PRODIGY: A Progressive Upgrade Approach For Elastic Optical Networks

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***Abstract*—C-band enabled Elastic optical networks (EONs) have been one of the most deployed optical network solutions in the world. However, as traffic demands continue to increase, capacity exhaustion is inevitable. There are two major technologies, namely, multiband elastic optical networks (MB-EONs) and space division multiplexed elastic optical networks (SDM-EONs) that can enhance capacity. Each technology offers a tradeoff between better capacity and deployment overhead which directly affects the network performance. Considering the different characteristics of these two technologies, we present our proposed strategy, Progressive Optics Deployment and Integration for Growing Yields (PRODIGY), to gradually migrate the current C-band EONs. PRODIGY uses various proactive measures, inspired by Swiss Cheese Model, to make the network robust for handling network traffic peaks and ensure that the service level agreement is met. We present a detailed comparison of our proposed strategy with customized baseline strategies, and demonstrate the superiority of our proposed approach.**

I. Introduction

Internet traffic continues to grow rapidly - an overall compound annual growth rate (CAGR) of 15-33% for 2018-2023 is observed by CISCO [1]. The existing C-band single core fiber in elastic optical networks (EONs) offers a spectrum of 4 THz which is not sufficient to sustain the projected network traffic growth. In multiband EONs (MB-EONs), other bands apart from C-band such as O, S, E and L are allowed for the utilization on the same fiber. These bands can increase the capacity up to 54 THz in ITU G.652.D fibers [2]. Similarly, space division multiplexing (SDM) allows parallel transmission of lightpaths on multiple cores in a single optical multicore fiber which scales the capacity up many fold [3]. However, the deployment of these technologies is costly and causes temporary disruption in network operations, and therefore a well thought out progressive upgrade plan is necessary.

Progressive network upgrade enables the network operator to replace the current fiber technology with the latest technology over time. However, the links that are selected for upgrade in the upgrade plan remain unavailable until the new technology is deployed and tested. This disrupts network operations during the upgrade. Service level agreements between users and the network are a commonly used practice to guarantee a desired network performance. Network traffic is volatile in nature and thus a minimum capacity must be guaranteed in order to satisfy it. Upgrading to a new technology also incurs procurement cost and deployment cost. In addition, the network performance is dependent on the capacity available for utilization which is different from the raw fiber capacity. The available capacity for network traffic is dependent on physical layer impairments (PLIs) which impact the quality of transmission. There are different PLIs for EON, MB-EON and SDM-EON. The timing of the upgrade must ensure that the resulting performance is above a minimum threshold. In this paper, we use bandwidth blocking probability (BBP) as the performance metric of interest, and we have to ensure that it stays below the allowed maximum BBP over the lifetime of the network's operation. The network upgrade plan must align with these constraints and requires calculated efforts using the available network information. Researchers have started addressing the upgrade problem. Various upgrade strategies for C to C+L band are proposed in [4]–[6]. However, these approaches do not take the network guarantees, network constraints and SDM fiber technologies into consideration.

In this paper, we present our proposed strategy, Progressive Optics Deployment and Integration for Growing Yields (PRODIGY), which gradually upgrades the network while satisfying the network constraints. We consider the PLIs and make an informed decision of selecting the best fiber technology for upgrade. PRODIGY executes a multi-stage batch upgrade strategy which upgrades a batch of links at a time over multiple years/periods such that the network satisfies all the network constraints, maintain the desired network performance, and judiciously uses the available capital.

The paper is organized as follows. The network and traffic models are presented in Section II. The prerequisite for the proposed work and PRODIGY are presented in Section III and Section IV, respectively. Simulation results are presented in Section V, and finally Section VI concludes the work.

II. System Model and Problem Statement

A. Network and Traffic Model

Notations used in the paper are described in Tab. I. The network topology with set of nodes/vertices V and set of links E is denoted as $G(V, E)$. The matrix of connection arrival rates for each s-d (source-destination) pair is denoted Λ. Time is divided into slots of size τ. The time slot τ, time slots for traffic upgrade $T^{'}$, upgrade interval T, *network lifetime* and time for upgrading are shown on a time scale in Fig. 1. Network lifetime is defined as the network operation time during which the network performance requirements are guaranteed; i.e., the BBP never exceeds the given threshold. In this example, the

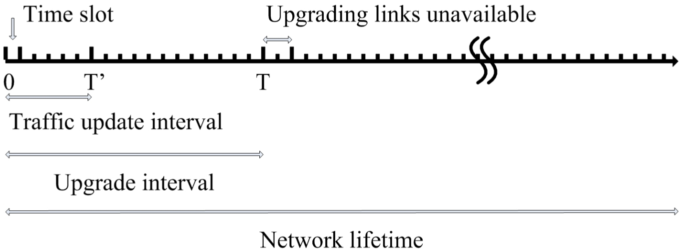


Figure 1: Time scale and notations.

traffic matrix is updated every 6τ and the Upgrade Plan is laid out for 18τ. The links under upgrade, as per the Upgrade Plan, are unavailable for 2τ. At t = 0, each arrival rate in Λ is set to λ_0. After every traffic update interval (T' slots), each arrival rate is increased by a random amount (uniform distribution) in the range [0, 1 + $\frac{\alpha}{100}$]. Poisson connection arrival process with exponentially distributed holding time of mean 1 slot (τ) is assumed. In order to model a realistic network scenario, we assume τ to be equal to 1 day and express other time variables accordingly.

Table I: Symbols and Notations

Symbols	Notations
Network Model	
b	Active band in the optical fiber technology
c	Number of cores in the optical fiber technology
t_i	i^{th} time slot
τ	Slot width
T	Time window of time slots for which the upgrade plan is laid out
T'	Time window of time slots to increase the network traffic
Λ_{t_i}	Network traffic matrix at time t_i
α	Traffic scaling percentage for each time slot
D	Set of datarates in the network
M	Set of modulations
S_b	Number of frequency slots on band b of 12.5 GHz slot width
$\beta_{d,m}$	Number of frequency slots required to carry the datarate d using modulation m
Upgrade	
p	= $bcb'c'$ i.e. policy of upgrade where the current fiber technology b-c is upgraded to b'-c'
p^0	= $b_0c_0b'c'$ i.e. policy of upgrade where the base fiber technology b_0-c_0 is upgraded to b'-c'
p_e	Policy of upgrade, p, in which link e is getting upgraded from type b-c to type b'-c'
τ_p	Disruption time to execute policy p
Ψ_{bc}	Effective capacity offered by the fiber technology b-c
$C^E(p)$	Equipment cost; = 0 if b = b', c = c'
$C^{De}(p)$	Deployment cost; = 0 if b = b', c = c'
$C^{Di}(p)$	Disruption cost; = 0 if b = b', c = c'
$C(p)$	Upgrade cost for policy p where, $C^U(p_e) = C^E(p_e) + C^{De}(p_e) + C^{Di}(p_e). \quad (1)$
$C^O_{t_i}(p_e)$	Operational cost of link e for policy p_e at time t_i.
B^X	Guaranteed bandwidth blocking to ensure the agreed quality of service to end users
$\hat{B}$	Limit of bandwidth blocking to trigger proactive upgrade ($\hat{B} < B^X$)
E^U	Set of links to upgrade

Each link has two fibers in opposite directions. Each fiber technology can be represented as b-c where b is the active optical band and c is the number of cores. In this work, we consider MB-EON technologies, which are C-band only and C+L band, and SDM-EON single-core and three-core fiber technologies[1]. Thus, we have four fiber technologies (denoted in b-c format), viz., single-core fiber with C band (C-1; lowest/base technology), single-core fiber with C+L bands (C+L-1), three-core fiber with C band (C-3), and three-core fiber with C+L bands (C+L-3; highest technology). We assume that all network links are initially in the lowest technology of C-1 (= b_0-c_0). We use five modulations, viz., BPSK, QPSK, 8QAM, 16QAM, 32QAM with corresponding generalized signal to noise ratio (GSNR) threshold as 9 dB, 12 dB, 16 dB, 18.6 dB, and 21.6 dB, respectively which corresponds the bit error rate of 10^{-3} [7].

Each demand is of size 100 Gbps. The number of shortest paths for every s-d pair is denoted as K. Spectrum continuity, spectrum contiguity and spatial continuity are imposed. The spectrum is assigned such that the GSNR requirement is met for the selected modulation and for the existing connections on adjacent bands and/or cores as per the fiber technology.

We calculate congestion coefficient, denoted as χ_e, to represent the utilization of capacity of link e using Eq. (2), which consists of two terms - the first representing dynamic congestion and the second representing static congestion. The dynamic congestion is due to spectrum occupancy; here x_i is a binary variable set to 1 if a slot is busy and to 0 if it is free. The static congestion is due to possible/future occupancy due to other SPs passing through this link e. Here K_e denotes the number of SPs passing through link e. E^k denotes the number of links on the k^{th} SP. Ψ is the effective capacity and is defined below in Def.II.1. The two terms are divided by 2 so that $0 \leq \chi_e \leq 1$.

Definition II.1 (*Effective Capacity)***.** The effective capacity of technology b-c, denoted as Ψ_{bc}, is the total number of frequency slots in the base technology (b_0-c_0) to achieve the same BBP with the same load and network model when the BBP is obtained in each case by assuming all the links are of the same technology.

For example, the effective capacity of (C+L-1) can be obtained in two steps. First, we set up a network where all the links are (C+L-1) and then obtain the BBP for a load and network model. Then, we set up the network with all the links being (C-1) and increase its spectrum (i.e., number of frequency slices, FSs) until we obtain the same BBP as for (C+L-1) for the same load and network model. The spectrum on (C-1) required to obtain the same performance as (C+L-1) is the effective capacity of (C+L-1). The effective capacity of link l with fiber technology b-c on a k^{th} path is denoted as $\Psi^{k,l}_{bc}$. Similarly, the effective capacity of the base technology (C-1) and the highest technology (C+L-3) on the k^{th} path are denoted as Ψ^k_L and Ψ^k_X, respectively.

[1]We note that the proposed strategy is applicable to many bands and various numbers of cores per fiber. The PLI model presented in Section III helps in realizing the application.

$$\chi_e = \frac{\sum_{i=1}^{S^b} x_i}{2S_b} + \frac{1}{2K_e}\sum_{k=1}^{K^e}\left(\frac{1}{|E^k|}\sum_{l=1}^{|E^k|}\frac{\Psi_{b,c}^{k,l} - \Psi_L^k}{\Psi_X^k - \Psi_L^k}\right). \quad (2)$$

During the link upgrade, the link is unavailable for the duration of upgrade. The shortest paths are recalculated for all the lightpaths affected by the unavailability of link(s). These lightpaths are then rerouted in the network.

B. Problem Statement

Our objective is to come up with an upgrade plan in order to maximize the network lifetime while ensuring that the CapEx is fulfilled by the budget and the BBP is below threshold. At time instant t_0, all the links in the network are in the base technology of b_0-c_0. At any time t_i, given a) time window of T, b) traffic forecast for $(t_0 + T)$, i.e,. Λ_{t_0+T}, c) current network state $(G(V,E)(t_i))$, d) costs for upgrade, e) upgrade times, and d) budget Ξ, the aim is to find the set of links to upgrade E^U and corresponding upgrade technology $\{p_e, e \in E^U\}$ such that the network guarantees and network constraints are met. Each upgrade policy, p, incurs a cost of upgrade from technology b-c to b'-c' and is denoted as $C(p)$ and provides an increase in capacity. Here, $C(p)$ includes the equipment cost $(C^E(p))$, deployment cost $(C^{De}(p))$ and disruption cost $(C^{Di}(p))$. $(C^E(p))$ includes the cost of purchase of new fibers, mux, dmux, etx, while $(C^{De}(p))$ includes the cost of installation of new equipment and fibers to support the new technology (band or cores). During the upgrade process the link will be unavailable for τ_p time slots in the network, which means that the traffic needs to be rerouted in the network, thereby incurring a cost $(C^{Di}(p))$. We represent the capacity as effective capacity instead of raw capacity of $S_b \times c$ because, in the presence of physical layer impairments (PLIs), the raw capacity cannot be fully utilized.

III. Prerequisite For The Proposed Planner

In this work, GSNR is used as the quality of transmission (QoT) measure of a lightpath. The GSNR computation for MB-EON and SDM-EONs are different as the PLIs in each case affect the signal transmission to different extents. A lightpath in a coherent transmission system can be effectively modeled as an additive Gaussian noise channel. The SNR includes the effect of the Gaussian disturbances [8] and thus can be used to estimate the QoT. In MB-EONs along with C-band-only optical networks, the QoT is affected by both amplified spontaneous emission (ASE) and nonlinear interference (NLI) disturbances jointly with stimulated Raman scattering (SRS), which plays a major role in multiband optical transmission.

The launch power of each lightpath is denoted as P_{ch}. $P_{ASE,i}^d$ and $P_{NLI,i}^d$ denote the accumulated ASE and NLI noise powers of demand d accumulated over the propagation distance on the i^{th} channel. The total GSNR can be obtained by combining the effects of PLIs on each link on the complete path [9]. A lightpath may traverse a number of network links and each link can have one or more spans. The GSNR is calculated for each span on a path. The GSNR for channel i on span n out of N_s spans for demand d, denoted as $GSNR_i^d$, can be modeled as shown in (3):

$$GSNR_i^d = \left(\sum_{n=1}^{N_s}\Big(\frac{P_{ASE,i,n}^d + P_{NL,i,n}^d}{P_{ch}}\Big)\right)^{-1}. \quad (3)$$

Similarly, for SDM-EONs with weakly coupled multicore fibers (MCFs), GSNR can be obtained using (3). However, in MCFs the parallel transmission of signals from adjacent cores induces intercore crosstalk (XT) which degrades signal transmission. Therefore, we need to consider the XT impairment in the GSNR calculation using (4) [10].

$$GSNR_i^d = \left(\sum_{n=1}^{N_s}\Big(\frac{P_{ASE,i,n}^d + P_{NL,i,n}^d}{P_{ch}} + \mu_{XT,n}^d\Big)\right)^{-1}, \quad (4)$$

$$\mu_{XT,n}^d = K_n.L_n.10^{\frac{XT^{REF}+XT^{MARGIN}}{10}}, \quad (5)$$

where $\mu_{XT,n}^d$ is the crosstalk coefficient of a given span (indexed by n) for demand d on any channel. XT^{MARGIN} represents an additional margin with which XT is estimated; as suggested in [11] we assume XT^{MARGIN} = 8 dB for quantile q = 0.9999 [10]. XT^{REF} is the reference XT level. The value of K_n, which reflects the wavelength load in adjacent cores, depends on the XT estimation methodology applied. To get the optimal channel power we can use the assumption that at maximum length $P_{ASE,i,n} = 2P_{NL,i,n}$ [12]:

$$P_{ASE,i}^d = \sum_{n=1}^{N_s} 2n_{sp}hf_dB_d(e^{\alpha L_n^l} - 1). \quad (6)$$

Here, B_d and f_d denote the bandwidth and center frequency, respectively. L_n^l is the length of the n^{th} span on link l, α is the fiber attenuation coefficient, h is Planck's constant, n_{sp} is the spontaneous emission factor, which is assumed equal in C- and L-bands for simplicity.

The NLI noise can be modeled using the closed form approximations as inter-channel stimulated Raman scattering (ISRS) Gaussian noise [13]. In this model, both Kerr and ISRS nonlinear effects have been taken into account. The total NLI noise is comprised of self channel interference (SCI) and cross channel interference (XCI) as shown in (7):

$$P_{NLI,i}^d = P_{SCI}^{d,i} + P_{XCI}^{d,i}. \quad (7)$$

The SCI and XCI contributions of demand d on link i are calculated using (8) and (9). In these equations, γ is the fiber nonlinearity coefficient, C_r is the slope of the linear regression of normalized Raman gain spectrum, $\phi_d = \beta_2 + 2\pi\beta_3 f_d$ and $\phi_{d,d'} = (\beta_2 + \pi\beta_3(f_d + f_{d'}))(f_{d'} - f_d)$ where β_2 and β_3 are group velocity dispersion (GVD) parameter and its linear slope, respectively. Furthermore, D^i denotes the number of demands using link i, and D^iP is the total power at link i. The summation in (9) is computed over all demands (except demand d) using link i.

The center frequency of demand d, when modulation m is selected, required number of frequency slots are N_m^d, and k is the index of first FS is given in (10). Here, f_{end} is the

$$P_{SCI}^{d,i} = N_i \frac{8}{81}\frac{\gamma^2 P^3}{\pi\alpha^2}\frac{1}{\phi_d B_d^2}\left[\frac{(2\alpha - D^i P C_r f_d)^2 - \alpha^2}{\alpha}\text{asinh}\left(\frac{3\pi}{2\alpha}\phi_d B_d^2\right)\right] + \left[\frac{4\alpha^2 + (2\alpha - D^i P C_r f_d)^2}{2\alpha}\text{asinh}\left(\frac{3\pi}{4\alpha}\phi_d B_d^2\right)\right] \quad (8)$$

$$P_{XCI}^{d,i} = \frac{N_i 16}{81}\frac{\gamma^2 P^3}{\pi\alpha^2}\sum_{d'}\frac{1}{\phi_{d,d'} B_d'}\left[\frac{(2\alpha - D^i P C_r f_d')^2 - \alpha^2}{\alpha}\text{atan}\left(\frac{2\pi^2}{\alpha}\phi_{d,d'} B_d\right)\right] + \left[\frac{4\alpha^2 - (2\alpha - D^i P C_r f_d')^2}{2\alpha}\text{atan}\left(\frac{\pi^2}{\alpha}\phi_{d,d'} B_d\right)\right] \quad (9)$$

end frequency, g is the number of guard bands and Δ is the bandwidth of a single frequency slot. Here, f_{end} depends upon the bands or total number of FSs, denoted as N, in use. The following values for the parameters required for the GSNR calculations are used: f_{end} = 196.04 THz, n_{sp} = 1.5, α = 0.2 dB/km, β_2 = -21.6 ps^2/km, β_3 = 0.14 ps^3/km, γ = 1.2 1/W/km, C_r = 0.028 1/W/km/THz, and g = 1.

$$f_{d,m,k} = f_{end} - \left(k - 1 + \frac{N_m^d + g}{2}\right)\Delta. \quad (10)$$

IV. Progressive Optics Deployment and Integration for Growing Yields (PRODIGY)

We now present our proposed upgrade planner, called PRODIGY. PRODIGY answers three questions from the perspective of the network operator, viz.: a) when to upgrade the network, b) which links to upgrade, and c) what technology to upgrade each link to. Here upgrade policy is the set of link IDs, fiber technology to upgrade each link to, and upgrade initiation time. Each upgrade takes a finite amount of time depending on the technology from and to which a link is upgraded.

Algorithm 1 PRODIGY

Input: Network topology, network statistics, available fiber technologies, upgrade time per fiber technology, CapEx per fiber technology, demand forecast, network parameters

Output: Upgrade Plan

```
Verify that the current network can't handle the forecast traffic.
Get Congestion Coefficients for each link using Eq. 2.
Arrange the links in decreasing order of Congestion Coefficient.
Initialize: MUBS ← 1
while MUBS ≤ |E| do
    Find the link(s) from the list to fit as per sequence in a batch
    which are
        a) not in the highest technology,
        b) there is enough budget to upgrade,
        c) preserve network connectivity when selected.
    if selected upgrade plan can provision forecast traffic then
        Save this as Upgrade Plan;
        break
    end if
    MUBS = MUBS + 1
end while
```

The pseudo-code for PRODIGY is given in Algo. 1. PRODIGY runs periodically and finds the upgrade policy based on the current network state and capacity requirement for the forecast traffic, which answers the first question. It uses congestion coefficients, calculated using (2), of the links to get the sequence of links to upgrade. As upgrading all these links at once may disconnect the network, these links are put into batches so that network connectivity is preserved when a single batch is upgraded. PRODIGY starts searching for the upgrade policy with smallest batch size, by setting the Maximum Upgrade Batch Size (MUBS) to 1, such that all the upgrades are done in the upgrade window sequentially. When all the links in the Upgrade Plan are upgraded in the upgrade window, the network becomes ready for the forecast traffic before the next upgrade starts. Here, the upgrade window, denoted as T (Tab. I), is the duration for which the upgrade plan is laid out. Such a plan also reduces the capital expenditure (CapEx) and operational expenditure (OpEx), and increases the network lifetime. This answers the second question. Finally, as it is a gradual migration, PRODIGY chooses the next higher technology than the current link technology to help in minimizing the upgrade cost. Note that the order of fiber technologies from lowest to highest in this work is C-1, C+L-1, C-3, C+L-3. This answers the final question.

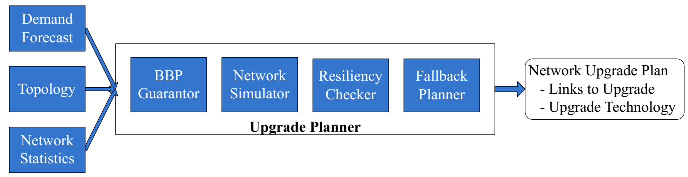


Figure 2: Upgrade planner flow.

PRODIGY is inspired from the Swiss Cheese Model to stop the enablers for failures to reach the working network. The model highlights that no single layer of protection is perfect, and each has its own potential weaknesses. However, when multiple layers of protection are combined, the weaknesses in each layer are offset by the strengths in the other layers, reducing the overall likelihood of an accident or failure occurring. Here each slice of cheese represents the interface and the holes on it let the enablers pass that layer. The sequence of layers is such that the holes are misaligned so that the enablers do not affect the functioning of the network. PRODIGY maintains the sequence of layers such that the enablers are handled before they affect the network. The first slice is Safe Capacity, which represents the extra capacity kept for traffic peaks which were not predicted in the forecast traffic. The second slice is Guarantor which is a network simulator to ensure that the network can sustain the forecast traffic. To verify an upgrade plan, the network simulator creates an instance of the same network with all the links upgraded according to the upgrade plan and then runs it for a scaled forecast traffic. The arrival rates in the forecast traffic are scaled by $(1 + \frac{\phi}{100})$ to enable safe capacity. The third slice is the Resiliency Checker which ensures the network stays connected during the upgrade process and is resilient to the unavailability of the links undergoing upgrade. The final slice represents the Fallback Planner which calls the Planner in case the network performance becomes worse than $\hat{B}$ to trigger a proactive upgrade.

V. Simulation Results

We now present simulation results to evaluate PRODIGY and compare it with some baseline upgrade planners. We use British Telecom (BT) topology as shown in Fig. 3a. Initially, all the network links are assumed to have a pair of oppositely-directed single-core C-band fibers. The C-band is assumed to have a spectrum of 4 THz with each slice being 12.5 GHz for a total of 320 FSs per fiber. Poisson connection arrival process with exponentially distributed holding time of 1 (arbitrary time unit) is assumed. The upgrade period is set to 90 units, i.e., T = 90. The network traffic increases every 30 time units, i.e., $T^{'}$ = 30. A single simulation run terminates when either all the links are upgraded to the highest technology or BBP crosses the threshold B^X or the links which are yet to be upgraded are not sufficient to lay out an upgrade plan. The datarate for each demand is set to 100 Gbps. Every s-d pair has a single shortest path. A total of five modulations are used, viz., BPSK, QPSK, 8QAM, 16QAM, and 32QAM. A coherent transceiver that operates at 28 Gbaud with an optical channel bandwidth of 37.5 GHz (i.e., three FSs) is used. GSNR-aware first fit policy is used for resource allocation. BBP is the ratio of the sum of the bandwidth of blocked connection requests to total requested bandwidth. Bandwidth dropping probability (BDP) is the ratio of the sum of the bandwidth of dropped connection requests during rerouting to total requested bandwidth. A hard BBP threshold is set to 0.1 (B^X = 0.1) and BBP to initiate proactive upgrade is set to 0.09 ($\hat{B}$ = 0.09). We set $\alpha = 5$ (which is an average of 2.5% increase per $T^{'}$ slots or 38.49% CAGR if a time slot is equal to 1 day) and ϕ = 3. We consider the CapEx of 500, 1000, 1200, and 1500[2] and OpEx per time slot of 5, 10, 12 and 15 for C-1. C+L-1, C-3, and C+L-3, respectively. The equipment costs, deployment costs and disruption costs are set to 10 for C-1, 20 for C+L-1, 30 for C-3, and 40 for C+L-3. The time slots required for upgrade (τ_p) are 5, 10, 12 and 15 for C-1, C+L-1, C-3, and C+L-3, respectively. We set Ξ = 183.75 (= $\frac{35}{2} \times \frac{5+10+12+15}{4}$) such that sufficient budget is available for half of the links getting upgraded in an upgrade window.

As this is the first work that considers upgrade to SDM, we do not have any algorithms in the literature with which to compare PRODIGY. Accordingly, demonstrate PRODIGY's superior performance by comparing it with two baseline upgrade planners, GREEDY and NO-UPGRADE. Here, GREEDY chooses as big a batch size as possible so as to finish upgrading the network as early as possible. On the other hand, NO-UPGRADE never upgrades any link. BBP and BDP for the three upgrade planners are shown in Fig. 3b. The distribution of fiber technologies for different time slots is shown in Fig. 4.[3] At a time slot, if a link is not available because it is being upgraded, it is marked as UPGRADING. The simulation setup is inspired by realistic networks [14] and can run for days to mimic real world backbone networks. However, considering time limitations and to keep the network performance realistic in the paper, we kept the load higher and used higher traffic increments with respect to time to reduce the execution time. This results in a sharp increase in BBP. The average execution time of PRODIGY for BT is $\approx$ 101 hrs and 5.881 million lightpaths are provisioned.

In the case of PRODIGY, the BBP increases gradually and remains under the threshold, and network lifetime is highest. On the other hand, in the case of NO-UPGRADE, the BBP crosses B^X in less than 2000 time slots. In addition, GREEDY fails because either the link pool does not satisfy the constraints of connectivity, technology selection, and/or budget, or the BBP increases sharply. GREEDY is successful in partially upgrading the network, uses the highest CapEx, and has a low network lifetime. Choosing a bigger batch size to upgrade in parallel can speed up the network upgrade process, but the unavailability of many links at the same time sharply increases the BBP.

We have also reported the statistical comparison of all the planners in Tab. II. The CapEx and OpEx are normalized over total time slots. The lifetime of the network is the highest with PRODIGY. In addition, averaged cumulative CapEx and OpEx of PRODIGY helps the network operator to intelligently plan the budget allocation.

Table II: Statistical comparison of Upgrade Planners.

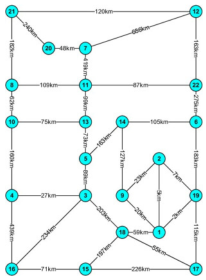
Upgrade Planner	Processed Time Slots	Lightpaths Provisioned	Normalized CapEx	Normalized OpEx
NO-UPGRADE	1600	975,616	0	175
GREEDY	1080	517,558	19.44	169.17
PRODIGY	3510	5,881,295	31.88	79.61

VI. Conclusions and Future Work

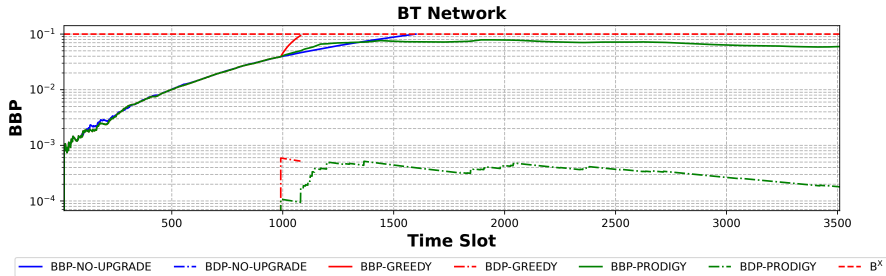
The existing C-band enabled Elastic Optical Networks (EONs) are facing capacity challenges due to growing traffic demands. Multiband elastic optical networks (MB-EONs) and space division multiplexed elastic optical networks (SDM-EONs) are two major technologies that offer better capacity but also have deployment overheads that impact network performance. To address this challenge, we proposed an upgrade strategy, Progressive Optics Deployment and Integration for Growing Yields (PRODIGY), which gradually migrates the current C-band EONs to MB-EONs and SDM-EONs. PRODIGY utilizes the Swiss Cheese Model to implement proactive measures and ensure the network's robustness during network traffic peaks, while also meeting the service level agreement. A detailed comparison of PRODIGY with baseline strategies shows that PRODIGY can meet the objectives more efficiently and enable gradual migration of EONs to MB-EONs and SDM-EONs.

[2]The CapEx may depend on the fiber technology to upgrade from and to upgrade into. However, in this work we consider the CapEx based on the fiber technology to upgrade into.

[3]The BT topology has 35 links.

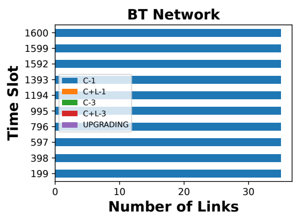


(a) BT network topology.

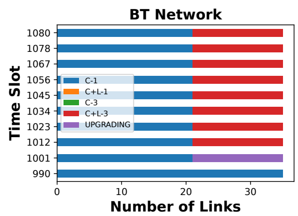


(b) BBP and BDP vs time for BT topology at λ_0 = 300.

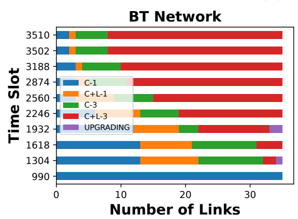
Figure 3: BT network topology and blocking performance.



(a) NO-UPGRADE



(b) GREEDY



(c) PRODIGY

Figure 4: Time slots vs distribution of fiber technologies.

Moving forward, we intend to expand our work in various directions. Our first goal is to enhance PRODIGY to align better with resource selection strategies as discussed in [15] and consider advanced fiber technologies. In addition to the above, we plan to make PRODIGY provide information on the locations where new links can be deployed along with the technology of deployment [16]. Finally, as we have previously done in our works [17], [18], we intend to utilize machine learning to automate network performance, and for traffic forecast and GSNR predictions.

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