A Dynamic Network Design for High-Speed Enterprise Access Links

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Abstract—This paper proposes a new two-wavelength design for large-enterprise access links. The goal of this design is to lower power consumption and equipment costs without having a significant impact on performance. In our design, one wavelength is used as part of a lower-rate static circuit for general-purpose IP traffic, while the second wavelength is dynamically configured into a high-rate circuit for large dataset transfers whenever needed. A few provider-router ports are shared among a larger number of customers given that large dataset transfers are relatively infrequent. This leads to potential start-time delays, but results in significant power and cost savings. Using analytical models, we provide a quantitative power-and-cost comparison of our dynamic solution with the static always-on high-rate single-circuit solution used currently. The number of shared provider-router ports is kept large enough based on the number of customers to ensure that the probability of start-time delay exceeding a threshold is less than 1%.

Keywords—Wavelength-division multiplexing (WDM); dynamic optical circuits; access links; energy-efficient; power; cost

I. Introduction

Problem statement and motivation Optical links are required for high-speed communications across long distances. Hence most Wide-Area Network (WAN) and Metro-Area Network (MAN) links are optical. Access links from large enterprises such as research universities and national laboratories are also optical because of their use of high communications rates such as 10 Gbps. As network operators upgrade their networks and enterprises purchase their network services, cost and power consumption are two major considerations. They are closely related to specific network architectures, since for example, router-port costs for IP service are greater for higher rates, and power consumption is more for higher-rate router interfaces and Long-Reach (LR) transponders [1]. Therefore, the problem statement of this work is to determine if alternative designs can lower power consumption and equipment costs for high-rate enterprise access links.

Our motivation for addressing this problem comes from the Research and Education Network (REN) community. Core REN providers, such as Internet2 and ESnet, have upgraded their link rates to 100 Gbps, and regional RENs are making similar upgrades. Correspondingly, large universities and national laboratories are now considering upgrades of their access links to 100 Gbps. The main application driver for such an upgrade is large scientific dataset transfers. Scientists at universities and national laboratories use external supercomputing centers to run their compute-intensive big-data analytics and simulation software, and then have a need to transfer the generated (large) datasets back to their university clusters. The bottleneck link rate in such transfers is a determinant of file-transfer throughput. For example, to move a 10 TB dataset will require only a few minutes if the end-to-end bottleneck link rate is 10 Gbps instead of hours if the rate was 10 Gbps (assuming low-loss paths). Parallel file systems are used in clusters to sustain high I/O rates [2] and achieve close-to-100 Gbps transfer throughput.

Aggregate general-purpose traffic on access links from large universities and national laboratories is currently less than 3-4 Gbps on existing 10 Gbps Ethernet (10GE) access links [3]. Nevertheless, these enterprises are considering upgrades to 100GE in order to support large scientific dataset transfers.

Solution approach Our key novel idea comes from the above-described observation that high access-link rates are not needed all the time, but instead, are required only for infrequent large dataset transfers. Our solution proposes the use of two wavelengths on access links: the first wavelength is used in a static circuit of lower-rate (e.g., 10GE) for general-purpose IP traffic, and the second wavelength is used in a higher-rate (e.g., 100GE) circuit that is dynamically configured for large dataset transfers whenever needed. In the provider network, each such dynamic circuit is terminated on one of all the customers, where $N < K$. A provider-network controller enables the dynamic sharing of the $N$ provider-router ports through a reconfigurable optical platform. In addition, these shared high-speed router ports can be powered off when there are no ongoing transfers.

We refer to our solution as the dynamic solution in contrast to the conventional static solution in which all customers’ access links are upgraded to the higher rate, e.g., 100GE, to carry both IP-traffic and large dataset transfers on a single wavelength. The tradeoff between power-and-cost savings of our dynamic solution relative to the static solution vs. the potential additional delay incurred for large dataset transfers (in having to wait sometimes for a free port) is evaluated in this study.

Novelty and contributions The novelty lies in our multi-wavelength design for enterprise access links, which uses a high-rate dynamic circuit for transfers of large datasets, and a lower-rate static circuit for general-purpose IP traffic. The key contributions of this work are (i) a new access-link design, (ii) a comparative evaluation of the design with a static
single high-rate access link on power and cost metrics, and (iii) quantification of start-time delay penalty incurred in our design.

Section II reviews prior work. Section III describes our proposed dynamic solution, and reviews the conventional static solution. Section IV presents an evaluation of the power and cost savings of the dynamic solution relative to the static solution, and also quantifies the start-time delay penalty of the dynamic solution. The paper is concluded in Section V.

II. Related Work

Energy-efficient techniques for networks are of increasing importance [4]. Accordingly, various technologies, ranging from hardware-level optimization to dynamic resource adaptation to novel system architectures, are being developed [5]. In Low Power Idle (LPI), a scheme adopted in the IEEE 802.3az standard, an Ethernet interface is placed in low-power mode when there are no packets to be transmitted [6]. However, LPI was reported to yield insignificant power savings on a lightly loaded 1GE university access link [7]. This is because of the overhead incurred in waking up the Ethernet interface and putting it back to sleep. Frame transmission efficiency, which is the ratio of the time spent transmitting a single frame to the sum of wake-up time, sleep time and frame transmission time, is expected to be worse on 100GE links when compared to lower-rate links due to the smaller frame transmission times. A competitor to LPI was Adaptive Link Rate (ALR) [8], in which the transmission rate of the interface is adapted to the traffic load. However, long switching times and frequent oscillations impede the ability of ALR schemes to save energy. Therefore, our work considers a scheme that fits more into the “novel system architectures” end of the spectrum of energy-saving technologies.

The estimation of power consumption and equipment costs for new network designs requires accurate (input) values for component power and component costs. Prior work [1] [9], provided traceable and well-defined power consumption estimates for optical multi-layer network equipment. We followed the method used in this prior work to obtain updated power values from publicly available product datasheets. Cost values were presented using normalized monetary units for equipment spanning four network layers, Internet Protocol/Multiprotocol Label Switching (IP/MPLS), Ethernet, Optical Transport Network (OTN), and Wavelength-Division Multiplexing (WDM), by Huelsermann et al. [10] and Rambach et al. [11]. As the second paper was more recent, we used component cost values from this paper in our cost evaluation.

III. Static and Dynamic Solutions

The static solution is conventionally used today. In this solution, the access-link optical circuit (carried on one wavelength) from each enterprise network terminates on a separate IP-router port within the provider’s network. The port stays “always-on” allowing for file-transfer applications to be executed with no modification even for large dataset transfers. Since IP is a connectionless service, an application can simply set up a TCP connection, which does not involve any of the intermediate routers/switches, and start sending user data within IP packets.

In our proposed dynamic solution, two separate wavelengths are used on an access-link fiber from each enterprise for: (i) general-purpose traffic, and (ii) large dataset transfers. The wavelength for general-purpose traffic is used in a circuit that extends between a customer IP router and a provider IP router, and is static and always-on. This first link can be operated at a lower rate than the single access link in the static solution since it needs to be sized only for general-purpose traffic. The second wavelength is used in a dynamically controlled circuit for rare large dataset transfers, i.e., the circuit is setup and released dynamically only when needed. The circuit extends between a Data Transfer Node (DTN) cluster in the customer network and an IP router in the provider network. DTN clusters are part of ScienceDMZ, which is an architecture proposed to bypass enterprise firewalls and enable high-speed network paths for large dataset transfers [12].

A Dynamic Access-Link Controller (DALC) (see Fig. 1) enables the dynamic sharing of N provider-router high-speed ports among K customers (where N < K), and the dynamic powering on-and-off of these ports. An application signals its need for this second access-link circuit to be established before a large dataset transfer by sending a control-plane message to the DALC. If one of the N shared provider-router ports is free, the DALC will provision the second access-link circuit by configuring the provider optical platform (see Fig. 1) to crossconnect the second wavelength from the corresponding customer network to the link that leads to the free provider-router port. The DALC will also add an entry in the IP routing table of the provider router to enable packet forwarding on to this dynamically established second access-link circuit for just the large dataset transfer flows. Similarly, a control-plane client running on the DTNs in the customer network will add an entry to the IP routing tables of the DTNs to use this dynamically established second access-link circuit for the large dataset transfer flows. If there is no available provider-router port, the controller responds to the requesting application with a delayed start time.

Fig. 1 illustrates a generic system model that is used to describe both the static and dynamic solutions. The model shows K customer networks, each of which consists of an IP router (IC), an optical platform (OC), and a DTN cluster.
TABLE I: Differences Between Static and Dynamic Solutions

<table>
<thead>
<tr>
<th>Feature</th>
<th>Static Solution</th>
<th>Dynamic Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_1 \leftrightarrow O_p$</td>
<td>$m_1 = 1$</td>
<td>$m_d = 2$</td>
</tr>
<tr>
<td>DALC</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>$D_c \leftrightarrow I_c$</td>
<td>$R_{1s} = R_{2d}$</td>
<td>$R_{1d} = 0$</td>
</tr>
<tr>
<td>$D_c \leftrightarrow O_c$</td>
<td>$R_2 = 0$</td>
<td>$R_{2d}$</td>
</tr>
<tr>
<td>$I_c \leftrightarrow O_c$</td>
<td>$R_{1s} \geq R_{1d}$</td>
<td>$R_{3d}$</td>
</tr>
<tr>
<td>$I_p \leftrightarrow O_p$</td>
<td>$R_3 = KR_{1s}$</td>
<td>$R_{3d} = KR_{1d} + NR_{2d}$</td>
</tr>
<tr>
<td>$O_C$</td>
<td>Transponder</td>
<td>2 transponders and a MUX/DMX</td>
</tr>
<tr>
<td>$O_p$</td>
<td>$K$ transponders</td>
<td>Fig. 2</td>
</tr>
</tbody>
</table>

(D$_C$), and a provider network with an IP router ($I_p$) and an optical platform ($O_p$). The DTN cluster initiates large dataset transfers while general-purpose traffic flows into the IP router $I_c$ from other internal subnetworks. The links are marked with symbols, $R_1$, $R_2$, $R_3$, $R_s$ ($R$ for rate) and $m$ As. Using the additional $s$ subscript for the static solution and the $d$ subscript for the dynamic solution, Table I describes how the values are selected for these various link rates, and how the optical platforms and access links differ in the two solutions.

Row 1 of Table I shows that the static solution requires only one wavelength ($m_1 = 1$) across the access link, while the dynamic solution requires two wavelengths ($m_d = 2$). To enable the dynamic sharing of the $N$ provider-router high-speed ports, a DALC is needed only in the dynamic solution as shown in Row 2 of Table I.

The DTN cluster is connected to the customer router in the static solution, but to the optical platform in the dynamic solution, which explains why $R_{1d}$ and $R_{2d}$ are 0 as shown in Rows 3 and 4 of Table I. Rows 3 and 4 also show that the rate of the link from the DTN is the same in both solutions, and hence $R_{1s} = R_{2d}$. In other words, large dataset transfers from/to the DTN cluster are aggregated with general-purpose IP traffic by the IP router $I_c$, and carried on the single wavelength circuit via the optical platform $O_C$ on to the access link in the static solution, while in the dynamic solution, the large dataset transfers from the DTN cluster are directly fed into the second wavelength circuit at the optical platform $O_C$, and thus isolated from the general-purpose traffic, which uses the first wavelength circuit across the access link.

Row 5 shows that in the static solution $R_{3s} \geq R_{1s}$ because general-purpose IP traffic and large dataset transfers are merged by the IP router $I_c$. On the other-hand, in the dynamic solution the link between the IP router $I_c$ and the optical platform $O_C$ should be sized for only general-purpose IP traffic. For example, in the dynamic solution, $R_{3d}$ could be a 10GE link when $R_{2d}$ is a 100GE link, while in the static solution, $R_{1s}$ and $R_{3s}$ could both be 100GE links given that the IP router multiplexes packets from/to the internal subnetworks with the large dataset transfer packets from/to the DTN cluster.

Row 6 shows that in the static solution, the access links from the $K$ customers are hardwired to high-rate $R_{1s}$ ports in the provider IP router $I_p$, while in the dynamic solution, $K$ lower-rate $R_{3d}$ ports and a smaller number $N$ higher-rate $R_{2d}$ ports are required in the IP router $I_p$.

Rows 7 and 8 show how the optical platforms required in the customer and provider networks differ in the two solutions. Since LR colored optics interfaces in the IP layer are generally more expensive than in other electrical layers [11], we assume the use of transponders that convert the gray optical signals (e.g., 1310 nm) of the IP-router interfaces to the Dense WDM (DWDM) ITU-T grid signals (in the C and L bands) used on the access link. Therefore, in the static solution, the optical platform required in each customer network consists of just a single transponder, and $K$ transponders are required in the provider network.

In the dynamic solution, in each customer network, two transponders are required to convert the gray-optics signals, $R_{3d}$ from the IP router $I_c$ and $R_{2d}$ from the DTN cluster switch $D_c$, to ITU-T grid DWDM wavelengths, and a WDM multiplexer/demultiplexer (MUX/DMX) is required to transport the two wavelengths on the same fiber. The optical line amplifiers/regenerators required on long-distance access links are common for the static and dynamic solutions, and hence are not considered in the comparison.

A design for the provider optical platform $O_p$ required in the dynamic solution is illustrated in Fig. 2. Each customer’s incoming composite WDM signal, after being amplified by an optical preamplifier, is demultiplexed into two signals. The $R_{3d}$ signal carrying general-purpose IP traffic from each customer network is converted from the ITU-T grid wavelength to a gray optical signal at 1310 nm by a transponder (TXP), which is then sent to a dedicated router port (RP) on the provider IP router $I_p$. The second wavelength from each of the $K$ customer networks is fed to a block titled Dynamic Switch in Fig. 2. This switch connects to $N R_{2d}$ transponders that convert the ITU-T grid signals to gray optical signals, which are then conveyed to the $N$ shared router ports on $I_p$. By placing these higher-rate transponders between the optical switch and the router ports, rather than between the demultiplexers and the optical switch, we reduce the number of the higher-rate transponders from $K$ to $N (N < K)$.

Two options for the Dynamic Switch are illustrated in Fig. 3. In Option (a), a photonic switch is used as a reconfigurable space fabric. It can be configured dynamically to connect any incoming port to any outgoing port. In Option (b), a WDM multiplexer is used to first merge all the second wavelengths from the $K$ customer access links onto a single fiber. Since most current transponders have tunable lasers and
broadband photo-detectors [13], we assume that the DALC can dictate the particular wavelength to use for each customer $R_{2d}$ transponder in the setup phase for the second circuit. Correspondingly, the DALC will configure the Wavelength Selective Switch (WSS) to pass through specific wavelengths ($\Lambda_1$ to $\Lambda_K$) from customers onto selected wavelengths ($\Lambda_1'$ to $\Lambda_K'$) to the links connecting to the $I_P$ router ports.

**IV. Evaluation**

The static and dynamic solutions can be compared on power consumption and equipment costs. The dynamic solution has a disadvantage relative to the static solution in that a customer may be required to wait before starting a large dataset transfer, as described in Section III. Therefore, we first characterize start-time delay in the dynamic solution, and then compare the power consumption and equipment costs of the static and dynamic solutions.

**A. Start-time delay in dynamic solution**

In the dynamic solution, if an application requests the setup of the high-speed access circuit for a large dataset transfer and none of the $N$ shared ports on the provider IP router are available, then the DALC responds with a delayed start-time. The purpose of this analysis is to quantify the start-time delay under certain assumptions.

**Model** The system is modeled as an $M/M/N/K/K$ queueing system (a.k.a., a finite-population Blocked Call Queueing (BCQ) system [14]), in which calls are queued when resources are unavailable rather than rejected as in a Blocked Call Clearing (BCC) system. This model assumes the following: a Poisson arrival process, exponential service-time distribution, $N$ servers, $K$ buffers, and a finite population of size $K$. In effect, this model assumes that each customer issues only one request at a time for the dynamic access-link setup.

The state transition diagram for this BCQ system is shown in Fig. 4. The probability $p_n$ of being in state $n$ is

$$p_n = \begin{cases} 
\rho n! \rho^k / n! \rho^k / k!, & 0 \leq n < N \\
\rho n! \rho^k / n! \rho^k / k!, & N \leq n \leq K 
\end{cases}$$

To quantitatively characterize the start-time delay $D$ in the dynamic solution, the metric considered here is the probability $P(D > \tau)$ that a call is delayed longer than a threshold $\tau$ [15]

$$P(D > \tau) = \frac{\rho}{KU} e^{-\rho/\mu} \sum_{n=N}^{K} p_n (n - N) \sum_{i=0}^{N-1} (n/\mu)^i / i!$$

The average number of customers being served is $KU$.

**Numerical results** Fig. 5 shows the probability of calls being delayed by a value greater than the threshold $\tau$, which is set to 20 minutes, as a function of $K$, the number of customers. The plots correspond to different values of the number of shared provider-router ports ($N$), and traffic load ($\rho$).

![Fig. 5: Probability of calls receiving a start-time delay greater than 20 minutes, as a function of the number of customers ($K$), for different values of the number of shared provider-router ports ($N$), and traffic load ($\rho$)](image)

where

$$p_0 = \sum_{n=0}^{N-1} \rho n! / n! \rho^k / k!$$

and $\rho$, traffic load, is the ratio of per-customer call arrival rate $\lambda$ to service rate $\mu$, i.e., $\rho = \lambda / \mu$.

Fig. 5 shows that under light loads $\rho = 0.01$, increasing $N$ from 1 to 2 drops the probability of calls receiving a delayed start-time greater than 20 minutes to be under 0.01 (or 1%) even when the number of customers $K$ is as high as 20. In other
words, two shared provider-router ports are sufficient to keep the start-time delay penalty small under low loads (at \( \rho = 0.01 \), with \( \mu = 1/800 \) second, the call arrival rate is roughly 1 call per day per customer). We chose the above values based on the fact that large dataset transfers are rare events that are initiated by a limited number of users. Similarly, we see that the minimum \( N \) values needed to keep the probability of start-time delay metric below 1% are 3 and 4 for traffic load values of 0.05 and 0.1, respectively. In other words, if traffic load increases by a factor of 10, e.g., by increasing the arrival rate of large dataset transfer requests, then 20 customer networks can share just 4 provider-router ports using our dynamic solution while incurring a small delay penalty.

Table II presents a sensitivity analysis for different values of the threshold \( \tau \), traffic load \( \rho \), and service rate \( \mu \). It shows that for a relatively small service rate, i.e., \( \mu_2 \), the minimum value of \( N \) needed is not sensitive to the delay threshold \( \tau \).

### B. Power and cost comparisons

This subsection presents a comparison of the power consumption and equipment costs of the static and dynamic solutions making certain assumptions.

#### Model

We use a component-based model [1] to characterize the differential power consumption of the static and dynamic solutions. The power-consuming components in the network systems (IP router, optical platform and DTN cluster switch in customer and provider networks) can be divided into two categories, chassis and line cards. Since the power consumption of a chassis is the same in both solutions, it is left out of the comparison.

Table III lists the power consumption and costs of components, and Table IV explains the notation. In the first column of Table III, the symbols \( \Phi_{dc} \), \( \Phi_{dp} \), \( \Phi_{ac} \) and \( \Phi_{ap} \) used to represent the components in customer (\( C \)) and provider (\( P \)) networks in the static (\( s \)) and dynamic (\( d \)) solutions. The component column in Table III lists the IP router (\( I \)), optical platform (\( O \)) and DTN cluster switch (\( D \)), at ends of links identified by their rates. For example, \( I_C(R_{1s}) \) denotes a link card with rate \( R_{1s} \) in the IP router of a customer network, and \( O_P(R_{4s}) \) denotes a transponder card with rate \( R_{4s} \) of the optical platform in the provider network, in the static solution (see links marked rates \( R_1 \) and \( R_4 \) in Fig. 1).

Using the symbol \( \mathbb{P} \) to denote power, \( \Phi_{dc}^\mathbb{P}, \Phi_{dp}^\mathbb{P}, \Phi_{ac}^\mathbb{P} \) and \( \Phi_{ap}^\mathbb{P} \) represent the power consumption of the customer-network and the provider-network components in the static and dynamic solutions, respectively. Each of these power values is determined by summing the power of individual components multiplied by the corresponding multiplicative factors shown in the fourth column of Table III. For example, the power consumption across the \( K \) customer networks in the dynamic solution, \( \Phi_{dc}^\mathbb{P} \), is given as follows,

\[
\Phi_{dc}^\mathbb{P} = K \left( O_C^\mathbb{P}(R_{3d}) + I_C^\mathbb{P}(R_{3d}) + O_C^\mathbb{P}(MD_{4ch}) \right) + KU \left( O_C^\mathbb{P}(R_{3d}) + D_C^\mathbb{P}(R_{3d}) \right)
\]  

(5)

The first term in (5) has a \( K \) factor, which corresponds to the always-on access links for general-purpose IP traffic from each of the customer networks. The factor \( KU \) in the second term of (5), used for the dynamic access-link circuits, describes the average number of customers under service, as described in Section IV-A. In the dynamic solution, the DTN switch port and the optical-platform transponder within the customer network, and the optical-platform transponders and shared router ports in the provider network, can be powered-off when they are not in use. The presence of the application-to-DALC signaling phase allows these ports to be powered on as part of the dynamic access-link configuration phase. Hence instead of \( K \), we use the factor \( KU \). The difference in power consumption between the static and dynamic solutions is

\[
\Delta^\mathbb{P} = \Delta_C^\mathbb{P} + \Delta_P^\mathbb{P}
\]  

(6)
where $\Delta_C^\rho$ and $\Delta_P^\rho$ separate out the power savings in the customer networks and provider network, respectively, and are defined as follows,

$$\Delta_C^\rho = \Phi^\rho_c - \Phi^\rho_{dc}$$  \hfill (7) \\
$$\Delta_P^\rho = \Phi^\rho_{sp} - \Phi^\rho_{dp}$$  \hfill (8)

The cost model is similar to the power model and the only difference comes from the multiplicative factors. For instance, the provider-network cost in the dynamic solution, $\Phi^\rho_{dp}$, is

$$\Phi^\rho_{dp} = K\left(\Phi^\rho_c (R_{3d}) + \Phi^\rho_{dc} (R_{3d}) + \Phi^\rho_{ff} (MD_{4ch})\right)$$

$$+ N\left(\Phi^\rho_c (R_{2d}) + \Phi^\rho_{dc} (R_{2d})\right) + \Phi^\rho_C (DS_{q8})$$  \hfill (9)

in which the multiplicative factor is $N$ for the components $O_p(R_{2d})$ and $I_p(R_{3d})$, instead of $KU$ for the power consumption $\Phi^\rho_{dp}$. The final term in (9) is $\Phi^\rho_C (DS_{q8})$, which denotes the power consumption of the Digital Switch shown in Fig. 2. As Fig. 3 illustrates, there are two options for the Digital Switch, which is the reconfigurable unit. The power consumption in these two options are given by $\Phi^\rho_C (PS)_a$, and the sum of $\Phi^\rho_c (MD_{4ch})_b$ and $\Phi^\rho_C (WSS)_b$ (see Table III), where PS stands for Photonic Switch (Option (a)), and WSS stands for Wavelength Selective Switch (Option (b)).

**Input assumptions** To compute numerical values for power and cost savings, we make the following assumptions. First, we choose the following link rates: $R_{1s} = R_{2d} = 100GE$, $R_{3s} = 100GE$, and $R_{kd} = 10GE$. As Table I shows, all link rates for the static and dynamic solutions can be determined from these four values.

Table III lists our input assumptions for the power and costs of the components. The power numbers were obtained from various vendor datasheets, and compiled into a technical report, which is posted on a public Web site [16]. The cost values are obtained from a 2013 paper [11], which defines the unit SCU, as STRONGEST Cost Unit, named after the project. One SCU corresponds to the 2012 cost of a 10GE optical transponder with a reach of 750 km. All cost values are normalized to this cost.

Combining the component power and cost numbers of Table III, and the $U$ values from (4) for different values of $K$, $N$, and $\rho$, we computed numerical values for power savings and cost savings using the equations described above.

**Numerical results** Our delay analysis showed that to meet the requirement that $P (D > \tau) < 1\%$ for $\tau = 20$ min, the minimum number of shared provider-router ports, $N$, needed was 2, 3 and 4, for traffic load $\rho$ values of 0.01, 0.05 and 0.1, respectively. In other words, these are the maximum $N$ values needed to meet our delay-performance requirement.

Here, we consider the question of whether smaller values of $N$ can lead to improved power savings. Therefore, under the low-load $\rho$ value of 0.01, we considered the power savings, $\Delta_C^\rho$, when $N$ was lowered to 1 from the 2 value needed for delay performance, and for $\rho = 0.1$, we lowered $N$ to 3 from the 4 value needed for delay-performance. Fig. 6 shows that the power savings are trivial (the plots for $\rho = 0.01$, $N = 1$ and 2 overlap, so do the plots for $\rho = 0.1$, $N = 3$ and 4). Therefore, $N$ should not be reduced from the 2 and 4 numbers

![Fig. 6: Power savings of the dynamic solution relative to the static solution for different values of the number of customers ($K$), shared provider IP router ports ($N$), and traffic load ($\rho$)](image)

required for delay performance under traffic loads of 0.01 and 0.1, respectively. In other words, given the negligible power savings, it is not worth sacrificing delay performance.

A key point illustrated in Fig. 6 is that significant power savings (measured in kW) is possible with our dynamic solution relative to the static solution. In addition, the average power savings per customer network, $\Delta_C^\rho/K$, is more than 1.4 kW for both the $\rho = 0.01$, $N = 2$ and $\rho = 0.1$, $N = 4$ cases1, which is twice the power consumed by the chassis of a typical edge router that supports 100GE ports [16].

Fig. 7 shows the consumer-network and provider-network cost savings, $\Delta_C^\rho$ and $\Delta_P^\rho$, respectively, and the total cost savings $\Delta^\rho$. These plots show that significant equipment cost savings are feasible with the dynamic solution relative to the static solution. Current-day costs of a 10GE LR transponder is approximately $40K$, which means that with 1000 SCU, the savings are in the millions of dollars. Fig. 7 also illustrates that lowering $N$ from 4 to 2 does not yield significant cost savings. The slight dip in the plots when $K$ is 14 occurs because the selected provider router slot capacity was 140 Gbps, which means that for $K$ larger than 14, a second card is required to accommodate the dedicated router ports for the general-purpose IP traffic.

The dynamic solution requires two wavelengths across the access link while the static solution requires only one wavelength. However, this requirement will not necessarily increase the cost to customers. This is because in the static solution, an enterprise needs to lease a high-speed (e.g., 100GE) static circuit, and the provider correspondingly needs to charge a high price for this circuit because it requires a dedicated transponder and router port. In contrast, in the dynamic solution, the provider could lower the cost for the high-speed access-link wavelength because this wavelength is not connected, i.e., it is left “hanging” until the customer network sends a signaling message to connect it to one of $N$ shared transponders and router ports as shown in Fig. 1. The savings in cost to the

1The per-customer network power savings does not vary a lot for different values of $K$, and the standard deviations are less than 0.1 in both cases.
provider through the use of shared transponders and router ports can be passed along to the customer, which could then be used by the customer to cover the price of the lower-speed wavelength for general-purpose IP traffic. Furthermore, some large enterprises already have dark-fiber leases, which allows the enterprises to light-up wavelengths on their own as needed. In this case, the second wavelength required in the dynamic solution will not result in additional expenses for the customer beyond those characterized in the cost analysis above.

In summary, for our assumed values, we can state that having 2 shared provider-router ports when traffic load is 0.01, and 4 when traffic load is 0.1, yield considerable cost and power savings while keeping the probability of start-time delay exceeding 20 minutes below 1%.

V. Conclusions

Significant power and cost savings are possible with a reconfigurable two-wavelength large-enterprise access network design if high rates are required only infrequently, e.g., for large dataset transfers. A lower-rate static optical circuit can be used on one wavelength for general-purpose IP traffic. Furthermore, some large enterprises already have dark-fiber leases, which allows the enterprises to light-up wavelengths on their own as needed. In this case, the second wavelength required in the dynamic solution will not result in additional expenses for the customer beyond those characterized in the cost analysis above.

In summary, for our assumed values, we can state that having 2 shared provider-router ports when traffic load is 0.01, and 4 when traffic load is 0.1, yield considerable cost and power savings while keeping the probability of start-time delay exceeding 20 minutes below 1%.

VI. Future work

By using colorless, directionless, contentionless Reconfigurable Optical Add/Drop Multiplexers (ROADMs) in the provider optical platforms, the use of dedicated optical circuits for large dataset transfers can be extended end-to-end, i.e., between two customer DTN clusters. We plan to develop and evaluate such a solution.

VII. Acknowledgment

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References