Exploring the 5G Digital Divide in the Non-Contiguous US: LEO Satellites to the Rescue?

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5G cellular networks and Low-Earth-Orbit (LEO) satellite networks, such as Starlink, promise enhanced performance and coverage capabilities. While a large number of research works have evaluated these technologies in the mainland US, their performance in non-contiguous US regions remains under-explored, despite their unique challenges and significant visitor demands. Through extensive drive tests covering over 4200+ km across Alaska, Maui (Hawaii), and the mainland US (as a baseline), while simultaneously measuring the performance of the three major US mobile operators and Starlink, this work presents the first detailed evaluation of cellular and Starlink network coverage and performance in the non-contiguous US regions. Our study shows a persistent digital divide between mainland and non-contiguous US for cellular networks in terms of coverage and performance, highlighting the challenges of cellular deployments in non-contiguous US regions. Starlink provides substantially higher performance than cellular networks most of the time, but area-specific challenges, including unique terrains in Hawaii and sparse satellite deployment in Alaska, significantly degrade performance compared to the mainland US. Additionally, we explore the spatiotemporal diversity between cellular and Starlink performance and study the potential of multipath transport to bridge the connectivity gap in non-contiguous US regions.

CCS Concepts: • **Networks → Mobile networks**; **Network measurement**; **Network performance analysis**.

Additional Key Words and Phrases: 5G; LEO Satellite Networks; Cellular Networks; Digital Divide; Measurement; Network Performance; Multipath; Emulation; Dataset

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1 Introduction

The wireless landscape is currently undergoing a significant transformation, with 5G networks playing a pivotal role in this process. Via a combination of innovations such as higher-order

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modulation schemes, (massive) MIMO, wider channels, flexible slot scheduling, network slicing, etc., 5G promises ultra-high bandwidth and ultra-low latency, far surpassing the performance of its precursor, 4G LTE. Such high data rates and low latency promise to unlock bandwidth-intensive, latency-critical applications such as Augment Reality, Mixed Reality, Connected Autonomous Vehicles, and industrial automation.

Despite these ambitious promises, the real-world deployment of 5G has revealed several limitations. While existing studies and articles [2, 3, 20, 29, 36, 56] demonstrate that 5G can achieve peak data rates of 3+ Gbps and sub-1 ms PHY latency under ideal conditions, other works [6, 10, 28, 30, 56] have also highlighted that its coverage and performance often remain fragmented and inconsistent, especially when traveling across diverse regions in the US. Notably, prior evaluations have largely focused on the contiguous United States, leaving a gap in our understanding of how 5G performs in non-contiguous regions such as Alaska (AK) and Hawaii (HI). These regions face distinct challenges, including diverse terrains, limited access to fiber backhaul in remote rural environments, which necessitating the use of alternatives such as microwave or satellite links [26, 66], a heavy reliance on long-distance terrestrial or submarine cables, and limited spectrum availability [15], all of which can significantly impact network performance and availability. As such, the first goal of this work is *to assess 5G's reach and effectiveness in these regions, which is crucial to determine whether a digital divide exists between the mainland and the non-contiguous US*. Such a divide would carry important implications, not only for local residents who rely on cellular connectivity for daily communication and services, but also for the millions of tourists traveling through these regions, where network availability and performance could significantly affect navigation, safety, and overall experience.

Assuming such a digital divide between the mainland and non-contiguous US indeed exists, our second research goal is *to understand whether and how the emerging Low Earth Orbit (LEO) satellite networks, such as Starlink, can reliably bridge connectivity gaps left by terrestrial cellular networks and mitigate the digital divide*. LEO satellite networks have gained traction in recent years as a promising alternative Internet access technology in remote and inaccessible regions where traditional wired or wireless networks fall short. Recent studies [27, 28, 34, 50] suggest that LEO satellite networks can offer competitive performance compared to cellular networks in the mainland US, raising the possibility that they could extend meaningful connectivity to harder-to-reach regions such as AK and HI.

However, whether LEO satellite networks can reliably supplement cellular performance in the non-contiguous US remains an open question. While prior work suggests promising results in the mainland US, the unique geographic and infrastructure challenges of AK and HI complicate the picture. These challenges include: (1) The long distance of Hawaii and Alaska from mainland may introduce higher latency, as many ground stations are concentrated within the mainland US. (2) The diverse terrains and challenging topography of these regions can significantly impact communication. For example, obstructions caused by dense rain forests in HI or rugged mountains in AK can severely block Line of Sight (LoS) communication leading to performance degradation. (3) Varying satellite orbits and inclinations in different regions may lead to large differences in coverage and performance. As such, answering our second question requires the first in-depth study of LEO satellite network coverage and performance in these non-contiguous regions.

To address both of our research questions, we conduct, to our knowledge, the first measurement study of cellular and LEO satellite networks in the non-contiguous US. Via three extensive drive trips covering over 4200+ km in Alaska, Maui, HI, and the mainland US (Los Angeles to Omaha), as a baseline, we simultaneously measure the coverage and performance of the three major US cellular operators (AT&T, Verizon, and T-Mobile) and Starlink's LEO satellite network. Our measurements span diverse area types and comprehensively evaluate key network metrics such as downlink/uplink (DL/UL) throughput, network latency, and outage rates. Additionally, we explore the spatiotemporal diversity between cellular and Starlink performance and study the potential of multipath transport protocols (e.g., Multipath TCP) to bridge the connectivity gap in the non-contiguous US. The key findings of our work are summarized as follows:

• Our results show significantly lower 5G coverage in the non-contiguous US compared to the mainland US, which is further exacerbated in rural areas with frequent periods of no connectivity. The disparity is evident not only in terms of overall 5G coverage, but also in the lack of high-speed 5G deployments (with the exception of T-Mobile in HI). As a result, cellular networks consistently underperform in the non-contiguous US in comparison to mainland US, in terms of both throughput and latency. Zero-throughput occurrences are frequent even in areas with cellular connectivity, highlighting ongoing coverage challenges. Additionally, greater UE-server distances and limited network resources due to sparse deployments pose as a bottleneck in achieving higher performance in these regions.

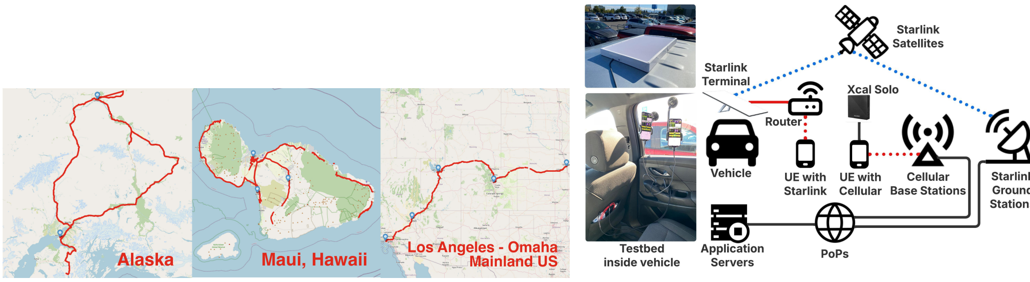
• Similar to cellular networks, Starlink's performance in the mainland US significantly surpasses its performance in Alaska and Hawaii due to area-specific challenges. Sparse satellite coverage in Alaska leads to coverage gaps and increased latency, whereas unique terrains in rural Hawaii lead to high outage rates despite dense satellite coverage. Additionally, the longer UE-server distances in the non-contiguous US compared to the mainland US significantly inflate the RTT in those regions.

• Starlink outperforms cellular networks in most scenarios across the non-contiguous US, providing superior DL throughput and enhanced reliability. However, Starlink provides much lower DL peak data rates compared to 5G-mid, and it often exhibits lower UL TCP performance and higher RTT (especially in Alaska) compared to cellular networks, highlighting inherent challenges such as packet loss and congestion control inefficiencies in LEO satellite networks. Our study further reveals substantial diversity in the performance of cellular networks and Starlink at a given location and time, suggesting that multipath transport protocols have great potential to improve overall performance and reliability.

• To assess this potential, we evaluate the performance of Multipath TCP (MPTCP) via trace-driven emulation. Our results confirm that multi-link access techniques can significantly improve performance and reduce outage rates, especially in rural areas. While combining Starlink with a cellular network can simultaneously boost throughput and reliability in the DL direction, Starlink's lower UL TCP throughput compared to cellular networks introduces an interesting tradeoff between performance and reliability in the UL direction, emphasizing the need for careful network pairing strategies to maximize benefits.

Contributions. In summary, this work makes the following contributions: (1) We collect a large dataset covering both cellular and Starlink network performance in the non-contiguous and contiguous US, obtained via extensive drive-test measurement campaigns spanning over 4200+ km. (2) Leveraging this unique dataset, we conduct the first large-scale evaluation of cellular and LEO satellite networks in the non-contiguous US, examining their coverage, throughput, latency, and reliability, in comparison to the mainland US. (3) We evaluate the potential of MPTCP to improve performance and reliability in the non-contiguous US, highlighting opportunities for a synergistic integration of cellular and LEO satellite networks to address connectivity gaps. (4) Our dataset and scripts are publicly available [1].

The rest of the paper is organized as follows: §2 describes the data collection methodology; §3 and §4 discuss the coverage and performance of cellular networks and Starlink, respectively, in non-contiguous US regions; §5 compares the performance of the two technologies in the non-contiguous US regions, and explores their spatiotemporal diversity; §6 evaluates the benefits of combining the two technologies via multipath transport (MPTCP); §7 discusses the related work and §8 concludes the paper.



(a) Measurement drive routes. (b) Experimental devices and setup.

Fig. 1. Methodology.

2 Methodology

2.1 Drive Tests

We conducted two major measurement campaigns, driving 1400+ km in the non-contiguous US: Alaska (June 20-26, 2024) and Maui, HI (August 16-19, 2024), covering the major cities and vast rural areas. Additionally, we conducted a third driving trip (2800+ km) in the mainland US, from Los Angeles, CA to Omaha, NE (November 1-4, 2024), to use it as a baseline against the cellular and Starlink performance in the non-contiguous US. We note that it is inherently difficult to identify mainland regions with topography/terrain similar to those of Alaska and Hawaii. Instead, our goal was to compare the performance in the contiguous vs. non-contiguous US in two distinct area types: urban centers and large, sparsely populated, rural areas. Our selected mainland route satisfies this goal, including extensive rural segments and diverse terrains (across desert basins and mountainous regions), as well as a few major urban hubs with state-of-the-art 5G deployments (e.g., Los Angeles, Las Vegas, and Denver). We believe this combination provides a balanced and practical baseline for cross-region comparison under realistic deployment conditions. The routes of the measurement campaigns are shown in Fig. 1a.

2.2 Testbed

Our testbed is shown in Fig. 1b. We used Samsung Galaxy S24 Ultra, a state-of-the-art smartphone at the time of our measurement campaigns, as the user equipment (UE) for data collection over both cellular networks and Starlink. All our experiments were conducted with 4 UEs, each connected to a different operator (Verizon, T-Mobile, and AT&T, and Starlink), to *concurrently* measure the performance over all four networks. For our server-side infrastructure, we used an AWS EC2 server in Oregon for all three trips. Additionally, to evaluate the benefits of edge computing, we deployed AWS EC2 Wavelength edge servers in Los Angeles, Las Vegas, and Denver for tests done with Verizon in those cities. Note that Amazon does not offer a Wavelength server in AK or HI.

For the cellular measurements, we obtained multiple unlimited data plans from Verizon, T-Mobile, and AT&T. Note that T-Mobile in AK does not have its own infrastructure, but instead provides services by roaming partners. Additionally, while performing tests with the roaming-enabled T-Mobile service in AK, we were often rate-limited to data rates less than 1 Mbps. Therefore, we do not discuss T-Mobile's coverage and performance in AK.

For the LEO satellite network measurements, we used a Gen 3 standard Starlink terminal with a dish router and the "Roam Unlimited" plan. The UE connects to the Starlink router via an 802.11ax 6e link. The Starlink terminal is tightly mounted flat on top of the vehicle sunroof, facing directly upward to the sky to ensure an unobstructed field of view while in motion (see Fig. 1b). This mounting approach avoids the partial blockage issues in motion observed with the older Gen 2 Standard terminal (e.g., Fig. 2 in [34]), where the unit was installed at a fixed tilted angle that could reduce visibility to satellites located behind the terminal. The terminal employs a two-dimensional phased-array antenna with the Software-Assisted Orienting technique [63], which electronically steers its beam to maintain satellite connectivity without requiring manual or mechanical adjustment. We note that we intentionally used the standard Starlink terminal combined with the Roam Unlimited personal plan, similar to another recent study [28], instead of the specialized Flat High Performance terminal and/or the unlimited mobile priority business plan. The standard terminal paired with the Roam Unlimited service plan already supports mobility at a much lower cost ($514 vs. $2,249-$4,149 with different data caps) and provides a realistic view of the performance accessible to general consumers, aligning with the purpose of our study.

2.3 Experimental Methodology

All our measurements were conducted while driving within legal US highway and city speed limits, representing realistic mobility scenarios for users on the road. Throughout each driving route, we conducted a suite of tests in a round-robin fashion, including backlogged TCP DL/UL throughput tests using nuttcp, ICMP-based Ping RTT measurements, and ICMP traceroute tests. Each TCP test ran for 2 min and application layer throughput was logged every 500 ms. Each RTT test ran for 30 s and sent one ICMP packet every 200 ms.

We found that tweaking the TCP congestion control algorithm and network buffers impacts end-user performance. Fig. 2 compares the cellular and Starlink downlink throughput with the default TCP configuration (Cubic with a max network buffer of 4 MB) vs. BBR with a large network buffer of 450 MB. While the impact of the congestion control algorithm (CC) and network buffer size on the cellular network performance is minimal, we observe very poor performance of Starlink with the default configuration. Hence, we used the combination of BBR and 450 MB network buffer for all our TCP downlink tests (over both cellular and Starlink). However, since we used unrooted commercial off-the-shelf smartphones, we could not change the CC or network buffers on the UE side; as a result, for uplink tests, we used the default configuration.

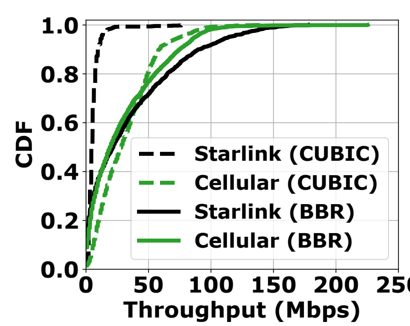
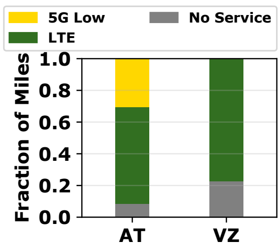


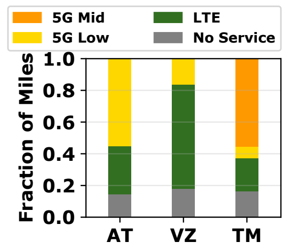
Fig. 2. Downlink throughput with different congestion control and buffer sizes.

Since COTS smartphones do not grant access to lower layer cellular KPIs, such as handover details or LTE/5G bands, we used Accuver XCAL Solo [5] devices, which access the Qualcomm diagnostic interface on the smartphones, allowing us to capture signaling messages between the UE and the base station and to gather lower layer KPIs essential for a comprehensive analysis of network coverage and performance. XCAL also records GPS coordinates with meter precision.

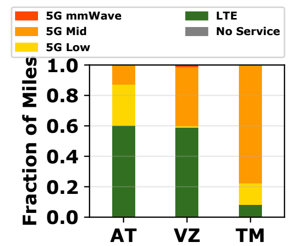
For Starlink-specific data collection, grpcurl [24] was utilized to fetch and save terminal information from gRPC APIs exposed on the router's local network. In addition, by performing reverse DNS lookups on Starlink's user IPs, we discovered that Starlink embeds Point-of-Presence (PoP) information in the DNS Pointer (PTR) records of the public IPs assigned to its users. For example, one such PTR record resolves to the hostname 'customer.sttlwax1.pop.starlinkisp.net' for a user IP in Alaska. The segment 'sttlwax1' follows the CLLI (Common Language Location Identifier) standard, which indicates that the associated PoP is located in Seattle. Leveraging this naming convention, we were able to extract the PoP locations used by Starlink over time by collecting the user IPs recorded in the TCP uplink test logs and issuing reverse DNS queries on them. We then augmented the time-series records of Starlink PoP locations with the UE's GPS coordinates by



(a) AK.



(b) HI.



(c) Mainland US.

Fig. 3. Coverage of three cellular networks, AT&T(AT), Verizon (VZ), and T-Mobile (TM).

aligning timestamps with the XCAL logs, which are used for visualization of the PoPs along each driving route in § 4.1.

3 Cellular Networks in Non-Contiguous US Regions

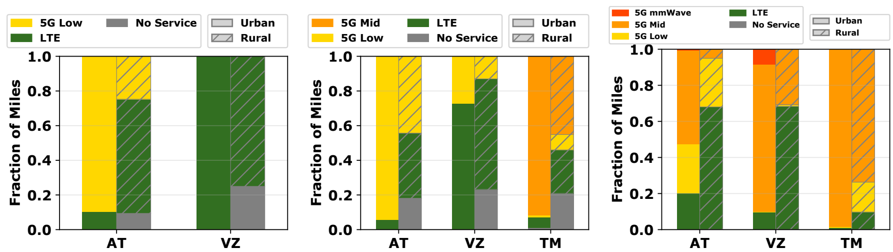
In this section, we examine the cellular network deployments in AK and Maui, HI, and compare them against the deployments in the mainland US, focusing on two aspects: (1) network coverage, and (2) end-to-end performance.

3.1 Coverage

Figs. 3a, 3b, 3c show the cellular technology coverage of the three major US operators in AK, HI, and the mainland US route (ML), respectively, defined as the fraction of miles covered by a specific technology over the total distance covered during throughput and RTT measurements.

Fig. 3a shows that *5G coverage in AK is disappointingly low for both operators.* Verizon offers no 5G service, while AT&T's 5G coverage is 30%, but it is limited to 5G-low, which provides extended range with reduced data rates. Throughout our driving trip, we encountered no high-speed 5G (5G-mid or mmWave). Additionally, a non-negligible fraction of the coverage bars – 9% for AT&T and 23% for Verizon – is marked by "No Service", showing periods of complete service failures. In contrast, Fig. 3c shows that 5G coverage for all three operators is much higher along the mainland US route, even though that route also includes vast rural areas, similar to AK and HI. T-Mobile, which offers service only via roaming partners in AK, provides 92% 5G coverage along the mainland US route mostly in the mid bands (78%). The other two operators offer lower 5G coverage compared to T-Mobile (40%), but still significantly higher compared to AK. Additionally, both operators offer 5G midband service along the mainland route, in contrast to AK. Verizon's 5G service is almost exclusively in the mid bands while AT&T's 5G midband service is limited to 13%. Finally, all three operators offer continuous cellular coverage along the mainland driving route. The fraction of "No Service" periods in Fig. 3c is only 0.07% for AT&T and 0% for Verizon and T-Mobile.

Fig. 3b shows that the overall 5G coverage for all three operators is higher in HI compared to AK, but still *worse than in the contiguous US, with the exception of AT&T.* Surprisingly, AT&T's 5G coverage is higher in HI than on the mainland route (55% vs. 40%), but, similar to AK, it is again limited to 5G-low. In contrast, in the mainland US, the operator offers limited 5G-mid coverage (13%). Verizon's 5G coverage is only 16% in HI and also includes only 5G-low. T-Mobile has the largest 5G coverage in HI (63%) among the three operators, and it is the only operator offering 5G midband service (56% coverage). However, its coverage is still lower than on the mainland route (92% 5G coverage, with 78% contributed by 5G-mid). Additionally, all 3 operators face complete service failures, similar to AK, and the fraction of "No Service" is higher than in AK – 14%/18%/16% for AT&T/Verizon/T-Mobile.



(a) AK. (b) HI. (c) Mainland US.

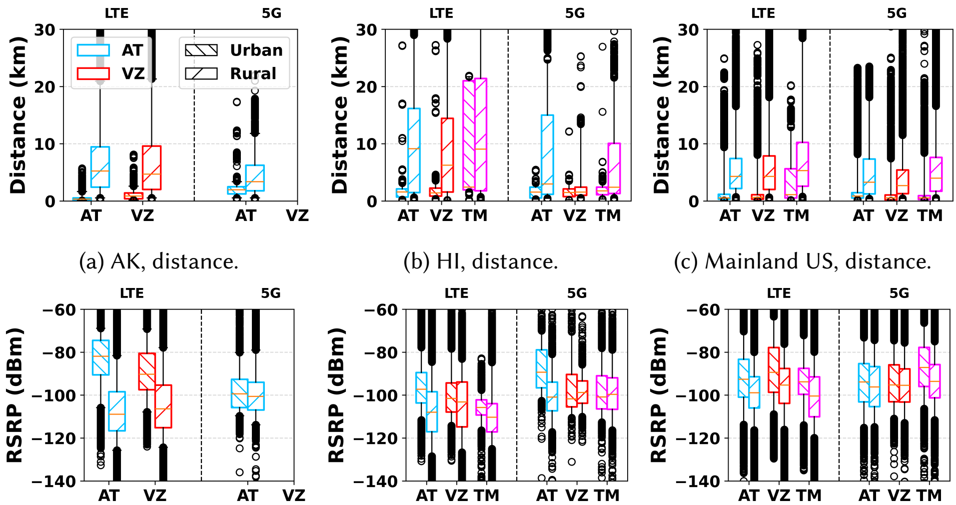
Fig. 4. Coverage breakdown by area type.

Our coverage results, particularly the absence of 5G midband coverage in AK and the limited 5G midband coverage in HI, can be explained by the limited spectrum availability in these regions. In the contiguous US, AT&T and Verizon primarily rely on the C-Band (3.7–3.98 GHz) spectrum for their 5G midband deployments, while T-Mobile relies mainly on the 2.5 GHz band inherited from Sprint. However, these bands are not equally available in AK and HI. Specifically, the C-Band spectrum was not auctioned in AK and HI due to the continued operation of incumbent satellite services in the same frequency range, which the FCC deemed essential for regional connectivity [15]. Consequently, AT&T and Verizon provide only 5G-low or no 5G service in AK and HI, as we saw in Figs. 3a, 3b. Additionally, a substantial portion of the 2.5 GHz band in AK has been licensed to the Alaska Tribal Network through the FCC's Rural Tribal Priority Window [16], resulting in limited commercial access to that spectrum; as a result T-Mobile relies exclusively on partnership networks in AK, as we mentioned in §2. In contrast, T-Mobile retains 2.5 GHz licenses in HI (subject to FCC divestiture conditions [17]), where it offers a substantial 5G-mid coverage (Fig 3b), although much lower compared to the mainland US.

We further break down the overall coverage based on the area type in Fig. 4. In AK, AT&T offers almost 90% 5G coverage in urban areas (Anchorage and Fairbanks), while LTE is the dominant technology in the rural areas, where 5G coverage is only 25% (Fig. 4a). Similarly, in HI, the urban areas exhibit higher 5G coverage, with AT&T and T-Mobile showing substantial ($\geq$ 90%) 5G-low and 5G-mid coverage, respectively (Fig. 4b). In contrast, in rural areas, we observe again a sharp decline in 5G coverage for all 3 operators – from 94/27/93% down to 44/13/54% for AT&T/Verizon/T-Mobile, although T-Mobile still offers satisfactory 5G-mid coverage (45%). Additionally, in both regions, the "No service" periods observed in Fig. 3, are exclusively experienced in rural areas, further emphasizing the connectivity gap.

Fig. 4c shows a very different picture for the mainland route. In urban centers, all three operators offer high 5G-mid coverage, ranging from 52% for AT&T up to 98% for T-Mobile, with Verizon also offering a non-negligible 5G-mmWave coverage (9%). In rural areas, Verizon and T-Mobile offer much better 5G coverage than in the non-contiguous US regions, with a substantial amount of 5G-mid service (31% and 74%, respectively). Interestingly, AT&T's 5G coverage in rural areas of the mainland route is worse than in rural Maui; only 32% (vs. 44% in rural HI) with negligible 5G-mid coverage. However, the operator offers almost full cellular coverage (0.07% "No Service") in rural areas of the mainland route, in contrast to rural HI.

UE-BS distance. To further understand the coverage results, we show in Figs. 5a-5c boxplots of the distances between the UE and the LTE/5G base stations (BSs) the UE was connected to during our drives in AK, HI, and the mainland route, respectively, broken down by area type. These distances provide an idea of the range of cellular BSs. We calculate the UE-BS distance using the Timing



(a) AK, distance. (b) HI, distance. (c) Mainland US, distance.

(d) AK, RSRP. (e) HI, RSRP. (f) Mainland US, RSRP.

Fig. 5. UE-BS distance and RSRP in AK, HI, and the mainland route.

Advance (TA) field,[1] extracted from XCAL. We observe that distances to LTE BSs are typically longer than to 5G BSs and distances in rural areas are typically much longer than in urban areas (suggesting sparser deployments), although there are some exceptions. We also observe very large outliers regardless of region, area type, or technology; both LTE and 5G(-low) BSs can have a range longer than 30 km.

In urban areas, the distances are very short for both technologies in all three regions, with median and 75-th percentile values typically less than 2 km. The only exception is T-Mobile, with a 75-th percentile of 5.6 km for LTE in the mainland US and 21 km in HI. Recall from Figs. 4b, 4c that T-Mobile offers very limited LTE coverage in urban areas of HI and the mainland US, suggesting that the operator maintains very few LTE BSs in cities in those regions and BSs outside city limits are often used to fill 5G coverage holes inside cities. Another notable observation is that AT&T's 5G distances are longer than the LTE distances in AK urban areas in spite of the near-full 5G coverage (Fig. 4a), suggesting a sparse 5G-low deployment.

In rural areas, the distances in AK are similar to the mainland for both technologies, with median values in the range of 4-5/2-3 km for LTE/5G and 75-th percentiles in the range of 7-10/5-7 km. In contrast, in rural HI, the LTE distances are much longer compared to the mainland US, with 50-th/75-th percentiles in the range of 6-9/14-21 km vs. 4-5/7-10 km. On the other hand, the 5G distances have lower median values compared to the mainland but much higher 75-th percentiles, suggesting heterogeneous deployments (with respect to the distance to the highways and/or Tx power). The only exception here is Verizon's 5G-low service in rural HI with distances similar to those in urban HI (75-th percentile of 2 km), which explains the very limited 5G coverage offered by Verizon in these areas (Fig. 4b).

Signal strength. Figs. 5d-5f show boxplots of the Reference Signal Received Power (RSRP) in AK, HI, and the mainland route, broken down by area type and technology. In the case of LTE, the RSRP is typically higher in urban areas compared to rural areas; the median values range from -110 to -95 dBm in rural areas vs. -105 to -81 dBm in urban areas. The only exception is Verizon in HI, where

[1]TA is used to synchronize the transmission timing of a UE with the BS to compensate for the propagation delay of the radio signals.

the LTE RSRP has similar 50-th/75-th percentiles in both area types, despite the big discrepancy in UE-BS distances (Fig. 5b), suggesting that the operator uses power control to provide good LTE coverage in many rural areas. On the other hand, the differences in 5G RSRP between the two area types are much smaller. One notable discrepancy here is AT&T in HI, where the 5G RSRP is much higher in urban than in rural areas, which is consistent with our observations about the UE-BS distances in Fig. 5b. A second exception is T-Mobile in the mainland US. However, note that T-Mobile's 5G RSRP in both urban and rural areas of the mainland US is the highest among the three operators.

When we compare the non-contiguous regions vs. the mainland US, we observe surprisingly that AT&T in urban AK areas offers better LTE signal than all three operators in urban areas of the mainland US. Similarly, Verizon's LTE RSRP in urban AK is similar to the operator's LTE RSRP in urban areas of the mainland US, where Verizon offers the highest LTE RSRP among the three operators. On the other hand, the LTE RSRP for all three operators in rural AK/HI is much lower than the LTE RSRP in rural areas of the mainland US. In the case of 5G, the RSRP for all three operators in the non-contiguous US regions is much lower than in the mainland US, regardless of the area type. The only exception here is AT&T, which surprisingly offers higher 5G RSRP in urban HI than in the urban centers of the mainland US.

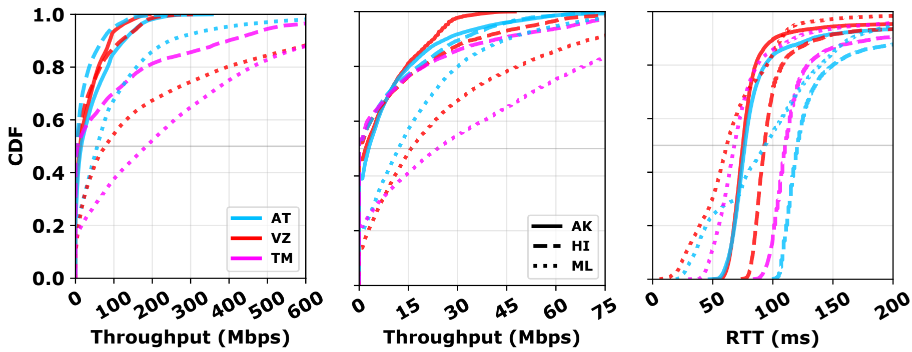
Remarks. Overall, we observe a persistent *digital divide* between the mainland and non-contiguous US regions in terms of 5G coverage, which is further exacerbated in rural areas for two of the three major cellular operators. The disparity is evident not only in the overall 5G coverage but also in the lack of high-speed (5G-mid and mmWave) 5G deployments (with the exception of T-Mobile in HI). While urban areas benefit from better 5G coverage (although still worse than in the mainland US), rural areas continue to face significant challenges, with a heavier reliance on LTE along with sparse deployments, poor signal strength, and frequent "No Service" events.

We also observe different deployment strategies for the three operators in the non-contiguous vs. contiguous US. T-Mobile offers the best 5G coverage in the mainland US, but relies exclusively on roaming partners in AK. AT&T, on the other hand, offers the most extensive 5G coverage in AK and higher coverage than Verizon in HI (although limited to 5G-low), but its 5G coverage in the rural regions of the mainland route is lower than in rural HI.

3.2 Network Performance

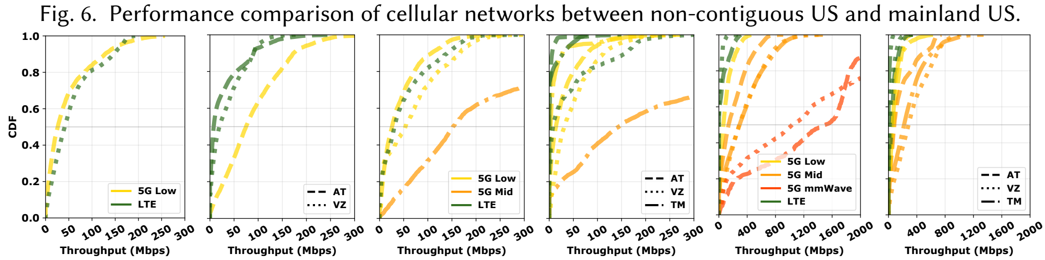
DL Performance. Fig. 6a shows the TCP throughput with each operator in AK, HI, and the mainland route (ML). Our first observation is that there is a significantly high fraction of zero-throughput values for all three operators in the non-contiguous regions. In AK, the fraction of zero-throughput samples for AT&T/Verizon is about 24%/32%. The situation worsens in HI, where the fraction of zero-throughput samples for AT&T/T-Mobile/Verizon is 40%/47%/40%. Notably, the fraction of zero-throughput samples in Fig. 6a is much higher than the percentage of "No Service" coverage in Fig. 3, suggesting that, in certain cases, even if the UE was connected to cellular network, there was practically no data exchange with the network.

In AK, AT&T and Verizon exhibit comparable performance with 50-th/75-th percentiles of 15/67 Mbps vs. 11/49 Mbps, although AT&T's 5G-low coverage yields a higher peak throughput (355 Mbps vs. 193 Mbps). In HI, T-Mobile outperforms the other two operators by a substantial margin, thanks to its 5G-mid service. The 50-th/75-th/100-th percentile with T-Mobile is 6/136/937 Mbps vs. 5/49/306 Mbps for Verizon and 3/26/272 Mbps for AT&T. Despite all operators demonstrating peak DL speeds of hundreds of Mbps, *the overall throughput in both regions remains significantly lower compared to the mainland US*. The 50-th/75-th/100-th percentile on the mainland route is 184/399/1469 Mbps with T-Mobile, 77/308/3154 Mbps with Verizon, and 57/133/2409 Mbps with



(a) TCP DL. (b) TCP UL. (c) RTT.

Fig. 6. Performance comparison of cellular networks between non-contiguous US and mainland US.



(a) AK, urban (b) AK, rural (c) HI, urban (d) HI, rural (e) ML, urban (f) ML, rural

Fig. 8. TCP DL throughput breakdown by technology and area type.

AT&T. Additionally, the fraction of zero-throughput samples on the mainland route is 10-19% for the three operators, much lower than in the non-contiguous US.

In Fig. 8, we break down the DL throughput by cellular technology and area type. We make two observations: (1) The majority of the zero-throughput samples in AK/HI observed in Fig. 6a originate from LTE in rural areas, highlighting the challenges of cellular deployments in such areas. Figs. 5d, 5e show that the LTE RSRP is much lower in rural areas in both regions indicating very sparse deployments. (2) While urban areas exhibit in general higher performance than rural areas, as expected, we observe a notable exception for AT&T in AK. Its 5G-low service performs much better in rural areas, achieving a 50-th/75-th percentile of 75/129 Mbps compared to only 26/65 Mbps in urban areas, despite the similar RSRP in both areas (Fig. 5d). Fig. 7 shows that the number of 5G-low resource blocks for AT&T in rural areas is much higher than in urban areas. This suggests an insufficient deployment of 5G base stations in AK, which cannot meet the higher network demands from denser population in Anchorage and Fairbanks, leading to degraded performance due to contention for network resources among users.

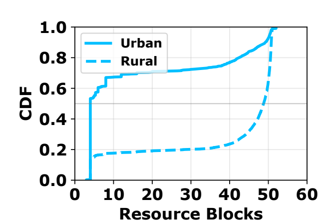
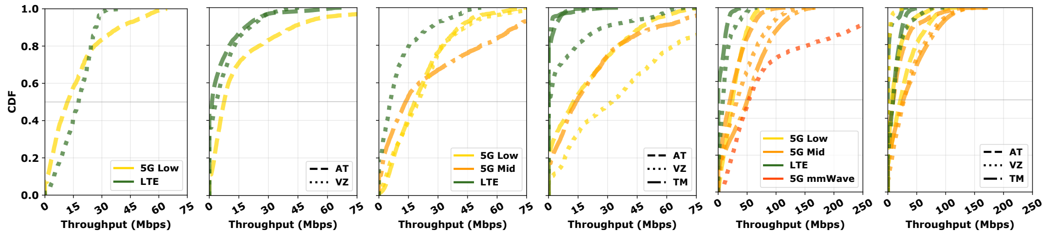


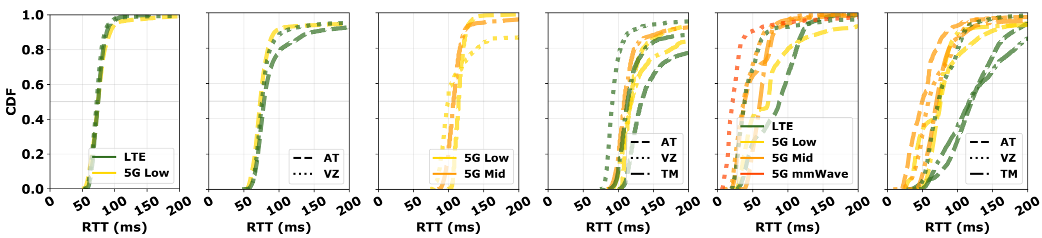
Fig. 7. Resource blocks of AT&T 5G-low in AK.

UL Performance. Fig. 6b shows the UL throughput in AK, HI, and the mainland route. Similar to DL, we notice a significant portion of zero-throughput samples in both non-contiguous US regions (39-46% in AK, 52-53% in HI vs. only 14-22% in the mainland US). In AK, the UL throughput trends are similar to the DL ones, with both operators having roughly similar values – 3/12 Mbps vs. 2/11 Mbps at the 50-th/75-th percentile – and AT&T exhibiting higher peak values. In HI, unlike the DL case where T-Mobile outperformed the other two operators by a substantial margin, T-Mobile and



(a) AK, urban. (b) AK, rural. (c) HI, urban. (d) HI, rural. (e) ML, urban (f) ML, rural

Fig. 9. TCP UL throughput breakdown by technology and area type.



(a) AK, urban. (b) AK, rural. (c) HI, urban. (d) HI, rural. (e) ML, urban. (f) ML, rural.

Fig. 10. RTT breakdown by technology and area type.

Verizon achieve similar UL performance, while AT&T's UL throughput is slightly lower. Despite these variations, *UL TCP throughput across all operators remains significantly lower than in the mainland US*. The median UL throughput is 0 Mbps in HI for all three operators and the gap with the mainland UL throughput at the 75-th percentile is 13-46 Mbps.

A breakdown of the UL TCP throughput based on area type and technology (Fig. 9) again shows that most zero-throughput samples in AK/HI are contributed by LTE in the rural areas. Additionally, for a given operator, regardless of the region, the UL LTE throughput is always lower compared to the 5G counterpart. Interestingly, T-Mobile's 5G midband service does not offer significant advantages in the UL case, due to limited use of Carrier Aggregation [30, 69]. In particular, in rural HI, Verizon's 5G-low service offer much better UL performance than T-Mobile's 5G-mid service. The same observations hold true in the mainland with two notable exceptions for the rural areas: Verizon's 5G-low performs very poorly and AT&T's 5G-mid performs worse than 5G-low. However, 5G-low for Verizon and 5G-mid for AT&T contribute a negligible fraction to the overall cellular coverage of the corresponding operator in rural areas of the mainland US (Fig. 4c).

Network Latency. Fig. 6c shows the RTT of cellular networks in AK, HI, and the mainland route. We observe that *the RTT values for Verizon in AK and all three operators in HI are much higher than in the mainland US* (by 14 ms in AK and 26-42 ms in HI in the median case). The higher latency in non-contiguous US regions, especially for HI, can largely be attributed to the longer UE-server distance compared to the mainland US (recall that we used the same server in OR for all our measurements). Additionally, the Wavelength edge servers in three mainland cities further reduce the RTT for Verizon in the mainland US. Our results show a need for deployment of edge servers in non-contiguous US regions to reduce the end-to-end latency and improve the QoE of different latency-critical apps. Interestingly, AT&T exhibits very high RTTs along the mainland US route. AT&T's RTT in the mainland is similar to Verizon's RTT in HI in the median case (94 ms vs.

92 ms), and higher than both Verizon's and T-Mobile's RTT in HI at the 75-th percentile (129 ms vs. 100/123 ms), suggesting that the operator de-prioritizes ICMP traffic in the mainland US.

In AK, the RTT trends align with the throughput trends, with Verizon and AT&T exhibiting similar RTT values, despite Verizon offering only LTE service (Fig. 3a). Similarly, in HI, Verizon offers the lowest RTT despite its limited 5G coverage (Fig. 3b) compared to the other two operators. In particular, T-Mobile's RTT is much higher than Verizon's, despite the extensive 5G midband coverage, suggesting that T-Mobile de-prioritizes non-heavy ICMP ping traffic in HI.

We further break down the latency by technology and area type in Fig. 10. We make two observations. First, for a given operator, its 5G service does not always offer lower latency compared to its LTE service in the non-contiguous US (5G-low for AT&T in urban AK and T-Mobile in rural HI). In contrast, 5G offers always better RTT than LTE in the mainland US. In particular, Fig 10f shows that the LTE RTT with AT&T and T-Mobile is very high in mainland rural US areas. Recall that LTE contributes substantially to AT&T's overall coverage in mainland rural areas but only a negligible fraction to T-Mobile's overall coverage (Fig. 4). This explains the overall high RTT for AT&T in the mainland US in Fig. 6c. Second, the latency, in particular the peak values (upper quartile) typically increases substantially in rural areas compared to urban areas. The only exception is Verizon in HI, where its LTE service in rural areas offers lower latency than its 5G-low service in urban areas.

Remarks. In summary, we observe significant performance disparities between non-contiguous US regions and the mainland US in terms of both throughput and latency, which reinforce the digital divide we highlighted in §3.1. Frequent zero-throughput occurrences, particularly in rural areas, even when the UE is connected to the network, and sparse 5G deployments resulting in high contention for network resources and lower performance compared to LTE, highlight ongoing challenges. Network latency is a more complex issue. Greater UE-server distances increase the latency in non-contiguous US compared to the mainland US; however, operator policies related to de-prioritization of ICMP traffic for certain technologies in different regions further complicate the matter. Overall, these findings underscore the need for improved infrastructure and localized edge servers to bridge the performance gap with the mainland US.

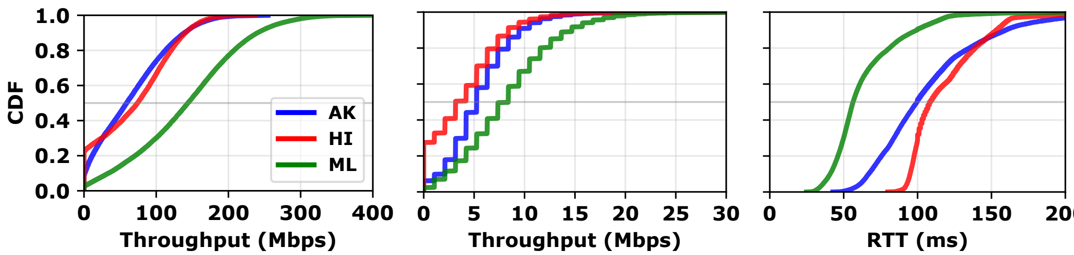
4 Starlink in Non-Contiguous US Regions

LEO satellite networks, offering higher throughput and lower latency than traditional geostationary satellites, have recently gained traction as an alternative Internet access technology, particularly in remote and underserved regions with poor wired/wireless connectivity. In this section, we conduct the first study of the performance of Starlink, the most popular LEO satellite network, in non-contiguous US regions, and compare it against the performance in the mainland US.

4.1 Background

The routing topology of the Starlink network consists of a mix of space and terrestrial paths. The Starlink architecture has four primary components: (a) Starlink constellation with thousands of LEO satellites connected via inter-satellite links (ISLs) for communication between satellites, (b) Ground stations (GSs), which connect satellites to terrestrial infrastructure via fiber, (c) Starlink backbone network, which consists of a hierarchical structure of Points of Presence (PoPs) and Internet Exchange Points (IXPs), enabling internal and Internet-bound connectivity, and (d) user terminals, which directly communicate with satellites to gain Internet access.

Starlink relies on a "bent-pipe" design, where satellites reflect signals between terminals and ground stations. However, when there is no GS in the coverage area of a LEO satellite, ISLs may be utilized to relay the traffic to a neighboring satellite and eventually transmit the data to a nearby GS. The Starlink constellation operates on multiple orbital planes at varying inclinations and altitudes.



(a) TCP DL. (b) TCP UL. (c) RTT.

Fig. 12. Comparison of Starlink performance between non-contiguous US and mainland US.

Different orbital planes have different number of satellites deployed. As of July 2025 [48], the 43° and 53° inclination orbits, which serve the mainland US and HI, have 7,121 satellites deployed. In contrast, AK is primarily served by the 70° and 97.6° inclination orbits, which have 617 and 293 satellites deployed, respectively.

4.2 Regional Allocation of Starlink PoPs

For network performance analysis, knowing the locations of PoPs is important, as they indicate where packets enter or exit an operator's network. This, in turn, determines the routing distance and the minimum round-trip time to target servers. However, obtaining PoP locations in cellular networks is challenging due to the absence of publicly available information and the limited availability of DNS PTR records [70]. In contrast, Starlink offers greater transparency. It provides DNS PTR records for user-assigned IPs and includes location hints of the associated PoPs in the hostnames, as discussed in § 2. In this section, we examine how Starlink PoPs are allocated to UEs along our measurement route across different regions of the US.

We visualize links from UE's locations to PoP locations in Fig. 11. In general, all observed Starlink PoPs are located within the mainland US. For Alaska, only a single PoP, located in Seattle, was used. In contrast, for the island of Maui, Hawaii, we observe two PoPs, located in Los Angeles and San Jose, respectively. Interestingly, the allocation of these two PoPs to Maui appears evenly split across the measured points on the island. We conjecture that this may be due to similar distances to both PoPs (approximately 3,800–4,000 km), or possibly due to Starlink employing load-balancing strategies. Along the route from Los Angeles, CA to Omaha, NE, we observe three PoP locations: Los Angeles, Salt Lake City, and Denver. Starlink appears to assign each PoP to cover a distinct surrounding area, with each PoP acting as a central hub. Moreover, we observe no overlap in coverage between different PoPs.

Fig. 11. Regional allocation of Starlink PoPs in AK, HI, and mainland US.

4.3 Network Performance

Fig. 12 provides a comprehensive comparison of Starlink performance, including DL throughput, UL throughput, and latency, in AK, HI, and mainland US. Figs. 12a, 12b show that the median DL/UL throughput is comparable in both non-contiguous US regions (HI exhibits slightly higher DL throughput and slightly lower UL throughput) and Fig. 12c shows that Starlink's RTT is higher

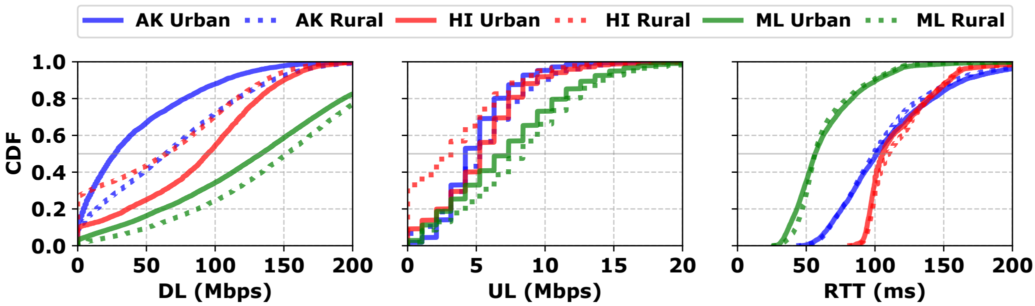


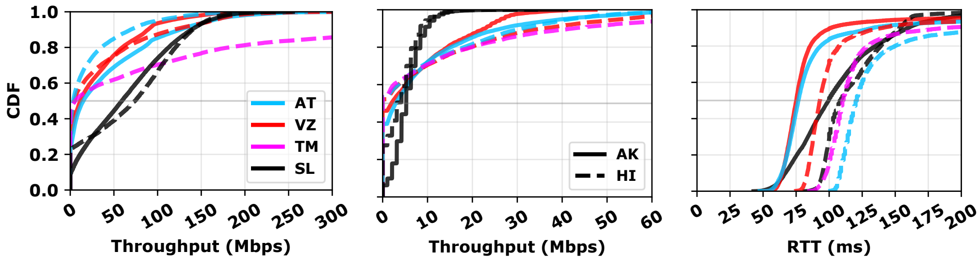
Fig. 13. Starlink performance breakdown in urban and rural areas.

in HI than in AK. This is expected, since the UE-server distance is longer in HI than in AK. These figures also show that *Starlink on the mainland route demonstrates exceptionally strong performance in terms of all metrics compared to the non-contiguous regions.* First, it maintains near-perfect connectivity. The fraction of zero-throughput samples on the mainland route is only 2.6%/2.4% in the DL/UL direction, in stark contrast to the 9.4%/6.2% of zero-throughput samples observed in AK and 22.4%/27.5% in HI. Second, it offers superior performance compared to AK and HI, particularly in the DL direction. The median improvement is 85/3.2 Mbps in the DL/UL direction compared to AK and 69/5.2 Mbps compared to HI. Third, it achieves the lowest latency among the three regions – lower than 50 ms about 30% of the time, with a 50-th/75-th percentile of 56/74 ms vs 100/125 ms in AK and 109/133 ms in HI.

The lower Starlink performance in AK compared to the mainland US is probably due to the different inclination orbits serving the two regions. As mentioned in §4.1, AK is served by the 70° and 97.6° inclination orbits, which have only a few 100s of satellites, in contrast to the 43° and 53° inclination orbits serving the mainland US, which have 7,000+ satellites. The much sparser satellite deployment in AK possibly results in coverage gaps and service interruptions, as well as high queuing delays as the user terminal queues packets until it locates a nearby satellite. On the other hand, HI is served by the same inclination orbits as the mainland US. However, the high number of zero-throughput samples in HI suggests areas of heavy occlusion, which disrupt performance. Finally, the RTT in the mainland is lower than in AK/HI due to the much shorter UE-server distances on the mainland route compared to the non-contiguous regions. Using rough calculations and the PoP locations in Fig. 11, we estimate the distance from Maui to the AWS server in Boardman, OR via the PoP in San Jose/LA to 4,752/5,326 km, corresponding to a one-way propagation latency of 24-27 ms,[2] and the UE-server distance from Anchorage/Fairbanks in AK via the PoP in Seattle to 2,589/2,723 km (13-14 ms). In contrast, the UE-server distance on the mainland route varies between 2,159 km (when the UE is in Omaha via the PoP in Denver) and 847 km (when the UE is in Salt Lake City using the PoP in the same city), corresponding to a propagation delay of only 4-11 ms. The much higher RTT in the non-contiguous US, particularly in HI, can also affect TCP performance.

The much higher fraction of zero-throughput samples in HI compared to AK is counter-intuitive, as HI is served by the 43/°53° inclination orbits consisting of a much denser constellation of satellites, compared to the 70° and 97.6° inclination orbits serving AK. To investigate this, we break down Starlink's performance based on area type in Fig. 13. It shows that Starlink throughput exhibits different trends for the two regions. In AK (and the mainland US), Starlink DL/UL performance is higher in rural areas. This is expected and in line with the findings of previous studies [34], as tall

[2]assuming a propagation speed equal to 2/3 the speed of light in vacuum [65]



(a) TCP DL. (b) TCP UL. (c) RTT.

Fig. 15. Starlink vs Cellular performance comparison in non-contiguous US.

buildings in urban areas cause occlusion to the satellite signal and degrade the performance. In contrast, in HI, the performance is higher in urban areas. We conjecture that this counterintuitive result stems from HI's unique terrains. Unlike AK's urban areas (Anchorage and Fairbanks), the urban areas of Maui, HI are characterized by the absence of vertical constructions. On the other hand, a large part of Maui's rural areas are covered by dense rain forests, leading to higher levels of occlusion.

Fig. 14 supports our conjecture, showing the outage rate reported by the Starlink gRPC API – the fraction of outage duration relative to the total measurement duration in each region. The results show a significantly higher outage rate of 11.8% in rural HI, compared to just 0.3-2.5% across other combinations of region and area type. Note that an outage is reported only when the signal is 100% blocked. Given that rural areas in HI have a higher outage rate, we conjecture that the overall signal degradation was much higher due to occlusion, leading to worse performance in the rural areas of HI and a higher fraction of zero-throughput samples.

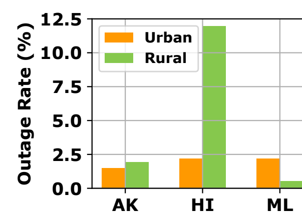


Fig. 14. Starlink outage rate in urban and rural areas.

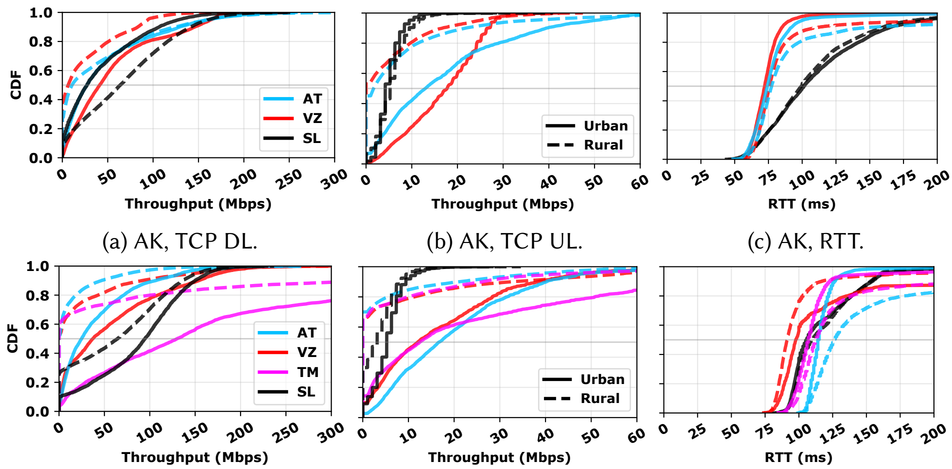
Fig. 13 also shows that the RTT is unaffected by the area type in all three regions. This is in contrast to cellular networks, where operator prioritization policies for different cellular technologies can result in drastic differences between the urban and rural RTTs (Fig. 10).

Remarks. In summary, similar to cellular networks, our analysis in this section reveals significant disparities in Starlink performance between the non-contiguous US regions and the mainland US, due to area-specific challenges, including unique terrains in Hawaii and sparse satellite deployment in Alaska. Additionally, the longer UE-server distances in the non-contiguous US compared to the mainland US significantly inflate the RTT in those regions.

5 Cellular Networks vs. Starlink in Non-Contiguous US Regions

In the previous two sections, we showed that both cellular networks and Starlink face unique challenges in the non-contiguous US regions and their performance is significantly lower than in the mainland US. In this section, we compare the performance of the two technologies in the non-contiguous US regions, and discuss their spatiotemporal diversity.

DL Performance. Fig. 15a compares the TCP DL throughput of Starlink (SL) and the 3 cellular operators in AK and HI. We make two observations. First, *Starlink consistently outperforms AT&T and Verizon in both regions and outperforms T-Mobile in HI 71% of the time*. However, T-Mobile's extensive 5G midband coverage in HI allows it to achieve a peak throughput of 937 Mbps, whereas Starlink's throughput is capped at 237 Mbps. Second, in both regions, Starlink has a lower fraction of zero-throughput samples than the 3 cellular operators – 9% vs. 24-32% in AK, 22% vs. 40-47% in



(a) AK, TCP DL. (b) AK, TCP UL. (c) AK, RTT.

(d) HI, TCP DL. (e) HI, TCP UL. (f) HI, RTT.

Fig. 16. Starlink vs Cellular performance breakdown by area type in non-contiguous US.

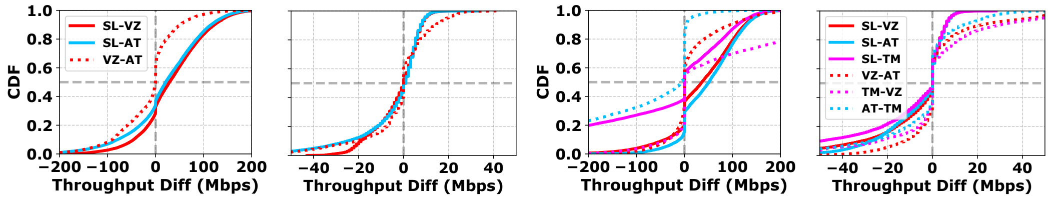
HI. These numbers suggest that *Starlink delivers more consistent connectivity than cellular networks in the non-contiguous regions, but does not completely eliminate outage periods.*

In Fig. 16, we break down the performance based on area type. In AK (Fig. 16a), Starlink significantly outperforms both cellular networks in rural areas, with a median DL throughput of 64 Mbps vs. only 11/6 Mbps for AT&T/Verizon. In urban areas, Starlink performs similarly to AT&T (27 Mbps in the median case) despite its 5G service (recall from Fig. 8a that AT&T's 5G-low service performs poorly in AK urban areas), but performs worse than Verizon' LTE service (27 Mbps vs. 41 Mbps in the median case).

In HI (Fig. 16d), Starlink significantly outperforms AT&T and Verizon in both urban and rural areas, yielding a median throughput of 94/65 Mbps in urban/rural areas vs. 37/0 Mbps for Verizon and 25/0 Mbps for AT&T. It also reduces the fraction of zero-throughput samples significantly in rural areas (26% vs. 53/52% for Verizon/AT&T), but it has a higher fraction of zero-throughput in urban areas, (9.7% vs. 5.5/6.0% for Verizon/AT&T). On the other hand, T-Mobile 's extensive 5G-mid coverage outperforms Starlink in urban areas (130 Mbps vs. 94 Mbps in the median case) and offers higher peak rates (above the 80-th percentile) than Starlink in rural areas. However, Starlink offers much more consistent coverage in rural areas, with a median throughput of 65 Mbps vs. 0 Mbps for T-Mobile and an outage rate of 26% vs. 61%.

UL Performance. Fig. 15b compares the UL throughput of Starlink and the 3 cellular networks. Unlike in the DL case (Fig. 15a), where Starlink largely outperformed the cellular networks, we observe a different picture in the UL case. Starlink's UL throughput is very low (only 5/3 Mbps in the median case in AK/HI) and lower than the cellular throughput about 36-38% of the time. Additionally, Starlink's TCP UL throughput peaks at 41/35 Mbps in AK/HI, while cellular TCP UL throughput can reach up to 47-111 Mbps in AK and 96-174 Mbps in HI. Recall that our UL TCP tests were done with Cubic, which is less resilient to packet losses compared to BBR (used for DL tests), and is probably contributing to Starlink's low UL performance.

Nonetheless, Starlink still eliminates a significant fraction of outage (or near-outage) periods compared to cellular networks. Starlink's fraction of zero-throughput samples is 6%/27% in AK/HI vs. 39-46%/52-53% for cellular networks. The performance breakdown based on area type (Figs. 16b,



(a) AK, TCP downlink. (b) AK, TCP uplink. (c) HI, TCP downlink. (d) HI, TCP uplink.

Fig. 17. CDF of throughput differences between operators at the same time and location.

Table 1. Fraction of concurrent outage time for each network pair. Numbers in () denote the fraction of outage time for each network individually.

		SL+AT	SL+VZ	SL+TM	AT+VZ	VZ+TM	TM+AT
DL	AK	3 (10, 21)	5 (10, 29)	N/A	13 (21, 29)	N/A	N/A
	HI	14 (21, 39)	17 (22, 40)	18 (23, 45)	26 (39, 37)	34 (45, 40)	30 (42, 39)
UL	AK	3 (5, 32)	2 (4, 35)	N/A	18 (29, 30)	N/A	N/A
	HI	16 (20, 40)	19 (24, 44)	19 (23, 43)	33 (43, 41)	28 (40, 36)	32 (42, 41)

16e) shows that cellular networks significantly outperform Starlink in urban areas in both non-contiguous US regions, while the trends for the rural areas are similar to those observed for the overall performance (in Fig. 15b).

Network Latency. Fig. 15c compares the latency of Starlink and cellular networks in AK and HI. We observe that Starlink's latency is significantly higher than the cellular latency in AK (100 ms vs. 75-77 ms in the median case) and falls between the best and worst latency observed among the cellular operators in HI (109 ms vs. 93/110/121 ms for Verizon/T-Mobile/AT&T in the median case).

As we mentioned previously, Starlink's latency is not affected by the area type (Fig. 13), while the cellular network RTT is affected significantly in HI, due to different distribution of cellular technologies in rural vs. urban areas (Fig. 10). Fig 16c shows that Starlink's RTT is always worse than the cellular network RTT in AK, regardless of area type. In HI urban areas (Fig 16f), AT&T and T-Mobile have more consistent RTTs than Starlink, outperforming Starlink about 40% of the time, but lagging behind about 60% of the time. In rural areas, AT&T has the worst RTT among all four operators, while T-Mobile and Starlink have similar RTT, although T-Mobile has higher worst case RTT (586 ms vs. 160 ms at the 95-th percentile). On the other hand, Verizon has the lowest RTT among the four operators in both area types.

Network Diversity. Up till now, our analysis has focused on the individual performance of Starlink and cellular networks in the two non-contiguous US regions. However, we have not yet explored how cellular and Starlink performance vary at a given time and location. To gain deeper insights into this spatiotemporal variation, we analyze the throughput difference of concurrent throughput samples for a given operator pair in Fig. 17.

Fig. 17 shows a significant diversity in performance for any given network pair in both traffic directions and both regions. The throughput difference between any network pair is often higher than 50 (10) Mbps and can exceed 150 (20) Mbps in the DL (UL) direction. Additionally, the throughput difference between Starlink and any cellular operator for concurrent throughput tests is negative 15-35% of the time in the DL direction and 45-50% of the time in the UL direction, suggesting that Starlink is unable to consistently provide better performance. This result indicates *a great potential for multipath transport to improve overall performance.*

Additionally, Table 1 presents the fraction of time during which both networks in a given network pair *simultaneously* experience an outage (0 Mbps throughput), as well as the fraction of outage times for each individual network. We clearly observe that the fraction of concurrent outage for any network pair is much lower than when we consider any network in isolation, suggesting again that leveraging multipath transport can greatly enhance connectivity.

Table 1 further shows that combining Starlink with a cellular network nearly eliminates outage events in AK, but not in HI, where the faction of concurrent outage events still ranges from 14% to 19%, indicating areas where no network is available. Nonetheless, in both regions, combining Starlink with a cellular network results in lower numbers of concurrent outage events compared to combining any two cellular networks, suggesting that *the use of two different network technologies has a greater potential to improve connectivity than relying solely on cellular infrastructure*.

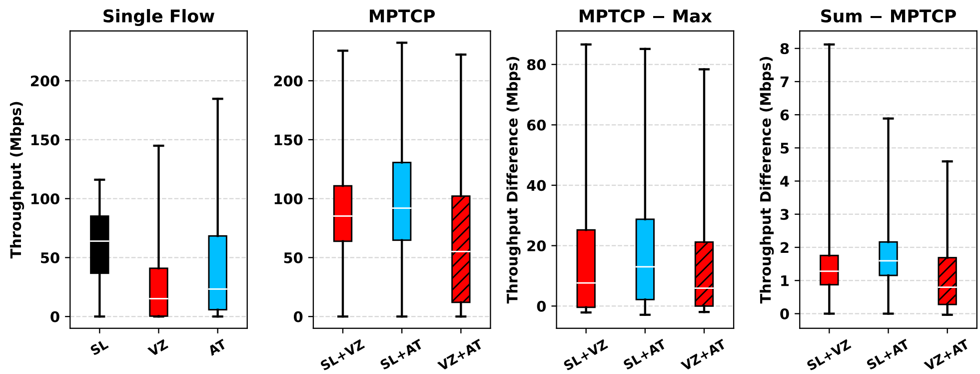
Remarks. In summary, our results demonstrate Starlink's potential to close the digital divide in non-contiguous US regions, offering improved connectivity and substantially higher DL throughput compared to cellular networks that rely on LTE or 5G-low service. Nonetheless, there is still a lot of room for improvement. Zero-throughput periods are still present (although less frequent compared to cellular networks), Starlink's DL throughput is lower than 5G-mid's throughput and its UL throughput is often lower than that of cellular networks, and higher RTTs compared to cellular networks are often observed, particularly in AK. These limitations are the result of both special terrain and geographical characteristics of the two non-contiguous US regions (e.g., dense rain forests in HI and lower satellite availability in AK, which falls outside the $43^o/53^o$ inclination orbit) and inherent challenges in LEO satellite networks, such as packet loss and congestion control inefficiencies, which are less pronounced in terrestrial networks. Our spatiotemporal analysis revealed substantial diversity in performance for any given pair of networks in both non-contiguous US regions, suggesting that multipath transport has a great potential to improve the overall user performance. We explore this potential in the next section.

6 Satellite and Cellular Network Synergy in the Non-Contiguous US

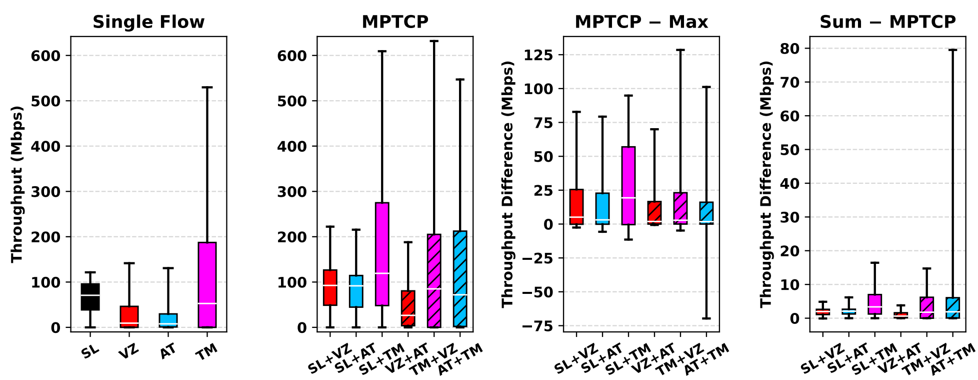
Given the inherent limitations of both cellular deployments and the Starlink network in the non-contiguous US regions, it is natural to consider multipath transport as a means for enhancing both performance and reliability in these regions. In this section, we evaluate the benefits of multipath transport using MPTCP [52], the most widely used multipath transport protocol [12, 13, 19, 32, 34, 39, 59, 60, 62, 64]. We compare the performance of MPTCP vs. single-path TCP via trace-driven emulation using iperf on MpShell [13], a variant of Mahimahi [57], following the methodology in [34].

Experimental methodology. We use the DL and UL throughput traces from our driving datasets in AK and HI and convert them to packet traces for replay on MpShell. Since the traces were collected simultaneously with different phones over different networks, they reflect the network conditions experienced by a user at the same location and time. We ran two types of emulation in the MpShell environment: (1) Single-path emulation, where MPTCP is disabled and two iPerf clients communicate with an iPerf server individually over different MpShell interfaces; (2) MPTCP emulation, where a single iPerf client communicates with an iPerf server over both MpShell interfaces using MPTCP.

For MPTCP, we experimented with different schedulers and congestion control algorithms. We found that the packet scheduler has minimal impact on performance, but BBR significantly outperforms all the other congestion control algorithms (Cubic, LIA [11], OLIA [39], BALIA [59]). Hence, we show in the following the results with the default scheduler, BLEST [19], and BBR. For a fair comparison, we also use BBR for the single-path TCP results. Similar to [34], we found that MPTCP brings minimal gains over single-path TCP with the default buffer size. Hence, we ran the



(a) AK.



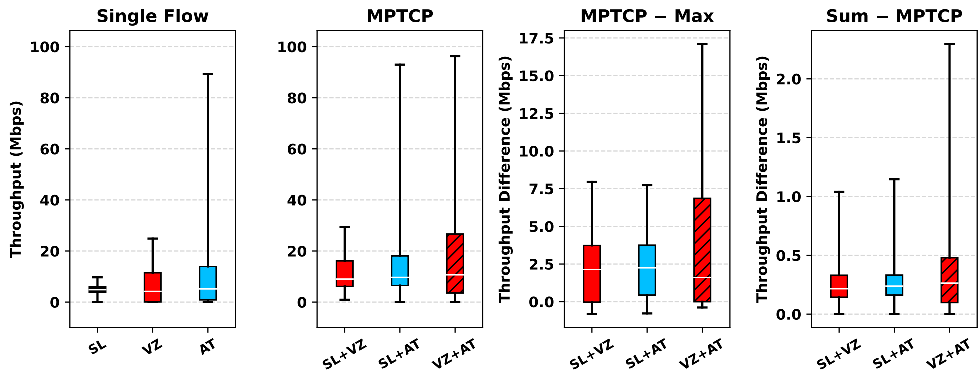
(b) HI.

Fig. 18. MPTCP vs. single-path TCP DL throughput comparison.

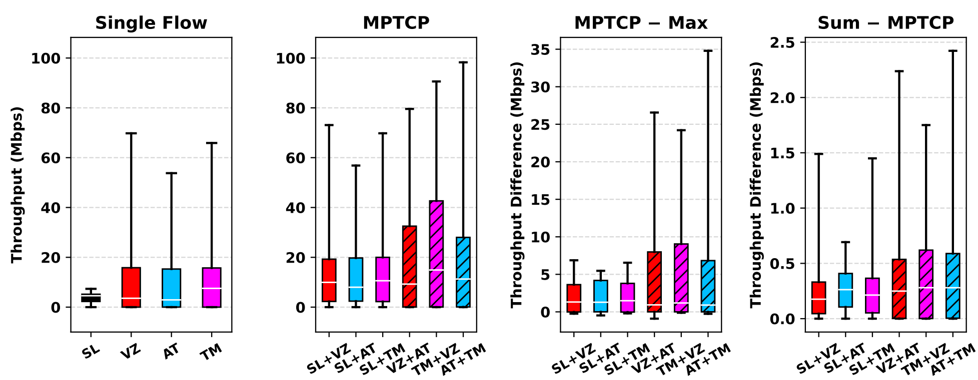
emulation with a buffer of 450 MB for both MPTCP and single-path TCP, same as in our driving tests. Finally, for each operator, we set the RTT equal to the minimum RTT extracted from our AK and HI ICMP ping measurements. This represents the default RTT (propagation delay). Changes to the RTT, e.g., due to congestion or packet losses, are reflected in the packet timestamps used to drive the emulation.

DL throughput. Fig. 18 shows boxplots of the single-path DL throughput of all networks and the MPTCP throughput for every pair of networks in AK and HI, respectively. We also evaluate the difference between the MPTCP throughput and the single-path throughput over the best path (*MPTCP − Max*). Recall that one of the three main goals in the design of MPTCP (RFC 6536 [11]) is that the MPTCP throughput should be higher than the single-path throughput over the best path. Finally, to evaluate how close MPTCP's performance is to the optimal performance, we plot the difference between the sum of the two single-path throughputs and MPTCP's throughput (*Sum − MPTCP*).

In AK (Fig. 18a), MPTCP provides a substantial increase in performance when Starlink is combined with either of the cellular operators, compared to using a single network, while it also reduces the outage time to less than 1%. The median MPTCP throughput is 85 Mbps for SL+VZ and 92 Mbps for SL+AT vs. 64/15/23 Mbps for SL/VZ/AT alone. More importantly, the 25-th percentile of the MPTCP throughput is 64 Mbps for SL+VZ and 65 Mbps for SL+AT vs. 37/0.3/6 Mbps for SL/VZ/AT alone.



(a) AK.



(b) HI.

Fig. 19. MPTCP vs. single-path TCP UL throughput comparison.

These improvements are particularly valuable in rural areas, where cellular networks frequently fail to provide connectivity. On the other hand, combining two cellular operators is less effective; the median MPTCP throughput for VZ+AT is only 55 Mbps, much lower than when one of the two cellular networks is combined with Starlink. More importantly, the 25-th percentile remains very low (12 Mbps) due to the large fraction of concurrent zero-throughput samples (Table 1).

We make two additional observations from Fig. 18a for every pair of networks: (i) MPTCP consistently provides performance better than or almost as good (within 2-3 Mbps) as the single-path performance of the best network. (ii) MPTCP's performance is very close to the theoretical optimal; the 75-th percentile of *Sum − MPTCP* is less than 3 Mbps for all three pairs of networks.

In HI (Fig. 18b), we observe trends similar to AK, but with two key differences. First, both Starlink and cellular networks in HI experience a higher fraction of zero-throughput samples and a higher fraction of concurrent outage time compared to AK (Table 1). As a result, combining Starlink with Verizon or AT&T brings moderate benefits in the median case compared to using Starlink alone, increasing the median throughput from 71 Mbps (with SL) to 93/92 Mbps (using SL+VZ/SL+AT). Second, T-Mobile's 5G mid-band coverage in HI leads to significantly higher gains for multipath transport. MPTCP with T-Mobile as one of the networks provides the highest best-case performance, surpassing 200 Mbps at the 75-th percentile and offering peak throughput of

500-600+ Mbps. However, combining T-Mobile with another cellular network still yields lower median throughput and significantly lower worst-case throughput (0-2 Mbps at the 25-th percentile) compared to combining Starlink with Verizon or AT&T. This result suggests that *combining Starlink with cellular networks has the best potential to simultaneously boost both performance and reliability.*

Fig. 18b shows that, similar to AK, MPTCP in HI consistently improves the performance over the best path (the 25-th percentile of $MPTCP - Max$ is 0 for all pairs of networks), although there are some notable exceptions, especially in the case of AT+TM. Also, MPTPC generally performs again quite close (but not as close as in AK) to the optimal most of the time, although again there are some notable exceptions. These exceptions include T-Mobile as one of the two networks, which often offers much higher throughput than the other operators (Fig. 15a) thanks to its 5G-mid service, confirming the well-known results that MPTCP performs suboptimally in the case of highly heterogeneous paths.

UL throughput. Fig. 19 shows the results for UL throughput. Similar to DL, multipath transport also shows great potential in improving UL performance. In contrast to DL, here combining two cellular networks yields similar median performance and higher best-case performance (above the 75-th percentile) compared to combining Starlink with a cellular network, as cellular networks often achieve higher UL throughput than Starlink (Fig. 15b). On the other hand, combining Starlink with a cellular network still offers higher reliability, thanks to the higher Starlink availability (lower fraction of zero-throughput samples). In particular in HI, Fig. 19b shows that all 3 pairs of cellular networks yield 0 Mbps at the 25-th percentile with MPTCP, while the combination of Starlink with a cellular network yields non-zero throughput at the 25-th percentile. Interestingly, MPTCP always achieves near-optimal performance in the UL direction in both regions. The max value for $Sum - MPTPC$ never exceeds 2.5 Mbps.

Remarks. In summary, multipath transport can provide significant improvements in terms of both performance and reliability, leveraging the complementary characteristics of Starlink and cellular networks. In the DL direction, combining Starlink with a cellular network shows the greatest potential, as it can simultaneously boost throughput and reliability, thanks to Starlink's superior performance and higher availability compared to cellular networks. On the other hand, in the UL direction, Starlink's lower TCP throughput compared to cellular networks introduces an interesting tradeoff between performance and reliability. Combining two cellular networks shows greater potential in improving the best-case performance, while combining Starlink with a cellular networks still offers higher reliability.

7 Related Work

5G Measurement Studies. A large number of measurement studies have evaluated various aspects of 5G including performance [6, 8, 9, 21, 28–31, 40, 42, 51, 53, 56, 58, 61, 67, 68], latency [20], handovers [23, 33, 37], carrier aggregation [69], resource allocation [14], power consumption [56], impact on application QoE [28, 30, 41, 56], beamforming [18, 55], roaming [22], multi-carrier access [10], and throughput prediction [7, 54, 69]. The works closest to ours are [6, 10, 28–30, 33], in which the authors perform extensive cross-country drive tests to characterize 5G coverage and performance, handovers, and multi-carrier access techniques. However, all these studies have been conducted either in the mainland US or in European cities. No work, to our best knowledge, has studied cellular network coverage and performance in the non-contiguous US.

Starlink Measurement Studies. Since the launch of Starlink, several recent experimental studies have characterized various aspects of its performance [4, 25, 35, 38, 43–45, 49, 50, 71]. While studies such as [4, 25, 35, 44, 45, 49, 71] broadly analyze Starlink's network performance in different regions of the world via targeted or crowd-sourced measurements, others like [38, 43, 71] evaluate Starlink's suitability for specific applications and services. However, all prior studies were done in the mainland US, parts of Africa, Asia, or Europe, and with the exception of [44], only conducted static measurements. Except for limited crowd-sourced measurements in Alaska conducted by [50], no existing study provides a comprehensive evaluation of Starlink's coverage and performance under driving in the non-contiguous US.

Synergy between Starlink and Cellular Network. A handful of works [27, 28, 34, 45–47] have performed a head-to-head analysis of Starlink networks with terrestrial cellular networks. Among them, [27, 28, 34] use a measurement methodology similar to ours, conducting measurements during cross-country drives, and [34] is the only work other than ours, which explores the potential synergy between Starlink and cellular networks via multi-link access techniques. However, none of these works have systematically evaluated the coverage and performance of Starlink and terrestrial cellular networks in the non-contiguous US or explored the digital divide in these regions. Our work addresses precisely these gaps.

8 Conclusion

This work presents the first comprehensive evaluation and head-to-head comparison of cellular and Starlink networks in the non-contiguous US, through extensive drive tests covering over 4200+ km in AK, HI, and the mainland US. Our results show a stark difference in cellular network coverage and performance between the non-contiguous and the mainland US, labeling a clear digital divide between the two regions. Starlink provides higher DL throughput and better network availability than cellular networks, but its UL TCP throughput and latency are often inferior to those of cellular networks. Additionally, unique terrains in HI and sparse satellite deployment in AK degrade Starlink performance in the non-contiguous US compared to the mainland US. Finally, our evaluation of MPTCP's performance via trace-driven emulation reveals that multipath transport shows great potential in bridging the connectivity gap in non-contiguous US regions, improving both performance and network reliability, and motivates further study towards this direction.

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