Targeted Defragmentation of a Production Optical Network

Srivatsan Balasubramanian, Vinayak Dangui, John P. Eason, Satyajeet Singh Ahuja
Meta Platforms Inc.

***Abstract*—We present a ILP framework that can provide the defragmentation plan for a targeted portion of a production optical network, unblocking capacity through remote reconfigurations, thereby helping with retaining backbone resilience despite mobility restrictions during the pandemic.**

***Index Terms*—Defragmentation**

I. Introduction

Meta Platforms' services are hosted by large server farms housed in data centers (DC) and Point of Presence (POP) sites, which are connected over a wide area optical network. Based on a demand forecast, a capacity plan is generated by a multilayer network planning tool that protects the backbone under different failure scenarios in the IP/MPLS layer with availability guarantees. The capacity plan is realized as IP adjacencies of specified bandwidth connecting routers along well defined SRLG (single fiber duct with many fiber strands called rails sharing the same fate) paths. The IP services are lit up using optical services which in turn are carried over optical channels. The optical channel is assigned a continuous and contiguous band of slices on every SRLG along the path.

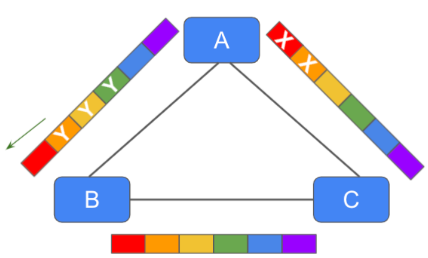

Fig. 1. Defragmentation in an example network

We perform spectrum assignment using a production optical pipeline with the objective of minimizing overall future network blocking. However, organic growth of optical network can create fragmentation of spectrum resources over time and lack of continuous and contiguous spectrum can block turning up additional capacity along the installed SRLG paths. Demand growth may require capacity augmentation and delays could result in production risk and potential deterioration of user experience. One solution is to turn up new fibers along these routes, but this takes months to deliver and may not even be feasible in certain circumstances like the pandemic when access to sites was restricted.

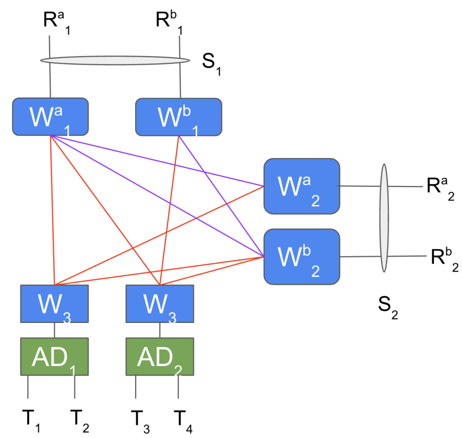

Fig. 2. Node Architecture Example

Another solution is to defragment the production network to make room for additional capacity. A toy example to illustrate defragmentation is described in Figure 1. Each SRLG has one rail and 6 spectrum slices. Suppose, connections X and Y are installed. Consider a connection Z which requires 3 slices along SRLG path A-B-C. SRLG A-C cannot be used since paths taken by adjacencies are already determined by the multilayer planning tool accounting for availability guarantees and a change here may affect these guarantees and cause significant operational churn to the capacity delivery process. SRLG A-B does not have 3 contiguous slices available to admit the demand. The defragmentation approach would be to reconfigure Y to shift one slice to the left, thereby allowing Z to be admitted.

II. Modeling

To realize defragmentation, constraints at the optical node level need to be considered. Our production optical network is a multi-vendor environment with a significant portion of the network having an installed base of colorless, directionless, reconfigurable optical add drop multiplexers (CD ROADMs) deploying flex-grid technologies. A sample CD node architecture that shows intra node connections is shown in Figure 2. The node has two SRLG degrees (S_1 and S_2), each having two fibers. Individual fiber strands within a SRLG are called rails. For instance, each SRLG in Figure 2 has two rails (a and b). The network has two types of cards - W (wavelength-selective switches (WSS) meant for switching across fibers) and AD

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(WSS and transponders meant for add/drop). The number of ports on both cards are limited (wss_{max}) due to which a full mesh within a node is not possible. In the example, (suppose wss_{max} = 3), spectrum cannot switch from rail R_1^b to R_2^a since the card W_1^b is not connected to W_2^a. Spectrum from R_2^b cannot drop on card AD_1 and spectrum from R_1^a cannot drop on card AD_2 due to lack of full mesh connectivity. An additional constraint due to CD technology is that if a slice s is used by AD_1 on a rail (say, R_1^a), s cannot be dropped by AD_1 from other rails.

Defragmentation has been studied in [1], [2] and in references therein. Prior work assumes non blocking node configurations unlike the more complex blocking node configuration predominantly seen in our production network in Fig. 2. Earlier work such as [3] assumes altering of SRLG paths of adjacencies, whereas due to design and operational constraints, the only flexibility that we have in the optical layer is in ability to select different rails within the same SRLG path. The dominant blocking node and multirail architecture necessitates an approach different from prior art. Additionally, we are not as concerned with traffic disruptions as in [4] since there is sufficient buffer built in the network but rather prefer small targeted defragmentations with minimal site visits.

We solve defragmentation problem using an integer linear programming (ILP) approach. The formulation targets a small portion of the network and defragments a set of installed optical channels with the goal of unblocking new optical spectrum that is continuous and contiguous while considering internal optical node constraints. This removes potential wait of several months for new builds to complete. We deployed this approach during the peak outbreak of COVID to unblock emergency capacity when all network facilities had restricted access.

Our ILP formulation has several weighted objectives: maximize newly admitted capacity, minimize field reconfigurations, and avoid site visits where possible. To make ILP scale, we define a target entity to be defragmented. The target entity is associated with the set of optical channels that become candidates for defragmentation. The target entity could be a set of SRLGs, a set of rails, a set of Add/Drop nodes, a set of slices, or a combination of the above, chosen based on network utilization. The tool attempts to reconfigure a subset of optical channels associated with this entity to admit new channels that are otherwise blocked. For instance, on a blocked optical channel, the traversed SRLGs are inspected and the SRLG with highest utilization is chosen as defragmentation entity. There are different types of reconfigurations possible in the field and differ in whether they require a site visit. For instance, changing the spectrum of a channel, or switching the channel to a different rail within the same SRLG (with prior installed W-W card connectivity) can be done through remote configurations. However, operations like switching to a new AD card (thereby requiring rewiring of router ports), or modifying W-AD or W-W connectivity within an optical node would require site visits. The formulation takes in an optical topology, blocked channels, the entity to be defragmented, and allowed reconfiguration type as input. The tool outputs the newly admitted channels and the reconfiguration required in the field to achieve this. By providing different incentives to the reconfiguration types, a solution with simpler remote configuration is found over a solution that requires site visit and complex field operations.

TABLE I
ILP SYMBOLS DEFINITION

S	List of all available slices in a rail of SRLG
D	List of blocked and defragmentation candidate channels
D_n	List of channels sourcing or sinking at node n
R	List of fiber rails
U_n	List of rails incident @ node n
$\chi^n_{c,r}$	1 iff AD c patches to rail r installed at node n
$\chi^n_{r_1,r_2}$	1 iff rail r_1 to r_2 patch is installed at node n
C_n	List of AD chassis @ node n
C_i^x	all ADs for channel i on src(x=o) and dst(x=d)
i	i^{th} channel in D
K_i	SRLG hops traversed by channel i, e.g. 1, 2, $\ldots h_i$
w_i	number of slices required by channel i
M_i	Ordered list of SRLGs in the path of channel i
R_{m_k}	List of rails in duct m_k, where m_k is SRLG in hop k
M_i	List of m_k, for every hop k traversed by channel i
V_i	Union of rails R_{m_k} for every hop k of channel i
X_i^r	1 iff rail r is assigned to channel i
Y_i^c	1 iff AD chassis c is assigned to channel i
Z_i^s	1 iff spectrum starting with s is assigned to channel i
$A1_i^{s,r}$	1 iff spectrum s is assigned to channel i on rail r
$A2_i^{s,c}$	1 iff spectrum s is assigned to channel i on AD c
$A3^n_{c,r}$	1 iff AD chassis c connects to rail r at node n
$A4^n_{r_1,r_2}$	1 iff rail r1 connects to rail r2 at node n

III. ILP FORMULATION

Rail Assignment: Each channel should should be assigned one rail along each SRLG of the path.

$$\sum_{s\in S}\sum_{r\in R_{m_k}} A1_i^{s,r} <= w_i,\ \forall i\in D,\ \forall k\in K_i \tag{1}$$

Rail Contention: No two channels are assigned the same spectrum on a given rail.

$$\sum_{i} A1_i^{s,r} \leq 1\ \forall r\in V_i,\ \forall s\in S \tag{2}$$

Rail CoRouting: Every slice belonging to a channel is corouted on the same rail

$$w_i * X_i^r <= \sum_{s} A1_i^{s,r},\ \forall r\in V_i,\ \forall i\in D \tag{3}$$

$$\sum_{r\in R_{m_k}} X_i^r = \sum_{s} Z_i^s,\ \forall i\in D,\ \forall k\in K_i \tag{4}$$

Rail Spectrum Continuity: Every channel is assigned the same spectrum in every rail of the path.

$$\sum_{r\in R_{m_k}} A1_i^{s,r} = \sum_{r\in R_{m_{k+1}}} A1_i^{s,r}\ \forall i\in D,\ \forall s\in S,\ \forall k\in K_i \tag{5}$$

Rail Intra node: A channel going through two consecutive fibers at a node counts as a port in respective wss.

$$w_i * A4^n_{r_1,r_2} \geq \sum_{s\in S} A1^{s,r_1}_i + \sum_{s\in S} A1^{s,r_2}_i - w_i \quad \forall i \in D_n,\ \forall r_1, r_2 \in U_n \tag{6}$$

$$\sum_{r_2\in U_n, r_1\neq r_2} A4^n_{r_1,r_2} + \sum_{r=r_1, c\in C'_n} A3^n_{c,r} <= wss_{max} \quad \forall r_1 \in U_n, \forall n \tag{7}$$

AD Assignment: All slices of the channel are carried by at least one AD card

$$\sum_{s\in S}\sum_{c\in C^x_i} A2^{s,c}_i <= w_i,\ \forall i \in D_n,\ \forall x \in [o,d] \tag{8}$$

AD Contention: No two channels are assigned the same spectrum on a given AD chassis.

$$\sum_i A2^{s,c}_i \leq 1\ \forall c \in C_i,\ \forall s \in S \tag{9}$$

AD Spectrum Continuity: Every channel is assigned the same spectrum on the first SRLG and AD card.

$$\sum_{c\in C^x_i} A2^{s,c}_i = \sum_{r\in R_{m_1}} A1^{s,r}_i,\ \forall x \in [o,d],\ \forall i \in D_n,\ \forall s \in S \tag{10}$$

AD CoRouting: Every slice belonging to a channel is co-routed on the same AD chassis.

$$w_i * Y^c_i <= \sum_s A2^{s,c}_i,\ \forall c \in [C^o_i, C^d_i],\ \forall i \in D \tag{11}$$

$$\sum_{c\in C^x_i} Y^c_i = \sum_s Z^s_i,\ \forall i \in D,\ \forall x \in [o,d],\ \forall m_k \in M_i \tag{12}$$

AD Intra node: Every channel going through a AD chassis and rail counts towards a port in AD chassis

$$w_i * A3^n_{c,r} \geq \sum_{s\in S} A1^{s,r}_i + \sum_{s\in S} A2^{s,c}_i - w_i\ \forall i \in D_n,\quad \forall c \in C'_n,\ \forall r \in U_n \tag{13}$$

$$\sum_r A3^n_{c,r} <= wss_{max},\ \forall c \in C'_n,\ \forall n \tag{14}$$

Slice Contiguity Assignment: Every slice that is allocated to the channel should be contiguous.

$$w_i * Z^s_i <= \sum_{j=0..w_i} \sum_{r_1\in m_1} A1^{s+j,r_1}_i,\ \forall s \in S,\ \forall i \in D_n \tag{15}$$

$$\sum_s Z^s_i <= 1\ \forall i \in D \tag{16}$$

Objective: The cost function uses weights α, β, γ, θ, κ, and μ to incentivize channel admission and penalize reconfiguration. s_o, r_o, and c_o are spectrum, rail and AD allocated to channel i if channel i is installed

$$\alpha \sum_i A1^{s,r}_i - \beta \sum_{s,s\notin s_o} Z^s_i - \gamma \sum_{r,r\notin r_o} X^r_i - \theta \sum_{c,c\notin c_o} Y^c_i - \kappa \sum_{r1,r2,n,\chi^n_{r_1,r_2}=0} A4^n_{r_1,r_2} - \mu \sum_{r1,r2,n,\chi^n_{c,r}=0} A3^n_{c,r} \tag{17}$$

TABLE II
DEFRAGMENTATION PRODUCTION SCENARIOS

Route	Capacity	Reconfigurations	Defrag Type
1	800G	3	1 SRLG
2	600G	15	1 SRLG
3	3T	30	2 SRLGs
4	600G	10	1 AD card
5	1T	15	3 AD cards

IV. RESULTS

The production network has several 100s of SRLGs. The tool was tuned to an aggregate of slices, computed as a factor of installed channel widths for scale. For instance, if we deploy (hypothetically) a mix of 50 GHz and 100 GHz channels, we could use 25 GHz as our minimum increment for ILP to scale. During the pandemic, several IP adjacencies were required to be augmented to prevent production risk due to the traffic surge, but were blocked due to lack of continuous and contiguous spectrum, and by the inability to build new fiber rails. Table II shows a few samples where capacities could be unblocked in the production network through defragmentation of selected entities. For example, in Route 3, all channels installed on 2 SRLGs became candidates, whereas in Route 5, all channels that traversed 3 AD cards became candidates. Entities (AD, SRLG) over a target utilization threshold (say, 60%) were chosen, and we gradually increased the number of defragmented entities if a ILP for fewer ones failed to admit the blocked channels. Capacities were unblocked with only remote reconfigurations permissible during the pandemic time - by remotely switching the assigned spectrum or changing path to different rail along the same SRLG path.

V. CONCLUSION

This tool is integrated with the production environment as a defragmentation service and we continue to defragment the optical network (with site visits, where necessary) to onboard blocked and emergency capacity expeditiously. The run times have been between minutes to an hour for most production use cases. As next steps, we are exploring ways to leverage this formulation for proactive defragmentation in order to drive higher spectrum utilization.

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