On the Benefits of Joint Optimization of Reconfigurable CDN-ISP Infrastructure

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Abstract—ISP networks have become a critical infrastructure in our society. Traffic in these networks is growing and is increasingly dominated by a small number of large CDNs connecting at multiple locations. Simultaneously, the networks are becoming more flexible, in terms of routing, CDN user mapping, and also regarding the IP topology: emerging optical technologies allow to flexibly reconfigure the network.

This paper studies the potential gains of these reconfiguration flexibilities. The idea is to make CDN-ISP infrastructure demand-aware, that is, to re-optimize it towards the changing end-user demands over time. We present an optimization framework and conduct an extensive evaluation using data from a large European ISP. We find that such a reconfigurable infrastructure has indeed a high potential: by leveraging spatial and diurnal traffic patterns, the efficiency of ISP networks and CDNs is improved significantly. Specifically, the required backbone capacity is reduced by 15% while reducing path lengths by 30%, on average and during the critical peak hour. Moreover, such infrastructures can leverage re-optimizations during specific events, like the COVID-19 pandemic, and under link failures. We optimistically assume a cooperative environment of ISPs and CDNs, and we conclude by discussing trends that foster the identified benefits in practice.

Index Terms—Optical networks, ISP, Hyper-giants, CDNs, Mixed Integer Programming, Network planning, Reconfiguration

I. INTRODUCTION

Communication networks in general and ISP networks in particular form a critical backbone of the digital society. Given the popularity of data-centric applications, related to health, science, social networking, business and entertainment, it is expected that the traffic carried by these networks will continue to grow explosively, especially to and from datacenters [1]. The COVID-19 pandemic has further highlighted the need for an efficient and reliable communication infrastructure, which is now also critical for, e.g., online teaching, virtual conferences and health services. As traffic demands continue to rise steeply, state-of-the-art approaches to design and operate networks may become expensive and inefficient.

In order to serve traffic workloads efficiently, over the last years, researchers alongside service providers have made a concerted effort to innovate at several layers of the networking stack. The proposals render networks more flexible and demand-aware and allow to exploit the specific spatio-temporal structure in the demand. For instance, ad-hoc traffic engineering in wide-area networks (WANs) has been replaced with software-defined centralized controllers (e.g., Google B4 [2] and Microsoft SWAN [3]), commodity hardware load-balancers have been replaced with software load-balancers [4], [5], and switch vendors’ management APIs have been replaced with in-house switch stacks [6], [7]. With each such technology investment, providers are improving the performance and cost-of-ownership of networks by adding reconfigurability to individual components.

The next frontier toward more adaptive networks is the physical (optical) layer: emerging optical technologies allow to reconfigure the network topology in a demand-aware manner [8], [9] within hours or even minutes [10]–[12], e.g., using WDM-based technologies, ROADMs, and elastic optical networks. This in principle allows to further improve the efficiency of networks: by providing “shortcuts” between more frequently communicating sites, the overall traffic may be reduced even in the short term, saving resources and improving latency [11], [13]–[15].

However, only little is known today about the potential benefits (e.g., related to performance, energy consumption, CapEx, QoS) and limitations of more adaptive optical networks, jointly optimizing along the different dimensions of flexibility, and hence also accounting for topological reconfigurability.

In this paper, we are particularly interested in the potential benefits of using adaptive and jointly optimized networks to
serve CDN traffic: the traffic of a small number of so-called hyper-giants \cite{16} constitutes the majority of the ISP’s workload today. For instance, the top-10 hyper-giants can make up to 75% of the total traffic \cite{1}. This traffic is also one of the main reasons for ISPs to upgrade their infrastructures \cite{16}. The study of CDN traffic is also interesting since, in addition to its enormous volume, hyper-giants increasingly interconnect with eyeball networks through multiple locations, which introduces an optimization opportunity to handle this traffic efficiently.

In summary, we consider the potential efficiency and performance benefits of reconfigurable combined CDN-ISP infrastructure. Fig. \cite{1} illustrates the scenario: the ISP operates a reconfigurable Optical Network (ON) to connect its customers to a hyper-giant peering at multiple locations. Since large CDNs connect at multiple peering points, in principle, operators can optimize the hyper-giants’ traffic steering on three fronts: on the optical network topology, on the IP layer, and in terms of peering point selection (i.e., mapping end-users to the “best” ingress point). Assuming a cooperative environment of CDNs and ISPs, we evaluate how CDN peering point selection can jointly be optimized with the ISP network and adapted towards changing end-user demands over time.

**A. Our Contributions**

This paper analyzes the benefits of exploiting the reconfiguration flexibilities available in modern network infrastructure, for an adaptive and demand-aware re-optimization along three fronts, routing, CDN user mapping, and the IP topology. Optimization of each of these layers or of combinations of two layers have already been evaluated in prior works. In contrast, we study to what extent and how a reconfigurable optical network topology can be combined with a clever request mapping to optimize hyper-giant traffic routing in an ISP network. We present an optimization framework which, given the peering locations (PoPs) of hyper-giants as well as the end-users’ demands, jointly optimizes and adapts the mapping from end-users to the hyper-giants’ PoPs, the IP layer topology and routing, as well as the routing in the optical domain.

We evaluate our approach empirically based on measurement data. We find that our approach can significantly lower the ISP’s network loads during the critical peak hour but also on average, and reduce the required backbone capacity by up to 15%. We also provide insights into the required amount and frequency of re-optimizations (the above major benefits are obtained using moderate hourly reconfigurations), the predictability of required optimization (optimizations repeat fairly well on a daily basis and can, hence, be planned ahead of time), as well as the benefits of adaptive reconfiguration during events such as the COVID-19 pandemic (2019-X) \cite{17} or under link failures.

Our analysis of the potential benefits of dynamic re-optimizations is optimistic in that it assumes a cooperative environment; hence, we conclude by discussing deployment scenarios to exploit these benefits in practice. **Reproducibility and research artifacts.** While we are not allowed to share the measured ISP traffic patterns due to privacy concerns, in order to facilitate followup work, we will make our framework implementation publicly available. We will also contribute all our evaluation results to the research community.

**B. Organization**

The remainder of this paper is organized as follows: \SII describes challenges that come from hyper-giant dominated workloads and elaborates on the opportunities in today’s increasingly flexible networks. \SIII introduces the optimization framework. The performance of our approach in comparison to existing approaches is evaluated using real data from a large European ISP in \SIV \SV elaborates trends that support deployment of our approach in CDNs’ and ISPs’ infrastructures. Finally, we provide a brief review of related works (§VI) and conclude our contribution (§VII).

**II. BACKGROUND AND MOTIVATION**

To understand the challenges and optimization opportunities for ISPs, let us revisit the typical architecture of today’s ISP networks in more details. To connect their user- or other networks-facing (edge) routers at different locations, ISPs operate optical networks (ONs) that are usually shared based on Dense Wavelength Division Multiplexing (DWDM). DWDM systems consist of reconfigurable optical add/drop multiplexers (ROADMs) that provide connectivity between two nodes in the optical topology, by switching/routing lightpaths through the fibers. IP routers connect to the ONs via the ROADM. For every lightpath that connects two IP routers, a transceiver/port must be available at both ends of the path. A single lightpath provides a fixed capacity. Multiple lightpaths can be aggregated to provide a single IP link with the accumulated capacity of the single lightpaths.

Combining multiple IP links, the ISP can build a topology where traffic that enters or leaves the network through the aggregation network towards end-users, or via peerings or internet exchanges towards other networks, is routed.

**A. The Challenge: Hyper-giant Traffic**

Given their size and the important role hyper-giants play today, the efficient delivery of their end-user traffic has become a main concern of ISPs \cite{18}. An efficient delivery, i.e., providing a good service while keeping network loads low, is also in the interest of the hyper-giants, which aim to offer a low latency and high QoE to their customers.

Today, hyper-giants and ISPs often leverage direct connections between their autonomous systems (so-called private network interconnects, short PNI) which gives them full control over the links \cite{19}. In fact, to inject traffic into the ISPs network closer to the end-users, ISPs and hyper-giants typically connect at multiple geographic locations \cite{19}, \cite{20}. This introduces steerability of the ingress point which distinguishes hyper-giant traffic from other traffic, henceforth called background traffic. Although background traffic can be much more volatile and exhibit more dense connectivity, the
large volume of hyper-giant traffic often dominates in ISP networks.

Reconfiguration of ISPs’ topology and routing to accommodate diurnal patterns of background traffic has been shown to be feasible [11]. The diversity of ingress points, however, introduces the challenge of how to map end-users to the “best” ingress point and adds a new dimension to the problem [16], [21], [22]. The volume and spatial-distribution of demands from end-users significantly vary over time, not only due to regular diurnal patterns, but also as a result of large events, e.g., [23]–[25] or the COVID-19 pandemic [26]. While a fixed user-to-ingress point mapping may work well at one point in time, it can lead to congested peerings or network paths at a different time. On the one hand, due to its sheer volume, a sub-optimal topology and routing for hyper-giants’ traffic results in large overheads for ISPs, e.g., in terms of resource efficiency. On the other hand, the deployed IP topology of the ISP affects shortest paths between end-users and the hyper-giants. Hence, end-user mappings, the ISP’s IP topology, and the routing interact with each other, which motivates a joint optimization approach accounting for reconfiguration.

B. Opportunity: Demand-Aware Re-Optimization

Re-optimizations accounting for the changing demand can be beneficial at different time scales. A first opportunity concerns diurnal traffic patterns in large eyeball networks. Typical traffic patterns show a large difference between the total traffic volume during the peak hour (typically in the evening) and the hour with the smallest amount of traffic (typically in the night). Our analysis of the traffic volumes arising at a large European ISP reveals that the difference can be as large as factor of 7. An interesting use case for more adaptive networks hence regards the joint re-optimization of CDN-user-to-ingress-point mapping and the ISP’s IP topology. Re-optimizing the topology frees up capacities on the fibers, enabling the ISP to offer additional, time-of-day-based services. One option is to temporarily sell bare lightpaths to customers that want to directly connect their sites during the low traffic hours (λ-service), e.g., for synchronization. Additional benefits may arise in terms of energy consumption: transceivers may be switched off, and potentially also IP nodes [27].

A second opportunity for potential savings for the ISP and better performance for end-users stems from joint re-optimization on larger scales, e.g., monthly. To accommodate growing demands, both hyper-giants and ISPs continuously invest into server, network, and peering infrastructure. Besides a simple upgrade of the capacity at already existing points of presence (PoP), this includes also interconnecting at new locations. While hyper-giants’ mapping systems usually try to leverage these new ingress points, joint re-optimization including topology and routing introduces also cost savings for the ISP, e.g., by using available transceivers and fibers more efficiently.

C. Enablers: Operational Flexibilities

The proposed joint reconfiguration is fostered by four trends arising in ISP networks that provide operational flexibility:

1. Flexible IP topology. The operation and deployment of lightpaths induces costs for the ISP (e.g., CAPEX for the required transceivers or energy costs for the operation of the lightpaths). Hence, ISPs typically aim at deploying as few lightpaths as possible while serving all demands, and accounting for additional requirements, e.g., related to resilience or business policies. Changing the IP topology on a long time-scale, e.g., for maintenance or to accommodate organic growth of traffic, is already common operation. Recent developments in optical switching and advances in Software-Defined Networks (SDN) in the optical domain render also short-term (re-)deployment of lightpaths feasible [28]. However, the time required for changing IP links is still in the order of minutes as multiple steps are necessary: First, the correct paths, including wavelengths, in the optical domain have to be set up. Whereas setting the configuration on a single ROADM is doable within a few seconds [12], setting an entire path can take several minutes [10], [11]. Afterwards, interfaces on the IP routers have to be set up and eventually, updated link characteristics are communicated to the routing entity, e.g., the Path Computation Element (PCE) [29]. Overall, this process can happen on the scale of minutes [11] and results in a first optimization opportunity: a programmable network controller can be used to reconfigure the IP topology throughout the day to optimize it for the changing demands.

2. Flexible traffic engineering. On top of the established IP topology, ISPs typically perform traffic engineering using IP or MPLS routing to avoid congestion in the backbone [30]. Recently, novel source-based routing approaches emerged in the context of Segment Routing (SR). Here, each node and adjacency is assigned a unique label (Segment ID). The edge routers push a stack of Segment IDs to forwarded packets which are then used to successively forward the packet [31]. Deployment of SR policies to the edge routers is often done using PCE [29]. This allows adaptable IP routing without propagating updates through the network and results in re-configuration times in the order of seconds [32]. In particular, when Adjacency Segment IDs are used to describe the path, re-convergence of the IGP due to IP topology changes is not necessary. Reachability information or shortest paths are not maintained on the routers in this case. The central controller configures Segment IDs for added or removed links and can update rules on the edge routers accordingly.

3. Flexible user mapping. Many hyper-giants employ clever schemes to map end-user requests to the desired ingress point/server, e.g., [33]–[36], often using DNS. The hyper-giant’s DNS system returns different IP addresses to end-users to route them via a specific peering and thereby, to optimize, e.g., their latency or the load of its servers. The benefits of flexible mappings that automatically adapt with the state of the network, have been shown to significantly reduce latency for end-users as well as backbone traffic load for ISPs, especially in CDN-ISP collaboration systems such as PaDIS [21] or FlowDirector [16].

Reconfiguration times depend not only on the agreed channel between hyper-giant and ISP, e.g., fully automated using ALTO [37], but also on the time until DNS changes are propagated to the end-users. Recent analyses show that this
can be in the order of minutes \cite{38}. This control over the ingress point hence describes our third enabler for short-term reconfigurability. Throughout this paper, we use the terms PoP assignment and user mapping interchangeably.

4. Centralized control for joint optimization. While the enablers discussed above are promising, the highest benefit can be obtained by joint optimization along all three interacting layers, as we elaborate in the evaluation. For example, changing the PoP assignment without sufficient capacity on the network path may lead to congestion. The SDN paradigm which is also emerging in ISP networks \cite{11}, is the fourth enabler: with its centralized control, this problem can be overcome.

III. JOINT OPTIMIZATION FRAMEWORK

In order to study the potential benefits of re-optimizing reconfigurable networks, we formulate a joint optimization framework. Given the hyper-giant and background traffic, our goal is to find assignments of end-users to hyper-giant peering locations, the routing on the IP layer, the capacities of the IP links, and their routing in the optical domain. The objective is to minimize the network capacity and account for re-configurations. This is subject to fulfilling all demands without violating capacities of peering, IP or optical (wavelengths) links. Our approach combines optimizations on single layers and jointly solves the following sub-problems: (1) assignment of end-user nodes to hyper-giants’ ingress PoPs, (2) design of the IP topology (connectivity & capacity), (3) selection of optical paths for the IP links, and (4) routing of hyper-giants’ and background demands in the IP topology. This modeling can leverage the flexibility of the three layers, e.g., demand can be routed via a dedicated IP link and optical path, or can use multi-hop IP routing to reduce resource fragmentation.

We start by describing the general joint optimization framework and then introduce specific optimization algorithms which come in different flavors, highlighting various aspects relevant in our evaluation.

A. Mathematical Model

Table I summarizes the sets and functions, Table II the constants, and Table III the decision variables.

**Sets.** The topology consists of two sets of nodes, IP nodes/ routers ($\mathcal{N}^{IP}$) and optical nodes ($\mathcal{N}^{Opt}$), which are collocated and connected via optical transceivers. Multiple IP nodes can be collocated with one optical node, e.g., one for peering with hyper-giants and another for end-user connectivity. Some of the IP nodes provide connectivity for end-users ($\mathcal{U}_h$) or hyper-giants ($\mathcal{P}_h$) but not for both, i.e., $\mathcal{U}_h \cap \mathcal{P}_h = \emptyset \ \forall h \in \mathcal{H}$, where $\mathcal{H}$ is the set of hyper-giants and $\mathcal{U}_h$ and $\mathcal{P}_h$ are hyper-giant-specific sets. The set of pre-calculated equal-cost candidate paths between IP nodes $a$ and $f$ in the optical domain is denoted by $P_{a,f}$.  

**Constants.** Hyper-giant demands are denoted as $d_{ah}$ and peering capacity between ISP and hyper-giants as $c^h_p$ in Gbps. The constant $d_{ab}^{bg}$ indicates the amount of background traffic between IP nodes $a, b$. Each IP router has a maximum number of ports $t_r$ which provide a capacity of $C$. The optical system restricts the number of lightpaths (wavelengths) on a fiber between $m$ and $n \in \mathcal{N}^{Opt}$ to $w_{mn}$.

**Variables.** The variable $\delta_{a,p,h}$ indicates if demand $u$ from hyper-giant $h$ traverses peering node $p \in \mathcal{P}_h$ to super sink $h$. $a_{ef}^{b}$ indicates if demand from $a$ to $f$ travels via IP link $e$, $f \in \mathcal{N}^{IP}$. $a_{ab,ef}^{bg}$ indicates if background demand from $a$ to $b$ traverses IP link $e$, $f \in \mathcal{N}^{IP}$. $y_{ef,p}$ indicates if IP link $p \in P_{e,f}$ and thereby the capacity $(\times C)$ of the trunk.

Table I: Sets and Functions

<table>
<thead>
<tr>
<th>(\mathcal{N}^{IP})</th>
<th>IP nodes (routers): At every PoP, there is at least one IP router.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mathcal{N}^{Opt})</td>
<td>Optical nodes (ROADM): At every PoP, there is one optical node which is connected to the IP router at that PoP.</td>
</tr>
<tr>
<td>(\mathcal{H})</td>
<td>Hyper-giants (HG): Entities that are responsible for the majority of the traffic.</td>
</tr>
<tr>
<td>(\mathcal{U}_h)</td>
<td>End-user demands of HG $h$.</td>
</tr>
<tr>
<td>(\mathcal{P}_h)</td>
<td>HGs’ Peering locations: Routers where the ISP connects via PNIs to the HGs.</td>
</tr>
<tr>
<td>(P_{e,f})</td>
<td>Equal-cost paths between $e, f \in \mathcal{N}^{IP}$ over the Optical Transport Network.</td>
</tr>
<tr>
<td>(i(u))</td>
<td>(\bigcup_{h \in \mathcal{H}} \mathcal{U}_h \rightarrow \mathcal{N}^{IP}) IP node where demand $u$ destines to.</td>
</tr>
<tr>
<td>(Q)</td>
<td>A large number.</td>
</tr>
</tbody>
</table>

Table II: Constants

| \(d_{ah}\) | HG Demand volume: Aggregated demand entering at router $i(u)$ towards the HGs in Gbps. Note that we allow multiple demands to the same HG from one $e \in \mathcal{N}^{IP}$. Different to others, e.g., \cite{39}, we do not differentiate between up- and down-link demands (request and reply). |
| \(c^h_p\) | Peering Capacity: Bandwidth of the PNI with $h \in \mathcal{P}_h$ in Gbps. |
| \(d_{ab}^{bg}\) | Background demand: Demand between IP routers $a, b \in \mathcal{N}^{IP}$ in Gbps. |
| \(t_r\) | Number of transceivers at IP router $e \in \mathcal{N}^{IP}$. |
| \(C\) | Capacity of a lightpath in Gbps. |
| \(w_{mn}\) | Fiber capacity: number of lightpaths that can be allocated on fiber between $m, n \in \mathcal{N}^{Opt}$, in $[0, 1]$ Maximum allowed IP link utilization. |
| \(l_p\) | Length of path $p \in P_{e,f}$. |
| \(\rho\) | Fraction of allowed reconfigurations. |

Table III: Variables

| \(\delta_{a,p,h}\) | $= 1$ if demand $u$ to $h$ flows over peering node $p \in \mathcal{P}_h$ to super sink $h$. |
| \(a_{ef}^{b}\) | $= 1$ if demand from $a$ to $f$ flows over IP link $e$, $f \in \mathcal{N}^{IP}$. |
| \(a_{ab,ef}^{bg}\) | $= 1$ if demand from $a$ to $b$ flows over IP link $e$, $f \in \mathcal{N}^{IP}$. |
| \(y_{ef,p}\) | IP trunk capacity: $y_{ef,p} \in \mathbb{N}$ denotes the number of lightpaths between $e, f \in \mathcal{N}^{IP}$ using path $p \in P_{e,f}$ and thereby the capacity $(\times C)$ of the trunk. |
| \(r_{ef}\) | $= 1$ if capacity of IP link changed in comparison to value from previous instance $(y_{ef,p}^t)$. |
which address flow conservation, demand fulfillment and capacity limitations on three layers. Besides, limitations in the number of transceivers per IP node as well as bi-directionality of IP links and maximum link utilization are considered:

\[
\sum_{p \in \mathcal{P}_h} \delta_{u, ph} = 1 \quad \forall h \in \mathcal{H}, \ u \in \mathcal{U}_h \quad \text{(1)}
\]

\[
\sum_{f \in \mathcal{N}^p: f \neq p} o^R_{u, pf} = \delta_{u, ph} \quad \forall p \in \mathcal{P}_h, \ u \in \mathcal{U}_h, \ h \in \mathcal{H} \quad \text{(2)}
\]

\[
\sum_{f \in \mathcal{N}^p: f \neq a} o^h_{u, af} - h_{u, af} = 0 \quad \forall e \in \mathcal{N}^p: e \neq u \wedge e \notin \mathcal{P}_h, \ u \in \mathcal{U}_h, \ h \in \mathcal{H} \quad \text{(3)}
\]

\[
\sum_{u \in \mathcal{U}_h} d_{uh} \leq c^p_p = \delta_{u, ph} \quad \forall p \in \mathcal{P}_h, \ h \in \mathcal{H} \quad \text{(5)}
\]

Eqs. (1) through (4) describe the flow conservation for hyper-giant demands and thereby address sub-problems (1) and (4). Specifically, Eq. (1) sets the fractions of routed demand per hyper-giant-end-user pair to be equal to 1, i.e., all demands from hyper-giants (super-source) to end-users must be served. At all IP nodes where no end-users are connected, ingressing and egressing flow of a demand must be equal (Eq. (2) and Eq. (3)). The destination node of a demand, it must sink (Eq. (4)). Eq. (5) limits capacity of peering nodes, i.e., the edges from the hyper-giant.

\[
\sum_{f \in \mathcal{N}^p: f \neq a} o^R_{ab, af} = 1 \quad \forall a, b \in \mathcal{N}^p \quad \text{(6)}
\]

\[
\sum_{f \in \mathcal{N}^p: f \neq e} o^R_{ab, ef} - o^R_{ab, ef} = 0 \quad \forall a, b, e \in \mathcal{N}^p, e \neq a, e \neq b \quad \text{(7)}
\]

\[
\sum_{e \in \mathcal{E}_{ab}} o^R_{ab, eb} = -1 \quad \forall a, b \in \mathcal{N}^p \quad \text{(8)}
\]

Eqs. (6) through (8) are similar flow conservation constraints for background demands. They ensure that flows originate at the sources, terminate at the sinks and that in- and egressing volumes at intermediate nodes are the same.

\[
\sum_{h \in \mathcal{H} \cup \mathcal{U}_h} o^h_{u, ef} \cdot d_{uh} + \sum_{a, b \in \mathcal{N}^p} o^R_{ab, ef} \cdot d^R_{ab} \quad \text{(9)}
\]

\[
\leq C \cdot u_{max} \cdot \sum_{e \in \mathcal{E}_{ef}} y_{ef, p} \quad \forall e, f \in \mathcal{N}^p: e \neq f \quad \text{(10)}
\]

\[
y_{ef, p} = y_{f, e, p} \quad \forall e, f \in \mathcal{N}^p, \ p \in \mathcal{P}_{e, f} \quad \text{(11)}
\]

\[
\sum_{f \in \mathcal{N}^p} y_{ef, p} \leq 2 \cdot t_e \quad \forall e \in \mathcal{N}^p \quad \text{(12)}
\]

Eq. (9) ensures that the demand flowing via IP link \(e, f\) does not exceed the given maximum IP link utilization and thereby, addresses sub-problem (2). It considers only the the edges adjacent to \(e\). Eqs. (10) and (11) account for bi-directionality of IP links, a lightpath is required for each direction, and bound the number of available transceivers per router (degree bound) respectively.

\[
\sum_{e, f \in \mathcal{N}^p} \sum_{p \in \mathcal{P}_{e, f}} y_{ef, p} \leq w_{mn} \quad \forall m, n \in \mathcal{N}^{opt} \quad \text{(12)}
\]

Eq. (12) limits the number of lightpaths that can be routed over a fiber and thereby addresses sub-problem (3). Note that the set of relevant paths, i.e., paths which use the optical edge \(m, n\), can be pre-calculated.

\[
\sum_{e, f \in \mathcal{N}^p} \sum_{p \in \mathcal{P}_{e, f}} y_{ef, p} \leq \sum_{e, f \in \mathcal{N}^p} y_{ef, p} \quad \text{(13)}
\]

Eq. (13) provides a lower bound for the objective to reduce the run-time of the solver. In the ideal case, i.e., with minimum resource fragmentation, an IP node with end-user demands is connected via a single link to a peering node which is able to serve all the demands from this IP node. The necessary capacity of such a link is determined by summing the demands of all hyper-giants at that IP node and accounting for the maximum IP link utilization. The summed capacities of all links provide a lower bound for the total deployed capacity which is subject to fragmentation of link capacities and requires connectivity to several peerings of the hyper-giants.

\[
\sum_{p \in \mathcal{P}_{e, f}} y_{ef, p} - y_{ef, p}^{t-1} \leq r_{ef} \cdot Q \quad \forall e, f \in \mathcal{N}^p \quad \text{(14)}
\]

\[
y_{ef, p} - \sum_{p \in \mathcal{P}_{e, f}} y_{ef, p} \leq r_{ef} \cdot Q \quad \forall e, f \in \mathcal{N}^p \quad \text{(15)}
\]

\[
\sum_{e, f \in \mathcal{N}^p} r_{ef} \leq \rho \cdot |\mathcal{N}^p|^2 \quad \text{(16)}
\]

Eqs. (14)-(16) limit the number of reconfigurations in terms of increased or decreased capacity per IP link. Eq. (14) pushes \(r_{ef}\) up if the capacity increases in comparison to the capacity of the previous timestamp \(y_{ef, p}^{t-1}\). Eq. (15) addresses capacity decreases in a similar way. Eq. (16) limits the total reconfigurations over all IP links.

**Objective.** The main objective is to minimize the total deployed capacity which is given by the sum of capacities of all IP links:

\[
\min \sum_{e, f \in \mathcal{N}^p} \sum_{p \in \mathcal{P}_{e, f}} y_{ef, p}. \quad \text{(17)}
\]

This objective function serves as a proxy for OPEX (e.g., power consumption) and CAPEX (e.g., transceivers to buy in long term). Additionally, it hints at the utilization of the optical topology that might in turn be used to operate \(\lambda\)-service during low traffic hours.

**B. Greedy Ingress PoP Assignment**

The MIP solves the sub-problems (1) - (4) simultaneously. In order to quantify the benefits of this joint optimization, we separate problem (1) and solve it with a greedy algorithm. The resulting PoP assignment is used as input for the MIP, which
solves sub-problems (2) - (4). We limit our evaluation to the separation of sub-problem (1) since it splits along the boundary between CDN and ISP. Moreover, this split first makes the demand more specific by fixing the source-destination-pairs for the hyper-giant demands and then optimizes the ISP’s network. Other splits, e.g., optimizing the IP topology first, would counteract the demand-aware nature of our approach.

Algorithm [1] shows a greedy assignment procedure for a single hyper-giant based on the shortest path length between end-users and peering PoPs in the optical topology. The algorithm starts by sorting the end-users PoPs of this hyper-giant by their demand volumes in descending order (l. 1). For every end-user node \( u \), it iterates over the peering nodes of this hyper-giant sorted by their distance to the end-user node in question (l. 4). If the peering node \( p \) has enough remaining capacity and the number of transceivers suffices to accommodate the total assigned demand, \( u \) is assigned to \( p \), i.e., \( \delta_{u,p,h} = 1 \) (l. 5). Otherwise, the next peering node is evaluated. The algorithm fails if not all demands can be assigned. The procedure is repeated for all hyper-giants.

Algorithm 1 Greedy Ingress PoP Assignment for a single hyper-giant \( h \).

| Input: | \( c^h_p, d_{uh} \) \( \forall u \in \mathcal{U}_h, p \in \mathcal{P}_h \) |
| Output: | \( \delta_{u,p,h} \) |
| 1: | sort \( u \in \mathcal{U}_h \) by their demand volume \( d_{uh} \) |
| 2: | \( \text{allocDemand}[p] \leftarrow 0 \) \( \forall p \in \mathcal{P}_h \) |
| 3: | for \( u \in \mathcal{U}_h \) do |
| 4: | sort \( p \in \mathcal{P}_h \) by distance to \( u \) |
| 5: | for \( p \in \mathcal{P}_h \) do |
| 6: | if \( \frac{\text{allocDemand}[p]}{c} + d_{uh} \leq \frac{c^h_p}{2} \) then |
| 7: | \( \delta_{u,p,h} \leftarrow 1 \) |
| 8: | \( \text{allocDemand}[p] \leftarrow \text{allocDemand}[p] + d_{uh} \) |
| 9: | else |
| 10: | \( \delta_{u,p,h} \leftarrow 0 \) |
| 11: | end if |
| 12: | end for |
| 13: | end for |

C. Optimization Flavors

Combining different flexibilities for sub-problems (1)-(4) results in four different optimization flavors which we later compare in the evaluation. Note that for each flavor, we adapt the MIP accordingly, i.e., fix variables:

Baseline uses ingress PoP assignment, IP connectivity and routing from the real data, without performing any additional optimization; it determines the capacity of the IP links to serve all demands. Note that the topology might include some requirements for particular links due to business policies.

ISP-only uses the ingress PoP assignment extracted from the real data and optimizes the IP topology and routing with fixed PoP assignment. This ISP-only approach reflects a scenario where the CDNs are not following the cooperation.

2-step optimizes the PoP assignments using Algorithm [1] and uses the optimal approach with the PoP assignment for IP topology and the routing. Thus, CDNs are cooperative but optimization is done separately in two steps.

Joint jointly optimizes all three layers, PoP assignment, IP topology and routing, using the exact approach from §III-A.

IV. Evaluation

This section empirically answers our fundamental question: can we leverage reconfigurable topologies to improve ISP traffic steering and resource management? To do so, we first outline the attributes of the optical infrastructure, the traffic and the optimization approaches (§IV-A). We then assess to what extent we benefit from reconfigurations – if at all – and what frequencies of reconfigurations are needed (§IV-B). We complement this analysis by evaluating the benefit of jointly optimizing along all available dimensions (§IV-C) and a dissection of the costs in terms of observed reconfigurations concerning the topology’s recurrence and stability (§IV-D).

We conclude by considering how our results generalize to specific scenarios. To this end, we investigate our approach in the context of the traffic workload during the COVID-19 pandemic, a scenario with link failures, and a scenario with randomized demands (§IV-E and §IV-F).

A. Settings

The evaluation relies on real topology and traffic data collected from a large ISP with > 15 million fixed line and > 30 million mobile users. We limit data to the network in the ISP’s home country which consists of more than 10 Points-of-Presence (PoPs) and serves more than 50 PB of daily traffic.

Optical infrastructure. The optical network (ON) consists of \( \mathcal{V} \) nodes and \( \mathcal{E} \) edges. Each edge has an optical capacity of \( w_{mn} = W = 100 \) lightpaths (wavelengths). Connectivity between access routers of the end-users and core routers is fixed, and optical reconfigurability is limited to the core layer. Hence, we aggregate the access routers into the corresponding core routers. Thereby, we reduce the original set of IP routers (> 1k) to the core routers and the largest peering routers resulting in < 30 IP routers in total. While this reduction is rooted in the capabilities of the network, additionally, it also makes the optimization more tractable. At some PoPs multiple IP nodes are connected to the optical node. Every router can support \( t_r = 100 \) transceivers. A single lightpath has a capacity of \( C = 100 \text{ Gbps} \). Moreover, the maximum IP link utilization is limited to \( u_{max} = 50\% \) to accommodate traffic in cases of failures. The hyper-giants’ peering locations and capacities are also extracted from the ISP’s data.

Traffic (Demands). To create traffic demands, we first collect real traffic data from the FlowDirector system [16]. FlowDirector gathers > 45 billion NetFlow records per day at the border routers of the ISP. Then, we differentiate two types of demand samples: HT and BT.

For HT, a demand sample contains only flows belonging to the top-10 hyper-giants in the ISP network. It makes > 75% of the total traffic in the ISP’s backbone network. In order to create the input for our model, the flows are aggregated. For HT, the aggregation is done based on the hyper-giant, the origin peering router, and destination core router of the
flows. For background traffic (BT), we select the traffic that does not belong to any of the top-10 hyper-giants. Then, we aggregate flows based on their origin and destination core routers. Further, as described later (§IV-B), the demands are split and aggregated according to the time windows, e.g., two hours or one day. Therefore, the average rate per demand over one hour is calculated. Finally, the maximum value of the time windows is used as demand value in the optimization. We use either HT-only or AllTraffic, the combination of HT and BT, as input to the optimization.

Optimization approaches. The main performance objective is the deployed capacity in the IP topology which serves as a proxy for OPEX (e.g., power consumption) and CAPEX (e.g., transceivers to buy). The evaluation examines the optimization approaches from §III-C and a theoretical baseline (Theo. min.). This baseline calculates the deployed capacity for the case where all end-user nodes are directly connected to only one peering node (CDN PoP), building a star topology. Such a star topology requires that there are PoPs with sufficient capacity where all hyper-giants peer with the ISP. An assumption that does not generally hold as the set of peering locations usually differs among the hyper-giants [16]. Moreover, Theo. min. ignores capacity limits of the fibers and number of transceivers per router.

If not stated otherwise, each optimization determines all components of the solution (PoP assignment, IP topology). We use the Python API of IBM ILOG CPLEX 12.9 [40] to implement the MIPs. The solver time limit is set to 1 hour.

B. Reconfiguration Intervals

1) Monthly-based reconfigurations: According to a previous study, the collaboration between CDNs and ISPs is carried out on a daily to monthly basis [16]. Hence, we believe that investigating reconfigurations on a monthly basis is a good starting point. In this case, re-optimization is performed once per month on maximum values of the weekly peak-hour demands of that month. We investigate the traffic from April 2018 to April 2019 and focus on HT-only due to space restrictions.

Fig. 2 shows the total capacity normalized to the value of Joint at March 2018. The gray vertical lines indicate dates when the peering of at least one of the hyper-giants changed, i.e., peering capacity increased/decreased or its location changed. Here, we might see whether re-optimization benefits both hyper-giants and ISPs.

Reconfiguration leads to capacity savings. For all algorithms, the trend of the total capacity increases over time. Baseline performs significantly worse (≈ 35%) on average than all other algorithms. The benefit of ISP-only
comes from changing IP link capacities more aggressively and adapting the IP routing in contrast to Baseline. Going a step further and also including CDN user mapping into the optimization, Joint saves up to 15% in comparison to ISP-only. Doing a greedy mapping here (2-step) still saves 5–10% in comparison to ISP-only. Overall, there is no clear trend of benefiting from peering changes for all approaches. To summarize, introducing monthly reconfigurations leads to substantial savings in infrastructure upgrades. However, the question remains whether such optimization can really sustain all traffic changes within a month: for instance, events can lead to severe traffic changes at specific locations, which might be obscured by the aggregation with the global maximum. Hence, we look into this by considering the traffic demands of a week.

2) Weekly-based and daily-based reconfigurations: We divide a week into four hour long time windows and use the maximum demand hour of each window as input. Here, we again assume to know the peak hour per day/week in advance and run three optimizations: Joint, 2-step, ISP-only. We want to answer the question whether the peak hour’s topology sustains all traffic patterns of this week while keeping the maximum IP link utilization constraint. Fig. 5 visualizes the fraction of time windows sustained by the peak traffic hour solutions.

Coarse reconfiguration intervals do not sustain traffic. The result, however, is negative: for all three week-peak-hour-based solutions, the fractions are < 100%, i.e., there is at least one point in time when the solution cannot satisfy the end-user demands. Similarly, the results for daily re-optimizations are shown. The result is again negative. There are several days of the week for which daily re-optimization is not sufficient. This demonstrates the need for reconfigurations on smaller time-scales.

3) Hourly-based reconfigurations: Fig. 4 shows the total deployed capacity throughout a day. Optimization is performed periodically every two hours based on the traffic maximum of the considered time-period. The grey area contrasts the total traffic volume. The lines and markers indicate the values of the best integer solutions found within the time-limit of the solver. Values are normalized to the maximum values from the AllTraffic case, i.e., maximum value of Baseline for capacity values and maximum value of traffic volume for total traffic.

Intra-day reconfigurations save up 44% of capacity over time. As before, all three algorithms save consistently more than 30% of capacity in comparison to Baseline. Moreover, they have a consistent order throughout the day: Joint performs best with an average gap of 3% to Theo. min., followed by 2-step and ISP-only with gaps of 11% and 25%. Thus, jointly optimizing ingress PoPs routing and topology can save non-negligible fractions of capacity.

In addition to the savings compared to the Baseline, reconfiguration on a bi-hourly-bases also opens the possibility to exploit the diurnal demand patterns: The ratio between peak hour (around 20:00) and the deepest valley (around 02:00) is ≈ 7 for both traffic cases. This variance is also reflected in the deployed capacity for all algorithms. Re-optimizing the network saves 44% of the summed capacity over the day. This directly translates to reduced OPEX, e.g. by energy savings, or freed fiber capacity that can be re-used for other services. Hence, there is a need for reconfiguration on an hourly-basis in order to efficiently use the capacity.

C. Need for Joint Optimization and Reconfigurations

In this section, we answer the question how joint re-optimization of the IP-topology and PoP assignment can serve ISPs and hyper-giants. Further, we provide insights into the efforts in terms of reconfigurations. We consider both HT-only and AllTraffic, i.e., we always highlight the differences between both traffic types.

1) The benefits of the ISP and the hyper-giants: Whereas the previous section showed that we can generally save capacity when considering hyper-giant traffic, this section takes a deeper look into the impact also of the BT. BT accounts for ≈ 25% of traffic volume (Fig. 4 vs. Fig. 5). While Baseline does not experience a significant rise in capacity, the other approaches account for this increase in traffic. The differences diminish: Joint still achieves the best performance, but 2-step and ISP-only come closer. Nevertheless, re-optimization still exhibits 15% (in contrast to 30% for HT-only) better performance than Baseline—reconfigurations can still lead to significant savings for ISPs.

We now deepen the analysis of the differences among the optimization flavors. For this, we look at the attributes of the solutions, i.e., their link capacities, the average path lengths, and the average number of IP hops.
Joint optimization creates smaller topologies. Fig. 6 compares the number of IP links and the distribution of their capacities for all algorithms with HT-only and AllTraffic; here, we take the sample at 18:00. For HT-only, significant differences between the algorithms are visible: 2-step deploys the smallest number of links followed by Joint and ISP-only. But it has significantly larger link sizes (the maximum capacity is almost twice as that of ISP-only). Moreover, ISP-only has the largest number of very small links as indicated by the shape of the violin. This is inefficient from the capacity point of view as it results in large excess capacities but increases connectivity. Joint is between these two.

For AllTraffic, the differences in numbers reduce, as for all algorithms the number of links significantly increases. However, the medians of the capacity distributions (red cross) drop for all algorithms which means that the added links have mainly small capacities to add the necessary connectivity for BT. The reduced number of links for Joint results in shorter paths for HT as described in the following.

Joint optimization decreases mean path length. One primary goal of hyper-giants is an efficient delivery of their traffic towards end users. This does not only manifest in high throughput, but also in small latency values. The average path length measured either in IP hops or real distance (arbitrary unit) are two ways to assess this aspect: for instance, the shorter the paths, the lower the expected latency.

Fig. 7d contrasts the mean path lengths for the AllTraffic scenario. When comparing the average path length of the HT and the BT, we observe that HT is consistently routed via shorter paths (average lengths of 0.3) than BT (average lengths of 0.45). The algorithms themselves do not clearly impact the average path lengths: for instance, the shorter the paths, the lower the expected latency.

In contrast, when looking at the average number of IP hops (Fig. 7b), Joint shows a superior solution: it always has the least amount of average IP hops for the HT which reduces the total required capacity in the network (bandwidth tax). Here, ISP-only suffers from the PoP assignment strategy: their average path lengths are \( \approx 50\% \) higher — a clear benefit of the joint optimization. As elaborated later, ISP-only has a very diverse PoP assignment which results in longer path to reduce the deployed capacity. On the other hand, Joint is able to determine such a PoP assignment that most traffic is routed via direct links. For BT, the differences among the algorithms are less strong.

In order to understand the solutions (i.e., how the "designed" topologies look like), we compare the approaches with respect to the used CDN PoPs and the IP node degrees. For the used PoPs, we look at each end user node and determine the number of PoPs this end user node addresses. For the degree of the IP nodes, we determine the number of links to other IP nodes. Aggregated end-user mappings reduce IP node degrees by 10%. Fig. 8a shows boxplots of the number of peering locations (CDN PoPs) that are used by the end-user nodes for the peak (20:00) and valley (02:00) times of the traffic. ISP-only uses the mappings from the collected data and shows that most end-user PoPs have hyper-giant demands routed via almost all CDN PoPs, i.e., demands are less aggregated. For 2-step and Joint, the fractions of used PoPs are smaller and vary throughout the day. The rational behind this is that both algorithms try to group the demands and route them via the same PoP and path in the topology to reduce fragmentation of IP capacity. As the size of the demands increases towards the peak hour and peering capacities are limited, mappings have to be adapted, become more distributed, and more PoPs are used during the peak hour. Fig. 8b illustrates that this behavior leads to reduced nodal degrees of the end-user nodes. Recalling the ideal situation, where all traffic of the end-user node is routed via a single link, this is the desired behavior and the potential that is exploited by the joint optimization. For AllTraffic, the differences in node degree are smaller as also observed for the total deployed capacity (cf. Fig. 5).

2) Are there any drawbacks for hyper-giants? The optimization in this work focuses on cost reductions for ISPs. Although this leads to shorter distances between hyper-giants and their end users, this might affect the utilization of the resource provisioning of hyper-giants. Hence, we look at the traffic share of the hyper-giants’ PoPs, a potential indicator for the PoP utilization. We believe that hyper-giants rather prefer evenly and constantly utilized peerings (better load distribution and less changes over the day).

Utilization of peerings is unbalanced. Fig. 8c shows the allocated traffic share over the peering locations of the hyper-
giants. For ISP-only, load distribution values are similar for both HT-only and AllTraffic. This is an expected behavior, as the hyper-giant demands do not change for both optimization scenarios – but it proves the operation of the optimization approaches. Similar observations hold for 2-step. However, the overall traffic share is lower for the majority of PoPs. In order to sustain all demands, 2-step uses a PoP with a high traffic share, as shown by the outlier above a value of 0.3 (hatched box). Baseline is left out as it has the same results as ISP-only.

In contrast to ISP-only and 2-step, Joint shows changes in distribution and variability during the day. Values range from 0.1 to 0.5. As a consequence, hyper-giants might have to adapt their peering capacities, and potentially also their routing towards peering points, over the day more frequently – a potential trade-off for hyper-giants between operational efforts and lower latency values.

D. Reconfigurations: Analyzing Topological Impact

So far, our conclusion is positive: joint reconfigurations help to reduce needed capacity for ISPs and shorten the path length from end-users to hyper-giants. On the other side, operators have been (and still are) reluctant to use frequent, short-term reconfigurations in their network. Accordingly, in this section, we study (1) the impact of the total number of reconfigurations needed and (2) which type of reconfigurations drive the capacity gain. Based on such insights, operators can better trade off the costs in terms of reconfigurations and capacity gains according to their preferences.

1) Trade-off between reconfigurations and capacity deployment: As a first simple solution, we study the impact of longer reconfiguration periods on the total capacity; the different periods are 1, 2, 4 and 8 hours. As in §IV-B, we optimize for the peak demands of the time windows.

Large optimization periods reduce reconfigurations. Fig. 9 shows a Pareto plot between the normalized number of reconfigurations and the transceiver (TX) hours. TX hours represent the integral of the deployed capacity over time, normalized by Theo. min. As expected, longer periods reduce the amount of reconfigurations but they increase the spent TX hours. Among the algorithms, ISP-only performs worst in both dimensions. 2-step results in less reconfigurations compared to Joint at the cost of more TX hours which indicates one way to trade-off both objectives. The savings in reconfigurations reduce with increasing periods.

Considering Joint, we note significant savings ($\approx 45\%$) in reconfigurations when re-optimizing every 2 hours instead of 1 hour, while the TX hours increase only by $\approx 10\%$. For 8 hours, Joint has the least number of reconfigurations but also a significantly higher capacity (22%). This describes the landscape where operators can trade-off the TX hours savings against reconfigurations.

Consequently, we add a limiting reconfiguration constraint (cf. Eq. (16)) that makes the Joint approach a credible alternative for 2-step. The figure shows that optimizing every 2 hours and limiting the number of reconfigurations to 15 % can provide better results in terms of reconfigurations and TX hours than 2-step. Our proposed model does not only demonstrate the benefit of joint optimization of IP topology, routing, and PoP assignment, but also provides flexibility to adjust results based on, e.g., provider policies.

2) Impact of different reconfiguration types: Fig. 10 presents a breakdown of the reconfigurations into their types: IP links added, IP links removed, IP links with capacity increased, and IP links with capacity decreased.

Adjacency changes impact only small share of the traffic. Fig. 10a shows the normalized number of reconfigurations for all types. While $\approx 50\%$ of the reconfigurations for Joint and ISP-only are adjacency changes, the share is smaller for 2-step. Also Joint in combination with the reconfiguration limit mainly impacts link sizes. Here, the algorithm avoids changes to the adjacency matrix of the IP topology and adaptations are mostly facilitated by changes in capacities. Note, however, that capacity savings cannot be achieved without any link adaption. Assessing the size of the modified links, Fig. 10b illustrates the link capacities before the change (and after the change for additions). While there is no clear pattern among the algorithms for scaling links up or down, additions and removals are restricted to very small links for ISP-only, 2-step, and Joint with limited reconfigurations. This suggests, that only minor fractions of the traffic are affected by these changes and hints towards a stable topology structure.

End-user re-mappings foster capacity savings. Fig. 10c visualizes the changes in the PoP assignment and in the IP routing when the CDN PoP for the demand stays the same. The observed behavior in §IV-C1 results in high numbers of end-user mapping changes and according routing changes for the demands for Joint without (**) and with limit (15%) on the reconfigurations which represent another factor to trade-off for the reduced capacity. 2-step and ISP-only show more static mappings but still high numbers of changes in the routing of the demands. This demonstrates how reconfigurations of the CDN user mapping foster the capacity savings.

3) Stability of topology: Motivated by the observation that mainly small capacity links are removed and added to the topology (cf. Fig. 10b), we ask to what extend there is a persistent structure in the topologies.

Large fraction of traffic is routed via persistent links. Fig. 11 shows fractions of links (Fig. 11a) and carried traffic...
Figure 10: Details on reconfigurations by type, algorithm and affected entities for HT-only. Joint which deploys least capacity in the network, requires more and more evolved types of reconfigurations.

(Fig. 11b) for persistent parts of the topology, i.e., for links that exist throughout multiple optimization periods. The figures evaluate two time windows for persistence: per day and per week. For 2-step and ISP-only, the fraction of adjacencies that exists over the whole day is consistently > 10% and carries between 70 – 90% of traffic. For Joint, the persistence is less strong on a day-by-day basis (5–10% of the links) which aligns with the observations of reconfigurations of larger links. Also the fraction of carried traffic over this stable topologies is smaller but with 40% still significant. Considering the span of a week, for Joint, less than 5% of the links exist all the time. For 2-step and ISP-only, the fractions are still > 10% and the links carry > 60% of the traffic. These observations underline that most reconfigurations affect only small fractions of the traffic and that significant parts of the traffic are routed via stable parts of the topology that are only scaled up and down. Moreover, setting a stable topology on a daily basis and temporarily adding small links upon short term spikes, allows to maintain higher operational confidence while gaining from reconfigurability.

E. Special Event COVID-19 and Failures

We evaluate the benefits of our approach in situations with increased and changed traffic patterns. As a case study, we use data collected during the recently active COVID-19 pandemic. The samples are aggregated from 4 hour windows on three different days. BEFORE is a day in the week just before the major lock-down in the country of the ISP. AFTER 1 and AFTER 2 are the same weekday in the two subsequent weeks.

Fig. 12a shows the deployed capacity during peak hour for the case of unlimited reconfigurations. For all algorithms, the deployed capacity increases for AFTER 1 and AFTER 2 in comparison to BEFORE by ≈ 13% and ≈ 4% respectively. This is in line with the increase in traffic volume observed [25], [41], [42]. The decrease of deployed capacity and traffic volume for AFTER 2 aligns with the decrease of video streaming quality by two hyper-giants [43]. The already observed behaviors of the algorithms from sections before are not affected significantly by the traffic increase with Joint being ≈ 10% better than ISP-only and ≈ 2% better than 2-step.

Events impact reconfiguration behavior. Fig. 12b contrasts the changes in capacity between AFTER 1 and BEFORE for several transitions throughout the day. It shows the differences in summed capacity of all links added or with increased capacity and all links removed or with decreased capacity. For all algorithms, AFTER 1 has higher capacity increase from 04:00 to 08:00 compared to BEFORE (difference > 0), while the capacity added in the transition from 08:00 to 12:00 is lower. Only for Joint, we also observe higher differences in the amount of removed capacity which indicates more changes in connectivity. Thereby, Joint can use the ISP’s optical infrastructure and CDN peerings more efficiently.

Joint IP routing and user mapping restoration increases robustness upon IP link failures. Although our approach does not directly optimize the network for resilience, we evaluate the ability to restore from single failures out of the 25 largest IP links of the topology. Such a scenario reflects failures of transceivers. To evaluate the worst case scenario, we assume that 100% of the link capacity becomes unavailable. To start with, we focus on two restoration possibilities: IP routing and CDN PoP assignment and keep the IP topology
fixed. Note, that we do not optimize for resilience, hence the following analysis provides only an outlook.

Fig. [13] compares the ratios of successful restorations of the three algorithms against the allowed link utilization. While Joint shows increasing restoration success with more relaxed link utilization and eventually can restore 80%, 2-step and ISP-only saturate quickly around only 50%. The distribution of the IP link capacities (Fig. [6]) reveals that ISP-only deploys more links but the single links’ capacity is smaller. This in turn leaves only little headroom to allocate traffic in case of re-routing. On the other hand, 2-step deploys few large links, which carry high traffic volumes. Failures of those IP links require high excess capacity for restoration, making it less flexible. We acknowledge that not all failures can be restored but leave consideration for future work.

F. Randomized Demand Patterns

Finally, we assess the generalization of our results to randomized demand patterns. As described in §IV-A, the data has a specific structure, and hence, it is challenging to generate randomized demands that are feasible. For instance, given the peering capacities of the hyper-giants, uniform sampling of demands can lead to situations where demands exceed the available capacity of the peering, or where a feasible routing cannot be found. Therefore, to avoid infeasible problem instances, we scramble the existing input data along the spatial dimension. That is, we shuffle the assignment of IP end-user nodes and peering nodes to the optical nodes. Thereby, the relations between peering capacities and demand sizes are preserved.

Fig. [14] shows the cumulative distribution functions of the relative differences between the algorithms. It uses the input data from Fig. [4] and randomizes it with 30 seeds – 360 samples in total. Joint ("ISP-o.-J") and 2-step ("ISP-o.-2-step") both perform better than ISP-only. For Joint, all differences are > 0 with an average of 0.2, i.e., a 20% improvement. 2-step gains 11% on average compared to ISP-only on the randomized data. Moreover, the difference between 2-step and Joint ("2-step-J") is ≥ 0 for all samples. In 75% of the instances, Joint can save more than 5% of deployed capacity compared to 2-step, and 40% of the instances show savings ≥ 10%. Overall, this demonstrates that the gains of joint re-optimization generalize also to less structured demand patterns.

V. DISCUSSION: REAPING THE POTENTIAL BENEFITS

Our evaluations based on data from a large ISP revealed a significant potential of a joint optimization and adaptation of and for hyper-giants’ traffic – for the ISP in terms for reduced costs or increased resource efficiency, and for the hyper-giants in terms of reduced latency. In the following, we discuss limitations and avenues on how these benefits may actually be reaped.

A. Generalization and Scalability

Our evaluations consider only one ISP topology, a limitation of our work that stems from the lack of publicly available data for other topologies (cf. §IV-F). Nevertheless, we expect the results to generalize to other ISP networks as well since those networks share important properties, at least to those of comparable size. First, similar traffic patterns like the diurnal pattern and dominance of hyper-giants’ traffic in ISP networks have also been observed for other ISPs [44]. Traffic demands increase and patterns might change, as also observed during the COVID-19 pandemic [42]. Our sensitivity analysis with synthesized demands confirms our observations and provides us further confidence in the robustness of the results. A second aspect of the generalization is whether the optimization is tractable on other ISPs. Our modeling results in an NP-complete problem which might lead to run-time problems on larger problem instances. Limiting the solver run-time to 1 hour has provided results close to the optimum in our case but might not be sufficient on other topologies or even faster reconfiguration cycles. Hence, designing more tailored algorithms might be necessary for real deployments. We leave this for future work.

B. Business-related Trends

Emerging cooperation. Many inefficiencies related to how CDN traffic is delivered through ISP networks today, are due to the lack of information. While ISPs have detailed knowledge of their network topology (the two lower layers in Fig. [1]), their knowledge of the demand of content and distribution flexibilities is usually very limited (upper layer in Fig. [1]); and vice versa for the hyper-giant [21], [45], [46]. Several recent studies presented promising approaches to improve information sharing and cooperation [16], [21], [47]–[50]. Moreover, it has been shown that major players adopt such approaches for information exchange [19], which we argue can and should be extended to account also for topological flexibilities.

Hyper-giants acting as ISPs and vice versa. In addition to emerging collaborations, we can already note that some hyper-giants become ISPs and provide connectivity for end users. Either on traditional fixed line access [51] or via less established interconnects such as satellite links [52]. Similarly, ISPs started to provide content services, e.g., [53], [54]. There is an increasing number of entities unifying ISP and hyper-giant. Hence, our approach of joint optimization is becoming more relevant.
C. Technological Trends

From a technical perspective, our approach largely benefits from the increasing adoption of softwarization and centralized control approaches in ISP networks, e.g., [11]. In particular, there are two major aspects to realize the envisioned system.

Centralized data collection and operation. The joint optimization relies on detailed knowledge of the current state of topology and routing, and particularly on information about the future demands. Systems that implement such data collection in a highly scalable way are already in operation at the ISP, e.g., [16], using widely deployed protocols such as BGP or IS-IS for routing data and NetFlow or IPFIX for collection of demand data. Prediction of future demands based on the collected ones is already possible with deployed systems [10] and fostered by omnipresent advances in machine learning. Also data from the CDNs, e.g., server loads or content availability, is already being collected by CDNs to implement their user-mapping systems [33]. Besides the centralized database, also the control and decision making has to operate on a global level to leverage the joint optimization. Large ISPs and hyper-giants have shown that centralized control entities are feasible already today, cf. [2], [3], [11]. Depending on the particular situation, i.e., CDN-ISP cooperation or implemented by one party, detailed integration of all parts into one system is necessary. However, further work to integrate control over the three layers is still necessary.

Deploying configurations. Finally, configurations have to be communicated to the network equipment in case of IP topology and routing or to the mapping systems for content requests. Run-time reconfigurations of network devices have strongly been fostered with the continuing trend of softwarization and programmability of networks. Most devices offer programmable interfaces to change configurations and the state of the network. For instance, in the optical domain, NetConf and TL1 are prominent examples for such interfaces. But often the specifics are vendor dependent potentially posing a challenge for system integration. Note that while such interfaces offer easy triggering of changes, actual realization by the device might still be limited by other technological aspects. For the deployment of user mappings, approaches depend on the involved entities. For CDN-ISP collaboration, communication between the parties should happen in a reliable and automated way. ALTO [37] has already been adopted by some players to achieve this [16]. Other approaches might include custom APIs between mapping system and centralized control, e.g., in the case of converged roles of CDN and ISP. Reconfigurations can lead to interruptions or additional overhead, e.g., if states have to be synchronized over the network or if IGP has to re-converge. A specific detail here is the scheduling of reconfigurations to reduce service interruptions and to guarantee correctness of the networking state during reconfigurations, e.g., using a make-before-break strategy [55]. The specific costs depend on the actual system design. A deeper analysis particularly for reconfiguring on all three layers is subject to future work.

VI. Related Work

To the best of our knowledge, this paper provides the first study of how reconfigurable topologies can be used to improve CDN traffic routing in ISPs. Our paper builds upon several important existing results in the area of optical networks, CDN-ISP collaboration, and network resource optimization, which we will discuss in turn in the following.

Capacity planning and routing in optical networks. Capacity planning is a classic problem in optical networks and there already exists a large body of literature, also accounting for multi-layer aspects. For a survey, we refer to [13], [56], [57]. Much existing related work on operational network optimization revolves around the impact of optical network reconfiguration on the routing stability [58], [59], the reconfiguration and adaption of virtual topologies that overlay optical networks to changing traffic demands [60], issues related to incremental deployment [14], [61], as well as regenerator placement problems (i.e., computing ROADM locations). All these works consider the demand given by source-destination pairs and do not shape it via optimizing end-user mappings like our proposed approach does. There is also interesting work on content-oriented and application-aware optical network optimization [39], [62], and multi-layer resource allocation [15], [63], [64], e.g., in the context of the Facebook network [65]. A case study related to CDNs is conducted in [66], however, without considering reconfigurations. In particular, these works consider optimizations on the demand level but optimize only two layers neglecting flexibility of IP grooming [39], [66], and they do not adapt over time [39], [62], [65]. Adaptive operation is provided by [15], [63] along with integration of application requirements. However, the demand is given again by fixed source-destination pairs. While there exist several efforts to render operations of optical wide-area networks more adaptive [9], [67], we are not aware of any related work on the optimization of ISP networks along all the three dimensions arising in the context of CDNs: topology, routing, and end-user mapping. In particular, the few existing two layer solutions which account for multiple mapping locations, such as [39], do not support IP grooming. We also note that while our focus in this paper is on ISP topologies, the opportunities introduced by reconfigurable optical networks has recently also received much attention in datacenters, e.g., [68]. However, the technologies and constraints in datacenters are fairly different from the ones in ISPs (e.g., in terms of routing [72], availability of wireless channels [68], and concerning the workloads [73]), and existing results are not easily transferable.

CDN-ISP collaboration. There is interesting work on how collaborations between CDNs and ISPs can be improved. This work, however, mainly focuses on traffic engineering (TE), neglecting the potential of topology modification. For related work on joint content placement and TE in this context see [47], [49], [74], [76]. All this work is limited to user mapping and TE but ignores adaptive optimization of the ISP’s topology. A recent case study considers the joint content distribution and TE of adaptive videos in telco-CDNs [77], assuming a caching system where CDNs can deploy media.
objects. In contrast, we consider a scenario where requests are handed over at peerings to the CDN. The papers closest to ours in the context of CDN-ISP collaboration are PaDIS [21] and FlowDirector [16]. Both systems collect topology and routing information from the ISP network to create a ranked mapping between the IPs of the ISP’s users and the CDN’s servers, e.g., based on distance or number of hops. The mapping is an additional input to the CDN’s mapping system to improve content delivery by serving via servers at closer locations and shorter paths. Both aid the CDNs’ mapping systems but only collect information from ISP’s network and do not adapt it.

**Optimization and resource allocation.** The optimization problem considered in this paper is related to the virtual network embedding problem, which has been studied in the context of optical networks as well [78]–[83]. See [84] for an overview of existing solutions in this context. However, in contrast to the embedding problem, in our case, node allocations are already given (namely, the end-user locations and the hyper-giant’s peering locations, modeled as super nodes), but the topology is flexible. The link-only embedding problem boils down to routing, but does not support the selection of multiple (content) locations. That said, the approaches in [78], [80], [82] for supporting addition and removal of IP links, could not be reused in our setting; however, these approaches do not consider re-embedding of virtual links which maps to re-routing of demand in our scenario. We note that also works on mapping service function chains on optical networks, e.g., [85], are different from our approach as the optimization regards the mapping, not the topology.

**VII. Conclusion**

Motivated by emerging reconfigurable network infrastructures, this paper initiated the study of the potential benefits of dynamic and demand-aware re-optimizations. To this end, we presented an optimization framework to improve the delivery of hyper-giant traffic across ISP networks, leveraging short-term reconfigurability along three dimensions, topology, routing, and user mapping. Using extensive empirical analyses in collaboration with a large ISP, we found that such joint optimization is indeed worthwhile, and can benefit both the ISP and the hyper-giant. The observed benefits are two-fold. First, the required backbone capacity is reduced by 15% and second, path lengths are shortened by 30%, both on average and during the critical peak hour. Moreover, we show that infrastructure re-optimizations can also be leveraged in specific situations, for example during the COVID-19 pandemic or under link failures.

We understand our work as a first step, and believe that our approach opens several interesting directions for future research. In particular, while a more efficient use of the physical infrastructure benefits OPEX (e.g., in terms of fewer deployed lightpaths and reduced power consumption), it will be interesting to further evaluate the benefits for quality-of-experience of specific applications. Furthermore, while we have focused on a large ISP, it would also be interesting to study whether similar benefits can be obtained even in smaller ISPs, and at higher reconfiguration granularity.

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