Internet Backbones in Space

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ABSTRACT

Several "NewSpace" companies have launched the first of thousands of planned satellites for providing global broadband Internet service. The resulting low-Earth-orbit (LEO) constellations will not only bridge the digital divide by providing service to remote areas, but they also promise much lower latency than terrestrial fiber for long-distance routes. We show that unlocking this potential is non-trivial: such constellations provide inherently variable connectivity, which today's Internet is ill-suited to accommodate. We therefore study cost–performance tradeoffs in the design space for Internet routing that incorporates satellite connectivity, examining four solutions ranging from naïvely using BGP to an ideal, clean-slate design. networking architecture in which end-hosts obtain information and control over network paths. However, a pragmatic and more deployable approach inspired by the design of content distribution networks can also achieve stable and close-to-optimal performance.

CCS CONCEPTS

• **Networks** → **Network architectures**; **Routing protocols**; **Network economics**; **Public Internet**; **Network dynamics**; *Network simulations*; *Topology analysis and generation*;

KEYWORDS

Low-Earth-orbit satellite networks, routing, Internet

1 INTRODUCTION

A new gold rush is unfolding in space as commercial enterprises begin to launch constellations of hundreds to thousands of satellites into low Earth orbit (LEO). This massive deployment will be used to provide broadband Internet service, targeting a market with a potential annual revenue of tens of billions of dollars [6]. While similarly ambitious past efforts were largely unsuccessful, the "NewSpace" industry is counting on new technologies such as satellite miniaturization and rocket reusability to make global LEO-based connectivity profitable.

Such satellite networks (SNs) could expand Internet coverage at broadband speeds and low latency to the most remote areas. Beyond last-mile consumer connectivity, SNs could even disrupt Internet transit connectivity. A LEO-based transit Internet service provider (ISP) would provide global reach and much lower latency for long-distance communication than terrestrial fiber: for distances beyond a few thousand kilometers, the latency overhead of ground-to-LEO-satellite communication is more than compensated by the faster speed of light in vacuum compared to fiber [25] and by avoiding long, meandering fiber routes. Besides superior coverage and lower latency, SNs are expected to introduce competition where regional monopolies hinder development and maintain high prices.

However, realizing these exciting prospects requires addressing new challenges. SNs are fundamentally different from terrestrial networks: the topology changes perpetually as satellites fly over ground stations and move relative to each other, requiring constant re-routing within the SN. At first glance, it may appear that these physical-layer changes within an SN are an entirely internal matter for the SN, which can be safely ignored by peers. However, three factors make it difficult for an SN to abstract away its quirky physical-layer characteristics from network peers and cause problems in the *external* connectivity: (a) atmospheric effects and satellite failures result in time-varying connectivity; (b) commercial viability will necessitate partial deployments, which provide sporadic connectivity based on the temporary presence of satellites; and (c) the lower latency but higher cost of satellite-based transit will require the possibility to differentiate traffic, allowing deliberate decisions about when to prefer a satellite path over a terrestrial one.

We investigate the above challenges in detail, illustrating the difficulty of integrating SN-based transit into Internet routing. To this end, we take readers on a journey through a series of four routing approaches, starting with simply having a satellite-network autonomous system (SN-AS) participate in Border Gateway Protocol (BGP) routing. The poor performance and routing instability of this first-cut approach motivates our other designs, which expose different tradeoffs in cost for the SN-AS, the extent of cooperation required from other ASes, and performance in terms of utilizing SN-AS bandwidth and achieving low latency.

Our final design can be deployed without large changes to the Internet's routing system. It draws inspiration from how the infrastructure of content distribution networks (CDNs) works today: directing clients to nearby, available satellite ground stations (GSTs) is a problem similar to finding nearby CDN servers. Our approach exploits the fact that fiber connectivity is available as a control channel for satellite connectivity; in settings where fiber connectivity is unavailable, the solution is straightforward: the only recourse is to use satellite connectivity, as intermittent or expensive as it may be.

We evaluate the performance of this CDN-inspired approach in terms of the global communication latency it delivers in comparison with the optimal path choices that are achievable only via a clean-slate approach. We find that our design makes only minor compromises on performance in the average case, while also being practically deployable.

The main contributions of this work are the following:

- We quantitatively expose the challenges involved in integrating satellite networks into Internet routing.
- We survey the solution space, highlighting the tradeoffs involved between cost and other barriers to deployment on the one hand, and routing stability and performance on the other hand.

- We show that two straightforward, first-cut approaches to the problem either cause instability or are too costly. This analysis involves a study of partial deployment of an SN in a custom simulator that simulates satellite orbits, and the resulting connectivity and latency.
- By fleshing out a clean-slate Internet routing approach explicitly aimed at accommodating SNs, we draw out the ideal routing properties in this setting.
- Lastly, we propose a deployable and effective routing mechanism. Evaluating our approach with physical connectivity which varies based on historical rain data, we show that on average, our mechanism's routing performance nearly matches that of the clean-slate approach.

2 UNDERSTANDING THE PROBLEM

2.1 Anatomy of a satellite network

An SN consists of two components: the *space segment*, a constellation of satellites interconnected with inter-satellite links (ISLs), and the *ground segment*, some number of terrestrial ground stations (GSTs) that form bidirectional communication links with the constellation, called ground-to-satellite links (GSLs). GSTs are points of presence with multiple antennas capable of tracking many satellites simultaneously and are also connected to the ground fiber network. A typical end-to-end connection through an SN may thus consist of terrestrial connectivity between GSTs and terrestrial end-points, up and down GST-satellite connections, and potentially several ISLs.

Our interest is in LEO satellite constellations, in which satellites orbit the Earth at altitudes of a few hundred to few thousand kilometers above the Earth's surface. Such low orbits imply low latency for the GST–satellite connections, unlike traditional satellites in geostationary Earth orbit (GEO). For long-distance communication, LEO constellations can thus achieve end-to-end latencies lower than terrestrial fiber due to the circuitousness of terrestrial fiber routes and the speed of light in fiber being slower than in air or vacuum, roughly $2c/3$. The downside is that LEO systems are inherently dynamic: unlike GEO satellites, LEO satellites move fast relative to the Earth and to each other. Thus, the connectivity between GSTs and satellites and end-to-end paths through satellites vary over time.

2.2 Goal: an SN selling Internet transit

There is obvious utility in last-mile satellite-based connectivity, especially for home consumers in remote areas. However, an SN may also offer Internet transit to other ISPs. A simple illustrative use case of such an arrangement is for tier-3 ISPs, who may purchase low-latency transit from an SN and sell it as a premium low-latency add-on service to enterprises and home users. But more generally, any ISP could purchase SN transit to offer premium low-latency service to its own customers. We omit further discussion of the direct-to-consumer scenario, as it is simple to implement from the perspective of Internet routing, and focus on an SN aiming to offer transit connectivity.

Such an SN seeks to profit from carrying latency-sensitive long-haul transit. It would most likely offer more expensive transit, due to the limited network capacity, in comparison with fiber.

2.3 Why is the goal non-trivial?

There are two key issues that complicate the interaction of SNs with other ASes. First, SNs provide time-varying connectivity and performance due to several fundamental reasons, listed below. Such short-term–time-variant connectivity is difficult to incorporate into Internet routing, where routing *stability* is a key concern, and route changes are slow to propagate.

- LEO satellites move at high speeds relative to the Earth. As a result, latency and bandwidth will fluctuate as GSTs switch between satellites.
- Crowding in the radio spectrum for GSLs will push the use of higher frequency bands with more bandwidth. At these frequencies, atmospheric rain fade severely degrades radio communication, reducing throughput by orders of magnitude.[1]
- Deploying hundreds or thousands of satellites will take years. If the operators cannot generate revenue from a partial deployment, given the capital-intensive nature of the industry, they will run a serious risk of failure, as with past attempts [30, 42]. In partial deployments, connectivity will be volatile.
- ISLs will also be bandwidth-constrained, with capacity estimates ranging from 5 to 20 Gbps. Augmenting the throughput between dynamically changing 'hot' end-points will require non-shortest path routing, trading off some latency for bandwidth.

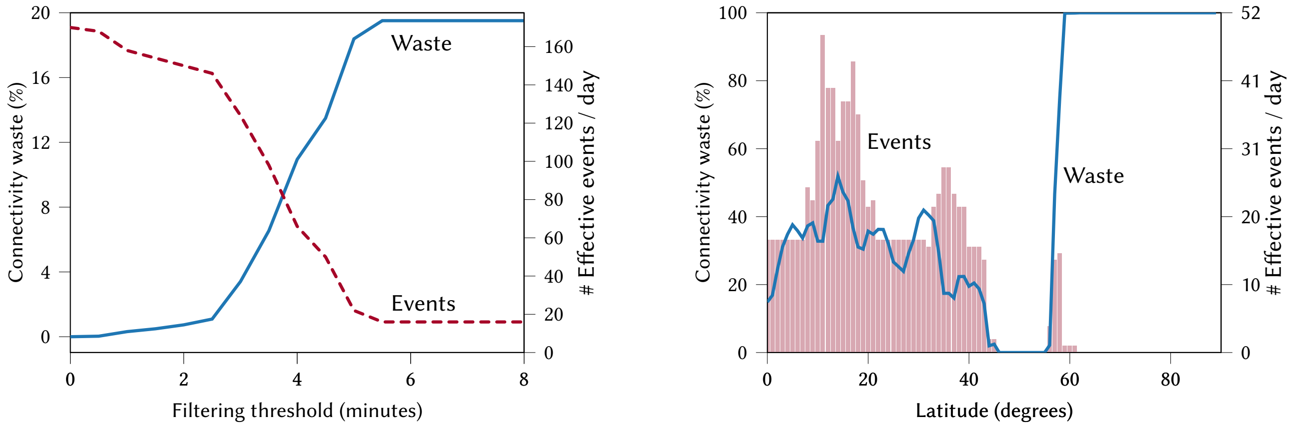
A second difficulty stems from the cost–performance tradeoff that is already present in the Internet, but sharpened by SNs. SNs can provide connectivity with much lower latency than today's Internet for long-distance routes. But this connectivity will be limited in bandwidth due to SN resource constraints; thus, the high demand for this scarce resource, along with the cost for deployment and upkeep of the constellation, will increase its price. However, Internet routing does not accommodate real-time advertisements of changing path latency that would allow network peers to make appropriate path choices.

2.4 What if an SN just uses BGP?

The obvious first-cut method for integrating an SN into Internet routing would be to operate it like any other AS today, a SN-AS. We will refer to this approach as the "white-box" model, as changes to the connectivity of GSLs are transparently exposed to the inter-domain routing infrastructure.

The fatal problem with this approach is its lack of support for performance and connectivity dynamics. If the highly variable connectivity information is announced via BGP, it will create high levels of route churn and cascades of BGP updates, causing global routing instability. However, announcing connectivity changes less frequently would mean either not using satellite bandwidth even when available, or even worse, not promptly withdrawing routes

[1]Even on short ranges, rain fade attenuates millimeter waves from a few dB to tens of dB, depending on rain conditions and frequencies used [36].



(a) The number of connect–disconnect events at 40° latitude and the percentage of connectivity waste as a function of the filtering threshold.

(b) The number of connect–disconnect events and the percentage of connectivity waste by latitude. The filtering threshold is set to 6 minutes.

Figure 1: The effect of the filtering threshold on the number of connect–disconnect events and the resulting connectivity waste. Based on a 10 % deployment of the SpaceX phase 2 constellation. Because of the relative motion of the satellite orbital planes and the Earth, these figures are independent of longitude.

that cease to exist, creating black holes. As we quantitatively show, there is no profitable operational point in this tradeoff space.

We evaluate the impact of a partially deployed SN being naïvely added to the Internet's BGP routing system through simulation. We calculate the number of events that would trigger external routing updates, i.e., a GSL becoming either available or unavailable. Using a custom-built simulation tool, we model the orbits of a 10 % deployment of the SpaceX phase two satellite constellation[2] and determine the volatility of coverage. Our simulations show that satellites frequently become available only for a short duration of a few minutes. Since such availability windows are too short to be useful for Internet routing, we use filtering to remove windows below a certain threshold, thus reducing the number of routing updates. In contrast, an availability window that is filtered out (i.e., not announced) induces connectivity waste. Figure 1a, which shows both the number of events and the amount of waste as the threshold varies, illustrates the tradeoff between the frequency of announcements and the efficient usage of the SN. While the graph displays the values for a latitude of 40°, Figure 1b shows that there is a similar tradeoff at different latitudes. Even if the threshold is fixed at 6 minutes and most events are filtered out, close to 20 events per day remain for each GST, each triggering at least one BGP update. This is despite setting the threshold so high that 15 – 45 % of available connectivity is wasted.

Further, each of the connection–disconnection events discussed above results in at least one, but in most cases *many* BGP announcements, as many prefixes from different ASes become unreachable worldwide after the disconnection of a single GST. This is further aggravated by the fact that both end-stations of a satellite path suffer from the same volatile connectivity behavior. The resulting large volume of BGP announcements will trigger route flap damping and disable routes, preventing the use of satellite paths. Frequent connectivity interruptions would thus make it extremely challenging to integrate constellations directly into today's Internet routing fabric. Connectivity variations rooted in factors other than partial deployment (see §2.3) would pose similar issues for inter-domain routing using this white-box approach.

3 MANAGING SN DYNAMICS INTERNALLY?

Drawing on extensive research in networking on problems like failover routing, could we manage the SN's time-varying connectivity similarly, hiding connectivity changes from network peers by the SN-AS *internally* re-routing over backup terrestrial connectivity? In the following, we examine such a "black-box" approach.

This design requires building (or leasing) redundant terrestrial connectivity between the GSTs. It is an entirely *intra-domain* solution, placing the burden for ensuring Internet-like stability on the SN-AS, thus assuring external network peers that familiar connectivity expectations will hold.

In this case, unlike the white-box approach (§2.4), the SN-AS must operate both the GSTs and a terrestrial wide area network (WAN) interconnecting the GSTs as a backup network. This is essential to shift the burden of redundant connectivity from external peers to the SN-AS. When traffic arrives at a GST which does not have active GSLs due to any of the connectivity-limiting factors discussed in §2.3, the traffic can be opaquely re-routed through the terrestrial WAN, thus preventing any inter-domain instability and packet loss.

While superficially attractive, this approach is costly: the large expense of building and operating the ground segment must be

[2]Phase *one* will be composed of satellites without ISLs, and is therefore only suited for remote access and last-mile connectivity. Phase two, on the other hand, will be the first complete satellite constellation to provide Internet services to have ISLs. Further phases will add more reliable and redundant systems.

borne entirely by the SN, instead of being distributed among a large number of terrestrial network peers. As the following estimates show, these additional costs greatly heighten the risk of economic failure for an SN.

We study the cost of deployment of the ground segment of a SN using a *cost model* along the lines to the one proposed by del Portillo et al. [9]. In this model, the total cost of a ground-segment deployment is divided into recurring and non-recurring costs. The non-recurring costs are subdivided into (i) infrastructure construction costs, (ii) the cost of antennas in GSTs, and (iii) the cost of leasing or building the WAN to interconnect the GSTs. We disregard the recurring operational expenditure as we are interested in the lower bound of the bootstrapping costs.

GST cost. We estimate the cost of building a single GST by using the Facilities Pricing Guide of the Department of Defense of the United States [33]. According to the guide, the cost for a US-based satellite ground station is on the order of 7 million dollars. To this value, the cost of the antennas on site has to be added. According to a previous analysis [8], 30 antennas per GST maximize throughput while simultaneously minimizing the interference in next-generation satellite constellations. Regarding the cost of an antenna, it is hard to estimate what the impact of economies of scale will have on production. However, we can assume that a lower-bound is the cost of Very Small Aperture Terminals (VSATs). These antennas cost from 20,000 up to a few hundred thousand dollars. Assuming a mid-range value of 100,000 dollars, the price for the 30 antennas of a single GSTs around three million dollars.

Wide area network. A simulation is required to assess the cost of interconnecting GSTs with a WAN, as it depends not only on the number of stations but also on their location. The choice of the optimal placement of GSTs given cost and performance constraints is a hard problem, and is outside the scope of this article. Therefore, we use a simple heuristic to simulate the positioning of the stations: we choose the positions of GSTs by sampling from a probability distribution based on the gross domestic product (GDP) per unit area of the globe [31]. This is based on the observation that most GSTs will be built in populous, economically developed areas with high demand for such services.

Then, we estimate the cost of the interconnecting WAN in the following way. First, we compute the distances from the GSTs to their closest Internet exchange point (IXP).[3] These GSTs are deployed to provide inter-domain routing services; we ignore the ones that provide only single-homed last-mile access. Second, we filter out all the connections that are longer than 1000 km and any trans-oceanic hops, as these can be realistically leased from existing fiber. At the same time, we assume that the remaining connections will have to be built anew.

This construction provides an optimistic lower bound on the amount of fiber that the SN operator should deploy to maintain redundant connectivity between any pair of GSTs. Pricing the deployment of fiber at 10,000 dollars per kilometer—a very conservative figure—we estimate the cost of the fiber alone. Table 1 shows the results of the simulation for a varying number of GSTs. Note that this analysis excludes equipment to light the fiber, support facilities and staff, management costs, and leasing prices for trans-oceanic fiber. The use of more sophisticated topologies for redundancy could increase this cost manifold. Beyond raw costs, there are complex competitive issues: as a provider of physical connectivity, the SN would need to lease connectivity from its direct terrestrial competitors.

To back this figure, we perform the simulation again with a different choice of GSTs: we assume that they are deployed in all cities in the world with more than 300,000 inhabitants. This would minimize the communication latency between these major centers. The deployment of the WAN for the 1833 GSTs required would cost 11.85 billion dollars. Looking at Table 1b, we see that the cost for the same number of GDP-sampled GSTs is on the same order of magnitude, but slightly less expensive.[4]

Table 1: Overall cost of some black-box deployments.

(a) Breakdown of the costs for each GST.

Item of expenditure	Cost
Infrastructure building	7 M$/GST
Antennas	3 M$/GST
Interconnecting WAN	10 k$/km

(b) Sample results of the cost model. For random deployments, the average cost over 1000 simulations is reported.

GST deployment type	# GSTs	WAN (B$)	Total (B$)
GDP-based (random)	100	0.47	1.5
	500	2.3	7.3
	1000	4.6	15
	1833	8.5	27
At biggest cities	1833	12	30

Summing up. The three parts of the deployment cost presented in this section are summed up and shown in Table 1 (“Total”), for some simulated deployments of GSTs. The estimated cost of the whole SpaceX Starlink constellation is expected to be on the order of 10 billion dollars, and many are already doubting its economic viability and chances of success [44]. The black box model adds the cost of the WAN on top of this, more than doubling the original figure and highly increasing the risk of failure for the SN.

4 OPTIMAL ROUTING

The two models presented so far were unable to deliver a scalable and cost-effective system for routing on satellite backbones. But their shortcomings help us translate our high-level objective (§2.2) to concrete properties an ideal routing system must provide to support SNs. We next discuss how these ideal properties can be achieved.

[3] To obtain the locations, we reverse-geolocated the database of IXPs found at https://www.euro-ix.net.

[4] An interesting but, in retrospect, unsurprising observation is that the distribution of IXPs follows the distribution of GDP more closely than population. This further supports our choice of GDP-based GST sampling in §3.

Stability & cost. We have shown that SNs have peculiar characteristics, and that the integration in the Internet's fabric is far from straightforward. The fluctuating behavior of GSLs—in terms of connectivity, latency, and bandwidth—has to be hidden from the terrestrial BGP routing, to prevent excessive route churn and avoid long convergence times. Further, the analysis of the deployment cost of the ground segment shows that it can be prohibitive, matching or even surpassing the cost of the space segment itself. Sharing the cost of the deployment of the GSTs among different entities lowers the cost significantly for the SN-ASes, as well as speeding up the creation of access points to the satellites.

Finally, the cost of satellite-based transit will likely be higher than its terrestrial counterpart, as bandwidth will be a scarce resource. In the ideal case, low-priority, high-bandwidth traffic traverses the terrestrial Internet, while only high-priority traffic with low-latency requirements is sent on the satellite path. This raises the question of which entity will make the final decision on the choice of forwarding path. We remain agnostic to this dilemma, but we note that any successful satellite Internet architecture must deploy a system—no matter if it is in software at the endpoint, or implemented in the ISPs' routers—that chooses between satellite and terrestrial paths, controlling the cost of connectivity. Otherwise, satellite internetworking will remain a niche application.

In summary, to have any chance to be deployed, an architecture needs to (i) shield the terrestrial Internet from the SN's instability, (ii) allow for distributed deployments, splitting cost among entities, and (iii) enable the choice of the satellite path "on-demand".

Performance. In meeting the above requirements, the resulting system must not compromise the key performance metric and greatest promise of SNs: communication latency. Latency optimization needs to be dynamic, as the length of satellite path segments changes as satellites move, and the GSTs chosen as source and destination may become disconnected because of weather phenomena. This requires a routing architecture that provides *path control* (PaCo), and is thus able to dynamically select the end-to-end path, making informed choices about the state of the links on-route. Again, different entities can be the enforcing point of path control: ISPs may choose the optimal satellite path negotiating it with the SN-AS, or clients use paths from a selection provided by their ISPs. By contrast, the current Internet architecture gives no control on the path, aside from the choice of the next hop.

Achievability of the optimum. A system with the properties described above can be built using a path-aware-network (PAN) architecture [41]. PANs (i) distribute information about the state of the network to end hosts (*path awareness*), and (ii) enable them to make routing decisions based on this information (*path choice*). This increases the overall stability and performance of the network. Information on the state of the GSLs can be disseminated ahead of time, since most of the changes that affect them are due to orbital dynamics and weather conditions, and are therefore *highly predictable*, at least on short timescales. Path awareness makes this additional information readily available to communicating entities that can select a satellite path with the best possible latency. Stability is ensured by avoiding the withdrawal of prefixes at GSL failure, while relying on the application to select another available path.

We next use the SCION architecture [35] to describe how such an optimal PAN-based solution could be implemented.

SCION implementation. In SCION's control plane, paths are discovered by means of path-construction beacons (PCBs), that are exchanged between neighboring ASes at regular intervals. ISPs then distribute policy-compliant paths to end hosts, who can then choose from these according to application-specific requirements.

This system can be leveraged to embed more information in the PCBs (and, in turn, in the paths distributed to end hosts) on the status of the GSLs and of the constellation. Specifically, for each ground station on the path, we suggest to include (i) a representation of the connectivity variations of the GSLs, called *connectivity profile*, and (ii) a time-varying bandwidth class, representing the total bandwidth available from the GST to the satellites. The connectivity profile ensures that the path can be disseminated with no need for continuous announcements and withdrawals: the end host can determine whether the path is available at any point in time by intersecting the connectivity profiles of the GSTs on the path. The bandwidth class is used, in case the path is determined to be available, to check if the SN can support the bandwidth required for the communication. This bandwidth class will be computed as a function of the weather over the GSTs and the number of satellites in view. This can be used to estimate if the path, even if it is connected in principle, is actually unusable due to adverse conditions.

With this extension, SCION enables any AS to deploy a ground station, while at the same time avoiding inter-domain instability thanks to the *preemptive* dissemination of the connectivity profiles and bandwidth classes. Additionally, SCION enables native network-wide multipath, allowing traffic differentiation based on latency and bandwidth requirements: latency-critical traffic can be sent over the satellites while the rest can be forwarded on the terrestrial network, thus improving the cost-effectiveness of the system.

SCION has seen increasing deployment during the past years, with a production network spanning 5 ISPs, and a research network with 50 ASes,[5] but is still not widely available today. Therefore, we now present a system design that reaps comparable benefits to the clean-slate PAN-based solution in the average case—as we will show in our evaluation of the two systems—while being implemented with today's standard internetworking technologies.

5 A CDN-LIKE SATELLITE NETWORK

The networks of ground stations have a number of similarities with modern CDN networks: both systems are deployed to provide low-latency services, and they both face challenges due to their geographically distributed nature. Given these similarities, we propose a CDN-like infrastructure design for inter-domain satellite-networking services.

First, we will present the modes of deployment for the GSTs and the ground segment of the constellation. Then, we will provide an outline of the communication protocol. Finally, we will discuss how this system delivers the required properties.

[5] https://www.scionlab.org/

5.1 Ground station deployment

GSTs connecting to the SN are deployed inside hosting networks in strategic locations, following the strategy taken by many modern CDN providers. A small number of sites interconnected in a backbone serve the most congested areas, while the majority of sites are hosted by partnering networks that want to offer satellite services. In the second case, the infrastructural costs will be shared with the hosting ISP, greatly lowering the bar for diffused construction of GSTs. Even though the GSTs are multihomed and connected to the Internet, the reliability of the WAN interconnecting GSTs is lost, and additional measures must be put in place in order to mitigate the volatility of the satellite connection.

Every time a new GSTs is added to the network, its location is logged in a database shared among all GSTs. When in operation, GSTs continuously exchange information about connectivity and bandwidth available on their GSLs, as well as predicted outages based on short-term weather forecasts. We call a GST *inactive* if it has no GSL that is connected or if its available bandwidth is below a minimum threshold. Inactive GSTs will re-route their traffic to *active* GSTs over terrestrial networks.

5.2 Communication overview

We present an overview of the communication between source and destination end hosts over the SN.

Source to s-GST. The source initiates the communication by preparing a packet with the IP address of the destination and encapsulating it inside another IP packet with the address of the *geographically closest GST*, called source GST (s-GST). Similar to current CDN deployments, the choice of the closest GSTs relies either on DNS lookups or IP anycast, and is subject to similar tradeoffs. A recent study by Li et al. [27] shows that the performance of anycast can closely approximate the optimum—always choosing the nearest site—if the BGP announcements are augmented with geolocation information.

s-GST to d-GST. The s-GST receives the packet, decapsulates the internal packet and inspects the information contained. Two different cases arise at this point:

(1) The s-GST active. Then, using the information contained in the packet, the s-GST computes the active GST geographically closest to the destination (d-GST). The packet is forwarded over the satellite path, employing the internal routing protocol of the SN-AS.
(2) The s-GST is inactive. It will then forward the packet to its nearest active GST, which will then forward the packet to the SN. If none is available, the packet is re-routed on the terrestrial Internet. Since the GST is multihomed, this is achieved by removing the encapsulation and using the default routes of the BGP control plane. In case of congestion on the GSLs, a load balancer will determine the re-routing of packets to other nearby GSTs.

We call this scheme *re-routing* (ReRo), and compare its effectiveness against the optimal path-control scheme (see §6.2).

Determining the d-GST. Although the source can determine the s-GST, the s-GST itself needs a way to determine which other GST will be the optimal d-GST, that is to say which GST is closest to the destination. If GST address discovery is performed by DNS, the SN-AS already internally possesses a mapping between IP addresses and their closest ground stations, and can therefore use it to find the d-GST. If anycast is used, IP geolocation can be employed for the first transmission. When a packet is received from the destination, the s-GST can cache the GST the destination replied through.

d-GST to destination. When the packet arrives at the d-GST, it is forwarded via standard BGP routing to the destination.

5.3 Properties

The CDN-like SN integration system presents the following high-level features, which make it a good candidate for inter-domain routing with satellite constellations:

Satellite/Terrestrial path selection. The satellite path can be chosen by tunneling to the closest GST. The terrestrial path can be used by simply sending to the destination IP address. This creates an effective satellite/terrestrial path selection mechanism with little deployment and communication overhead.

Stability. Even without a global WAN, the terrestrial re-routing at GSTs successfully shields the terrestrial control plane from the many fluctuations of the GSLs. Thus, satellite constellations can be used in an inter-domain fashion without harming the existing infrastructure.

Distributed deployment. With the proposed deployment, the SN-AS does not need to single-handedly build all of the infrastructure (as with the black-box architecture). The cost of the GSTs' deployment is shared among the SN-AS and the hosting networks. Moreover, a global WAN interconnecting all the GSTs is not required, further lowering the total expenditure.

Almost-optimal latency. As we will see in §6.2, a deployment that reliably selects the geographically closest GST is able to deliver almost-optimal latency.

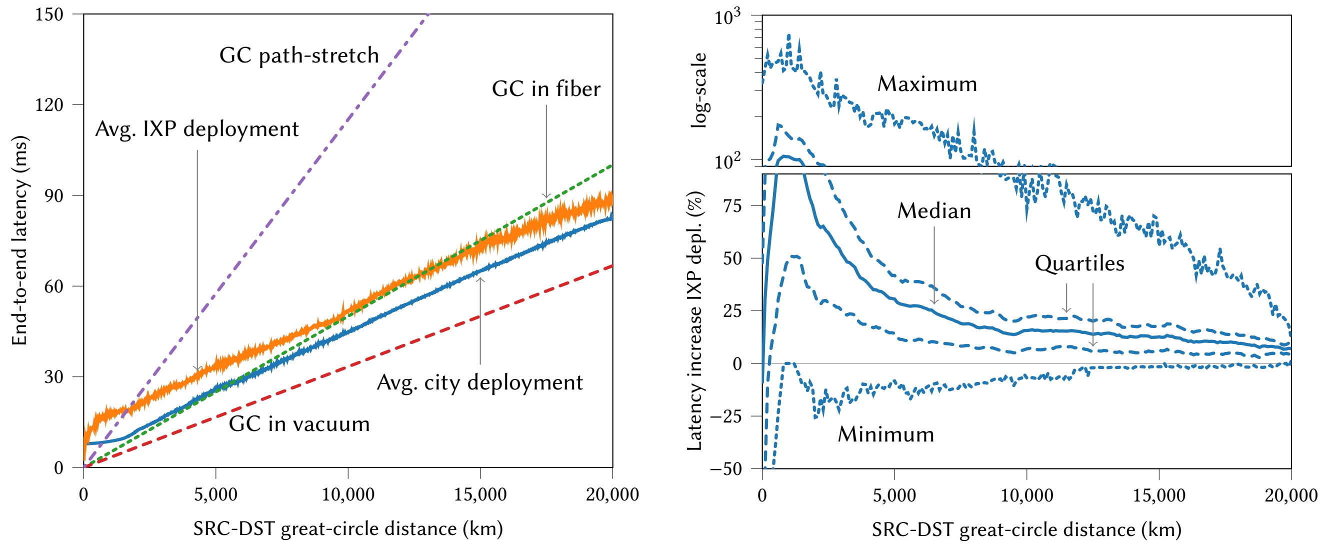
6 QUANTITATIVE EVALUATION

We evaluate the CDN-like approach on latency, since it is the primary benefit that SNs provide for multihomed customers.

First, we evaluate the tradeoff between communication latency and the number of GSTs deployed. Second, we measure the performance losses that are introduced by the internal re-routing that the CDN-like deployment performs to avoid constantly announcing and withdrawing prefixes through the satellite network. To do so, we compare against the optimal PAN-based protocol.

Simulation scenario. The satellite constellation considered in our simulation is SpaceX Starlink, in its deployment phase *two* [21]. The ISLs, four per satellite, are assumed to be connected to two in-plane (fore and aft satellite in the orbit) and two cross-plane (in the left and right neighboring planes).

The benefit of SNs for rural communities is last-mile connectivity, for which the routing challenges discussed in this work do not apply. We thus focus on cities, for which the main benefit is multihoming with a low-latency provider. We sample source and destination from the set of medium- and large-sized cities (> 300,000 inhabitants)



(a) End-to-end latency. Latency estimates for the terrestrial path based on great-circle (GC) distance are shown for comparison.

(b) Increase in latency when GSTs are deployed at IXPs, instead of all sources (cities).

Figure 2: Comparison of the communication latency in the IXP-based and source-based deployments, assuming all GSTs are active.

according to UN data [10]. Because the SN does not have coverage near the poles, we restrict the set to the 1833 cities in the −56° to 56° latitude range.[6]

6.1 Latency under GST placement

Given the set of sources, we explore the tradeoff between low latency and low cost in determining the number of GSTs and their locations. In this first experiment, we assume that all GSTs are active; our experiments on topologies with connectivity disruptions follow below. We consider the following two cases: (i) there is a GST at every source (city). This is the baseline optimal case, in which no terrestrial routing is needed to reach the entry point to the SN. (ii) GSTs are deployed at IXPs. We choose this setting since:

- IXPs are already hot-spots of connectivity, providing the infrastructure required to exchange traffic, and where many entities have their POP co-located [45].
- The number of IXPs is much lower than the number of city-sources we consider. In fact, we consider IXPs from the Euro-IXP dataset, which contains a list of global IXPs and the city in which they operate. We geolocate the cities to obtain their geographical position. Since many IXPs are located in the same city, from the initial 626 IXPs in the dataset we extract 353 unique locations.

These two characteristics combined make IXPs a particularly attractive choice for GST deployment, as the presence of customers, the existing infrastructure, and the relatively small number reduces the cost of the ground segment.

[6]Higher latitudes will be covered when additional phases of the constellation are deployed.

In the first deployment case, with a GST in every city, we compute the latency over the optimal satellite path for every city-city pair. In the second case, with a GST in every IXP, the path latency is computed as follows:

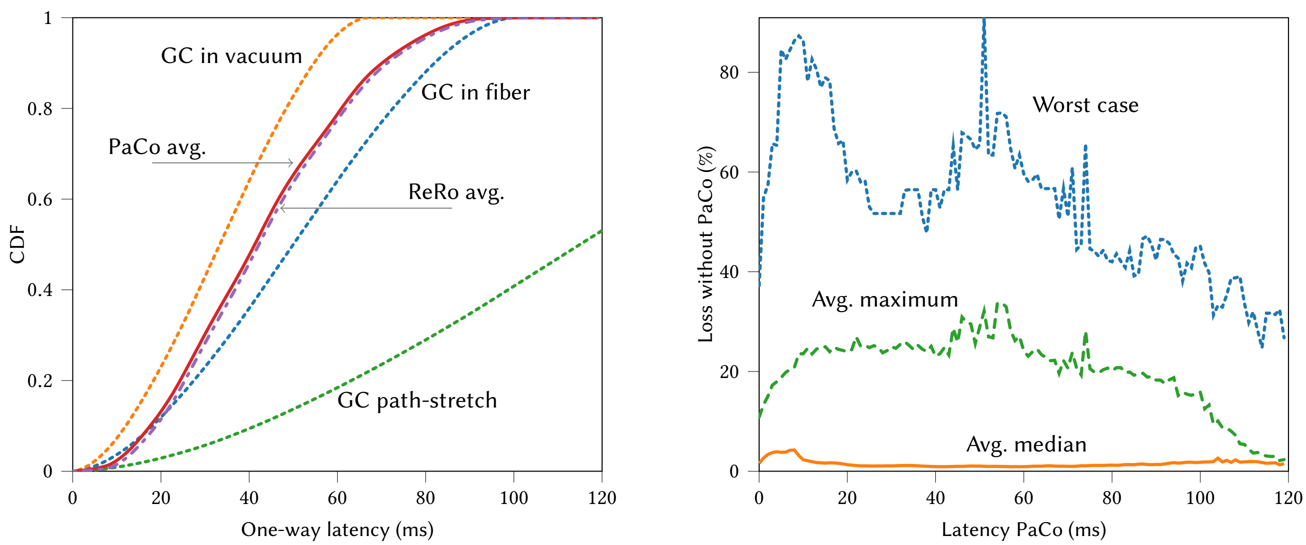
(1) The great-circle distance from the source to the closest GST is computed. This figure is multiplied by a *terrestrial path stretch* factor of 2.3, to account for the tortuous path of fiber on land [40], and divided by the speed of light in fiber (which is 2c/3) to obtain the latency of the source-GST hop.

> **Errata:** the terrestrial path stretch factor of 2.3 over the great-circle distance as computed by Singla et al. [40] *already accounts for the slower speed of light in fiber.* We present the results with the correct stretch factor, as well as a sensitivity analysis of this parameter, in Appendix B. The authors are grateful to Roland Bless and Paul Seehofer for discovering this inaccuracy.

(2) The same operation is repeated for the destination, finding the GST closest to the destination.
(3) The GST-to-GST latency over the satellite path is computed by dividing the path length by the speed of light in vacuum.

The three terms just described are finally added together to obtain the end-to-end latency. For these experiments we disregard failures and disconnections, and assume that all GSTs are active in each deployment.

Results. Figures 2a and 2b show the results of the simulation. Unsurprisingly, deploying a GST close to every source gives better performance in terms of latency. However, SNs are most beneficial for long-distance communication, where the space segment latency becomes the dominating latency factor, while the average extra



(a) CDFs of average obtainable latencies. Latency estimates for the terrestrial path based on the great-circle (GC) distance are shown for comparison.

(b) Absolute worst case latency loss, average maximum loss and average median loss computed across the different simulation scenarios.

Figure 3: Comparison of the latency loss from having to terrestrially re-route traffic instead of employing path control.

latency of routing via IXPs remains at 10ms. This increase can however be substantial in relative terms (Figure 2b), when the end-to-end latency is low.

6.2 Latency under rain fade

Path control in PANs allows the source to influence the forwarding path. If the source knows which GSTs are active, it can choose the ingress and egress GSTs to the SN accordingly, and avoid re-routing induced by temporary GSL failures. This is in contrast to the CDN-like deployment, in which traffic is re-routed from inactive GSTs to active ones, which incurs in additional latency.

As discussed above, GSL outages and thus increased path latency of the re-routing approach can have a number of causes. In the partial deployment setting that we studied above, a GST becomes inactive when satellites move out of view. However, the main difficulty for routing was the *frequency* with which GSLs become available and unavailable. This is in contrast to the total downtime of GSLs, which will be the determining factor for increased path latency. In the long term, rain fade will be the most critical factor for total down time, since it persists even after upgrades to the constellations are made. Thus, we focus our simulation efforts on investigating this phenomenon.

Given the deployment of GSTs at IXPs as in the previous experiment, we use rainfall data to simulate the effects of weather disruptions. To this end, we use historical weather data provided by NOAA [32], and for the duration of 2018 we analyze the rainfall accumulation in two instants every day. Then, we use 11 different thresholds to determine whether GSTs are inactive: a GST is inactive if the rainfall in its location exceeds the threshold. Using different thresholds allows our results to generalize with respect to the transmission parameters—such as coding and modulation, transmission power, transmission frequency—used by the GSLs, while still allowing us to capture the correlation in the GST failures induced by rainfall. This results in 7744 different simulation scenarios, each with a set of disabled GSTs. We simulate the effects of ReRo and PaCo on the topologies obtained by disabling the GSTs of each of these sets.

When using ReRo, the source connects to the nearest GST. If it is inactive, the nearest active ground station is computed over a simulated GST WAN, increasing the terrestrial path length. The same is done for the destination, and the two terrestrial segments are finally joined by the satellite-based path between the GSTs. To simulate PaCo, instead, we optimize the first hop between the three nearest GSTs to the source and destination. We chose to use the three nearest GSTs to constrain the optimization space, keeping the path-choice possibility for the source limited locally. Moreover our simulations show that the returns of allowing the selection between more than three nearest GSTs are rapidly diminishing. Using PaCo, the increase in terrestrial path length due to ReRo can be mitigated, and some minor optimization over the best satellite path can be performed. In fact, choosing a GST that is further away, but has a more direct path through the ISLs can marginally improve latency.

We simulate both ReRo and PaCo end-to-end latency for every city-city pair, assuming the deployment of GSTs at IXPs as in the previous experiment (§6.1). The simulation is repeated for each of the sets of inactive GSTs induced by rainfall.

Results. The results of the simulations are summarized in Figures 3a and 3b. In Figure 3a we notice that the CDF of path control and the CDF of re-routing are very close, showing that, on average, the difference in the performance of the two systems is small. This is also confirmed by the analysis of the losses that are introduced by re-routing instead of performing path control (Figure 3b): on

Table 2: Properties of the evaluated systems. The dollar ($) denotes the infrastructure the SN-AS has to deploy at its own expense; the check-mark (✓) denotes the routing stability and latency properties each system achieves.

	Infrastructure				Latency	
Systems	SN	GSTs	WAN	Stability	ReRo	PaCo
White Box	$					
Black Box	$	$	$	✓		
CDN-like	$	$[a]		✓	✓	
Optimal (PAN)	$			✓	✓	✓

[a]Part of this cost will be shared with partnering networks.

average, the loss is on the order of a few percent. These losses are negligible, even more given that the one-way communication latency is very low even across great distances, and fluctuations of a few milliseconds are tolerable. However, we also see that, in each simulation scenario, these fluctuations can be substantial, degrading the performance of the network by more than 30 % ("Avg. maximum"). In the absolute-worst case across all simulations, the loss in performance can be higher than 80 % ("Worst case").

7 SUMMARY OF FINDINGS

We conclude this first exploration in the area of inter-domain routing with satellite constellation with a summary of the results presented so far in Table 2. We compare different routing architectures on three aspects that determine their suitability to the task. These properties are (i) the cost of deployment, (ii) the stability of the architecture in the face of the disruptions caused by the SN, and (iii) the latency performance of such systems. Our findings are:

- While the white-box solution would be the easiest to deploy today, the analysis of link disruptions shows that it is severely lacking: it is highly susceptible to SN's instability, and BGP gives no guarantees on the latency of the selected paths.
- The black-box solution improves stability by adding redundant links, but increases costs manifold. This poses limits to the scalability of the system and hinders performance, as seen in Figure 2b, with constraints on the number of GSTs. Moreover, the losses on the path from the host to the SN-AS are unpredictable, as such paths are chosen by BGP.
- The CDN solution solves the scalability problem by hosting GSTs inside other networks, while the performance of the terrestrial routing is improved by the use of anycast (with geolocation annotations). Sending traffic to the closest GST—and eventually re-routing—provides almost-optimal performance in the average case (Figure 3).
- An architecture that implements path-control, enabling addressing of the optimal GST, would further lower the communication latency, providing an average improvement of more than 10% in the 95th-percentile.

8 RELATED WORK

"NewSpace" networking: Bhattacherjee et al. [3] and Handley [20] have outlined agendas for research on LEO SNs in recent position papers, centered mainly on the low-latency and multipath potential of such networks. In a prior workshop paper [26], we examined the difficulties BGP would face if used to disseminate routes for such networks. We extend that work in substantial ways here by proposing different ways of integrating SNs into terrestrial inter-domain routing and evaluating them using simulations that take dynamic connectivity and rain fade into account.

Ground-segment deployment modeling Del Portillo et al. studied in detail various aspects of the deployment of the ground segments of next generation satellite networks [7–9]. The focus of their work is on constellations used as last-mile ISPs. In this setting, the authors analyze the coverage of SNs, and propose ground segment designs for extremely high frequency radio and optical GSLs. The cost model we discuss in §3 is simplified from their works [9].

Inter-domain satellite routing: The only prior work on integrating SNs into inter-domain routing is, to the best of our knowledge, Border Gateway Protocol–satellite version (BGP-S) [13, 14]. BGP-S is a protocol designed during the first wave of interest in satellite constellation networks, in the early 2000's. It is a modification of BGP version 4, and designed to be inter-operable with it. It takes into account the fact that the latency over SNs can differ significantly from the latency of terrestrial links: if a satellite path has lower latency than other terrestrial paths to the same destination, the satellite path is chosen for forwarding. BGP-S rests on a series of assumptions that restrain its applicability to the next generation of satellite constellations: it assumes a maximum of one GST per AS and relies on the fact that the SN provides *static* connectivity and static path metrics, without disruptions. As we have shown, these assumptions are unlikely to hold in new SNs.

Other work [23, 52] has analyzed routing instability caused by satellite networks, but due to the topologies analyzed, the characteristics of the networks involved and the proposed solutions are substantially different. For instance, both these efforts propose variants of bundling updates about topology changes, a solution amenable at the small scales tackled. Similarly, work on geostationary satellites Internet [5, 11] addresses a different setting due to the satellites' lack of motion with respect to the Earth and each other.

Intra-domain satellite routing: Routing inside a satellite constellation is a well studied topic [4, 12, 15–17, 19, 28, 29, 39, 43, 46–49, 51]. These works describe methods to achieve high-performance routing on the dynamic network created by the ISLs. However, these works do not consider the effects that SNs have on the Internet as a whole. As we note in §3, managing an SN-AS with only intra-domain routing imposes a substantial economic and management burden for backup terrestrial routes.

Routing under mobility: Broader work on routing under mobility, e.g., *Ad hoc On-Demand Distance Vector* (AODV) routing [34] and *Dynamic Source Routing* (DSR) [24], could lend itself to SNs. However, this work's generality comes at the cost of not exploiting the predictable nature of SNs.

Path-aware networking: Path-aware networking is an emerging paradigm that encompasses many Internet architectures and routing schemes proposed in the past 15 years. Among these are: Platypus [37, 38], the Postmodern Internetwork Architecture (PoMo) [2], Pathlet Routing [18], the New Interdomain Routing Architecture (NIRA) [50], NEBULA [1] and SCION [35]. The *Path-Aware Networking Research Group* (PANRG) [22] at the IRTF is undertaking standardization of the methods applications may use to communicate their requirements to the network.

9 CONCLUSION

The prospect of large constellations of low-earth orbit satellites offering Internet service is an exciting development for networking. Such networks promise to reduce end-to-end latencies for long-range communication by more than half, and extend the Internet's reach to remote areas. Unlocking this potential requires, however, integrating such networks into the current Internet fabric.

While a white-box or black-box deployment approach may appear attractive, mainly due to the familiarity to current terrestrial deployments, such approaches unfortunately encounter several major challenges: (i) the highly dynamic nature of GSLs creates scalability limitations for BGP, especially due to weather disruptions; (ii) during early phases of deployment, connectivity will fluctuate so often that slow routing convergence with BGP could make the partially deployed constellation unusable; (iii) changes in the configuration of the ISLs force a bandwidth–latency trade-off in forwarding; and (iv) the higher cost and lower bandwidth of SN links complicates their use for all data traffic, thus complicating the management of differentiated traffic.

To address these challenges, we first propose an optimal solution based on the SCION path-aware-networking architecture. Given this clean-slate baseline, we then develop a more pragmatic solution based on a CDN-like architecture. Both these systems improve over the white-box and black-box models, lowering the deployment costs by reducing the requirements on the infrastructure of the SN-AS and increasing performance by virtue of shorter terrestrial paths. We compare the performance of the systems in terms of end to end latency: the CDN-like approach achieves almost-optimal latency in the average case, and trades optimal worst-case performance for an easier and faster integration in today's Internet.

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A REPEATABILITY OF RESULTS

All the results presented in the paper are based on simulation. This section contains the information necessary to replicate these results from a high-level perspective. For all the low-level details on installing dependencies, running simulations and analyzing results, we refer to the supplementary materials submitted alongside the paper, as they contain the simulation code and the instructions for use.

A.1 Datasets

We require the following datasets as inputs to the simulations:

- The global gridded gross domestic product (GDP) dataset, representing the GDP per unit of surface of the earth. This can be obtained from NASA's Socioeconomic Data and Applications Center [31].
- The geolocation of IXPs on Earth. We parse the dataset provided by IXP-DB at https://ixpdb.euro-ix.net/, mapping city names to latitude-longitude coordinates. The resulting map IXP–geolocation is provided with our submission.
- The list of cities that exceeded 300,000 inhabitants in 2018, sourced from the UN's World Population Division [10].
- We gather historical weather data from NOAA's Global Forecast System Analysis (GFS-ANL) [32]. In particular, from their datasets we extract the six-hour rainfall accumulation at two times of the day, 06:00–12:00 and 18:00–24:00.

A.2 Satellite network simulator

We now describe the high level functions of our in-house satellite network simulator. This simulator is then used to compute the latencies for experiments 2 and 3.

Space segment network topology. Given the parameters of the constellation (in our case SpaceX Starlink phase 2), the simulator generates a graph in which satellites are nodes and ISLs are links. The simulator can reproduce the orbital motion of the satellites over time, and can therefore capture the changes in the satellite network graph as time progresses.

Ground network topology. The traffic sources in our simulations are always cities of over 300,000 inhabitants. The GSTs are interconnected in a network that is obtained by Delaunay triangulation of the GST locations, to simulate the local connections between neighboring GSTs. Depending on the routing scheme used, the sources can be directly connected to the geographically nearest GST (re-routing) or to the N-nearest GSTs (path-control with parameter N).

Space and ground network connection. The interconnection points of the Space and ground networks are the GSTs. A GST can connect to an overhead satellite if the satellite is above a minimum elevation angle over the horizon (40° for Starlink).

Latency simulation. Experiments 2 and 3 require the simulation of the communication latency between all source-pairs of cities. The end-to-end latency is composed of the latency of the space segment, computed as path-length times c, and the latency over the ground segment, computes as path-length times $2c/3$. The optimization is executed as follows:

(1) The latency to all reachable GSTs is computed for both source and destination. In the case of re-routing this is either the nearest GST, in case the nearest GST is inactive, the active GST that is closest to the first one. In the case of path-control, the reachable GSTs are the N-nearest GSTs.
(2) For all pairs of reachable source and destination GSTs, the optimal latency over the ISLs is computed by taking the shortest path over the SN graph. The latency on the GSLs is also taken into account.
(3) Finally, the optimal path is chosen to be the one with the minimum sum of the latency of the three components:
    - source→source-GST
    - source-GST→destination-GST
    - destination-GST→destination

A.3 Experiment 1: Estimation of GST costs

We analyze the costs of deployment of a specific ground segment according to the cost model described in §3. The simulation computes the three components of the cost model (infrastructure, antennas, and WAN), given the number of deployed GSTs N and a number of sampling rounds R. The simulation proceeds as follows:

(1) The costs of infrastructure and antennas is obtained by multiplying the expenditures for one GST (Table 1a) by N.
(2) To estimate the cost of the WAN, the simulator uses the gridded GDP distribution to obtain a probability mass function over the grid G. The probability of sampling a cell of coordinates (x, y) is:

$$P_{(x,y)} = \frac{\mathrm{GDP}_{(x,y)}}{\sum_{(i,j)\in G} \mathrm{GDP}_{(i,j)}}$$

(3) For each sampling round, the simulator: samples N GST locations from the distribution; computes the distance from each the GST to the closest IXP; multiplies the distance in km by the cost of fiber per km.
(4) The cost obtained in all of the rounds is then averaged to obtain an estimate of the cost of the WAN.

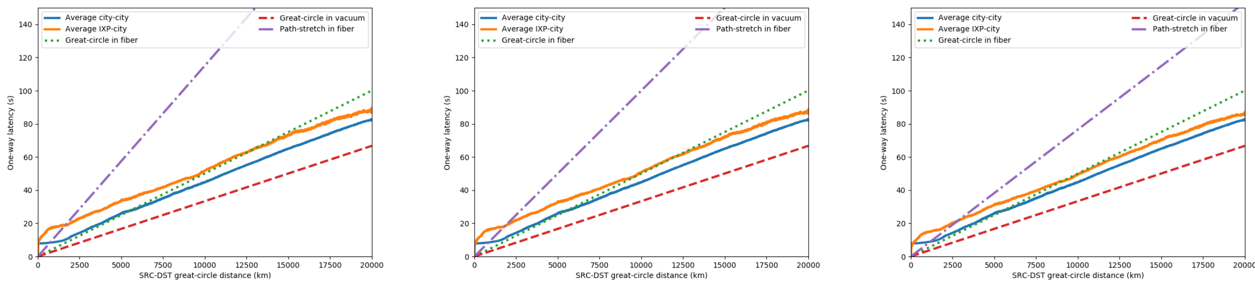
The simulation also outputs the cost of deploying GSTs at cities with population above 300,000, as discussed in §3.

A.4 Experiment 2: Latency under GST placement

This simulation measures the communication latency comparing the case in which the GSTs are deployed at the sources of traffic (large cities) against the case in which the GSTs are only deployed at IXPs. No failures at GSTs are assumed in this simulation instance. The simulation is executed as described in §A.2. Notice that the in the case of GSTs at large cities, since the traffic source and the GSTs' locations coincide, no terrestrial path is needed.

A.5 Experiment 3: Latency under rain fade

In this last experiment, the GSTs are only selected to be co-located with IXPs. Path-control and re-routing are compared on the same topology, where some ground stations have been deactivated due to rain effects. The deactivation heuristic is described in §6.2.

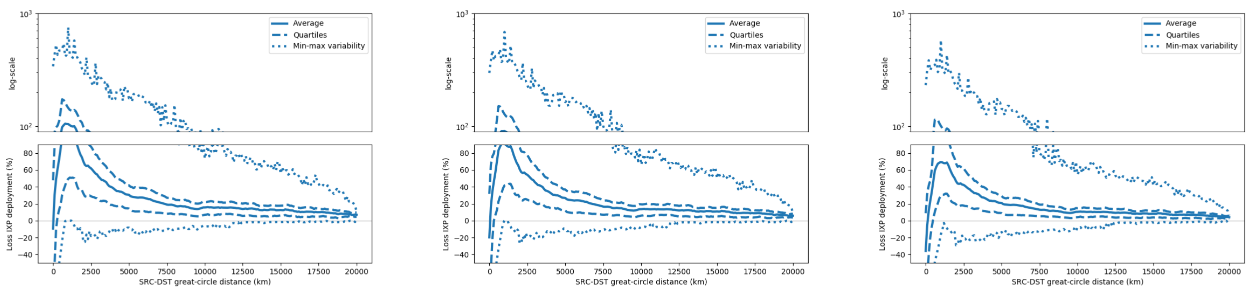


(a) Terrestrial path stretch factor= 2.3

(b) Terrestrial path stretch factor = 2.0

(c) Terrestrial path stretch factor = 1.53

Figure 4: The variation in path stretch changes the angular coefficient of the "Path stretch in fiber" line, as well as moving the "Average IXP-city" closer to "Average city-city".



(a) Terrestrial path stretch factor = 2.3

(b) Terrestrial path stretch factor = 2.0

(c) Terrestrial path stretch factor = 1.53

Figure 5: The loss given by the IXP deployment diminishes as path stretch decreases.

B UPDATED RESULTS AND TERRESTRIAL PATH STRETCH FACTOR SENSITIVITY

As mentioned in the errata in §6.1, in the original version of this paper the simulations were executed considering a *terrestrial path stretch factor* of 2.3, as well as the lower speed of light in fiber. In total, therefore, the terrestrial path-length inflation over the great-circle distance in the experiments of §6 amounted to $2.3 \cdot 1.5 = 3.45$. However, in the original work by Singla et al. [40], the factor of 2.3 already includes the lower speed of light in fiber, and therefore the terrestrial path stretch factor—given by the fiber topology alone—is 1.53. The terrestrial paths considered in the original simulations are thus longer, and do not accurately represent the reality of Internet connections.

Roland Bess and Paul Seehofer (Karlsruher Institut für Technologie) first noticed this inaccuracy and kindly notified the authors. We are grateful for their help and attention.

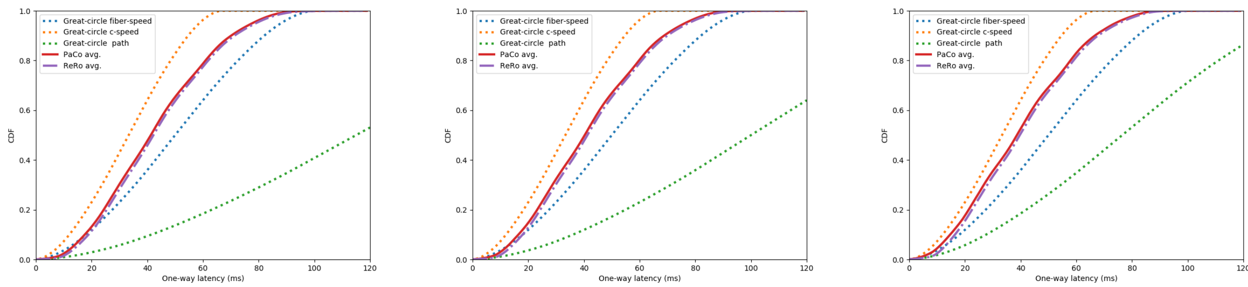
In this appendix we will present the results with the updated parameter. Moreover, we also show two other values for comparison—thus evaluating stretches in $\{1.53, 2.0, 2.3\}$—to analyze the dependence of our results on the path stretch. We show that, albeit changes in the results are visible, their magnitude is small and the conclusions of the original paper hold even with the lower paths stretch factor of 1.53.

B.1 IXP-city vs city-city

In this simulation, changes in terrestrial path stretch only affect the terrestrial path between a city and the nearest IXP (Figure 4). Therefore, the changes in the overall loss are mainly visible at close range, where the terrestrial path is a significant fraction of the overall path. This is noticeable in particular in Figure 5.

B.2 PaCo vs ReRo

The difference between PaCo and ReRo is small in the average case (Figure 6). However, the effect of changing the terrestrial path stretch is visible in the worst case. Since both PaCo and ReRo have to route at least some part of the path on the ground, they are both affected by the change in terrestrial path stretch. Therefore, the relative change is even smaller than in the previous experiment (Figure 7).

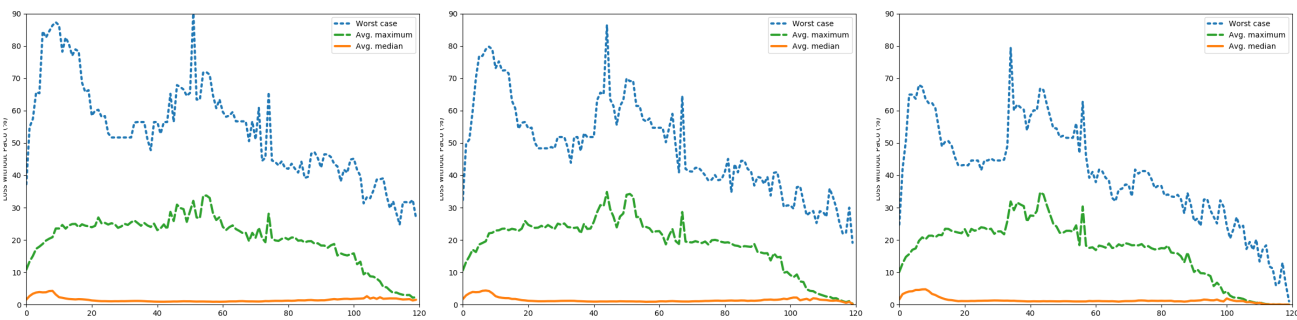


(a) **Terrestrial path stretch factor** = 2.3

(b) **Terrestrial path stretch factor** = 2.0

(c) **Terrestrial path stretch factor** = 1.53

Figure 6: In the CDFs of average one-way latencies, the change is not noticeable, if not for the shape of the "Great-circle path" line (green-dotted).



(a) **Terrestrial path stretch factor** = 2.3

(b) **Terrestrial path stretch factor** = 2.0

(c) **Terrestrial path stretch factor** = 1.53

Figure 7: The loss for using ReRo instead of PaCo also diminishes by a few percent. Changes in the average values are almost unnoticeable.