvement (Sengupta et al., 2022; De Schepper & Briscoe, 2023). All improvements are statistically significant (α = 0.05, independent-samples t-test p 0.8), confirming both practical and statistical significance.

Table 5: Packet and Burst Loss Rates Across Link Speed and Traffic Intensity Conditions

Link Speed	Traffic Intensity	Conventional Loss (%)	ANDT Loss (%)	Reduction (%)
10G	Low	0.52	0.04	92.3%
10G	High	4.21	0.38	91.0%
100G	Low	0.31	0.02	93.5%
100G	High	5.14	0.41	92.0%
400G	Low	0.22	0.01	95.5%
400G	High	3.63	0.28	92.3%

The packet/burst loss rates for all of the 6 link-speed and traffic-intensity conditions for corresponding transmission paradigms are summarised in Table 5. Each configuration resulted in loss reductions above 91% for ANDT (da Silva & Pedroso, 2022). Between swapping with 0.41% losses on domestic losses -> and conventional protocol -> 5.14% packet loss under high intensity traffic reflecting actual load at cloud data center peak loads (100G). Thus no cycles of retransmissions caused. These results echo ECN-based pre-notification principles found in RFC 9331 (De Schepper & Briscoe, 2023), where proactive signaling is shown to remove burst loss in optical switching systems, which constitutes the main cause of congestion and loss of data packets.

Table 6: Global Optical Fiber Market Growth and Broadband Performance Benchmarks (2020–2023)

Year	Market Value (USD Billion)	Global Avg. Speed (Mbps)	Connections >100 Mbps (%)	Best-Case Latency (ms)
2020	5.12	85.7	21%	~10
2021	6.34	112.5	27%	~8
2022	7.45	165.2	33%	~6
2023	8.07	205+ (Singapore)	39%	~4

The data presented in Table 6 provides a context of global expansion of optical fiber market and trends of global broadband performance from 2020 to 2023 for this study. The sector has grown from USD 5.12 billion in 2020 to USD 8.07 billion in 2023, with broadband connections over 100 Mbps increasing from 21 per cent to 39 per cent of the total (Liu, 2019; Drainakis et al., 2023). Best case latency in Singapore (4 ms) is considered the global performance target that networks enabled by ANDT are built to achieve and maintain during intensive high-demand computing workloads in varied deployment environments.

6. DISCUSSION

This concludes that Advanced Notification-Based Data Transmission is a viable high-performance protocol strategy in optical fiber networks for feeding computing systems and gives significant empirical support to that claim. To tackle the first objective of improving throughput and latency, ANDT offer a 69.6% decrease in average latency and 31.3% enhancement in throughput efficiency against traditional transmission, Table 4 shows. This is in line with the a priori benefits of proactive control signaling described by De Schepper and Briscoe (2023) in the L4S simplified operating points in the congestion state space from announcing states proactively can prevent queue saturation, as opposed to reacting with causes after packet drop events. The first is that the correspondence between simulations and RFC-level protocol theory is strong ANDT's notification mechanism performs at the optical layer what ECN does at the IP transport layer. When computing exists, the latency cutting down occurring on most ANDT-enabled scenarios is very essential. Inter-process communication (IPC) latency is a significant factor impacting task synchronization, pipeline stalling and parallel workload completion time in distributed computing environments. Sengupta et al. Programmable data planes allow sub-millisecond responsiveness through real-time in-network round-trip time monitoring, ANDT uses this feature to steer switching resources to prepare for incoming data arrivals. This degree of accuracy under ANDT (Table 4) yields a 5.6 ms average latency (Table 6), which is near the 4ms match of Singapore's commercial fiber infrastructure, demonstrating the protocol's practicality for real-world deployment. Moreover, Sundberg et al. Continuous eBPF-based latency monitoring (2023) can return real-time metrics to protocol adjustment loops, such a feedback framework allows us to dynamically calibrate ANDT notifications based on the current conditions in a live network.

On the second of the two objectives processing gain in performance of computing systems, the results shown in Table 5 indicate an improvement of over 91% in packet loss for ANDT over all the link speeds and traffic intensities examined. This is particularly critical under 100G high-intensity conditions where traditional loss rates of 5.14% brings large TCP retransmission overhead and application-layer disruption on computing clusters. Albino's Results (described further in section 5.4) The substantial improvement in burst loss under ANDT (0.41% at 100G high intensity) is consistent with greater ideal theoretical predictions from OBS control architectures that utilize advance resource reservation to avoid mid-transit dropping (Saridis et al., 2015). Then further important load balancing implications: Barbette et al. The need for precisely the sort of pre-committed switching state that ANDT has captured is highlighted in the high throughput programmable loadbalancer framework of (2022), where they demonstrate that high traffic per-connection consistency preservation is impossible without such a construct. The improvement on resource utilizations (37.3%) provided in Table 4 is very meaningful to data centers from an operational perspective. More used channels that have reserved bandwidth means more saving on infrastructure and less energy per transmitted bit. Kachris and Tomkos (2012) cite the energy efficiency of optical interconnects as a main adoption factor; the pre-allocation mechanism of ANDT helps this efficiency by preventing unnecessary retransmission cycles that waste bandwidth and switching energy. Xu et al. Deterministic wavelength assignment delivers exactly that (ANDT's notification channel at network scale) and (2023) went on to show that computing architectures based on WDM achieve measurable benefit from it. Trevisan et al. Peak-hour congestion identified as the dominant cause of user-experienced performance degradation; consistent finding of five-year ISP-level performance study (2020), pattern of degradation directly addressed by ANDT proactive design.

DWDM capacity data based on Brackett's (1990) original analysis and adapted from Puttnam et al. (2023) show that existing wavelength space can be dialed up for dedicated notification channels, without reducing primary data capacity. Using 96-channel DWDM operating at 400 Gbps per channel and reserving two channels to carry ANDT notification signaling results in less than 1.3% capacity overhead across the network enabling large scale coordinated operation. Rademacher et al. Accommodating 301 Tbps, it was found that the E-band was previously unused in commercial systems and headroom of entire spectral resources that has been left untapped due to insufficient demand (i.e., ANDT notification traffic) could be fully exploited without any capacity-data trade-offs. Both objectives of the study are validated in the context of high-speed optical fiber networks for computing systems thus the results confirm that ANDT achieves statistically and practically significant improvements in all the metrics measured.

7. CONCLUSION

In this work we consider Advanced Notification-Based Data Transmission (ANDT) in high-speed optical fiber networks that serve computing systems. We confirm through simulation experiments in six network topology scenarios that ANDT achieves 69.6% lower average latency, 31.3% higher throughput efficiency, a packet loss rate over 91% lower, and a burst loss rate over 91% lower than conventional transmission protocols when applied to a DTN. Such enhancements can be accomplished on existing DWDM infrastructure by designating dedicated notification wavelength channels for advance allocation of resources at close to zero capacity cost. The global optical fiber market amounting to USD 8.07 billion in 2023, enabling unprecedented transmission capacities up to 22.9 Pb/s, is the perfect substrate for ANDT deployment. ANDT implementation in quantum optical networks, AI driven dynamic spectrum allocation systems, and real-time reconfiguration and control of optical circuit switching architectures should be investigated in future research.

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