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Rapport om bredbåndsdækning for Starlink

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OPLÆG

SDFI's bredbåndskortlægning viser at der medio 2023 var omkring 50.000 bolig- og virksomheds-adresser der ikke har adgang til en 100/30 Mbit/s bredbåndsforbindelse - restgruppen. Ifølge SDFI's seneste fremskrivning af restgruppen vil der være omkring 20.000 bolig- og virksomhedsadresser uden adgang til 100/30 Mbit/s i 2025. Der forventes at være tale om spredte restgruppeadresser i 2025, hvoraf Region Hovedstaden vil være den region med flest estimerede restgruppeadresser (5.500-7.000 adresser).

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Resumé

Starlink opfylder ikke stringent målsætningen om 100/30 Mbit/s bredbåndsforbindelse når mange Starlink-brugere er aktive i det samme geografiske område, selvom Starlink kan levere godt bredbånd. Især er det målsætningen om 30 Mbit/s i uplink der ikke kan opnås med Starlink da beam-kapaciteten, der skal deles mellem brugerne, kun er omtrent 30 Mbit/s i samme geografiske område.

Hovedkonklusionerne er, at:

- Starlink ikke kan levere en bredbåndstjeneste, der lever op til bredbåndsmålsætningens krav om minimum 100 Mbps download og 30 Mbps upload, da især kravet til upload ikke kan opfyldes.
- Starlinks bredbåndstjeneste for mange restgruppeadresser vil kunne udgøre en væsentlig forbedring, i forhold til den tjeneste restgruppeadresserne har adgang til i dag.
- Starlink har kapacitet til at levere forbedrede bredbåndstjenester til 20-40 pct. af restgruppen – flest i Region Nordjylland; Starlink vil dog kun være i stand til at levere forbedrede bredbåndstjenester til 4-5 pct. af restgruppen i Region Hovedstaden (dvs., ca. 280 adresser).
- Maksimalt omkring 4.000 bolig- og virksomhedsadresser i den restgruppe på 18-20.000, der er tilbage i 2025, vil kunne opnå en forbedret bredbåndsforbindelse med Starlink, i forhold til den bredbåndstjeneste de har adgang til i dag; Starlink skønnes at kunne levere en bredbåndsforbindelse med oplevede datarater på 60-100 Mbit/s download og 5-10 Mbit/s upload[1], svarende til en tilfredsstillende bredbåndstjeneste.
- Den testede brugeroplevelse ved bredbåndsforbindelse over Starlink er tilfredsstillende ved samtidigt brug af streaming, browsing, videomøder, hjemmekontor mm.; kun ved krævende online spil er den øgede systemforsinkelse i Starlink mærkbar.

Opsummering

Starlink

Starlink er et amerikansk firma der leverer satellitbaserede bredbåndsløsninger. Ved abonnenten opsættes en udendørs antenne med en størrelse på ca. 40 × 60 cm som skal have frit sigte til satellitterne. Starlink-satellitmodtageren har indbygget opvarmning til at smelte sne og is fra overfladen på antennen. Satellitteknologien som Starlink anvender kaldes Low Earth Orbit (LEO);

[1] Intervaller for de medianværdier som man ville kunne se i en speedtest (bemærk, dataraterne vil variere meget fra speedtest til speedtest).

satellitterne bevæger sig omkring jorden i en højde på ca. 540 km. LEO-satellitterne bevæger sig med høj hastighed over himmelrummet, og når en satellit fjerner sig fra et dækningsområde tager en ny satellit over således at dataforbindelsen forbliver intakt. Ved udgangen af 2023 havde Starlink mere end 5.500 satellitter i kredsløb, og der er foreløbigt planer om at udvide til 12.000 satellitter. Hver satellit har mange antenne-beams, hvor hver beam dækker et geografisk område på jorden på ca. 400 km^2 (gennemsnit for Danmark).

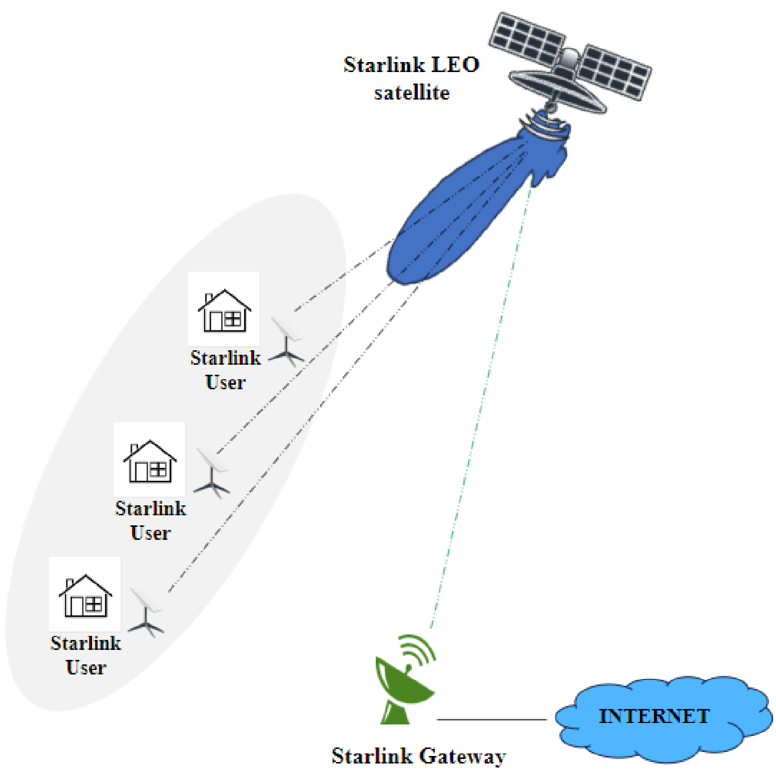
Starlink havde ved udgangen af 2023 ca. 2.200.000 abonnenter globalt, heraf de fleste i Nordamerika. Tilgangen af abonnenter er lukket i visse områder for at sikre at Starlink kan levere en tilfredsstillende servicekvalitet. Udover faste bredbåndsløsninger er Starlink også begyndt at tilbyde mobilservice over satellit.

Starlink som alternativ service for restgruppen

Restgruppeadresserne er typisk forbundet med xDSL (kobbernet). Ved xDSL er forbindelsen fra distributionscentralen til den enkelte adresse en-til-en, dvs. dedikeret per adresse, og én adresse vil derfor ikke have fordel af at der ikke anvendes data på en anden restgruppeadresse. Den opnåede datarate i downlink og uplink ved xDSL er generelt givet ved afstanden fra distributionscentralen til adressen.

I Starlink er kvaliteten af satellit-forbindelsen typisk ens for alle brugere, men forbindelsen er *en-til-mange* (downlink), eller *mange-til-en* (uplink) indenfor et antenne-beam. De aktive brugere på adresserne skal derfor deles om beam-kapaciteten indenfor det enkelte antenne-beam.

Den maksimale datarate som en bruger kan opleve, peak-dataraten, svarer til beam-kapaciteten på ca. 400 Mbit/s i downlink og ca. 30 Mbit/s i uplink. Opfattes bredbåndsmålsætningen på 100 Mbit/s downlink og 30 Mbit/s uplink i gængs forstand vil der således kun være kapacitet til én bruger per beam i uplink og 4 brugere i downlink indenfor et gennemsnitligt geografisk dækningsområde på 400 km^2.



Med gængs forstand forstås at de nævnte datarater er kontinuert opnåelige, f.eks. som resultat af en speedtest. Pga. den delte ressource er dette derfor, strengt taget, kun muligt med én bruger i dækningsområdet med 100/30 Mbit/s bredbåndsforbindelse. Flere brugere vil skulle dele kapaciteten: Hvis Starlink beam-kapaciteten skal deles ligeligt mellem *N* aktive brugere i restgruppen, indenfor et beam der dækker 400 km^2, vil de i gennemsnit få tildelt ca. 400/*N* Mbit/s i downlink og ca. 30/*N* Mbit/s i uplink. Som eksempel vil 40 aktive brugere per antennebeam, der alle udnytter forbindelsen fuldt ud, i gennemsnit tildeles 10 Mbit/s i downlink og 0.75 Mbit/s i uplink. Alle brugere vil dog få oplevelsen af peak-datarater på henholdsvis 400 og ca. 30 Mbit/s i korte intervaller.

I praksis vil de 40 brugere ikke have kontinuert brug af dataforbindelsen, og Starlink vil derfor automatisk fordele enhver ledig kapacitet i beamet i forhold til efterspørgslen på adresserne indenfor beam'ets dækningsområde. Dette medfører at man som bruger, i praksis, vil have oplevelsen af datarater der er væsentlig højere end eksemplet tilsiger.

Oplevet servicekvalitet via Starlink

Test af opnåelige datarater og tidsforsinkelser

Starlink-målinger refereret i denne rapport er foretaget på Aalborg Universitet, Aalborg, i perioden december 2023 til februar 2024. Starlink-målingerne viser en maksimal datarate i downlink på 417 Mbit/s og ca. 30 Mbit/s i uplink. Disse målte værdier er i god overensstemmelse med eksterne referencer.
Med en tilbudt datarate[2] på 100 Mbit/s i downlink og 30 Mbit/s i uplink, svarende til bredbåndsmålsætningen, viser målingerne at Starlink med en enkelt bruger per antenne-beam er i stand til at levere 97 Mbit/s i downlink og 17 Mbit/s i uplink i 80% af tiden.

I opstillingen på AAU blev der anvendt op til tre Starlink-modtagere, hver med påtrykt konstant datarate på 100 Mbit/s i downlink og 30 Mbit/s i uplink. I downlink var der kun minimal degradering i målt datarate per bruger da den samlede datarate på 3 × 100 Mbit/s stadig er lavere end beam-kapaciteten. I uplink blev det målt at datararaten ved 2 brugere blev reduceret til ca. 15 Mbit/s i 80% af tiden, og ved 3 brugere ca. 10 Mbit/s per bruger. Beam-kapaciteten i uplink på ca. 30 Mbit/s bliver således ligeligt fordelt mellem brugerne.

Starlinks middelsystemforsinkelse (ping tid) blev målt til 76 ms, hvilket er 2-3 gange højere end en typisk kablet xDSL- eller fiberforbindelse. Denne test blev afviklet med og uden en (tilbudt) konstant datarate på 100 Mbit/s i downlink som baggrundsbelastning af Starlink forbindelsen, dog uden væsentlig indvirkning på systemforsinkelsen. Specielt i forhold til tidsforsinkelsen har engelske studier af brugeroplevelsen vist at overskyet himmel og nedbør giver anledning til øget tidsforsinkelse over forbindelsen, hvilket indvirker på applikationer som spil og browsing men kun i mindre grad den opnåede gennemsnitlige datarate. I vores test af Starlink fra Aalborg har vi dog ikke observeret mærkbar forringelse i forbindelse med overskyet himmel eller nedbør.

[2] Dvs. den datarate som brugeren forsøger at afvikle, og specifikt i disse test, den datarate som en bredbånds-forbindelse forventes at leve op til.

Test af brugsscenarier

Flere typiske brugsscenarier blev afprøvet over Starlink for at teste brugeroplevelsen, for tilfældet hvor der kun var én Starlink-modtager aktiv. Der blev benyttet en kombination af flere samtidige applikationer og gaming. Ved samtidig video streaming fra YouTube blev der ikke observeret udfald. Ved test af online videomødeprogrammet TEAMS blev der ligeledes ikke observeret udfald eller bemærket forsinkelser. Ved test af web-browsing blev der ikke bemærket udfald eller forsinkelser. Ved den samtidige afvikling af online spil blev dataforbindelsen over Starlink dog udfordret. Ved test af online-spil som kræver hurtig reaktion, f.eks. bilspil og kampspil, blev forsinkelsen tydeligt bemærket. I perioder under testen blev der bemærket systemforsinkelser over Starlink der var væsentligt større end gennemsnitsforsinkelsen på 76 ms. Det blev konkluderet, at mens systemforsinkelsen over Starlink ikke indvirker på typiske applikationer, herunder mange spil, så reduceres brugeroplevelsen væsentligt ved konkurrencemæssige spil (E-sport). Som reference målte analysevirksomheden Ookla i perioden november 2022 til november 2023 en forsinkelse på 58-66 ms [1] for Starlink i USA.

Estimat af antal brugere per beam i Starlink

I det følgende estimat af antal brugere per beam, som Starlink kan servicere, ses der bort fra bredbåndsmålsætningen (i gængs forstand), og i stedet estimeres det hvor mange restgruppeadresser per beam Starlink kan servicere og stadig give en væsentlig forbedring af dataforbindelsen over den nuværende (xDSL).

Det er vores estimat, at der for hver restgruppeadresse skal reserveres en middeldatarate på 10 Mbit/s i downlink i 2025 for at opnå en *tilfredsstillende bredbåndstjeneste*. Det svarer til, i krævet middeldatarate, at hver restgruppeadresse samtidigt mindst kan streame en video eller IP-TV-kanal (ca. 4 Mbit/s), have én bruger der browser (op til 1 Mbit/s), have én bruger der spiller online (op til 1 Mbit/s), og have én bruger der deltager i et online videomøde (op til 4 Mbit/s)[3]. Selvom den tilbudte middeldatarate på 10 Mbit/s umiddelbart kan opfattes som lav, vil den *brugeroplevede* datarate typisk være op til 10 gange højere da alle restgruppeadresser ikke anvender de 10 Mbit/s konstant; Starlink systemet vil automatisk give de samtidigt aktive brugere adgang til den fælles beam-kapacitet på ca. 400 Mbit/s og dermed fordel af at Starlink-beam-kapaciteten er en fælles ressource. Der findes ikke eksakte beregninger af hvad den brugeroplevede datarate vil være, hvorfor vores estimat er baseret på et kvalificeret skøn. Som indledningsvis eksemplificeret, så *er det vores skøn at Starlink har kapacitet til at give en tilfredsstillende bredbåndstjeneste med brugeroplevede datarater på op mod 100 Mbit/s for ca. 40 restgruppeadresser per antenne-beam*. Til reference målte analysevirksomheden Ookla for andet kvartal 2023 en downlink-datarate (median) på 117 Mbit/s, hvilket dog må forventes at falde hvis antallet af brugere i Danmark stiger; i USA, hvor antallet af Starlink brugere er væsentligt højere end i Danmark, ligger den tilsvarende målte datarate på 60-80 Mbit/s i perioden fra november 2022 til november 2023. Vores skøn for de

[3] De krævede datarater er baseret på estimater fra forskellige (uofficielle) kilder; se evt. Appendix C for videomøde.

brugeroplevede downlink-datarater over Starlink er 60-100 Mbit/s ved 40 restgruppeadresser per antenne-beam.

For uplink er vores skøn af den brugeroplevede datarate væsentlig lavere for *tilfredsstillende bredbåndstjeneste* ved ca. 40 restgruppeadresser per antenne-beam, eftersom 1) beam-kapaciteten i uplink er begrænset til 30 Mbit/s og derfor kun tillader en middeldatarate på 0,75 Mbit/s, og 2) dataraten (median) for en enkelt bruger blev målt til 21,3 Mbit/s. De fleste services, som f.eks. browsing og streaming, er meget asymmetriske og kræver kun en uplink-datarate på 5-10% af downlink-dataraten. For spil er asymmetrien ca. 50%, og tilsvarende for online videomøder. Ved 40 brugere der streamer 4 Mbit/s ville den nødvendige uplink kapacitet være ca. 8 Mbit/s, altså langt under Starlink's uplink beam-kapacitet og den enkelte links formåen, hvorimod 40 brugere der anvender online videomøde ville kræve en kapacitet på 80 Mbit/s der langt overstiger Starlink's uplink beam-kapacitet. Da det fremtidige brugermønster ikke er kendt er det behæftet med meget stor usikkerhed hvad der bliver den brugeroplevede datarate i uplink ved 40 restgruppeadresser per antenne-beam. Ookla speedtests fra november 2022 til november 2023 for USA rapporterer målte uplink-datarater (median) på 7,5-10 Mbit/s. Vores forsigtige skøn for de brugeroplevede uplink-datarater er 5-10 Mbit/s ved ca. 40 restgruppeadresser forbundet over Starlink, per antenne-beam[4].

Starlink's potentiale i forhold til restgruppens nuværende datarater

Fordelingen af restgruppens nuværende (2023) uplink- og downlink-datarater er givet i Tabel 1. Bortset fra Region Sjælland har ca. 1/3 af restgruppen en uplink-datarate på under 1 Mbit/s; for Region Sjælland er andelen med uplink-datarate under 1 Mbit/s noget større (44%). Fordelingen er tilsvarende for restgruppens andel der kun kan opnå 5 Mbit/s i downlink.

	Downlink		**Uplink**	
Region	**% < 5 Mbit/s**	**% < 20 Mbit/s**	**% < 1 Mbit/s**	**% < 2 Mbit/s**
Hovedstaden	21	44	27	50
Sjælland	31	63	44	65
Nordjylland	25	46	27	51
Midtjylland	30	53	35	57
Sydjylland	31	54	39	56
Danmark (samlet)	26	50	33	55

Tabel 1 Den nuværende (2023) restgruppes adgang til downlink og uplink datarater, per region og samlet [Kilde: SDFI, 2023].

[4] Estimaterne for brugeroplevede downlink- og uplink-datarater kan sammenholdes med f.eks. amerikanske FCC's retningslinjer der angiver minimum 25 Mbit/s i downlink og 3 Mbits/s i uplink [15] som tilfredsstillende bredbåndstjeneste, herunder bl.a. til anvendelser indenfor telemedicin [16].

Især for restgruppeadresser med lavest datarate vil Starlink give en væsentlig forbedring. For restgruppeadresser med 1-2 Mbit/s i uplink og 5-20 Mbit/s i downlink vurderes det også at der vil kunne leveres en forbedret bredbåndstjeneste over Starlink. Den samlede restgruppe der har under 2 Mbit/s i uplink og under 20 Mbit/s i downlink udgør 50-55% af restgruppen for alle regioner. For restgruppeadresser med større datarater, ca. 45-50% af adresserne, skønnes det at Starlink ikke vil give en væsentlig forbedret bredbåndstjeneste. Ud over dataraten skal ulempen ved den højere systemforsinkelse af Starlink-satellitsystemet tages i betragtning.

Andel af restgruppen hvor Starlink skønnes at kunne levere tilfredsstillende bredbåndstjeneste

Den grundlæggende antagelse i vores skøn er at Starlink kan give tilfredsstillende bredbåndstjeneste til 40 restgruppeadresser per antenne-beam. Dette estimat er ikke eksakt idet der indgår et skøn for den *brugeroplevede* datarate i forhold til 100/30 Mbit/s bredbåndsmålsætningen.
Danmark er dækket af ca. 107 antenne-beams, hvilket giver potentiale for totalt 4.280 restgruppeadresser set over Danmark samlet set. Antages fordelingen i Tabel 1, for tilgængelige downlink- og uplink-datarater i 2023, at holde for SDFIs fremskrivning af restgruppen i 2025 med samlet omkring 20.000 adresser, vil der være omkring 10.000 adresser i restgruppen der kan få væsentlig gavn af Starlink (ca. 50% som gennemsnit for søjlerne '< 20 Mbits/s' og '< 2 Mbit/s' i Tabel 1). Antages det at disse adresser er ligeligt fordelt indenfor de enkelte regioner kan Starlink derfor levere en væsentlig forbedret, og tilfredsstillende, bredbåndstjeneste for omkring 40% af denne restgruppe (4.280 ud af 10.000 adresser), eller omkring 20% af den totale restgruppe på 20.000.

Der er væsentlig forskel fra region til region indenfor dette estimat, selv med antagelse om ligelig fordeling af den potentielle restgruppe indenfor hver region og at denne udgør samme andel i 2025. Tallene varierer fra region til region, inklusive for uplink og downlink andel, men simplificeret er der 50% af restgruppeadresserne i hver region med lavest datarate hvor Starlink vil kunne give en (væsentlig) forbedret bredbåndstjeneste. I region Hovedstaden kan der supporteres 280 adresser ud af den potentielle restgruppe på 3500, 50% af maksimalt 7000 adresser i SDFI's 2025 fremskrivning, hvilket svarer til 8% af denne gruppe. I de øvrige regioner kan Starlink give en væsentlig forbedring for et større antal adresser da restgruppen er spredt over et større areal, hvorved flere antenne-beams er aktive i det tilhørende geografiske område. For regioner uden for hovedstaden er de tilsvarende tal at Starlink er i stand til at levere en væsentligt forbedret bredbåndstjeneste for 40-85% af den potentielle restgruppe, størst i Region Nordjylland. Beregnes andelen af restgruppeadresser ud fra den totale restgruppe er tallene respektive 4% for region Hovedstaden og 20-42% for de andre regioner.

Fremskrivning af Starlink kapacitet og datarater

Starlink forventer at mere end fordoble antallet af satellitter fra de nuværende ca. 5.500 til 12.000 satellitter. På nuværende tidspunkt er Danmark dækket af satellitter med en bane hen over

Nordtyskland. Når satelliternes antenne-beams skal dække Danmark sker det fra en skrå vinkel, hvorfor beam'ets dækningsområde bliver udstrakt i forhold til det cirkelformede dækningsområde der opstår når satellitten befinder sig lige over området. Tilsvarende sker når der er få satellitter i en bane hvor antenne-beams skal dække i en skrå vinkel for at sikre dækning af områder mellem satellitterne. Begge dele forbedres med flere satellitter i Starlink-systemet. Arealreduktionen mellem et udstrakt dækningsområde på ca. 400 km^2 og et ideelt cirkelformet område på ca. 200 km^2, når satellitten befinder sig lige over dækningsområdet, giver en fordobling som en øvre grænse for fremskrivning af kapaciteten fra Starlink systemet over Danmark. Dermed er det teoretisk muligt at supportere det dobbelte antal adresser samlet set, dvs. omkring 80% af den potentielle restgruppe (den del af restgruppen der kan få væsentlig gavn af Starlink) eller 40% af den samlede restgruppe. Med hensyn til brugeroplevelsen forventes det ikke at dataraten forøges i downlink, men flere satellitter vil sikre at brugerens uplink-datarate kommer tættere på de maksimale ca. 30 Mbit/s.

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1 Introduction

This document describes the initial evaluation and analysis of data rate coverage from the Starlink constellation in Denmark with respect to the situation for the residual group (restgruppe) of broadband end users. The evaluation is based on publicly known characteristics of the Starlink system and some preliminary experimental tests. We first provide some gross estimates based on known Starlink characteristics and then discuss the results of an experiment from the location of Aalborg.

2 Starlink coverage in Denmark

Despite the lack of official information, there are several sources which have investigated essential characteristics of the Starlink system. Based on these some gross estimations can be made for the number of supported broadband users.

2.1 Supported number of users terminals

In 2021, the Starlink constellation had more than 2500 LEO satellites deployed [2], and by end of 2023, more than 5000 [3]. Currently, orbits with different orbital planes passing by the north of Germany, at an altitude of approximately 540 km, cover almost the whole country of Denmark. As indicated in Figure 1 there are several ground stations located in Germany. Having the possibility to connect directly from the LEO satellite to a ground station (gateway) is essential in terms of achievable data rates over the satellite link. Several polar orbits are passing over Denmark, but since there are no ground stations in the northern part [4], these are assumed to be intersatellite connected with low throughput.

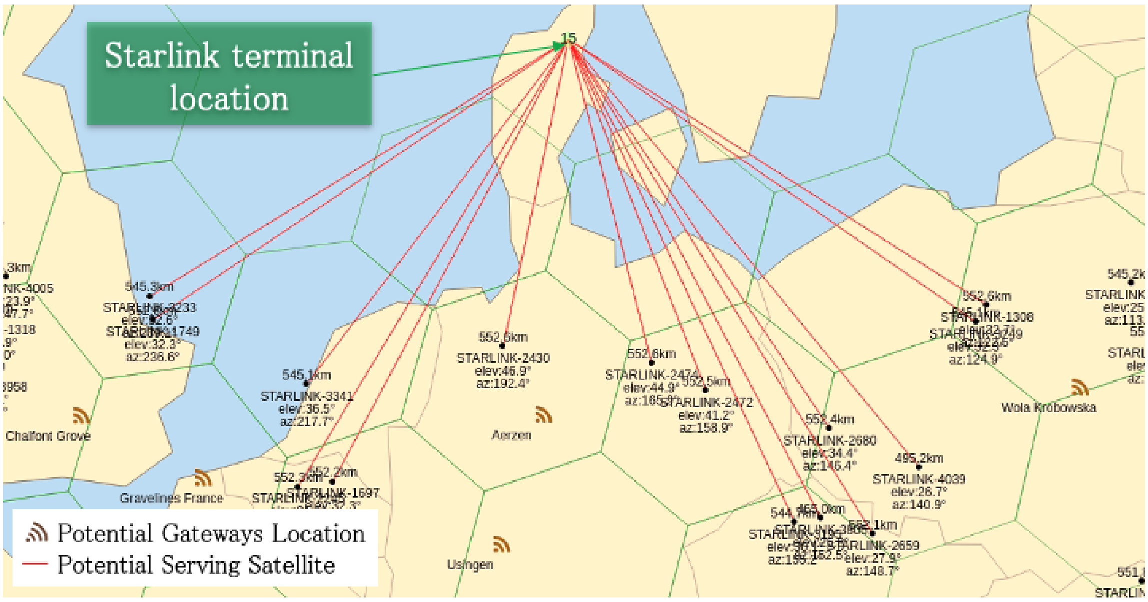

Figure 1. Example Starlink connectivity from Denmark, location of Aalborg, to the Starlink satellite constellation over Northern Germany; indicating locations of ground stations to which satellites convey the traffic from/to the terminal (generated from [4]; Resolution 2 Uber H3 cells).

The orbital passage has an average duration of approximately 7 minutes per satellite, therefore satellite-to-satellite handover occurs quite frequently when a terminal is connected to the Starlink constellation. All terminal-to-satellite connections are in the *Ku*-band: 10.7 - 12.75 GHz for downlink (from satellite to terminal) and 12.75 - 13.25 / 13.75 - 14.5 GHz for uplink (terminal to satellite). There are 8 channels in each direction, but different bandwidths of 250 MHz and 62.5 MHz, respectively (4 to 1).

Each satellite can project 48 downlink spotbeams on the surface of the earth, and 16 uplink spotbeams. At nadir, a spotbeam covers approximately one H3 cell resolution 5 of average area 252 km2[5] [5] with an almost circular footprint. However, due to the slant angle when viewed from Denmark, with no overhead satellite constellation, the beam footprint becomes elongated elliptical (beam spread). This means, as an example, that the beam footprint in the Copenhagen area covers multiple H3 cells (Figure 2), with the capacity in a single beam divided over a larger area.

How many resources are dedicated to a single area is difficult to say – in principle, multiple beams can cover – and depends on channel reuse patterns (to control interference), resource policies (time share dedicated to a single cell), customer data plans (average data rate capping), etc., but for simplicity and approximate calculation, in agreement with typical assumptions, we will assume that one beam is dedicated 100% to cover a given area. In the Capital Region the beam footprint is approximately 377 km2, or 1.8 H3 cells in Figure 2, and with a total area of 2568 km2 this area will have the capacity from 7 beams (≈ 2568 / 377, cf. Table 1).

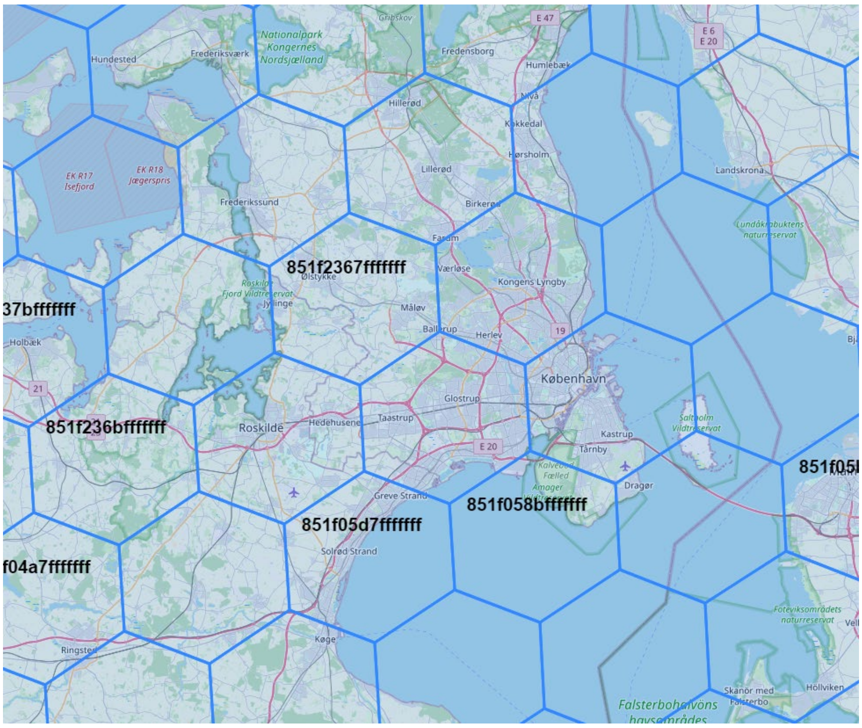

Figure 2. Resolution 5 Uber H3 cells in the Copenhagen area [6]; each cell at this location is approximately 207 km2.

[5] The average cell size of Uber's hexagonal cell system H3 varies around the globe.

Although there are eight different channels available on each satellite, not all are used at the same time, and due to regulatory constraints, no cell can have coverage from two beams (from two different satellites) on the same channel. In the following, we will assume that only one 250 MHz channel is used in each cell with a peak capacity of 417 Mbit/s [5][6]. With some gross approximations, and busy hour assumption, a certain portion of that is available for time sharing between terminals on the ground (Appendix A).

If each terminal has a requirement for 10 Mbit/s average downlink data rate, and a responsive broadband experience during busy hour, somewhere between 21 and 42 (theoretically) terminals can be served at the same time. Taking the example of 37 terminals for a good broadband connection (see assumptions in Appendix A) it is quite clear that Starlink is a solution only for sparse terminal distributions: The equivalent user density at 37 terminals is approximately 1 user per 10 km2, assuming the average beam footprint of 400 km2 across Denmark.
To accommodate customers in the residual group [7], an overprovisioning factor between 21 and 27 is needed in the Capital Region (5500 – 7000 users share 7 times 37 broadband connections), i.e., minimum 21 customers are required to share the broadband experience or only every twentieth customer gets the broadband experience at the same time. At the other extreme, for the Northern Jutland Region, the overprovisioning factor is approximately 2.5 and therefore almost every second customer can get the broadband experience.

Region	Area (km2)	Beam footprint (km2)	No. beams	No. broadband connections (busy hour)	No. users to share broadband experience
Capital	2568	377	7	259	21 - 27
Sealand	7273	377	19	703	5
Northen Jutland	7933	504	16	592	2.5
Central Jutland	13053	412	32	1184	3
Southern Jutland	12191	302	40	1480	3
Denmark	42952	400	107	3959	4.5 - 5

Table 1. Supported broadband connections (terminals) in different regions and the approximate overprovisioning factor required for the respective residual groups [7] assuming 37 terminals per antenna beam (see text); for assumptions, see Appendix A and Appendix B.

[6] Whereas a single terminal likely handles only one channel, eight channels allow the projection of eight spot beams onto a single cell simultaneously, or all 8 channels active in a single beam, increasing cell capacity by a factor of 8. However, as per assumptions in [14], we assume that only one channel is active at a time within a given cell due to inter-cell interference management (neighboring cells are each serviced with different channels).

We have assumed an average data rate of 10 Mbit/s, with traffic delivered in bursts with short latency, assuming this can qualify for a satisfactory broadband service. The peak data rate per Starlink data frame in this calculation is assumed to be 417 Mbit/s, which can be achieved reliably due to the downlink link budget and one-to-many time-division multiplexing channel (see test results in Section 4). The broadband connections and the resulting overprovisioning factor in Table 1 is based on 37 terminals per beam. For a mix of different services, with different and often more relaxed service requirements, a number between 37 and the theoretical maximum of 42 is probably more realistic. In case we have assumed 40 terminals (users) to be served by one beam, the numbers in Table 1 change proportionally, e.g., with this assumption Starlink can serve 259 × (40/37) = 280 terminals in the capital region at 10 Mbit/s, improving slightly the overprovisioning factor to the range 20 – 25.

For comparison to the numbers listed above, estimations in [8], based on generic spectral efficiency estimates for satellite services and all eight channels available with frequency reuse 2, suggest that Starlink can provide a mean user capacity of 25 Mbit/s for a user density of 1 user per 10 km2 during busy hour, and a significant drop to 2.5 Mbit/s if the user density increases to 1 user per km2.

Numbers for uplink are more difficult to estimate due to the impact from limitations in the link budget (see test results in Section 4). For what concerns achievable peak data rates, given the bandwidth ratio of 4, the peak data rate in uplink is 417 Mbit/s / 4 ≈ 104 Mbit/s. But, since there is only one third the number of beams in uplink compared to downlink, we will assume a time-division multiplexing factor of 3 on uplink so that the maximum achievable average data rate is about 34 Mbit/s. Whereas, theoretically, customers can enjoy peak uplink data rates of 104 Mbit/s, and in practice much less as illustrated in Section 4, due to the fact that there is only 34 Mbit/s to share on average, the 37 terminals supported in downlink at 10 Mbit/s would have to be content with 0.8 Mbit/s in uplink.

3 Impact from weather conditions

In reference [9] authors collected data from several end users, in the UK and internationally. They observed several sources of variability, particularly impact from satellite handovers and weather conditions on the response time of the network. The packet losses and associated delay in delivering information via a Starlink connection can affect more delay sensitive services. For instance, the authors observed that the difference between clear sky and light rain conditions meant a doubling of the page refresh time in a web browsing session. They also observed strong evidence that the regular and quite frequent handovers lead momentarily to high packet loss, whereas there was no immediate observable impact on the throughput (average data rate) from a user perspective.
A more recent study from the Netherlands/Germany [10] found that the impact of precipitation on downlink throughput is clear (significant), but not on uplink throughput. The study also shows, however, that other (unexplained) factors impact on the throughput and the observed decrease in throughput with increasing precipitation, and overall, the decrease is relatively small.

Another interesting observation of relevance to the Danish case, from the study in [9], is that they observed major geographic variations in achievable data rates which they attributed to the number of subscribers in the respective areas – the more recent introduction of the Starlink service, the lower number of subscribers and the higher attainable throughput per subscriber. This indicates that there is no strict service guarantee for the broadband experience over Starlink but rather that it depends (also) on how many users want to be served in each region.

4 Tests on Starlink coverage

Several tests have been made to investigate the achievable throughput via Starlink from the location of Aalborg. The tests have been made in a static open (roof top) position over time durations of 1 hour, 3 hours and 24 hours, with no precipitation; results for 24 hours are given in this document which reflect the case of the shorter tests. The details of the experimental approach are described in [11]. The main characteristic is that a set amount of traffic is requested in both uplink and downlink directions simultaneously, respectively default 30 Mbit/s uplink and 100 Mbit/s downlink.

4.1 Test configuration

A commercial Starlink Residential Generation 1 terminal was used with the antenna placed on the roof of a building at approximately 10 m height facing the South (Figure 3). The roof position gives the antenna an almost unobstructed view towards the Starlink satellite constellation over Northern Germany.

Figure 3. Starlink Residential Generation 1 antenna at test location in Aalborg, Fredrik Bajers Vej 7, Aalborg Øst, facing south.

4.2 Test results for downlink and uplink throughput

In the following results, we show the “instantaneous” throughput values over a 24-hour observation interval, with requested data rates of 100 Mbit/s downlink and 30 Mbit/s uplink as per the broadband link requirements [7]: The throughput was measured over 1 s intervals using *iPerf3*[7], hence "instantaneous" corresponds in reality to a 1 s averaged value. From a user perspective, a 1 s average gives a good indication of the "instantaneous" experience, but it also leads to some artifacts in the results. For this reason, we also show the 5 s averaged values which could further indicate how the Starlink connection impacts application performance, e.g., video playback with buffering.

4.2.1 Downlink and uplink throughput statistics 24 hour

4.2.1.1 Downlink

Figure 4 shows the cumulative distribution function of the achieved 1 s and 5 s averaged results, with selected percentile statistics summarized in Table 2.

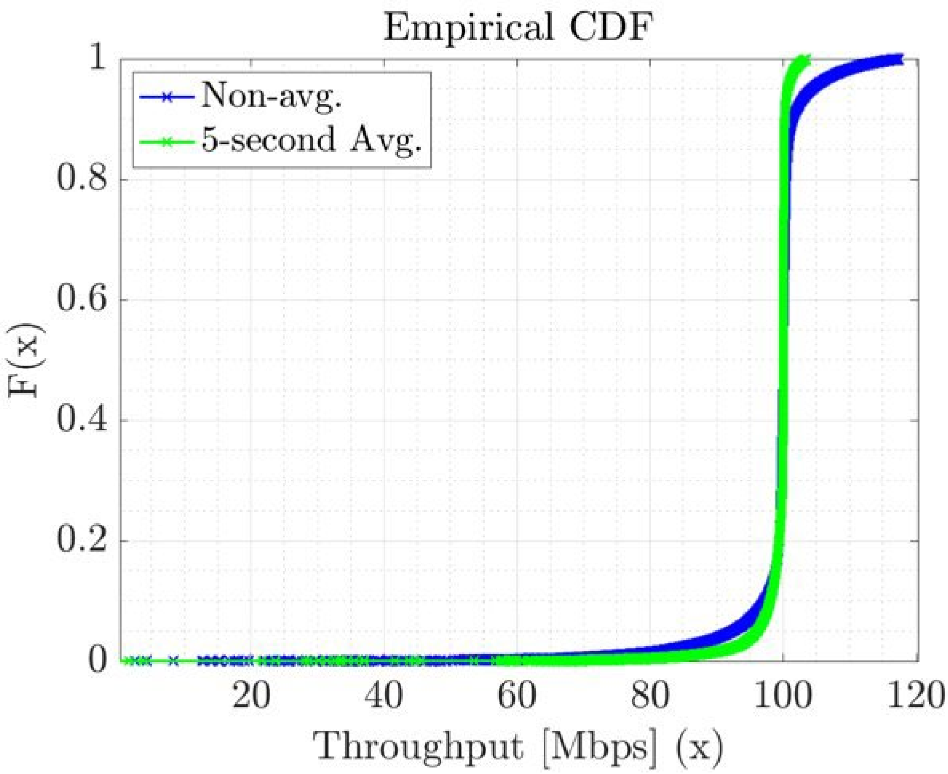

Figure 4. Cumulative distribution function for downlink throughput (1 s and 5 s averages).

[7] Distributed under BSD license.

Percentile	Throughput [Mbit/s] Non-Avg.	Throughput [Mbit/s] 5-seconds avg.
1%-ile	74.6	86
10%-ile	97.1	98
50%-ile	100 Mbps	100

Table 2 Downlink throughput statistics for 24 hour tests – 1 s and 5 s intervals.

Downlink throughput exhibits stable performance with almost no difference between 10 and 50 percentile values, irrespective of the averaging; over 1-hour intervals tests show even closer percentiles. Averaging only impacts at low percentiles, helping to conceal the intermittent link interruptions to the end user application. The median throughput is almost identical to the requested (offered) throughput of 100 Mbit/s.

4.2.1.2 Uplink

Figure 5 shows the cumulative distribution function of the achieved 1 s and 5 s averaged results, with selected percentile statistics summarized in Table 3.

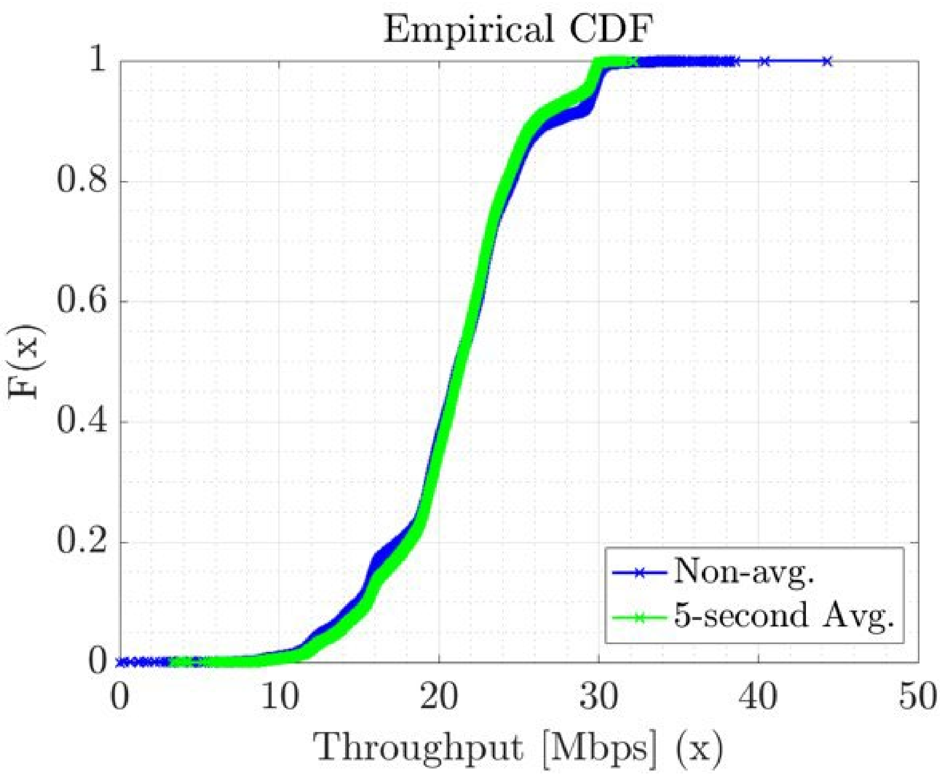

Figure 5 Cumulative distribution function for uplink throughput (1 s and 5 s averages).

Percentile	Throughput [Mbit/s] Non-Avg.	Throughput [Mbit/s] 5-seconds avg.
1%-ile	10	10.8
10%-ile	15	15.5
50%-ile	21.3	21.4

Table 3 Uplink throughput statistics for 24 hour tests – 1 s and 5 s averages.

Averaging has no major effect to uplink throughput. From the distribution, the most noticeable difference to downlink is that uplink throughput varies considerably, with achieved "instantaneous" median throughput 30% below the requested value. For uplink, the 1-hour results are identical.

4.2.2 Downlink and uplink throughput traces

Figure 6 shows the time averaged traces of the downlink throughput. As we observed from the statistics, the throughput is stable close to maximum throughput. Most of the time the "instantaneous" throughput meets the requested throughput, and only occasionally it drops below; generally, the momentary deviations up and down, and particularly up, are a result of the *iPerf3* measurement method (buffering of UDP traffic whenever the service is unavailable) and should be ignored. Despite the seemingly many drops in throughput, 90% of time it is above 98 Mbit/s.

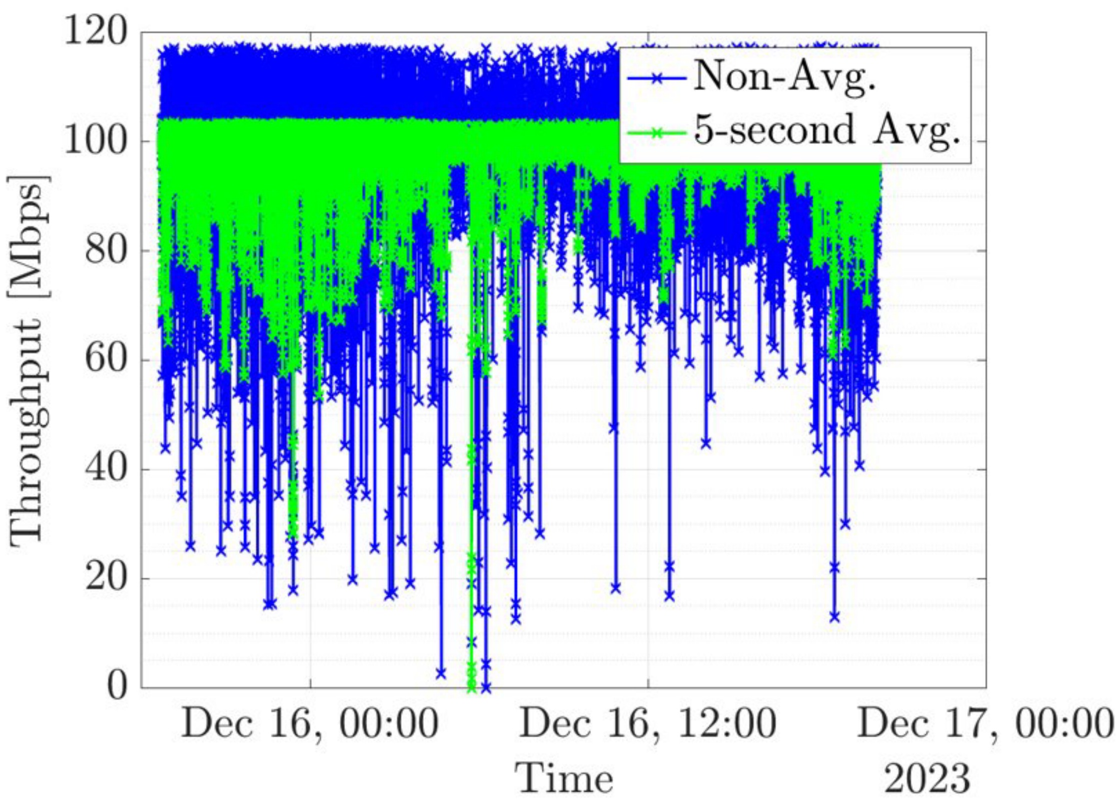

Figure 6 Time trace of downlink throughput (1 s and 5 s averages).

Figure 7 shows the uplink throughput trace over 24 hours. In uplink the variations are so pronounced that averaging has minimal effect. Although it seems, like the downlink case, that a 30 Mbit/s throughput can be achieved, it only exceeds 21 Mbit/s 50% of the time (same as the average throughput due to the distribution symmetry), and 25 Mbit/s 10% of the time. The maximum of the 5 s averaged time trace fits well with the requested throughput of 30 Mbit/s.

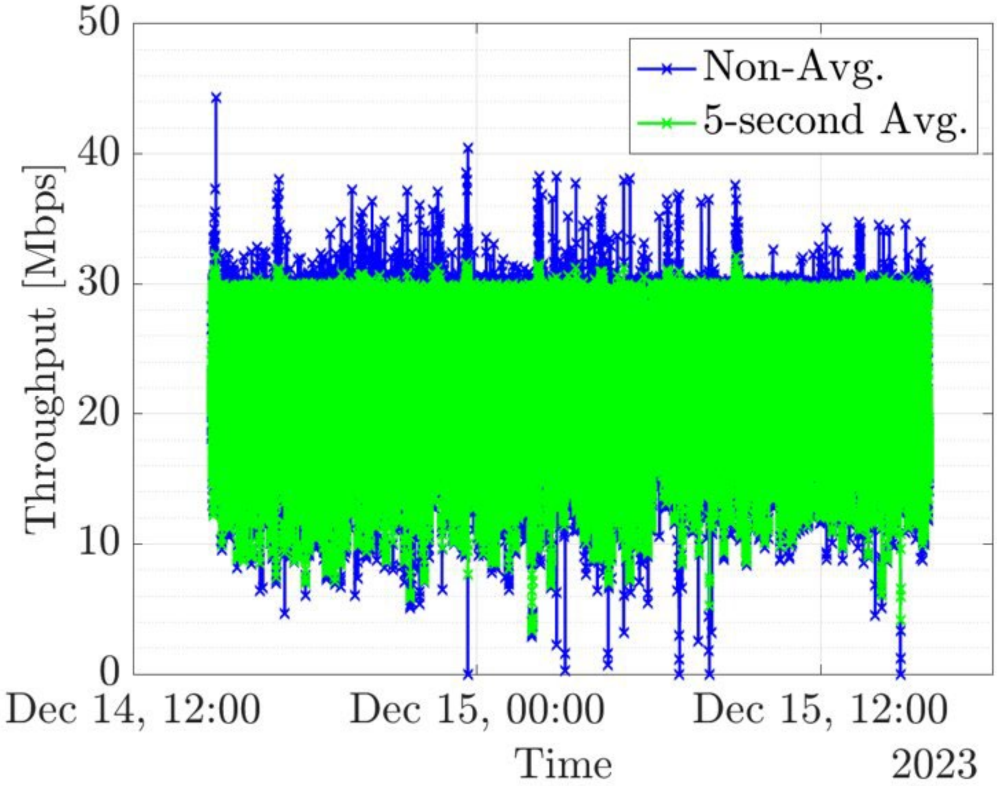

Figure 7 Time trace of uplink throughput (1 s and 5 s averages).

4.2.3 Link saturation throughput

Two tests were conducted to investigate the saturation of the downlink and uplink throughput. During the first test, 1-hour tests were conducted with a requested downlink data rate of 400 Mbit/s and uplink 200 Mbit/s.

For uplink, the statistics are almost identical to the 24-hour throughput statistics at lower requested data rate, cf. distribution in Figure 8 and time trace in Figure 9. Of particular interest is the throughput at the start of the time trace in Figure 9 where up to 55 Mbit/s is achieved "instantaneously" and 5 s averaged. It is believed that Starlink dedicates an uplink beam at the start of the connection and then fallback to the time-division multiplexing to account for the ratio between uplink and downlink beams, c.f. Section 2.1. Hence it shows that it is possible for the uplink to reach throughputs nearing 100 Mbit/s, although from this location somewhat lower due to limitations on the uplink link budget. After the initial transient, the throughput is considerably reduced and achieves at the median level the same as in the tests reported in Section 4.2.1.2 –

around 21 Mbit/s. This seems to confirm the resource multiplexing/sharing assumed in Section 2.1 which would cap the maximum achievable throughput at around 34 Mbit/s.

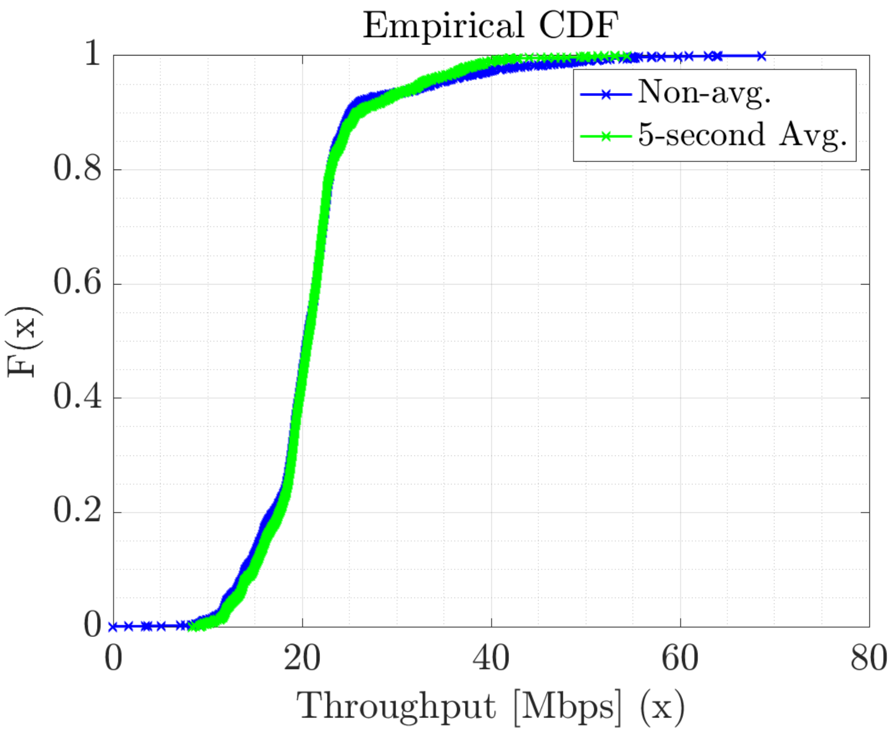

Figure 8 Cumulative distribution function for uplink throughput (1 s and 5 s averages); median values are 20.5 Mbit/s (1 s averaging) and 20.6 Mbit/s (5 s averaging); requested uplink throughput 200 Mbit/s.

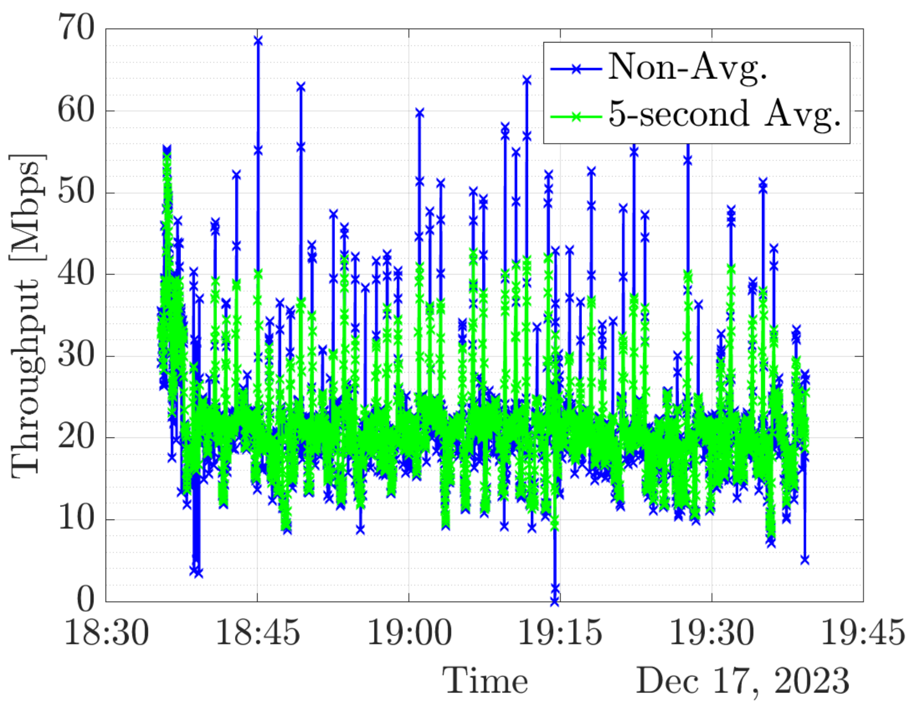

Figure 9 Time trace of uplink throughput (1 s and 5 s averages); requested uplink throughput 200 Mbit/s.

For downlink the test revealed that saturation was not achieved (median of 398 Mbit/s achieved when 400 Mbit/s requested) and therefore another, shorter, 15 minutes test at high requested data rate (700 Mbit/s) was conducted. The result in Figure 10 and Figure 11 shows that a peak data rate of approximately 420 Mbit/s was achieved. This maximum corresponds well with the assumption of 417 Mbit/s in Section 2.1.

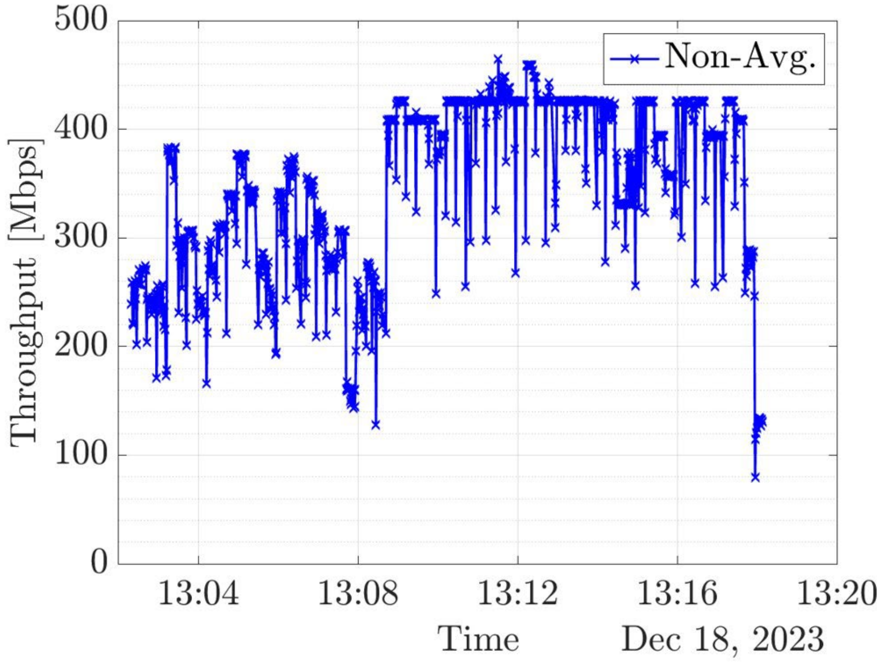

Figure 10. Downlink throughput trace at 700 Mbit/s requested data rate (1 s averaged throughput).

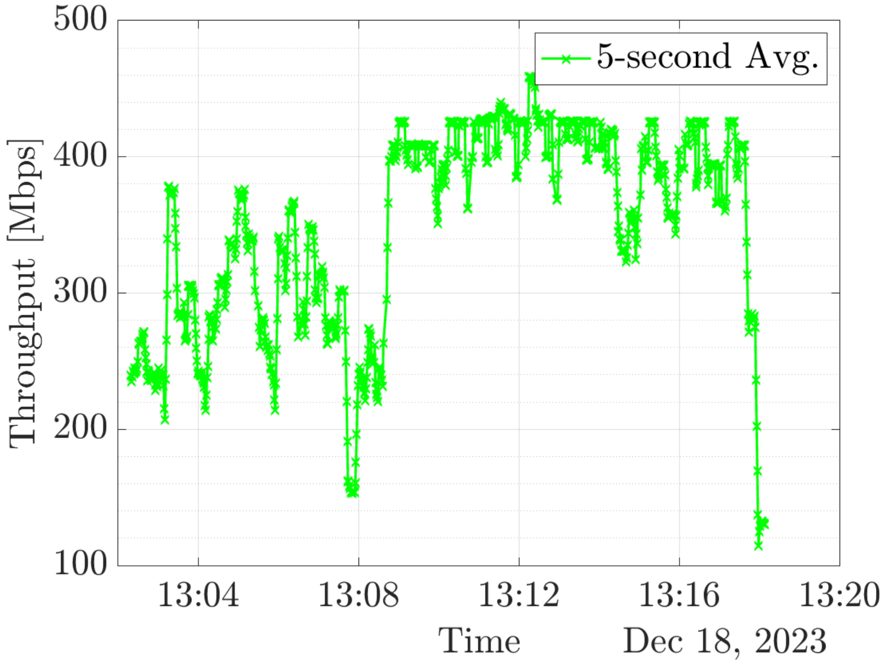

Figure 11 Downlink throughput trace at 700 Mbit/s requested data rate (5 s averaged throughput).

4.3 Summary

The experimental results show that a 100 Mbit/s throughput is achievable in downlink, and even 420 Mbit/s. These are likely single user per beam results but illustrate that it is possible to get the peak data rate in downlink, and a corresponding share depending on the number of users. Speed tests reported in [12] for European locations, analyzed for the period 2021 – 2023, show a median of 150 Mbit/s.
Uplink seems to be the limiting factor in delivering a 100/30 Mbit/s broadband experience, mainly since there is little uplink cell capacity to share. Peak data rates of 100 Mbit/s are possible, but our results show a clear limitation of the median throughput at around 21 Mbit/s, assumed due to time-division multiplexing of the uplink beam resources in combination with limitations on the uplink link budget. In comparison, speed tests reported in [12] show a median of 21 Mbit/s for European locations. Also, throughput varies considerably over time and may therefore have more subtle impact on broadband experience than just achievable mean throughput.

Even just considering downlink from our theoretical calculations, it is obvious that Starlink is only a solution for very sparse terminal distributions – the calculated equivalent terminal/user density is approximately 1 user per 10 km2: For the most sparsely populated region, Northern Jutland, and the one with fewest users in the residual group, almost only every second customer can get the 100 Mbit/s broadband experience, under the assumption that these users want the broadband experience at the same time (busy hour), and they would have to share a limited uplink capacity.

5 Tests on single/multi-user application experience

Another set of tests were made to investigate the user experience in different applications and with different number of concurrent users and/or different combinations of services.

5.1 Test configuration

Two commercial Starlink Residential Generation 1 terminals and one Generation 2 terminal were used for this test, all with antennas placed on the roof of the building shown in Figure 3 and spaced approximately 1 meter apart.

Tests were conducted with a WiFi connected client as the default. A separate uplink/downlink throughput test showed no difference between a WiFi connected client and a cabled ethernet connected client for this setup.

For the single-user multi-service test in Section 5.2 one of the Starlink terminals was used, and for the multi-user tests in Section 5.3 all three terminals were used but in different combinations. All terminals are in the footprint of the same beam.

5.2 Test results for single-user experience

Figure 12 shows the single-user gaming experience according to typical gaming traffic of 64 1500-byte packets per second (average data rate of approximately 1 Mbit/s). Latency is measured as the round-trip time, using a ping test (ICMP protocol). The tolerable latency for most gamers can vary over quite a wide range, up to 100 ms, although some sources (e.g., intel) claim that performance degrades beyond 50 ms. The average latency measured in our tests, over one million samples, is 78 ms and thus in the acceptable range. The tests were conducted with precipitation (rain and snow) and overshadowed conditions. Performance is rather stable, with 90% of values are below 99 ms and a mere 17 ms standard deviation, which seem to contradict the results from [9] in which weather conditions led to occasionally long response times.

When the ping test is run simultaneously with a 100 Mbit/s download (as in Section 4.2), the latency results seem unaffected, and actually improve slightly, c.f. Figure 13. The reduction might be related to the resource allocation in the Starlink system since the small ping load benefits from already allocated resources ("piggybacking"). The download is unaffected by the concurrent ping test (gaming application).

	Non-Loaded Latency [ms]	Loaded Latency [ms]
Mean	78.8	64.6
Median	76.5	62.5
Std. Dev.	17.3	16.4
Max.	472	485
90%-ile	98.9	79.5

Table 4 Latency statistics with/without simultaneous 100 Mbit/s download.

The objective, quantified, tests in Table 4 were complimented with subjective multiservice tests in which online gaming was running alongside a combination of two of three possible simultaneous services – video streaming, video calls, and online editing of documents. Subjective evaluations were made by two different gaming experienced users.

From their experience, 20-40 ms latency is considered optimal for gaming purposes while below 20 ms is exceptional and 50-100 ms is acceptable. Via Starlink it is possible to get quite steady latency, in the acceptable interval, for well-optimized games, even when other services such as video call run simultaneously (see Appendix C); the presence of other simultaneous services did not make any substantial difference to the overall experience. This, however, applies when the game pace is slow. When the pace picks up, and it requires fast reaction times, for example when driving a fast vehicle or fighting opponents, the latency is very noticeable and greatly degrades the experience.

In some few instances, latency can increase sharply making even slow-paced gaming challenging and making it completely impossible to react quickly. For instance, a period of 1 - 2 minutes with high latency was experienced during the tests, where user input was delayed by one or several seconds. The overall conclusion from the two users is that gaming is possible but may not be enjoyable over Starlink, and for competitive gaming you will have a large disadvantage due to the latency and occasional latency increase.

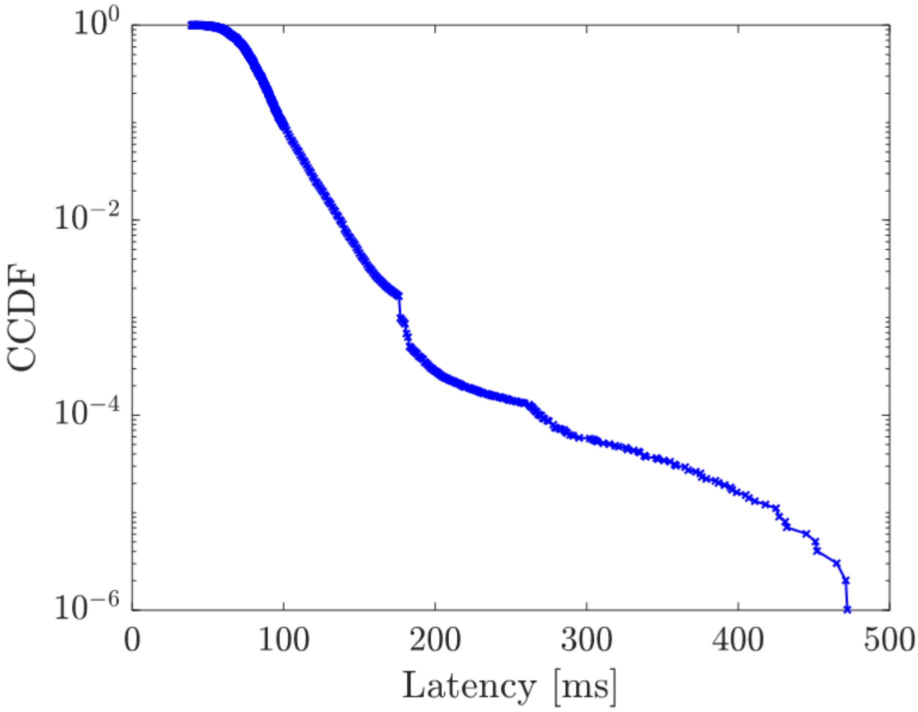

Figure 12 Cumulative distribution function for ping latency (round trip time); the distribution mean is 78 ms (same as median) with 90% of values below 99 ms (standard deviation 17 ms).

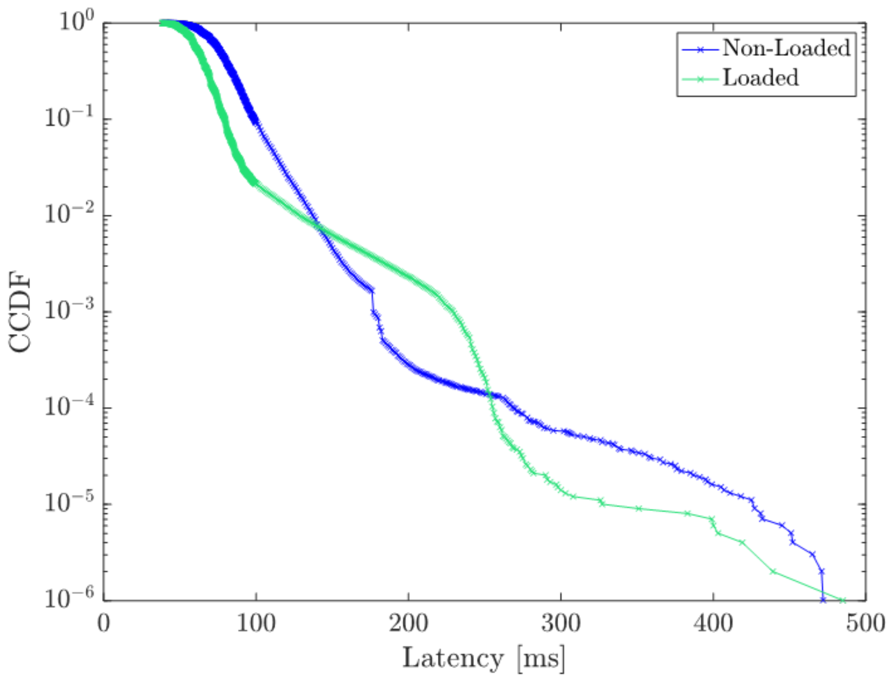

Figure 13 Cumulative distribution function for ping latency (round trip time) under load; the distribution mean is 65 ms (same as median) with 90% of values below 80 ms (standard deviation 16 ms).

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5.3 Test results for multi-user experience

Figure 14 shows the throughput experienced by a single user when one or two other users are active within the same beam, all requesting 100 Mbits/s in downlink. Largely, the throughput is unaffected since the user's requested data rate can be accommodated within the available beam capacity. Figure 15 shows the individual user throughputs when all three are active at the same time. The lower tails of the distributions are different from the similar case in Figure 14 ('3-Users'), but in terms of median throughput the result is the same.

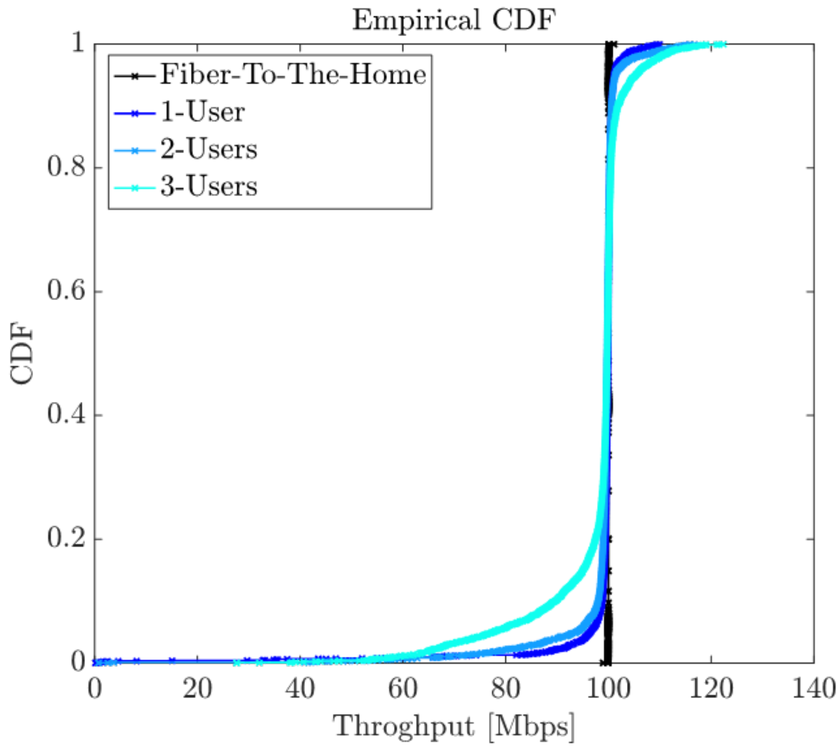

Figure 14 Cumulative distribution function for downlink throughput (1 s averages) when other users (1 or 2) are connected in the same antenna beam.

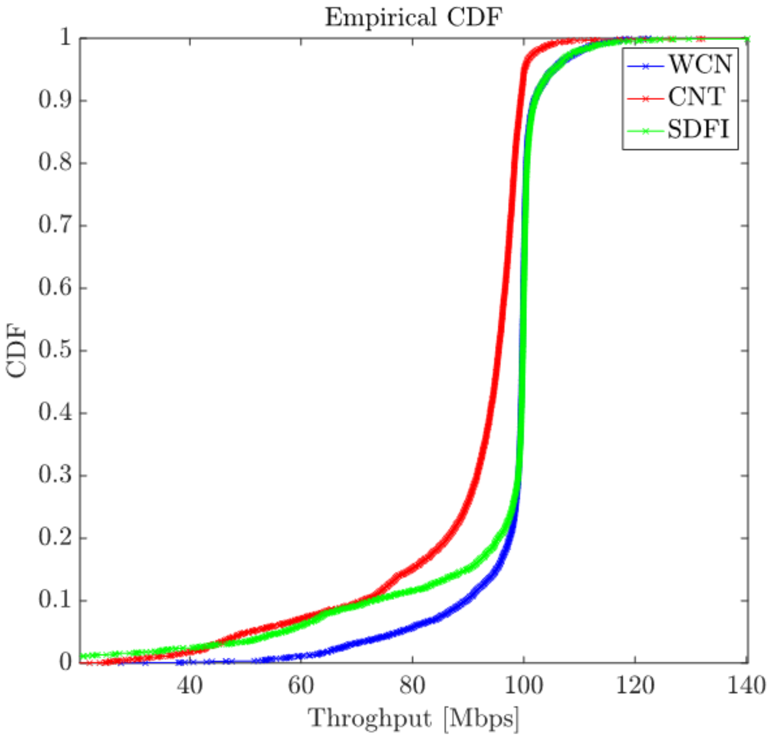

Figure 15 Cumulative distribution function for downlink throughput (1 s averages) for three simultaneous users connected in the same antenna beam (individual user throughput distributions).

The comparable results for the uplink case are shown in Figure 16 and Figure 17, when all users are requesting 30 Mbits/s in uplink. The distributions show more variation, as seen previously in Section 4.2.1, but they are also different between users, specifically for the user on the second-generation terminal. When we measure the individual throughputs, Figure 17, the shape of the distributions becomes even more skewed, giving the impression of much lower throughput for particularly the SDFI terminal (e.g., 50% median value at approximately 2 Mbit/s). However, the distributions are heavy tailed which makes the mean values higher: From a beam capacity point of view the available capacity ought to be split approximately according to 15 Mbit/s each for two users and 10 Mbit/s each for three users; however, each of the three users will still face the uplink link budget limitation[8] in trying to achieve 30 Mbit/s and therefore split according to the single-user data rate, i.e., the mean achieved data rate in Figure 5 and Figure 8 (where mean is close to median), leading to mean data rates of 11 Mbit/s for two users and 7 Mbps for three users. The actual achieved (short term mean) data rate is probably somewhere in between the two estimates, depending on how the user is scheduled by Starlink when requests are made. In the experiments we have seen mean data rates for three users varying between 7 and 10 Mbps.

For the results in Figure 16 and Figure 17 the second-generation terminal had a Starlink Roam subscription (mobile), whereas the first-generation terminals had a Starlink Residential (fixed)

[8] It is generally assumed, for downlink and uplink, that Starlink schedules users in bursts according to time-division principles, whereby also users requesting lower average data rates will face link budget limitations on their uplink transmissions.

subscription. By design, Starlink makes quality-of-service differentiation between the two, down-prioritizing the Roam subscription, which is believed to be the explanation for the different distributions. The tests were repeated after changing all three terminals to Residential subscriptions, with the effect that the distributions look more the same and with the median more equal to the mean (symmetrical distribution).

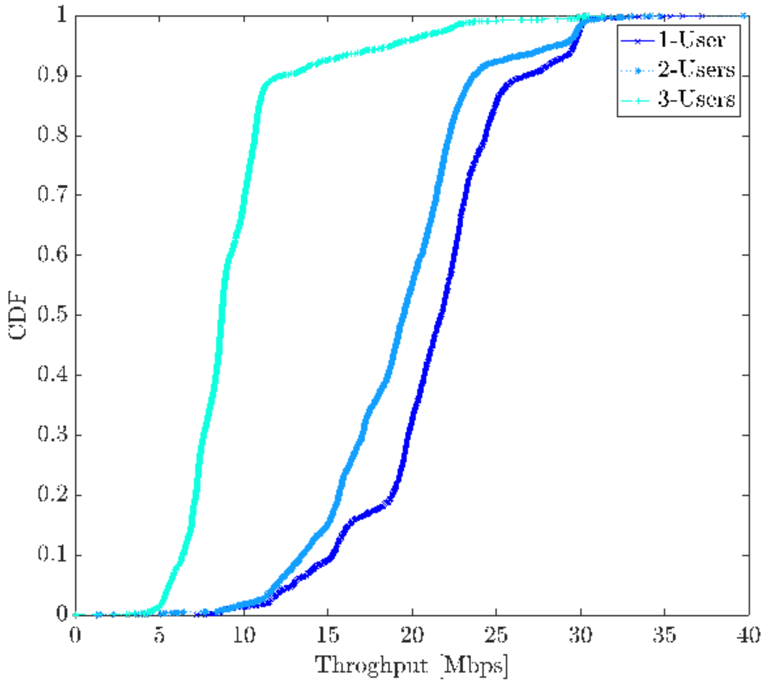

Figure 16 Cumulative distribution function for uplink throughput (1 s averages) when other users (1 or 2) are connected in the same antenna beam; the single user case is similar to Figure 5.

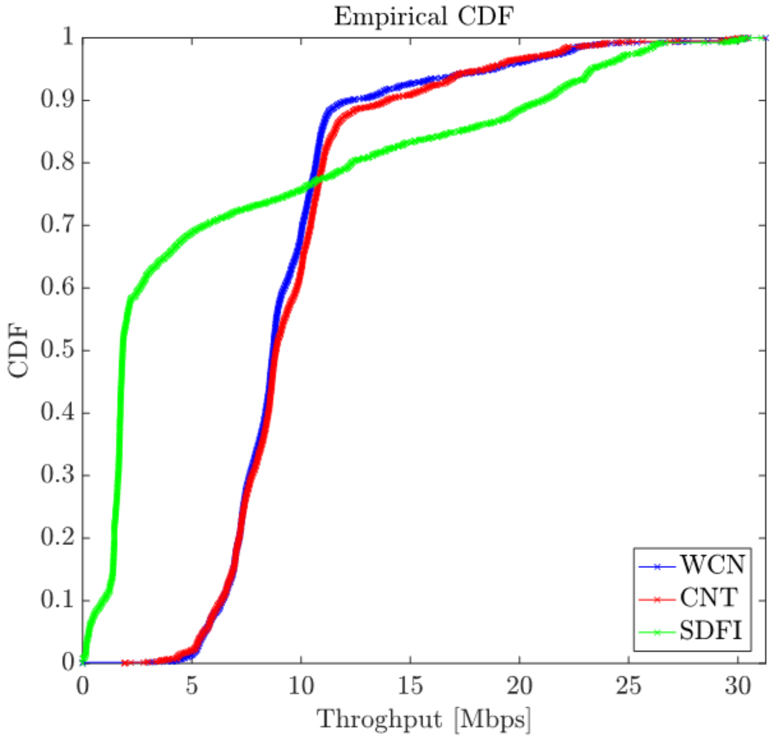

Figure 17 Cumulative distribution function for uplink throughput (1 s averages) for three simultaneous users connected in the same antenna beam (individual user throughput distributions).

5.4 Summary

Subjective and objective tests of running different services over a single user connection revealed that Starlink does not degrade the experience of the service, expect for competitive gaming where longer latencies will be a disadvantage to the user. This is somehow expected given the LEO satellite connection with its inherent longer delays in communication. Based on published results, weather conditions impact the broadband experience, however, the present tests for single-user, multi-service, user experience under precipitation did not show large variations in latencies or other subjective performance degradation.

Multi-user tests, with three Starlink terminals within the same antenna beam coverage, confirmed that the throughput splits with the number of users. For downlink, tests were conducted with a requested data rate of 100 Mbit/s per user, hence with no effect to the actual throughput since the total is below the beam capacity. Similarly, the uplink throughput is expected to split approximately according to the total maximum beam capacity of 30 Mbit/s, however, splits according to the achieved single user throughput of approximately 21 Mbps; presumably, due to the scheduling in the Starlink system, users will face the uplink link budget limitation irrespective of the number of users, but the actual achieved (short term mean) data rate is probably somewhere in between the two cases, depending on how the user is scheduled by Starlink when requests are made. The throughput distribution in uplink behaves very different from downlink, having very skewed and heavy tailed distribution. It has not been possible to determine the exact reasons for this behavior except that the Starlink subscription has a clear impact.

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Appendix A Capacity calculation and assumptions

From information in [5], the maximum downlink capacity per beam is 417 Mbit/s[9] if the satellite has direct gateway connection (with inter-satellite connection this number is much reduced). If one assumes that data is serviced to terminals in bursts at the peak throughput of 417 Mbit/s, i.e., in a time-division multiplexing fashion, the required duty cycle[10] for 10 Mbit/s average data rate is 10/417: This corresponds to one Starlink data frame, 1.33 ms, delivered at peak throughput every 55 ms. For illustration and example, the following considers streaming versus live video transmission at 10 Mbit/s.

For a streaming service the average data rate is high but with some fluctuations over time due to the variable rate video encoding (see Appendix C). Since streaming is non-real time, typically there is a buffer at the client side of up to 5 seconds to absorb variations in the available maximum throughput (carried traffic) on the communication link. Besides making the video playback continuous at the user side, we can also assume that the buffering absorbs the statistical variations in the actual carried traffic from multiplexing many users in a single beam. Therefore, to calculate the number of served users it is reasonable to simply divide the beam capacity by the required average throughput of the streaming service; thus, for 10 Mbit/s streaming, Starlink can accommodate approximately 42 users per beam.

For a live video transmission, data needs to be delivered with time constraints and any violation of this will degrade the delivered service. To make sure that data are delivered in time it is necessary to lower the number of served users to be able to handle the statistical variations from multiplexing many users in a single beam. As a simple approximation/illustration of the impact, we can assume an Erlang C (m/m/1) queuing system which delays packets until delivery is possible (blocked calls delayed). In case we were to utilize only half of the maximum beam capacity, i.e., 50% total offered traffic, 95% of (packet) bursts will be carried within 2 Starlink frames (with an average delay of one third of the frame). Thus, although theoretically the duty cycle constraint allows 417/10 ≈ 42 users to be served, with the service level constraint only half can be accommodated, i.e., about 21 at 10 Mbit/s average data rate. With a relaxed service requirement, and more reasonable for a live video transmission, requiring that 99% of all (packet) bursts are serviced within 55 ms, we can utilize 88% of the theoretical capacity and accommodate 37 users (with an average delay of 8.5 frames).
From this, we see that even with a stringent requirement of having a 10 Mbit/s average data rate live video transmission delivered in (packet) bursts every 55 ms, and 99% of them delivered in time, the number of served connections drops only from 42 to 37. This is an indication of the high trunking efficiency/gain of Starling, i.e., having a high total beam capacity available to serve a large number of users.

[9] Based on information in [14], 417 Mbps corresponds roughly to 16 QAM at coding rate 0.5 in each of 1024 subcarriers and 302 symbols per 1.33 ms frame, accounting for subcarrier (1000/1024) and symbol (294/303) overhead.

[10] Also known as channel occupancy, i.e., the offered traffic in Erlang equal to arrival rate times holding time.

Appendix B Satellite visibility and beam projection

Based on the satellite information provided in [4], and assuming connections are made to the Starlink satellite constellation over Northern Germany, the beam projection (beam footprint) can be calculated for the different regions of Denmark, c.f. Table 5.

Region	Home location (lat., long.)	Azimuth (degrees)	Satellite elevation (degrees)	Slant range (km)	Beam footprint (km2)
Capital	55.685756, 12.546284	130 - 225	50 - 60	659	377
Sealand	55.537669, 11.822215	130 - 225	50 - 60	659	377
Northen Jutland	57.048353, 9.972234	150 - 200	45 - 50	723	504
Central Jutland	56.240234, 9.338581	140 - 210	50 - 55	678	412
Southern Jutland	55.266544, 9.082166	130 - 225	60 - 65	614	302

Table 5 Satellite visibility in different regions of Denmark based on the North Germany Starlink satellite constellation; satellite information based on [4] with approximate azimuth and elevation ranges as seen from the home location. Slant range is calculated based on the average satellite elevation and the average height of the constellation (approximately 550 km) using the expressions in [13].

For the calculations, the satellite spot beam is calibrated to cover a size H3, resolution 5, cell at nadir in the Northern part of Germany, corresponding to a cell area of 215 km2: at an assumed average height of 550 km this leads to a beamwidth of 1.72 degrees (beam solid angle of 0.041 degrees).

The slant range is calculated based on the average satellite elevation and the average height of the constellation using expressions in [11]. Whereas the calibration footprint is circular, the beam projection becomes elliptical at slant angle (a conical section) with an increased footprint. Given the slant range and the beamwidth, using vector calculus, one can calculate the conical intersection between the radiating beam and the local plane, and thus the area of the conical section. The resulting footprint varies across Denmark and reaches 504 km2 in the Northern part of Jutland where the satellite constellation over Northern Germany is seen at the lowest elevation angles. The calculated footprint in Northern Jutland is shown in Figure 18; it measures 21.7 km East-West and 29.5 km North-South. Due to the beam spread, the beam center and the center of the ellipse are slightly off (beam center marked by a red asterisk).

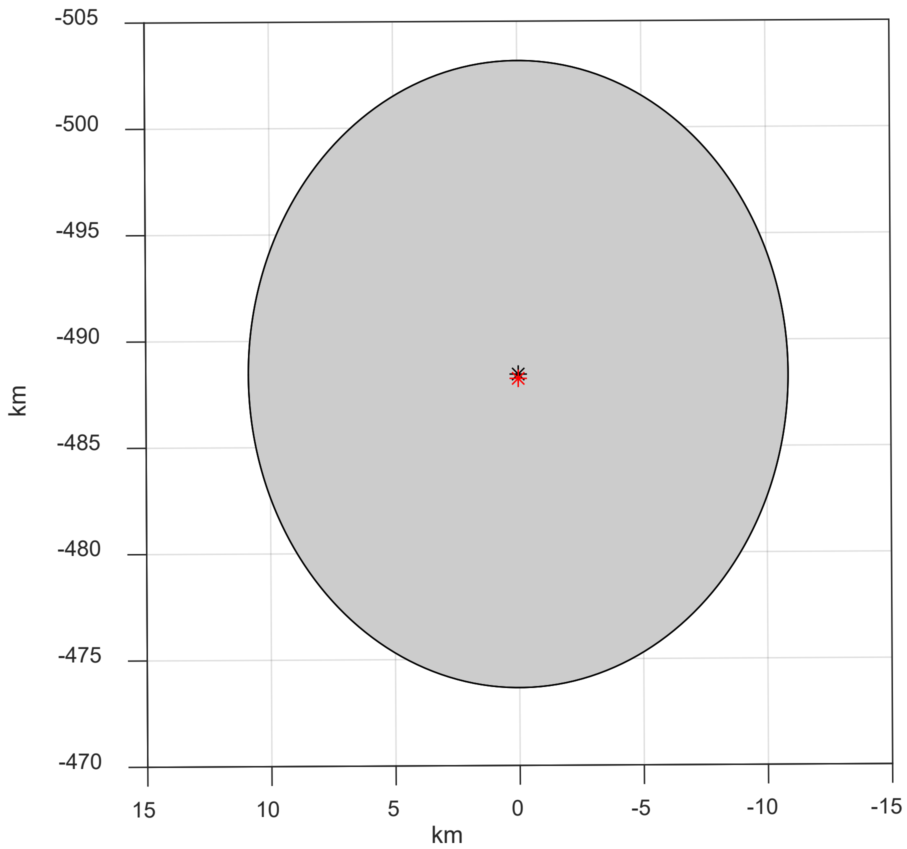

Figure 18 Example beam projection (footprint) in Northern Jutland (504 km2); scale offset is to an arbitrary reference frame.

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Appendix C Video call through Starlink connection

Figure 19 shows the downlink and uplink throughput during an approximately 8 minutes long video call over Starlink. The mean for uplink and downlink is in the range from 2 to 3 Mbit/s, although with considerable variation as a result of the variable rate video encoding. The uplink throughput is somewhat lower than the downlink. This could be a result of adaptation to the available maximum throughput on the two link directions as measured in the coverage tests (Section 4.2.3).

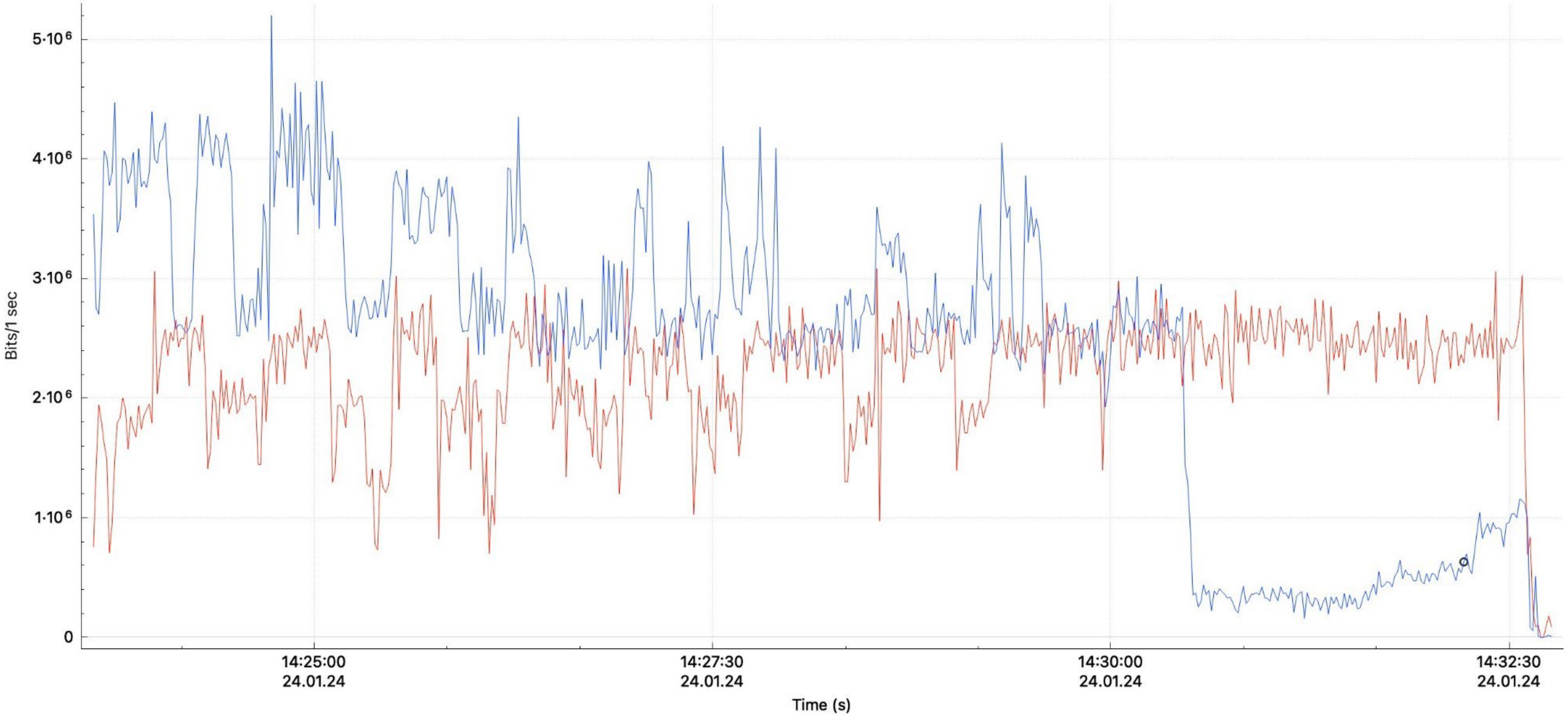

Figure 19 Time trace of downlink and uplink throughput (bits/s) during a video call over the Starlink connection.