

SCULPTOR Has Your Back(up Path): Resilient, Efficient Interdomain Routing for Large Service Providers

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Abstract

Large cloud and content (service) providers help serve an expanding suite of applications that are increasingly integrated with our lives, but have to contend with an unreliable, unpredictable public Internet to route user traffic. To enhance reliability to dynamic scenarios such as failure and DDoS attacks, large service providers overprovision to accommodate peak loads and build emergency systems for shifting excess traffic. We take a different approach with SCULPTOR, which uses a service provider’s global resources to handle dynamic traffic conditions. SCULPTOR ensures users have many interdomain routes to deployments, and moves excess traffic to backup paths to avoid congestion and minimize latency. As predicting interdomain routes is challenging, SCULPTOR builds models of Internet routing to solve a large integer optimization problem at scale using gradient descent. We prototyped SCULPTOR on a global public cloud and tested it in real Internet conditions, demonstrating that SCULPTOR uses service provider infrastructure up to 28% more efficiently than other solutions, reduces congestion on links during site failures by 17% on average, and enables service providers to achieve low latency objectives for up to 17% more traffic.

1 Introduction

Cloud and content providers (hereafter Service Providers) enable Internet applications used daily by billions of users. The applications have increasingly stringent performance and reliability demands, as the Internet is increasingly used for mission-critical applications (*e.g.*, enterprise services [36]) and as performance requirements become tighter (*e.g.*, virtual reality requires ≤ 10 ms round trip latency [51] and ≤ 3 ms jitter [71]). To meet these stricter requirements with the same fundamental Internet protocols, Service Providers have deployed interconnected sites and connected with thousands of networks in hundreds of locations, offering rich connectivity and distributed capacity.

The deployments’ physical resources (*e.g.*, peering links,

servers) are provisioned to accommodate demands from (ingress) and to (egress) user networks. Service Providers balance egress demands across links to minimize congestion and latency [65, 81, 28]. However, it is difficult to do the same on the ingress since (a) ingress traffic can only be controlled indirectly, by directing users to different *prefixes*, and (b) it is difficult to advertise prefixes in a way that exposes paths that can handle dynamic loads. Current approaches to routing try to achieve low steady state latency, but do not consider whether low latency paths can support dynamic loads (§2.3).

Given this lack of control, resource overload occurs due to link failures [50], DDoS attacks [54, 79, 61], flash crowds [32, 41, 43], and route changes that cause significant traffic shifts [52, 48, 27, 49, 56, 50]. This overload can lead to degraded service for user traffic [53, 59, 37].

Service Providers may respond to resource congestion by (a) proactively overprovisioning resources [72, 2, 45] or (b) reactively draining congested links and moving some of that traffic to other resources with free capacity [50]. However, we demonstrate in Section 2.3 that overprovisioning resources can require overprovisioning rates as high as 70%, significantly increasing expenses.

Service Providers can also drain traffic from overloaded links/sites by *withdrawing* prefix announcements that are also advertised via other healthy links/sites [54, 50, 62], so that traffic destined to those prefixes is forced to arrive on other links/sites after BGP converges (within tens of seconds [86]). However, this solution to overload is error-prone [45], post-hoc, unpredictable, and ineffective (§2.3).

To solve these problems, we propose a system — SCULPTOR (Scouring Configurations for Utilization, Loss, and Performance-aware Traffic Optimization & Routing) — that proactively advertises multiple prefixes to peers to expose diverse routing options, then assigns user traffic to paths towards these prefixes to optimize latency in a way that avoids congestion at links/sites. Our key insight is to quickly search over the large advertisement configuration search space by modeling how different strategies perform, while predicting very little about the actual paths taken under different config-

urations since predicting interdomain paths is hard.

We make two contributions. First, we present an interdomain routing optimization framework that can be used to minimize performance metrics (*e.g.*, maximum link utilization, latency, latency under single link failures) over different sets of prefix advertisements (§3.2). Part of our framework is a model for predicting performance in unknown scenarios, which is important as changing routing configurations and then issuing measurements is slow. This model enables SCULPTOR to efficiently optimize over a large space without measuring every possible configuration (§3.3). We then optimize these (modeled) performance metrics using gradient descent, which is appropriate in our setting due to the high dimension of the problem and the parallelism that gradient descent admits (§3.4). This modeling enables SCULPTOR to assess 13M configurations (6,000 \times more than other solutions) while only measuring tens (§5.5).

Second, we prototype and evaluate our framework in a system, SCULPTOR, at Internet scale using the PEERING testbed [64], which is now deployed at 32 Vultr cloud locations [76]. Vultr is a global public cloud that allows customers to issue BGP advertisements via more than 10,000 peerings (§4).

We demonstrate that SCULPTOR computes prefix advertisements that give users low latency both during normal operation and under variable network conditions, and allows Service Providers to use their deployments more efficiently than using other advertisement strategies, reducing costs.

Specifically, we found that SCULPTOR reduces latency during both steady state and failure: SCULPTOR improves the amount of traffic within 10 ms of optimal by 3% in steady state (§5.2), 11% during link failure, and 17% during site failure. SCULPTOR also reduces congestion on links during site failures by 17% on average, giving Service Providers more confidence that services will still be available during partial failure (§5.3). Hence, SCULPTOR can serve more traffic with less congestion and do so with almost the same latency that an optimal (but unreasonably expensive) solution can.

Providing good backup paths to handle dynamic conditions improves more than just latency — we find that by load balancing traffic on backup paths during peak times, we can satisfy very high peak demands with the same infrastructure. SCULPTOR can handle flash crowds (DDoS attacks, for example) at more than 3 \times expected traffic volume, drastically reducing the amount of overprovisioning that Service Providers need, thus reducing costs. SCULPTOR can also handle large diurnal swings of almost 2 \times expected load (§5.4).

Hence, SCULPTOR improves interdomain routing for users to Service Providers, uses Service Provider resources more effectively, and acts as a tool for more efficient capacity planning, preparing Service Providers to provide the increasingly reliable, performant service that our applications need.

2 Motivation and Key Challenges

Service Providers offer their services from tens to hundreds of geo-distributed sites. The sites for a particular service can serve any user, but users benefit from reaching a low latency site for performance. Sites consist of sets of servers which have an aggregate capacity. Service Providers also connect to other networks (often thousands) at sites via dedicated links or shared IXP fabrics. Each such link also has a capacity. When utilization of a site or link (collectively, a resource) nears/exceeds 100%, performance suffers, so Service Providers strive to keep utilization reasonably low. Resources can also fail completely due to, for example, physical failure and misconfiguration.

2.1 Tighter Requirements, Variable Conditions

Evolving Internet use cases and new applications with strict performance requirements are pushing Service Providers to offer more reliable, performant service. For example, Service Providers increasingly offer mission-critical services such as enterprise solutions [36] which are predicted to be a \$60B industry by 2027 [31], so ensuring performant, reliable operation is more important for these services than ever. Similarly, gaming, an immersive application that requires latency within 50 ms [51], is an industry that now generates more revenue than the music and movie industries *combined* [6].

Despite their desire to provide these emerging applications, Service Providers still face challenges in providing reliable performance especially under dynamic conditions caused by factors *outside* their network. For example, peering disputes can lead to congestion on interdomain links/inflated paths [17, 20], and DDoS attacks can bring down sites/services [61, 53, 59, 37] despite the considerable effort in mitigating DDoS attack effects [54, 79]. Moreover, recent work shows that user traffic demands are highly variable due to flash crowds and path changes and so are much harder to plan for than inter-datacenter demands [43, 56, 14]. Operators regularly report these traffic surges on social media and blog posts [32, 41, 52, 48, 27, 49].

2.2 Routing Traffic to Satisfy Requirements

A challenge in offering low latency, reliable services to users is routing traffic from user networks to Service Provider networks, since Service Providers lack full control of which interdomain path traffic takes. BGP, the Internet’s interdomain routing protocol, computes paths in a distributed fashion, giving each intermediate network a say in which paths are chosen and which are communicated to other networks. Service Providers can, however, advertise their reachability to peers/providers (*i.e.*, “expose paths”) in different ways to increase the chance of there being good paths for users. Today,

Service Providers either direct users to specific sites using unicast prefix advertisements [38, 65, 12], or use anycast prefix advertisements to provide relatively low latency and high availability at the expense of some control [8, 35, 86, 85].

Anycast, where Service Providers advertise a single prefix to all peers/providers at all sites, offers high availability following failures since BGP automatically reroutes most traffic to avoid the failure after tens of seconds [86]. Prior work shows that this availability comes with higher latency in some cases [44, 35]. Unicast can give clients lower latency than anycast by advertising a unique prefix at each site [12] but can suffer from reliability concerns [36].

Recent work proposes/studies hybrids of unicast and anycast which achieve a tradeoff between performance and availability [8, 82, 85, 36]. This latter class of solutions advertises different prefixes to subsets of all peers/providers to offer multiple low latency path options across different links/sites. We refer to these solutions as *selectivecast* solutions since they are *selective* about who they advertise prefix reachability to and have traits of both anycast (advertising at many sites to many peers/providers) and unicast (multiple prefixes, selectivity).

2.3 Current Approaches Do Not Consider Dynamic Conditions

Existing approaches to expose low latency paths do not, however, plan for changing traffic conditions. These approaches only strive to give users low latency *primary* paths. Figure 1 shows how a certain dynamic scenario, failure, can lead to performance problems, even with *selectivecast* advertisements. In normal operation, user traffic is split evenly across two prefixes (Fig. 1a). However when site B fails, BGP chooses the route through Provider 1 for all traffic, causing link overutilization (Fig. 1b).

Instead, the current state-of-practice to handle dynamic conditions is to reactively drain traffic from overloaded links/sites by *withdrawing* prefix announcements while still advertising them via other healthy links/sites [54, 50, 62]. After BGP reconverges the traffic destined to those prefixes then arrives on other links/sites advertising those prefixes. However, this solution to handling dynamic conditions is error-prone [45], post-hoc, unpredictable (as BGP is unpredictable), and ineffective. For example, TIPSy only achieves 70% prediction accuracy and (in a case study) required several prefix withdrawals to mitigate a single congested link [50].

Another common solution to handling dynamic conditions is to overprovision resources to handle predicted peak loads [72, 2, 45], but Figure 2 demonstrates that doing so can incur excessive costs. Figure 2 computes differences in peak utilization on links between different successive time periods, using longitudinal link utilization data from OVH cloud [57]. We split the dataset into successive, non-overlapping 120-day planning periods and compute the 95th percentile link uti-

lization (“near-peak load”) for each link and for each period. We then simulate assigning future capacities from period to period by setting each link’s capacity for the next period as the near-peak load in the current period multiplied by some overprovisioning factor. We compute resulting average link utilizations in the next period assuming that overprovisioning factor, and count the total number of links we see congestion on assuming that overprovisioning rate.

Figure 2 plots the hypothetical median utilization across links and periods and the number of congestive events as we vary the overprovisioning factor. Figure 2 shows that overprovisioning to accommodate peak loads introduces a tradeoff between inefficient utilization and congestion. Low overprovisioning factors between 10% and 30% lead to more efficient utilization (60-70%) but lead to thousands of congestive events. High overprovisioning factors lead to far less congestion, but only roughly 50% utilization. Using backup paths instead to handle relatively rare peak loads can help achieve both utilization and low congestion. One Service Provider also stated that solely installing extra capacity is not a feasible solution without shifting traffic [65].

2.4 Key Differences in Interdomain

Prior work finds ways to prepare for intradomain failure even under dynamic traffic conditions [77, 46, 10, 34, 14], which implicitly requires allocating backup paths. Compared to this intradomain setting, two key differences in the interdomain setting are that (a) a Service Provider cannot precisely control the paths traffic takes since BGP relinquishes this control to other networks and (b) a Service Provider cannot easily determine the bottleneck capacity of paths before placing traffic on them. We explicitly address the former problem and leave the latter problem as future work.

We model paths from users to the Service Provider through the public Internet as non overlapping, except at the peering link through which each path ingresses to the Service Providers’ deployment. Users share the capacity of those peering links. We assume the peering link is the bottleneck of each path. We consider traffic *ingressing* the deployment since, in the egress setting, the Service Provider has full control over traffic up until the egress point, which is the only part of the egress path the Service Provider can control. Existing systems direct egress traffic to optimize performance and mitigate congestion [65, 81, 28].

Although we do not explicitly address problem (b) above, we implicitly address it by finding failure-resistant interdomain routing strategies (*i.e.*, we find backup paths to route around congestion), and there are natural extensions of our setting that consider such effects. For example, one could use congestion-detection mechanisms along paths to trigger traffic shifts to other, healthier (backup) paths. Other prior work on ingress [36] and egress traffic engineering [81, 65, 40] also does not explicitly address this problem.



Figure 1: In normal operation traffic is split between two sites by directing half the traffic to each prefix (1a). When site B fails, there is enough global capacity to serve all traffic (each link can handle 1 unit) but no way to split traffic across multiple providers given available paths leading to link overload (1b). A *resilient* solution is to advertise prefix 2 to an additional provider at site A, allowing traffic splitting across the two links (1c).

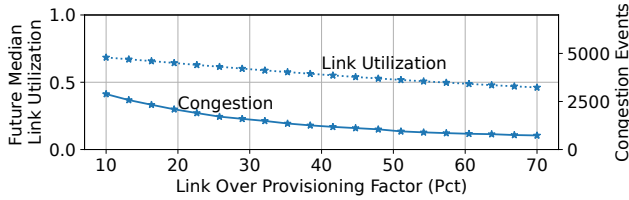


Figure 2: Planning for peak loads to avoid congestion requires inefficient overprovisioning.

Service Providers lack interdomain control for their ingress traffic, but there is hope that they can handle dynamic conditions. A Service Provider has enough global capacity to handle even large changes in traffic or sudden traffic shifts from one link to another [14, 1, 33], and should do so without reconfiguring BGP (§2.3). Figure 1c shows that this planning is possible — advertising prefix 2 to provider 2 at site A a priori allows the Service Provider to split traffic between the two links during failure *without reconfiguring BGP*, avoiding both overload and risky reconfiguration.

2.5 Key Challenges

Since a Service Provider has lots of global capacity, placing traffic on paths to optimize performance objectives subject to capacity constraints would therefore be simple if all the paths from users to the Service Provider were available. However, making paths available uses IPv4 prefixes, which are monetarily expensive and pollute BGP routing tables. IPv6 is not a good alternative, as IPv6 routing entries take 8× the amount of memory to store in a router so would pollute global routing tables even more. Prior work noted the same but found that advertising around 50 prefixes was acceptable [82, 36], and most Service Providers advertise fewer than 50. Since we cannot expose all the paths by advertising a unique prefix to each connected network, we must find some subset of paths to expose.

Finding that right subset of paths to expose that satisfies performance objectives, however, is hard since there are expo-

entially many subsets to consider and since measuring paths takes time. The number of subsets is on the order of 2^n to the number of peers/providers Service Providers have which, for many Service Providers is $> 2^{1,000}$. Therefore, we have to predict how different subsets of paths perform which is challenging since interdomain routing is difficult to model, and since there are too many possible dynamic traffic conditions (failures, attacks) over which to assess these predictions.

3 Methodology

3.1 SCULPTOR Overview

SCULPTOR’s high level goal is to find an advertisement strategy that optimizes latency subject to capacity constraints during both steady state and dynamic network conditions. Considering capacity constraints when optimizing latency means that some traffic placement decisions become correlated since different users share the same capacity. Hence, considering capacity constraints makes computing optimized latencies a large optimization problem ($O(10k)$ constraints, $O(1M)$ decision variables) (§3.2.2).

Minimizing this objective function requires evaluating it with several different inputs, but performing such measurements (*i.e.*, advertising prefixes) takes time, and so is not scalable. It would take at least 20 minutes per test to avoid route flap dampening which translates to years of optimization given the problem sizes that we consider (millions of evaluations). Instead, we estimate latency by predicting paths. Predicting interdomain paths is hard, however, so we model paths probabilistically (§3.3.1), and update this model over time using a small number of measurements in the Internet (§3.5).

Computing latency probability distributions for each user network and then computing how correlations among those networks impact utilization *millions* of times is also intractable so, when optimizing, we compute approximately optimal user traffic placement onto paths. Our approximation

assigns users in a way that balances a desire for low uncongested latency (§3.3.2), and a desire for load balancing to avoid congestion (§3.3.3).

SCULPTOR’s power comes from its precise formulation of a global traffic engineering problem and the local approximations to this problem it makes to form a tractable solution. These approximations allow SCULPTOR to compare millions of possible advertisement strategies at milliseconds per computation, but only conduct tens in the actual Internet to refine its routing model. We now more thoroughly describe how SCULPTOR encounters and overcomes each of these challenges.

3.2 Problem Setup and Definitions

3.2.1 Setting and Goal

We aim to advertise relatively few prefixes to connected networks to offer low latency paths under dynamic conditions from user networks to the Service Provider subject to capacity constraints on links. Adding capacity constraints on sites (*e.g.*, servers) in addition to links would be a straightforward extension. We encourage low latency under dynamic conditions by minimizing latency during both steady state and single link/site failures, as minimizing for both intuitively encourages good primary and backup routing options.

We assume the Service Provider has some technology for directing traffic towards prefixes. Examples include DNS [12, 8, 38], multipath transport [60, 18], or control-points at/near user networks [63, 36]. DNS offers slow redirection due to caching [36] but is the most readily deployable by the largest number of Service Providers, whereas Service Provider-controlled appliances offer precise control but may not be a feasible option for some Service Providers. Service Providers with stronger incentives to provide the best service to users will invest in better options with more control, and eventually multipath transport will see wide enough deployment to be used by all Service Providers. Today, MPTCP is enabled by default in iOS [5] and Ubuntu 22 [24], and MPQUIC can be installed on any device in user space with applications [84]. SCULPTOR assumes that all users can be precisely directed to each prefix.

Service Providers connect to peers/providers at sites via physical connections we call peering links. Users route to the deployment through the public Internet to a prefix, over one of the peering links via which that prefix is advertised. The path (and therefore peering link) is chosen via BGP. We consider users at the granularity of user groups (UGs), which generally refer to user networks that route to the Service Provider similarly and experience similar latency, but could mean different things to different Service Providers (*e.g.*,/24 IPv4 prefixes, metros). UGs generate known steady state traffic volumes, v_{UG} , and the Service Provider provisions capacity at links/sites to accommodate this load. We assume a system run

by the Service Provider measures latency from UGs to Service Provider peering links l enumerated as $L_{UG,l}$. (Having these measurements is a reasonable assumption [9, 12, 19, 82, 36]). For a given UG, paths towards prefixes may be different and so may have different latencies.

3.2.2 Precise Problem Formulation

As in prior work [82, 36], we model an advertisement configuration A as a set of $\langle \text{peering}, \text{prefix} \rangle$ pairs where $\langle \text{peering}, \text{prefix} \rangle \in A$ means that we advertise that prefix via that peering. We then seek an advertisement configuration that minimizes latency (\mathcal{L}) during normal operation (N) and single link/site failures (F_l):

$$\min_A \sum_{UG} \mathcal{L}_{UG}(A, N) v_{UG} + \sum_l \alpha_l \sum_{UG} \mathcal{L}_{UG}(A, F_l) v_{UG} \quad (1)$$

The weighting factors α_l control the tradeoff between a desire to minimize steady state latency and to minimize failure-state latencies. Having different α_l for different links/sites l is not necessary, but allows operators to, for example, optimize for failures/conditions that are more likely.

We cannot just compute $\mathcal{L}_{UG}(A, N)$ by assigning each UG to its lowest-latency path, as paths from many UGs share links that are capacity constrained. Instead, we need to consider other path options that may have higher uncongested latency but can be used to avoid causing congestion.

A given advertisement configuration during normal operation exposes a set of paths $P(A, N)$ to UGs through peering links (l), each of which we identify with tuples (UG, l) . (Considering failure scenarios F_l is similar). To compute the latency $\mathcal{L}_{UG}(A, N)$ a UG experiences under an advertisement configuration A under deployment N , we solve for the globally optimal allocation of UG traffic to paths under A . This allocation is the solution to the following linear program for the allocation of UG traffic to paths $w_{UG,l}$.

$$\begin{aligned} w_{UG,l}^* = \arg \min_{w_{UG,l}} \quad & \sum_{UG, l \in P(A, N)} L_{UG,l} w_{UG,l} + \beta MLU \\ \text{s.t.} \quad & w_{UG,l} \geq 0 \\ & \sum_l w_{UG,l} = v_{UG} \quad \forall UG \\ & MLU \geq \frac{\sum_{UG} w_{UG,l}}{c_l} \quad \forall l \end{aligned} \quad (2)$$

Latency for a UG in Equation (1) is then the weighted sum of path latencies $L_{UG,l}$ according to this optimal allocation: $\mathcal{L}_{UG}(A, N) = \sum_l L_{UG,l} w_{UG,l}^*$.

The minimization term in Equation (2) is the sum of latency and maximum link utilization (MLU), weighted by a parameter β . β represents a tradeoff between using uncongested links/sites and low propagation delay and is set by the Service

Provider based on their goals. We first solve Equation (2) with $MLU = 1$ to see if we can allocate traffic to paths with zero congestion. However such congestion-free solutions do not always exist for arbitrary advertisement strategies A .

The first/second constraints in Equation (2) require that UG volume on a link $w_{UG,l}$ be non-negative and sum to the UG 's total volume v_{UG} across all links. Constraining MLU to be at least as much as the utilization of each link (the third constraint) and then minimizing a sum including it forces MLU to be the maximum link utilization. Hence, optimizing Equation (2) amounts to finding low latency assignments of UG s to links that cause minimal congestion. (We also tried similar optimization problems with different utilization penalties than MLU , such as total utilization across paths, and found that they led to similar evaluation results.)

By searching for solutions to Equation (2) in both normal operation N and under link/site failure F_l we encourage low latency, resilient advertisement strategies in Equation (1).

3.3 Accommodating Internet's Limitations

Solving Equation (1) is challenging because computing $\mathcal{L}_{UG}(A, N)$ requires advertising prefixes in the Internet, which can only be done infrequently to avoid route-flap-dampening. For example, in our optimization (detailed below) we compute $\mathcal{L}_{UG}(A, N)$ for millions of different A which could take tens to hundreds of years at a rate of advertising one strategy per 20 minutes. Hence we model, instead of measure, UG paths and improve this model over time through relatively few measurements.

3.3.1 Probabilistic UG Paths

Representing both Equation (1) and Equation (2) as a single mixed-integer linear program (*i.e.*, solving directly for A) would be feasible if we knew exactly how UG s routed to all possible advertisements, but routing is hard to predict [55, 4, 50, 62].

We instead model routing probabilistically and update our probabilistic model over time as we measure how UG s route to the deployment, adapting methods from prior work [82, 67, 36]. That is, in Equation (1) we model $\mathcal{L}_{UG}(A, N)$ probabilistically and denote the corresponding random variable with a tilde: $\tilde{\mathcal{L}}_{UG}(A, N)$. Our probabilistic model assumes a priori, for a given UG towards a given prefix, that all ingress options that prefix is advertised to for a UG are equally likely. Upon learning that one ingress is preferred over the other, we exclude that less-preferred ingress as an option for that UG in all future calculations for all prefixes for which both ingresses are an option. As we exclude more options, latency/path distributions on unmeasured scenarios converge to the true latency/path. An example of this process is shown in Figure 3, where we refine our latency estimate towards an

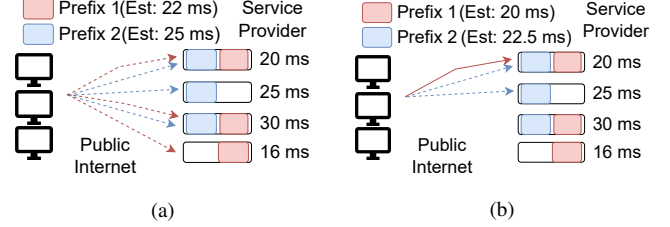


Figure 3: With no knowledge of routing preferences, we estimate latency from this UG to both the red and blue prefixes with the average over possible ingress latencies (3a). We measure towards the red prefix (*e.g.*, using `traceroute`) and learn that the first ingress has higher preference than the third and fourth ingresses. We use this information to refine our latency estimate towards the blue prefix (since the third ingress is no longer a possible option (3b)) without measuring the blue path.

unmeasured prefix (blue) using measurements towards other prefixes (red).

3.3.2 Capacity-Free UG Latency Calculation

To assign traffic to prefixes we should solve Equation (2). However, for unmeasured advertisements, we only have an estimate of the distribution of possible (as opposed to actual) paths. For a given A , there are many possible paths from UG s to prefixes, so Equation (2) is too challenging to solve even probabilistically. Instead, when computing $\tilde{\mathcal{L}}_{UG}(A, N)$ we assume every user takes their lowest-latency path. Such decisions do not take capacity into account, which we account for later.

Since we model paths as probabilistic, user path choices and what latency UG s experience ($\sum_{UG} \tilde{\mathcal{L}}_{UG}(A, N) v_{UG}$) is also probabilistic. We model the objective function in Equation (1) as the *expected value* of the summations. That is, if the latencies for UG across different paths under advertisement A are $\tilde{\mathcal{L}}_{UG}(A, N)$, we compute the distribution of the minimum choice, $\min_l \tilde{\mathcal{L}}_{UG}(A, N)$, and then compute the distribution over the sum $\sum_{UG} \min_l \tilde{\mathcal{L}}_{UG}(A, N) v_{UG}$. We use the minimum latency choice as a simple approximation of how traffic is directed to sites for which we can compute a probability distribution.

3.3.3 Imposing Capacity Violation Penalties

It could be that such minimum latency assignments lead to congested links, especially during link/site failures. We would like to penalize such advertisement scenarios, and favor those that distribute load more evenly without solving Equation (2) which would take too long. Hence, before computing the expected latency, we first compute the probability that links are congested by computing the distribution of link utilizations from the distribution of UG assignments to paths. We then inflate latency for UG s on likely overutilized links.

That is, for each possible outcome of UG assignments to links, we compute link utilizations and note the probability



Figure 4: A UG has a path to two prefixes, green and blue. The green prefix is only advertised via ingress A and the blue prefix is advertised via two ingresses B and C, each of which are equally likely for this UG. If the UG prefers B over C, we assign the client to the blue prefix (10 ms) while if the UG prefers C over B we will assign the client to the green prefix (15 ms). Hence the initial expected latency is the average of 10 ms and 15 ms corresponding to whether this UG prefers ingress B or C (4a). However, ingress B does not have sufficient capacity to handle this UG’s traffic and so is congested with 50% probability corresponding to the 50% probability that this user prefers ingress B. We artificially inflate this UG’s expected latency (and all other UG’s using ingress B) to reflect this possible overutilization (4b).

those UGs reach each link. We then accumulate the probability a link is congested as the total probability over all possible scenarios that lead to overutilization. We discourage UGs from choosing paths that are likely congested using a heuristic — we emulate the impact of congestion by inflating latency in this calculation for UGs on those paths proportional to the overutilization factor. After emulating the effect of this congestion, we recompute the distribution of average UG latency **without changing UG decisions**, and take the expected value of this random variable in Equation (1) as a proxy for the true latency. We do not change UG decisions as doing so could induce an infinite calculation loop if new decisions also lead to congestion. This heuristic penalizes advertisement strategies that would lead to many overutilized links if every user were to choose their lowest latency option. We show an example in Figure 4.

During optimization we observed that these heuristics tended to yield accurate estimates of overall benefit when averaged across the entire deployment (*i.e.*, Equation (2)), despite inaccuracies in predicting any individual UG’s latency or link’s utilization.

3.4 Solving with Gradient Descent

Even with our efficient objective function approximations, we cannot solve Equation (1) directly/exhaustively since the optimization variable is an integer matrix. Instead, we approximate the optimization variable A as a continuous variable with entries between 0 and 1 and threshold its entries at 0.5 to determine if a prefix is advertised/not advertised to a certain peer/provider. We then solve Equation (1) using gradient descent, approximating gradients between adjacent advertisements using sigmoids, adopting methods used in the optimization literature [42].

Gradient descent is appropriate for two reasons. First, it is parallelizable, which is important given the high dimension of A (tens to hundreds of thousands of entries representing all $\langle \text{peering}, \text{prefix} \rangle$ pairs). Second, it simultaneously weighs several (possibly opposing) goals in Equation (1) according to their global importance in minimizing the objective. Intuitively, Equation (1) has opposing goals, since advertising prefixes to expose backup paths may push some UGs off their lowest-latency route but may also encourage demand spreading under dynamic conditions, which is more important than having the *lowest* steady state latency..

We do not compute all entries of the gradient of Equation (1) since there are too many to compute. Instead, we use Monte-Carlo techniques, subsampling entries of the gradient to estimate the gradient as in prior work [68].

Upon thresholding entries of our optimization variable A at 0.5, we obtain an advertisement strategy to test in the Internet. We conduct such advertisements during optimization if we have not advertised another strategy in the last hour (to avoid route flap dampening). Conducting such advertisements refines our latency estimates as they inform us of which ingresses are more preferred.

Minimization scales linearly with the number of UGs, quadratically with the number of peers/providers, and linearly with the number of prefixes. Despite this high complexity, in practice the implementation runs quickly (minutes per gradient step) relative to the rate at which we can advertise prefixes (once an hour). Although solving Equation (1) does not have convergence guarantees, we have found that it finds good solutions over a wide range of simulated topologies, and converges quickly with thousands of UGs and $\langle \text{peering}, \text{prefix} \rangle$ pairs (§5).

3.5 Exploration to Improve Model

As, a priori, we do not know UG preferences, we may be uncertain about the benefit of other advertisement strategies which could make solving our model using gradient descent noisy/unstable. For example, an adjacent strategy could have better *expected* latency than the current one but have much worse *actual* latency. Gradient descent would then push us towards a worse strategy.

To improve convergence, we periodically compute benefit distributions on adjacent advertisement schemes and look for strategies for which we are very uncertain about whether it will be better or worse. One could use different measures of uncertainty — we choose entropy. Testing advertisement strategies in the Internet takes time (as measuring all paths takes time) but we observed that it improves convergence.

4 Implementation

We prototype SCULPTOR on the PEERING testbed [64], which is now available at 32 Vultr cloud sites. We describe how we

built *SCULPTOR* on the real Internet and how we *emulate* a Service Provider including their clients, traffic volumes, and resource capacities. (We are not a Service Provider and so could not obtain actual volumes/capacities, but our extensive evaluations (§5) demonstrate *SCULPTOR*’s potential in an actual Service Provider and our open/reproducible methodology provides value to the community.)

4.1 Simulating Clients and Traffic Volumes

To simulate client performances, we measured actual latency from IP addresses to our PEERING prototype as in prior work [36] and selected targets according to assumptions about Vultr cloud’s client base.

We first tabulate a list of 5M IPv4 targets that respond to ping via exhaustively probing each /24. Vultr informs cloud customers of which prefixes are reachable via which peers, and we use this information to tabulate a list of peers and clients reachable through those peers.

After tabulating peers, we then measure latency from all clients to each peer individually by advertising a prefix solely to that peer using Vultr’s BGP action communities and pinging clients from Vultr. We also measure performance from all clients to all providers individually, as providers provide global reachability.

In our evaluations, we limit our focus to clients who had a route through at least one of Vultr’s direct peers (we exclude route server peers [11]). Vultr likely peers with networks with which it exchanges a significant amount of traffic [65], so clients with routes through those peers are more likely to be “important” to Vultr. We found 700k /24s with routes through 1086 of Vultr’s direct peers. In an effort to focus on interesting optimization cases, we removed clients whose lowest latency to Vultr was 1 ms or less, as these were assumed to be addresses related to infrastructure, leaving us with measurements from 666k /24s to 825 Vultr ingresses.

As we do not have client traffic volume data, we simulate traffic volumes in an attempt to both balance load across the deployment but also encourage some diversity in which clients have the most traffic. To simulate client traffic volumes, we first randomly choose the total traffic volume of a site as a number between 1 and 10 and then divide that volume up randomly among clients that *anycast* routes to that site. Client volumes in a site are chosen to be within one order of magnitude of each other.

Although these traffic volumes are possibly not realistic, we believe that by demonstrating the efficacy of *SCULPTOR* over a wide range of subsets of sites and simulated client traffic volumes, we demonstrate that *SCULPTOR*’s benefits are not tied to any specific choice of sites or traffic pattern within those sites.

4.2 Deployments

We use a combination of real experiments and simulations to evaluate *SCULPTOR*. Both cases use simulated client traffic volumes, but our real experiments measure real paths using RIPE Atlas probes, while our simulations use simulated paths.

4.2.1 Experiments in the Internet

We assess how *SCULPTOR* performs on the Internet using RIPE Atlas probes [70], which represent a subset of all clients. RIPE Atlas allows us to measure paths (and thus ingress links) to prefixes we announce from PEERING, which *SCULPTOR* needs to refine its model (§3). However, RIPE Atlas does not have large coverage, as probes are only in 3,000 networks, and we are limited by RIPE Atlas probing rate constraints (15k traceroutes/day).

4.2.2 Simulations

We also evaluate *SCULPTOR* by simulating user paths. Simulating user paths allows us to conduct more extensive evaluations as experiments take less time and use clients in more networks. To limit computational complexity, we select 100 clients with a route through each ingress. Service Providers could similarly limit computational complexity by optimizing over, for example, a certain percent of the traffic which is a common practice in the networking optimization literature [8, 47, 36, 56].

4.3 Setting Resource Capacities

We assume that resource capacities are overprovisioned proportional to their usual load. However, we do not know the usual load of links and cannot even determine which peering link that traffic to one of our prefixes arrives on, as Vultr does not give us this information. (This limitation only exists since we are not a Service Provider, as a Service Provider could measure this using IPFIX, for example, to measure steady state link loads.) We overcome this limitation using two methods (corresponding to our two deployments in Section 4.2), each with their pros and cons.

For our first method of inferring client ingress links, we advertise prefixes into the Internet using the PEERING testbed [64], and measure actual ingress links to those prefixes using traceroutes from RIPE Atlas probes [70]. Specifically, we perform IP to AS mappings and identify the previous AS in the path to Vultr. This approach has limited evaluation coverage, as RIPE Atlas probes are only in a few thousand networks. In cases where we cannot infer the ingress link even from a traceroute, we use the closest-matching latency from the traceroute to the clients’ (known) possible ingresses. For example, if an uninformative traceroute’s latency was 40 ms to Vultr’s Atlanta site and a client was known to have a 40 ms

path through AS1299 at that site, we would say the ingress link was AS1299 at Atlanta.

The second method we use to determine ingress links is simulating user paths by assuming we know all user routing preference models (§3.3). We use a preference model where clients prefer peers over providers, and clients have a preferred provider. When choosing among multiple ingresses for the same peer/provider, clients prefer the lowest-latency option. We also add in random violations of the model. This second approach allows us to evaluate our model on all client networks but may not represent actual routing conditions. However, we found that our key evaluation results (§5) hold regardless of how we simulated routing conditions (we also tried completely random routing), suggesting that our methodology is robust to such assumptions. Prior work also found the preference model to be valid in 90% of cases they studied [82].

Given either method of inferring client ingress links (RIPE Atlas/simulations), we then measure paths to an *anycast* prefix and assign resource capacities as some overprovisioned percentage of this catchment. (Discussions with operators from Service Providers suggested that they overprovision using this principle.) We choose an overprovisioning rate of 30%.

5 Evaluation

SCULPTOR compares favorably to all other solutions on all studied dimensions. In particular, it yields an advertisement strategy that gives clients lower latency paths and fewer congested links during both steady state (§5.2) and failure (§5.3). We then demonstrate that SCULPTOR can handle dynamic loads such as flash crowds or diurnal patterns by exposing well-performing backup paths for users (§5.4).

5.1 General Evaluation Setting

We compare SCULPTOR’s advertisement strategy to other advertisement strategies. The strategies include

anycast: A single prefix announcement to all peers/providers at all sites, which is a very common strategy used by Service Providers today [25, 15, 8, 75, 58, 80, 85].

unicast: A single prefix announcement to all peers/providers at each site (one per site). Another common strategy used in today’s deployments [38, 12].

AnyOpt/PAINTER: Two proposed strategies for reducing steady state latency compared to anycast [82, 36].

One-per-Peering: A unique prefix advertisement to each peer/provider, so many possible paths are always available from users. This solution serves as our performance upper-bound, even though it is prohibitively expensive. (We do not know an optimal solution with fewer prefixes.)

For our evaluation on the public Internet (§4.2.1), we limit the scale of our deployment to 10 large sites to avoid reach-

ing RIPE Atlas daily probing limits. These 10 sites were Miami, New York, Chicago, Dallas, Atlanta Paris, London, Stockholm, Sao Paulo, and Madrid. We found it valuable to thoroughly evaluate how our system works in a few countries, rather than sparsely evaluate how it works over many countries. We do not compute the solution for AnyOpt for our evaluations on the Internet since AnyOpt did not perform well compared to any other solution in our simulations, and since computing AnyOpt takes a long time. We use 12 prefixes, which is low, since we do not have many prefixes. Choosing RIPE Atlas probes to maximize network coverage and geographic diversity, we select probes from 972 networks in 38 countries which have paths to 484 ingresses.

For our simulated evaluations (§4.2.2), we compute solutions over many random routing preferences, demands, and subsets of sites to demonstrate that SCULPTOR’s benefits are not limited to a specific deployment property. We evaluate SCULPTOR over deployments of size 3, 5, 10, 15, 20, 25, and 32 sites. Each size deployment was run at least 10 times with random subsets of UGs, UG demands, and routing preferences. We use one tenth of the number of peers/providers as the number of prefixes in our budget for all solutions (except **One-per-Peering**). For larger deployments (20-32 sites) we use approximately 60 prefixes, and for smaller ones (3-15 sites) we use between 10 and 30. Prior work found that using this many prefixes to improve performance was a reasonable cost [82, 36]. Over all studied deployments, we consider paths from clients in 42k /24s to 868 peers/providers.

In solving Equation (2), the lowest link utilization solution may have overloaded resources in failure scenarios. We say all traffic arriving on a congested link is congested and do not include this traffic in latency comparisons (actual latency would be a complicated function of congestion control protocols and queueing behavior). We comment separately on how much traffic is congested.

We compute both average overall latency and the fraction of traffic within 10 ms (very little routing inefficiency), 50 ms (some routing inefficiency), and 100 ms (lots of routing inefficiency) of the **One-per-Peering** solution for each advertisement strategy.

5.2 Lower Latency in Steady State

5.2.1 Internet Deployment

We compute the latency that each advertisement solution achieves compared to the **One-per-Peering** solution for each UG. Figure 5a shows a CDF of these differences weighted by traffic, demonstrating that SCULPTOR outperforms other solutions with realistic routing. SCULPTOR is only 3.0 ms worse than (the unreasonably expensive) **One-per-Peering** solution whereas the next best solution, **unicast**, is 8.4 ms worse. SCULPTOR also serves 88.8% of traffic within 10 ms of **One-per-Peering**, whereas the same is true for only 69.5%



Figure 5: SCULPTOR finds advertisement solutions that yield low steady state latency subject to capacity constraints both on the Internet (5a) and in simulation (5b).

of traffic with a unicast solution.

PAINTER does not do as well as unicast here (but does in simulation), which may be because of our relatively low budget of 12 prefixes. We use more prefixes in our simulations, and prior work noted that the most significant gains when using roughly 40 prefixes [36].

5.2.2 Simulations

Figure 5b shows the average latency compared to the One-per-Peering solution over all simulated deployments at each deployment size. Average latency for SCULPTOR ranges from 0.1 to 2.5 ms worse than (the undeployable) One-per-Peering. The next-best solution (PAINTER) is on average 1.2 ms and 2.4 ms worse than SCULPTOR.

anycast comparatively performs the worst with UGs being on average 17.9 ms worse than One-per-Peering whereas SCULPTOR performs the best with UGs being 1.3 ms worse than One-per-Peering. Interestingly, unicast (6.1 ms worse than One-per-Peering) actually performs better than AnyOpt (10.1 ms worse than One-per-Peering) which could be due to the different setting AnyOpt was designed for (AnyOpt was designed to optimize latency without capacity constraints over a small number of provider connections which does not capture the realities of many Service Providers).

These average latency improvements translate into quantifiable routing inefficiency for different fractions of traffic (we include full results in Appendix A.1). SCULPTOR has on aver-

age 94.8% traffic within 10 ms of the One-per-Peering solution, 99.2% within 50 ms, and 99.9% within 100 ms. These percentages compare to the next-best solution, PAINTER, which has on average 91.7% traffic within 10 ms of the One-per-Peering solution, 97.4% within 50 ms, and 99.2% within 100 ms.

5.3 Better Resilience to Failure

We next assess SCULPTOR’s ability to provide resilience to ingress failures and site failures. Examples of such failures include excessive DDoS traffic on the link/site (thus using the link/site as a sink for the bogus traffic), physical failure, draining sites, and/or planned maintenance. Figure 6 demonstrates that SCULPTOR shifts traffic without overloading alternate links/sites more effectively than any other solution *without reconfiguring BGP* which is error-prone [45] and slow [86].

In these evaluations, we fail each ingress/site once and compute UG to link allocations using Equation (2). For each advertisement strategy and failed component, we compute the difference between achieved latency and One-per-Peering latency for UGs who use that component in steady state. For example, if the Tokyo site fails, we report on the post-failure latency of UGs served from Tokyo before the failure and not of other UGs.

We separately note the fraction of traffic that lands on congested links for each solution. We do not include congested traffic in average latency computations but say such traffic does *not* satisfy 10 ms, 50 ms, or 100 ms objectives.

5.3.1 Internet Deployment

Figure 6a demonstrates that SCULPTOR offers lower latency paths for more UGs during single link failure in realistic routing conditions. On average, SCULPTOR is only 7.2 ms higher latency than One-per-Peering while the next best solution, unicast, is 12.6 ms worse than One-per-Peering. PAINTER struggles to find sufficient capacity for UGs, with 40.8% congestion.

Single site failures (shown in Appendix A.2) show similar results. On average, SCULPTOR is 18.8 ms higher latency than One-per-Peering while the next best solution, unicast, has 16% congestion and PAINTER has 86% congestion during site failure.

5.3.2 Simulations

We show the fraction of traffic within 50 ms of the One-per-Peering solution for link and site failures in Figure 6b and Figure 6c (further results are in Appendix A.2).

For single-link failures, anycast comparatively performs the worst with UGs being 55.4 ms worse than One-per-Peering on average, whereas SCULPTOR ranges



Figure 6: SCULPTOR improves resilience to failure both on the Internet (6a) and in simulation (6b, 6c).

from 1.4 ms and 9.8 ms worse than One-per-Peering on average. SCULPTOR also avoids more congestion, with only 0.6% of traffic being congested on average while PAINTER (the next-best solution) leads to 2.3% of traffic being congested on average. Single-site failure exhibits similar trends where SCULPTOR is 10.5 ms worse than One-per-Peering and has 22.9% traffic congestion, on average, while PAINTER leads to 19.5 ms worse than One-per-Peering and 39.9% congestion on average.

When looking at routing inefficiency, SCULPTOR has 78.2% of traffic within 10 ms of the One-per-Peering solution on average, 93.0% within 50 ms, and 97.2% within 100 ms during link failure. These statistics compare to the next-best solution, PAINTER, which has 66.9% within 10 ms, 83.4% within 50 ms, and 90.4% within 100 ms. Site failures show similar trends (full results are in Appendix A.2).

Differences quoted above may seem small (for example, 11.3% in the amount of traffic within 10 ms of One-per-Peering between SCULPTOR and PAINTER), but represent potential fractions of *trillions* of requests per day made across the whole world [65]. Large Service Providers recently emphasized that these seemingly small gains make large differences [22, 78].

5.4 Efficient Infrastructure Utilization

One response to increased link/site utilization is to install more capacity so that there is sufficient headroom to satisfy peak demand. Figure 7 shows that this response is not always necessary with better routing — SCULPTOR finds ways to distribute load over existing infrastructure to accommodate increased demand without adversely affecting latency. We quantify this improved infrastructure utilization by showing how much extra peak load each routing strategy can help satisfy without congestion, where peak load is distributed according to two realistic traffic patterns: flash crowds and diurnal effects.

We define a flash crowd as a transient traffic increase at a single site. Examples of flash crowds include content releases (games, software updates) that spur downloads in a particular region. Since increased demand is highly localized, we can spread excess demand to other sites if paths to those sites exist.

To generate Figure 7, we identify each client with a single

“region” corresponding to the site at which they have the lowest possible latency ingress link. For each region individually, we then scale each client’s traffic in that region by $M\%$ and compute traffic to path allocations using Equation (2). If there are S sites in the deployment, we thus compute S separate allocations per M value where each allocation assumes inflated traffic in exactly one region. We increase M until any link experiences congestion when we (separately) scale volume in any region. For example, if Atlanta experiences congestion with a 60% increase in traffic for Atlanta clients, but no other region does, we call $M = 60\%$ the critical value of M .

Our diurnal analysis uses a similar methodology. We comment on results here and include figures showing those results in Appendix A.3. We define a diurnal effect as a traffic pattern that changes volume according to the time of day. Diurnal effects might be different for different Service Providers, but a prior study from a large Service Provider demonstrates that these effects can cause large differences between peak and mean site volume [14]. We sample diurnal patterns from that publication and apply them to our own traffic. We group sites in the same time zone and assign traffic in different time zones different multipliers — in “peak” time zones we assign a multiplier of M and in “trough” time zones a multiplier of $0.1M$. The full curve is shown in Appendix A.3. Similar to our flash crowd analysis, we increase M until at least one link experiences congestion at least one hour of the day.

5.4.1 Internet Deployment

Figure 7a shows how congestion varies over M for our flash crowd analysis. SCULPTOR has roughly the same resilience to flash crowds (critical $M = 235$) as unicast (critical $M = 248$), and both these solutions have far more resilience than PAINTER (critical $M = 35$) and anycast (critical $M = 22$). Our diurnal analysis (appendix A.3) shows similar results, with both unicast and SCULPTOR achieving a critical M value of 95 while PAINTER’s is 40.

5.4.2 Simulations

Figure 7b plots the average over simulations of critical M values that cause congestion for each deployment size under flash crowds.

Figure 7b shows that SCULPTOR finds ways to route more traffic without congestion than other solutions. SCULPTOR

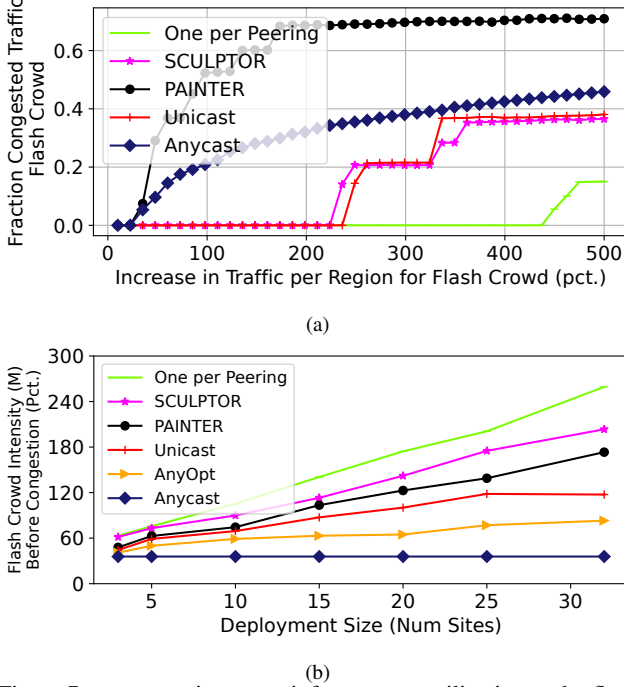


Figure 7: SCULPTOR improves infrastructure utilization under flash crowds so that Service Providers can underprovision compared to peak loads.

can handle single-site flash crowds at 200% more than the expected volume for deployments with 32 sites, creating a 3 \times savings in provisioning costs assuming Service Providers plan for peak loads (22% more than PAINTER). SCULPTOR also handles more intense diurnal traffic swings (full results in Appendix A.3), allocating traffic to paths without congestion for between 11% and 23% more intense swings than both PAINTER and unicast with 32 sites. Hence, instead of scaling deployment capacity to accommodate peak time-of-day traffic, Service Providers can re-distribute traffic to sites in off-peak time zones.

Moving traffic to backup paths does not necessarily mean reduced performance. SCULPTOR usually increases latency by less than 5 ms on average up to the critical M value. In practice, Service Providers can move less latency-sensitive traffic onto these backup paths so as to not impact high-level application goals. Some intradomain traffic engineering systems use similar mechanisms [33, 29, 28].

Prior work noted similar benefits by satisfying user requests in distant sites [14], but moved traffic on their own backbone to realize these gains. SCULPTOR’s benefits are orthogonal to this prior work, and useful for Service Providers without private backbones, as they use the public Internet to realize the same result. From conversations with operators from both Meta and Microsoft, we also learned that their systems (Edge Fabric [65] and Fastroute [23]) do not always shift traffic on their backbones since backbone capacity is precious.

It is interesting that PAINTER provides similar benefits to unicast— this result is likely since PAINTER only aims to

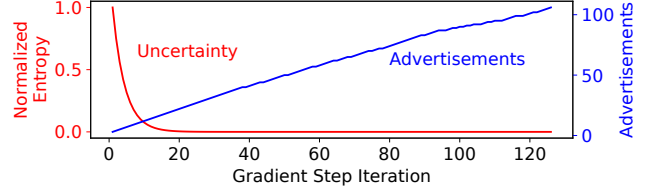


Figure 8: SCULPTOR’s model entropy decreases exponentially with few path measurements.

reveal low latency primary paths for users, whereas unicast guarantees reachability to all sites guaranteeing users a minimum number of paths (one of which may have capacity).

5.5 Why SCULPTOR Works

SCULPTOR tries to solve a challenging integer optimization problem with an objective function it can only approximate and, as our analysis demonstrates, finds solutions that outperforms other approaches to the problem. SCULPTOR’s quickly predicts how other advertisement strategies perform so that it can pick the best ones. This prediction is an approximation of true performance (§3.1) and the question we aim to answer here is why those approximations work.

First, SCULPTOR compares far more advertisement strategies than the other solutions. In our 32 site deployments over 200 gradient steps SCULPTOR estimates latencies in approximately 13M scenarios across every single UG. PAINTER only considers thousands (2k), and AnyOpt considers 1k (a configurable number). Tango [7], a system that exposes better paths by advertising prefixes, also measures roughly thousands of different advertisements but that system is meant for a different setting and so is not directly comparable to SCULPTOR.

PAINTER has a simple method of estimating latencies in unseen scenarios, but its greedy approach means that it only considers a single strategy per measurement iteration. AnyOpt can estimate latencies in unseen scenarios, but randomly searches through the space. Hence, both AnyOpt and PAINTER conduct a large number of measurements on the Internet relative to the configurations they estimate. SCULPTOR, on the other hand, only conducts measurements for exploration (§3.5) or for strategies that SCULPTOR thinks will yield good performance (§3.4). Figure 8 shows how SCULPTOR’s model entropy exponentially decreases as it makes these measurements on the Internet. (We plot the maximum entropy of unmeasured advertisement strategies (§3.5).) Intuitively, this quick convergence is likely since latency is much easier to predict than paths — UGs have similar latency to many ingresses at the same site, so being uncertain about which paths UGs take usually does not matter from a latency optimization perspective.

6 Related Work

Egress Traffic Engineering Prior work noted that traffic from large service providers to users sometimes experienced suboptimal performance (congestion, high latency) due to BGP’s limitations [81, 65, 40]. SCULPTOR works in tandem with these systems, similarly working with BGP, but to optimize ingress traffic. Other work also shifts traffic to other links/sites to lower cost [83, 69, 14]. SCULPTOR adapts this idea in a new way but instead uses the public Internet to carry traffic to lower costs.

Ingress Traffic Engineering Other work aims to overcome the limitations of BGP to perform ingress traffic engineering [8, 47, 23, 82, 86, 85, 36], but optimizes for steady state conditions. SCULPTOR optimizes for dynamic traffic conditions, reducing costs and enhancing performance compared to these solutions as we demonstrate in Section 5. Pecan [74] and Tango [7] exhaustively expose paths between endpoints and so may provide resilience to dynamic traffic conditions if the right paths were exposed. However, exposing all the paths does not scale to our setting since there are too many paths to measure, and doing so would require too many prefixes.

Other work and companies create overlay networks and balance load through paths in these overlay networks to satisfy latency requirements [73, 30, 3, 16, 43]. SCULPTOR can work alongside these overlay networks, by advertising the external reachability of these nodes in different ways to create better paths through the overlay structure.

Prior work built a BGP playbook to mitigate DDoS attacks [62], but it is unclear if those strategies would scale to large service providers (they tested on a few sites and a few providers). SCULPTOR provides a scalable approach to dealing with arbitrary dynamic traffic conditions over thousands of peering links.

Microsoft withdraws prefixes to mitigate congestion on links [50]. However, as they demonstrate in their paper, such actions are unpredictable and can lead to further congestion. SCULPTOR instead plans ahead, minimizing congestion time and providing better resilience guarantees.

New Last-Mile Technology to Improve Performance Xlink uses MPQUIC over 5G, WiFi, and LTE to offer improved bandwidth for video streaming services on mobile devices [84]. DChannel uses both of 5G’s high bandwidth and low latency channels to optimize web performance [66]. TGaming [13] uses feedback from a 5G network telemetry system to improve performance. All of these systems can work alongside SCULPTOR, as SCULPTOR uses multiple endpoints (as opposed to multiple sources) to enhance performance.

Intradomain Failure Planning Large Service Providers have shown significant interest in reducing the frequency/impact of failures in their global networks [21, 26, 39, 45]. SCULPTOR works alongside these systems by, for example, enabling Service Providers to shift traffic away from

failed components/regions while still retaining good performance.

Other prior work tried to plan intradomain routes to minimize the impact of k-component failures [77, 46, 10, 34, 14]. SCULPTOR uses different strategies to accomplish a similar goal that account for the unique challenges in interdomain routing (see Section 2.4 for a more thorough comparison).

7 Conclusions

As the role that Service Providers play in our daily lives increases, and as applications require increasingly demanding performance from the network, Service Providers need better guarantees that their services will continue to work well in an unpredictable Internet. SCULPTOR uses efficient Internet models and optimization techniques to provide these better guarantees by tapping into the unused capacity of a Service Provider’s global resources, offering better resilience to link/site failure and traffic growth. SCULPTOR is a step towards providing the truly resilient, performant service that the applications which enable our daily lives need.

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A Further Results

A.1 Steady State Latency

In addition to quantifying average latency during steady state, we also compute the fraction of traffic within 10 ms, 50 ms, and 100 ms of the *One-per-Peering* solution during steady state. Figure 9 shows how *SCULPTOR* compares more favorably to the *One-per-Peering* solution than other advertisement strategies.

A.2 Latency During Link/Site Failure

We show additional evaluations of *SCULPTOR* during link and site failures. ?? shows that *SCULPTOR* provides good resilience to site failures on the Internet, and Figure 11 shows similar results for link and site failures in our simulations.

A.2.1 Internet Deployment

SCULPTOR provides better resilience than other solutions to site failures on the Internet, yielding no congested traffic and on average 18.1 ms worse than *One-per-Peering*. The next best solution, *unicast*, yields 16.1% congestion and, for uncongested traffic, 28.1 ms worse latency than *One-per-Peering* on average.

A.2.2 Simulations

A.3 Infrastructure Utilization Further Results

Here, we show detailed results for our diurnal analysis (described in Section 5.4). Figure 12 shows the shape of our diurnal curve taken from observed diurnal traffic patterns at a large service provider [14]. Figure 13 *SCULPTOR* provides better resilience to larger diurnal swings both on the Internet (Fig. 13a) and in simulation (Fig. 13b), therefore using the same infrastructure more efficiently than other advertisement solutions.

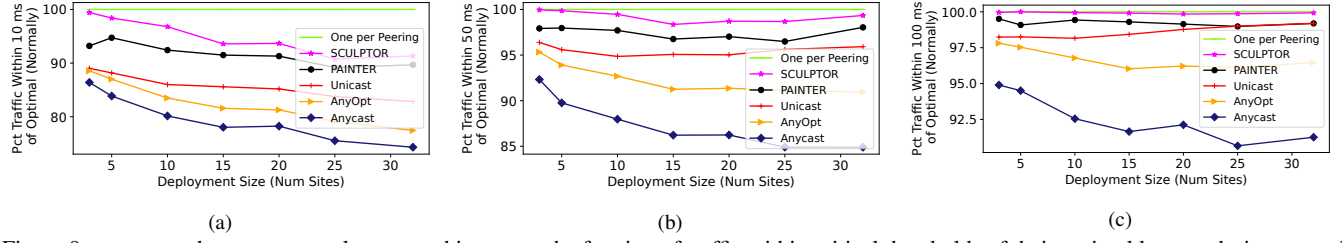


Figure 9: SCULPTOR lowers average latency and increases the fraction of traffic within critical thresholds of their optimal latency during normal operation.

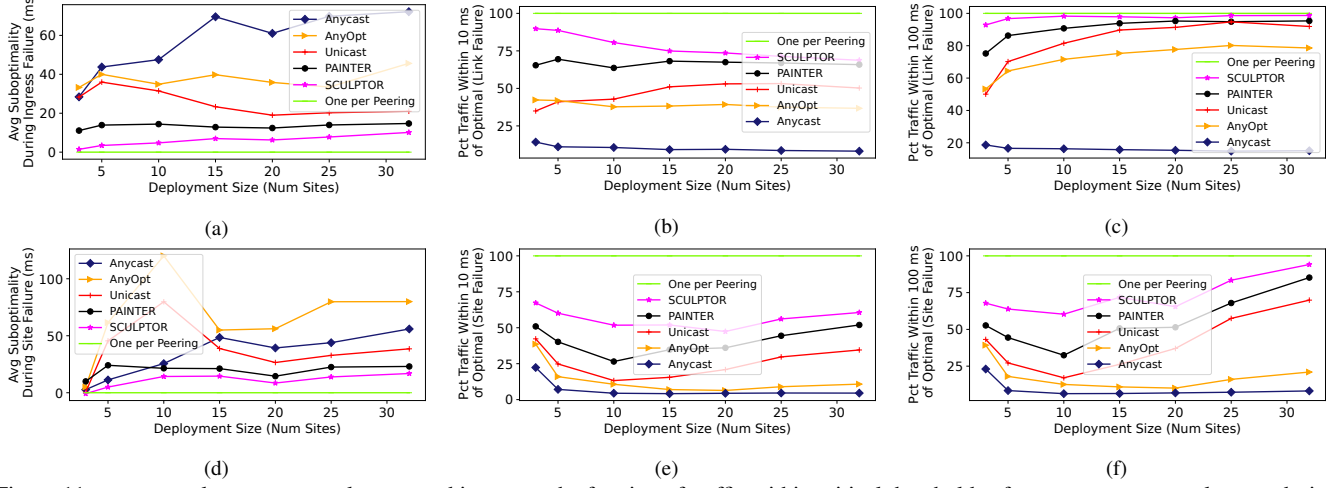


Figure 11: SCULPTOR lowers average latency and increases the fraction of traffic within critical thresholds of One-per-Peering latency during both link and site failures over many simulated deployments.

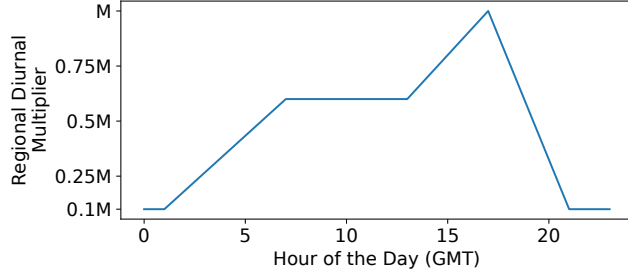


Figure 12: The diurnal traffic shape we apply in Section 5.4, taken from prior work [14].

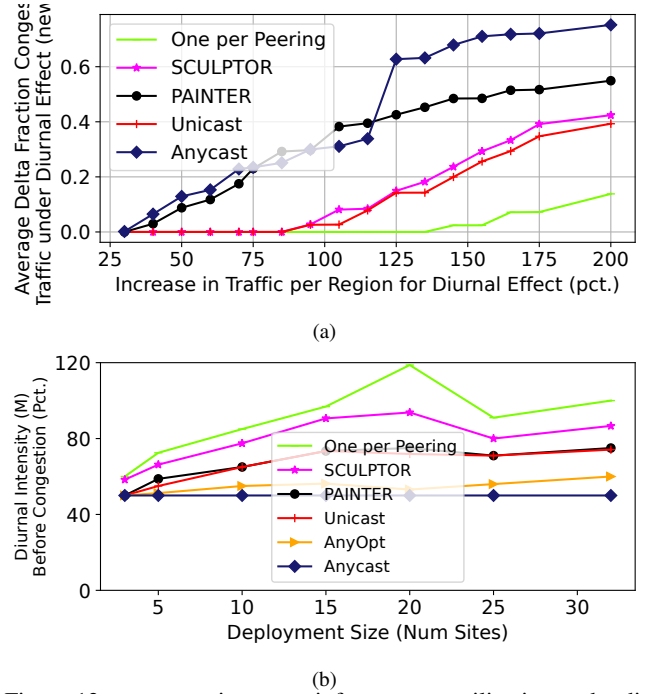


Figure 13: SCULPTOR improves infrastructure utilization under diurnal traffic patterns so that Service Providers can underprovision compared to peak loads.

