Megaconstellations: Revolutionizing Internet Connectivity

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***Abstract*—Recent ideas to launch thousands of interconnected satellites into orbit have initiated a space race of the 21st century. These large satellite systems aim to supply rural areas worldwide with fast, broadband Internet access. This paper is an introduction to this emerging topic, and it provides an overview of the history of artificial objects in space, current statistics of Starlink, and challenges the providers face. The second part features a literature research discussing the rather undisclosed technical details of Starlink and the hybrid routing mechanisms used in megaconstellations. This paper also compares the findings of two performance-based evaluations of Starlink and discusses the dimension of the performance gap between Megaconstellations and terrestrial networks. We also review the guides provided by SpaceX that explain the need for sustainable technology in the field of Megaconstellations to mitigate collision risks and challenges concerning increased space debris.**

***Index Terms*—megaconstellations, starlink, satellites**

1. Introduction

With the recent drop in space launch costs due to advanced manufacturing and reusability options, the potential for leveraging space technology to address modern-day challenges has significantly increased [1]. One of the most influential technologies in this field are satellites. Satellites are most commonly used for scientific earth observations, climate monitoring and communication.

The first satellites were mainly used to allow for transatlantic communication. These so-called geostationary satellites operate at an altitude of around 35 786 km (GEO) and are stationary relative to a fixed point on the Earth's surface. This ensures broad coverage by utilizing a small number of satellites [2].

On the other hand, a significant disadvantage is the high propagation delay that comes with the high altitude. Due to this trade-off, geostationary satellite connections cannot meet current standards of their terrestrial counterparts [3].

A solution to the high latency can be achieved by launching the satellites to a lower altitude. The closest possible orbit to the Earth lies within the low Earth orbit (LEO) region. This region ranges from 160 km to over 1600 km, with the lowest satellite currently orbiting at 167.4 km. LEO also inherits many other artificial objects like the International Space Station (ISS) at an altitude of 400 km [4].

The problem with this approach is the smaller coverage, which can be solved by increasing the number of satellites. This use of multiple satellites working together for a common purpose is known as a satellite constellation. In the context of the Internet, the ideal system leverages thousands of satellites. Such an enormous constellation is often described as a Megaconstellation [5].

2. History

This section focuses on the history of satellite-driven Internet. It discusses the history of the first geostationary provider up to modern Megaconstellations such as Starlink. It will also compare the most important providers.

2.1. Geostationary Internet

The first ideas for a communication satellite in GEO were published in 1945 by the fiction author Arthur C. Clarke. His article [6] presented the base for the early GEO satellites. The first reliable GEO satellites for communication were "Syncom 2" and "Syncom 3". Syncom 3's reliability was proven in 1964 when the Olympics in Japan were transmitted "live via satellite" to the US. Some of the first communication satellites were later updated to support Internet connections. A few ground stations connect these satellites with the terrestrial networks.

The first satellite with the sole purpose of providing broadband Internet (e-BIRD) was successfully launched in 2003 by Eutelsat. It still delivers Internet to Europe to date. Modern satellites utilize the high-frequency Ka-Band to maximize throughput. KA-SAT and Viasat-1 (2010) are the first to use this new technique [7], [8].

2.2. The Teledesic Network

This section corresponds closely to papers by Patterson [3] and Sturza [9] from the Teledesic Corporation.

The concept of launching Megaconstellations into LEO has been around since 1990. The "Teledesic Corporation" was the first company to practically attempt such a project. Teledesic planned to launch over 900 satellites to provide affordable broadband internet globally by 2002. The quality of service of this network was planned to be comparable to terrestrial networks with fiber-like delays and low bit error rates while providing 24-hour coverage for almost everyone on Earth. The capacity was planned to be equivalent to over 20 million users on traditional wired connections. Data rates on the Teledesic network

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were meant to be adjustable with symmetrical and asymmetrical communication rates of up to 64 Mbit s^{-1}. Adjustable refers to them being scalable based on application demand.

The different satellites in the network can be seen as nodes communicating with eight neighboring nodes using a fast packet-switching technology. To ensure global coverage it was planned to split up the Earth into 20 000 supercells, with each being targeted by 64 transmit and receive beams from a satellite at all times. Data was planned to be distributed encrypted over the links in fixed-length packets of just 512 bit.

Due to financial difficulties, the project was suspended in 2002. Teledesic never launched any operational satellites [10].

2.3. Starlink

The current most influential Megaconstellation is operated as a subsidiary of the well-known aerospace company SpaceX under the name of "Starlink". Starlink was founded in 2014 by Elon Musk to supply rural areas with broadband internet and to provide global mobile broadband [11].

After the design phase, the first test launches were made in 2018 with two prototype satellites. The first 60 operational ones were launched in 2019, and Starlink went public in early 2021 [11], [12]. Because of the ability of SpaceX to launch the satellites using their own spacecraft and their advanced reusability options, they were able to launch a fleet of more than 6000 until August 2024. There are currently 4996 satellites in operation, and SpaceX plans to increase this number to around 40 000.

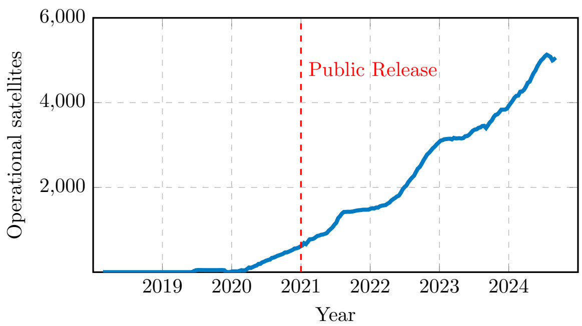

Figure 1: Starlink operational satellites over time [13]

These numbers were accumulated by Jonathan McDowell [13] with the operational satellites over time shown in Figure 1.

SpaceX uses their Falcon 9 rocket to deploy around 60 satellites per launch, with individual launches happening almost every week [11]. Starlink is currently in its second generation, with the second-generation satellites being four times more capable than those of the earlier generation [14]. In January 2024, SpaceX also launched new satellites with direct-to-cell capabilities. SpaceX plans to scale this new LTE Service network in the upcoming years with hundreds of new satellites [15]. Further explanations on the technical aspects of Starlink can be found in Section 3.

2.4. Provider Overview

Multiple other companies compete in this "space race" of the 21st century. Not only SpaceX, but also Amazon and Boeing have recently planned to launch their own constellations.

Companies like Iridium and Globalstar that have been around since the time of Teledesic, have also sent operational satellites into LEO.

Table 1 provides an overview of the most important providers. It shows information about the altitude of the satellites, planned and operational amount of satellites as well as the year when the constellation went into operation. It is closely based on data by Xingchi He [12].

TABLE 1: Important Megaconstellations [12]

Constellation	Planned	Operational	Since	Altitude (km)
Starlink	34224	4996	2020	≈ 500
OneWeb	648	616	2023	1200
Iridium-NEXT	66	80	2018	780
Globalstar-2	24	25	2013	1410
Kepler	360	16	2021	$550 - 650$
GW (China)	12992	0	-	$500 - 1200$
Amazon Kuiper	3236	0	-	$590 - 630$
Boeing	132	0	-	1056

The altitude plays a crucial role in this comparison, as it influences the amount of satellites needed. Starlink sticks out as the constellation with the highest number of planned and operational satellites.

Jonathan McDowell's statistics [13] state that there are currently 20 planned constellations with a total amount of planned satellites of 547 127. Only 7060 of them have already been launched.

3. Technical Details

This section will discuss the technical details as well as the performance of Megaconstellations. Starlink will serve as the primary example.

3.1. Starlink satellites

The newest Starlink satellites have a flat design and are relatively small with an overall mass of 250 kg. These second generation satellites have four times the capacity of the earflier generation. The generation 2 satellites are split up into two seperate versions. The "V2 mini" version that is not the full-size V2 satellite was designed to be compatible with the Falcon 9. Due to this design, up to 60 satellites can be distributed in one Falcon 9 launch. SpaceX is currently constructing the "Starship", a new rocket with a higher payload capacity to increase this number even more [14]. The Starship will be used to launch full-sized V2 satellites.

The new satellites utilize a Star Tracker to accurately calculate the position of each node. These new satellites also use inter-satellite links (ISL) to communicate with neighboring nodes. In the current generation, optical links in the form of three lasers are used. They can reach a transmission rate of up to 200 Gbit s^{-1}. There are eight antennas on each satellite that utilize the Ka-Band, Ku-Band and E-Band frequencies. A Starlink satellite can adjust its path using an inbuilt ion engine based on argon gas. The engines can not be recharged in space yet and satellites without fuel will deorbit either naturally or controlled [16].

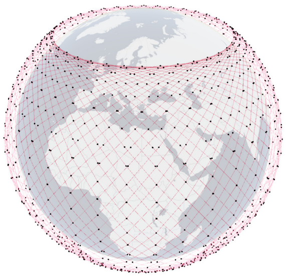

Figure 2: Starlink Shell one [17], [18]

Figure 3: Standard Dish with motors [23]

The satellites are launched into different groups, also known as shells. Each shell inherits different orbits in planes at different angles relative to the equator (inclination). The first Starlink shell has 72 orbits organized into orbital planes at a 53° incline [17]. Figure 2 shows the first Starlink shell with the majority of the current Starlink satellites. Other shells also serve regions near the poles with far fewer satellites [19].

A Starlink satellite can be operational for around five years before deorbiting naturally [20].

3.2. Starlink ground infrastructure

To function as intended, every constellation needs a connection to the Earth. These connections are usually established between a ground station (GS) and a satellite that is currently in view [21].

Most geostationary satellites only need a single GS, because of their fixed position relative to Earth. This is not the case for LEO satellites as most of them are only in view of a fixed point for around ten minutes [17]. LEO satellites do not have a fixed position to Earth to withstand gravitational pull. Various GSs have to be placed strategically around the globe to support all the satellites that orbit in and out of view and to operate the constellation effectively [21]. Starlink currently utilizes around 150 fixed GSs as gateways to the Internet, with most of them being located in the US and Europe [22].

Another big part of the ground infrastructure of Starlink are the private dishes that the subscribers use to connect to the network. These dishes communicate with currently visible satellites through a User Link (UL). The dish is wired to a router through Ethernet, which opens a local network for connections via WiFi or Ethernet [17].

For the visibility of satellites, the sky has to be mostly clear and the setup location of the dish has to be wide enough. The tilt of the dish also needs to be adjusted frequently with options for self-adjustment, as seen in Figure 3 [17]. There are currently six variants of the Starlink kit with options for an overall higher performance.

3.3. Routing and Traffic Management

Routing and Traffic Management are essential factors when evaluating networks. They are influencing factors on the efficiency and the overall connectivity of terrestrial and non-terrestrial networks.

Megaconstellations must have a sophisticated routing system in place to ensure accurate packet routing even with rapidly moving next hops (satellites). This is especially important in Megaconstellations where multiple hops take place using ISLs [24]. As shown in Section 2.2, Teledesic planned to incorporate a fast packet switching technology through ISLs.

Starlinks first generation approach was based on a bent-pipe strategy. Bent-pipe refers to a satellite only being used to relay a signal to a different point on Earth's surface. This was used, because generation 1 did not utilize ISLs yet. Indirect satellite communication was possible by using GSs as intermediate steps, but it was somewhat inconvenient. As shown by Ma et al. [17], a connection to Starlink generally only involved one hop due to this.

The signal from the dish was practically only redirected to the closest GS before switching to terrestrial services. This connection between the dish and GS can only be established successfully if their distance is at most 1000 km.

Sending a packet between two dishes in range of the same satellite was also tested in [17]. The experiment showed that the communication still had to be relayed through a GS instead of the ULs of the dishes communicating through the satellite.

As the generation 2 satellites are equipped with optical ISLs, it has become possible to route packets directly between satellites. This multi-hop approach can be beneficial in increasing the overall connectivity of the system. It increases the autonomy of the network as the routing is not dependent on a ground segment that may not have broadband connections in place. An advantage over ground infrastructure is also the vacuum as a propagation environment for wireless signals. The ultra-low latency of ISLs also enables real-time data sharing [24].

A handover to another satellite is needed if a node in a currently established link moves out of view, as visibility between nodes is crucial for ISLs to function [24].

The routing system for Megaconstellations can be set up in a hybrid manner. It consists of characteristics of static and dynamic routing.

Static routing might seem counterintuitive when looking at dynamically moving satellites, but the topology of

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a Megaconstellation is predictable. The orbit period of the satellites can be cut into time slots that represent a stable snapshot of the network topology. Traditional routing algorithms like the Dijkstra algorithm can be utilized to find the optimal path in a given snapshot [24]. An algorithm that is optimized to constellations called "StepClimb" is described in [25].

Static routing cannot adapt to unpredictable real-time situations, such as defective satellites in the Megaconstellation. For these situations, a dynamic routing approach has to be used. The routing tables of the satellites have to be kept up-to-date. This can be achieved by periodically flooding the states of each node to all satellites, which can create an immense overhead. To solve this issue, satellites on a higher altitude acting as routing managers can be used [24]. This multi-layer approach with satellites in MEO (medium earth orbit) or GEO is yet to be used in Starlink.

Load balancing and congestion control are also crucial factors of networks and even more significant challenges for Megaconstellations. As the distribution and demand of the subscribers are uneven around the globe, there are imbalanced regional traffic loads. Minimum hop routing strategies and the resulting paths may be congested in high-traffic areas. The used routing algorithms have to account for this as well [24].

3.4. Performance

The Performance of Starlink has been evaluated in papers by Mohan et al. [19] and Ma et al. [17] This section sums up the most important findings and compares these papers.

SpaceX states the following: "Starlink users typically experience download speeds between 25 and 220 $\mathrm{Mbit\,s^{-1}}$, with a majority of users experiencing speeds over 100 $\mathrm{Mbit\,s^{-1}}$. Upload speeds are typically between 5 and 20 $\mathrm{Mbit\,s^{-1}}$. Latency ranges between 25 and 60 ms on land, and 100+ ms in certain remote locations" [26]. Remote locations for Starlink are Oceans and Islands as well as the polar regions.

A measurement by Mohan et al. [19] using global online speed test data shows that the median latency of Starlink lies within 40 ms and 50 ms. In Well-Provisioned Regions like Seattle and the US, the latency is consistently well below 50 ms. This is likely the case because of the wide coverage of GSs in these regions. South American regions like Colombia and regions in Oceania show a low performance with latencies exceeding 100 ms. It was also shown that the latency of Starlink under load increased [19]. This performance analysis by Mohan et al. [19] reflects the promised performance closely.

The latency of Starlink has a very high variation in contrast to the stable latency in terrestrial networks. The reason for this is the continuous movement of the satellites and the handovers that are needed to keep connections active [17].

Sami et al. [17] features an experimental approach to measure the performance for connections from northern American terrain to a variety of AWS servers worldwide. The measurement has shown that the latencies using Starlink were higher, but the difference was mostly negligibly small. The throughput rates compared to terrestrial connections cannot be neglected. Starlinks upload rates only reach around 10% of the terrestrial connections.

Mohan et al. [19] have measured that Starlink achieves around 50-100 $\mathrm{Mbit\,s^{-1}}$ in download rates and 4-12 $\mathrm{Mbit\,s^{-1}}$ in upload rates. This corresponds to the data measured by Sami et al. [17]. These throughput rates - as for the latencies - lack stability.

There is currently a gap between the performance of Starlink and terrestrial connections, which occurs most prominently in well-provisioned areas. Starlink outperforms terrestrial connections in some underprovisioned areas like Columbia, where the local ISPs average 70 and 100 $\mathrm{Mbit\,s^{-1}}$ in latency, but Starlink averages 50 and 70 $\mathrm{Mbit\,s^{-1}}$. In regions like the Philippines, Starlink performs worse than local ISPs, which is a result of the low distribution of ground stations. This same conclusion can be made from the above mentioned measurements in [17].

Users of Starlink experience higher overall latencies and lower throughput comparable to cellular connections. The current gap will most likely continue to shrink with the expanding infrastructure of Starlink in Space as well as on the ground [19].

4. Challenges

It is important to note that Megaconstellations do not only come with positive aspects, but also non-favorable impacts. SpaceX offers articles and guides that discuss solutions to these challenges.

There are currently 22 384 objects orbiting in LEO with a total mass of 6120.8 t. These objects stem from space missions since 1957, including mission payload and other debris. Some debris and particles also originate from so called fragmentation events due to collisions and explosions [27].

Since the age of Megaconstellations, the payload launch traffic into LEO has increased from under 500 to over 2500 launches. The expanding number of objects in space increases the risk of a collision in future space missions [27]. Starlink satellites have an inbuilt collision avoidance capability in place to mitigate this risk.

Objects within LEO reenter the atmosphere at any time and sometimes have unpredictable re-entry paths. SpaceX uses controlled and well-tracked deorbits of non-operational satellites to reenter them into the atmosphere [20].

Starlink satellites can be visible to the naked eye while being lifted into their operational orbit. They can still be visible to observatories on Earth when they are illuminated by the sun in their foreseen orbit, disrupting astronomical observations. Generation 2 of Starlink utilizes different materials to mitigate the brightness of the satellites [28].

5. Conclusion and future work

Megaconstellations is an emerging topic that has become more important in the last five years but still remains rather unknown. This paper provided an overall introduction to Megaconstellations and their importance.

SpaceX's project of "Connecting The Unconnected" aims to deliver Internet to areas around the globe with no connection to terrestrial services. Starlink can deliver broadband internet to the highest mountains and the smallest isles in the ocean. Starlink can be utilized in emergencies and can act as a lifesaver.

Megaconstellations may not be the optimal way of connecting to the Internet when connecting from a well-connected area like Europe or the US, but they can revolutionize the connectivity in places like Colombia. With the performance gap getting smaller, Megaconstallations may be a viable option for well-provisioned areas in the future.

As the topic is relatively young, there is a great amount of potential for future work and optimizations. Future research could explore the simulation of constellations to find optimal routing solutions or technical improvements to mitigate collision risks. Exploring the environmental and social impact could also be an important topic.

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