Multilayer Planning for Facebook Scale Worldwide Network

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***Abstract*— Facebook continues to see hyper-exponential and unpredictable growth for both machine-to-machine and machine-to-user traffic. Achieving high service availability in an economical way is a massive design and optimization challenge for planning Facebook's large scale backbone network. The multilayer planning algorithm developed for this study at Aria Networks, models the IP and optical layer together, explores solutions beyond shortest paths, and scales to solve a topology with 100+ sites, and 200+ links. Based on topology and traffic data from the Facebook production network, we demonstrate savings in excess of 25% for the total cost of ownership of the network, using a multilayer design with high priority services protected in IP/MPLS layer and low priority services restored in the optical layer.**

Keywords—Network Design; IP Over WDM; Planning;

I. INTRODUCTION

The Facebook backbone provides connectivity between different Point of Presence (POPs) sites and datacenters to enable the social network. This backbone typically requires IP/MPLS services to be carried over a fiber optical network under the sea and over a terrestrial mesh distributed around the world. This geographically distributed infrastructure, due to its large exposure radius, is prone to failures. Since failures are inevitable, a design and plan for the infrastructure should account for recovery mechanisms in the face of failures.

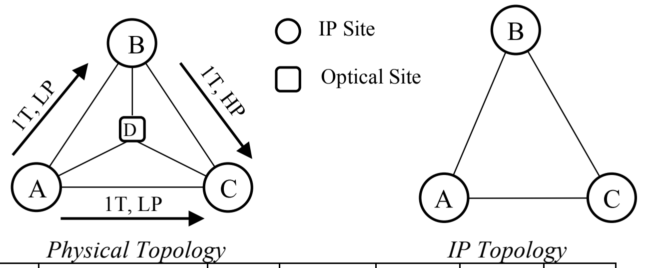
Traditionally, operators design networks with protection in IP layer using rules of thumb built around parameters like topology, traffic, hop lengths etc. The majority of the network plan is manual, network layers are designed separately for simplicity, and often lacks a benchmark to assess its optimality. The algorithmic complexity of a holistic multilayer design makes it difficult for a tool to scale up and model a worldwide production network, taking into account its policies and constraints. The Facebook backbone has been witnessing a dramatic growth in traffic and the simplistic approach of optimizing each layer in the stack separately would lead to a sub-optimal network plan and unacceptably high network spend. To maximize the utility of deployed network hardware, it's important to leverage the flexibility offered by every layer and this makes a strong case for multilayer planning.

To reduce infrastructure costs and still meet service availability guarantees, one of the architectural entities to be evaluated is the adopted failure resilience model. Failure resilience feature is available in both IP/MPLS and optical layer. IP Fast Reroute and MPLS Fast Reroute are shared protection mechanisms available in the higher layer (termed L3) that can guarantee protection within sub 50 msec. Layer 1 (L1) supports dedicated 1+1 protection feature that guarantees sub 50 msec recovery, but does not share resources. Layer 0 (L0) optical restoration allows sharing of spectrum by different services across failure scenarios but restoration times can be high, at times, as long as a few minutes. The backbone has a mix of high priority and low priority support services. The high priority services have stringent availability requirements. The cumulative downtime, in the time window of availability measurement, due to long L0 restoration times, is not acceptable for crucial services. Such long restoration times, however, may be considered a reasonable tradeoff for low priority support services. One of the questions that we try to address while solving the multilayer design problem is to classify services based on their availability requirement, and identify which layer should be used to recover from failures, when each layer has its own resilience capabilities.

The multilayer design problem with an objective of minimizing total cost of ownership (TCO) of a network consists of the following four sub-problems: (i) L3 topology design sub-problem, which requires the identification of optimal router bypasses and terminations in the IP topology. (ii) L3 routing sub-problem, which requires the identification of optimal path taken by the IP services on the IP layer. (iii) L0 express design sub-problem, which requires the identification of optimal optical bypasses in the physical topology under steady state and failure scenarios. (iv) L0 routing sub-problem, which requires identification of the optimal path taken by the services in the L0 layer. Ideally, in all these sub-problems, the algorithm should consider paths beyond the shortest paths in both L0 and L3, and optimality should be with respect to the global objective of network TCO, but this leads to a state space explosion even for a medium sized network. In the algorithm we designed for this study, we analyze paths beyond the shortest paths only in Layer 0, which in itself improves quality of our solutions significantly.

The choice of algorithm to solve this challenging design problem affects both performance and solution quality. A chosen algorithm should represent the problem in an efficient way, not get stuck with local minima easily while sampling the large state space associated with exploring paths beyond shortest paths, and converge fast to a good solution. In an effort towards making the planning process automated and scalable, the solution developed by Aria Networks [1] for this study is an evolutionary genetic algorithm that can solve the multilayer design problem in a holistic way incorporating realistic costs of routers, optics, and fibers. Using this framework, and distributing resilience between IP and optical layers, we are able to show TCO savings in excess of 25% in the Facebook worldwide network that has 100+ sites and 200+ links.

The rest of the paper is organized as follows. In Section II, we summarize related work. Section III describes an example scenario to illustrate the cost savings of a multilayer design. Section IV provides a description of the developed multilayer



No.	Scenarios	IP Ports	Optical Ports	Regen Ports	Total Cost	QoS
I	L3 Protected L0 UnProtected	120	120	0	600	Yes
II	L3 UnProtected L1 1+1	60	120	60	780	Yes
III	L3 UnProtected L0 Restoration	60	60	20	380	No
IV	HP L3 Protected LP L0 Restored	80	80	20	480	Yes

Figure 1. Cost Vs. QoS tradeoff for different failure resilience models on a three node example network topology

framework. Simulation results are presented in Section V followed by our conclusions and future work in Section VI.

II. RELATED WORK

A good summary of the rich literature in the area of multilayer network planning is described in [2]. Here, we selectively identify past work that is directly relevant to the current study. The work in [3] optimizes the IP topology using a greedy hill climbing approach, and quantifies the IP port counts turned up for different flavors of optical restoration. The authors of [4] dimension optical layer in addition to, but separately from the IP layer, for a network with special hardware accelerated optical protection. Very few of the published studies are from the network provider community [5,6]. The study in [5] analyzes optical resilience scheme in a 14 node, 23 link dual rail network that has integrated IP and DWDM interfaces and suggests traffic classification, allowing restoration of low priority traffic in the optical layer. The authors in [6] suggest using shared backup routers instead of a dual plane configuration, and use photonic layer restoration to recover from router failures and show savings in a 20 node network. An ILP framework for comparing IP protection and optical restoration is provided in [7]. The work in [8] formulates joint layer CAPEX optimization as an ILP formulation and highlights the cost benefits and energy savings for doing restoration in a fixed grid and flex-grid optical layer.

The novelty of our contribution which differentiates our work from all the previous work is four fold. First, the optimization is performed with an objective to minimize network TCO, assuming actual costs of IP ports, optical ports and fiber costs seen in our production network. Second, the developed algorithm framework explores solutions beyond the shortest paths in the optical layer to achieve significant network cost savings. It is a fully automatic design tool that solves the green field and brown field multilayer problem taking into account optical reach, and site space/power constraints. Third, the tool scales to model networks in excess of 100+ sites and 200+ optical links and quickly converges to a high quality solution while solving for a worldwide network. Fourth, the study is based on a realistic worldwide network topology, with forecast demand projection based on a realistic content provider production network. The tool provides distributed resilience for different services, each at a specified layer (IP or optical), based on service availability requirements, and routes IP circuits in the optical layer honoring optical closure constraints.

III. PROBLEM STATEMENT

The Facebook backbone network consists of IP/MPLS capable routers connected to a DWDM network through 100G grey optic interfaces. The optical network is a multi-vendor environment with CD Reconfigurable Optical Add Drop Multiplexers (ROADMs), deploying fixed grid and flex-grid technologies. In this study, we analyze the role of optical restoration in the Facebook backbone using a multilayer algorithm and validate if it can bring about significant savings. The tradeoff between Quality of Service, recovery layer, and network cost is illustrated through a small example network.

Consider a network with physical and IP topology as shown in Fig. 1. Sites A, B, and C have IP routers, while D is an optical site. Each physical link is of length 1000 km and assume for this example that the maximum optical reach before requiring regeneration is 1000 km. The network is designed to recover from single fiber failures. Three IP services are defined, each of size 1T, with service B =>C of high priority (HP), and services A=>C, and A=>B of low priority (LP). 100G optical and 100G IP ports are used in the network and are costed as 4 units and 1 units respectively. Total network cost is computed as the sum of IP port and optical port costs in Fig.1. The cost of commons is ignored since line card costs dominate deployment costs.

Scenario I is the traditional IP protection model. IP service A=>B is routed on shortest path along IP link A-B, and during its failure is routed along IP links A-C and C-B. Each IP link is dimensioned by recording the highest watermark achieved for all transport link failures. This requires 6T capacity to be provisioned in the IP layer. In Scenario II, L3 is unprotected, but L1 is 1+1 protected. Optical service A=>B uses physical links A-B as work path, and A-C-B as backup path. The backup path requires regeneration at an intermediate point, and hence for each 100G IP service, 6x 100G optical ports is turned up (2x for work path and 4x for protect path). This design turns up 3T in the IP layer, but has the highest network cost due to its lack of resource sharing in the optical layer.

Scenario III uses optical restoration. Optical service A=>B is routed on physical link A-B and restored along physical path A-D-B. 20 x 100G optical ports are turned up at site D for regeneration. These regen ports can be reused by other services as well since work paths of the services are disjoint. This design turns up 3T in the IP layer and has the lowest network cost due to sharing in the optical layer. However, note that the long restoration times may not be sufficient to meet the Quality of Service (Qos) guarantees required by the high priority service B=>C. Scenario IV is the multilayer design where services A=>B and A=>C are restored in the optical layer by sharing 1T of regen optical ports at D, while B=>C is recovered in the IP layer. Since IP demands are unidirectional, under failure of

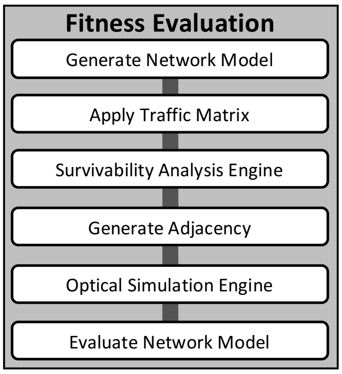


Figure 2. Fitness evaluation phase flow chart

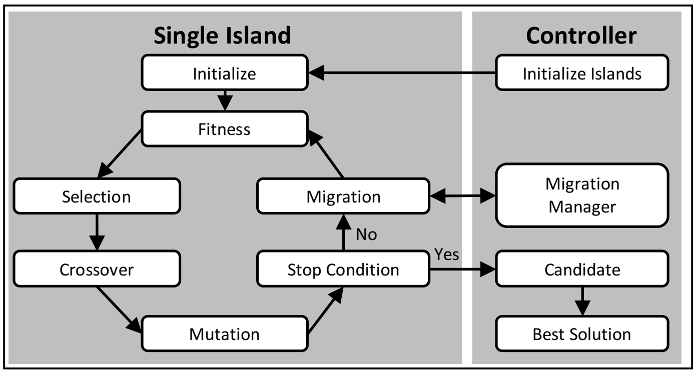


Figure 3 Flow chart of the genetic algorithm.

link B-C, physical link A-B requires no additional capacity, but additional capacity of 1T is required on link A-C. A total of 4T is turned up in the IP layer, and multilayer design is the lowest cost design that meets all QoS requirements.

In scenarios where optical layer restoration is used, it is not possible to protect from L3 failures like IP port failures. At least one spare IP port and optical port are equipped per L3 chassis for recovering from L3 port failures. Also, the IP ports need to be connected to the optical ports through a reconfigurable patch panel to recover from a port failure. Another observation is that, while Scenario I and II turn up only 3 fibers, Scenarios III and IV turn up 6 fibers. Network TCO for the different scenarios should include the fiber cost as well.

To classify services as L3 protected (fast protection) or L0 restored (slow restoration) on the backbone, we use two parameters - service availability requirements and reliability of assets over which a service gets routed. Following aspects are considered: (i) steady state IP hop count of a service (ii) number of traversed fibers per IP hop, and (iii) average reliability of a fiber. For each failure, we identify the unreliability credit earned by the demand due to L1 restoration, assuming restoration downtime of 5 minutes per failure. If the total average unreliability budget earned by a demand over a specified time, say 1 year, is higher than the total maximum allowable downtime, then we enforce that this service be IP protected. Otherwise, it is restored in the optical layer. We apply the developed multilayer tool to minimize TCO for Facebook's worldwide network and compare the performance of L3 protection with multilayer resilience.

IV. ALGORITHM DESCRIPTION

The multilayer algorithm takes an input topology that includes IP & optical nodes, transport links and a traffic matrix with resilience requirements and failure scenarios to be modeled. The tool optimizes topology and routing for a network with an objective of minimizing the network TCO based on an input equipment and fiber price list. We utilize a class of adaptive heuristic search algorithm known as Genetic Algorithms (GAs), which are inspired by the process of natural selection and biological evolution for optimization. They are frequently used to generate high quality solutions in a reasonably short time period for NP-Hard problems that have complex fitness landscapes and scale to large input sizes, where otherwise, the computational needs can become overwhelming.

A 'chromosome' representation is formulated for the problem; this encapsulates all variables that are required to produce a valid solution during the fitness evaluation phase. The chromosome representation in our GA consists of two parts: a bit-string and a tunnel path directory. The bit-string represents a subset of IP adjacencies that are chosen in a given instance and the path directory specifies the routing of associated adjacencies in the physical layer. The tool considers the placement of multiple IP links between router pairs to improve resilience in failure scenarios and explores complex physical layer paths beyond the shortest path. These techniques drastically improve the L0 and L3 resilience and increase the quality of solution produced by the tool but come at the cost of an increased search space.

A policy based framework that can enforce constraints on solutions like preventing select adjacencies from being created and limiting the adjacency degree of a router is provided. For instance, a policy may restrict design of an IP circuit that crosses both the Atlantic and Pacific Ocean, since such a circuit would have limited practical availability. The constraints generated by this framework are utilized by the fitness evaluation phase, shown in Fig. 2. The evaluation models traffic routing and uses the *Survivability Analysis Engine* [1] to simulate L0 failure scenarios from which equipment and fiber capacity requirements are generated. These requirements are then fed into the *Optical Simulation Engine* [1] where all of the optical constraints and requirements are evaluated and regen cards are turned up as necessary. Based on the site level space/power limitation, it splits regeneration points along several sites in a path to optically close the route. Say, the engine requires 1T to be turned up on a route that needs one regen to be placed on one of two optical sites along the route. Suppose there is sufficient power to turn up only 500G on either of the sites, the algorithm splits the regen between the two sites to make the route optically closable. The monetary cost of the resultant design is translated into a fitness value and penalties are included if any of the constraints have been broken, like in the case of a service not meeting protection guarantee or latency exceeding its specified threshold.

During the evolutionary process, crossover and mutation operators combine and modify chromosomes in an individual pool of solutions (genepool) with the aim of discovering new

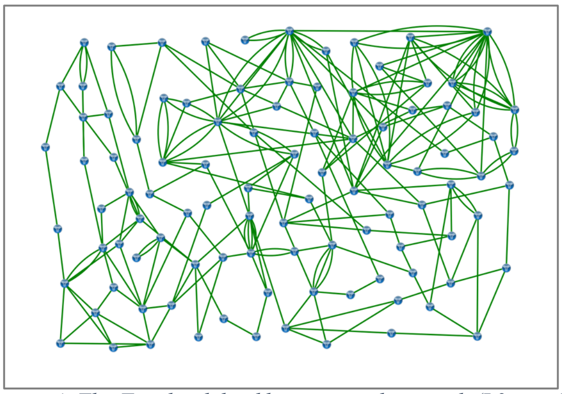


Figure 4. The Facebook backbone optical network (L3 not shown)

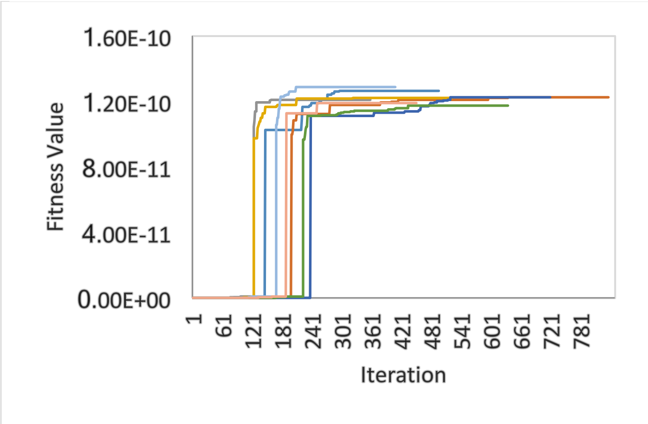


Figure 5. Fitness evolution during a genetic algorithm simulation

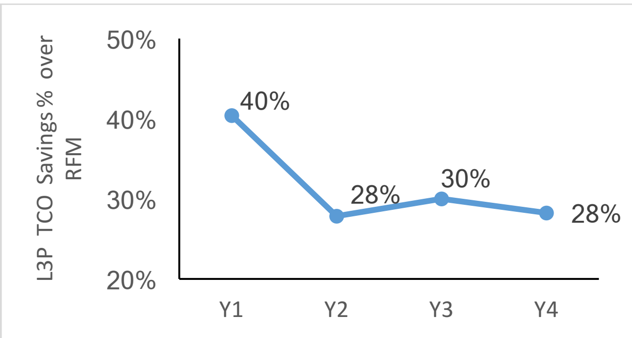


Figure 6. L3P TCO Savings expressed as a % over RFM TCO

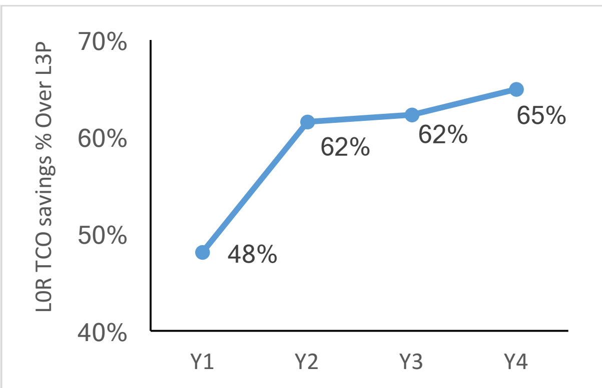


Figure 7. L0R TCO savings expressed as a % over L3P TCO

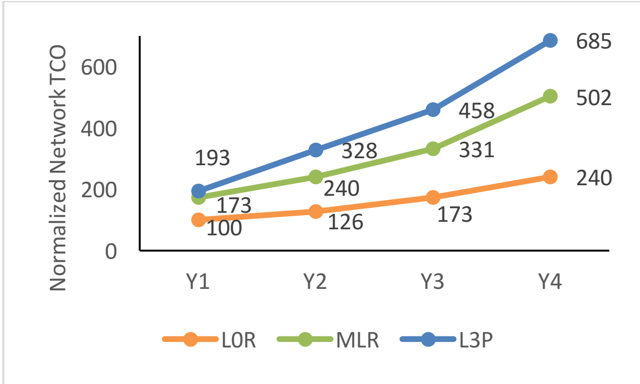


Figure 8. Network TCO over time normalized to L0R TCO Y1 value (which is set to the value 100)

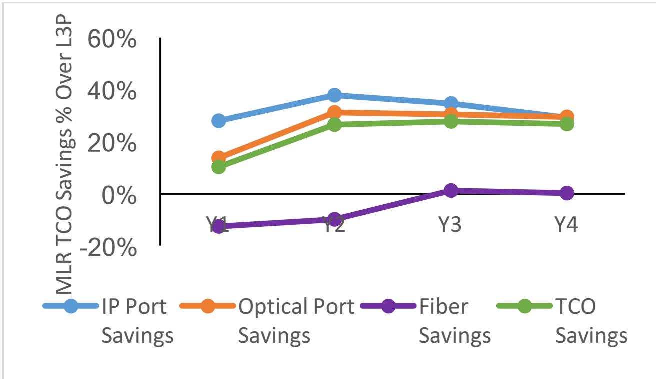


Figure 9. MLR savings breakup expressed as a % over corresponding L3P costs

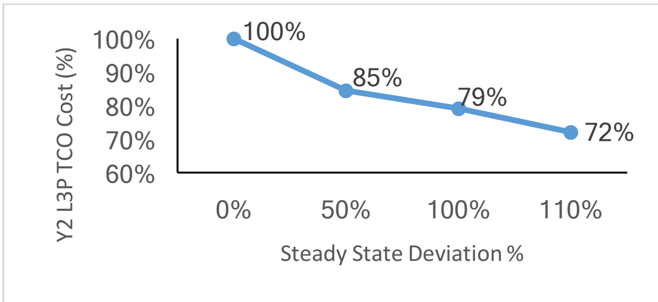


Figure 10. Y2 L3P TCO cost reduction as a function of steady state deviation from the shortest physical path

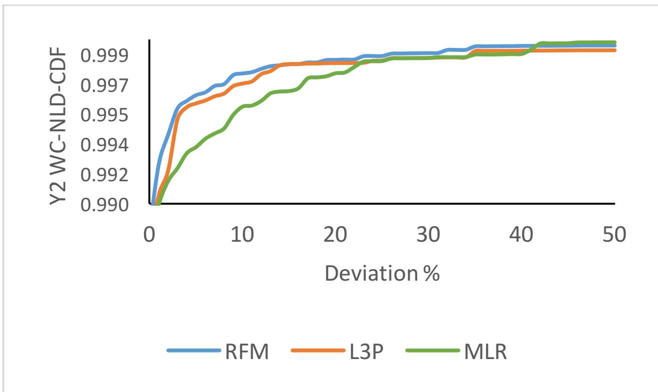


Figure 11. Y2 Worst Case Network Latency Deviation CDF

and improved solutions. The improvements can range from lowering work/protection path latency to increasing the distribution of bandwidth on the underlying optical topology and assist with the end goal of converging to the lowest monetary cost solution. Single point crossover generates new 'offspring' solutions based on the data stored by the 'parents'. Improvements in solution quality are the result of desirable features from parents being combined in contrast to mutation which aims to discover 'new' features in the problem space by modifying elements in a single existing solution. Custom mutation operators were designed to target sub-optimal areas of a solution and seek to improve them. The operators target parameters like tunnel path latency, demand protection tolerance and bandwidth utilization. The introduction of such targeted mutations increases the amount of useful mutation that is performed as part of the search and reduces the time required to discover good candidate solutions.

The overall complexity of the problem means that convergence to local optima becomes a prominent issue even on a small-scale input topology. A concurrent, multiple-genepool approach, as shown in Fig. 3, with island population migration [9] has been used to ensure that the search space is adequately covered and that evolution does not stagnate. Multiple genepools evolve in parallel and solutions are moved between these pools at set intervals. The injection of diverse individuals into other genepools reduces the probability of a genepool stagnating on local optima by introducing new features that can be combined in the pool. Step change improvements to the fitness in a pool can often be correlated to migration events between genepools. Multiple genepools ensure that several unique optima are explored in parallel while the migration model ensures that, as time progresses, all islands converge towards the global optima.

Each genepool is initialized using a statistically diverse seeding operator to maximize the distribution of solutions across the search space. Furthermore, the genepool selection and genetic operators have been tailored to maximize diversity and mitigate the risk of premature convergence within an individual genepool. For a given scenario, multiple instances of the GA are run in parallel over a server cluster to provide the best solution and further mitigate premature convergence.

V. SIMULATION RESULTS

The Facebook worldwide network has 100+ sites (including IP and Optical only sites) and 200+ optical links (including subsea, aerial and terrestrial fibers). The Facebook optical network with optical Add/Drop sites connected by fibers is shown in Fig. 4. The fiber distance is used as IGP metric to perform shortest path routing on the IP layer. The deployed routes in the production network are used to identify optical closures in the tool. The coherent 100G wavelengths in the network are boosted by EDFA, and hybrid RAMAN amplifiers to enable optical closure of routes in excess of 2500 kms. The tool assumes this as the reach value for routes that are not yet deployed and turns up regeneration ports for longer candidate routes. The space/power constraints at the optical sites are specified and honored for regeneration purposes. The maximum fiber capacity is assumed to be 9.6 Tbps. The IP and optical interfaces are designed for 100G increments, with IP interfaces designed for a maximum utilization of 80% to buffer occasional packet bursts. With an initial traffic volume of 35T in Year 1 (Y1), the network is simulated for three additional years (Y2, Y3, and Y4) with an assumed growth rate of 50% YoY. Based on the approach outlined in Section III for classifying traffic priority, roughly 50% of the traffic is restored in the optical layer.

All single fiber failure scenarios are analyzed to dimension the network. The network is optimized each year for the specified traffic matrix. This assumption is reasonable since the focus is on network optimality and network disruptions can be planned in a phased manner to allow cost saving reconfigurations. The GA optimization is allowed to deviate from the shortest paths with no latency deviation limits. The cost of a 100G optical port is 4x the cost of a 100G IP port. The backbone network is connected by 25000+ km of dark fiber, and since these assets have already been acquired, the fiber cost we assumed in the study corresponds to the cost for Operations, Administration and Maintenance (OA&M) of a fiber. This cost is specific to each fiber depending on the region, and the fiber type (terrestrial, aerial, subsea etc.) The actual costs for IP ports, optical ports, and fiber costs are used and GA optimizes the network design for lowest network TCO.

Three GA optimized models are analyzed in this study. (i) L3P – this model protects all services only in L3. (ii) L0R – this model restores all services only in L0. (iii) MLR – this model has multilayer resilience with high priority services protected in L3 and low priority services restored in L0. Additionally, we introduce a baseline that does protection only in L3 using an IP topology designed as a restricted full mesh (called RFM), by pruning adjacencies between routers that have low inter-router traffic. RFM avoids transit traffic at intermediate sites, has the lowest latency, but has limited grooming capabilities.

Fig. 5 displays the evolution of the best fitness observed in the individual genepools over a run of the GA (with a greater fitness representing a more optimal solution). Once a single pool has discovered a superior solution, it does not take long for migration to improve the overall solution quality observed in other pools. This is seen as the step function in the plot and emphasizes the impact of migration between genepools. The convergence of all genepools to solutions with similar (but unique) fitness's highlights the benefit of a multi-genepool solution and illustrates how the approach improves convergence to the global optima.

The TCO savings of L3P expressed as a % over TCO of RFM is shown in Fig. 6. In Y1, L3P shows 40% TCO savings over RFM, and in the subsequent years, it is 28% or more. In Y1, when traffic is low, the express capacity turned up in RFM is underutilized, whereas the GA is able to identify the right mix of bypasses and terminations in L3P and show superior savings. As traffic increases, the turned up express paths in RFM have higher utility, and L3P savings over RFM reduces, but still continues to be significant. The good balance of transit and grooming achieved by L3P makes it clear that GA solution for L3P is of high quality.

The TCO savings of L0R expressed as a % over TCO of

L3P can be seen in Fig. 7. In Y1, L0R shows 48% TCO savings over L3P, and in subsequent years, it is 62% or more. The GA is able to achieve this savings by effectively sharing regen ports across different failure scenarios, and the port sharing efficiency of optical restoration improves with increase in traffic. This gives the assurance that the GA solution for optical restoration is of high quality as well. However, note that L0R savings comes at the expense of not being able to meet QoS constraints for all the high priority services and is hence not a feasible solution for deployment.

The TCO required for L3P, MLR, and L0R for different years normalized to the TCO for L0R in Y1 (which is set to a value of 100) is presented in Fig. 8. In Y1, when L0R TCO costs 100 units, L3P costs 193 units and MLR costs 173 units. In general, it is seen that MLR TCO lies between L0R and L3P TCO. This highlights the significant network savings achieved by MLR by offloading resilience from L3 to L0 for low priority services. The over provisioning of IP ports due to L3 protection for some or all traffic must be transported by an equivalent amount of optical ports as well thereby increasing equipment costs on the whole for both L3P and MLR and the cost differential over L0R increases with increasing traffic.

The MLR TCO cost savings expressed as a % over L3P costs is shown in Fig. 9. The graph shows the individual breakup of savings for components like IP port costs, optical port costs, fiber operational costs, and TCO over the corresponding costs for L3P. MLR shows 10% savings over L3P in Y1, but in subsequent years, shows a consistent savings of 26% or more. Note that in Y1, MLR turns up more fibers than L3P to improve fiber diversity (similar to Scenario IV in the three node example illustrated earlier) and promote optical resource sharing for restoration of low priority services. The gains in equipment savings offsets the fiber cost increase but leads to a lower net savings for MLR in Y1. In Y1, traffic is low and optical restoration cannot be leveraged sufficiently by MLR to get savings as high as in the subsequent years that have higher traffic. Also, due to low traffic, when resilience is offloaded to optical layer for low priority services, the network is underutilized, but with subsequent years, utilization improves, leading to better savings. Also, most of the additional fibers required for diversity are turned up in MLR ahead of time in Y1, and hence incremental fiber expense over time reduces.

The sensitivity of Y2 L3P TCO as a function of steady state work path deviation from the shortest path in the L0 layer, with unconstrained recovery deviation, is shown in Fig. 10. When the threshold for deviation from the shortest path for steady state is set to 0%, L3P TCO is the same as RFP TCO (and this value is normalized to 100%). As the threshold increases, L3P savings is realized. When the threshold is set to 110%, the best L3P design with 72% cost (28% savings) is generated.

It is important to study worst case recovery path latencies under failure scenarios. We plot the cumulative distribution function (CDF) of latency deviation from the steady state path to analyze the impact of failures on GA optimized runs. For each service, the probability distribution of deviation from the steady state path is computed based on the failure probability of the fiber (derived from field failure rates), whose failure caused the reroute. This CDF per service is further weighted by its bandwidth to arrive at the worst case network latency deviation CDF (WC-NLD-CDF). The WC-NLD-CDF of Y2 MLR and L3P are benchmarked against RFM in Fig. 11. L3P performs slightly better than MLR and RFM shows the best latency. RFM has the shortest latency and worst case deviation on failures due to its express full mesh paths. Both MLR and L3P have a longer tail than RFM, but is not fully shown here so as to focus only on the portions where the models differ significantly. It is seen that with a probability of 0.999, the deviation for RFM is within 26% of the steady state path latency, while it is within 35% and 38% for L3P and MLR respectively. It is clear that the network savings from MLR comes with no significant latency penalty.

VI. CONCLUSIONS

In this study, we focused on developing a scalable multilayer design tool that can explore longer paths in the optical network, and take optical reach characteristics into account. By having low priority services restored in the optical layer in the Facebook worldwide network, we are able to achieve TCO savings in excess of 25%. The authors are currently investigating algorithm extensions that enable exploring traffic engineered paths that allow routes beyond the shortest paths in L3. To make the optical restoration solution deployable in the production network, there are a few challenges to be addressed by the optical vendors including software (in designing an online engine for computing optical closures), control (in providing open APIs for real time path computation), and economics (the optical ports costs should reduce).

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REFERENCES

[1] Aria Networks Ltd., *Network Planning & Optimization,* http://www.aria-networks.com/network-planning-network-optimization/, 2016

[2] C. Rozic, D. Klonidis, and I. Tomkos, "A survey of Multi-layer Network Optimization", Invited Paper, IEEE International Conference on Optical Network Design and Modeling, May, 2016

[3] O. Gerstel, C. Filsfils, T. Telkamp, M. Gunkel, M. Horneffer, V. Lopez, and A. Mayoral, "Multi-layer capacity planning for IP-optical networks", IEEE Communications Magazine., vol.52, no.1, pp.44-51, Jan. 2014

[4] S. Balasubramanian. S.J. Hand, P. Mahajan, S. Melle, S. Roy, T. Veluswamy, J. Perrett, and O. Assil, "A Novel IPoOTN Packet-Optical Architecture for Econimical and Fast Protection of Link/ IP Port failures", Optical Fiber Communications Conference (OFC), March 2015

[5] M. Gunkel, "Multi-layer restoration - the impact on the optical layer," OFC, 2014, vol., no., pp.1-3, 9-13 March 2014

[6] A. Mayoral, V. Lopez, and O. Gerstel, "Minimizing resource protection in IP over WDM networks: Multi-layer shared router", IEEE/OSA Journal of Optical Communication Networks, March 2015

[7] M. Ruiz, O. Pedrola, L. Velasco, D. Careglio, J. Fernandez-Palacios, and G. Junyent, "Survivable IP/MPLS-Over-WSON multilayer network optimiztion", J. of Opt. Comm. and Netw., vol 3, pp 629-640, 2011

[8] P. Papanikolaou, K. Christodoulopoulos, and E. Varvarigos, "Joint Multilayer planning of survivable elastic optical networks", Optical Fiber Communications Conference (OFC), 2016

[9] W. N. Martin, J. Lienig, and J. P. Cohoon, "Island (migration) models: evolutionary algorithms based on punctuated equilibria", Handbook of Evolutionary Computation, pp. C6.3:1 to C6.3.16, 1997