Exploring Low-Earth Orbit Network Design

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ABSTRACT

Mega-constellations of low-Earth orbit (LEO) satellites beaming Internet connectivity from space is not fiction anymore – with multiple early movers like SpaceX, OneWeb, and Telesat actively deploying/offering services globally, and many other providers still entering this 'space', LEO broadband is quickly getting democratized. Nevertheless, the rationale behind picking the constellation design parameters remains largely unknown to the community. Constellation design is a complex high-dimensional problem governed by satellite capability and launch constraints, budget, target market and traffic demands, and performance optimization metrics. In this early-stage work, we pick SpaceX Starlink's constellation budget and intuitive target markets and understand the impact of design parameter choices on various network performance metrics like throughput, latency, and coverage. The findings help in effectively pruning the high dimensional parameter search space and could offer critical domain knowledge to a full-fledged LEO network design framework.

CCS CONCEPTS

• **Networks → Network simulations**; **Network measurement**; **Network performance modeling**; **Network performance analysis**; *Network design principles.*

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1 INTRODUCTION

The Internet is going through a massive upgradation as LEO satellite mega-constellations gear up to beam connectivity from space. Dense deployments at low heights (few 100 km) offer bandwidth and latency comparable [28] to today's Internet with a strong promise to further improve as inter-satellite laser (ISL) links, operating at the speed-of-light in space, are rolled out [8]. SpaceX Starlink currently has 4,500+ satellites in LEO [35] and has started offering broadband services in more than 56+ countries [13]. SpaceX recently received FCC approval to deploy 7,500 Starlink Gen2 satellites [9] that are all supposed to be equipped with ISLs [37]. Longer term, SpaceX plans to deploy 30K+ [3, 9] LEO satellites in orbit. OneWeb currently has 618 satellites in LEO, enough for global coverage given their design [14]. Amazon's Kuiper Systems and Telesat plan to deploy around 3,236 and 1,671 satellites, respectively [2, 4].

The Secret sauce of constellation design: The proposed constellation's orbital parameters might appear arbitrary and show no specific pattern, i.e., Starlink's first two shells operate in 72 orbits with 22 satellites per orbit, but the last two retrograde shells have 6, 4 orbits with 58, 43 satellites per orbit. In Starlink Gen2, VLEO shells operate in 48 orbits with 110 satellites per orbit, and LEO shells operate in 28 orbits with 120 satellites per orbit. In contrast, Kuiper plans to deploy multiple uniform shells with the same number of orbits and satellites per orbit per shell. Starlink Gen2's last two shells design is similar to the Kuiper design with fewer satellites. Given the humongous billion dollar investments [33] associated with the deployment and management of these 'flying' global infrastructures, we believe their network design is not *random.* In this early-stage work, we explore the LEO constellation design space to find useful insights into these design choices, which, otherwise, is lacking due to 'secret sauce' business strategies.

Putting our work in context: In a previous attempt by Iridium and Iridium NEXT, a few 100 satellites were deployed, and there was a surge in related research [17, 18, 23, 26, 30]. However, today's mega-constellations consist of thousands of satellites with ISLs, spread across multiple shells. This new scale opens up the possibility to build constellations with highly optimized network performance. As space players announced plans to deploy mega-constellations for global Internet coverage, authors in [16, 19, 20] framed a broad research scope on topology design, routing, and congestion control challenges while identifying the possible latency benefits of such networks. But these works did not shed light on superior trajectory design. Recent work [21, 22] focus on

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(i) extensive performance comparison of four mega constellations i.e., Starlink, OneWeb, Kuiper, and Telesat, and (ii) optimal placement of base stations to maximize throughput, with the main focus on optimizing only the terrestrial part of the entire topology. As opposed to these efforts, our work focuses on the "high-dimensional problem" of designing a performant LEO constellation while optimizing multiple inter-coupled performance metrics.

Our contributions: Our long-term objective is to develop an LEO network design framework that takes as inputs the budget, various constraints (launch sites and launch trajectories, satellite capabilities, FCC/ITU requirements, etc.), traffic matrices, use cases (broadband vs. constellation for gaming), etc. and outputs probable design choices. New entrants in this 'space' could adopt the framework to arrive at an informed network design. Toward this vision, the key contribution of this early-stage work is to quantify and understand the impact of various orbital design parameters on the network performance (throughput, latency, and coverage). This is an essential step toward significantly reducing the parameter search space of this otherwise high-dimensional problem. We pick SpaceX Starlink's [3] first shell to demonstrate our findings.

Paper outline: The remainder of the paper is organized as follows. §2 summarizes our overall background and problem overview. §3 presents the experimental evaluation, and §4 discusses some of the future work.

2 PROBLEM OVERVIEW

In this section, we discuss the LEO network design problem in the context of the orbital design parameters and their impact on network performance. We limit ourselves to circular (non-eccentric) orbits, which are proposed by all the large players – Starlink [3, 9], OneWeb [6], and Kuiper [2]. Eccentric orbits could introduce non-uniformity in performance over time and. hence, are not suitable for 'global' broadband offerings.

Design parameters: The number of satellites is usually divided into more than one shell (s). Each shell is characterized by a number of design parameters, such as the number of orbital planes o, the number of satellites per orbital plane n, altitude h, angle of inclination i (i.e., the angle between the orbital plane and the Earth's Equator) and phase offset p (i.e., the relative difference in the positioning of satellites between two adjacent orbits). The minimum angle of elevation e is the minimum grazing angle for sustaining a communication link between the terrestrial ground stations and the satellites in a constellation.

Curse of high dimensionality: The design of a constellation needs to be decided upon a combination of seven parameters: s, o, n, i, h, p, and e. LEO constellation providers usually declare a minimum angle of elevation (e) while satellites could operate at values higher than e. Software-defined phased array antenna can form a beam at any angle above the minimum angle of elevation (hardware limit). Starlink currently operates with $e = 25°$, and after complete deployment will operate with $e = 40°$ [1]. Very low value of e allows ground stations and user terminals to connect satellites just over the horizon, with the longer radio links subject to high atmospheric attenuation. Fig. 1 shows how e determines the coverage area of individual satellites. Given the high dynamicity of LEO and the Earth's rotations, routes and network performance could vary across time. Thus, ideally, constellation performance needs to be evaluated multiple times, t, over a period of a day. An exhaustive search space would be composed of $|s| \times |o| \times |n| \times |i| \times |h| \times |p| \times |e| \times |t|$ different constellation instances, where $|x|$ denotes the number of choices of variable x. Applying some domain knowledge would trim down the search space. t, for example, could be restricted to the shorter orbital period (depends on the height h; ~95 min at 500 km) of a shell, as satellites come back to their previous positions and adjacent orbits could offer replacements to ground stations thus leading to comparable network performance[1]. i, for example, can be restricted between 30° and 90°. i below 30° condenses all the satellites close to the Equator, and most ground stations lose coverage. Also, we have observed in simulations that the performance (for i) from 90° to 150° is symmetric to the results of 30° to 90°. The values of h are subject to the availability of the altitude (no other satellite shells close by [11, 24]) and approval from FCC/ITU. Also, in our simulations, we observe that a few kilometers of change in altitude do not change performance significantly.

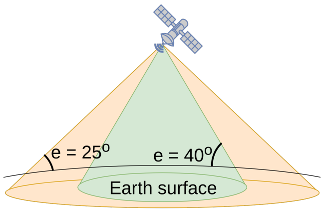

Figure 1: e vs. coverage.

Each parameter combination takes time to evaluate – generating the graph and evaluating the performance metrics (discussed next) takes a few tens of minutes, and a naive n-dimensional grid search would take many years to complete even with 10,000 cores. Hence, in this work, we pick a subset of the key parameters and perform coarse-grained 1-dimensional performance evaluation for each of them. The scope of this paper is restricted to the analysis of four parameters, i.e., o, n, i, and e, and the corresponding search space reductions. We use $p = 0.5$ to uniformly distribute satellites [20, 31] and evaluate single shells (s) of deployment. While in this work, to focus solely on trajectory design, we assume a simple +Grid [20] connectivity with satellites in an

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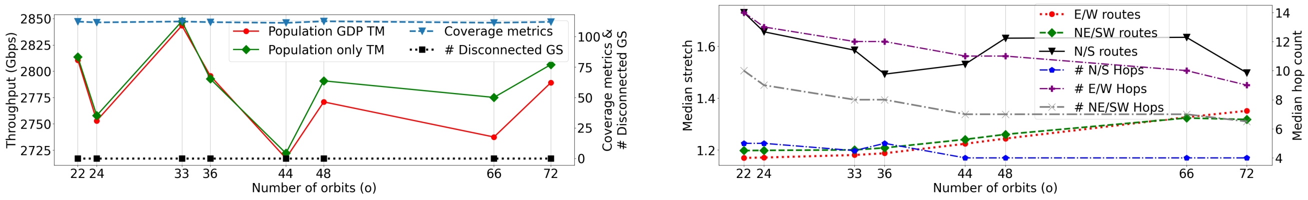
[1] For Starlink's first shell, the performance variation over time is at most 10%. Hence, our simulations are restricted to the epoch.



(a) (b)

Figure 2: Varying o results in (a) minor fluctuations ($\leq 5\%$) in throughput (left Y-axis) and no change in coverage (right Y-axis) (b) The median stretch (left Y-axis) of E/W and NE/SW routes inflates with a higher o whereas N/S routes show relatively high median stretch for all value of o; the number of hops in routes falls (right Y-axis) when o is higher.

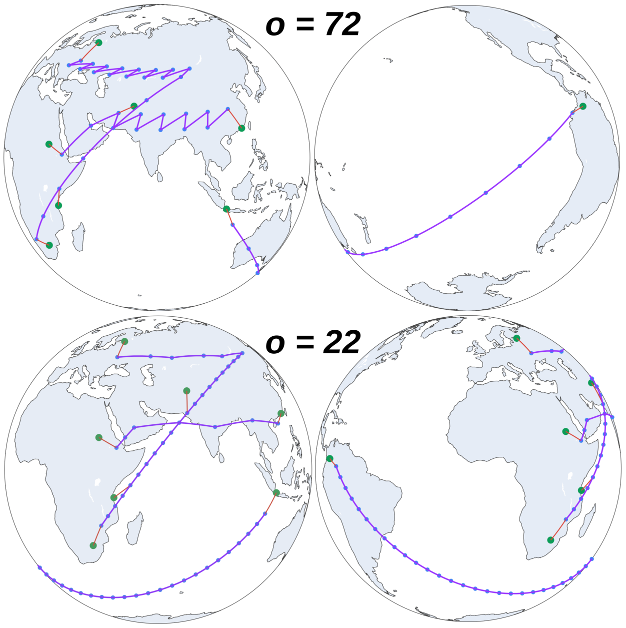


Figure 3: Visuals of the shortest paths with different o. No straight path for N/S routes as $i = 53°$. For large o, E/W paths could be zigzag, inflating stretch. For GS pairs in different hemispheres, paths tend to follow a single orbit.

orbit setting up 4 ISLs with their immediate north-south-east-west neighbors, a joint trajectory and topology optimization is left to future work.

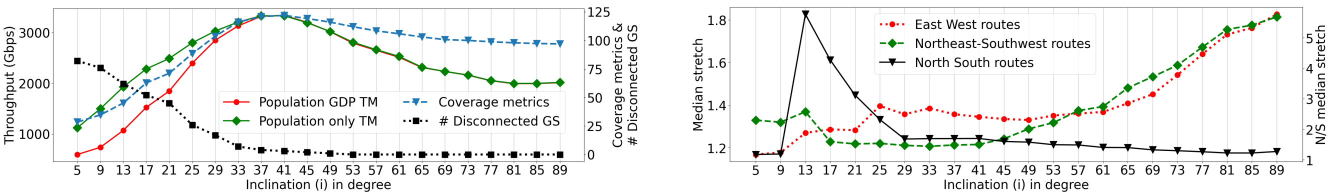
Model & assumptions: We generate an LEO constellation as a network graph where the nodes are satellites and ground stations (GS), and the edges consist of ISLs, and ground-to-satellite links (GSL). While some of the proposed constellations use exclusively bent-pipe architecture [7] (no ISLs), here we study constellations with ISLs that offer lower latencies over longer distances compared to terrestrial fiber. Our work can be easily extended to bent-pipe constellations. The bandwidth of the ISLs is optimistically assumed to be 50 Gbps [5, 10, 12], whereas the GSL capacities are calculated using Shannon's capacity theorem [34] and upper Ka-band specifications [21]. We use a free space path loss model [29] for modeling atmospheric loss in GSLs.

Traffic matrices (TMs): We use some intuitive traffic demand models as follows: we assume that GSes are located in 100 highly populated cities around the globe, serving the city's cumulative traffic demand. The city-pair demands follow a gravity model [32] – demands are directly proportional to the product of the population or GDP (Gross domestic product) weights and inversely proportional to the squares of the geodesic distances. Although various intuitive TMs can be formulated, in this work, we limit ourselves to the following two TMs:

(1) *Population only*: Demands across GS pairs are weighted based on the population of the cities [15]. We assume 10% of the population as the target market and, on average, 300 Kbps usage per head [22].
(2) *Population-GDP*: This TM consists of the same population centers as above. We assume that the target market of a city is 10% of the entire population (across all cities), weighted by its GDP (normalized to the total GDP).

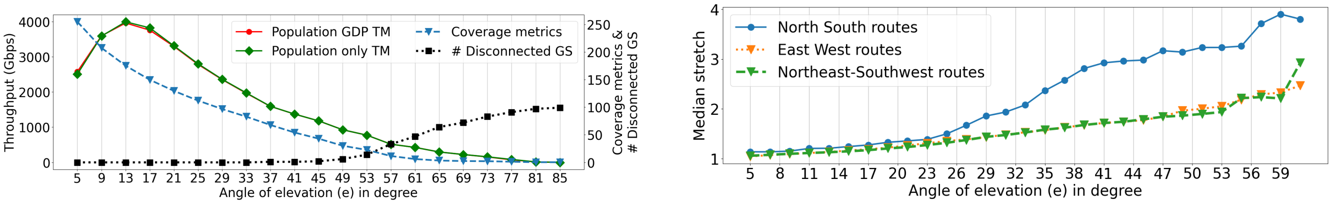
Network performance metrics: We evaluate the constellations on the following three performance metrics.

(1) **Throughput** is measured as a multi-commodity flow across GSes. At any given time, 20 shortest paths are calculated between the GSes using Yen's algorithm [36]. We use a linear program (details omitted for brevity) that maximizes the end-to-end throughput across all GS pairs, constrained by the capacity limits of the individual links.
(2) We quantify network latency in terms of **stretch**, which is the ratio of the shortest-path distance between the source-destination GS pairs and their geodesic distance. Note that for terrestrial fiber, the speed of light is $2/3^{rd}$ the speed of light in air, thus resulting in a stretch of 1.5 even for the most optimistic deployment along the geodesic line.
(3) **Coverage** of a constellation is measured as $C = \sum_{t=0}^{T} \sum_{g=0}^{G} \log n_{t,g}/T$, where $n_{t,g}$ denotes the number of satellites visible from the g-th GS at t-th time instance, G is the number of ground stations and T is the number of epochs. We use the $\log(.)$ function to model the diminishing returns (sub-linear increase in throughput) as the number



(a) (b)

Figure 4: Variations in (a) throughput, coverage, and (b) stretch (for different path orientations) for different values of i.



(a) (b)

Figure 5: Variations in (a) throughput, coverage, and (b) stretch (for different path orientations) for different values of o.

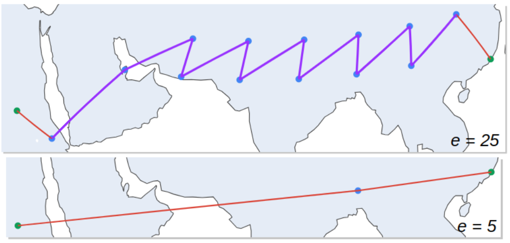


Figure 6: Visuals of best stretch route with extremely low e connecting satellite close to the horizon.

of visible satellites per GS increases. Note that our simple model replaces all city-level GSes with a single GS that could simultaneously connect to more than one satellite.

Notice that, only the throughput metric described above is weighted by the TMs; others are unweighted.

3 RESULTS: ANATOMY OF AN LEO CONSTELLATION

For this work, we focus on the impact of o (and n), i, and e orbital parameters [2] on network performance (i.e., throughput, coverage, and stretch) for Starlink's first shell of 1,584 satellites. Our simulator varies one parameter at a time while keeping the others fixed at their default values ($h = 550$ km, $o = 72$ ($n = 22$), $i = 53°$, and $e = 25°$) proposed in Starlink's FCC filings [3] across all experiments. We assumed $p = 0.5$ (the value is not available in the FCC filing) to spread satellites most uniformly in a shell [20, 31].

Changing number of orbits (o): The value of o does not affect the coverage but results in minor ($\leq 5\%$) fluctuations in throughput, as seen in Fig. 2(a). Note that we restricted the lower bounds of o and n to 20 because we observed that going beyond these values with $h = 550$ km and $e = 25°$ (Starlink first shell parameters) creates significant coverage gaps.

However, o impacts the stretch of geographical North-South (N/S), East-West (E/W), and North east-South west (NE/SW) routes as shown in Fig. 3. From Fig. 2(b) and Fig. 3, we can observe the following: (*i*) As o increases, E/W and NE/SW paths become more zigzag while navigating through the +Grid of many orbits. This path-length inflation results in a moderately higher stretch. Also, lower o naturally results in higher n, thus resulting in higher path diversity for E/W routes. (*ii*) N/S routes show a relatively high stretch than E/W and NE/SW routes since $i = 53°$ gives no straight path between two GSes in the N/S direction. (*iii*) When source and destination GSes are located on two different hemispheres (routes with high geodesic distance), the paths between such GS pairs primarily consume single orbits via intra-orbit ISLs. Therefore, the value of o could also decide the number of satellite hops, especially in long-distance routes. To have an idea of differences in hop counts over longer distances, refer to the right globes in Fig. 3.

Key takeaway: Changes in o do not affect coverage, result in a nominal change in throughput, and moderately impact stretch (while still keeping all stretch values within 1.5, i.e., the best terrestrial fiber stretch for geodesic deployment). Differences in o (and n) could lead to differences in path hop counts – more hops along a path means higher aggregate packet processing computation.

Changing inclination angle (i): Fig. 4 shows the network performance variations with different i. Note that setting the value of i to x means restricting satellites between latitude $x°N$ and $x°S$. From Fig. 4(a), we can observe the following: (*i*) Population-only TM gives relatively higher throughput

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[2] A full-fledged LEO network design should cover all such parameters.

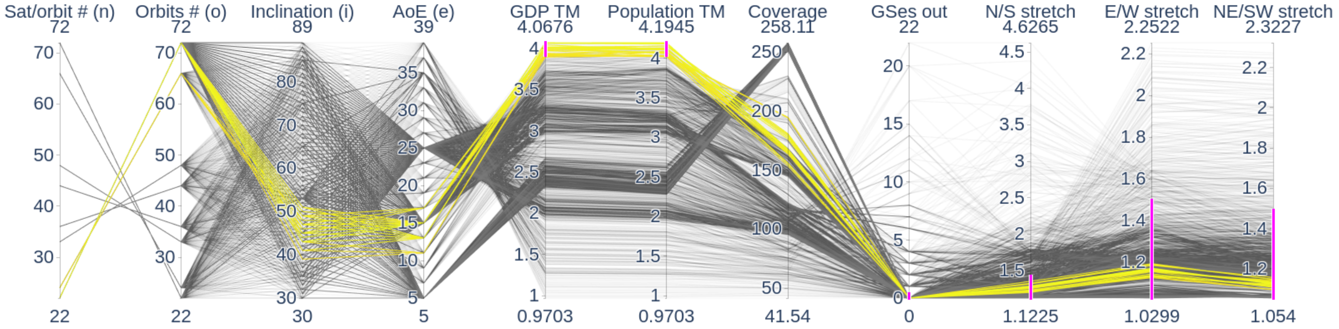

Figure 7: Parallel coordinate plot with the vertical axes representing the LEO design parameters and performance metrics; highlighted lines (in yellow) are possible parameter choices filtered by design objectives (vertical axes highlighted in pink), i.e., high throughput (in Tbps), stretch ≤ 1.5, and exhaustive GS coverage.

for lower *i* compared to Population-GDP TM since lower latitudes often correspond to low GDP but high population regions. (*ii*) Lower values of *i* affect the coverage, i.e., for $i \leq 33°$, GSes start losing coverage. (*iii*) Most of the population centers (hence, GSes) are located between latitudes 50° N and S; hence *i* values between 35° and 45° N/S offer higher throughput and better coverage. (*iv*) Polar orbits (higher *i*) result in lower satellite densities at lower latitudes (where the population is) hence affecting both throughput and coverage.

Fig. 4(b) shows that: (*i*) Lower the *i* better the stretch for E/W and NE/SW routes. (*ii*) As *i* increases, N/S routes experience lower stretch at the cost of inflation for both E/W and NE/SW routes.

Key takeaway: i between 35° and 45° offer high throughput, good coverage, and low (≤ 1.5) stretch for E/W and NE/SW routes. $i = 53°$ (default) slightly worsens the performance across all dimensions, albeit with the reward of coverage at higher latitudes (not demonstrated here).

Changing angle of elevation (*e*): For a fixed satellite height, *e* defines the coverage cone of the satellite. Hence, the lower the *e*, the more the number of satellites a GS could 'see'. Fig. 5 shows the following: (*i*) Higher *e* results in lower coverage and beyond a threshold ($e \approx 45°$) also leads to disconnected GSes. Such low coverage also affects the throughput for both TMs. (*ii*) $e \approx 13°$ offers optimal (in our simulations) satellite diversity to GSes, thus maximizing throughput for both TMs. Lower values result in lower throughput due to longer GS-satellite links over the horizon and associated high path loss.

Note, though, that lower the *e*, better the stretch due to more path diversity. Fig. 6 shows how $e = 5°$ reduces a route from Africa to Asia from 13 satellite hops ($e = 25°$) to 1 satellite hop and significantly smaller stretch.

Key takeaway: e, similar to i, has a performance knee (around 13°). This knee offers high coverage and throughput and low stretch. Very low e values can offer low stretch but at the cost of throughput.

'Good' *o*, *i*, and *e* combinations: In this early work, we vary the design parameters *o* (hence, *n*), *i*, and *e* for a 1,584-satellite constellation and Fig. 7 gives the parallel coordinate plot to demonstrate which combinations of these parameters result in 'good' performance. Note that the vertical lines represent (clipped ranges for clarity) the various parameters and also the performance metrics – throughput (for both Population Only and GDP-Populations TMs in Tbps), coverage, and path orientation-wise stretch. The horizontal lines map between the parameter values and the corresponding performance.

Assuming the design objectives are (*i*) high throughput and (*ii*) stretch lower than 1.5 (theoretical best achievable with terrestrial fiber) and constrained by a tight coverage criterion (each GS should be covered), we mark such mappings in yellow on Fig.7. Broadly speaking, Starlink's first shell design ($o = 72$, $n = 22$, $i = 53°$) is in the right ballpark, while a lower *e* (probably a hardware constraint for Starlink) could offer better path diversity and higher throughput.

4 FUTURE WORK

Our analyses shed light on Starlink's design choices and could identify ranges of parameter values that could offer 'good' performance given the budget, TMs, etc. Our findings call for a broader agenda:

Toward an LEO design framework This early-stage work is a concrete step toward building an LEO constellation design framework that takes as input all budget, deployment, demand, and design constraints and objectives, and outputs the optimal trajectory design choices. The framework is envisioned to offer a library of AI/ML tools and genetic/evolutionary algorithms custom-tuned with LEO domain knowledge to significantly reduce the search space. A matured framework could also consider non-networking factors like satellite collision probabilities, maneuvering needs, legal bindings, operational permits, etc.

Understanding specific use cases The framework should accommodate specific use cases like satellite imagery and IoT. While the design objectives and demands might change, the rest should be similar. Also, we plan to accommodate performance metrics that rightly capture the usefulness of having sun-synchronous orbits in a constellation.

Trajectory-topology joint design While we assumed +Grid to be the default topology for constellations, there is a scope to jointly optimize both trajectory and topology of a satellite shell. For example, while some trajectory designs could lead to paths with many hops, topology design [20] could counter such negative effects by accommodating longer hops.

Understanding packet-level performance The filtered design choices need to be evaluated thoroughly at a packet-level granularity using existing simulators and emulators [25, 27].

5 CONCLUSION

In this work, we study satellite trajectory design, picking a few important design parameters, one at a time, and quantifying their impact on LEO network performance. We show how for the SpaceX Starlink first shell budget and intuitive traffic matrices, the design parameter choices are reasonable, in general, with one clear exception – a lower minimum angle of elevation, if supported by their hardware, could offer better path diversity and throughput. The 1-dimensional analyses of both the angles of inclination and elevation demonstrate interesting performance 'knees', thus hinting at the possibility of reducing the search space of an n-dimensional search needed to find the 'best' configuration.

Ethics: Our work does not raise any ethical concerns.

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