Next-Generation Satellite Communication Networks

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***Abstract*—This paper gives an overview of our recent activities in the field of satellite communication networks, including an introduction to geostationary satellite systems and Low Earth Orbit megaconstellations.**

To mitigate the high latencies of geostationary satellite networks, TCP-splitting Performance Enhancing Proxies are deployed. However, these cannot be applied in the case of encrypted transport headers as it is the case for VPNs or QUIC. We summarize performance evaluation results from multiple measurement campaigns.

In a recently concluded project, multipath communication was used to combine the advantages of very heterogeneous communication paths: low data rate, low latency (e.g., DSL light) and high data rate, high latency (e.g., geostationary satellite).

***Index Terms*—satellite communication, Performance Enhancing Proxies, transport protocols, VPN, QUIC, multipath communication, hybrid access**

I. Satellite Communication

Satellite communication has been around for a very long time [1]. Until recently, Internet access via satellite has usually been provided by geostationary satellites (GEO) and has been a niche product among broadband access technologies. Upcoming Low Earth Orbit (LEO) satellite megaconstellations (e.g., *Starlink*) have received huge attention. The different orbits, visualized in Fig. 1, and their impact for network protocols will be discussed in the following sections.

A. Geostationary satellite systems

Geostationary satellites are above Earth's equator and match the Earth's rotation speed, i.e., viewed from the ground, the satellite appears always in the same location. The total capacity of such a high throughput satellite is several hundred Gbit/s [2] and spot beams are used to efficiently use the spectrum as illustrated in Fig. 2.

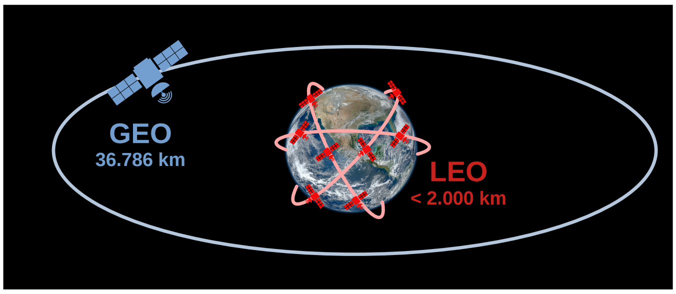

Fig. 1. Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO). Figure not to scale.

The user terminal requires a parabolic antenna which can be used for return link (user terminal to Internet) and forward link (Internet to user terminal). Data rates and prices are comparable or slightly more expensive compared to other broadband access technologies [3]. Data caps or prioritised data may apply.[1]

A significant drawback regarding GEO satellites is the high latency: Due to the large distance to the geostationary orbit and together with other delays, Round Trip Times (RTTs) of approximately $600\,\mathrm{ms}$ are typical.[2]

TCP performs poorly over such high-latency links, therefore TCP-splitting Performance Enhancing Proxies (PEPs) [4] are deployed in satellite networks, as shown in Fig. 4. However, with encrypted transport layer protocols, as it is the case with Virtual Private Networks (VPNs) or the recently standardized QUIC protocol [5], PEPs cannot be applied. This has significant performance impacts as described in Sec. II.

B. Medium Earth Orbit constellations

Communication satellites can also operate in Medium Earth Orbit (MEO) which is defined between LEO (less than $2000\,\mathrm{km}$) and GEO ($35\,786\,\mathrm{km}$). In that orbit, round trip times are better than GEO but worse than LEO. Currently, the most noteworthy example of a MEO constellation is

[1]With prioritised data, the best performance is guaranteed for a limited amount of data. Afterwards, performance may be degraded depending on the available system capacity, but no hard throttling (as it is often the case in cellular networks) is applied.

[2]One-way propagation delay from user terminal via geostationary satellite to ground station (or vice versa) is $2 \cdot d_{\mathrm{geo}}/c \approx 240\,\mathrm{ms}$, with c being the speed of light and distance to geostationary orbit $d_{\mathrm{geo}} = 35\,786\,\mathrm{km}$.

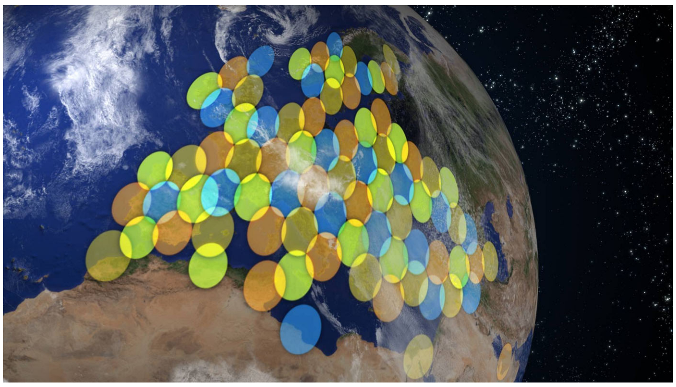

Fig. 2. Spot beams for the geostationary KA-SAT (Image source: https://commons.wikimedia.org/wiki/File:KA-SAT_spot_beams_coverage.jpg).

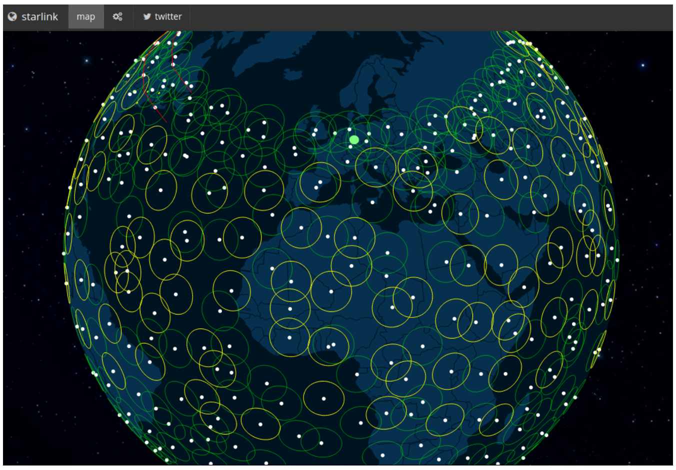

Fig. 3. Screenshot from https://satellitemap.space showing Starlink satellites (January 2021). Green (yellow) circles: satellite altitude greater (less) than 550 km. Due to the chosen orbital inclination of ~53°, satellite density is higher at such latitudes.

O3b mPOWER [6], which consists of 20 satellites above Earth's equator at an altitude of ~8000 km. This results in RTTs of ~150 ms.

C. LEO Megaconstellations

LEO satellite megaconstellations are not a new idea, many systems were planned in the 1990s but either failed economically or were canceled [7]. With an ever increasing demand for high-speed broadband Internet access and technology advancements, megaconstellations have again gained momentum. Pachler et al. [8] provide a good overview and comparison of LEO satellite constellation systems. At the time of writing, SpaceX's *Starlink* has nearly 2000 satellites in orbit (see Fig. 3 for illustration) and is available to customers in several countries.[3] The Starlink terminal is a phased-array antenna, costs for hardware and shipment were ~700 € and the monthly fee is currently 99 € in Europe. Starlink does not specify nominal link rates, first numbers from measurements are discussed later in Sec. II.

As it is difficult to set up LEO megaconstellation testbeds, simulation frameworks have been updated or released recently, e.g., for ns-3 [9], OMNeT++ [10], or Python [11]. It is unclear how accurate these simulation models represent the real Starlink system. Instead, a common research topic using beforementioned network simulators are inter-satellite links.

The enormous amount of satellites is problematic for observational astronomy [12]. Moreover, the risk of satellite collisions increases and any collision creating space debris increases the risk of further collisions, cf. *Kessler syndrome*.

II. Performance Evaluations

We have done several performance evaluation studies of QUIC and encrypted protocols over geostationary satellite links [2], [14]–[18]. Due to limited space we only present Fig. 5, taken from [2], which summarizes the key results best. It shows connection setup and object download time of varying object sizes via HTTPS over a real satellite link. We use initial connections without session resumption, TCP Fast Open or QUIC's 0-RTT. For more details of the test setup and implementations please refer to [2]. For TCP and TLS1.3 connection setup, two RTTs are required in total. Another RTT is required for HTTP request and response. This results in approximately $3 \cdot 700\,\text{ms} = 2.1\,\text{s}$. For small object sizes, the transmission duration is neglectable. For larger object sizes, TCP with the provider PEP provides the best performance. The non-applicability of PEPs is achieved by using `OpenVPN` (mode UDP) and results show an significant performance decrease for larger object sizes. Two QUIC implementations were used, both used 1-RTT for connection setup, saving one RTT compared to TCP/TLS1.3. `picoquic` has been optimized by its author for satellite paths, thus resulting in very good performance close to TCP with PEPs. `quicly` on the other hand does not provide good performance.

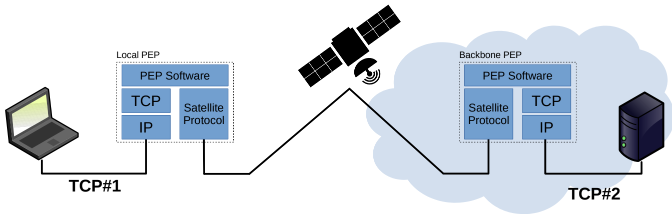

Fig. 4. Performance Enhancing Proxies and Split TCP, with an optimized protocol on the high-latency satellite link.

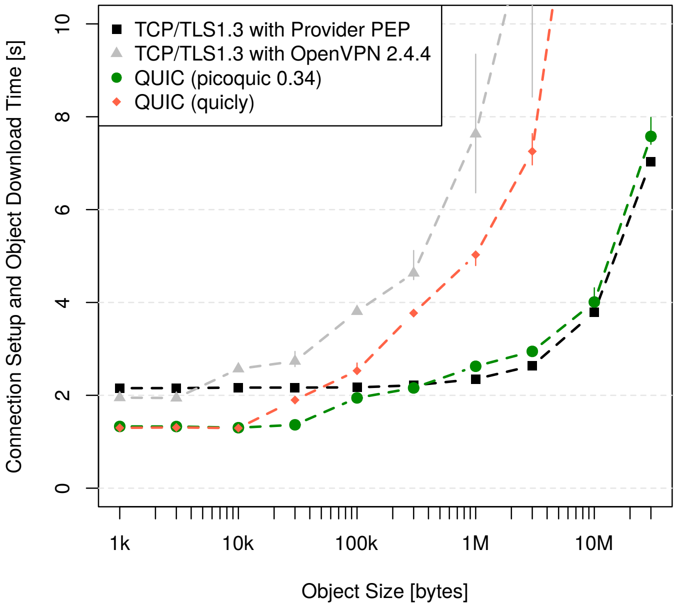

Fig. 5. Performance of transport layer protocols over geostationary satellite Internet (Konnect Zen, 50 Mbit/s forward link, 5 Mbit/s return link). Symbols represent medium values, vertical lines are first and third quartiles, respectively. Source: [2].

[3]E.g., North America, Canada, New Zealand, and parts of Europe, South America, Australia. See https://www.starlink.com/map for details.

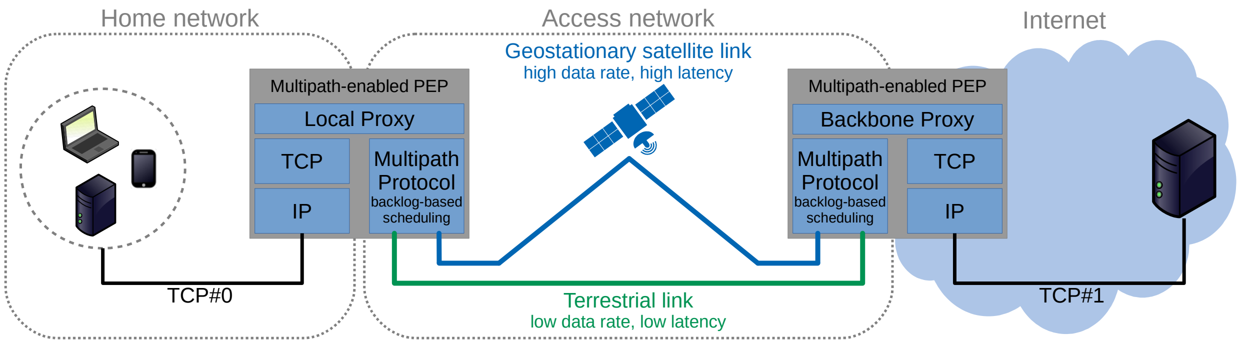

Fig. 6. Architecture for combining very heterogeneous communication paths [13]

In [18] we modified the QUIC Interop Runner to test a broad range of QUIC implementations over emulated and real geostationary satellite links. The results have shown that the performance of QUIC over geostationary satellite paths is poor in general, and performance among different implementations varies vastly.

In a technical report [16], [17] we measured a broad range of metrics (goodput, delay, packet loss) and applications using four different GEO providers, Starlink, and two terrestrial Internet access links (DSL and LTE). This comprehensive but high-level study has shown that Internet access via geostationary satellites is affordable and its usability depends on the application:

- Well-suited: e-mail, file downloads[4], video streaming[5]
- Noticable QoS degration: web browsing, VPNs
- Unsuitable (and not tested): latency-sensitive applications, e.g., interactive online gaming.

Regarding Voice over IP, only connection setup and packet loss was considered, but not the effect of high latency on users' Quality of Experience perception. Video conferencing needs to be evaluated in future measurements. The performance of Starlink was comparable to the terrestrial Internet access links. The baseline for selection of tariffs was a forward link rate of $50\,\mathrm{Mbit/s}$. Starlink achieved much higher goodputs: more than $200\,\mathrm{Mbit/s}$ in the forward link and ~$30\,\mathrm{Mbit/s}$ in the return link, but the achieved goodput was very unrealiable. This is in line with other Starlink performance measurements (e.g., [20], [21] or a website[6] collecting crowd-contributed measurements).

III. Multipath Communication with Terrestrial and Satellite Links

In a project[7] which was concluded end of 2020, the goal was to combine the advantages of multiple heterogeneous Internet access links. This is illustrated in Fig. 6: A low data rate, low latency path (e.g., DSL light) and a high data rate, high latency path (e.g., geostationary satellite) are combined to achieve a high data rate, low latency Internet access. However, the more heterogeneous the paths are, the more difficult multipath communication becomes. Therefore, a suitable architecture and scheduling algorithm was developed: PEPs are used to aggregate data from TCP senders, and the aggregated data is then used as scheduling decision. Flows with small backlogs (e.g., connection setups, HTTP requests) are sent on the terrestrial link, and the geostationary satellite path is used as soon as large amounts of data are transferred.

A detailed description of this solution is available in [13], together with an implementation as ns-3 simulation model. The simulation used the workload model from [22] which is rather outdated. A prototype implementation capable of loading real websites is under development but has not been published yet, early results are available in [23]. Results show that there is a clear benefit of using such a multipath solution [13], [23].

Our current approach relies on PEPs, and as described before this is problematic with encrypted transport protocols. Adaptation to an end to end protocol, e.g., Multipath QUIC [24], is future work.

IV. Conclusion and Future Work

Satellite communication is subject to disruptive changes. VPNs and the new QUIC protocol are problematic for geostationary satellite networks relying on PEPs. Using multipath communication is a possibility to combine the advantages of very heterogeneous communication paths. LEO megaconstellations like Starlink provide satellite Internet access with high data rates and low latencies but at a currently expensive price.

The discussed topics are also relevant for 5G (and beyond) networks: Multipath communication is referred to as *Access Traffic Steering, Switching and Splitting* (ATSSS) [25], and satellite communication is described by *Non-Terrestrial Networks* (NTN) [2], [26].

The performance of QUIC and related protocols is further evaluated and optimized in the ongoing *QUICSAT*[8] project. In the recently started *5G-AUTOSAT KI*[9] project, the integration of satellite links for automotive use-cases in the context of 5G networks and artificial intelligence will be researched.

[4] Assuming TCP and PEPs.
[5] Simplified video streaming tests only. Requires further evaluation, e.g., by using work from Wamser et al. [19]
[6] https://starlinkstatus.space/
[7] *TMC-IPv6*, see https://cris.fau.de/converis/portal/project/212438480
[8] *QUICSAT*, see https://cris.fau.de/converis/portal/project/264452360
[9] *5G-AUTOSAT KI*, see https://cris.fau.de/converis/portal/project/267171638

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