# Broadband Internet Access via Satellite: Performance Measurements with different Operators and Applications

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## Abstract

Fast and reliable broadband Internet access is essential, which was emphasized even more during the worldwide COVID-19 pandemic. Still, many locations do not have access to terrestrial broadband Internet access. Satellite communication provides area-wide coverage with high data rates. Europe is served by several geostationary satellites and the new Starlink megaconstellation in low Earth orbit is available since recently. This paper summarizes the findings of our comprehensive study in which we evaluated the performance of different applications over different Internet access technologies, with focus on Internet access via satellite. Four geostationary satellite providers, the Starlink megaconstellation, and two terrestrial access links (DSL and LTE) were selected. Results show that satellite communication provides fast and reliable Internet access. The high latency of geostationary satellite links is problematic for some applications, especially interactive applications and virtual private networks. The Starlink low Earth orbit megaconstellation is able to perform as good as terrestrial Internet access technologies.

## 1 Introduction

In last year's *15th ITG Fachkonferenz Breitbandversorgung in Deutschland* [2, 3] once again the high demand for broadband Internet access has been discussed. Not only since the COVID-19 pandemic and working from home, fast and reliable Internet access has shown to be essential. In this context, the German government and Bundesnetzagentur work on the right for basic telecommunication services called *Universaldienst* [4, 5].

Yet, many people (e.g., in rural areas) do not have access to terrestrial broadband Internet access. Internet via satellite [3] can fill these gaps: It provides high data rates and area-wide coverage. Over the last years, Internet access via geostationary satellites (GEO) has become established and provides powerful and affordable Internet access. More recently, satellite megaconstellations in the low Earth orbit (LEO) are having their breakthrough. At the time of writing, SpaceX has launched more than 2000 satellites for its Starlink megaconstellation, which has been available in Germany since 2021. Other competitors are following [5, 6, 8].

**Figure 1** illustrates the different orbits. With GEO satellites, a single satellite can cover large areas, and spot beams as shown in **Figure 2** are used for efficient frequency reuse. GEO satellites match the Earth's rotation, therefore they appear to be at a fixed position. Parabolic antennas are used for bidirectional communication. The high altitude leads to very high propagation delays: Assuming user terminal and ground station are at the Equator and the GEO satellite is directly above them, the propagation delay is at least 240 ms (user terminal via GEO satellite to ground station). In other locations and together with other delays, Round Trip Times (RTTs) of ~600 ms are common.

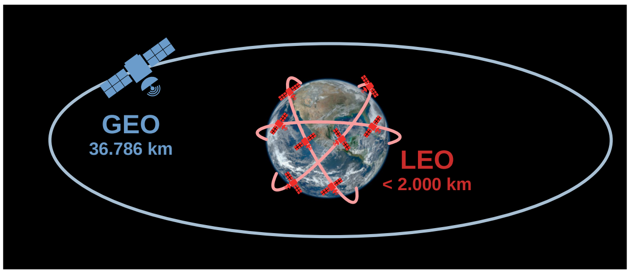


**Figure 1** Illustration of geostationary orbit (GEO) and low Earth orbit (LEO). Figure not to scale. A single GEO satellite provides high coverage, but the propagation delay is very high. For LEO, many satellites are required, thus also called megaconstellation.

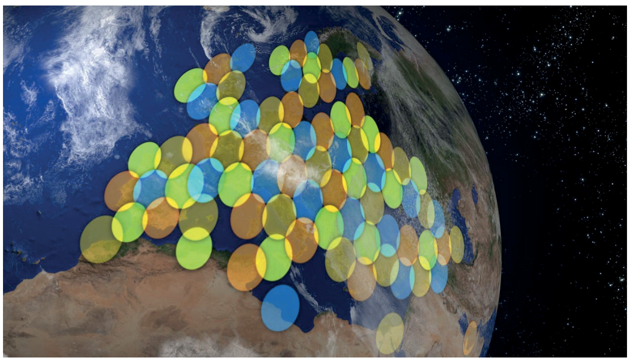

**Figure 2** Spot beams used for GEO satellites, in this example Eutelsat's KA-SAT. Image source: `https://commons.wikimedia.org/wiki/File:KA-SAT_spot_beams_coverage.jpg`

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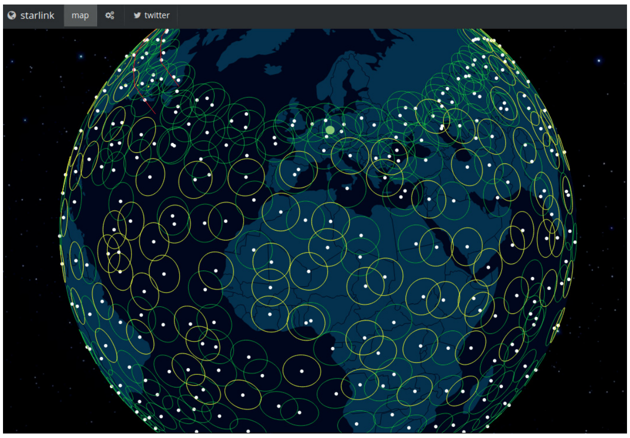



**Figure 3** `https://satellitemap.space` screenshot showing LEO Starlink satellites (January 2021). Green (yellow) circles: satellite altitude greater (less) than 550 km. Due to the chosen orbital inclination of ~53°, satellite density is higher at such latitudes.

LEO satellite are at altitudes less than 2000 km. Starlink uses altitudes at around 550 km, OneWeb is at an altitude of 1200 km [8]. With such altitudes, the propagation delay is only a few milliseconds. However, due to the lower altitude, a satellite moves very fast and covers only small areas. The former requires steerable antennas (e.g., phased-array antennas) and frequent handovers. The latter requires a large number of satellites. **Figure 3** illustrates this for the Starlink megaconstellation.

Due to high latencies, GEO satellite networks rely on Performance Enhancing Proxies (PEPs) [9] as shown in **Figure 4**. PEPs transparently split Transmission Control Protocol (TCP) connections and use an optimized protocol on the satellite link. PEPs are not applicable in case of encrypted transport layer headers, as it is the case with Virtual Private Networks (VPNs) and the new QUIC transport protocol [10]. The implications have been discussed in [3, 11] and will be further evaluated in this document, with focus on VPNs. Evaluation and optimization of QUIC is subject to future work [12].

This document is a summary of our measurement study [1] performed in early 2021, in which we evaluated the performance of widely used applications over different Internet access links. It was done in the context of the *European Electronic Communications Code* (EECC) [13] and *Body of European Regulators for Electronic Communications* (BEREC) *Guidelines detailing Quality of Service Parameters* [14]. A full report of our measurement study [1] is available online in German language, executive summary and presentation slides are available in English language.

## 2 Measurement Setup

We have selected four geostationary satellite systems, the new Starlink LEO megaconstellation and two terrestrial systems (DSL and fixed wireless LTE). **Table 1** lists the selected providers. The simplified measurement setup is shown in **Figure 5**. A measurement computer is connected

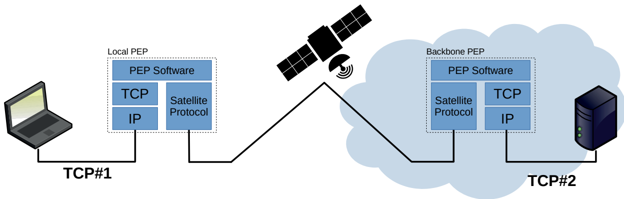



**Figure 4** Performance Enhancing Proxies and Split TCP used for GEO satellite networks.

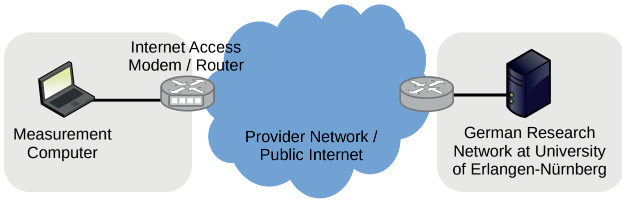



**Figure 5** Measurement setup for testing different Internet providers and applications. VPN client and server software was running on the local and remote computer, respectively.

to one of the Internet access links listed in **Table 1** and the remote host is connected to the university network via Gigabit Ethernet. More details regarding the providers and measurement setup are available in [1].

## 3 Evaluation

In the following, the evaluated applications are listed and their performance depending on the Internet access technology is briefly described. Again, more details are available in [1].

**Bulk Data Transfer** was tested intensively, both in the uplink and downlink direction.[1] Tests were performed with the `iperf3` tool with either one TCP flow (representative for a transfer of one file or large object) or ten TCP flows simultaneously (e.g., when multiple users or applications are active, also used in speed tests to better utilize the path capacity). Additional tests were performed by using the VPN software `OpenVPN` or `Wireguard` to analyse the impact of PEPs. In this document, we only present the results for a single flow in downlink direction:

- **Figure 6a** – no VPN software: The goodput comes close to the specified link rates[2], some satellite systems need a few seconds to get up to speed.
- **Figure 6b** – `OpenVPN`: The goodput is significantly lower compared to the non-VPN scenario for all access technologies except DSL. For Starlink, the performance impact is worst. The GEO satellite systems reach maximum goodput values between 10 Mbit/s and 15 Mbit/s, moreover it takes several seconds to reach high goodput values.

[1] In satellite and aeronautical networks, the uplink is referred to as *return link*, and the downlink is referred to as *forward link*.
[2] At the time of writing, Starlink did not specify exact link rates.

| Technology | Shared Medium | Provider Service Level Agreement | Download data rate Mbit/s | Upload data rate Mbit/s |
|---|---|---|---|---|
| GEO | yes | Konnect Zen (Eutelsat Konnect 7.2° East) | 50 | 5 |
| | | skyDSL2+ (Eutelsat KA-SAT 9° East) | 50 | 6 |
| | | Bigblu Konnect Bronze DE (Eutelsat KA-SAT 9° East) | 16 | 3 |
| | | Novostream Astra Connect L+ (Astra 28.2° East) | 20 | 2 |
| LEO | yes | SpaceX Starlink (Beta) | – | – |
| DSL | no | o2 DSL Max flat | 50 | 10 |
| LTE | yes | Congstar Homespot 100 | 50 | 25 |

**Table 1** Internet access providers used in our measurement study, see [1] for more details.

- **Figure 6c** – `wireguard`: It performs better than `OpenVPN`. Especially Starlink reaches goodput values as in the non-VPN scenario. The GEO satellite providers also reach higher goodput values compared to `OpenVPN`, but the goodput in the first seconds of a new connection is still poor.

Other tests are summarized as follows: In uplink direction, the same trends as in the downlink direction are present but less distinctive. This is because the uplink data rates are lower in general. With more TCP flows, the available channel capacity can be used faster and better. We refer to the full report [1] for more details.

**Round Trip Times (RTTs) and Packet Loss.** The RTTs for geostationary satellite Internet were in the range of 600 ms to 700 ms, whereas the other access technologies usually did not exceed 50 ms. Packet loss was below 0.1 % for all providers except Starlink which had packet loss ratios of ~1.8 %. However, this should be reevaluated in the future, because more satellites are now part of the Starlink system and further improvements might have been carried out.

**Windows File Sharing.** A typical home office use case is accessing files from a server accessible via VPN software. This is tested with the following three scenarios:

- Navigation in a shared directory. Opening a single directory takes significantly longer on geostationary satellite links compared to other access technologies.
- Copying a single 10 Mbyte file in the downlink. The copying over geostationary satellite links results in goodput values between 3 Mbit/s and 7 Mbit/s, whereas the goodput values of the other access links comes close to the advertised link rates.
- Copying ten 1 Mbyte files. Because files are copied sequentially, the performance is worse than copying a single large file. This is especially problematic for high latency links.

**Web browsing** was evaluated by using the `Browsertime`[3] framework and loading the *Alexa Top 50 Germany* websites. The evaluated metrics were *First Contentful Paint*, *Visual Complete 85%*, and *Page Load Time*. Additionally, network emulation has been applied to test slow DSL links (1 Mbit/s and 6 Mbit/s in the downlink, 128 kbit/s and 576 kbit/s in the uplink, respectively). Because for web browsing latency and data rate matter, slow DSL links are expected to show poor performance. Two different variants of the web browsing test have been set up:

- Worst-case scenario: Initial loading of websites, i.e., there is no cached content. No ad blocker has been used. Results are shown in **Figure 7**.
- Best-case scenario: Refreshing an already loaded website. This is possible by using the `browsertime --preURL` parameter, i.e., loading the same website twice and only evaluating the second run. Moreover, the `pihole`[4] ad blocker has been used, which results in loading less objects. Results are shown in **Figure 8**.

For all metrics, the loading times using geostationary satellite Internet are higher than the other access technologies, unless the terrestrial link becomes very slow (e.g., DSL light). Comparing the best-case scenario and worst-case scenario, the total times differ but the overall trend is the same.

**Video streaming** was not analysed in detail. The playout of Youtube videos has been tested and checked regarding the offered resolution and possible buffering events. 4K video streaming was possible except for two geostationary providers: Bigblu Konnect Bronze only had a downlink rate of 16 Mbit/s, which is not sufficient for 4K videos. Konnect Zen has a sufficiently high downlink data rate but limits video streaming to lower qualities. For these two providers, video streaming was possible in HD quality.

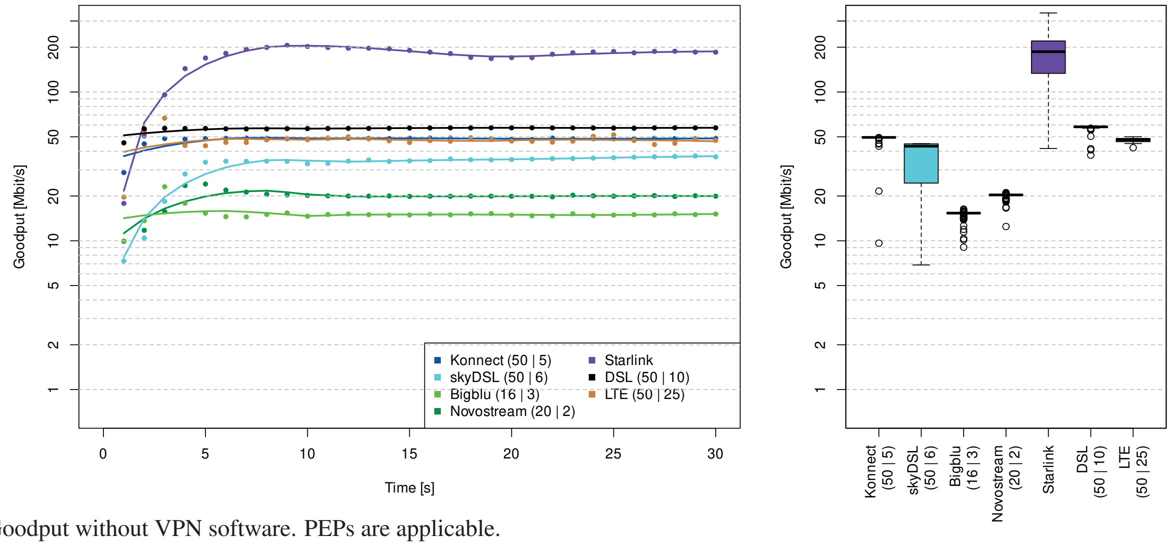
**Voice over IP** evaluation was limited to connection setup times using `SIPp`[5] and Mean Opinion Score (MOS) using `ViSQOL`[6]. Connection setup times correlated with RTT measurements, and packet loss was low enough for all Internet access links to result in very good MOS. However, users' perceived quality, especially regarding delays in conversations, was not rated in our measurements because Quality of Experience studies were out of scope.

[3] `https://github.com/sitespeedio/browsertime`

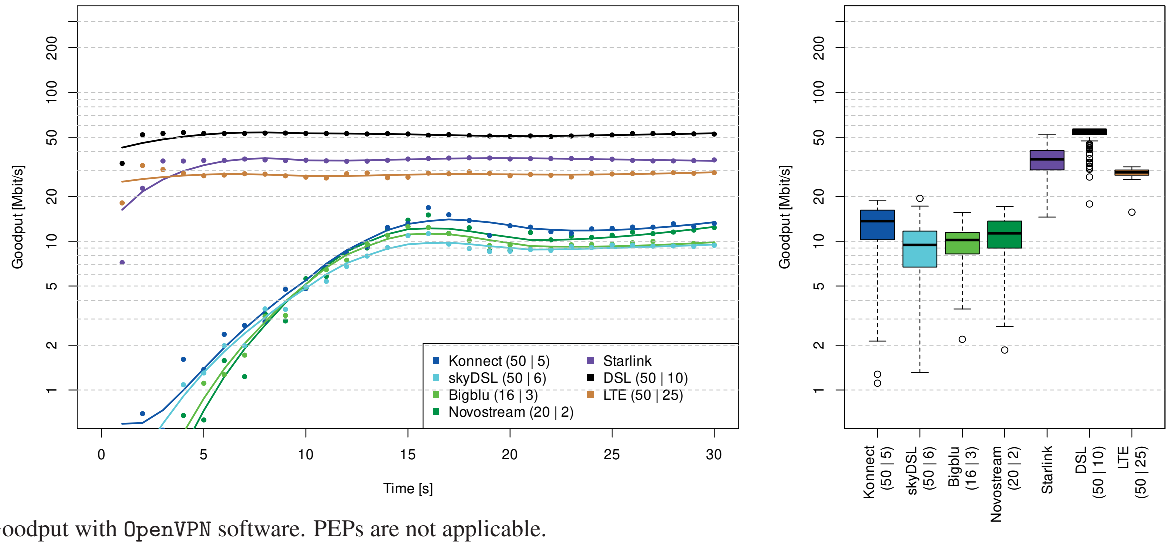
[4] `https://pi-hole.net`

[5] `http://sipp.sourceforge.net/`

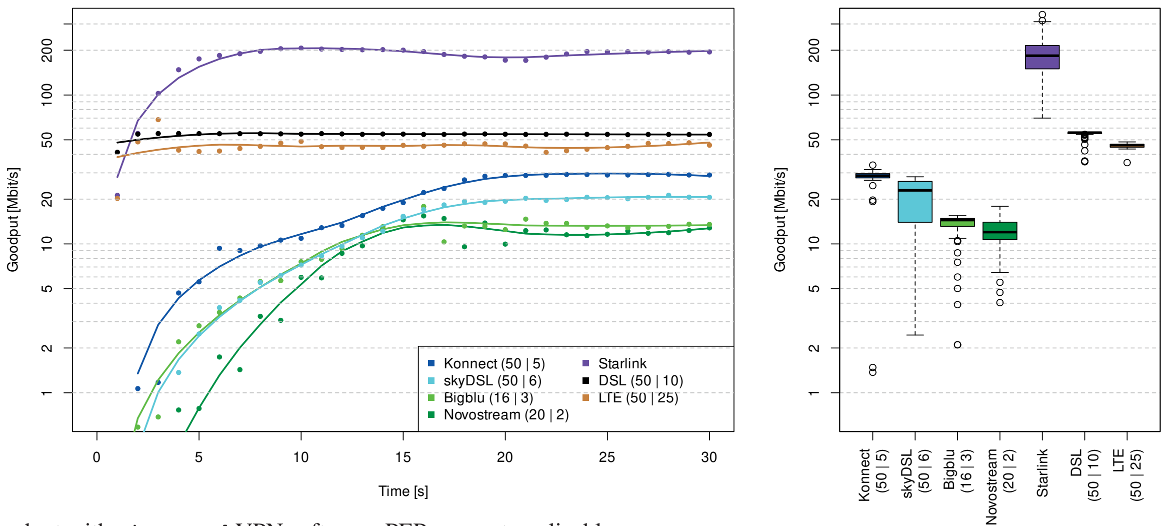
[6] `https://github.com/google/visqol`




**(a)** Goodput without VPN software. PEPs are applicable.

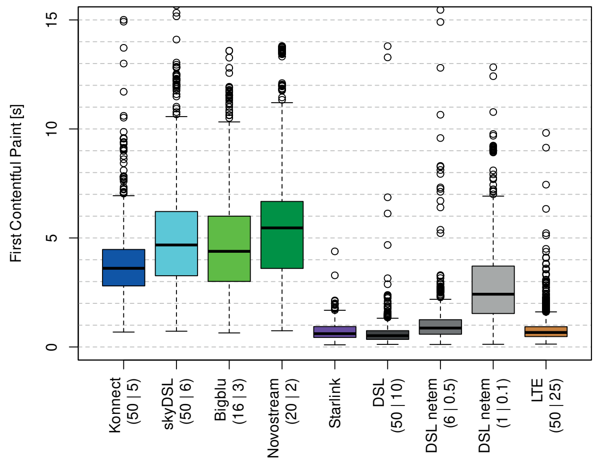



**(b)** Goodput with `OpenVPN` software. PEPs are not applicable.

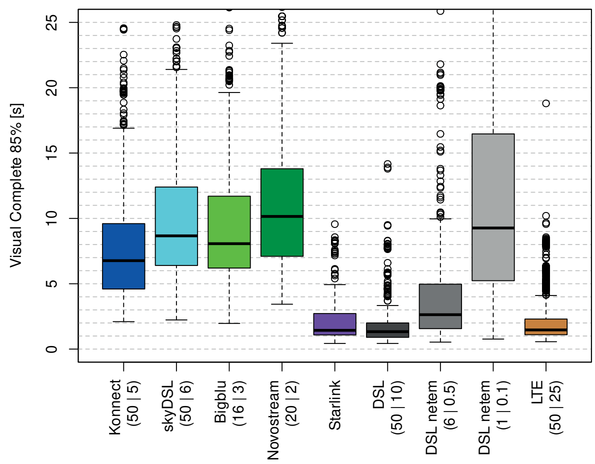



**(c)** Goodput with `wireguard` VPN software. PEPs are not applicable.

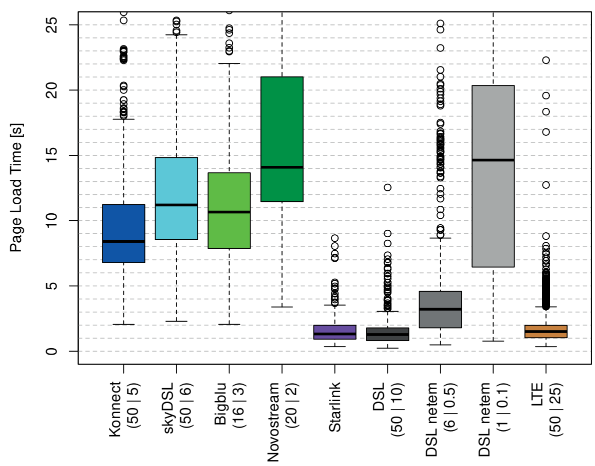
**Figure 6** Downlink data rate of a single TCP flow measured with `iperf3`. In the left figure, the average data rate in one second intervals is shown and plotted as points. For better visualisation, a polynomial regression (`R loess` function with $\alpha$-span $= 0.6$) is applied and plotted as line. In the right figure, the goodput averaged over the steady state from 15 s to 30 s is shown. Each experiment was repeated 100 times.




**(a)** First Contentful Paint

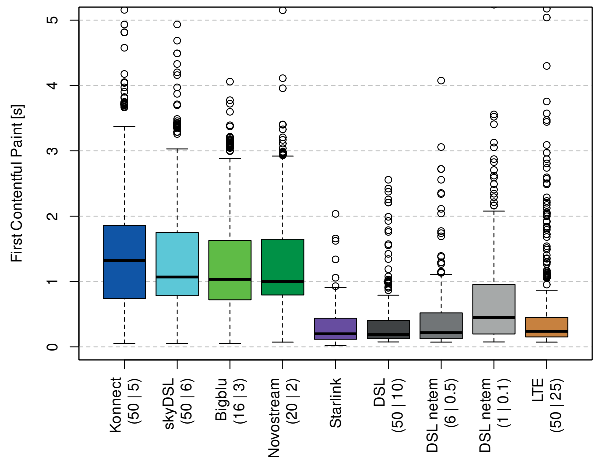



**(b)** Visual Complete 85%

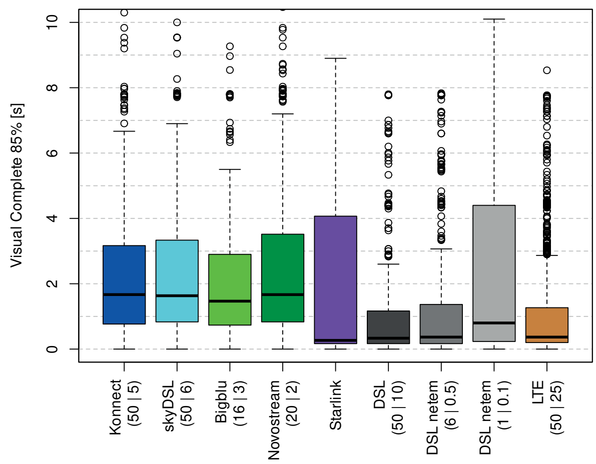



**(c)** Page Load Time

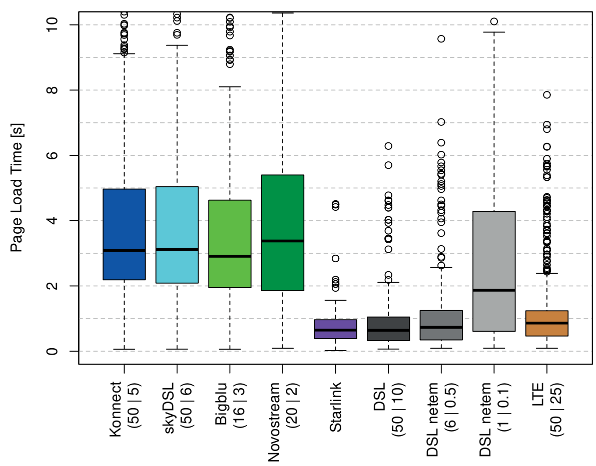
**Figure 7** Alexa Top 50 Germany websites measured with `browsertime` framework. Worst-case scenario of initially loading a website, no cached content, no ad blocker. 50 iterations.




**(a)** First Contentful Paint




**(b)** Visual Complete 85%




**(c)** Page Load Time

**Figure 8** Alexa Top 50 Germany websites measured with `browsertime` framework. Best-case scenario with cached content (using `browsertime --preURL`) and an `pihole` ad blocker. 50 iterations.

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| | Ping ms | Download Mbit/s | Upload Mbit/s |
|---|---|---|---|
| Worldwide | 56 | 116 | 11 |
| USA | 60 | 80 | 8 |
| EU | 43 | 163 | 16 |

**Table 2** Starlink performance measurements (average values, rounded to whole numbers) as of May 19th, 2022. Source: `https://starlinkstatus.space`

# 4 Related Work

Geostationary satellite systems have been around for a long time and are well-established, therefore many performance studies are available [1, 3, 15].

Regarding megaconstellations, recent studies have analysed the system design and performance as well as business models:

- Knopp et al. [6] have presented a *Unabhängige Trendanalyse zum Thema Megakonstellationen (HEUMEGA)*. They conclude that megaconstellations are an effective and economically feasible solution to provide broadband Internet access.
- Leschka et al. [5] have analyzed both geostationary satellite systems and LEO megaconstellations in the context of EECC and *Universaldienst*, including Quality of Service parameters, traffic volumes, and currently offered services by satellite Internet providers. The authors point out that additional capacities will be provided by additional satellites and satellite systems in foreseeable future.
- Obermann [7] studied the *Leistungsfähigkeit von Satelliteninternet gemäß dem Starlink-Konzept* and concluded that Starlink is not an alternative to fiber-optical networks. This is mainly due to the poor scalability of satellite networks: as in all wireless networks, the pysical channel is a *shared medium* among all users. Moreover, data rates and latencies in fiber-optical networks are still better than LEO satellite networks.

Apart from simulation and analytical studies [8], there are not many performance measurement studies for real megaconstellations yet. Uran et al. [16, 17] did early measurements of a Starlink terminal which complements our findings. The website `https://starlinkstatus.space` presents crowd-sourced ping and speed measurements from Starlink users all over the world. At the time of writing, more than 50 Starlink terminals were registered. **Table 2** shows values as of May 19th, 2022.

# 5 Conclusion and Future Work

Our measurement study has shown the strengths and weaknesses of satellite Internet. While Internet access via geostationary satellites is a well-established and affordable

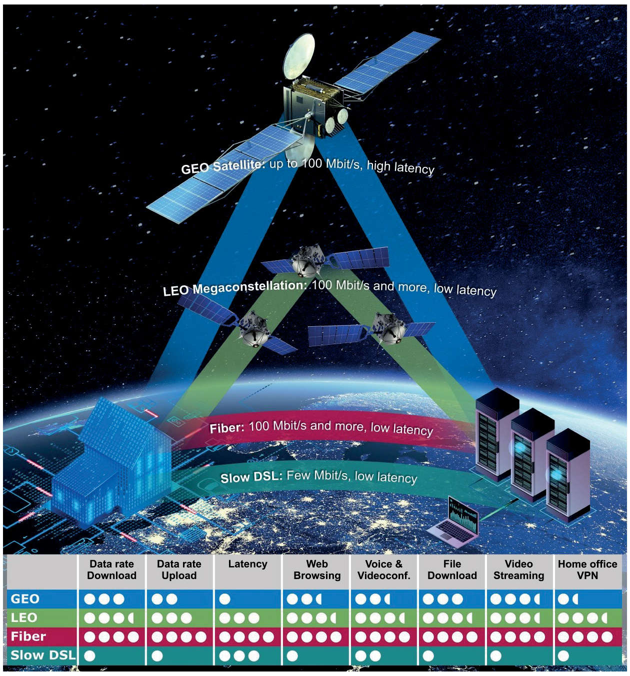


**Figure 9** Rating of different applications over different Internet access technologies based on measurements done by Friedrich-Alexander-Universität Erlangen-Nürnberg. Image © German Space Agency / Deutsches Zentrum für Luft- und Raumfahrt.

technology, its high latencies are problematic for some applications. The performance of the new Starlink megaconstellation is comparable with terrestrial Internet access links like DSL or LTE. However, the costs are rather high, and the performance needs to be further assessed in the future.

Based on our findings, we created an overview presented in **Figure 9**. Although not used in our measurements, we used fiber as reference, which is obviously the best Internet access technology. The Starlink LEO megaconstellation comes second, with high data rates and latencies comparable to terrestrial Internet access like DSL or LTE. Geostationary satellites suffer from high latencies, but the impact depends on the application. We additionally added very slow terrestrial Internet access links (e.g., *DSL light*) to the figure, which is not adequate for modern Internet-based applications.

Regarding future work, a more detailed analysis of the presented applications is desirable. Also, the deployment of QUIC needs to be considered. Evaluation and optimization of QUIC over satellite networks is ongoing work in the QUICSAT project.[7]

[7] `https://www.cs7.tf.fau.eu/research/quality-of-service/qos-research-projects`

## Acknowledgement

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