Delay is Not an Option: Low Latency Routing in Space

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ABSTRACT

SpaceX has filed plans with the US Federal Communications Committee (FCC) to build a constellation of 4,425 low Earth orbit communication satellites. It will use phased array antennas for up and downlinks and laser communication between satellites to provide global low-latency high bandwidth coverage. To understand the latency propertes of such a network, we built a simulator based on public details from the FCC filings. We evaluate how to use the laser links to provide a network, and look at the problem of routing on this network. We provide a preliminary evaluation of how well such a network can provide low-latency communications, and examine its multipath properties. We conclude that a network built in this manner can provide lower latency communications than any possible terrestrial optical fiber network for communications over distances greater than about 3000 km.

1 INTRODUCTION

As network bandwidths have increased, latency has emerged as being the limiting factor for many networked systems, ranging from the extremes of high frequency trading, to the more mundane effects of latency on VoIP, online gaming, and web performance[2]. Fundamentally, once traffic engineering has mitigated congestion[7, 9] and buffer bloat has been addressed, for wide-area traffic the remaining problem is that the speed of light in glass simply isn't fast enough.

In recent FCC filings[12], SpaceX proposed and subsequently received permission to launch *Starlink*, a constellation of low Earth orbit (LEO) satellites to provide low-latency, high-bitrate global Internet connectivity. These filings provide a great deal of detail about the RF links between the satellites and the ground, including how phased-array antennas can steer narrow transmission beams for both up and downlinks. The filings do not discuss in any detail satellite to satellite communications, but do state that free-space lasers will be used. No radio spectrum for satellite-to-satellite communication is requested, so lasers must be the primary communication link between satellites. Crucial to the low-latency story is that free-space lasers communicate at c, the speed of light in a vacuum, which is $\approx 47\%$ higher that in glass[4].

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Starlink represents a new category of wide-area backbone, where thousands of satellites move and connect in a predictable pattern, but due to orbital constraints the network is far from a simple static mesh. We ground our study in the basic properties of the Starlink deployment, and proceed by simulating routing designs on such a network. Where details are not publicly available, we adopt reasonable parameters from first principles. Our goal is to provide early insight into the interactions between the dynamic topology of the constellation, how routing might work over such a novel network architecture, and emergent end-to-end latency properties.

2 STARLINK

In Starlink's initial phase, 1,600 satellites in 1,150 km altitude orbits will provide connectivity to all except far north and south regions of the world. A second phase adds another 2,825 satellites in orbits ranging from 1,100 km altitude to 1325 km, increasing density of coverage at lower latitudes and providing coverage at least as far as 70 degrees North. Finally, in an additional FCC filing SpaceX proposes launching an additional 7,518 satellites in approximately 340 km VLEO orbits. In this paper, we examine only the LEO constellation.

SpaceX's FCC filings necessarily concentrate on the properties of phased-array beam steering and spectrum allocations, so as to demonstrate they will not interfere with other spectrum users. In contrast, we are mostly concerned with satellite-to-satellite communication, and primarily consider the RF up and down links from the point of view of which satellites can be reached from which ground location at any time. The main restriction is that satellites are considered reachable if, from the ground, they are within 40 degrees from the vertical.

The FCC filings also discuss debris risks when the Starlink satellites are finally de-orbited. We see that each satellite will have five 1.5 kg silicon carbide "communication components" that may survive reentry due to silicon carbide's melting point of 2,730C. This material is used in mirrors for laser communication links. A good working assumption is that each satellite will have five free-space laser links to connect to other Starlink satellites. In fact, as we shall explore, five laser links per satellite is also effectively the minimum number needed to build a low-latency dense LEO network.

While free-space optical communications have been tested in orbit, no high-bitrate system exists that operates over the moderate distances Starlink will use, except for SpaceX's own pair of test satellites launched in Feb 2018. In 2014, the European Data Relay System (EDRS) achieved 1.8 Gb/s from LEO to geostationary earth orbit (GEO), across a distance of 45,000 km[13]. ESA claims that the design is capable of 7.2Gb/s. In contrast, the distances in Starlink are much lower - most links are likely to be 1000 km or less. At EDRS distances, lasers will spread due to diffraction. If Starlink

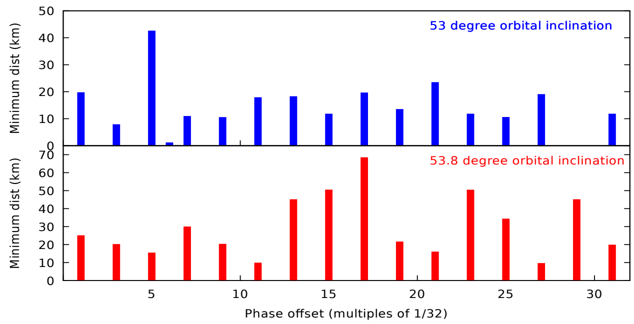

Figure 1: Minimum passing distance vs phase offsets

uses similar power lasers, the inverse square law suggests that received power on Starlink could be as much as 2000 times greater than on EDRS. It seems probable that free-space laser link speeds of 100 Gb/s or higher will be possible. However, in this paper we will refrain from modelling network capacity, as this is too speculative, and focus instead on latency, which is constrained only by topology and the speed of light.

The orbital data[12] for the LEO constellation are:

	Initial 1,600 sats	Final Deployment 2,825 satellites			
Orbital Planes	32	32	8	5	6
Sats per plane	50	50	50	75	75
Altitude (km)	1,150	1,110	1,130	1,275	1,325
Inclination	53°	53.8°	74°	81°	70°

Orbital Phase Offset. Let us first consider the initial phase of deployment: 1,600 satellites in 53° inclination orbits. To provide continuous coverage density, the 50 satellites in each orbital plane need to be evenly spaced around the orbit. In addition, the 32 orbital planes will need to be oriented so they cross the equator at evenly spaced longitudes. For us to calculate the satellites relative positions, we also need to know the phase offset between satellites in consecutive orbital planes. This information is not in the SpaceX filings.

The phase offset between orbital planes is a number between zero and one indicating when satellites in consecutive orbits cross the equator. If it is zero, satellite n in orbital plane p crosses the equator at the same time as satellite n in orbital plane $p+1$. If it is one, satellite n in orbital plane p crosses the equator at the same time as satellite $n+1$ in plane $p+1$. To achieve a uniform constellation with 32 orbital planes, phase offset must be a multiple of $^{1}/_{32}$.

The initial 1,600 satellites are all in 1,150 km altitude orbits with an inclination of 53°. The other key constraint, then, is that the satellites in different orbital places do not collide as the orbital planes cross. We simulated the 32 different possible phase offsets for orbits of this inclination. With all even multiples of $^{1}/_{32}$ as phase offset, satellites collide. The simulated minimum distances between satellites for the odd phase offsets are shown in the top graph in Figure 1. To minimize the probability of collision if station-keeping is not perfect, we conclude that the phase offset should be $^{5}/_{32}$.

Figure 2 shows the orbital planes and positions of the 1,600 satellites positions at one instant in time. A video of our simulations[8] shows their motion, and other results from this paper. It should be immediately clear that coverage provided is not uniform - the constellation is much denser at latitudes approaching 53° North and South. For example, London is located at 51.5° N, and will have approximately 30 satellites overhead within the 40° RF coverage angle.

For the second deployment phase, there are an additional 1,600 satellites in 53.8°inclination orbits. These are 40 km lower than the first phase satellites, so they orbit slightly faster. A 53°and a 53.8°satellite that start close together in the sky will slowly drift apart. To provide spatial diversity for the RF beams, it makes most sense to stagger their orbital planes so that the 53.8°orbital planes are equidistant between the 53°orbital planes at the equator. The bottom graph in Figure 1 shows minimum crossing distances vs orbital phase offsets for this constellation. We conclude that $^{17}/_{32}$ is the best phase offset, though a few other values also appear to be viable.

Performing a similar analysis for the satellites in higher inclination orbits, and arranging them to maximize minimum distance between their orbital planes, we end up with the 4,425 satellite constellation, as shown in Figure 3. Coverage over extreme latitudes is still sparse, but appears to be sufficient to satisfy FCC requirements to cover Alaska, and also provide some polar routes for long distance communication.

3 BUILDING A NETWORK

Given five laser links per satellite and knowledge of orbits, we can now approach the coupled problems of how to build a network, and how to route on that network. The first question is which satellites should we interconnect with lasers?

A dense LEO constellation like Starlink has two main advantages over terrestrial networks. First, it can connect almost anywhere, however remote. Second, the speed of light in a vacuum, c, is $\approx$ 47% higher than in optical fiber. The ability to connect anywhere is important, but we speculate that providing low-latency wide area communication will be where the money to maintain and operate such a network is made, connecting cities that are already well connected using optical fiber, but with lower latency as a premium service. Already there are new private microwave relay links between New York and Chicago[11], London and Frankfurt[1], and London and Paris. These links have relatively low capacity compared to fiber, but are of high enough value to the finance industry to be worth building new low latency links.

Starlink's LEO satellites will be in 1,110 to 1,325 km orbits. Although much lower than GEO, this is still too high to provide lower latency than fiber over shorter distances. However, over longer distances the extra latency getting between Earth and the nearest satellite may be more than offset by routing around the world between the satellites at c. The primary goal then, seems to be to connect key population centers with satellite paths that run close to the great circle route.

Let us first consider the 1,600 satellites in phase 1. To maintain good paths, most laser links must be up at any time. This constrains the solutions. Except at the extreme north and

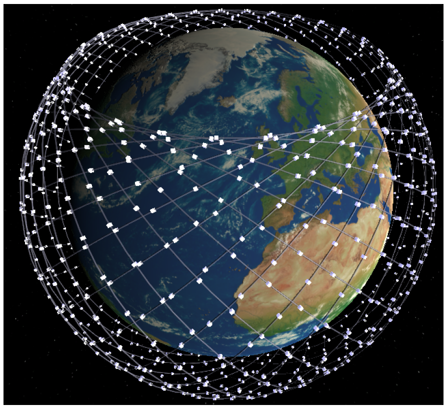

Figure 2: Phase 1 Satellite orbits

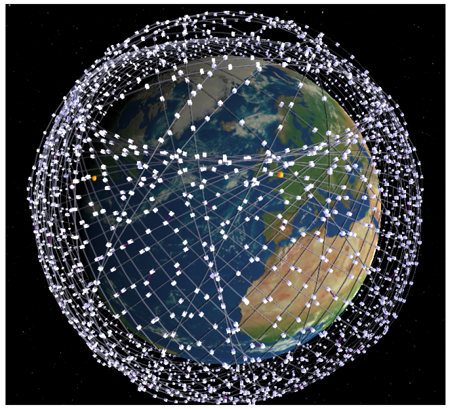

Figure 3: Phase 2 Satellite orbits

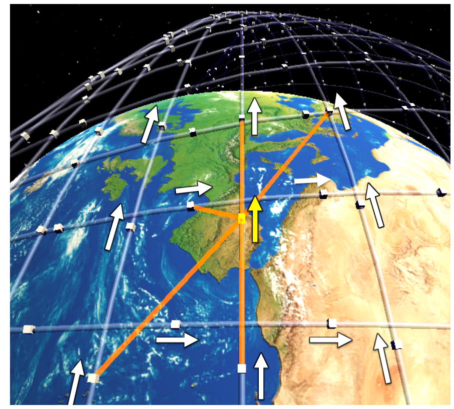

Figure 4: Lasers of one NE-bound sat.

south extents of their ground track, in any one region, half the satellites are traveling on a northeasterly track and half are on a southeasterly track[1]. All are traveling at ≈7.3km/s. A NE-bound satellite will not remain in range of a SE-bound satellite for long, so a laser between the two must track rapidly as the orbits cross, and must rapidly switch to a new satellite as the old one moves away. ESA's EDRS can bring up its optical link in under a minute[13]. Starlink may be quicker, given the shorter distances, but connections will not be instant.

From the point of view of any one satellite, two neighbors always remain in the same locations: the next one ahead on the same orbital plane, and the one behind on that orbital plane. Laser links to these neighbors only need to fine-tune their orientation, so these are the obvious candidates for the first two laser links. To form a network, we also need to link between different orbital planes. There are many options for how to do this. However, only the satellites in the neighboring orbital planes remain consistently in range, so connecting to these is the next priority so as to form a network where most of the links have high uptime.

Routing forwards and backwards along the orbital planes already provides good SW↔NE and NW↔SE connectivity, so it makes most sense to use the next pair of lasers to connect between the orbital planes in as orthogonal a direction as possible: either north-south or east-west. With a phase offset between orbital planes of $^5/_{32}$, connecting satellite n on orbital plane p to the nearest satellites ($n+1$ on orbital plane $p+1$ and satellite $n-1$ on plane $p-1$) is not the best solution, as these links nearly parallel those of the crossing orbital plane paths. Rather, connecting satellite n on orbital plane p to satellite n on plane $p+1$ and also to satellite n on plane $p-1$ provides very good east-west connectivity, while the $^5/_{32}$ phase offset ensures than the links are slightly offset from running exactly east-west, providing very direct paths in a wider range of nearly east-west directions.

It is also possible to provide reasonable north-south connectivity, but as most of the world's population in developed nations that are more likely to be willing to pay for latency are clustered in a band from 30°to 55°North, providing east-west connectivity seems to be the higher priority for phase 1.

[1]Such satellites launch eastwards to take advantage of Earth's rotation

The network resulting from this use of each satellite's first four laser links provides a good mesh network, but in any one region their are two distinct meshes - one moving generally northeast and the other moving southeast, with no local connectivity between the two without going the long way round the planet. Our simulations show that most traffic can route without switching between the two meshes, but using the final laser to provide inter-mesh links improves the routing options significantly, even if such lasers are down frequently, while they re-align from one crossing satellite to another.

This way of aligning the lasers is shown from the point of view of one satellite traveling northeast in Figure 4. The forward and backwards links remain in a constant orientation; the side links track very slowly as the satellite orbits, but always connect to the same neighboring satellite and always point close to an east-west orientation; the final link tracks crossing satellites very rapidly indeed. Figure 5 shows how the side laser links used this way provide good east-west connectivity; Figure 6 shows all the lasers.

4 ROUTING

How well does the network above provide low-latency routes? The simplest way to route is for each groundstation to connect to the satellite that is most directly overhead. This has the advantage of providing the best RF signal strength for uplinks and downlinks. We can then run Dijkstra's algorithm[5] over the satellite network using link latencies as metrics to provide the lowest latency paths.

Of course, the network is not static; the satellite most directly overhead changes frequently, the laser links between NE- and SE-bound satellites change frequently, and link latencies for links that are up change constantly. We can, however, run Dijkstra on this topology for all traffic sourced by a groundstation to all destinations, and do so every 10 ms with no difficulty, even on laptop-grade CPUs. In addition, all the link changes are completely predictable. If we run Dijkstra every 50 ms, for the network as it will be 200 ms in the future, and cache the results, we can then see whether packets we send will traverse a link that will no longer be there when the packets arrive. In this way, each sending groundstation can source-route traffic that will always find links up by the time

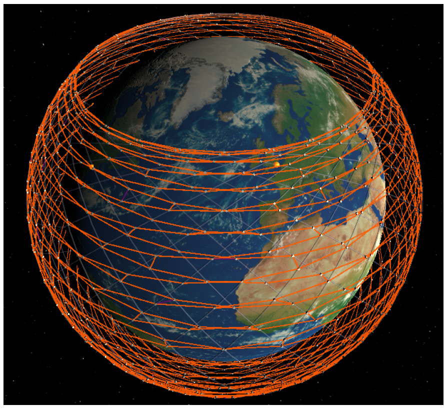

Figure 5: Phase 1 network showing just side links.

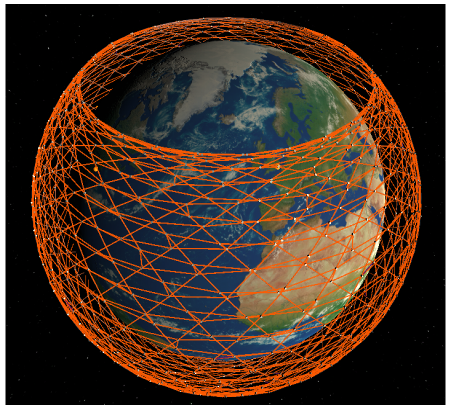

Figure 6: Phase 1 network showing all links.

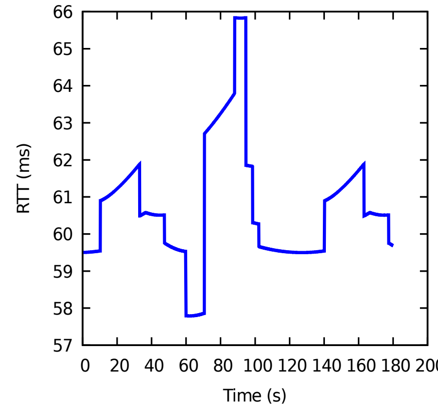

Figure 7: NYC to London RTTs via overhead satellites.

the packet arrives at the relevant satellite.[2]

How, then does the latency change as the network evolves? Figure 7 shows how the RTT from New York to London evolves over three minutes. Discontinuities are due to route changes within the satellite network, or a change of the satellite overhead the source or destination city. For comparison, the minimum possible RTT via optical fiber that follows a great circle path is 55ms, while the actual Internet RTT between two well connected sites in these cities is 76ms. The satellite RTT is, on average, fairly low. It certainly beats the current Internet RTT, and that 55ms great-cicle RTT is not realistic as it is not possible to lay fiber continuously on the most direct path. However, the large delay spike between 70 and 95 seconds is certainly undesirable.

Further analysis shows that these spikes are caused when the satellites directly overhead the two cities are on different parts of the constellation - either one is on a NE-bound satellite and the other on a SE-bound satellite, or vice versa. Although the fifth laser link on each satellite connects the two parts of the constellation, the path is not always very direct, and these links do not stay up for long as the satellites move.

Even if both satellites are on the same part of the constellation, routing vertically upwards to a satellite then horizontally then vertically downwards takes a longer path than necessary. Lower latency can be achieved by using a satellite lower in the sky in the direction of the destination. This is, of course, at the expense of 3dB lower RF signal strength[12], likely resulting in lower achievable bitrate.

Routing Both RF and Lasers To achieve the lowest delay, we need to include all possible RF up and down links into the network map that we run Dijkstra over. In this way, we always choose the best matched satellite pair for the uplink and downlink, and we use satellites that are in the correct direction. This usually results in using satellites that are fairly close to 40°from the vertical.

Figure 8 shows how the latency between New York and

[2]If each satellite makes instantaneous local routing decisions, as with greedy schemes such as GPSR[10], the latency distribution has a long tail, as packets find a previously good onward path has become unavailable part way.

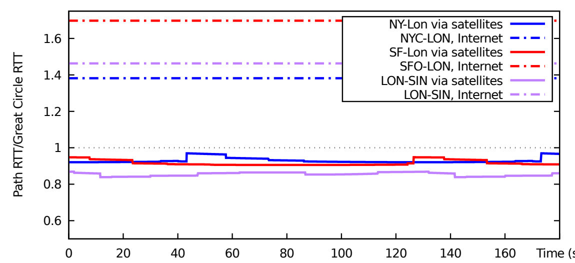

Figure 8: Latency using laser and RF co-routing.

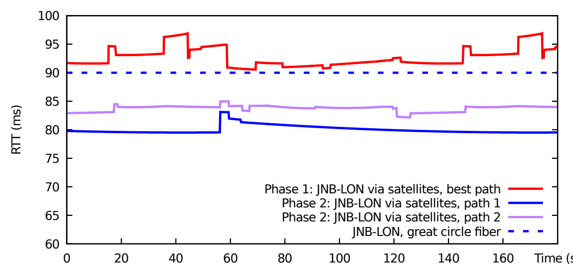

Figure 9: London-Johannesburg RTT.

London, San Francisco and London, and London and Singapore varies over three minutes when RF and laser links are co-routed in this manner. The y-axis shows the latency via satellite for that city pair, normalized by the latency via optical fiber laid tight along the great circle route. A value of one therefore shows an unattainable lower bound for optical fiber communication for that city pair. In all three cases, the satellite RTT is significantly less than this lower bound. For comparison, latencies of current Internet paths between well-connected sites in these cities are also shown.

We deliberately optimized laser paths for East-West traffic. The latitudes of San Francisco, New York, London, and Singapore are 37.7°N, 40.8°N, 51.5°N and 1.4°N, so although paths between then do not directly travel East-West, there is a large East-West component. What about North-South routes?

The red curve in Figure 9 shows the London-Johannesburg route. The satellite path has almost half the 182 ms latency of the best Internet path via fiber off the west coast of Africa. However, the satellite path is nowhere near optimal, as it has

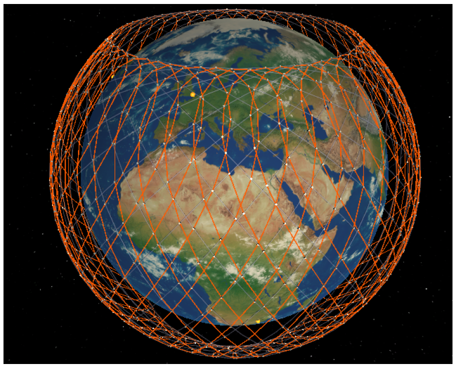

Figure 10: Phase 2a network showing just side links.

to zig-zag via SW and SE links. Can we do better?

Phase 2 Routing SpaceX's proposals for phase 2 include another 1,600 satellites in 53.8°inclination orbits. These orbits closely parallel the 53°orbits of the phase 1 satellites, but they are 40 km lower so complete an orbit in 53 seconds less than phase 1 (a complete orbit takes ≈107 minutes). As with the phase 1 satellites, it makes most sense to use the first laser pair to connect along the orbital plane. We now have a choice of how to use the remaining lasers.

We experimented with connecting adjacent 53°and 53.8° satellites, but the velocity difference makes this problematic - the direct East-West routing paths slowly become zig-zag before eventually the satellites switch to the next neighbor, and this adversely affects latency. To avoid this drift problem, we conclude that 53.8°satellites should connect to 53.8°satellites in the next orbital plane, even though they are more distant.

As figure 1 shows, the best phase offset between neighboring planes is $^{17}/_{32}$. This larger phase offset changes the options for the orientation of paths created by connecting to the neighboring orbital plane. We already have good NW-SE, NE-SW, and East-West connectivity from phase 1, and routing along the phase 2 orbital planes will increase the NW-SE and NE-SW capacity. Using the remaining lasers to improve the North-South direction is an attractive option. To do this, we offset the lasers by 2, connecting satellite n in plane p to satellite $n-2$ in plane $p-1$ and $n+2$ in plane $p+1$. Figure 10 shows just the side laser links of 53.8°satellites using this offset. We cannot achieve perfect N-S orientation, but the paths are very good at higher latitudes.

These N-S paths are complemented by the satellites in higher inclination orbits. For these there are only a few orbital planes too far apart to allow connections between neighboring planes, except near the poles. We use their remaining three lasers less methodically, allowing them to to opportunistically connect to each other or to 53°and 53.8°orbits as they come close. This provides reasonable polar coverage while allowing them to be used for N↔S traffic at lower latitudes.

The blue curve in Figure 9 shows that adding the phase 2 satellites has improved the London-Johannesburg latency by about 20% due to the more direct routing. The purple curve shows the second best path, calculated by removing all links used by the best path, and re-running Dijkstra on the remaining graph. This indicates that latency in such a network is not critically dependent on any one satellite or link.

Multipath While the biggest advantage to a dense LEO constellation is likely to be very low latency, the bandwidth of a single satellite path is likely to be insufficient to impact the business of long distance fiber networks. However a LEO constellation can provide many paths between the same city pair; with Starlink there may be 60 satellites within coverage range for latitudes close to 50°N. How does the latency of these additional paths compare with the best path?

Generally, the longer the distance, the more paths will be available that have lower latency than the best theoretical fiber path. New York and London are relatively close, so the potential satellite gain is lower. Both are major financial centers, so there is a great deal of latency-sensitive traffic. In Figure 11 we show the RTT over three minutes for the best 20 disjoint paths between them. This is calculated iteratively; first we run Dijkstra to calculate the best path, then we remove all the RF uplinks and laser links used by that path from the network graph. We then re-run Dijkstra to find the next best path, eliminate those links, and iterate. With this formulation, no satellite overhead either city can provide more than one up or downlink, and no intermediate satellite can be used by more than two paths. This implicitly assumes that laser links and RF links have the same capacity - this is unlikely in reality; whichever turns out to be the bottleneck, a real network will allow more paths than this, so the figure effectively shows an upper bound on path latency.

There are five paths that have lower latency than the great-circle fiber path, and all 20 paths have lower latency than the current Internet path. However, latency variability increases as the path gets worse: path 20 has much more variable latency than path 1, as it has fewer options available. In figure 12 we see the one-way latency of path 20 in more detail. 10% variability is likely insufficient to trigger spurious TCP timeouts, and increases in RTT are also unlikely to impact TCP. However, when latency decreases rapidly, reordering will occur, causing TCP to incorrectly assume a loss has occurred and triggering a fast retransmit.

5 RESEARCH AGENDA

A network such as Starlink raises many research questions, both for the network itself, and for traffic traversing it. For legacy Internet traffic, reordering must be avoided. Delay-based congestion control such as BBR[3] may not perform well over such a network. The network must be resilient to failures. And it must be capable of routing with low delay, even when traffic levels are high enough to saturate the best paths. We briefly discuss some of these questions.

Reordering. Reordering is different from that seen on a terrestrial network. So long as queues are not allowed to build in satellites, reordering is completely predictable, as all routes are known several hundred milliseconds in advance. One solution is to maintain a reorder buffer at the receiving groundstation. Packets that arrive over a lower delay path are

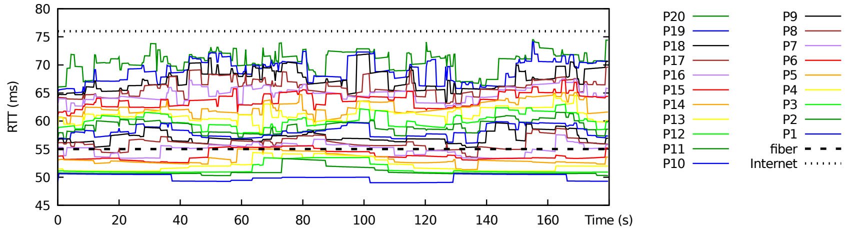

Figure 11: Phase 2 Multipath RTT, NYC-LON, best 20 disjoint paths.

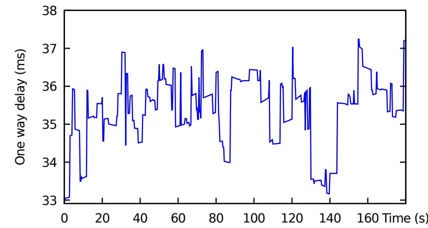

Figure 12: Latency on path 20.

simply queued until their one-way delay matches that of the higher delay paths. Doing this, the RTT on the 20th best path is still approximately 74ms, less than current Internet RTT.

We can do even better if the sending groundstation can annotate packets with a sequence number, a path ID, and the time t_{last} since it sent the last packet on the previous path. When the sending groundstation switches from a higher delay path to a lower delay one, reordering may occur. The first packet to arrive on the new path is identified by the receiving groundstation from the change of path ID. Suppose the known difference in path delays is t_{diff}. If any preceding packets are missing, the receiving groundstation queues all packets arriving on the new path until either all predicing packets have arrived, or time equal to $t_{diff} - t_{last}$ has elapsed. After this, all packets sent on the old path should have arrived.

Finally, as the sending groundstation knows future path latency, if there is a queue there that is longer than the difference in path delays, it may take packets from this queue out-of-order, sending them over different latency paths so that they arrive in-order at the receiving groundstation. For high-priority latency-sensitive traffic, we would hope that no such queue ever exists, but we expect that a large volume of lower priority traffic will also be present and fill in around the high-priority traffic. It is this traffic that might use a 20th best path, and it too must not suffer excessive reordering.

Failures. Such a network is inherently resilient to failures. If an RF transceiver fails, that satellite can still relay through traffic; there are many other satellites within range of a groundstation, so the impact on coverage is minimal. However, all groundstations need to be informed of any failure, so they can factor it in to their routing considerations. If the five transceivers on a satellite are interchangable, then of one failes, the constellation continues to perform almost unchanged so long as the four remaining transceivers are used for the links along the orbital plane, and for the side links. The link between NE-bound and SE-bound satellites is less critical because latency-based routing will often try to avoid such paths (see the latency spike in Figure 7), and other similar-latency paths will be normally be available. Again, everyone needs to know about the failure to factor it in to routing.

SpaceX have stated that they will have on-orbit spare satellites for each orbital plane—it uses very little fuel to adjust position along an orbital plane, but requires excessive fuel to perform a plane change. However, even without spares, the network has very good redundancy. Gaps in coverage can be routed around - for example, Path 2 in Figure 11 shows the latency achieved between London and New York is *all* the satellites on Path 1 were unavailable. The same is likely not true though for extreme latitudes, where coverage is much sparser. We note that SpaceX propose 75 satellites per orbital plane for the higher inclination orbits, rather than 50 in other orbits; we speculate that this closer spacing may allow laser links to bypass one failed satellite to reach the next.

Load-Dependent Routing. All the simulations above assume that no significant queuing happens in the satellites themselves. For high-priority (likely high cost) traffic, this can be ensured by admission control, so long as it forms a minority of the traffic. This is a similar model to that used on the terrestrial microwave links used for high frequency trading. Regular Internet traffic will not get such priority treatment, so a LEO constellation operator needs to perform active traffic engineering to avoid creating hotspots in the network. Others have demonstrated that shortest-path routing on mesh networks is particularly susceptible to creating hotspots[6].

In terrestrial networks, centralized load-dependent routing schemes such as B4[9] and LDR[7] can pro-actively route so as to achieve low latency without causing congestion. These schemes, however, make routing decisions on a minute-by-minute basis - too slow for routing on dense LEO constellations. It is an open question whether such schemes can be extended for this use, or if the latency between the controller and groundstations will always be too high.

We postulate that a hybrid solution may work well. High priority low-latency traffic always gets priority, admission control limits its volume, preventing it causing congestion and it gets explicit routing ensuring minimum latency. For the remaining traffic, satellites monitor link load; this is broadcast to all groundstations globally, so everyone is aware of hotspots. Because of the nature of a LEO constellation, these hotspots tend to be geographic rather than topological. Groundstations then randomize their path choice across slightly less favorable paths to load-balance traffic away from hotspots. In a traditional topology, this would likely lead to instability, where traffic flip-flops between the best path and a worse alternate. As our simulations show, dense LEO constellations have very many paths available, and many of them are of similar latency. This allows groundstations to be much more conservative about when they move traffic back to the lowest delay path, using timescales much longer than the latency of the broadcast load reports, so avoiding instability. We believe this is an interesting direction for future routing work on dense LEO constellations.

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