Are WANs Ready for Optical Topology Programming?

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ABSTRACT

In today's wide-area networks, the optical layer is a relatively static and inflexible commodity. In response, Optical Topology Programming (OTP) has been proposed to enable fast and flexible reconfiguration of wavelengths at the optical layer from higher layers. We answer whether WANs are ready for OTP, concluding they are not. We reach this judgement by measuring reconfiguration delay on a long-haul fiber span. To push the needle on OTP towards feasibility, we show how to reduce the time to provision a circuit by an order of magnitude—from minutes to seconds. Finally, we propose a method to quickly store and load optical network equipment settings, reducing the time to less than 1 second.

1 INTRODUCTION

As the world's online services (e.g., AI, ML) migrate onto the cloud, demands on optical layer will continue to grow. In response, inspired by reconfigurable topologies in data centers [1, 2, 4, 5, 7, 10–14, 21, 22], concerted efforts have been pursued to reconfigure the optical layer [9, 15, 18, 20]. Further, the recent development of OpenConfig [19] will enable a more flexible and programmable optical layer. Such an environment serves as a starting point for physical-to-network layer coordination via *Optical Topology Programming* (OTP), i.e., the ability to quickly and flexibly reconfigure wavelengths between endpoints in an optical network.

While a programmable optical layer is poised to benefit the higher layers of the network stack, the jury is out regarding whether wide-area networks (WANs) are ready. On the one hand, some believe that the optical layer is OTP-ready and point to the theoretical efforts and optimization techniques for a programmable physical layer [3, 8, 16, 20]. On the other hand, others argue that OTP cannot be achieved in today's WANs due to pragmatic issues (e.g., reconfiguration delay imposed by amplifiers) at the optical layer.

To shed light on the pragmatic issues, we empirically measure the reconfiguration delays imposed by optical equipment and automated test schemes in WANs. To this end, we conduct experiments using standard optical gear (including optical amplifiers connected via spools of single-mode fiber) deployed in today's operational backbones to (a) highlight the technical challenges associated with practically realizing OTP and (b) establish a baseline for the time required for light paths to stabilize (i.e., to be ready for sending data after wavelengths are added or removed from an optical path). Our experiments show that 2–6 *minutes* are typically required for light paths to stabilize when equipment is operated with *standard automated test and adjustment* features. Most importantly, our experiments highlight the fact that many of the features *unnecessarily stretch* the reconfiguration time. This leads to our conclusion that the WANs—operated based on standard best practices—are *not* ready for OTP.

We find that automated test and adjustment features impose a significant delay that suggests OTP is impractical. We suspect that studying the behavior of these automated features may uncover outdated assumptions builtin, and provide an opportunity to make OTP feasible. Based on this intuition, we explore those features in detail and find that disabling a select few (effectively operating the amplifiers in manual mode) dramatically decreases the reconfiguration delay to 13–27 seconds. We verify that operating the devices in manual mode has no impact on the IP-layer traffic.

Finally, we use a lookup table to reduce the reconfiguration time. As wavelengths are added or removed, amplifiers adjust their gain to maximize the optical signal-to-noise ratio. This process happens each time the set of wavelengths changes, but the results from the computation are the same for a similar set of wavelengths and amplifiers. Therefore, we store these parameters in a lookup table and show that wavelengths can be added in approximately 500 milliseconds.

In summary, we make the following contributions: 1) We measure reconfiguration delay on a long-haul fiber span. 2) We show how to reduce the time to provision a circuit by an order of magnitude—from minutes to seconds. 3) We propose a method to quickly store and load optical network equipment settings, reducing the time to less than 1 second.

2 MOTIVATION: IS OTP FEASIBLE NOW?

Perspective of the Optics Community. The is a prevailing sentiment that OTP is possible in today's WANs, pointing to efforts on a diverse set of fronts towards a programmable physical layer. Notable categories and examples include protocol descriptions for dynamic path provisioning [3], lab-based evaluations of multi-layer control [8, 9], amplifier modeling [16], and operations research [20]. However, these efforts are not enough to enable a highly programmable optical WAN. What is lacking here is a pragmatic evaluation of optical layer components and their readiness for providing dynamic wavelength services in response to changing network and application layer demands.

Perspective of the Networking Community. To the best of our knowledge, we are not aware of practical OTP-ready

WANs.[1] We posit that this is primarily due to the pragmatic issues in realizing OTP; this is also the widely accepted perspective of networking community [6]. More concretely, the efforts in the optics community [3, 8, 9, 16, 20] hardly begin to close the book on practical applications of OTP. For example, CORONET [3] presents protocols and abstractions for operating a WAN with OTP but falls short to demonstrate methods for quickly turning up waves, and settles for add-times on the order of minutes. Similarly, OWAN [9] demonstrates benefits for multi-layer control, but their testbed trivializes amplifier control by considering one amplifier per link; long-haul links typically have half a dozen or more amplifiers. AcCBR [16] is an ML framework for configuring amplifiers in a WAN, but requires additional hardware at each amplifier in the network to collect sufficient data to build its model. Finally, theoretical efforts such as those done by Papanikolaou et al. [20] show that multi-layer control clearly offers better performance and survivability in the case of outages, but only via numerical models, not practical implementations.

These contradictory perspectives indicate a chasm between the communities on the practicality and feasibility of OTP. To bridge this ongoing divide between the two communities, this paper seeks to shed light on the pragmatic issues in making optical layer OTP-ready using lab-based measurements.

3 LABORATORY-BASED EXPERIMENTS

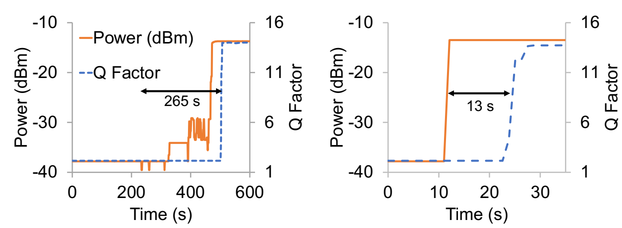
3.1 Objectives and Testbed

The main goal of this work is to investigate the feasibility of OTP by measuring the time taken by an optical path to stabilize to the point where it can be used to transport data after adding or removing wavelengths from higher layers. To this end, our testbed includes equipment found in points of presence (transponders, multiplexers) and on long-haul paths (amplifiers). Specifically, we employ three pairs of transponders, each of which transmits 10×10 Gbps *bands*. Band Multiplexing Modules (BMMs) receive these three 100 Gbps bands, and multiplex them onto a single fiber. The BMMs are equipped with Erbium Doped Fiber Amplifiers (EDFAs) which support variable gain from 19 to 26.5 dB. These EDFAs can boost a signal for approximately 80 km before another amplifier is needed. Our testbed has a seven amplifiers in total. For specific details on the testbed, see Appendix A.

Metrics. The key metrics for our tests are the level of total optical power (dBm—decibel relative to 1 milliwatt of power) into and out of each band multiplexer and amplifier, and Q or quality factor at the receive-end transponders where wavelengths are added or removed. We measure add-time for a circuit as the time that it takes for power and Q factor to stabilize after a wavelength change is made. We take measurements using an Optical Spectrum Analyzer (OSA) to measure power levels directly on the fiber, as well as SNMP Management Information Base (MIB) values available from the administrator interface.

3.2 Standard Reconfiguration Delay

Standard best practice in network operations assumes a stable and reliable physical layer topology. Due to this assumption, optical equipment vendors have implemented a host of automated tests and adjustment features—which we refer to as the *automatic mode*—to ensure that devices return to a stable/predictable state after certain events (e.g. adding/dropping wavelengths). This mode works as follows: a transponder *tests* a sending power level and receives feedback from the amplifier. The feedback instructs the transponders to increase or decrease (i.e., *adjust*) its power level. This process continues in a loop until the first hop amplifier is satisfied with the power level for the channel it receives. After the channel's power is accepted by the first amplifier, each successive amplifier on the path repeats a variation of this process with the amplifier before it. Upon reaching the transponder at the receiving end, the signal is decoded back into the electrical domain. Forward Error Correction (FEC) is implemented in hardware to correct any bits that are flipped due to noise on the channel. If any bits are uncorrectable, an alarm is raised. Subsequently, a signal is sent to the amplifiers to repeat their tests and adjustments to find gain settings that reduce Amplified Spontaneous Emission (ASE) noise thereby providing a higher-quality signal that can be recovered with FEC.



(a) Automatic mode: add-time is 4 min and 25 s. *Hence, today's WANs are not OTP-ready.*

(b) Manual mode: add-time is 13 s—over 19× faster than automatic mode (Figure 1a).

Figure 1: Comparison of automatic & manual modes.

Using our testbed, we evaluate the add/drop-time that can be reasonably expected by hardware operating in automatic mode. Figure 1a shows the ingress power to the first amplifier hop plotted with the Q factor of a corresponding wave within the band at the receiver. We evaluate the *add-time* as the difference between the first change in receiver power at the amplifiers and the stabilization of Q factor above 11 at the receiver. In this instance, the add-time for this wave is

[1]We note that for data center networks (DCNs), the networked systems communities have proposed a variety of programmable topologies [5]. However, our focus is on OTP-ready WANs and hence we defer our discussion on DCNs.

265 seconds. After running this experiment 8 times, we find that add-times vary from 2 to 6 minutes. We note that these estimates are conservative, underestimating add-times for longer spans with more amplifiers.

Main findings and implications. The add-time for long-haul optical circuits, in practice, is on the order of minutes. This implies that *today's WANs are not OTP-ready.* This is primarily due to two standard features from the telephony era: *(i)* transponders incrementally and conservatively increasing their sending power level until it reaches the target level for the first hop, and *(ii)* the Automatic Gain Control (AGC) loop, which sets the gain at each amplifier on the path.[2] The main implication of this finding is that these features, if manipulated appropriately, can provide an opportunity to make OTP feasible. Intuitively, for feature *(i)*, if the appropriate power level is known a priori for a transponder on an optical path, then the 4 minutes spent ramping up power can be saved by automatically applying that power. We focus on *(i)* next and address factor *(ii)* in § 3.4.

3.3 Reconfiguration Delay From *min* to *s*

Next, we investigate a method for reducing add-time via intervention in the protocol between the transponders and their ingress BMM. Typically, in automatic mode, the launch power for a wave is determined by a protocol between the transponder and the ingress BMM's amplifier. However, there is a configuration parameter on the BMM and transponder which enables us to side-step this negotiation process and set the launch power explicitly. This feature is available across devices from different vendors, thus, we take the transponder and BMM out of automatic mode and put them into "manual mode". In manual mode, the wave's launch power must be set such that the ingress BMM's amplifier receives it within a hardware-specific target range. In our case, the BMM's amplifier excepts to receive signals of -14 to -12.5 dBm from any band port. Thus, we set the transponder's sending power such that it hits the target. This value only needs to be determined once for any transponder/ingress amplifier pair.

Figure 1b shows the add-time for a circuit across 7 amplifiers with transponders operating in manual mode. We set the launch power to 0.5 dBm, and used a variable optical attenuator (VOA) to add/drop the signal. When attenuation is set to zero, power at the ingress BMM jumps to -13.5 in one time-step (1 second). 13 seconds later, the Q factor for the received signal increase beyond 11, then settles to 13.73. We also conducted an extensive analysis on the impacts of OTP on existing wavelengths (see Appendix B) and found that it is safe to add/drop waves in manual mode to increase the agility of the physical layer via OTP.

Hypothesis Testing. We conduct a t-test to determine if the difference between add-times for automatic and manual modes are significant. Our null hypothesis is that manual reconfiguration has no effect on the add-time for an optical circuit. We collected seven samples for automatic mode, and eleven for manual mode. The t-test resulted in a t-value of 9.09 with a p-value of 6.17×10^{-6}. This high t-value and low p-value give us confidence that manual mode configuration is much faster than automatic.

Main finding and implication. Based on this experiment, we find that optical circuits can be provisioned over 19× faster by setting the sender's power level manually. Moreover, in light of OTP, the warm-up time can be obviated without impact. This result suggests a way forward toward achieving OTP in today's WANs.

3.4 Toward *ms* Reconfiguration Delays

Our measurements in § 3.2 and § 3.3 lead us to conclude that amplifiers operate with no knowledge of their past configurations. That is, they can find an appropriate gain level for a set of signals. But if you take away one signal and add it again, they start from scratch to find how to efficiently boost it. This is understandable if fast reconfiguration is an objective (which it was not in the telephony era).

To address this issue, we propose a new mechanism that uses a lookup table to choose gain values at each amplifier, to further reduce reconfiguration delays and make OTP feasible in today's WANs. First, we describe how to construct the amplifier table, and then present latency measurements collected in building the table. Then, we use these measurements to predict the performance for add-times with a system that can access an amplifier table. For a series of amplifiers in the path, we also compare the reconfiguration delays resulting from the automatic and modes with the ones obtained using our proposed lookup mechanism. One might argue that a lookup table is too simple of an application. However to the best of our knowledge, this has not been developed before. We argue that this first OTP utility should be as simple as possible. Only after it is demonstrated can we develop more intelligent and efficient methods (e.g. machine learning), and perhaps drive down circuit add-time even further.

Amplifier Table. We start by building a simple local controller (LC), which will be the key point of coordination for various optical components. An LC resides on a VM near transponders for an optical path (OP) and maintains a table that relates an optical configuration (OC) (i.e., set of active wavelengths) to amplifier's gain and Quality of Transmission (QoT). OCs in the table are aggregated by power level to keep the size of the table manageable by a single VM.

The LC has two components: a management engine and an amplifier table. The management engine receives requests

[2] We focus our attention only on add-time because dropping optical circuits is trivial; our evaluations on the effect of drop on other waves were negligible.

and sets/gets values to/from optical path hardware (transponders, amplifiers, etc.). The amplifier table[3] is a data structure maintained by the management engine for rapidly provisioning optical circuits. When the LC receives a Configuration Change Request (CCR) (e.g., activate band n on OP x), it checks the amplifier table table to see if there is a configuration stored for the path where the present waves and the requested waves are all active. If it finds that configuration, it applies the gains corresponding to that table entry on all of the amplifiers of the path in parallel; commands are issued over the optical supervisory channel. If no such entry exists, the LC activates the requested circuit(s) and waits for AGC to set the appropriate gain on each amplifier. Then, it stores the stabilized gains for the CCR in the amplifier table and sends a response back to the requesting agent.

Measurements. We investigate two methods for constructing the amplifier table, namely TL1 and SNMP. These are the two APIs available for querying amplifiers pragmatically in today's WANs. We use both for polling the gain value from each amplifier along the path in parallel, and report the time for the operation over 100 iterations. We find that TL1's median gain access time is ∼3 seconds, 6× faster than the time to activate a light path in manual mode. We also find that with SNMP, we can reduce this latency to about half of a second. Therefore, we suggest that manufacturers enable an SNMP-like interface for configuring gain on amplifiers of long-haul paths. With this capability, we see the potential for speedup greater than 200× over the expected configuration time for light-paths in automatic mode (see Figure 2).

Performance. As shown in Figure 2, the expected time for adding a wavelength in manual mode, with no gain information, is about 20 seconds. Therefore any new configuration added to the path will be installed, on average, in 20 seconds. After the configuration metrics are stored in the amplifier table, any future request for that configuration can be added, on average, in 0.56 seconds (as indicated with SNMP).[4]

Validation. We collected Q factor and latency data on a 100 Gbps circuit. We found that adding noise to the channel, thereby triggering AGC changes, does not have any impact on the latency of Ethernet packets mapped into the ODU frames. We used a layer-3 traffic generator to produce packets of various sizes (95, 1500, and 9216 bytes) and found that RTT stayed constant, plus or minus 0.1 microsecond. The average jitter was constantly 0.0 microseconds. This implies that any noise that is added to an optical circuit by changing gain at amplifiers will not impact layer-3 performance. Therefore, it is safe to use the gain values stored in amplifier table.

[3]There are several systems issues including how many tables a network should maintain, how to populate the tables at scale, slow local vs. fast remote and their impacts on table lookup, etc. These issues are beyond the scope of this paper and will be considered in future work.

[4]For supplementary performance model on longer paths see Appendix C.

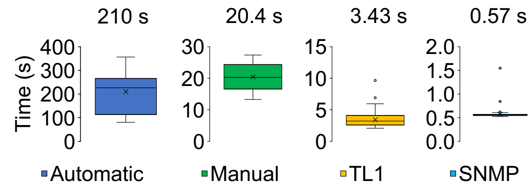


Figure 2: Reconfiguration delays for various modes.

4 DISCUSSION AND WORK IN PROGRESS

We believe that empirical measurement efforts like ours can identify and inform several scientific gaps between the optical and networking communities. In what follows, we describe two such gaps, outline how the measurements can help by designing useful tools, and elucidate the key challenges in building those tools. We leave the implementation and evaluation details for future work.

For one, the assumption of the "stable physical layer" model is at odds with the "dynamic physical layer" model of OTP. Understanding this dynamism calls for (a) creation of an end-to-end *optical layer traceroute* tool that can offer visibility (e.g., via TL1 or SNMP) into several optical devices in a network path, (b) unified interfaces to expose measurements from the optical layer to higher layers of the network stack, and (c) an adaptation framework to seamlessly adapt protocols at the higher layers in response to the dynamism of the optical layer (e.g., change ISIS or OSPF link weights in the face of Q-drop at the optical layer).

Another important question raised and addressed by this work is the perceived risk of disabling "automatic" mode. Clearly, there are opportunities for developing new capabilities for optical hardware that serve the same purposes in addition to supporting OTP. Measurement efforts offer the objective basis to evaluate the safety of these capabilities.

Building an end-to-end optical layer traceroute tool requires participation from network operators from several constituents (e.g. enterprises, transit providers, etc.). Second, designing cross-layer interfaces and exposing optical measurements from those interfaces call for expertise from and collaboration among optics, measurements, and networked systems researchers. Third, we posit that the fate of the envisioned measurement tools will be similar to layer-3 traceroute due to privacy and security reasons (e.g. blocking/dropping measurements, malicious intent to map the wavelength allocation in a network, etc.). Assuming participation from network operators, one way to address this challenge is to build an enclave (similar to secure containers in Intel SGX) in optical devices where SNMP or TL1 could be used to query the devices and provide responses *without* violating privacy and security restrictions [17].

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APPENDIX

A LAB HARDWARE DESCRIPTION

Our experimental testbed is shown in Figure 3. The testbed is symmetric with two simple fiber paths; all of the experiments reported below utilize a single path from West to East. We employ two types of transponders in our testbed; one pair of Advanced Optical Transport Network Line Modules (AOLMs) (Infinera AOLM-500-T4-1-C6), and two pairs of Digital Line Modules (Infinera DLM-n-C2). Throughout our experiments, all transponders send/receive streams of empty Optical Data Units at 100 Gbps. Note that ODUs can contain SONET, Ethernet, or IP packets in a live deployment. Each transponder sends ODUs on ten individual wavelengths called an Optical Carrier Group (OCG). Signals in an OCG are spaced at 200 GHz. The AOLMs transmit/receive OCG 1, which carries waves in the 191.75 to 193.55 THz range. The AOLM streams are modulated with Dual Polarization-Quadrature Amplitude Modulation (DP-QPSK). The DLMs transmit/receive OCGs 3 and 5 with OOK, carrying waves in the 191.85 to 193.65 THz and 193.95 to 195.75 THz ranges respectively. OCG properties are summarized in Table 1.

Together, the AOLMs and DLMs provide the capacity to light up to 30 wavelengths in each direction in our testbed. The transponders are connected to a series of three Bandwidth Multiplexing Modules (BMMs) (Infinera BMM2-4-CX2-MS-A cards in separate DTC-A chassis), which can optically multiplex up to 40 wavelengths (channels) onto fibers (organized in OCGs). The BMMs are also equipped with two

Erbium Doped Fiber Amplifiers (EDFAs) (one in each direction) with an operating range of 20 to 27.5 dB. The BMMs are connected via one-meter fiber jumpers, attenuated at 20 dB to simulate fiber loss from a span of 80 km. The third BMM in the series is connected to a 100 km span of single-mode fiber, and then to an amplifier (Infinera OAM-CXH2-MS in an OTC-1 amplifier chassis), which is used to regenerate signals on long haul paths. The path beyond the OAM is symmetrical to the path leading to it.

OCG	Range (THz)	Range (nm)	Modulation
1	191.75 - 193.55	1563.45 - 1548.91	DP-QPSK
3	191.85 - 193.65	1562.64 - 1548.12	OOK
5	193.95 - 195.75	1545.72 - 1531.51	OOK

Table 1: Optical Carrier Group (OCG) wavelength ranges and modulations used in our experiments.

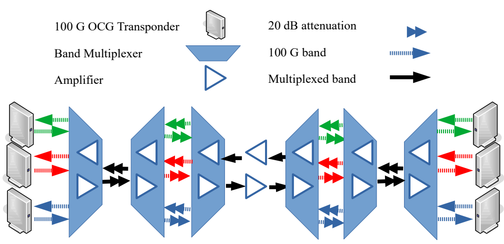


Figure 3: Configuration used in our lab-based experiments: six optical transponders, each of which generate 100 Gbps of Optical Data Unit (ODU) traffic over seven amplifiers.

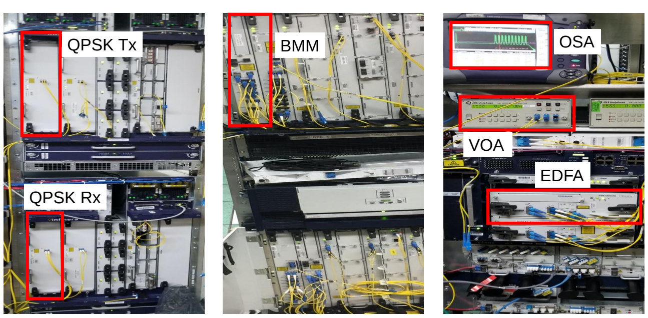
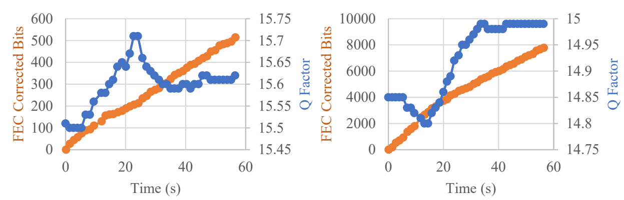


Figure 4: 100 Gbps QPSK transponders (left), band multiplexer (center), optical spectrum analyzer, variable optical attenuator, and erbium doped fiber amplifiers (right).

The equipment used in our lab is shown in figures 4. The optical equipment we use in our experiments is representative of equipment that is deployed in operational networks. The BMMs and amplifiers are high power (can transmit 80 to 100 km) and operate in the C-band (1550 nm frequency). IP routers with suitable transponder interfaces can connect directly to these BMMs. Amplifiers similar to those used in our setup are often arranged in series to enable transmission of signals over hundreds of kilometers.

B QUALITY OF TRANSMISSION

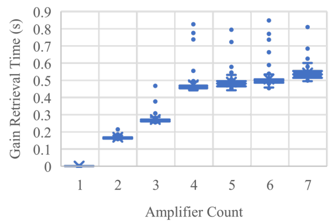
Next, we turn our attention to the following fundamental question: what effect does adding or dropping a set of wavelengths have on persistent connections, i.e., those optical frequencies sharing spectrum on a fiber with a dynamic DWDM channel? We call these persistent connections "witnesses" for short because they witness the addition or subtraction of a wave (or set of waves) within the fiber they traverse.



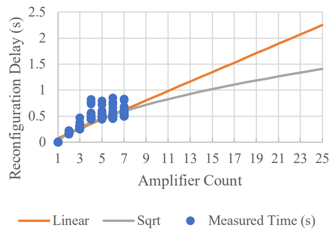
(a) OCG 3 (b) OCG 5

Figure 5: QoT measurements for witness waves while adding/dropping OCG1. During the add/drop, Q factor for the witness waves is relatively constant—varying by +/- 0.1. Errors accumulate at a linear rate as expected in a live transport network; 100% are corrected with FEC while running traffic over OCGs 3 and 5.

Figure 5 shows the Q factor and corrected/uncorrected bits from forward error correction (FEC) for a wave in OCGs 3 and 5; these measurements correspond to those shown in Figure 1b. From figure 5, we see that, although we add 50% more power to the circuit in the form of a third OCG, the Quality of Transmission (QoT) measures of the witness waves in OCGs 3 and 5 are not impaired. More concretely, the Q factor for the two waves varies *only* by +/- 0.1; FEC corrected all physical bit errors. To further assess the impact of adding/dropping waves, we installed a Tributary Optical Module 10G (TOM-10G-SR1) (which maps electrical signals to an optical 10 Gbps wave) to run IP perf traffic over a wave in OCG 3. This tool is commonly used for diagnostics/testing of optical WAN circuits. Analysis of the perf traffic over the TOM verifies that no packets were dropped for the witness wave while adding/dropping OCG 1.



(a) We collect 100 measurements for each set of amplifiers using SNMP.



(b) Linear (orange) and non-linear (gray) regression ($\sqrt{x}$) model projected for 25 amplifiers.

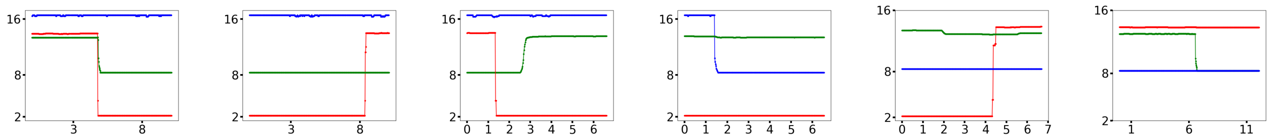
Figure 6: Gain retrieval time for a path of seven amplifiers (top), and projected reconfiguration time for longer paths (bottom).

We conduct more extensive tests of the impact on QoT for witness waves while adding/dropping random OCGs. In this test, we apply every permutation of the three OCGs on the fiber. Figure 7 summarizes the complete QoT analysis. Each sub-figure shows the Q factor for three wavelengths—one in each OCG. At least one of the wavelengths in each plot is the witness to the add/drop of all ten waves in an adjacent OCG. For instance, in 7-I, we see the witness wave in blue. The removal of both adjacent OCGs (two-thirds of the power on the circuit) does not impact the Q factor for waves in OCG-1. Looking over all of the plots, we see that adding/removing from the spectrum did not negatively impact any of the witness waves.

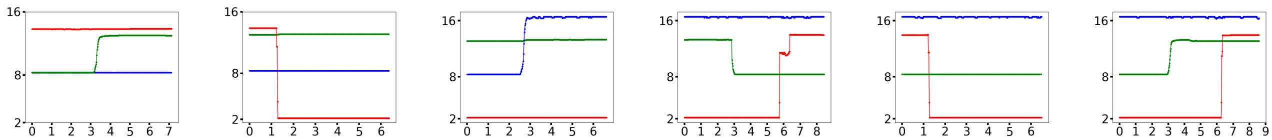
Main finding and implication. From these results, we find that adding 100 Gbps of capacity to an optical path does not adversely affect the witness waves on that path. Therefore, we conclude that it is safe to add/drop waves in manual mode to increase the agility of the physical layer via OTP.

C A PERFORMANCE MODEL FOR LONG-HAUL PATHS

Optical paths often traverse thousands to tens-of-thousands of kilometers. To predict the expected performance of an amplifier lookup table-based controller on these paths, we use a least-squares regression model trained with the seven amplifiers in our lab. We collected data by polling different subsets of amplifiers with parallel SNMP queries (the same method used in Figure 2). For each set of amplifiers tested, we repeated our measurement for the gain retrieval time 100 times. Figure 6 shows the data we collected (6a), and the model (6b). According to the model, an optical path with 25 amplifiers can be reconfigured in 1.5 to 2.3 s. This is much faster than the automatic mode. That is, the amplifiers in automatic mode can be expected to take more than 9 minutes (assuming a linear model, where 7 amplifiers take 155 s to reconfigure). In manual mode, we estimate the reconfiguration delay to be about 46 s, based on similar analysis.



I	II	III	IV	V	VI
Drop OCGs 1 and 3	Add OCG 1	Drop OCG 1, add 3	Drop OCG 5	Add OCG 1	Drop OCG 3
Starting λs: 1,3,5	Starting λs: 5	Starting λs: 1,5	Starting λs: 3,5	Starting λs: 3	Starting λs: 1,3
Ending λs: 5	Ending λs: 1,5	Ending λs: 3,5	Ending λs: 3	Ending λs: 1,3	Ending λs: 1



VII	VIII	IX	X	XI	XII
Add OCG 3	Drop OCG 1	Add OCG 5	Drop OCG 3, add 1	Drop OCG 1	Add OCGs 3 and 1
Starting λs: 1	Starting λs: 1,3	Starting λs: 3	Starting λs: 3,5	Starting λs: 1,5	Starting λs: 5
Ending λs: 1,3	Ending λs: 3	Ending λs: 3,5	Ending λs: 1,5	Ending λs: 5	Ending λs: 1,3,5

Figure 7: Q factor while reconfiguring OCGs present on a shared path. The y-axis is Q factor for a wave in each OCG, and the x-axis is time in minutes. When an OCG is dropped, Q drops to ~8 due to background noise.