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RESEARCH-ARTICLE

FjordLink: Comparison of Starlink and 5G Networks for Teleoperated Vessel Control

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FjordLink: Comparison of Starlink and 5G Networks for Teleoperated Vessel Control

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Abstract

The rapid growth of Low Earth Orbit satellite networks, such as Starlink, is increasing global connectivity by enabling low-latency broadband access in regions where wired and cellular networks fall short. Prior research focuses on the performance of Starlink in terrestrial settings. Yet, there is limited research on the performance of Starlink in coastal and maritime environments, raising the question of how Starlink performs in the presence of waves and tides.

In this paper, we introduce the FjordLink, a combined Starlink and 5G dataset for coastal maritime connectivity. We collect over 500,000 measurements using a Flat High Performance dish and 5G modems on a research vessel for four months. Starlink and 5G networks achieve median RTTs of less than 50 ms and mean upload throughputs exceeding 35 Mbps. Our results show that Starlink operates similarly (e.g., with a 10 ms median latency difference) in both maritime and terrestrial environments, and improves the 99th percentile latency compared to 5G networks. As a case study, we utilize traces from FjordLink in emulation to evaluate BBR, CUBIC, and Reno congestion control algorithms, where BBR achieves 18% higher upload throughput than CUBIC and Reno.

CCS Concepts

• **Networks** → **Network measurement**.

Keywords

Dataset, Starlink, 5G, coastal, maritime, remote control

ACM Reference Format:

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1 Introduction

The number of Low Earth Orbit (LEO) satellites, such as Starlink, is increasing in popularity and reaching more than 1 million active users worldwide [20]. LEO satellites provide significantly lower latencies than Geosynchronous Equatorial Orbit (GEO) satellites, making them a viable alternative for connectivity in remote regions where wired and cellular broadband networks fall short [7, 10]. While the coverage of cellular networks requires a wide deployment of base stations, the operation of LEO satellites requires a stable platform to mount the dish and an unobstructed view of the sky. LEO satellites not only provide extra coverage but can also integrate with existing and future cellular systems [1]. Thus, LEO satellites are a prime alternative to cellular networks for teleoperated driving, such as remotely controlled and autonomous vehicles [19] due to their low latency, sufficiently high bandwidth, and near-global coverage. Existing research mainly focuses on a terrestrial setting for the performance analysis of LEO satellites [3, 6, 12–14, 18] and tuning congestion control algorithms (CCAs) [8, 9]. Unlike land-based environments, the coastal maritime domain poses unique communication challenges, such as varying waves and tidal movements that affect line-of-sight due to unstable dish orientation. Therefore, we need new datasets to, for example, (1) compare the performance of LEO satellites and 5G networks in inland waterways and (2) test and develop CCAs.

In this paper, we introduce FjordLink¹, a combined Starlink and 5G dataset, collected using the Flat High Performance (FHP) kit during an extensive measurement campaign over 4 months, with more than 500,000 data points collected using a research vessel driving up to 20 km/h. Using the FjordLink, we compare the performance of Starlink versus 5G networks in supporting remote control and monitoring operations in coastal maritime routes. Under mobility, results show median round-trip times of 46 ms, 38 ms, and 40 ms for Starlink, 5G NSA, and 5G SA, respectively. The median jitter is 3.78

¹<https://github.com/ds-kiel/FjordLink>

ms, 6.42 ms, and 6.18 ms for Starlink, 5G SA, and 5G NSA, respectively. With a target bitrate of 50 Mbps, Starlink achieves a mean upload speed of 35 Mbps, compared to 49 Mbps for 5G NSA and 41 Mbps for 5G SA. Compared to being docked in a port, the performance of Starlink while moving stays relatively similar (e.g., 10% difference in median and mean latencies), but 5G networks suffer up to 10 times higher 99th percentile delays, thus making Starlink the better network when reaching the cellular edge. We also evaluate BBR, CUBIC, and Reno CCAs as a case study using the FjordLink. BBR achieves 18.6% and 19.4% higher upload throughput than CUBIC and Reno, respectively. However, this costs 5 and 2.3 times more than CUBIC and Reno, respectively, in terms of 99th-percentile retransmissions.

Overall, this paper makes the following contributions:

- Introduces the *FjordLink*, a combined Starlink and 5G dataset with more than 500,000 data points from a research vessel in coastal maritime routes.
- Analyzes the FjordLink dataset regarding latency, jitter, and throughput, and compares it to 5G networks. Under mobility, median round-trip times are 46 ms, 38 ms, and 40 ms for Starlink, 5G NSA, and 5G SA, respectively. With a target bitrate of 50 Mbps, Starlink achieves a mean upload speed of 35 Mbps, compared to 49 Mbps for 5G NSA and 41 Mbps for 5G SA.
- Demonstrates the utility of the FjordLink by evaluating the performance of CCAs under Starlink traces in an emulation environment, where BBR achieves 18% higher upload throughput than CUBIC and Reno.

The remainder of this paper is organized as follows: Section 2 presents background and related work, Section 3 details the measurement campaign, Section 4 analyzes the FjordLink dataset, and Section 5 concludes the paper.

2 Background and Related Work

In this section, we first provide a background on Starlink. Next, we examine the related work in Starlink measurements.

2.1 Starlink Background

SpaceX operates Starlink, a LEO satellite constellation, providing broadband Internet service for global network coverage. As of May 2025, Starlink includes over 6,750 satellites in orbit [20]. Starlink mainly connects to a new satellite every 15 seconds at fixed 12-27-42-57 seconds of a minute [9]. With latencies ranging from 25 to 60 ms, Starlink advertises download and upload speeds of up to 220 Mbps and 25 Mbps, respectively [21]. Starlink directs traffic to Points of Presence (PoP) locations where satellites connect to the Internet.

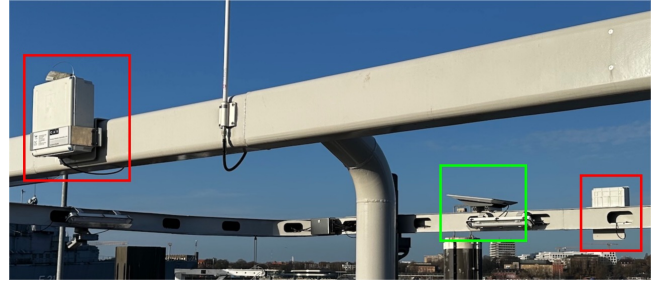


Figure 1: Our measurement setup includes a Starlink FHP dish (the green box) and two 5G routers (red boxes) on top of the mast of the MS Wavelab.

2.2 Related Work

Prior works mainly analyze the performance of Starlink in static and mobile scenarios on terrestrial environments [3, 6, 11–18]. For example, Ma et al. [16] measure latency, UDP and TCP throughput, packet loss, and routing information on a driving van. López et al. [15] collect latency measurements on a car in a rural area. Hu et al. [6] present a measurement study of Starlink and cellular networks on a car, examining upload and download throughput, latency, and packet loss, and investigating the potential benefits of enabling multipath communications. Beckman et al. [3] analyze the performance of Starlink under mobility and compare it to a cellular network around the Arctic Circle. Mohan et al. [18] compare the performance of Starlink measurements across 34 countries against cellular and fiber infrastructure. Laniewski et al. [14] collect and analyze the performance of Starlink in a static setting across changing weather conditions. Laniewski et al. [12, 13] also analyze the performance of Starlink under mobility and compare it to prior static measurements.

Unlike prior works, the FjordLink introduces a Starlink dataset for performance analysis in coastal maritime routes and compares it to 5G NSA and 5G SA networks. We measure inbound, outbound, and round-trip latency at a higher resolution of 10 Hz using the Two-Way Active Measurement Protocol (TWAMP) [2] and bidirectional throughput using iPerf3² in UDP mode. We also show the usefulness of the FjordLink in emulation and compare CCAs under latency, jitter, and throughput constraints.

3 Measurement Campaign

In this section, we detail our measurement campaign. We show an overview of our measurement setup and location in Figures 1 and 2. We collect data from the research vessel MS Wavelab, which operates on the Kiel Fjord, Germany, along coastal maritime routes, see our GitHub repository for a detailed coverage map. The dataset spans over 4 months.

²<https://github.com/esnet/iperf>

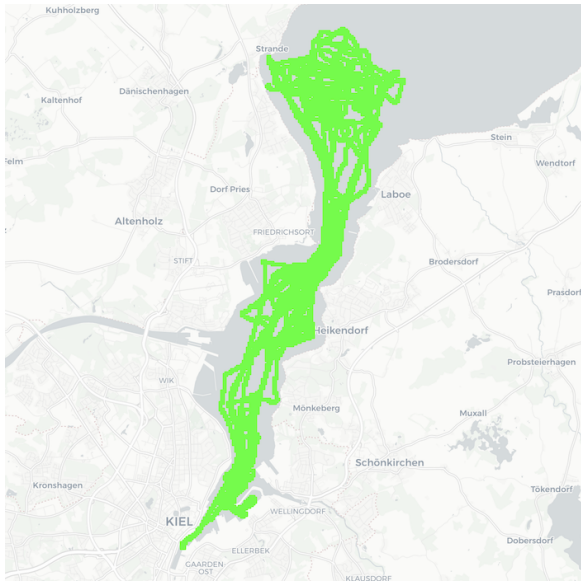


Figure 2: We measure network performance in the Kiel Fjord, Germany, covering a vertical distance of 17 km.

Table 1: Overview of captured features

Data Category	Features
TWAMP	Latency (ms), Jitter (ms)
iPerf3	Throughput (Mbps)
Starlink dish	PoP ping (ms), Position
5G router	Signal strength, Frequency, Position
Weather	Temperature, Wind, Precipitation

We base our cellular measurement campaign on a similar architecture outlined in the Fjord5G dataset [4]. We collect data from a Starlink Flat High Performance (FHP) dish and two 5G routers, one with Vodafone 5G SA service (operator #1) and the other with Deutsche Telekom 5G NSA service (operator #2). While Vodafone uses 5G bands n28, n3, and n78, Deutsche Telekom utilizes 5G bands n28, n1, and n78 in addition to LTE bands. While Starlink is mostly accessible with a clear line of sight, 5G performance degrades the further we are away from the coast and the base stations.

We show an overview of captured features in Table 1. We use TWAMP to measure one-way latency, round-trip time (RTT), and jitter. Additionally, we use iPerf3 to measure upload and download throughput as well as jitter using UDP. While TWAMP measures data at 10 Hz, both iPerf3 and Starlink dish provide data at 1 Hz. We measure latency, jitter, and throughput simultaneously for 30-second chunks, then wait for 15 seconds and repeat. Using 30-second chunks, we aim to get at least one satellite handover event, possibly two, in the logs for our analysis, see examples in Figures 3 and 6.

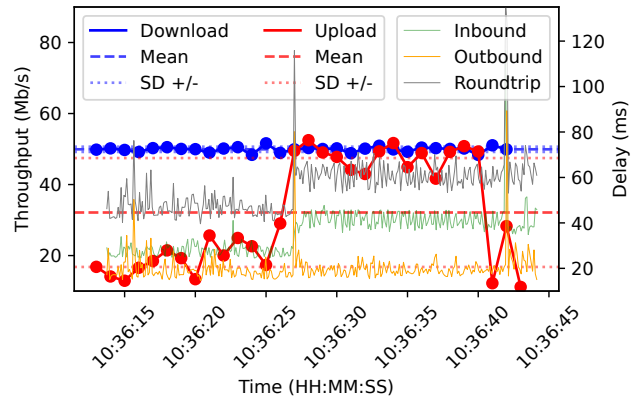


Figure 3: An example Starlink trace with bandwidth, latency, and jitter: Latency increases drastically during satellite handovers at seconds 27 and 42. The mean latency also increases on the new satellite after the handover at second 27. While download throughput remains consistent at 50 Mbps due to underutilization, upload throughput varies, especially after the switch to the new satellite, as it approaches the capacity limits.

Additionally, we provide weather data offered by the German Weather Service³ from stations in Kiel. However, we leave the correlation analysis of weather data to future work.

4 Analysis

In this section, we first give an overview of the FjordLink dataset. Next, we analyze latency, jitter, and throughput. Finally, we show a trace-based evaluation of CCAs.

4.1 Dataset Overview

Our dataset includes over 500,000 data points for latency, jitter, and throughput measurements, see Table 2. Most measurements come from Starlink while moving, rather than being docked in the port. We also collect measurements from 5G SA and 5G NSA networks for comparison. We show an example Starlink trace of a 30-second chunk with throughput measurements for upload and download, and latency measurements for inbound, outbound, and RTT in Figure 3.

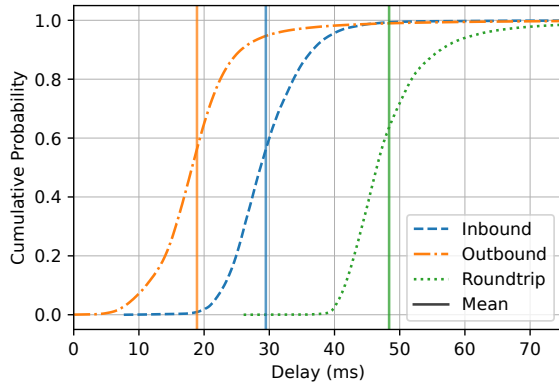
4.2 Latency and Jitter

We start with analyzing inbound, outbound, and round-trip latencies. We observe that Starlink achieves lower outbound delays than inbound, see Figure 4. This might be due to more users downloading data on a typical Starlink connection than uploading, thus creating load and congestion on the inbound. Under mobility, we measure mean latencies of 18.9

³<https://www.dwd.de>

Table 2: Number of data points in the FjordLink dataset

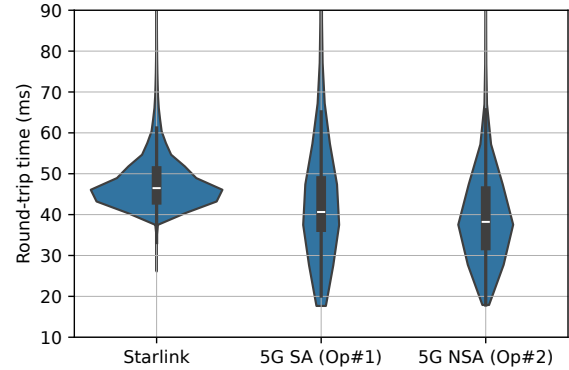
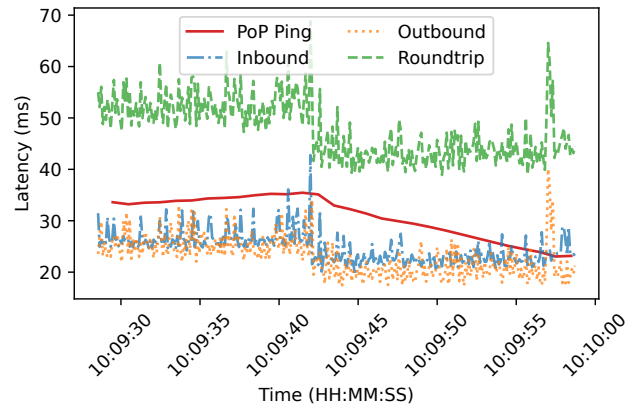
	Latency	Jitter	DL BW	UL BW
Starlink - Mobile (#)	526k	52k	14k	12k
5G SA - Mobile (#)	123k	12.5k	6.4k	6.6k
5G NSA - Mobile (#)	125k	12.6k	5.4k	6.1k
Starlink - In Port (#)	72k	7.2k	1.2k	2k
5G SA - In Port (#)	129k	12.8k	4k	4k
5G NSA - In Port (#)	63k	6.3k	2k	2k

**Figure 4: Comparison between Inbound, Outbound, and Round-trip latencies on mobile Starlink: Mean latencies are 18.9 ms, 29.5 ms, and 48.4 ms for outbound, inbound, and RTT, respectively. Starlink achieves lower outbound latencies compared to inbound.****Table 3: RTT percentiles for Starlink vs. 5G**

	99th	90th	Median	Mean
Starlink - Mobile (ms)	82	56	46	48
5G SA - Mobile (ms)	1376	156	41	120
5G NSA - Mobile (ms)	450	55	38	62
Starlink - In Port (ms)	107	77	55	59
5G SA - In Port (ms)	118	47	38	42
5G NSA - In Port (ms)	185	57	42	48

ms, 29.5 ms, and 48.4 ms for outbound, inbound, and RTT, respectively. For the 99th percentiles, Starlink still shows an RTT of around 82 ms while moving.

We compare RTTs between Starlink, 5G NSA, and 5G SA networks, see Figure 5 and Table 3. While moving, all three networks offer median latencies under 50 ms. However, Starlink provides significantly lower 99th percentiles than 5G NSA and 5G SA at 82 ms, 450 ms, and 1375 ms, respectively. Additionally, we observe that 5G NSA achieves overall lower latencies than 5G SA, most likely due to the limited availability and rollout of 5G SA at our locations.

**Figure 5: RTT comparison between Starlink and 5G networks while moving: 5G NSA and 5G SA offer lower median latencies than Starlink at 38 ms, 41 ms, and 46 ms, respectively. However, Starlink achieves lower 99th percentile latencies than 5G NSA and 5G SA at 82 ms, 450 ms, and 1375 ms, respectively.****Figure 6: Comparison between Starlink PoP and TWAMP Latencies: Once the Starlink connection switches to a new satellite at second 42, PoP ping and TWAMP latencies decrease. For the FjordLink dataset, the mean PoP ping is 28.15 ms, compared to 48.37 ms for TWAMP RTT, giving around 20 ms for communication between the PoP and our servers on land.**

Generally, the distribution of RTTs on Starlink stays within a tighter range compared to 5G networks. This implies that while all networks provide low latencies under optimal conditions, cellular networks tend to deteriorate more rapidly at the cellular edge. While in port, 5G networks offer more stable latencies with significantly lower 99th percentiles than in mobile environments. On the other hand, latencies increase by 9 ms for the median and 25 ms for the 99th percentile

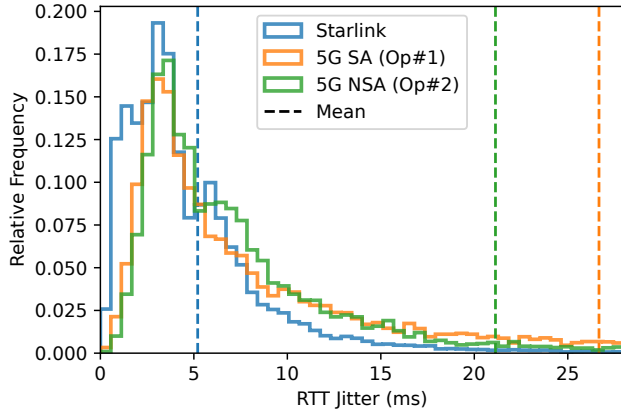


Figure 7: Jitter comparison between Starlink and 5G networks while moving: Median jitter is relatively low (e.g., below 5 ms) for all networks, and 5G networks have higher mean jitter values due to extreme outliers.

Table 4: Jitter percentiles for Starlink vs. 5G

	99th	90th	Median	Mean
Starlink - Mobile (ms)	28	10	3.8	5.2
5G SA - Mobile (ms)	262	39	6.4	27
5G NSA - Mobile (ms)	315	26	6.2	21
Starlink - In Port (ms)	33	11	4.0	5.8
5G SA - In Port (ms)	65	12	3.7	6.6
5G NSA - In Port (ms)	88	25	6.7	12

when Starlink is docked compared to when it is mobile. Overall, the stationary performance of all three networks is closer to each other in the port than it is while moving.

We compare the PoP ping and TWAMP RTT by showing an example trace in Figure 6. After the satellite handover at second 42, both Starlink’s own PoP ping and latency measurements from TWAMP decrease, possibly due to lower load on the new satellite. While the PoP ping does not show latency spikes at the handovers due to aggregation, our measurements capture latency spikes at seconds 42 and 57.

We plot jitter measurements between Starlink, 5G SA, and 5G NSA in Figure 7. While median jitter is below 5 ms across all networks, 5G networks experience higher mean and 99th percentile jitter due to higher extremes in the data. Prior research shows that passing a 20-ms jitter threshold lowers real-time video quality [5]. Therefore, switching to Starlink under poor cellular coverage can greatly improve real-time video quality. We provide jitter percentiles for Starlink versus 5G networks in Table 4. Jitter values are lower on 5G networks during docking, and increase slightly on Starlink. Both 5G SA and Starlink offer low jitter values when docked.

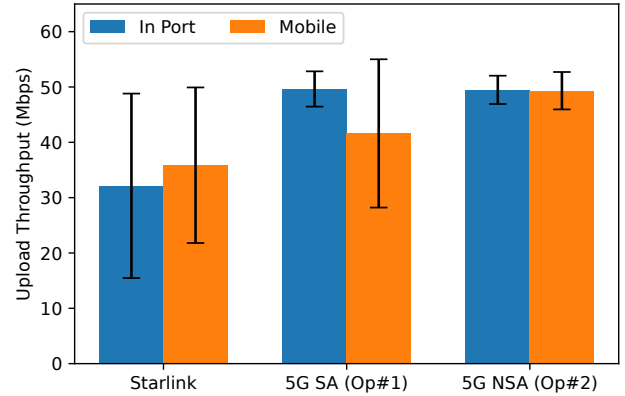


Figure 8: Upload throughput comparison between Starlink and 5G networks: Starlink provides lower upload throughput compared to both 5G networks. While docked in the port, 5G networks reach the desired 50 Mbps target, compared to a mean upload throughput of 32 Mbps for Starlink. While moving, the mean upload throughput decreases on 5G SA and increases on Starlink; however, both are within the standard deviation.

4.3 Throughput

In our throughput measurements, we target a bitrate of 50 Mbps in both upload and download directions, which is sufficient to sustain multiple HD/4K cameras used in teleoperation. This is because (1) remote operations are mostly bottlenecked in the uplink direction, (2) Starlink advertises an upload rate of 25 Mbps (i.e., likely resulting in uplink congestion), and (3) due to limited prioritized Starlink traffic.

First, Starlink and 5G networks easily reach the 50 Mbps target download throughput. We compare upload throughput for Starlink and 5G networks while docked in port and mobile settings in Figure 8. At a target bitrate of 50 Mbps, Starlink achieves upload bitrates of 32.14 Mbps and 35.86 Mbps, with standard deviations of 16.67 Mbps and 14.06 Mbps, respectively, while docked and mobile. 5G NSA performs the best while in motion, compared to 5G SA and Starlink. These results suggest that, in coastal maritime environments, cellular networks already sustain multi-camera teleoperation, whereas Starlink requires adaptive encoding.

4.4 Playback of Traces in Emulation

Utilizing our traces, we emulate upload and download bandwidth, directional latencies, and jitter using tc-netem⁴ to limit the network interface. We enforce the measured bandwidth and drop any excess traffic generated by BBR, CUBIC,

⁴<https://man7.org/linux/man-pages/man8/tc-netem.8.html>

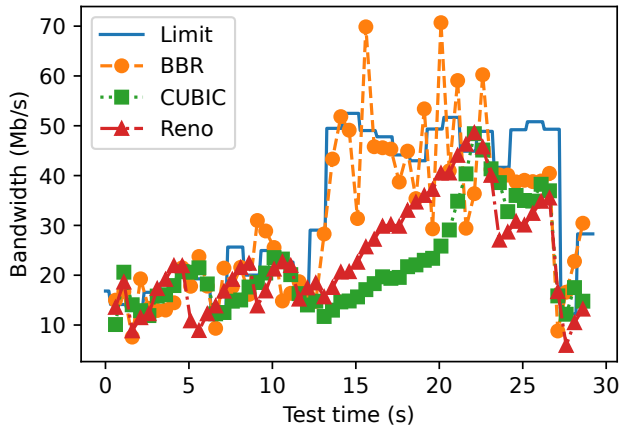


Figure 9: BBR, CUBIC, and Reno under bandwidth, latency, and jitter limitations in emulation: BBR reacts quickly to changes in the network, especially around the handover at around the 14th second, and increases its bitrate to reach maximum capacity, while CUBIC and Reno take longer to increase their bitrate.

Table 5: TCP retransmissions of BBR, CUBIC, and Reno CCAs in the emulation with 25 s and longer traces

	Max	99th	90th	Median	Mean
BBR	2217	1034.87	488.7	0.0	157.13
CUBIC	1210	145.82	29.0	0.0	9.56
Reno	1105	313.03	32.0	22.0	12.12

and Reno, mirroring how Starlink discards packets when its queue is full, see our GitHub repository for further details.

We present an example trace from the emulation for comparing CCAs in Figure 9. In fact, this is the same trace as Figure 3. Until the satellite handover around the second 14, all CCAs fluctuate around the network capacity. Once the satellite handover hits and capacity drastically increases, only BBR reacts quickly, while CUBIC and Reno take almost 10 seconds to reach the new capacity of the link.

We compare the uplink throughput of BBR, CUBIC, and Reno under emulation using 5k data points of upload measurements from FjordLink in Figure 10. BBR probes capacity more frequently and increases the bitrate, compared to CUBIC and Reno, where we observe similar probabilities for CUBIC and Reno in terms of upload throughput. This comes at an increased cost of retransmissions for BBR compared to CUBIC and Reno, see Table 5. The mean number of retransmissions for BBR is more than 10 times that of the mean values for CUBIC and Reno. For the 99th percentiles, we see that CUBIC achieves the lowest retransmission numbers.

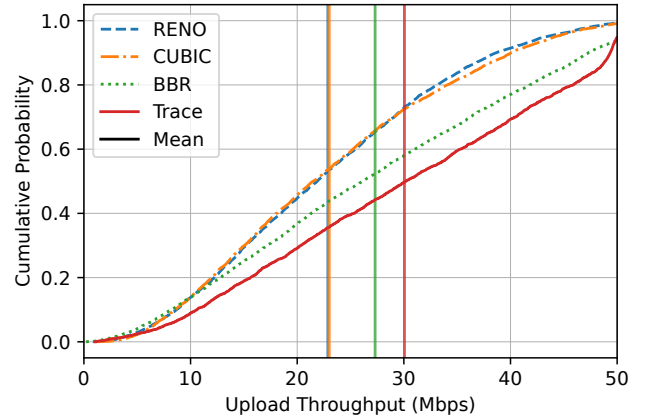


Figure 10: TCP upload throughput of BBR, CUBIC, and Reno in the emulation using 25-second and longer traces (i.e., 5k data points) under bandwidth, latency, and jitter limitations on Starlink traces: BBR achieves a higher mean upload throughput of 27.3 Mbps compared to Reno’s 22.87 Mbps and CUBIC’s 23.01 Mbps.

5 Conclusion

In this paper, we introduce FjordLink, a combined Starlink and 5G dataset with over 500,000 measurements from Kiel, Germany, for research on coastal maritime connectivity. Under mobility and when docked in the port, we compare the performance of Starlink against 5G SA and 5G NSA networks for uplink-dominated teleoperated vessel control. As a study, we evaluate BBR, CUBIC, and Reno CCAs on FjordLink traces in emulation under latency, jitter, and throughput limitations.

Under mobility, Starlink, 5G SA, and 5G NSA networks achieve comparable median RTTs of under 50 ms. The 99th percentile RTTs for Starlink are also lower compared to 5G networks. When comparing uplink throughput, Starlink falls behind 5G, with a mean of 35.86 Mbps, compared to 41.61 Mbps for 5G SA and 49.33 Mbps for 5G NSA, respectively. However, all three networks achieve the 50 Mbps download target. Starlink with the FHP dish performs as well in maritime scenarios with speeds of up to 20 km/h as in terrestrial environments, with a 10 ms median RTT difference, while significantly improving the 99th percentile compared to 5G. To demonstrate the usefulness of FjordLink for trace-based emulation, we evaluate BBR, CUBIC, and Reno on our traces and show that BBR achieves 18% higher upload throughput at the cost of more retransmissions than the others.

Acknowledgments

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