An Updated Comparison of Four Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband

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***Abstract*—Twenty years of technological improvements have raised once again the question of the economic viability of offering Internet access from space using non-geostationary orbits (NGSO). Trying to answer this question, many established satellite operators (e.g., SES, Telesat) and newcomers (e.g., SpaceX, Amazon) have recently filed applications for these types of constellations, with SES currently operating a NGSO constellation in MEO. The new architectures rely on thousands of high-throughput satellites, combined with an even-larger ground segment, which will compete with and complement the terrestrial Internet infrastructure where it is inefficient or non-existent.**

This paper provides an updated comparison of four of the largest LEO mega-constellations, namely Telesat's, OneWeb's, SpaceX's, and Amazon's, in terms of throughput estimation. First, we present the configuration of each constellation as described in their FCC filings (as of January 2021), including pending propositions. Then, we briefly describe the methodology and models used for the system performance analysis, which includes statistical analyses of each system's throughput, as well as orbit dynamics and atmospheric conditions. Finally, we discuss the results and argue how the changes in the filings affected the overall throughput estimation and satellite efficiency, in terms of average capacity utilization.

Despite having the fewest satellites, Telesat achieves a similar throughput as SpaceX thanks to their dual gateway connection and wider field of regard. OneWeb manages to achieve second-to-highest throughput thanks to their largest constellation, despite having the lowest satellite utilization. The reduction in minimum elevation angle and altitude improves SpaceX's previous results in both total throughput and satellite utilization. Amazon achieves the highest throughput at around 53.4 Tbps, at the cost of a larger ground segment. Finally, all architectures benefit from the usage of ISL, achieving improvements between 13% and 42% when using 20 Gbps connections.

***Index Terms*—Megaconstellation, Satellite communications, LEO, Starlink, SpaceX, Telesat, OneWeb, Amazon**

I. INTRODUCTION

A. Motivation

LEO constellations for global broadband services have been satellite operators' goal for almost three decades now. In the 90s, constellations such as Iridium and Globalstar started the trend of offering communication services from space using non-geostationary satellite orbits (NGSO). However, they failed to accomplish their objective due to the lack of economic viability of the projects [1]. Now, after two decades of technological advancements, new hardware and software technologies have renewed the operators' interest in global Internet coverage from space. In recent years, multiple companies have filed petitions to the Federal Communications Commission (FCC) for large constellations in NGSO. Four of these filings stand out due to their size and development maturity: Telesat, OneWeb, SpaceX, and Amazon.

The financial feasiblity of the new era mega-constellations relies on three factors: improved single-satellite performance (thanks to digital payloads, steerable multi-beam antennas, advanced modulation and coding (MODCOD) schemes, and frequency reuse strategies), reduced launching and manufacturing costs, and a growing economic pull coming from the ever-increasing demand for broadband access in isolated rural regions, together with the expected growth of aerial and maritime mobile users. The technological improvements allow operators to design architectures with more than 1,000 satellites and offer tens of Tbps.

In a previous publication [2], we presented a technical comparison of three of the largest LEO constellations for broadband services. This paper intends to update the results enclosed in this work according to the FCC filings changes since September 2018, which involve largely increasing the number of satellites for Telesat and OneWeb, and reducing the altitude of the constellation for SpaceX. Together with these three companies, we included Amazon's constellation in the updated comparison due to the similarities with the other three architectures and their advanced funding stage.

B. Literature review

In the early 90s, many companies filed for LEO constellations to offer phone and other communication services from space. None of the architectures managed to accomplish their objective, most companies attributing the failures to the economic viability of the systems, which led to early project cancellations and bankruptcy petitions. Many works followed the rise and fall of these constellations, analyzing mostly the Iridium (Maine [3], Finkelstein [4]) and Globalstar (Wiedeman [5]) constellations. A more general comparison of different

GEO, MEO, and LEO architectures was reported by Vatalaro [6] and Evans [7]. While the former presents a performance estimation in the presence of adverse atmospheric conditions, the latter gives a more general overview of the systems and discusses their technical challenges.

Regarding the new systems, work to date has focused on estimating the impact probabilities between satellites [8] and analyzing [9] and proposing solutions [10] for debris mitigation. The comparison between proposed LEO and established GEO constellations was also reported by Mclain [11]. When it comes to the performance comparison of the new-era constellations, scarce literature can be found. Reid [12] analyzes how the modern architectures can improve current navigation services. Del Portillo [2], for which this work is an update, covers in detail the comparison between Telesat, OneWeb, and SpaceX as of September 2018, in terms of orbital and frequency characteristics, and from a system performance perspective.

C. Objective

The objective of this work is to present an updated comparison of four of the largest LEO mega-constellations from a technical perspective and to estimate the systems' performance, in terms of total throughput and satellite utilization, based on the current filings as of January 2021.

D. Overview

The contents of this paper are organized as follows: Section II details each of the four configurations and compares them based on orbital characteristics; Section III provides a brief summary of the methods and models used to compute the system throughput estimation; Section IV presents the results of each constellation in terms of overall throughput and satellite performance; finally, Section V discusses the conclusions of this work.

II. CONSTELLATIONS ORBITAL CONFIGURATION

This section compares the system architecture of the four different mega-constellations considered in this paper (Telesat, OneWeb, SpaceX, and Amazon), as described in their FCC filings as of January 2021, including pending changes. The applications analyzed are the same as the ones previously compared in [2] plus modifications, to which we have added Amazon's system. As the second generation of SpaceX (understood as the system with 30,000 satellites using feeder links in E-band) is filed as a new application, it is not included in this work. Other architectures, such as ViaSat latest LEO proposal and SES O3b mPOWER, are outside the scope of this paper.

A. Telesat's system

As described in [13], [14] (filings in approved and pending status, respectively), Telesat's constellation consists of two phases: the initial phase comprises 298 satellites, while this number rises to 1,671 in the second phase. All satellites are distributed in two sets of orbits: the *polar* orbits, with an altitude of 1,015 km and an inclination of 98.98°, and the *inclined* orbits, with an altitude of 1,325 km and an inclination of 50.88°. The initial phase will consist of 6 polar planes with 13 satellites per plane plus 20 inclined planes with 11 satellites per plane. This phase is necessary to start service. The second phase will increase from 6 polar planes to 27, and from 20 inclined planes to 40. The second phase will also triple the number of satellites per plane in the inclined orbits (from 11 to 33). Each orbit is designed for a specific objective that allows Telesat to serve their customers more efficiently: while the polar orbits intend to provide coverage over the poles, the inclined orbits focus most of the capacity on populated regions.

The constellation is provided with intra- and cross-plane inter-satellite links (ISL). The on-board payload allows the formation of 4 steerable gateway beams plus 24 steerable and shapeable user beams. All the other satellite resources, such as power and bandwidth, will be dynamically allocated based on demand. The gateway beams will connect to strategically distributed gateway stations with up to 3.5 m antennas. The constellation will use 1.8 GHz for downlink (17.8-20.2 GHz) and 2.1 GHz for uplink (27.5-30.0 GHz), all in the Ka-band spectrum.

B. OneWeb's system

Just as Telesat's system, OneWeb's constellation [15]–[17] (filings in approved, pending, and pending status, respectively) consists of two phases: an initial phase with 716 satellites, and a second phase with 6,372 satellites. In both stages, all satellites will operate at the same altitude of 1,200 km. The initial phase consists of two sets of 12 and 8 planes with inclination 87.9° and 55°, respectively. The polar orbits will contain 49 satellites per plane, while this number reduces to 16 for the rest. The second phase intends to extensively cover the Earth regions with a higher population. To that end, the first set is enlarged from 12 planes to 36; the second set is drastically changed from 8 to 32 planes and from 16 satellites per plane to 72; and a third set is added, with similar characteristics as the second set, at inclination 40°. Like Telesat, OneWeb allocates a reduced set of satellites in highly inclined orbits to offer global coverage while focusing most of their capacity in populated regions.

According to the FCC filing, OneWeb will not use ISL at the beginning of operations, but they may consider it "*at some point in the deployment of the system*" [17]. In case they opt not to use ISL, their system would only allow to serve users that are simultaneously located in the same field of regard (FoR) as a gateway, which would require a larger number of gateways in order to offer global coverage. In the initial constellation, each satellite will have 16 highly-elliptical user beams. Regarding the final deployment, each satellite in the constellation can form up to 32 steerable user beams. In both, satellites will be capable of forming at least two steerable circular gateway beams. Gateway beams will provide Internet connection to the users by connecting to a strategically-located gateway, which will have antennas with a diameter between 2.4 m and 3.5 m. In terms of frequency usage, the satellites will use 2.1 GHz in the higher Ka-band (27.5-30.0 GHz) for gateway uplinks, 1.3 GHz in the lower Ka-band (17.8-19.3 GHz) for gateway downlinks, 500 MHz in the Ku-band (14.0-14.5 GHz) for user uplinks, and 2 GHz in the Ku-band (10.7-12.7 GHz) for user downlinks.

C. SpaceX's system

Out of the four projects considered in this work, SpaceX's system Starlink is the closest to becoming operational, as it already has several hundreds of satellites in orbit and is starting its beta testing. According to their FCC filing [18]–[21] (filings in approved, approved, approved, and pending status, respectively), the Starlink constellation will consist of 4,408 satellites divided into five different shells: the first shell, at 540 km, is divided into 72 orbital planes with 22 satellites per plane at 53.2° inclination; the second shell, at 550 km, is also divided into 72 orbital planes with 22 satellites per plane at 53° inclination; the third and fourth shell, both at 560 km and 97.6° inclination, contain 6 and 4 planes and 58 and 43 satellites per plane, respectively; finally, the fifth shell, at 570 km, consists of 36 orbital planes with 20 satellites per plane at 70° inclination. The first shell is considered the initial phase and is the one currently being deployed. Although the architecture seems much more heterogeneous than the previous two systems, the idea behind it is still the same: using a reduced set of satellites to offer coverage of the poles while focusing its capacity on populated regions.

Starlink plans to use optical ISL, which will allow them to serve users globally even when a gateway is not within the FoR of a satellite. Although specified in the filings, they did not include ISL in their initial launches. Each satellite can use the full frequency range in both polarizations to connect to a gateway, and up to four satellites can connect to a gateway at the same time. In terms of gateway positioning and characteristics, SpaceX plans to have a vast number of gateway stations worldwide, which will provide Internet access to their users. Most of the gateway stations' licenses filed up to this day (e.g., [22]) use a 1.5 m antenna for their connections. Similar to OneWeb, Starlink will use the Ka-band for gateway communications (17.8-19.3 GHz and 27.5-30.0 GHz for downlink and uplink, respectively) and the Ku-band for user links (10.7-12.7 GHz and 14.0-14.5 GHz for downlink and uplink, respectively).

D. Amazon's system

Amazon is the newest system considered, as their constellation was only announced in 2019 [23] (filing in approved state). Amazon will distribute their satellites in three orbital shells: the first, at altitude 590 km and 33° inclination will host 28 planes with 28 satellites per plane; the second, at altitude 610 km and 42° inclination, will be divided into 36 planes with 36 satellites per plane; and finally, the third shell, at altitude 630 km and 51.9°, will have 34 planes with 34 satellites per plane. The deployment will consist of 5 phases that will bring the constellation up to 3,236 satellites. In their initial phase, Amazon plans to launch half the satellites of the 630 km shell (17 planes with 34 satellites per plane). Due to the lack of highly inclined orbits, Amazon's system cannot offer global coverage as it cannot serve the poles. However, it concentrates all its capacity in regions where high demand is estimated.

From their FCC filing, Amazon does not specify if they plan to use ISL for their constellation. If they opt to not use them, the lack of cross-links would prevent them from serving zones with no gateways (e.g., maritime areas). Similar to other systems, the gateway antennas' diameter will be in the range of 1-2.4 m. In terms of frequency usage, Amazon will use the upper Ka-band frequencies for uplink (28.35-30.0 GHz and 27.5-30.0 GHz for user and gateway uplinks, respectively) and the lower Ka-band for downlinks (17.7-20.2 GHz for both user and gateway downlinks).

System	Altitude (km)	Inclination (°)	Planes	Satellites per plane	Number of satellites
Telesat	1,015	98.98	6	13	298
	1,325	50.88	20	11	
OneWeb	1,200	87.9	12	49	716
	1,200	55	8	16	
SpaceX	550	53	72	22	1,584
Amazon	630	51.9	17	34	578

TABLE I: Summary of the initial-phase orbit characteristics of each constellation. All four designs have already been approved by FCC.

System	Altitude (km)	Inclination (°)	Planes	Satellites per plane	State	Number of satellites
Telesat	1,015	98.98	27	13	P	1,671
	1,325	50.88	40	33	P	
OneWeb	1,200	87.9	36	49	P	6,372
	1,200	55	32	72	P	
	1,200	40	32	72	P	
SpaceX	540	53.2	72	22	P	4,408
	550	53	72	22	A	
	560	97.6	6	58	P	
	560	97.6	4	43	P	
	570	70	36	20	P	
Amazon	590	33	28	28	A	3,236
	610	42	36	36	A	
	630	51.9	34	34	A	

TABLE II: Summary of the orbit characteristics of the complete constellations. *A* represents shells approved by the FCC, while *P* represents pending changes.

E. Orbit configuration comparison

Up to this point, we have described the specific characteristics of the different architectures. Tables I and II summarize the most relevant characteristics of each architecture for initial and full deployments, respectively. Although difficult to compare due to the idiosyncrasies of each configuration, we can observe some general trends in the constellations' designs. The first aspect to notice is that all systems, except Amazon's, allocate a few satellites (between 12% and 28% of their total capacity) in polar orbits. This strategy allows the three companies to serve the poles, which traditionally have been under-served due to their difficult-to-reach position, and offer global service to any of their mobile users, which is very appealing for certain aerial and maritime routes. On the other hand, Amazon directs all of its effective capacity in populated regions. In all cases, most of the technological capacity (between 72% and 88% of the number of satellites) is focused in orbits with an inclination between 40° and 55°, which coincides with the most densely populated areas on Earth. The relation between visible satellites and population density can be observed in Figure 1.

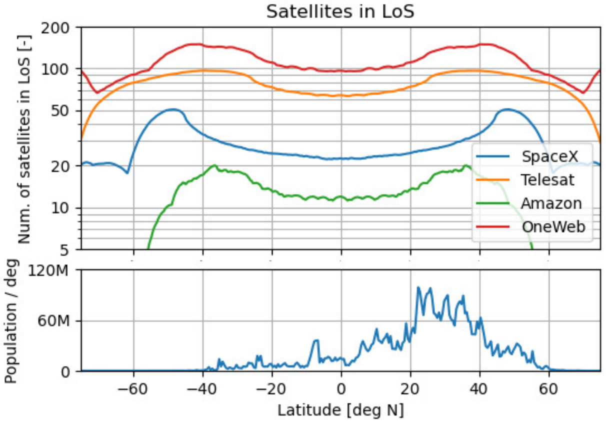


Fig. 1: Satellites in Line of Sight (LoS) for full deployment and number of population per latitude. The minimum elevation angle is different for each constellation and has been extracted from their respective filings.

F. Minimum elevation angle discussion

The different minimum elevation angles as presented in the filings are 10°, 25°, 25°, and 35° for Telesat, OneWeb, SpaceX, and Amazon, respectively. With these numbers, the constellations would achieve different number of satellites in line of sight (LoS) as shown in Figure 1. However, it is unlikely that Telesat, OneWeb, and SpaceX operate at such low elevation angles when the full constellation is deployed because it imposes additional constraints to ground terminals and reduces the effective throughput capacity due to higher losses. From the constellation dynamics, these numbers seem to be related to the initial deployments, where the elevation angles must be stretched to offer continuous coverage. When it comes to system throughput estimation, however, we consider that comparing the capacity based on the angle specified in the filings is unfair and would lead to confusing results, as will likely not be representative of their concept of operations. For this reason we have divided the results into two sections: estimation of throughput based on initial deployment using the filing's minimum elevation angle, and estimation of throughput based on final deployment and our assessment of the minimum elevation angle that will be used for operations.

III. METHODOLOGY AND MODELS

This section briefly describes each of the models used regarding atmospheric conditions, link budget, demand estimation, and ground segment representation. The methodologies, models, and assumptions are equivalent to the ones presented in [2]. For a more detailed description, readers should refer to that work. Our throughput estimation is based on four models:

Atmospheric models. We use a previously implemented [24] ITU model that accounts for gaseous, clouds, tropospheric scintillation and rain impairments.

Link budget model. We use a link budget model designed to compute the best modulation and coding scheme for any given situation.

Demand model. We use a demand proportional to the world population based on the Gridded Population of the World v4 dataset [25], with 0.1° resolution and assume that each individual consumes an average of 300 Kbps. Also, we assume (optimistically) that the total addressable market is 10% of the global population.

Ground segment. We optimize the ground segment using a genetic algorithm that maximizes the total coverage under 95% and 99% availability.

To compute the total throughput, we represent each satellite in the system as a node in a graph. At each point in time, the demand on Earth is evenly distributed among the satellites in LoS. Then, the satellites are connected with ground stations with supply depending on atmospheric conditions. Finally, ISL connects the node to adjacent satellites (2 intra-plane and 2 cross-plane, always in the same shell). The system throughput is estimated as the maximum-flow solution to the graph. To obtain an accurate estimation of throughput, we draw 10,000 atmospheric samples per scenario for 1,440 scenarios distributed within 1 day of operations.

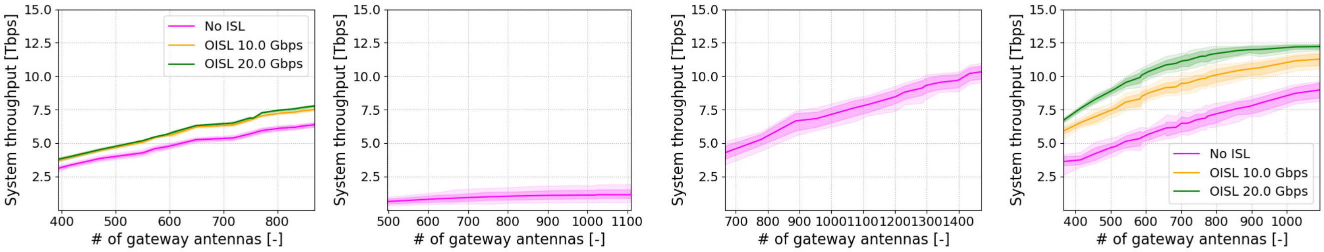
The satellite utilization is obtained by computing the ratio between average data-rate per satellite (obtained using the procedure described above) and the maximum data-rate per satellite (computed by running our link-budget model using the values from the FCC filings).

IV. RESULTS

This section presents the results for the total throughput estimated for the initial and final deployment. For the final architectures, we show the results as if all architectures used ISL. However, according to their FCC filings, only SpaceX and Telesat plan to use it from the start, while OneWeb and Amazon only consider it for later portions of the deployment.

A. Initial deployment

Figure 2 represents the total system throughput for the initial constellations as a function of the number of gateway antennas. For OneWeb and SpaceX, we estimated the total throughput without ISL, since they are not currently deploying it for their initial constellation. As shown, the total throughput without ISL is 6.37, 1.44, 10.3, and 8.97 Tbps for Telesat, OneWeb, SpaceX, and Amazon, respectively. With these results, SpaceX achieves the highest throughput of the four systems. However,



(a) Telesat (b) OneWeb (c) SpaceX (d) Amazon

Fig. 2: Total system throughput (Tbps) for initial deployment vs. Number of gateway antennas. Three scenarios are represented: no-ISL (purple), 10 Gbps ISL (yellow), and 20 Gbps ISL (green). The continuous line represents average values, whereas the shaded region represents interquartile values.

they also require twice the amount of gateway antennas compared to the other constellations, which is a direct result of the larger number of satellites and lack of ISL. It is also remarkable that Telesat and Amazon achieve higher throughput than OneWeb, despite using less satellites. The reason behind that is the usage of two satellite antennas to connect to gateways instead of one. In Telesat's and Amazon's architectures, the gateway uplink is the bottleneck in the communications link (this is general for all constellations, except for the initial constellation of OneWeb, where the bottleneck is the user downlink). Having two connections allows them to double the data-rate per satellite, highly increasing the system throughput without requiring more satellites. Telesat and Amazon would achieve 7.52 and 11.3 Tbps if they use 20 Gbps ISL.

	Telesat	**OneWeb**	**SpaceX**	**Amazon**	
ISL (Gbps)	20	0	0	0	20*
Number of satellites	298	716	1,584	578	
Max. system throughput (Tbps)	7.52	1.44	10.3	8.97	11.3
Avg. data-rate per satellite (Gbps)	25.2	2.01	6.50	15.5	19.6
Max. data-rate per satellite (Gbps)	34.4	9.97	19.7	50.8	
Satellite utilization (%)	73.4	20.2	33.0	30.5	38.5

TABLE III: Satellite utilization (%) of the four initial constellations. *Hypothetical values as Amazon does not specify if they will use ISL.

	Telesat	**OneWeb**	**SpaceX**
ISL (Gbps)	20	0	20
Number of satellites	117	720	4425
Max. system throughput (Tbps)	2.66	1.56	23.7
Avg. data-rate per satellite (Gbps)	22.74	2.17	5.36
Max. data-rate per satellite (Gbps)	38.68	9.97	21.36
Satellite utilization (%)	58.8	21.7	25.1

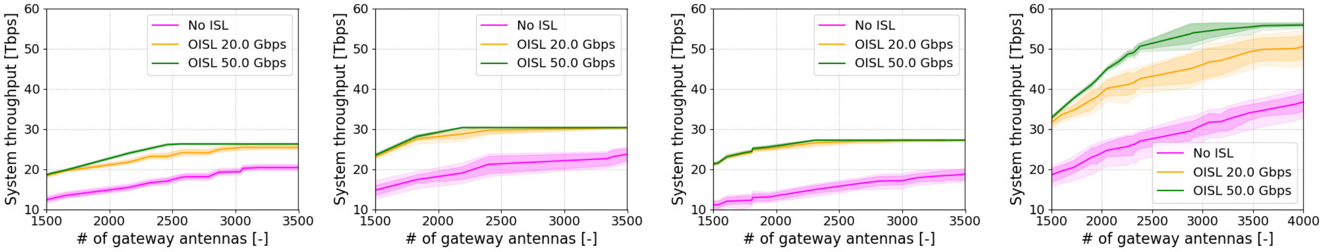
TABLE IV: Prior estimates of satellite utilization of Telesat, OneWeb, and SpaceX as of September 2018, extracted from previous results in [2].

Table III summarizes the satellite utilization of the four initial configurations. As shown, Telesat achieves a 73.4% utilization mainly due to their low minimum elevation angle, high altitude, an dual gateway links, which allows them to see multiple ground stations at any time and communicate to them to serve their demand. Compared to previous results summarized in Table IV, OneWeb worsens their results due to a higher saturation of the orbital planes. Despite not using ISL for their initial deployment, SpaceX achieves higher utilization thanks to a lower minimum elevation angle. Finally, Amazon would achieve similar utilization as SpaceX when not using ISL due to their similar altitude and minimum elevation angle. However, they would be able to achieve a 26% increase in utilization and throughput if they decide to use 20 Gbps ISL.

B. *Final deployment*

As mentioned in Section II, assuming the usage of the minimum elevation angle specified in the filings for the final deployment may lead to poor results regarding the actual performance of the systems. For this reason, we estimate the minimum elevation angle that will likely be used in practice. To that end, we simulated the constellations for different elevation angles and computed the coverage achieved within the -60° to 60° latitude band. Figure 4 shows the results obtained for the four architectures. The objective of the systems is to achieve maximum coverage with maximum minimum elevation angle, as a lower-than-necessary angle only worsens the communication link. For this reason we estimated these angles to be 40°, 70°, 35°, and 35° for Telesat, OneWeb, SpaceX, and Amazon respectively. The following results have been computed with the minimum elevation angles just mentioned.

Figure 3 represents the total system throughput on the final deployment as a function of the number of gateway antennas. From the plots, we can see that the maximum system throughput with a 20 Gbps optical ISL is: 25.4, 30.3, 27.2, and 53.4 Tbps for Telesat, OneWeb, SpaceX, and Amazon, respectively. OneWeb and Amazon would only achieve 26.9 Tbps and 41.4 Tbps, respectively, if they finally decide not to make use of ISL. We also observe that all architectures benefit from using ISL, increasing their total throughput between 13% and 42% for 20 Gbps optical links compared to not using it. SpaceX is the companies that benefit the most from using ISL, while OneWeb benefits the least, mainly due to differences in satellite configuration. Given the large number of satellites in all constellations, the number of gateway antennas necessary



(a) Telesat (b) OneWeb (c) SpaceX (d) Amazon

Fig. 3: Total system throughput (Tbps) for final deployment vs. Number of gateway antennas. Three scenarios are represented: no-ISL (purple), 20 Gbps ISL (yellow), and 50 Gbps ISL (green). The continuous line represents average values, whereas the shaded region represents interquartile values.

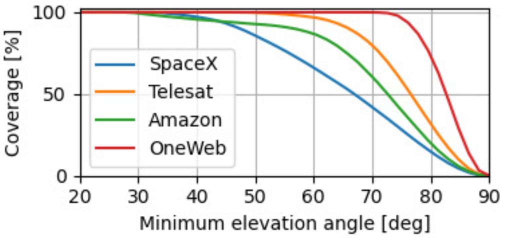


Fig. 4: Percentage of Earth covered (excluding the poles) vs. minimum elevation angle for the four systems

to achieve maximum throughput is remarkably high: more than 3000 for all cases.

Telesat manages to achieve similar throughput as SpaceX despite having less than half the satellites thanks to the dual gateway connection system. This system also allows Amazon to achieve the highest throughput. It is also important to notice that, although OneWeb and Amazon achieve higher throughput than Telesat and SpaceX, they also require a significantly larger ground segment with approximately 50% more gateway antennas. As shown for the 50 Gbps ISL, Telesat, OneWeb, SpaceX, and Amazon have maximum theoretical limits of 26.3, 30.3, 27.2, and 55.6 Tbps. This limit is a consequence of the maximum satellite saturation in combination with the demand distribution.

		Telesat		OneWeb		SpaceX		Amazon	
ISL (Gbps)		0	20	0	20*	0	20	0	20*
N_{GW}	2000	14.8	21.1	16.7	27.6	13.4	25.3	20.8	36.4
	2500	17.4	23.5	18.6	29.2	15.8	26.8	25.7	41.3
	3000	19.4	25.3	20.8	30.0	17.1	27.0	29.6	45.0

TABLE V: System throughput (Tbps) vs. Number of gateway antennas (N_{GW}). *Hypothetical values as OneWeb and Amazon don't specify if they will use ISL.

The numerical values for the different number of gateway antennas and ISL configurations are represented in Table V. When using 2500 gateway antennas, Telesat's, OneWeb's, SpaceX's, and Amazon's systems achieve a total throughput of 23.5, 18.6, 26.8, and 25.7 Tbps, respectively. In the case of SpaceX and OneWeb, increasing from 2000 to 3000 ground stations implies between 6% and 8% increase in total throughput. On the other hand, Telesat and Amazon achieve a 20% and 23% increase in that range, respectively. The reason behind this is the high necessity of gateway antennas in both systems due to the dual gateway connection of each satellite.

	Telesat	OneWeb		SpaceX	Amazon	
ISL (Gbps)	20	0	20*	20	0	20*
Number of satellites	1,671	6,372		4,408	3,236	
Max. system throughput (Tbps)	25.4	26.9	30.3	27.2	41.4	53.4
Avg. data-rate per satellite (Gbps)	15.2	4.22	4.76	6.16	12.8	16.5
Max. data-rate per satellite (Gbps)	34.4	19.7		19.7	50.8	
Satellite utilization (%)	44.3	21.4	24.2	31.3	25.2	32.5

TABLE VI: Satellite utilization (%) of the four constellations. *Hypothetical values as OneWeb and Amazon don't specify if they will use ISL.

Regarding satellite utilization, Table VI tabulates the values for the different constellations at maximum throughput. The results show a satellite utilization of 44.3, 24.2, 31.3, and 32.5% for Telesat, OneWeb, SpaceX, and Amazon, respectively, when using 20 Gbps ISL. OneWeb and Amazon would only achieve 21.4% and 25.2% respectively if they opt not to use ISL. Despite using an order of magnitude more satellites than for the initial constellation, Telesat manages to maintain the utilization above 40% thanks to the dual gateway communication and higher altitude. On the other hand, OneWeb drastically reduces its utilization as a consequence of increasing the capacity of their satellites (i.e., for this second scenario, the bottleneck is no longer the user link but rather the gateway link, which allows a higher capacity), achieving similar results as previous analysis. SpaceX increase their utilization around 25% from previous results, thanks to the combination of lower altitude and lower minimum elevation angle (from 40° to the estimated value of 35°). Finally, Amazon's utilization is similar to SpaceX when using ISL due to the similar configuration of the constellation. However, they suffer from not using ISL and they could increase the total throughput and satellite utilization by approximately 42% if they were to use a 20 Gbps ISL.

V. CONCLUSIONS

This paper presented an updated comparison of the four predominant architectures to offer broadband services in the LEO range (Telesat, OneWeb, SpaceX, and Amazon). After detailing each constellation's characteristics, we focused on the orbital configuration and satellite visibility. Then, we briefly mentioned the methods and models used for the system analysis. Finally, we presented the four systems' results in terms of total throughput and the number of gateway antennas in scenarios with and without ISL, and analyzed the satellites utilization. The main conclusions of this work can be summarized as follows:

- While Telesat's initial constellation improves the satellite utilization up to 73%, their final deployment worsens previous results due to the diminishing returns of using a larger network. The dual gateway communication system doubles the maximum effective capacity of their satellites, leading to throughputs comparable to SpaceX, despite having less satellites.
- OneWeb's initial constellation achieves the lowest throughput due to three factors: the user link bottleneck, not using ISL, and not using the dual gateway connection technology. However, in their final design, they compensate these factors by using a significantly larger number of satellites, achieving higher throughput than Telesat and SpaceX, at the cost of a larger ground segment.
- The reduction in minimum elevation angle allows SpaceX to offer better coverage, increasing their satellite utilization by 10% in their final deployment. Compared to previous results, they also manage to increase the total system throughput by 3.5 Tbps in the final design.
- Amazon's system throughput is the highest of the four systems considered. However, they accomplish this with a ground segment of around 4,000 gateways, due to the dual gateway connection of each satellite.
- Both OneWeb and Amazon experience lower throughput from not using ISL. By using 20 Gbps connections, they could achieve between 13% and 25% increase in total system throughput without any additional changes in satellites or ground segment.

From the estimations presented in this work, all constellations could offer a total capacity around tens of Tbps. With this magnitude of data-rates, they would not be able to compete with the current terrestrial networks, which move around thousands of Tbps [26], but could complement the coverage of the land infrastructure in regions where a cable connection is ineffective, inappropriate, or just unfeasible (e.g., rural areas, isolated coastal and insular regions, and aerial and maritime mobile users).

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