Running the Network Harder: Connection Provisioning with Degradation under Resource Crunch

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Abstract—The increased network flexibility introduced by new technologies, such as Software-Defined Networking, are motivating operators to consider running their networks at higher utilization levels. Traditionally, networks were operated at a small fraction of the network capacity (30-40%); recently, however, operators are considering running the network harder (60% utilization and above [1]). Higher utilization can increase the network operator’s revenue, but this gain comes at a cost: daily traffic fluctuations and failures might result in the network not being able to carry all offered traffic. We call such network congestion situations Resource Crunch. Dealing with Resource Crunch requires certain types of flexibility in the system. We focus on the scenario of demands with flexible bandwidth requirements, e.g., allocated connections might undergo service degradations to allow for a new connection to be provisioned—a demand that would otherwise be blocked. In these situations, it is important that the network operator makes an informed decision, since degrading a high-paying connection to allocate a low-value demand is not sensible. Accordingly, we show that, during Resource Crunch, the decision of whether or not to serve a demand (and which other connections to degrade) focusing on maximizing profits is of complex nature. In this study, we propose an abstraction of the network state, called Connection Adjacency Graph (CAG), to devise an efficient method to decide whether or not to serve a demand, and which other connections to degrade. We compare our method to existing greedy approaches and show that we outperform them during Resource Crunch.

Index Terms—Resource Crunch, High Utilization, Network Congestion, Connection Provisioning, Service Degradation, Flexible Bandwidth, Profit Maximization.

I. INTRODUCTION

Communication networks are designed to provide high availability for existing connections and high acceptance rates for new demands (i.e., new service requests). Traditionally, this dual goal has been achieved by deploying significant excess capacity (over-provisioning), commonly utilizing only 30-40% of the total capacity. The importance of over-provisioning is threefold: it provides redundancy for allocated connections, it accommodates traffic variations (both predictable daily fluctuations and unpredictable traffic surges, such as flash crowds), and it serves as a cushion for traffic growth. There is great interest in using excess capacity, since it creates opportunities to generate revenue from previously idle assets [2].

In this study, we define Resource Crunch as situations in which the network is temporarily faced with a larger offered load than it can possibly carry. The events that can cause Resource Crunch are either sudden increases in offered traffic (i.e., demand arrivals) and/or reductions in the deployed capacity (i.e., failures). In traditional networks, if a Resource Crunch occurs, some of the offered demands will not be served. Accordingly, the over-provisioning of traditional networks mitagate the chances of Resource Crunch occurrences.

Recent technological advances, such as Software-Defined Networking (SDN), allow networks to be operated at higher levels of utilization, thanks to the increased flexibility they provide. Some practical wide-area SDN networks today report average link utilization above 60% [1]. [3]. This higher utilization enables a larger revenue per unit of capacity when compared to traditional networks. As the forecast compound annual growth rate of general Internet traffic is 22% [4], many traditional networks will be pushed to higher levels of utilization to maintain profitability. A high level of utilization, however, increases the chances of Resource Crunch occurring. Thus, to shift from the traditional paradigm of low capacity utilization to a new paradigm of running the network harder, it is necessary to be prepared for Resource Crunch.

Dealing with Resource Crunch requires introducing new levels of flexibility in the system. Specifically, we consider Service Level Agreements (SLAs) with flexible bandwidth requirements. As network traffic can be classified according to Classes of Service [1], [5], [6], we consider that each type of service has different bandwidth flexibilities. In that sense, demands request a certain bandwidth if it is available, but might be satisfied with some smaller bandwidth, down to a predefined minimum. Thus, connections might undergo service degradations (lowering their bandwidth) to make room for an incoming demand, for example. We consider that an allocated connection generates a certain amount of revenue; however, if it undergoes a degradation, it generates less. In our study, we consider three classes of service [1], namely: Interactive (no bandwidth flexibility), Elastic (some bandwidth flexibility), and Background (large bandwidth flexibility), but our study can be generalized for more service classes.

An illustrative example detailing the fluctuations of traffic offered/carried throughout five regular days is shown in Fig. 1. The green curves exemplify how the load carried by a traditional network remains, on average, at a low percentage of the total deployed capacity, in this case 40%. The dark blue curve shows how the same network could be used to carry a higher amount of traffic, reaching 72% average utilization. At such higher utilization, however, Resource Crunch situations (red shaded areas) are not uncommon. The dashed light-blue curve is the minimum required bandwidth of all the offered demands
considering the acceptable degradation of each demand. In this example, the minimum required bandwidth never surpasses the total deployed capacity, indicating that, during Resource Crunch, there is a way to serve all offered demands, albeit at the expense of degrading some of them.

During a Resource Crunch, if a new demand arrives, the network might be unable to serve it at its requested bandwidth. We call those demands **crunched demands**. When a demand is crunched, the network operator has to decide whether or not to serve it (possibly by degrading some existing connections). If the demand is blocked, however, there might be penalties ranging from negative impacts on revenue to damages to the company’s goodwill. Our study investigates how to make that decision such that the operator’s profits are maximized, i.e., revenue generated from the served connections subtracted by penalties incurred from not serving some demands.

To solve this problem, we propose a novel representation of the network state: **Connection Adjacency Graph (CAG)**. This graph describes how allocated connections interact and how much revenue is lost when degrading any of them. With it, we develop an effective method to solve the problem we are studying and to analyze its complexity.

The rest of this study is organized as follows: in Section II we review related literature; In Section III Resource Crunch is discussed; in Section IV we review bandwidth-flexible connectivity demands and how they affect revenue; in Section V we study the problem of connection provisioning with degradation during Resource Crunch; in Section VI we solve the problem using the CAG; we present illustrative results in Section VII and we conclude in Section VIII.

II. RELATED WORK

The idea of running the network at high average link utilization has been studied through different perspectives. Achieving high utilization is a motivation to use certain technologies, such as SDN [1]. This study, however, tackle the problem from an implementation perspective. Its approach is based on filling the excess capacity with low-priority traffic that can be dropped if necessary, hence, carrying the same amount of high-priority traffic as a traditional network would.

Some studies have analyzed the problem of provisioning demands to achieve some utility maximization. In [2, 3] the goal consists of maximizing an abstract measure called *fair share*. The problem of, given a set of demands, a network, and some objective (e.g., availability, revenue, etc.), how to serve the demands such that the objective is maximized was also studied by [4, 5]. Our work differs from these studies in the following ways:

1) Differently from [3, 4], we aim at having a joint decision of path and bandwidth allocation;

2) Demands arrive at any time and must be served as soon as possible, hence, we need a solution that works dynamically, instead of statically (as in [4, 5]);

3) As demands arrive, we want to decide whether or not to serve that demand (and through what path) while affecting other connections the least, i.e., we do not perform re-routing of existing connections; and

4) We consider demands that have bandwidth flexibility.

Similar problems to ours have been analyzed in other works, however, without our goal of maximizing the network operator’s profits. In [6], service degradation was used to reduce blocking and increase network survivability. Flexibility in both time-to-complete and desired bandwidth was studied in [7], to allow for reliable multi-path provisioning, and in [8] for deadline-driven scheduling. Considering the optical and electrical layers, [10] proposed a service degradation scheme using multi-path routing for minimum-cost network design, and [11] analyzed the problem of provisioning degraded services while assuring QoS. The algorithm proposed in [11] is similar to [12]; however, the latter aims at maximizing the network operator’s revenue. These algorithms greedily search for a shortest path and serve a crunched demand by executing degradations in that path from a lower priority (e.g., cheapest) to a higher priority (e.g., more expensive).

III. RESOURCE CRUNCH

In a network being driven harder, a Resource Crunch can occur when a new demand arrives and/or a failure occurs.

A. Arrival of New Demands

As a new demand arrives, the total offered load to the network increases. Demand arrivals can be categorized as:

1) **Hourly/Daily Traffic Fluctuations**: On an hourly scale, the offered traffic changes according to time of the day, as shown in Fig. 1 and explored by several studies [12, 13]. These changes have a periodic-like behavior, roughly repeating everyday. Their peaks may generate Resource Crunch (see red areas of Fig. 1). Because of this periodicity, a crunch could last for a while until the offered traffic decreases.

2) **Traffic Surges**: This study is also applicable for sudden traffic peaks generated by unpredicted increases in traffic, such as those due to Flash Crowd [14].

3) **Traffic Growth**: Traffic growth can also cause Resource Crunch when network upgrades are not adequately dimensioned. Such long-duration Resource Crunch is not the subject of this study and is an open problem for future research.
B. Failures

Failures can cause Resource Crunch even if the offered load remains the same. This is because failures reduce the amount of available capacity (e.g., lowering the black line of Fig. 1). Traditional networks are typically engineered to endure some (usually simple) failures. However, in a network running at high utilization, failures and disasters might cause a Resource Crunch. In fact, natural (e.g., an earthquake) or man-made disasters (e.g., a Weapon of Mass Destruction) may inflict widespread damage to communication infrastructure [20], causing Resource Crunch even in traditional networks.

IV. Service Classes and Their Revenue Impacts

A. Service Classes

Network traffic can be classified in several ways. The IEEE P802.1p standard specifies eight different traffic types for Quality of Service implementation at the MAC level. However, as studied in [5] and summarized in [11], three classes of service are enough to describe traffic seen in practice. In this section, we provide an overview of each of them [1] and discuss their relationship with revenue. Table 1 summarizes these classes of service and adds some illustrative numbers (prices, bandwidths, and ratios) that will be utilized in Section [VII] Our work, however, is applicable to any number of service classes a network might have.

1) Interactive: These services directly impact end user experience (e.g., serving a user query), and they cannot suffer degradation. Also, they have the highest impact on revenue.

2) Elastic: These services are more flexible than Interactive Services, and end users either have more flexibility in terms of their utilization experience (as when making a video call, or sending an e-mail), or are not directly impacted by them (as when replicating a data update between Data Centers). We assume these services can be degraded and they have less impact on revenue than Interactive Services.

3) Background: These services relate to maintenance activities that are not directly accessible to end users (backup migration, synchronization, configuration, etc). We consider that these services can be significantly degraded (more than Elastic Services) and they have the smallest impact on revenue.

Table I. Service Classes and their Impacts on Revenue.

| Service Class | % of Total Traffic | Requested Bandwidth per Demand | Min. Required | Revenue Increase ($/Gbit/km) | Cost of Blocking ($/Gbit/km) |
|---------------|--------------------|-------------------------------|---------------|------------------------------|-----------------------------|
| Interactive   | 15%                | 2 Gbps                        | 2 Gbps        | 0.00000075                   | 0.00000075                  |
| Elastic       | 25%                | 3 Gbps                        | 2 Gbps        | 0.00000066                   | 0.00000003                  |
| Background    | 60%                | 5 Gbps                        | 2 Gbps        | 0.0000002575                 | 0.00000003                  |

B. Revenue Impacts: Connection Prices and Blocking Costs

Now, we discuss how connections of different service classes impact revenue (i.e., the network operator’s income). For a telecom operator, the relationship of bits to money tends to be direct. For a company such as Amazon, Google, or Microsoft, this relationship might involve different variables.

We consider that the revenue generated by a connection depends on the straight geographical distance between the source and destination of that connection. This removes distortions that paths longer than the shortest might create if a pricing based on the number of network hops was utilized instead.

The cost of blocking a demand is also considered in this study. This cost is a monetary representation of the damages to the image of the company, of the importance the operator places in each type of traffic, and other possible damages it might suffer from refusing service to a demand. In our results presented later, we assume blocking costs amount to 50% of the minimum revenue increase that would be generated from a demand (i.e., considering how long the demand would last), except for Background traffic that has no blocking cost.

Numerically, we base the prices used in the results of Section [VII] and presented in Table 1 on the bandwidth prices of Microsoft Azure [22]. We assume that transferring 1 GByte of Interactive data generates, on average, $0.09. For a US-wide network, where the average source-destination distance is 1500 km, the revenue per Gbit per kilometer that an Interactive demand generates is, thus, $0.00000075. For example, if an average-distance Interactive connection lasts 8 seconds, allocated at 1 Gbps bandwidth (totaling 1 GByte), the revenue generated is:

\[
\frac{0.00000075 \times 1500 \text{ km} \times 1 \text{ Gbps} \times 8 \text{ s}}{\text{Gbit} \cdot \text{km}} = 0.09
\]

V. The Problem of Serving Crunched Demands

Now, we first state the problem of Provisioning with Degradation under Resource Crunch (Section [V-A]); then, we provide some definitions that will be utilized in this study (Section [V-B]); finally, we use an example to show why a shortest-path approach is not sufficient to solve the problem (Section [V-C]).

A. Problem Statement

Provisioning with Degradation under Resource Crunch

I. Given:

- Network topology: nodes, links, capacities;
- A set of allocated connections: revenues, paths, requested and minimum bandwidths; and
- A crunched demand: bandwidth, source-destination nodes, offered revenue, blocking cost.

II. Output: A decision of whether or not to serve the demand. If yes, then also a set of other demands to be degraded, how much to degrade each of them, and the path on which to place the crunched demand.

III. Constraints: Link capacities, connection’s minimum bandwidths, crunched demand minimum bandwidth, all connections are non-splittable.

1The longer a connection is, the more revenue it generates; also, the greater the bandwidth it utilizes, the more revenue it generates (other Service Level Objectives can also impact revenue). Generalizing the revenue impact of a connection as its price, telecommunication markets favor value-based pricing instead of cost-based pricing [21]. In cost-based pricing, the price of a connection is directly proportional to the amount of resources utilized by that connection (i.e., the number of links it traverses). This approach does not consider the fact that, if a non-shortest path solution is offered to a client, a competitor that can provision a shorter path (providing the same bandwidth at a lower price) would be preferred. Thus, we consider a value-based pricing approach, through which the operator values its services based on the prices being used by its market competitors; to that end, we base the price of a connection on the straight geographical distance from its source to destination.
Our study considers a specialized version of the problem, focusing on Profit Maximization Provisioning with Degradation under Resource Crunch. Our goal is to maximize profits, measured by revenue generated from served connections after subtracting the cost of blocking demands.

We simplify the problem by only allocating crunched demands at their minimum required bandwidth (if such provisioning is possible). This allows for minimum perturbation of already allocated connections while it also conserves capacity for future demands. We consider, however, that there exists a registry of degraded connections (both served crunched demands and degraded connections) — ordered first by the revenue of each connection (highest first); secondly, by the hop-length of each connection (fewer hops first). Thus, when allocated connections depart, the degraded connections listed there are upgraded to a higher bandwidth if possible, i.e., to the highest possible bandwidth, up to the demand's maximum required bandwidth. For example, a scenario where a crunched demand is allocated at its minimum bandwidth and upgraded to a higher bandwidth almost immediately can occur.

B. Definitions

For a crunched demand to be served, the following conditions must be met:

a. A set of allocated connections must be found such that, after executing a service degradation to these connections, capacity will be freed-up from the crunched demand's source to its destination (i.e., service degradations create a liberated path in the physical network);

b. The liberated path must have enough capacity to serve the minimum required bandwidth of the crunched demand.

Then, we call the selected set of allocated connections a candidate degradation set.

c. Serving that demand by executing those service degradations must be a Profitable Decision.

We define Profitable Decision as the positive result of the following decision:

i. Given:
   - Crunched demand \( d_c \), its potential revenue increase \( \text{rev}(d_c) \), and its blocking cost \( \text{block}(d_c) \);
   - Candidate degradation set \( S_{\text{degrade}} \) and revenue that would be lost with it \( \text{cost}(S_{\text{degrade}}) \) (also called degradation cost).

ii. Decide whether:

\[
\text{rev}(d_c) + \text{block}(d_c) \geq \text{cost}(S_{\text{degrade}})
\]

Now, we define the optimum candidate degradation set as the candidate set that reduces the operator’s revenue the least, among all possible candidate sets that liberate a path from a crunched demand’s source to its destination.

The optimum candidate degradation set allows for the best Profitable Decision to be made. In other words, since \( \text{rev}(d_c) \) and \( \text{block}(d_c) \) of crunched demand \( d_c \) are immutable, the optimum candidate degradation enables the scenario with the best chances of being profitable to be considered.

We refer to the bandwidth that can be freed-up from a connection as its degradable bandwidth.

Figure 2. In this illustrative example, the initial state of the network can be seen in (a). Each link has 20 Gbps capacity. Five connections are initially allocated, each of their labels are organized as “Connection Number: Allocated Bandwidth in Gbps; Minimum Bandwidth in Gbps; Revenue per Gbit”. Distances are accounted for in the prices shown. Because all links are fully occupied, when a new demand, from node A to node E, arrives requesting 10 Gbps, it is crunched. This demand offers to pay $6 per Gbit, and has a blocking cost of $30.

C. Using Shortest Path to Solve the Problem

When a demand is crunched, one approach to decide whether or not to serve it (and where to allocate it) is to find the (k-)shortest path(s) between its source and destination. Then, select the cheapest set of connections that intersect that path such that, once degraded, a liberated path would be created. Finally, if performing those degradations is profitable, execute them and serve the demand. In general, this is the approach of [11], [15], [16].

This approach chooses the service degradations that will be executed based on what connections traverse some specific physical path (namely, one of the k-shortest). Such an approach may not perform very well, as can be seen in Fig. 2b. Consider that a crunched demand from A to E arrives. The shortest path is shown in solid red. This approach does not find a profitable solution, since degrading 10-Gbps connections C4 and C5 would decrease the total revenue $100 and the crunched demand would only increase the revenue $60 (while its blocking cost is $30). Hence, by using the shortest path, the crunched demand is blocked although a solution exists.
Alternatively, a shortest path algorithm could be executed taking as weights the degradation costs of connections. Also in this case, the solution found is inaccurate. This inaccuracy leads to blocking of crunched demands unnecessarily and, when crunched demands are not blocked, it does not necessarily find an good solution. For example, consider executing Dijkstra’s algorithm taking as weights the degradation costs. The final path found by such an algorithm is shown in solid red in Fig. 2c. The total degradation cost of that path is $70. Since the crunched demand is offering $60 and has a blocking cost of $30, it would be allocated. However, if the blocking cost of the crunched demand was zero, it would be rejected.

Note that the optimum candidate degradation set consists of connections C1 and C3. Degrading them by 10 Gbps would decrease revenue by $50, which is less then the revenue increase offered by the crunched demand (without even considering its blocking cost). This degradation allows for the crunched demand to be served by the solid red path of Fig. 2a.

Intuitively, the example of Fig. 2 indicates that the current problem is of a complex nature, and guaranteeing an optimum solution for any scenario through a polynomial procedure might be infeasible. In Section VI we propose a better polynomial-time algorithm to solve this problem, which, in certain cases, can find the optimum candidate degradation set.

VI. Provisioning Under Resource Crunch

We first provide a high-level description of the proposed algorithm. It consists of multiple steps, most of which use the Connection Adjacency Graph (CAG) — introduced in Section VI-B — to assist in finding a cheap candidate degradation set. CAG allows the decoupling of the problem, hence, we utilize it to find a cheap (possibly the cheapest) candidate degradation set, and then, if serving the crunched demand is a profitable decision, we provision the crunched demand through the shortest liberated path. Finally, because the problem is of complex nature (which will be discussed further), we propose some simplifications to reduce its complexity in Section VI-C.

A. The PROVISIONER Algorithm

Fig. 3 shows the high-level structure of the Provisioning Under Resource Crunch (PROVISIONER) algorithm. Each of the Processes A, B, C, D, E, and F shown in the flowchart will be introduced in the following sections; however, we now give an overall explanation of how they fit together.

The algorithm starts with a crunched demand $\alpha$, and executes a procedure to find a candidate set of allocated connections to be degraded, with the help of the CAG, to serve demand $\alpha$ (process A). If this procedure does not find a candidate set, the algorithm tries to find another candidate set through two steps. The first step (process B) consists of finding a series of candidate sets, with the assistance of the CAG, and then combining these candidate sets (process C) with the assistance of the Degradation Oriented Graph (explained in Section VIII). If a candidate set is still not found, the algorithm executes a Guided Degradation Algorithm (process D), also presented in Section VIII. If the candidate set is not found or not profitable, then $\alpha$ is blocked.

The algorithm can achieve optimality in certain cases. If a candidate is found through process A, then results are necessarily optimum. Processes B and C might still find an optimum solution. Process D, even though not optimum, has a good chance of finding a candidate set that is reasonably good. The ratio of optimal solutions can be altered through parameters $k_{CAG}$ and $k_{DOG}$.

B. Connection Adjacency Graph (CAG)

The main observation when choosing a path to allocate a crunched demand is that, when a connection is degraded, it frees capacity throughout its entire path, and not only on the single physical link that we are currently observing. Referring to Fig. 2, if connections C5 and C4 are degraded to make room for a crunched demand from A to E, capacity will be freed not only through links A-F and E-F, but also on link B-F. Hence, rather than forcibly degrade services to liberate capacity throughout some predefined path (similarly to the first approach of Section V-C), it might be more beneficial to traverse longer paths by fully utilizing the capacity liberated by a connection once we choose to degrade it.

To capture the previous observation, we introduce a novel representation of the network state, the Connection Adjacency Graph (CAG). CAG is a directed, weighted graph that provides an abstract view of how connections interact, allowing for cheap degradation candidates to be found. To generate it, we use the following steps:

1) For each connection in the network that has some degradable capacity, create a vertex (called a vertex) and
Note the cheapest path in 4b: Dummy Source - C1 - C3 - Dummy Destination.

Figure 4. CAGs representing the network of Fig. 2. 4a shows the network in state 2a. 4b shows the CAG after the crunched demand from A to E arrives. Note the cheapest path in 4b Dummy Source - C1 - C3 - Dummy Destination.

associate with each vertex a list of the physical nodes on the path of that connection;

2) For any link (i,j) in the network which has free capacity, we create a dummy connection between i and j which has cost zero to degrade, and an associated vertex.

3) For each pair of vertices l,k, add directed edges (l,k) and (k,l) if both connections l and k have at least one physical node in common.

4) Each edge entering a vertex l has a weight equal to the cost of degrading one unit of bandwidth of the connection associated with l;

5) For a crunched demand from s to t, create a dummy source vertex and connect it to each vertex that is associated with node s (as usual the edge weight is the cost of degrading one unit of bandwidth for the vertex's connection). Similarly, create a dummy destination node, and connect each vertex associated with t to it (edges with zero weight).

The CAG can be kept in memory and only updated as connections arrive/depart. When a connection is provisioned, it is necessary to add a vertex representing it in the CAG. It is also necessary to check if that connection exhausted any previously-free capacity on any of its links. In that case, the vertices that represented those free capacities must be removed from the CAG (after adding the new vertex). When a connection departs, it is necessary to check if it is liberating any free capacity on any link that was previously fully occupied. In this case, it is necessary to add vertices representing the new free capacities to the CAG (while removing the vertex of the departing connection). CAG would also allow for other weighting schemes (which will not be studied in this work).

As an example, the initial state of the network shown in Fig. 2a is represented by the CAG of Fig. 4a. Notice how the physical topology of Fig. 2a is abstracted in the CAG. When the crunched demand from node A to node E of the previous example arrives, we can add a pair of dummy vertices representing those nodes, as shown in the CAG of Fig. 4b.

Remark 1. All paths that we refer to are simple paths. We define a singleton path as a simple path in the physical network whose edges have either free capacity or degradable capacity of at most one connection in each of the path’s links.

In other words, a singleton path is a path whose edges do not include degradable capacities of more than one connection in the same link, nor include some combination of free capacity and degradable capacity in the same link.

Lemma 1. A singleton path maps to a CAG path.

Proof. Since a singleton path traverses a set of free capacities or degradable capacities of connections (one per link), that singleton path can be represented in the CAG as the path going, in the same order, through the vertices that represent those free capacities and connections.

Lemma 2. Degradation cost of one unit of bandwidth in a singleton path is the weight of the CAG path which represents that singleton path.

Proof. Since weights of CAG edges are costs of degrading the connection that each edge points to, then a path in CAG has the weight equivalent to the cost of degrading the connections that form the equivalent singleton path.

Theorem 1. A cheapest source-to-destination CAG path represents the cheapest possible candidate degradation set that allows for some capacity to be freed from a crunched demand’s source to its destination.

Proof. By contradiction, suppose there exists a cheaper candidate degradation set. Consider, also, the singleton path that traversed all connections and free capacities in that cheaper candidate set. However, since any singleton path can be mapped to a CAG path, there must exist a CAG path that represents such singleton path (Lemma 1). Since the degradation cost of that singleton path is the same weight of the CAG path that represent it (Lemma 2), that candidate degradation set cannot be cheaper than the cheapest set found before.

Some simplifications have been made so far. To consider the Profit Maximization Provisioning with Degradation under Resource Crunch problem in its entirety, we consider two opposite scenarios, i.e., we separately analyze the case where crunched demands fit in the degradable bandwidths of allocated connections (i.e., in a singleton path) and the case where they do not. We study each of them with the assistance of the CAG in the following subsections.

1) Crunched demands that fit in degradable bandwidths: In the PROVISIONER algorithm, when a crunched demand arrives, it finds the cheapest path in the CAG from that source to destination. This is the first procedure to be executed in the algorithm and it generates the first degradation candidate set.

If the crunched demand requests a minimum bandwidth that can be allocated in a path liberated by that CAG path, then an optimum result is found. This is because:

i. There exists no other cheaper degradations that could liberate a path for the crunched demand, and

ii. The path liberated from that degradation is sufficient to fit the minimum requested bandwidth of such demand, and thus it is not necessary to free up more capacity to serve that crunched demand.

Figure 4. CAGs representing the network of Fig. 2. 4a shows the network in state 2a. 4b shows the CAG after the crunched demand from A to E arrives. Note the cheapest path in 4b Dummy Source - C1 - C3 - Dummy Destination.
With such degradation candidate set, the operator can then decide if serving the crunched demand is a Profitable Decision.

In this scenario, the problem of Section VI can be solved optimally in polynomial time. However, not all of the demands fit in the degradable capacity of a cheapest degradation. In the example of Figs. 2 and 4 the crunched demand from A to E only requests 10 Gbps and every other connection can be degraded in 10 Gbps; however, this is a simplification for illustrative purposes.

2) Crunched demands that do not fit in degradable bandwidths: This scenario accounts for processes B and C of Fig. 3. In this case, the cheapest degradation found in process A does not liberate enough capacity in the network for the crunched demand to be served.

Thus, there are three possible assumptions in this case:

a. There might exist a more expensive degradation that could liberate enough capacity for the crunched demand;

b. It might be necessary to degrade more than one connection per link in the physical network (or to use the free capacity along with the degradable capacity of some connection) to serve the crunched demand;

c. The network might be so populated by degraded connections that it is simply not possible to further degrade other connections to make room for the crunched demand.

To solve this scenario, we resort to the observation:

Remark 2. When more than one singleton path traverses the same link, they might be joined to form a larger-capacity non-singleton path.

Consider, for example, that when a degradation is performed, a path is liberated in the physical network with capacity 10 Gbps, since only 10 Gbps were liberated in one of its links (i.e., the bottleneck link). Consider, now, that a second degradation is executed such that this degradation increased the liberated capacity on the bottleneck link to a total of 20 Gbps. Note that each degradation is mapped to different singleton paths and executing both of them generated a non-singleton path (as it traverses the degraded capacity of two connections on the bottleneck link) of larger capacity.

An optimal solution, in this scenario, can still be achieved through the following steps:

1) Find all source-to-destination CAG paths;

2) List all combinations of all the CAG paths found before;

3) Among all the combinations listed, select the set that (together) liberate non-singleton paths with enough capacity for the crunched demand to be served (note that some combinations might not help in finding a larger-capacity non-singleton path); and

4) Among the selected combinations, choose the cheapest.

This approach will find the cheapest combination of candidate degradation sets, since it executes a brute-force-like investigation of all possible degradations. However, there might exist a factorial number of CAG simple paths and, among them, there might exist an exponential number of combinations. Thus, optimality in this case is not guaranteed through a polynomial-time procedure, as it was previously.

In Section VI-C, we avoid this brute-force approach by introducing simplifications to the algorithm.

C. Dealing with the Complexity of the Problem

We introduce two methods to deal with the complexity presented in Section VI-B2. Both these methods rely on the following simplification of the problem: instead of taking into account all possible CAG paths, as mentioned in the brute-force approach, we only consider the \( k_{CAG} \) shortest paths (which can overlap both in vertices and edges). This simplification is represented by process B of Fig. 3.

After calculating the \( k_{CAG} \) shortest paths, we utilize the Degradation Oriented Graph (DOG) to combine them in an efficient manner. Note that two or more singleton paths can only form a larger-capacity non-singleton path when they share at least one link (although this is not a sufficient condition). Thus, DOG only combines CAG paths when such combination might lead to singleton paths being joined to form a larger-capacity non-singleton path. It is process C of Fig. 3 and will be described in Section VI-C1.

If a candidate degradation set is not found after processes B and C, we use the Guided Degradation Algorithm (GDA) to look for a good candidate. GDA is represented by process D of Fig. 3 and will be presented in Section VI-C2.

1) Degradation Oriented Graph: DOG is a directed bipartite graph, and, to generate it, follow the steps:

1) Create two vertices for each of the \( k_{CAG} \) cheapest CAG paths: west vertex and east vertex. Add an edge going from east vertex to west vertex;

2) Connect the west vertices to all other east vertices whenever the singleton paths that map to the CAG paths they represent have at least one physical link in common;

3) Add a source and connect it to all west vertices. Add a sink and connect all east vertices to it;

4) All edges in the DOG have weight equals to 1.

An example of a DOG can be seen in Fig. 5, where five paths of the CAG of Fig. 4b were considered.

Since there might exist a factorial number of DOG paths, we introduce a second level of simplification: we only look for the \( k_{DOG} \) shortest paths in the DOG. For the results presented in this study, we set \( k_{CAG} = 15 \) and \( k_{DOG} = 30 \).

After all \( k_{DOG} \) combinations of the \( k_{CAG} \) cheapest CAG paths are investigated to find a candidate degradation set, it might be the case that no combination can liberate enough capacity for the crunched demand to be served. In this scenario, we utilize the Guided Degradation Algorithm.

2) Guided Degradation Algorithm: Represented by process D of Fig. 3, this algorithm works by augmenting the
amount of degradable capacity in a given path. Once the $k_{CAG}$ cheapest paths are known, this algorithm finds other cheap connections whose degradation might aid in liberating more capacity in the path initially liberated by that candidate degradation set of the CAG path. Effectively, GDA induces free capacity throughout a path similar to what the greedy shortest-path approach of Section V-C did; however, instead of looking for a shortest path, GDA uses as a starting point a path whose initial liberation is cheap (which might not be the shortest physical path). The algorithm works as follows:

1) For each CAG cheapest path, find the $k_{GDA}$-shortest singleton paths that would be liberated by performing the degradation indicated by the CAG path;
2) For each $k_{GDA}$ singleton paths $P_{single}$ found, consider all links that do not have enough liberated capacity for the crunched demand. For each of them, find at most the $\delta$ cheapest connections that overlap the link and add them all to a set $S_{cheap}$;
3) Order the elements of $S_{cheap}$ according to:

$$f(c) = \frac{\text{com}(c, P_{single})}{\text{len}(P_{single})} \cdot \text{cost}(c)^{-1}$$

where $c$ is a connection listed in $S_{cheap}$; $\text{com}(c, P_{single})$ is the number of links in common between $c$ and the singleton path; and $\text{cost}(c)$ is the degradation cost of $c$.
4) Pop elements out of the ordered $S_{cheap}$ until enough capacity is liberated along the singleton path or until the set is emptied. When a path for the crunched demand is found, record it and its degradation cost and proceed;
5) Finally, compare the cost of liberating each of the paths found and return the cheapest combination.

This algorithm either finds a degradation candidate set or the crunched demand is blocked. The time complexity of the GDA is polynomial, i.e., the number of iterations in the performed is equal to number of CAG paths; and, in each iteration:

a. Finding $k_{GDA}$-shortest paths is a polynomial procedure;
b. In each link, at most $\delta$ connections are considered;
c. Sorting connections is also a polynomial procedure.

VII. ILLUSTRATIVE NUMERICAL EXAMPLES

A. Simulation Settings

A dynamic network simulation was implemented to evaluate the performance of the proposed algorithm. Our focus is to analyze Resource Crunch caused by traffic fluctuations. A period of five consecutive days was simulated where Resource Crunch happened every day, as follows:

a. New demands arrive with exponential inter-arrival times.
The mean inter-arrival times vary throughout the day to reflect the daily traffic fluctuations, in a cyclical pattern similar to that of Fig. 1. For simplification purposes, we consider that these variations have a sinusoidal shape;
b. All connections have exponentially-distributed durations of mean 30 minutes;
c. New demands are generated such that 15% of offered traffic is Interactive, 25% is Elastic, and 60% is Background (see Table I);
d. Demands uniformly select a source-destination pair and request for a certain amount of bandwidth from end-to-end according to its type.

We consider the topology of Fig. 6 with 100 Gbps links in both directions. Three scenarios were considered:

- **Scenario 1**: offers a traffic whose daily variations have a peak-to-valley ratio of 2. The average link utilization is 75%. Average mean inter-arrival time throughout the day is six seconds;
- **Scenario 2**: has a peak-to-valley ratio of 3.5, and average link utilization 50%. Average mean inter-arrival time throughout the day is ten seconds;
- **Scenario 3**: has a peak-to-valley ratio of 5 and average link utilization 50%. Average mean inter-arrival time throughout the day is ten seconds.

Note that Resource Crunch happens whenever the average number of crunched demands goes above a threshold. On average, for Scenario 1, Resource Crunch happens every day from 5 PM to 1 AM (8 hours); for Scenario 2, it happens from 7:30 PM to 10:30 PM (3 hours); and for Scenario 3, from 6:30 PM to 11:30 PM (5 hours).

We compare our results with three greedy algorithms and a baseline approach. The baseline approach consists of not resorting to service degradation whatsoever. In this case, during Resource Crunch, the network simply rejects the incoming crunched demands. The greedy approaches are based on [10], [14], [15], with small changes to account for the distance-based pricing scheme being considered:

- **Greedy Cheapest**: consists of the approach of V-C;
- **Greedy Expensive**: similar to the above but sorts connections from most-revenue-generating to least;
- **Greedy Expensive $k$**: same as Greedy Expensive, but considers the k-shortest paths ($k = 5$).

The registry of degraded demands explained in Section V-A is utilized by PROVISIONER and all the greedy approaches.

B. Profit, Revenue, and Cost Impacts

Fig. 7 shows how each approach performs relative to the baseline. In Fig. 7a with regards to blocking costs; in Fig. 7b with regards to revenue increases; and, in Fig. 7c, with regards to profit increases. These results consider the entire Resource Crunch of each day, throughout the five days.

PROVISIONER performs better in two ways: it favors crunched demands that have higher impact on revenue, while degrading the demands that have lower revenue impacts (7b); and it blocks demands that have lower blocking costs (7a).
This dual behavior results in a significant improvement over the greedy approaches when comparing their effects on profits in [7]. The profit increases of Fig. 7c are directly related to the peak offered traffic and inversely related to the duration of the Resource Crunch (as will be explained in the following paragraphs). This leads Scenario 3 (with a shorter duration than 1, and higher peak than 2) to a higher overall profit increase when compared to the baseline.

The bars in Fig. 7c compare the profit increases of each approach to the baseline. However, if we contrast the approaches among themselves, it is clear that PROVISIONER performs much better than the second best algorithm (Greedy Expensive k). The red arrows in Fig. 7c show the comparison between PROVISIONER and Greedy Expensive k.

Greedy Cheapest has a poor overall performance. Since it tries to degrade cheapest connections, it tends to degrade shorter ones. With that, each crunched demand only liberates enough capacity to place itself. After a while, the network gets crowded with crunched demands and thus loses overall degradable capacity. Thus, new crunched demands are blocked due to a lack of degradable capacity. The other greedy approaches, however, free more capacity as they degrade more expensive connections (i.e., longer connections).

Fig. 8 shows how PROVISIONER does not waste resources by allocating low-value Background demands. In Fig. 9, the average path length of crunched demands that are served is shown. Greedy Cheapest has an average path length close to the physical network average shortest-path length. As Greedy Expensive does not favor short crunched demands, it generates a higher average path length for the crunched demands it serves, and Greedy Expensive k behaves similarly, however, using even longer paths.

As shown in Fig. 9, PROVISIONER serves demands through longer paths compared to Greedy Cheapest and Greedy Expensive. This higher occupation of the network hinders the search of cheap degradations for future crunched demands. Thus, the shorter the Resource Crunch lasts, the better PROVISIONER performs. So, shortest-path routing is not necessarily more revenue efficient, as short durations of Resource Crunch and demands (average 30 minutes) make longer paths worthwhile.

Figure 7. Impact of PROVISIONER compared to greedy approaches relative to the baseline. These results consider the state of the network immediately before the Resource Crunch compared to the state of the network immediately after the crunch is resolved.

Figure 8. Hourly view of crunched demands by type of traffic. Background traffic has zero blocking cost.
With the CAG, we proposed the PROVISIONER algorithm. We compared the results of our method with existing greedy approaches and showed how our method outperforms them. The results confirmed that the CAG is efficient in maximizing profits, that it gives priority to high-paying traffic, and that shortest-path routing is not the best option to maximize revenues during Resource Crunch.

Future work includes analyzing splittable connections and predicting how and when network upgrades should be performed in a high-utilization network.

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