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Published in:
2024 IEEE 100th Vehicular Technology Conference, VTC 2024-Fall - Proceedings

DOI (link to publication from Publisher):
10.1109/VTC2024-Fall63153.2024.10757869

Publication date:
2024

Document Version
Early version, also known as pre-print

Fixed Broadband Service via Starlink in Under-Served Areas - the Danish case

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***Abstract*—This paper investigates the possibility of using satellite connectivity via Starlink for achieving full digital inclusion in areas where traditional mobile or fixed-broadband are not cost-effective options due to low population density. The evaluation is based on experimental data and focuses on Starlink's performance in terms of throughput, specifically assessing its potential to meet the target of 100 Mbps downlink (DL) and 30 Mbps uplink (UL) speeds established by the Danish government for a full digital inclusion of households located in under-served areas. The experimental results indicate that the UL target is the limiting factor, even when a single user is active within the coverage area of a satellite beam. We observe that the UL and DL maximum throughput divide in equal proportion to the number of active users and the maximum (single-user) throughput of approximately 400 Mbps DL and 21 Mbps UL, the latter limited by UL link budget. Based on these numbers, and further assumptions, we analyse to what extent Starlink can provide a satisfactory broadband service to the approximately 20.000 households not meeting the Danish broadband targets by 2025. Whereas the targets cannot be met in a strict sense, we estimate that Starlink can provide *satisfactory broadband service* to approximately 4000 households across Denmark with experienced data rates of 60-100 Mbps DL and 5-10 Mbps UL, which, if households are selected out of the ones having the otherwise lowest speeds by 2025, corresponds to a significantly improved broadband experience. In the region with the lowest population density this amounts to 42% of households in the group not fulfilling the targets by 2025, and opposite, in the Capital region 4-5%.**

***Index Terms*—Starlink, Digital Divide, Starlink Connectivity, Satellite Measurements, Satisfactory Broadband Service**

I. Introduction

Having internet connectivity is a fundamental requirement for economic and social progress in both developed and developing countries. Despite its significance, approximately 2.6 billion people worldwide, roughly 37% of the global population, still lack quality internet access, with rural and developing regions being disproportionately affected [1] - the so-called *digital divide*.

Starlink's Low Earth Orbit (LEO) satellite network emerges as a promising solution to provide internet connectivity, especially in areas where traditional deployment methods like fixed broadband or cellular networks may not be cost-effective due to low population density. Starlink has global coverage and capacity to deliver high-speed connectivity with relatively low latency, effectively overcoming geographical constraints and infrastructure limitations. As an example to be used in this paper, Starlink may also be an alternative to extend and improve coverage in under-served areas in Denmark. Despite the large progress Denmark has made in digital connectivity there are still regional disparities in digital broadband coverage. Surprisingly, the Capital Region trails behind the other regions having a coverage of 96.2%, in contrast to 98.9% in the sparsely populated region of Northern Jutland. Additionally, while an impressive 94.5% of households in Denmark can access Gigabit speeds, there are still 5.5% of the households experiencing low speeds [2]. Denmark targets a broadband speed of 30 Mbps upload and 100 Mbps download for full participation in the digital society, in line with the recommendation of the European Commission. In comparison, until as recent as Spring 2024, the US Federal Communications Commission (FCC) has been suggesting a minimum of 3 Mbps upload and 25 Mbps download [3].

Multiple factors can impact the performance of Starlink, encompassing aspects such as orbital coverage, weather conditions, network re-configurations, or user density in specific regions. Existing studies have mostly concentrated on throughput tests to probe achievable uplink and downlink speeds. For instance, [4] explored Starlink's performance in different geographical locations, revealing significant variation, with measured downlink (DL) throughput ranging from 45 to 124 Mbps and uplink (UL) throughput from 6 to 11 Mbps. Similar findings were reported in [5], and attributed to the dynamic nature of network paths with satellite movements and handovers. Generally, Starlink users are expected to experience higher variations in throughput and latency compared to terrestrial broadband. In [6], a multifaceted approach using samples from 34 different countries compared Starlink's performance with cellular 5G and fiber for real-time applications, demonstrating that the satellite performance strongly depends on proximity to ground infrastructure. Additionally, [7] provided latency and throughput results for a single-user scenario, comparing them with a 5G non-standalone network as a potential alternative for fixed-broadband deployment in rural areas. The conclusion suggests that Starlink can outperform 5G in the DL case but faces limitations in the UL. Few studies have considered the impact of weather conditions. A recent more elaborate study was published in [8], utilizing a six-month dataset to conclude that rain intensity, and, potentially, overcast conditions affect Starlink's performance.

The results in this study originates from Public Sector Consultancy to the Danish Agency for Data Supply and Infrastructure (SDFI) with the aim to explore to what extent Starlink can provide a satisfactory broadband service to customers in the *residual group* [9], i.e., the danish households not meeting a 30 Mbps upload and 100 Mbps download speed. The study is based on measurements made from the location of Northern Jutland, aiming to determine the available (single-user) packet latency and maximum throughput in UL and DL, and how these performance metrics change when up to three users are simultaneously active within the same beam coverage area. The observations are used to estimate the possible improvements in digital broadband coverage for the Danish case, including the added capacity and expected broadband experience for the *residual group*. Key contributions of the paper compared to state-of-the-art are new insights to the UL and DL beam capacity available in the beam coverage area, the throughput and latency distributions when multiple users are present within a single beam, and how these results can be used to estimate the improvement to the digital divide based on the Danish case.

The paper is structured as follows: Section II introduces the measurement setup and the studied performance metrics. Section III presents the experimental results, including interpretations for the later Section IV; subsections III-A and III-B present multi-user results for, respectively, DL and UL throughput and latency. Section IV presents and discusses the Danish case and Section V concludes the paper.

II. Experimental Setup

The measurements presented in this paper were conducted using three Starlink terminals, one first-generation (*Gen-1*) and two second-generation (*Gen-2*), as shown in Figure 1. The three terminals were positioned atop a 10-meter high building located in a suburban area of Aalborg in the North of Denmark, all having a clear view to the sky. The satellite coverage for this location mainly encompasses orbits passing over the Northern part of Germany, at a slant range of approximately 700 km and elevation of 40-45 degrees over the horizon. The three terminals were connected via Wi-Fi to three different laptops, which were used for evaluating Starlink performance and will be referred to as Starlink User-x (SU-x), with x representing an identifier in the range 1 to 3. User SU-1 was connected to the Gen-1 terminal. All three terminals had the Starlink Residential (fixed broadband) subscription.

The assessment of Starlink's performance was conducted with a focus on DL and UL throughput, as well as latency. While latency may not be explicitly included as a requirement for inclusive connectivity, its significance in certain applications, such as gaming or smart farming applications, cannot be overlooked. Latency performance was evaluated using the Linux *ping* functionality, which provides statistics on the Round-Trip Time (RTT) for the transmitted packets. Specifically, packets with a size of 64 bytes were transmitted with a fixed interval of 100 ms from the testing laptop through the Internet to a remote server located in Denmark.

Throughput measurements were performed by employing the *iPerf3* tool. Operating on a client-server model, this tool enables the determination of the maximum achievable bandwidth on IP networks [10], i.e., the amount of data that can be sent over a connection in a measured amount of time. In our tests, in order to probe the speed of the connection, i.e., how fast data can be sent, we configured the tool to use the User Datagram Protocol (UDP) with a 1-second measurement (averaging) interval. All data transfer successfully, per definition, thus equivalently we refer to the measurement as throughput throughout the paper. As a default, to align with the targets specified by the Danish government, data packets were transmitted (requested data rate) corresponding to network speeds of 100 Mbps DL and 30 Mbps UL. Tests were conducted to evaluate DL throughput, with data being downloaded via Starlink from a remote server located in Denmark, and upload throughput, where the Starlink users were uploading data to the same remote server.

Fig. 1. Starlink antenna configuration used to obtain the experimental data: one *Gen-1* (left) and two *Gen-2* (right) Starlink Standard Actuated antennas.

To study the impact of concurrent user connections within a single Starlink beam, we assess the three Key Performance Indicators (KPIs) - latency, throughput UL and DL - under different scenarios. First, we evaluate the KPIs when a single Starlink terminal is actively transmitting or receiving (*1-User* results), and then the degradation when two (*2-Users* results) or three (*3-Users* results) Starlink terminals are transmitting and receiving at the same time. This approach allows us to understand the performance variations when multiple users are active within the coverage area of the same satellite beam.

III. Experimental Results

Little information is available as to the specific operating principles of the Starlink network, except for what can be inferred from official FCC documents and official/unofficial sources who have attempted "reverse-engineering". Initially, we therefore conducted multiple 24-hour and 1-hour tests to examine the saturation levels of both DL and UL throughput within the coverage area of a single beam. A 15-minute UL and DL trace from these tests is depicted in Fig. 2. In the DL we observe a sustained throughput of around 420 Mbps over several minutes. From several such tests, we conclude that these levels are attained when this is the only user active within the beam coverage area (see Section III-A), and that this indicates the maximum data rate. This observation aligns closely with the assumed beam capacity of 417 Mbps used in [11], considering a single Uber H3 hexagonal cell of size 5 and a Starlink satellite with a direct gateway connection as can be assumed for the constellation over Northern Germany (inter-satellite connection significantly reduces this number according to [11]). Further to this, it is also consistent with the assumption in [12] of having one DL beam dedicated 100% to cover a given area with a single carrier, out of the eight carriers available in the Ku-band.

For the UL throughput we see much lower sustained values, around 21 Mbps. However, at the beginning of the trace, values reach up to 55 Mbps over a few seconds. Our analysis suggests that this can be attributed to Starlink allocating a dedicated UL beam at the start of the connection, and then transitioning to time-multiplexing to balance the UL/DL beam ratio: From information available in the FCC documents, and [11], it is known that each satellite can project 48 DL and 16 UL beams on the surface of the earth; hence, for every DL beam dedicated 100% to a H3 cell, an UL beam will need to be time-multiplexed between three such cells. Further, because of the different frequency bandwidths in the two directions, 250 MHz DL versus 62.5 MHz UL, the maximum rate a user can be allocated in UL is approximately 100 Mbps, versus approximately 400 Mbps DL. The average UL throughput in Fig. 2 does not reach 100 Mbps, nor one third of this, 33 Mbps. However, with some support from the following throughput statistics, which caps slightly above 30 Mbps (cf. Fig. 4), we conclude that while a maximum data rate of 100 Mbps is theoretically possible in UL, the uplink data rate is limited by link budget: In case users are scheduled in short bursts with maximum data rate, UL and DL, the link budget limitation will affect the sustainable rate the same, no matter whether the UL beam is allocated 100% or 33%, but longer allocation will naturally lead to higher throughput. In DL there is no such limitation and the sustainable (average) rate is simply determined by the maximum data rate and the time-share, i.e., the fraction of time that a user is being scheduled. The momentary peaks in the throughput visible in Fig. 2, and particularly Fig. 2b, is an artifact resulting from the short measurement (averaging) interval in combination with a requested (forced) data rate and packet buffering in the MAC/PHY layer.

Based on the observed maximum data rates, we will assume, correspondingly, that the beam capacity is approximately 400 Mbps DL and 30 Mbps UL, whereas the user can be allocated instantaneous rates of 400 Mbps DL and up to 100 Mbps UL. Starlink will dynamically distribute, i.e., time-share, the available capacity in the beam based on demand from the currently active users within the beam coverage area.

Figures 3-4 and 6 illustrate, respectively, the DL and UL

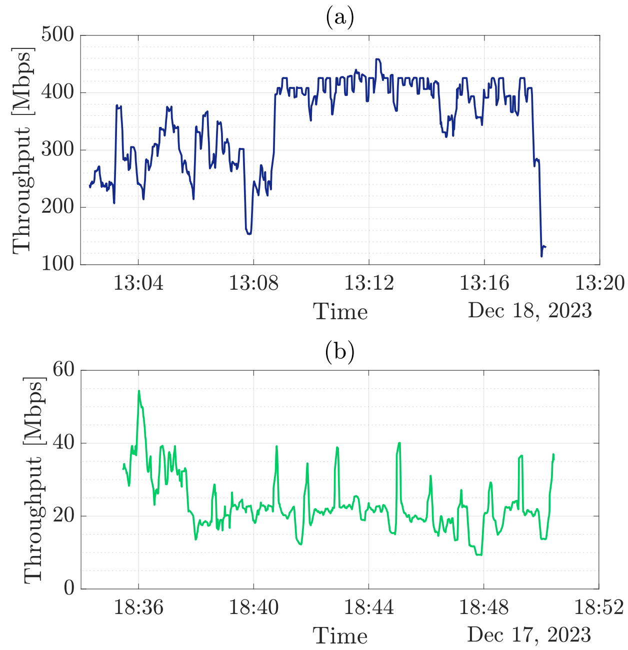

Fig. 2. 15-min. throughput time traces observed with 700 Mbps in DL (a) and 200 Mbps in UL (b) requested data rate in *iPerf*. Overall variations across time are assumed to be a result of resource allocation policy.

TABLE I
DL AND UL THROUGHPUT, AND LATENCY (PING), STATISTICS FOR MULTI-USER STUDY.

KPI	Scenario	Mean	Median	Std. Dev.
DL throughput [Mbps]	*1-User*	98.9	99.9	7.7
	2-Users	98.7	99.7	6.4
	3-Users	97.4	99.7	9
UL throughput [Mbps]	*1-User*	21.1	20.9	4.7
	2-Users	11.6	9.7	5.6
	3-Users	7.7	6.7	3.7
Latency [ms]	*1-User*	78.8	76.5	17.3
	2-Users	84.5	81.4	19.5
	3-Users	105.3	67.4	95.3

throughput and latency cumulative distributions experienced by a specific Starlink user (SU-1) in each of the studied scenarios (*1-User, 2-Users*, and *3-Users*). These figures represent the extent of performance degradation observed by the user when one or more Starlink users are connected in the same beam and actively transmitting simultaneously. For the sake of comparison to what users in urban and populated areas may achieve, the same KPIs measured for a user with Fiber-To-The-Home (FTTH) access are presented in the figures. A summary of the main statistics is provided in Table I.

A. Multi-user results - throughput

The results in Fig. 3 show the throughput experienced by SU-1 when no other, one, or two other users are active within

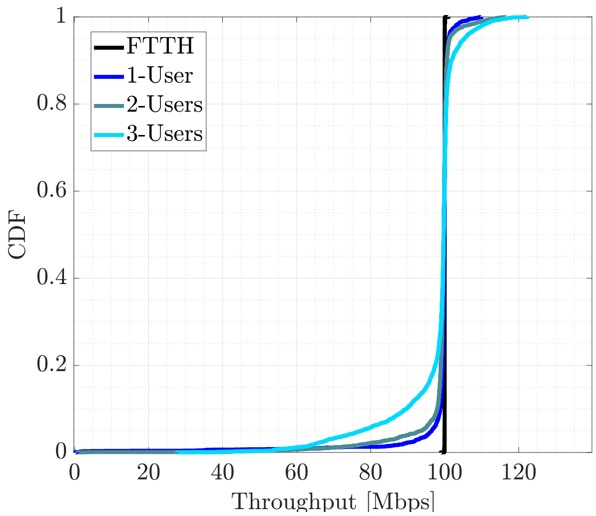

Fig. 3. Cumulative distribution function for DL throughput (SU-1), with or without other users connected in the same beam (1 or 2).

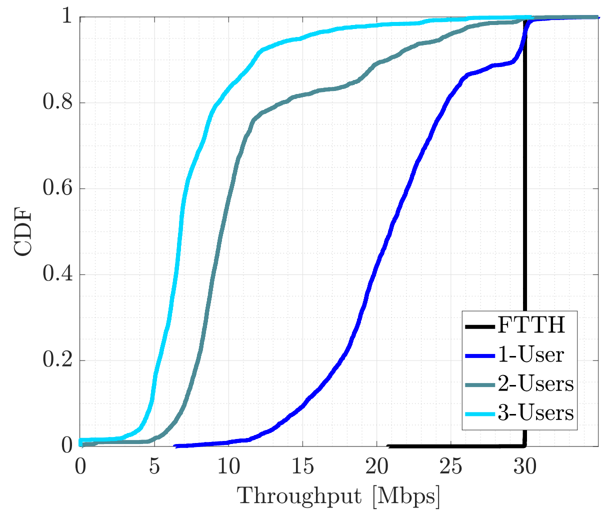

Fig. 4. Cumulative distribution function for UL throughput (SU-1), with or without other users connected in the same beam (1 or 2).

the same beam coverage area, all requesting 100 Mbps in DL. The throughput is overall unaffected since the user's requested data rate can be accommodated within the available beam capacity. Based on our assumption for DL beam capacity, it is expected that the similar result for four users will show only a modest degradation in the median throughput.

The UL throughput distributions, depicted in Fig. 4, exhibit considerably higher variability relative to the mean/median value. In the single-user scenario, as discussed previously, the user cannot sustain the full beam capacity of 30 Mbps, due to link budget limitations, but a medium data rate of approximately 21 Mbps. The range of measured throughput, 1-second average, is predominantly concentrated in the range from 10 Mbps to 30 Mbps. When additional users initiate UDP traffic with a requested data rate of 30 Mbps, we observe that the median throughput divides approximately according to the single-user median data rate, i.e., median data rates of 10.5 Mbps for two users and 7 Mbps for three users; if users were able to achieve the maximum data rate when scheduled, we should expect sustained rates of $30\,\mathrm{Mbps}/3 = 10\,\mathrm{Mbps}$ for the case of three users, however, with link budget limitations and instantaneous rates being dependent on the UL Signal-to-Noise-Ratio (SNR), lower and more variable rates will result. From other similar tests it has been observed that the throughput distributions can be very asymmetrical, having a split closer in average than median data rate.

Figure 5 shows the throughput distributions of each individual, simultaneously active, Starlink User (SU-x). In the DL (Fig. 5a), all users have comparable median throughput (95.5 Mbps for SU-1, 99.8 Mbps for SU-2, and 99.7 Mbps for SU-3); differences in the tail behaviour may be attributed to different scheduling allocations or differences between the Starlink terminals, although for DL there is no clear difference between SU-1 (Gen-1) and SU-2/SU-3 (Gen-2). For the UL (Fig. 5b), where the three users simultaneously requested an

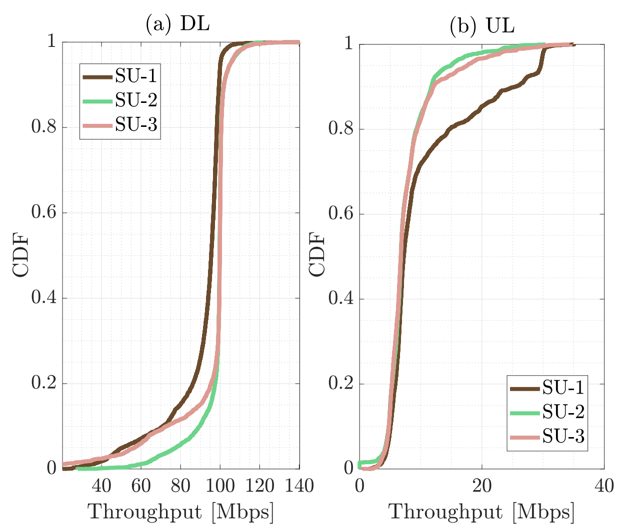

Fig. 5. Cumulative distribution function for DL (a) and UL (b) throughput for individual Starlink Users (SU-x) when the three users are connected in the same beam.

upload data rate of 30 Mbps, similar comparable throughput is observed (7.2 Mbps for SU-1, 6.7 Mbps for SU-2 and SU-3); in this case, there is a distinctly different behaviour for SU-1 (Gen-1) in the upper tail of the distribution.

B. Multi-user results - latency

Figure 6 shows the latency distribution for a specific Starlink user (SU-1), comparing single-user performance with scenarios involving two and three users connected within the same beam. In the single-user test, the mean latency is approximately 79 ms, encompassing two-way propagation (accounting for approximately 9 ms), processing and network (internet) delay. In comparison, the fixed-broadband connection (FTTH) shows an average latency of 14.9 ms. When one or more other

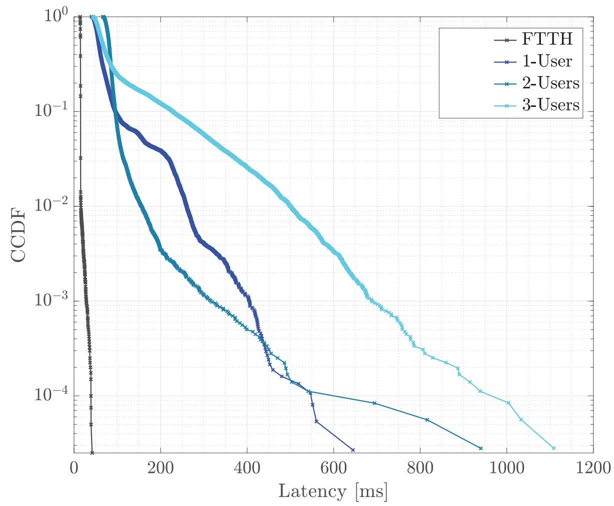

Fig. 6. Complementary cumulative distribution function for latency (SU-1) when other users (1 or 2) are connected in the same beam.

TABLE II
CURRENT DISTRIBUTION OF BROADBAND SPEEDS FOR DANISH HOUSEHOLDS IN THE RESIDUAL GROUP [*Source: SDFI, 2023*].

	Downlink		**Uplink**	
Region	**%< 5** [Mbps]	**%< 20** [Mbps]	**%< 1** [Mbps]	**%< 2** [Mbps]
Capital	21	44	27	50
Sealand	31	63	44	65
North Jutland	25	46	27	51
Central Jutland	30	53	35	57
South Jutland	31	54	39	56
Denmark	26	50	33	55

Starlink users connect within the same beam the mean latency degrades (Table I), and particularly the standard deviation increases fivefold for the case of three simultaneous users. This degradation, and resulting variability, is quite different from fixed-broadband connections with dedicated "last-mile" connections; in Starlink the access medium is shared and will cause delay to some user data packets, increasing variability and mean delay.

IV. STARLINK COVERAGE FOR THE DANISH CASE

Despite the large proportion of Danish households who can access Gigabit speeds, the Danish agency SDFI estimates that there will a *residual group* of around 20,000 households by 2025 without access to the 30 Mbps upload and 100 Mbps download speeds [13]. Surprisingly, out of this *residual group*, 5,550 to 7,000 of them will be in the Capital Region around Copenhagen, and approximately half of them with access to speeds lower than 2 Mbps upload and 20 Mbps download (cf. Table II). SDFI is currently exploring different technologies for improving the digital broadband coverage for this group of households. Strictly speaking, Starlink's shared medium will be unable to support more than four simultaneous users with DL speeds of 100 Mbps, and hardly one with UL speed of 30 Mbps. For this reason, we set out to estimate how Starlink might be a viable option to bring a significant improvement for the part of the residual group with access to the lowest speeds. It is our estimate, based on multi-service tests over Starlink and other estimation, that a *satisfactory broadband service* can be achieved by reserving an average data rate of 10 Mbps DL and 0.5 - 1 Mbps UL, supporting a combination of services such as streaming, browsing, online gaming and interactive meeting for a household; based on the results in Section III, this allows serving 40 users (households) in each Starlink satellite beam. A fundamental premise for the estimate is, besides the trunking gain of serving many users from a shared pool of resources (statistical multiplexing), that the activity pattern of the 40 users is such that only a fraction have/need simultaneous access, i.e., few users are active at the same time. We did not find studies in the open literature where large-scale multi-service, multi-user, tests have been conducted, and therefore this is to be considered a best estimate. When users are active, their data transmissions will achieve instantaneous peak data rates of close to 400 Mbps DL and up to 100 Mbps UL, but much lower average rates since the capacity is shared. In particular, average rates will be considerably lower for UL due to the lower UL beam capacity and the limitation on data rates implied by the results in the previous section. We estimate that although, on the face of it, the average rates with 40 users per beam are low, 10 Mbps DL and 0.5 - 1 Mbps UL, accounting for the activity pattern it is possible to achieve *user experienced* data rates in the range 60 - 100 Mbps and 5 - 10 Mbps, respectively. Some support for the estimates is provided by measured median data rates in this range, reported in Ookla® speed tests for the United States (USA) where the number of Starlink users are reasonably mature. The much lower UL data rates partly excludes the use of services like online video meeting, requiring high symmetrical data rate, and competitive gaming, requiring low and stable delay - this is obviously not possible but only for a very low number of active users given the results in the previous section.

TABLE III
SUPPORTED BROADBAND CONNECTIONS (HOUSEHOLDS/USERS) IN DIFFERENT REGIONS OF DENMARK AND CORRESPONDING SHARE OF THE RESIDUAL GROUPS IN THE REGION.

Region	**Area** [km^2]	**Spotsize** [km^2]	**Connections** [no.]	**Share** [%]
Capital	2568	377	280	4-5
Sealand	7273	377	760	22
North Jutland	7933	504	640	42
Central Jutland	13053	412	1280	36
South Jutland	12191	302	1600	36-40
Denmark	42952	400	4280	21-24

The beam capacity available in a given area on the ground depends on factors such as channel reuse patterns and resource allocation policies. In alignment with the observations in Section III, we assume that a given area is covered by a single 250 MHz carrier with one DL beam dedicated 100% and one UL beam 33%. The given area on the ground, the beam footprint or spotsize, depends on the elevation angle and satellite height among other things. By assuming that a Starlink beam, from a satellite $550\,\mathrm{km}$ above the northern part of Germany, covers approximately one Uber H3 cell, resolution 5, at nadir, corresponding to an almost circular footprint of $215\,\mathrm{km}^2$, it is possible to calculate the corresponding footprint at slant angle for the different regions of Denmark. This footprint, now elliptically shaped due to the slant angle and resulting beam spread, varies from $302\,\mathrm{km}^2$ in the southern part of Denmark, close to Germany, to $504\,\mathrm{km}^2$ in the northern part of Denmark, covering multiple H3 cells on the ground. Consequently, the beam capacity is spread over a larger area. Given the assumptions, it is possible to estimate the number of served households in the different regions, cf. Table III. As an example, the Capital Region, covering an area of $2568\,\mathrm{km}^2$, can be assumed to be covered by seven beams (approximately $2568\,\mathrm{km}^2/\,377\,\mathrm{km}^2$) with the capacity to serve $7 \cdot 40 = 280$ households with *satisfactory broadband service* (in the above definition). This is a mere 4-5% of the residual group in that region. If users are selected out of the ones having the otherwise lowest speeds by 2025, i.e., the approximately 50% fraction with lower than $20\,\mathrm{Mbps}$ DL and $2\,\mathrm{Mbps}$ UL in Table II, Starlink can give a significantly improved broadband experience to these users in the Capital Region. In other regions, due to a lower number of users spread over a larger area, the situation improves. For example, despite being the northernmost of the Danish regions, in the region of Northern Jutland Starlink is estimated to be able to serve 640 households, corresponding to 42% of the residual group in that region by 2025, or 84% if counted and selected among the ones having the lowest speeds. For the country as a whole, we estimate that Starlink will be able to provide *satisfactory broadband service* to more than 4.000 users across Denmark, covering overall 21-24% of the residual group by 2025.

V. Conclusions

In this paper, we reported on new, controlled, experimental results on the Starlink network. Specifically, we measured the peak data rate in downlink and uplink, and performed multi-user tests to characterize throughput and latency when up to three Starlink terminals are simultaneously active. From these results, we observe peak data rates of $420\,\mathrm{Mbps}$ in downlink when a single Starlink terminal is active in the beam coverage area. In uplink, although peak data rates up to $100\,\mathrm{Mbps}$ seems theoretically possible, the sustained average throughput is limited to approximately $21\,\mathrm{Mbps}$ due to time-multiplexing of uplink beam resources and constraints imposed by the uplink link budget. Based on the experimental results, the capacity within a single antenna beam is sufficient to serve four simultaneous $100\,\mathrm{Mbps}$ connections downlink, and theoretically one $30\,\mathrm{Mbps}$ uplink.

Based on these findings we considered Starlink as a solution for under-served areas in the Danish case. We investigated to what extent Starlink can significantly improve the broadband experience for households, or users, in the so-called *residual group*, containing approximately 20.000 households by 2025 that cannot meet the target of $100\,\mathrm{Mbps}$ downlink and $30\,\mathrm{Mbps}$ uplink speeds established by the Danish government for full digital inclusion. In the region with the lowest population density we estimate that Starlink can provide satisfactory broadband service to 42% of users in the group not fulfilling the target in that region by 2025, and 4-5% of these users in the Capital region. The different percentage coverage is a combination of the effect of population density, regional area and satellite beam footprint. For the country as a whole, we estimate that Starlink will be able to provide satisfactory broadband service to 4280 households, corresponding to one user per $10\,\mathrm{km}^2$. The study case should be applicable to other regions, including those with an overhead satellite constellation. This would increase capacity per area, but not significantly the available peak data rates. While the current work has been performed with, and assumed, static users, we are currently exploring Starlink performance under mobility conditions.

Acknowledgment

This research has received funding from Styrelsen for Dataforsyning og Infrastruktur (SDFI) in Denmark. The authors would like to express their gratitude to the SDFI team for their valuable support and feedback throughout the process of obtaining these results.

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